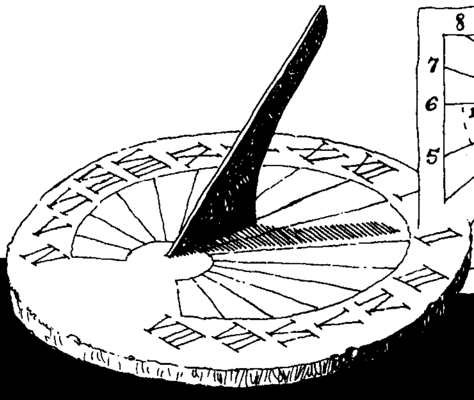
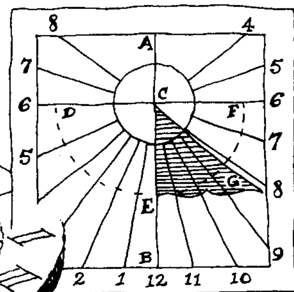
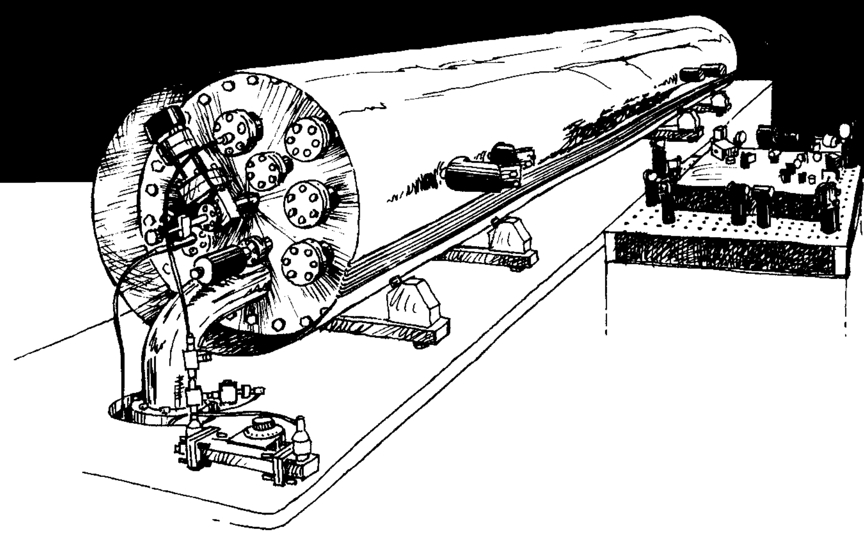
**James Jespersen and Jane Fitz-Randolph**





# From Sundials To Atomic Clocks



## Understanding Time and Frequency

U.S. Department of Commerce • Technology Administration
National Institute of Standards and Technology

Monograph 155, 1999 Edition

# From Sundials To Atomic Clocks

## Understanding Time and Frequency

**James Jespersen and Jane Fitz-Randolph**

Illustrated by John Robb and Dar Miner

March 1999

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

TECHNOLOGY ADMINISTRATION
Gary R. Bachula, Acting Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Raymond G. Kammer, Director

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## Contents

## III. FINDING AND KEEPING THE TIME



## IV. THE USES OF TIME



## V. TIME, SCIENCE, AND TECHNOLOGY

# PREFACE

It has been two decades since the first edition of this book appeared. Over that time launching artificial satellites has become routine, computers have become household items, digital messages routinely travel between cities and nations by communication satellites and optical fibers, astronomers have identified black holes, and researchers have learned to manipulate individual and small groups of atoms. These changes have had a profound impact on the arts of time keeping and distribution and on our understanding of the nature of time and space.

In this new edition I have attempted to deal with these matters, and many others, by introducing six new chapters and by making numerous changes and additions to the chapters from the first edition.

In the beginning I imagined this book would be of most use and interest to a general audience. In that regard it offered an eclectic, too eclectic I sometimes thought, introduction to time, timekeeping, and the uses of time, especially in the scientific and technical areas. But as I soon discovered, many of my colleagues referred to the book, on occasion, to brush up on an item here and there. Perhaps this is not surprising. The business of generating, maintaining and applying time and frequency technology is a vast enterprise. Although this second edition does not pretend to give an in-depth, textbook presentation, I hope it still maintains scientific integrity while continuing to be comprehensible to the general reader.

Finally, in 1988, the National Bureau of Standards (NBS) was renamed the National Institute of Standards and Technology (NIST). Where historically appropriate I refer to NBS, otherwise the current designation, NIST, is used.

James Jespersen
March 1999

## ACKNOWLEDGEMENTS

As I said in the preface, time and frequency is a vast subject which no single person can be expert in. Therefore this book could not have been written without the help and support of many people. The first edition benefited greatly from the encouragement and suggestions of James A. Barnes who first conceived the idea of writing this book. That first edition also came under the scrutiny of George Kamas who played the role of devil's advocate. Critical and constructive comments came from others who helped to extend and clarify many of the concepts. Among those were Roger E. Beehler, Jo Emery, Helmut Hellwig, Sandra Howe, Howland Fowler, Stephen Jarvis, Robert Mahler, David Russell, Collier Smith, John Hall, William Klepczynski, and Neil Ashby. Finally, Joanne Dugan, diligently and good naturedly prepared the manuscript in the face of a parade of changes and rewrites.

Like the first edition, the second edition owes much to a host of people. First, Don Sullivan, Chief of the Time and Frequency Division of the National Institute of Standards and Technology, like his predecessor Jim Barnes, provided continuing support and much beneficial criticism. Without his efforts this second edition would have not materialized. Matt Young, with his ever present eagle eye, found more ways to improve the book than I ever could have imagined. Barbara Jameson brought coherence to many a disjointed thought while Edie DeWeese corrected many a miscue.

I also thank the following people for their useful and critical comments on individual chapters: Fred Walls, Mike Lombardi, Dave Wineland, Marc Weiss, Chris Monroe, John Bollinger, and Jun Liang.

Much of the success of the first edition was due to the novelty and ingenuity of the art work. Fortunately, for me, Dar Miner has been able to continue that tradition.

Last, but not least, hurrahs to Gwen Bennett who not only prepared the manuscript, but deciphered my practically undecipherable scribbling.

## DEDICATION

The authors dedicate this book to the many who have contributed to humanity's understanding of the concept of time, and especially, to Andrew James Jespersen, father of one of the authors, who—as a railroad man for almost 40 years—understands better than most the need for accurate time, and who contributed substantially to one of the chapters.

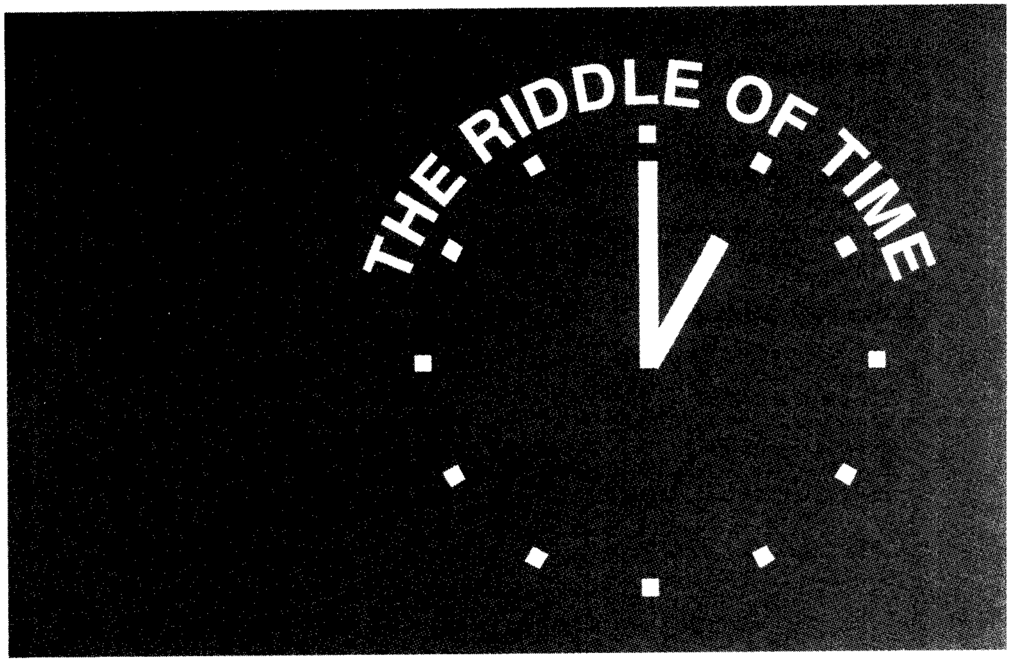
## PREFACE TO FIRST EDITION

This is a book for laymen. It offers an introduction to time, timekeeping, and the uses of time information, especially in scientific and technical areas. It is impossible to consider time and timekeeping without including historical and philosophical aspects of the subject, but we have merely dabbled in these. We hope historians and philosophers will forgive our shallow coverage of their important contributions to humanity's understanding of time, and that scientists will be forbearing toward our simplified account of scientific thought on time in the interest of presenting a reasonably complete view in a limited number of pages.

Time is an essential component in most disciplines of science ranging from astronomy to nuclear physics. It is also a practical necessity in managing our everyday lives, in such obvious ways as getting to work on time, and in countless ways that most persons have never realized, as we shall see.

Because of the many associations of time, we have introduced a certain uniformity of language and definition which the specialist will realize is somewhat foreign to his particular field. This compromise seemed necessary in a book directed to the general reader. Today the United States and some parts of the rest of the world are in the process of converting to the metric system of measurement, which we use in this book. We have also used the American definitions of billion and trillion; thus a billion means 1000 million, and a trillion means 1000 billion. Additionally, in numbers with more than four digits, every third digit is marked with a space rather than a comma to avoid confusion in countries where the comma is a decimal marker.

Several sections in this book—the "asides" printed over a grey background—are included for the reader who wishes to explore a little more fully a particular subject area. These may be safely ignored, however, by the reader who wishes to move on to the next major topic, since understanding the book does not depend upon reading these more "in-depth" sections.


THE RIDDLE OF TIME

# I. THE RIDDLE OF TIME

# Chapter 1

# THE RIDDLE OF TIME

- It's present everywhere, but occupies no space.
- We can measure it, but we can't see it, touch it, get rid of it, or put it in a container.
- Everyone knows what it is and uses it every day, but no one has been able to define it.
- We can spend it, save it, waste it, or kill it, but we can't destroy it or even change it, and there's never any more or less of it.

All of these statements apply to time. Is it any wonder that scientists like Newton, Descartes, and Einstein spent years studying, thinking about, arguing over, and trying to define time—and still were not satisfied with their answers? Today's scientists have done no better. The riddle of time continues to baffle, perplex, fascinate, and challenge. Pragmatic physicists cannot help becoming philosophical—even metaphysical—when they start pursuing the elusive concepts of time.

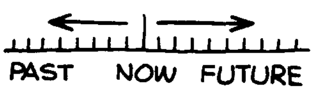
Much has been written of a scholarly and philosophical nature about time. But time plays a vital and practical role in the everyday lives of us all, and it is this practical role which we shall explore in this book.

### THE NATURE OF TIME

LENGTH
MASS
TIME
TEMPERATURE

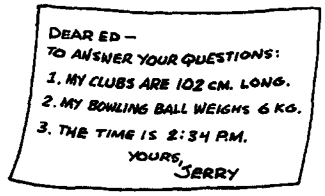
Time is a necessary component of many mathematical formulas and physical functions. It is one of several basic quantities from which most physical measurement systems are derived. Others are length, temperature, and mass. Yet time is unlike length or mass or temperature in several ways. For instance—

- We can see distance and we feel weight and temperature, but we cannot apprehend time by any of the physical senses. We cannot see, hear, feel, smell, or taste time. We know it only through consciousness, or through observing its effects.
- Time "passes," and it moves in only one direction. We can travel from New York to San Francisco or from San Francisco to New York, moving "forward" in either case. We can weigh the grain produced on an acre of land, beginning at any point, and progressing with any measure "next." But when we think of time, in even the crudest terms, we must always think of it as now, before now, and after now. We cannot *do* anything in either the past or the future—only "now."




- "Now" is constantly changing. We can buy a good meter stick, or a one-gram weight, or even a thermometer, put it away in a drawer or cabinet, and use it whenever we wish. We can forget it between uses—for a day or a week or 10 years—and find it as useful when we bring it out as when we put it away. But a "clock"—the "measuring stick" for time—is useful only if it is kept "running." If we put it away in a drawer and forget it, and it "stops," it becomes useless until it is "started" again, and "reset" from information available only from another clock.

- We can write a postcard to a friend and ask him how long his golf clubs are or how much his bowling ball weighs, and the answer he sends on another postcard gives us useful information. But if we write and ask him what time it is—and he goes to great pains to get an accurate answer, which he writes on another postcard—well, obviously before he writes it down, his information is no longer valid or useful.




This fleeting and unstable nature of time makes its measurement a much more complex operation than the measurement of length or mass or temperature. However, as we shall learn in Chapter 22, many of our basic measurement units are being turned into "time measurements."

## WHAT IS TIME?

Time is a physical quantity that can be observed and measured with a clock of mechanical, electrical, or other physical nature. Dictionary definitions bring out some interesting points:

- **time**—A nonspatial continuum in which events occur in apparently irreversible succession from past through present to the future. An interval separating two points on this continuum, measured essentially by selecting a regularly recurring event, such as the sunrise, and counting the number of its recurrences during the interval of duration.

  *American Heritage Dictionary*

- **time**—1. The period during which an action, process, etc. continues; measured or measurable duration. . . 7. A definite moment, hour, day, or year, as indicated or fixed by the clock or calendar.

*Webster's New Collegiate Dictionary*

At least part of the trouble in agreeing on what time is lies in the use of the single word *time* to denote two distinct concepts. The first is *date* or *when* an event happens. The other is *time interval*, or the "length" of time between two events. This distinction is important and is basic to the problems involved in measuring time. We shall have a great deal to say about it.

## DATE, TIME INTERVAL, AND SYNCHRONIZATION

We obtain the date of an event by counting the number of cycles, and fractions of cycles, of periodic events, such as the Sun as it appears in the sky and the Earth's movement around the Sun, beginning at some agreed-upon starting point. The date of an event might be 13 February 1961, 8h, 35m, 37.27s; *h*, *m*, and *s* denote hours, minutes, and seconds; the 14th hour, on a 24-hour clock, would be two o'clock in the afternoon.

In the United States literature on navigation, satellite tracking, and geodesy, the word "epoch" is sometimes used in a similar sense to the word "date." But there is considerable ambiguity in the word "epoch," and we prefer the term "date," the precise meaning of which is neither ambiguous nor in conflict with other, more popular uses.

*Time interval* may or may not be associated with a specific date. A person timing the movement of a horse around a race track, for example, is concerned with the minutes, seconds, and fractions of a second between the moment the horse leaves the gate and the moment it crosses the finish line. The *date* is of interest only if the horse must be at a particular track at a certain hour on a certain day.

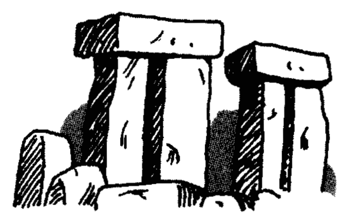
WHEN?
HOW LONG?
TOGETHER!

Time interval is of vital importance to *synchronization*, which means literally "timing together." Two military units that expect to be separated by several kilometers may wish to surprise the enemy by attacking at the same moment from opposite sides. So before parting, soldiers from the two units synchronize their watches. Two persons who wish to communicate with each other may not be critically interested in the date of their communication, or even in how long their communication lasts. But unless their equipment is precisely *synchronized*, their messages will be garbled. Many sophisticated electronic communications systems, navigation systems, and proposed aircraft-collision-avoidance systems have little concern with accurate dates, but they depend for their very existence on extremely precise synchronization.


The problem of synchronizing two or more time-measuring devices—getting them to measure time interval accurately and together, very precisely, to the thousandth or millionth of a second—presents a continuing challenge to electronic technology.

## ANCIENT CLOCK WATCHERS

Among the most fascinating remains of many ancient civilizations are their elaborate time-watching devices. Great stone structures like Stonehenge, in Southern England, and the 4000-year-old passage grave of Newgrange, near Dublin, Ireland, that have challenged anthropologists and archaeologists for centuries, have proved to be observatories for watching the movement of heavenly bodies. Antedating writing within the culture, often by centuries, these crude clocks and calendars were developed by people on all parts of our globe.



In the Americas, Maya, Inca, and Aztec cultures developed elaborate calendars. As the Conquistadors explored the New World they were baffled by advanced city-states—many larger than those they knew in the Old World—with elaborate monuments and temples. Often these structures served as sophisticated calendars marking important religious holidays and significant dates for planting crops and other critical agricultural events. As in all great civilizations, time and its keeping reflected nature's order folded into society's organizations.

Cuzco, the capital city of the Incas, was itself a vast calendar. Throughout the city, lines of sight provided clear views of the Sun as it rose and set on important occasions. Later studies revealed 41 sightlines, all radiating from Coricancha, called the Temple of the Sun by the Spaniards.

In the Mayan civilization, whose classical period spanned the second through the tenth centuries, the day, embodied by the rising and setting Sun, was the basic unit of time. But to the Mayans the day was more than a building block to be divided and multiplied—it was time itself. Time began as the Sun appeared in the early morning sky and was swallowed up as the Sun disappeared at sunset in the western sky. The Mayan day also included the notion of cyclic time with time reversing direction at each sunrise and sunset.

AZTEC CALENDARS
1 YEAR = 260 DAYS
1 YEAR = 365 DAYS

Modern Mexico City lies on the ruins of the ancient Aztec capital, Tenochtitlán, established on an island in Lake Texcoco in 1325. Excavations of the buried city and other Aztec sites reveal that the Aztecs kept two calendars: one based on 260 days and the other on 365. They combined the two calendars to create a cycle 52 years long—possibly the average life span at the time. The end of one cycle and the beginning of the next was signaled by a celestial event—the passage of the Pleiades through a specific location in the nighttime sky. The passage signaled that the gods were pleased and would renew life's cycle for another 52 years.

Today, scientists are finding increasing evidence that even the less cosmopolitan Native Americans of the plains of North America were dedicated timekeepers. Stones laid out in formation, such as the Medicine Wheel in northern Wyoming, formerly thought to have only a religious purpose, are actually large clocks. Of course they had religious significance, also, for the cycles of life—the rise and fall of the tides, and the coming and going of the seasons—powers that literally controlled the lives of primitive peoples as they do our own, naturally evoked a sense of mystery and inspired awe and worship. Astronomy and time—so obviously beyond the influence or *control* of man, so obviously much older than anything the oldest man in the tribe could remember and as nearly "eternal" as anything the human mind can comprehend—were of great concern to ancient peoples everywhere.

### CLOCKS IN NATURE

The movements of the Sun, Moon, and stars are easy to observe, and you can hardly escape being conscious of them. But there are countless other cycles and rhythms going on around us—and inside of us—all the time. Biologists, botanists, and other life scientists study but do not yet fully understand many "built in" clocks that regulate basic life processes—from periods of animal gestation and ripening of grain to migrations of birds and fish; from the rhythms of heartbeats and breathing to those of the fertile periods of female animals. These scientists talk about "biological time" and have written whole books about it.

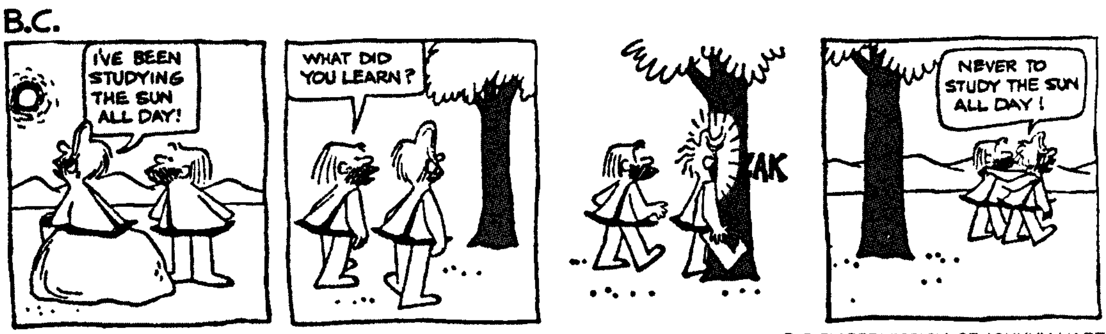
Geologists also are aware of great cycles, each one covering thousands or millions of years; they speak and write in terms of "geologic time." Other scientists have identified accurately the rate of decay of atoms of various radioactive elements—such as carbon-14, for example. So they are able to tell with considerable dependability the age of anything

that contains carbon-14. This includes *everything* that was once alive, such as a piece of wood that could have been a piece of Noah's Ark or the mummified body of a king or a pre-Columbian farmer.

In a later chapter we shall see how new dating techniques, made possible by the laser, have revolutionized our understanding of the Earth and our solar system.

### KEEPING TRACK OF THE SUN AND MOON

Some of the stone structures of the earliest clock watchers were apparently planned for celebrating a single date—Midsummer Day, the day of the Summer solstice, when the time from sunrise to sunset is the longest. It occurs on June 21 or 22, depending on how near the year is to leap year. For thousands of years, the "clock" that consists of the Earth and the Sun was sufficient to regulate daily activities. Our ancient ancestors got up and began their work at sunrise and ceased work at sunset. They rested and ate their main meal about noon. They didn't need to know time any more accurately than this.




B.C. BY PERMISSION OF JOHNNY HART AND FIELD ENTERPRISES, INC.

But there were other dates and anniversaries of interest and in many cultures calendars were developed on the basis of the cycles of the Sun, the Moon, and the seasons.

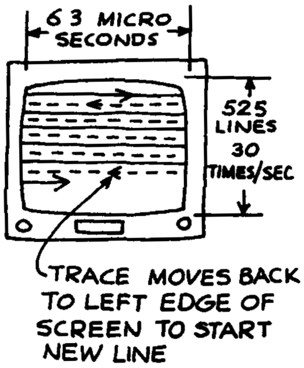
If we think of time in terms of cycles of regularly recurring events, then we see that timekeeping is basically a system of counting these cycles. The simplest and most obvious to start with is days—sunrise to sunrise, or more usefully, noon to noon, since the "time" from noon to noon is, for most practical purposes, always the same, whereas the hour of sunrise varies much more with the season.

You can count noon to noon with very simple equipment—a stick in the sand or an already existing post or tree, or even your own shadow. When the shadow points due North—if you are in the northern hemisphere—or when it is the shortest, the Sun is at its zenith, and it is noon. By making marks of a permanent or semipermanent nature, or by laying out stones or other objects in a preplanned way, you can keep track of and count days. With slightly more sophisticated equipment, you can count full moons—or months—and the revolutions of the Earth around the Sun, or years.


The Egyptians were probably the first to divide the day into smaller units. Archaeologists have investigated tall, slender monuments or obelisks, dating back to 3500 B.C., whose moving shadows doubtless provided an easy way to follow the course of the day. Later, more-refined obelisks are ringed with marker stones providing an even better accounting of the day.

By 1500 B.C., the Egyptians had developed portable shadow clocks, or sundials, which divided the sunlit hours into 10 segments with 2 more divisions for the morning and evening twilight hours.

Handsome sundials still decorate our gardens and buildings even though they have long been replaced by modern clocks and watches. Often these sundials are marked with scales allowing the observer to correct the "shadow time" for the season of the year. But even with the most advanced sundials there are problems to work out. One is that the cycles of the day, month, and year do not evenly divide into one another. It takes the Earth about 365¼ days to complete its cycle around the Sun, but the Moon circles the Earth about 13 times in 364 days. This gave early astronomers, mathematicians, and calendar makers some thorny problems to work out.




**THINKING BIG AND THINKING SMALL—AN ASIDE ON NUMBERS**

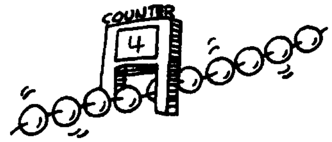
Some scientists, such as geologists and paleontologists, think of time in terms of thousands and millions of years. In their vernacular, a hundred years more or less is insignificant—too small to recognize or to measure. To other scientists, such as engineers who design sophisticated communication systems and navigation systems, one or two seconds' variation in a year is intolerable because it causes them all sorts of problems. They think in terms of thousandths, millionths, and billionths of a *second*.

The *numbers* they use to express these very small "bits" of time are very large. 1/1 000 000 of a second, for example, is one microsecond. 1/1 000 000 000 of a second is one nanosecond.

To keep from having to deal with these cumbersome figures in working out mathematical formulas, they use a kind of shorthand, similar to that used by mathematicians to express a number multiplied by itself several or many times. Instead of writing $2 \times 2 \times 2$, for example, we write $2^3$, and say, "two to the third power." Similarly, instead of writing 1/1 000 000, or even 0.000 001, scientists who work with very small fractions express a millionth as $10^{-6}$, meaning 0.1 multiplied by itself 6 times. A billionth of a second, or nanosecond, is expressed as $10^{-9}$ second, which is 0.1 multiplied by itself 9 times. They say, "ten to the minus nine power."

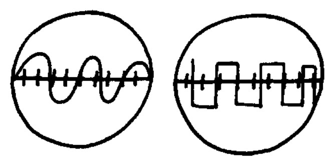
A billionth of a second is an almost inconceivably small bit—many thousands of times smaller than the smallest possible "bit" of length or mass that can be measured. We cannot think concretely about how small a nanosecond is; but to give some idea, the impulses that "trigger" the picture lines on the television screen come, just one at a time, at the rate of 15 750 per second. The whole picture "starts over," traveling left to right, one line at a time, the 525 lines on the picture tube, 30 times a second. At this rate it would take 63 000 nanoseconds just to trace out one line.

Millionths and billionths of a second cannot, of course, be *measured* with a mechanical clock at all. But today's electronic *devices* can count them accurately and display the count in usable meaningful terms.



Whether you are counting hours or microseconds, the principle is essentially the same. It's simply a matter of dividing units to be counted into identical, manageable groups. And since time moves steadily in a "straight line" and in only one direction, counting the swings or ticks of the timer—the *frequency* with which they occur—is easier than counting the pellets in a pailful of buckshot, for example. "Bits" of time, whatever their size, follow one another single file, like beads on a string; and whether we're dealing with 10 large bits—hours, for example—or 200 billion small bits, such as microseconds, all we need to do is to count them as they pass through a "gate," and keep track of the count.

The "hour" hand on a clock divides a day evenly into 12 or 24 hours—depending on how the clock face and works are designed. The "minute" hand divides the hour evenly into 60 minutes, and the "second" hand divides the minute evenly into 60 seconds. A "stop watch" has a finer *divider*—a hand that divides the seconds into tenths of a second.



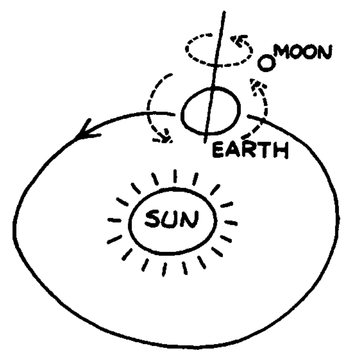
When we have large groups of identical items to count, we often find it faster and more convenient to count by tens, dozens, hundreds, or some other number. Using the same principle, electronic devices can count groups of ticks or oscillations from a frequency source, add them together, and display the results in whatever way one may wish. We may have a device, for example, that counts groups of 9 192 631 770 oscillations of a cesium-beam atomic frequency standard, and sends a special tick each time that number is reached; the result will be very precisely measured one-second intervals between ticks. Or we may want to use much smaller bits—microseconds, perhaps. So we set our electronic divider to group counts into millionths of a second, and to display them on an *oscilloscope*.

Electronic counters, dividers, and multipliers make it possible for scientists with the necessary equipment to "look at," and to put to hundreds of practical uses, very small bits of time, measured to an accuracy of one or two parts in $10^{11}$; this is about 1 second in 3000 years. Days, years, and centuries are, after all, simply units of accumulated nanoseconds, microseconds, and seconds.

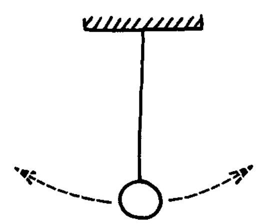
Chapter

1 **2** 3 4 5 6 7
8 9 10 11 12 13 14
15 16 17 18 19 20 21
22 23 24 25 26 27 28
29 30 31

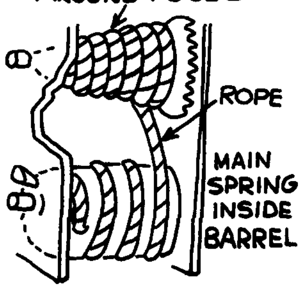
# EVERYTHING SWINGS



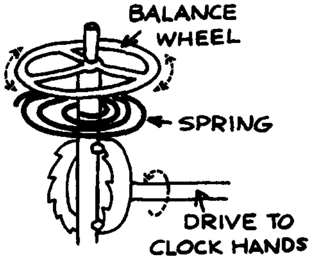

The Earth swings around the Sun, and the Moon swings around the Earth. The Earth "swings" around its own axis. These movements can easily be observed and charted from almost any spot on Earth. The observations were and are useful in keeping track of time, even though early observers did not understand the movements and often were completely wrong about the relationships of heavenly bodies to one another. The "swings" happened with dependable regularity, over countless thousands of years, and therefore enabled observers to predict the seasons, eclipses, and other phenomena with great accuracy, many years in advance.



When we observe the Earth's swing around its axis, we *see* only a part of that swing, or an arc, from horizon to horizon, as the Sun rises and sets. A big breakthrough in timekeeping came when someone realized that another arc—that of a free-swinging pendulum—could be harnessed and adjusted, and its swings counted, to keep track of passing time. The accuracy of the pendulum clock was far superior to any of the many devices that had preceded it—water clocks, hour glasses, candles, and so on. Furthermore, the pendulum made it possible to "chop up" or refine time into much smaller, measurable bits than had ever been possible before; one could measure—roughly, to be




AS MAIN SPRING UNWINDS, LEVERAGE BETWEEN BARREL AND FUSÉE CHANGES




sure—seconds and even parts of seconds, and this was a great advancement.

The problem of keeping the pendulum swinging regularly was solved at first by a system of cog wheels and an "escapement" that gave the pendulum a slight push with each swing, in much the same way that a child's swing is kept in motion by someone pushing it. A weight on a chain kept the escapement lever pushing the pendulum, as it does today in the cuckoo clocks familiar in many homes.

But then someone thought of another way to keep the pendulum swinging—a wound-up spring could supply the needed energy if there were a way to make the "push" from the *partially* wound spring the same as it was from a *tightly* wound spring. The "fusee"—a complicated mechanism that was used for only a brief period—was the answer.

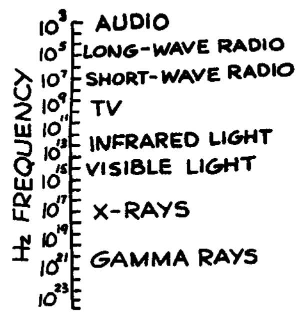
From this it was just one more step to apply a spring and "balance wheel" system directly to the pinions or cogs that turned the hands of the clock, and to eliminate the pendulum. The "swings" were all inside the clock, and this saved space and made it possible to keep clocks moving even when they were moved around or laid on their side.

But some scientists who saw a need for much more precise time measurement than could be achieved by conventional mechanical devices began looking at other things that swing—or vibrate or oscillate—things that swing much faster than the human senses can count. The vibrations of a tuning fork, for instance, which, if it swings at 440 cycles per second, is "A" above "Middle C" on our music scale. The tiny tuning fork in an electric wrist watch, kept swinging by electric impulses from a battery, hums along at several hundred vibrations or cycles per second.

As alternating-current electricity became generally available at a reliable 60 swings or cycles per second—or 60 hertz (50 in some areas)—it was fairly simple to gear these swings to the clock face of one of the most common and dependable timepieces we have today. For most day-to-day uses, the inexpensive electric wall or desk clock driven by electricity from the local power line keeps "the time" adequately.

But for some users of precise time, these common measuring sticks are as clumsy and unsatisfactory as a liter measuring cup would be for a merchant who sells perfume by the dram. These people need something that cuts time up with swings much faster than 60ths or 100ths of a second. The power company itself, to supply electricity at a constant 60 hertz, must be able to measure swings at a much faster rate.

Power companies, telephone companies, radio and television broadcasters, and many other users of precise time have long depended on the swings or vibrations of quartz crystal oscillators, activated by an electric current, to divide time intervals into *megahertz*, or millions of cycles per second. The rate at which the crystal oscillates is determined by the thickness—or thinness—to which it is ground. Typical frequencies are 2.5 or 5 megahertz (MHZ)—2½ million or 5 million swings per second.

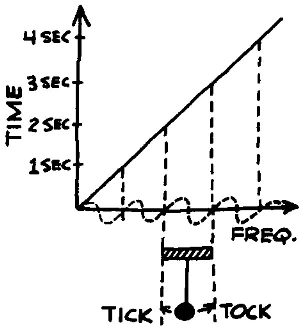



Incredible as it may seem, it is relatively easy to measure swings even much faster than this. What swings faster? Atoms do. One of the properties of each element in the chemistry Periodic Table of Elements is the set of rates at which its atoms swing or resonate. A hydrogen atom, for example, has a resonant frequency at 1 420 405 752 cycles per second, or hertz. A rubidium atom has one at 6 834 682 608 hertz, and a cesium atom at 9 192 631 770 hertz. These are some of the atoms most commonly used as measuring sticks for precise time—the "atomic clocks" maintained by television network master stations, some scientific laboratories, and others. Primary time standards, such as those maintained by the U.S. Naval Observatory or the National Institute of Standards and Technology (NIST), are "atomic clocks."

Everything swings, and anything that swings at a constant rate can be used as a standard for measuring time interval.

## GETTING TIME FROM FREQUENCY

The Sun as it appears in the sky—or the "apparent Sun"—crosses the zenith or highest point in its arc with a "frequency" of once a day, and 365¼ times a year. A metronome ticks off evenly spaced intervals of time to help a musician maintain the time or *tempo* of a composition she




is studying. By moving the weight on its pendulums she can slow the metronome's "frequency" or speed it up.

Anything that swings evenly can be used to measure *time interval* simply by counting and keeping track of the number of swings or ticks-provided that we know how many swings take place in a recognized unit of time, such as a day, an hour, a minute, or a second. In other words, we can measure time interval if we know the *frequency* of these swings. A man shut up in a dungeon, where he cannot see the Sun, could keep a fairly accurate record of passing time by counting his own heartbeats—if he knew how many times his heart beats in one minute—and if he has nothing to do but count and keep track of the number.


The term *frequency* is commonly used to describe swings too fast to be counted mentally, and refers to the number of swings or cycles per second—called hertz (Hz), after Heinrich Hertz, who first demonstrated the existence of radio waves.

If we can count and keep track of the cycles of our swinging device, we can construct a time interval at least as accurate as the device itself—even to millionths or billionths of a second. And by adding these small, identical bits together, we can measure any "length" of time, from a fraction of a second to an hour—or a week or a month or a century.

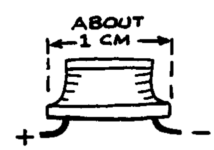
The most precise and accurate measuring device in existence cannot tell us the *date*—unless we have a source to tell us when to *start* counting the swings. But if we know this, and if we keep our swinging device "running," we can keep track of both time interval and date by counting the cycles of our device.

## WHAT IS A CLOCK?

Time "keeping" is simply a matter of counting cycles or units of time. A clock is what does the counting. In a more strict definition, a clock also keeps track of its count and displays what it has counted. But in a broad sense, the Earth and the Sun are a clock—the most common and most ancient clock we have, and the basis of all other clocks.

When ancient peoples put a stick in the ground to observe the movement of its shadow from sunrise to sunset, it was fairly easy and certainly a natural step to mark off "noon" and other points where the shadow lay at other times of day—in other words, to make a sundial. Sundials can tell the time reliably when the Sun is shining. They are of no use at all when the Sun is not shining. So people made mechanical devices called clocks to interpolate or keep track of time between checks with the Sun. The Sun was a sort of "master clock" that served as a primary time scale by which the secondary mechanical clocks were calibrated and adjusted.

Although some early clocks used the flow of water or sand to measure passing time, the most satisfactory clocks counted the swings of a pendulum or of a balance wheel. Recently in the history of timekeeping, accurate clocks that count the vibrations of a quartz crystal activated by an electric current or the resonances of atoms of selected elements such as rubidium or cesium, have been developed. Since "reading" such a clock requires counting millions or billions of cycles per second—in contrast to the relatively slow 24-hour cycle of the Earth–Sun clock—an atomic clock requires much more sophisticated equipment for making its count. But given the necessary equipment, we can read an atomic clock with much greater ease, in much less time, and with many thousands of times greater precision than we can read the Earth–Sun clock.




METAL CAPSULE CONTAINING QUARTZ CRYSTAL USED IN WRIST WATCHES

A mechanism that simply swings or ticks—a clockwork with a pendulum, for example, without hands or face—is not, strictly speaking, a clock. The swings or ticks are meaningless, or *ambiguous*, until we not only count them but also establish some base from which to *start counting*. In other words, until we hook up "hands" to keep track of the count and put those hands over a face with numbers that help us count the ticks and oscillations and make note of the accumulated count, we don't have a useful device.

The familiar 12-hour clock face is simply a convenient way to keep track of the ticks we wish to count. It serves very well for measuring time interval, in hours, minutes, and seconds, up to a maximum of 12 hours. The less familiar 24-hour clock face serves as a measure of time interval up to 24 hours. But neither will tell us anything about the day, month, or year.

## THE EARTH–SUN CLOCK

As we have observed, the spin of the Earth on its axis and its rotation around the Sun provide the ingredients for a clock—a very fine clock that we can certainly never get along without. It meets many of the most exacting requirements that the scientific community today makes for an acceptable standard:

AVAILABILITY

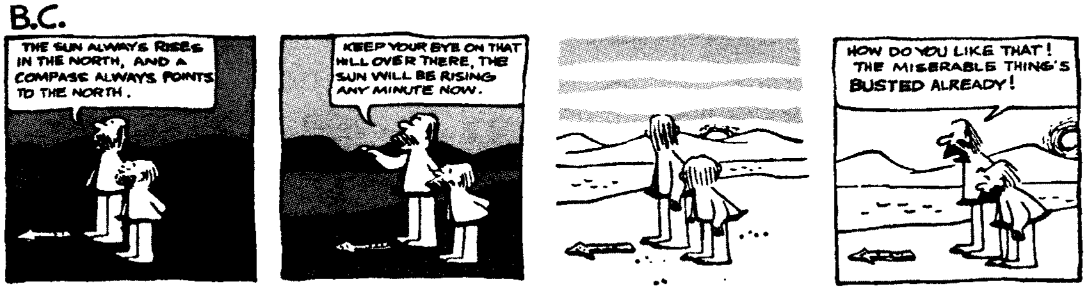
RELIABILITY

STABILITY

- It is *universally available*. Anyone, almost anywhere on Earth, can readily read and use it.
- It is *reliable*. There is no foreseeable possibility that it may stop or "lose" the time, as is possible with manufactured clocks.
- It has great overall *stability*. On the basis of its time scale, scientists can predict such things as the hour, minute, and second of sunrise and sunset at any part of the globe; eclipses of the Sun and Moon, and other time-oriented events hundreds or thousands of years in advance.

In addition, it involves no expense of operation for anyone; there is no possibility of international disagreement as to "whose" Sun is the authoritative one, and no responsibility for keeping it running or adjusted.

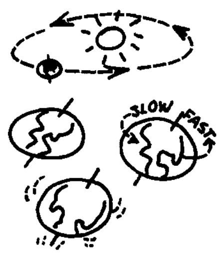
Nevertheless, this ancient and honored timepiece has some limitations. As timekeeping devices were improved and became more common—and as the study of the Earth and the universe added facts and figures to those established by earlier observers—it became possible to measure





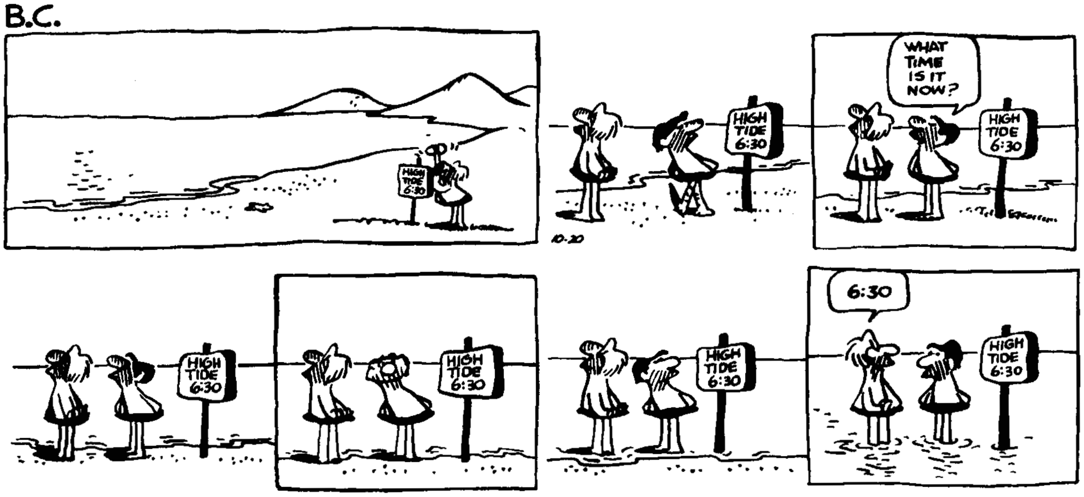

precisely some of the phenomena that had long been known in a general way, or at least suspected. Among them was the fact that the Earth–Sun clock is not, by more precise standards, a very stable timepiece.

- The Earth's orbit around the Sun is not a perfect circle but is elliptical, so the Earth travels faster when it is nearer the Sun than when it is farther away.
- The Earth's axis is tilted to the plane containing its orbit around the Sun.
- The Earth spins at an irregular rate around its axis of rotation.
- The Earth wobbles on its axis.




For all of these reasons the Earth–Sun clock is not an accurate clock. The first two facts alone cause the day, as measured by a sundial, to differ in time, as we reckon it today, by about 15 minutes a day in February and November. These effects are predictable and cause no serious problem, but there are also significant, unpredictable variations.

Gradually, clocks became so much more stable and precise than the Earth–Sun clock as time scales for measuring short time intervals that solar time had to be "corrected." As mechanical and electrical timepieces became more common and more dependable, as well as easier to use, nearly everyone looked to them for the time and forgot about the Earth–Sun clock as the master clock. People looked at a clock to see what time the Sun rose, instead of looking at the sunrise to see what time it was.

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## METER STICKS TO MEASURE TIME

If we have to weigh a truckload of sand, a bathroom scale is of little use. Nor is it of any use for finding out whether a letter will need one postage stamp or two. A meter stick is all right for measuring centimeters—unless we want to measure a thousand or ten-thousand meters—but it won't do for measuring accurately the thickness of an eyeglass lens.

Furthermore, if we order a bolt 5/16 of an inch in diameter and 8-3/16 inches long—and our supplier has only a *meter* stick, he will have to use some arithmetic before he can fill our order. His *scale* is different from ours. Length and mass can be chopped up into any predetermined sizes anyone wishes. Some sizes are easier to work with than others, and so have come into common use. The important point is that everyone concerned with the measurement agrees on what the *scale* is to be. Otherwise a liter of tomato juice measured by the juice processor's scale might be different from the liter of gasoline measured by the oil company's scale.

Time, too, is measured by a scale. For practical reasons, the already existing scale, set by the spinning of the Earth on its axis and the rotation of the Earth around the Sun, provides the basic scale from which others have been derived.

## WHAT IS A STANDARD?

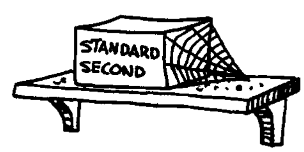
The important thing about measurement is that there be general agreement on exactly what the *scale* is to be and how the basic *unit* of that scale is to be defined. In other words, there must be agreement upon the *standard* against which all other measurements and calculations will be compared. In the United States, the standard unit for measuring length is the meter. The basic unit for measurement of mass is the kilogram.

The basic unit for measuring time is the second. The second multiplied evenly by 60 gives us minutes, or by 3600 gives us hours. The length of days, and even years, is measured by the basic unit of time, the second. Time intervals of less than a second are measured in 10ths, 100ths, 1000ths—on down to billionths of a second and even smaller units.

Each basic unit of measurement is very exactly and explicitly defined by international agreement; each nation directs a government agency to make *standard units* available to anyone who wants them. In our country, the National Institute of Standards and Technology, a part of the Department of Commerce with headquarters in Gaithersburg, Maryland, provides the primary standard references for ultimate calibration of the many standard weights and measures needed for checking scales in drug and grocery stores, the meters that measure the gasoline we pump into our cars, the octane of that gasoline, the purity of the gold in our jewelry or dental repairs, the strength of the steel used in automobile parts and children's tricycles, and countless other things that have to do with the safety, efficiency, and comfort of our everyday lives.

NIST

The National Institute of Standards and Technology is also responsible for making the second—the standard unit of time interval—available to many thousands of time users everywhere—not only throughout the land, but to ships at sea, planes in the air, and vehicles in outer space. This is a tremendous challenge, for the standard second, unlike the kilogram, cannot be sent in an envelope or box and put on a



shelf for future reference, but must be supplied constantly, ceaselessly from moment to moment-and even counted upon to give the date.

### HOW TIME TELLS US WHERE IN THE WORLD WE ARE

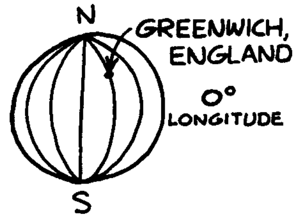
One of the earliest, most important, and universal needs for precise time information was—and still is—as a basis for place location. Navigators of ships at sea, planes in the air, and small pleasure boats and private aircraft depend constantly and continuously on-time information to find out where they are and to chart their course. Many people know this, in a general way, but few understand how it works.


Ancient people discovered long ago that the Sun and stars could aid them in their travels, especially on water where there are no familiar "signposts." Early explorers and adventurers in the northern hemisphere were particularly fortunate in having a pole star, the North Star, that appeared to be suspended in the northern night sky; it did not rotate or change its position with respect to Earth as the other stars did.

These early travelers also noticed that as they traveled northward, the North Star gradually appeared higher and higher in the sky. By measuring the elevation of the North Star above the horizon, then, navigators could determine their distance from the North Pole—and conversely, their distance from the equator. An instrument called a sextant helped to measure this elevation very accurately. The measurement is usually indicated in *degrees of latitude*, ranging from 0 degrees latitude at the equator to 90 degrees of latitude at the North Pole.

Measuring distance and charting a course east or west, however, presented a more complex problem because of the Earth's spin. But the problem also provides the key to its solution.

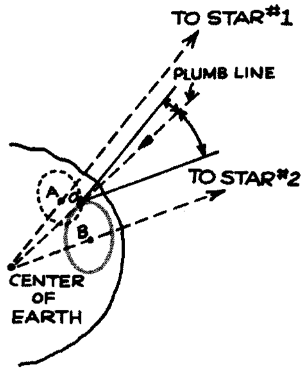
For measurements in the east-west direction, the Earth's surface has been divided into lines of *longitude*, or meridians; one complete circuit around the Earth equals 360 degrees of longitude, and all longitude lines intersect at the North and South Poles. By international agreement, the line of longitude that runs through Greenwich, England, has been labeled the zero meridian, and longitude is measured both east and west from this meridian to the point where the measurements meet at 180 degrees, on the opposite side of the Earth from the zero meridian.




At any point on Earth, the Sun travels across the sky from east to west at the rate of 15 degrees in 1 hour, or 1 degree in 4 minutes. So if a navigator has a very accurate *clock* aboard his ship—one that can tell him very accurately the time at Greenwich or the zero median—he can easily figure his longitude. He simply gets the time *where he is* from the Sun. For every four minutes that his clock, showing Greenwich time, differs from the time determined locally from the Sun, he is one degree of longitude away from Greenwich.

At night he can get his position by observing the location of two or more stars. The method is similar to obtaining latitude from the North Star. The difference is that whereas the North Star appears suspended in the sky, the other stars appear to move in circular paths around the North Star. Because of this, the navigator must know the *time* in order to find out where he is. If he does not know the time, he can read his location with respect to the *stars*, as they "move" around the North Star, but he has no way at all to tell where he is *on Earth*! His navigation charts tell him the positions of the stars at any given *time* at every season of the year; so if he knows the time, he can find out where he is simply by referring to two or more stars, and reading his charts.

The principle of the method is shown in the illustration. For every star in the sky there is a point on the surface of




the Earth where the star appears directly overhead. This is Point A for Star #1 and Point B for Star #2 in the illustration. The traveler at Point 0 sees Star #1 at some angle from the overhead position. But as the illustration shows, all travelers standing on the black circle will see Star #1 at this same angle. By observing Star #2, the traveler will put herself on another circle of points, the gray circle; so her location will be at one of the two intersection points of the gray and the black circles.

She can look at a third star to choose the correct intersection point; more often, however, she has at least some idea of her location, so she can pick the correct intersection point without further observation.

The theory is simple. The big problem was that until about 200 years ago, no one was able to make a clock that could keep time accurately at sea.

### BUILDING A CLOCK THAT WOULDN'T GET SEASICK

During the centuries of exploration thousands of miles across uncharted oceans, the need for improved navigation instruments became critical. Ship building improved, and larger, stronger vessels made ocean trade—as well as ocean warfare—increasingly important. But too often ships laden with priceless merchandise were lost at sea, driven off course by storms, with the crew unable to find out where they were or to chart a course to a safe harbor.


Navigators had long been able to read their latitude north of the equator by measuring the angle formed by the horizon and the North Star. But east-west navigation was almost entirely a matter of "dead reckoning." If only they had a *clock* aboard that could tell them the time at Greenwich, England, then they could easily find their position east or west of the zero meridian.

It was this crucial need for accurate, dependable clocks aboard ships that pushed inventors into developing better and better timepieces. The pendulum clock had been a real breakthrough and an enormous improvement over any timekeeping device made before it. But it was no use at all at sea. The rolling and pitching of the ship made the pendulum inoperative.

In 1713 the British government offered an award of £20 000 to anyone who could build a chronometer that would serve to determine longitude within half a degree. Among the many craftsmen who sought to win this handsome award was the English clock maker, John Harrison, who spent more than 40 years trying to meet the specifications. Each model became a bit more promising as he found new ways to cope with the rolling sea, temperature changes that caused intolerable expansion and contraction of delicate metal springs, and salt spray that corroded everything aboard ship.

ROLLING SEA
TEMPERATURE
SALT SPRAY

When finally he came up with a chronometer that he considered nearly perfect, the government commission was so afraid that it might be lost at sea that they suspended testing it until Harrison had built a second unit identical with the first, to provide a pattern. Finally, in 1761 Harrison's son William was sent on a voyage to Jamaica to test the instrument. In spite of a severe storm that lasted for days and drove the ship far off course, the chronometer proved to be amazingly accurate, losing less than 1 minute over a period of many months and making it possible for William to determine his longitude at sea within 18 minutes of arc, or less than of one-third of one degree. Harrison claimed the £20 000 award, part of which he had already received, and the remainder was paid to him in various amounts over the next two years—just three years before his death.

Harrison's difficulty in receiving his just award was more political than technical. As he built ever-improved versions of his chronometer, astronomers pursued an astronomical solution to the longitude problem. Their idea was to

CLOCK IN THE SKY...
- LENGTHY CALCULATIONS

HARRISON'S CLOCK...
- RELATIVELY SIMPLE CALCULATIONS

replace Harrison's chronometer with a "clock" in the sky. The idea was an old one going back to at least 1530. The concept was simple, but in practice it was well beyond the measurement skills of the astronomers of that era. We can understand the method by describing a version proposed by Galileo Galilei in 1610.

Galileo was the first to point the newly invented telescope to the heavens. Among the bewildering things Galileo observed were four moons of Jupiter. In his usual meticulous fashion, Galileo determined the orbits of the moons and was soon able to predict the times at which the moons disappeared behind Jupiter's disk—eclipsed by Jupiter. Here was a clue to a clock in the sky. Galileo reasoned that a navigator equipped with a table of Jovian moon eclipse times could calibrate his local clock. If, for example, an eclipse of one of the moons occurred at 9:33 in the morning Greenwich time, then the navigator could watch for the eclipse, note the time the eclipse occurred relative to his local clock, and correct it accordingly. Since the eclipses of the moons occurred fairly often it would not be necessary to wait long periods of time to make clock corrections. That was the idea anyway.

JUPITER

GALILEO DISCOVERED FOUR MOONS

There were practical problems. First, the navigator needed a telescope to make the necessary observations. That in itself was not a big obstacle, but sighting Jupiter's moons on the heaving deck of a ship rolling in high seas was a different matter. Further the observations needed to be made at night, and the sky might be overcast. All in all, the clock in the sky did not look like a promising solution to ship navigation. Nevertheless, the method and variations on it worked well enough on land for cartographers to make the first truly accurate maps of the world.

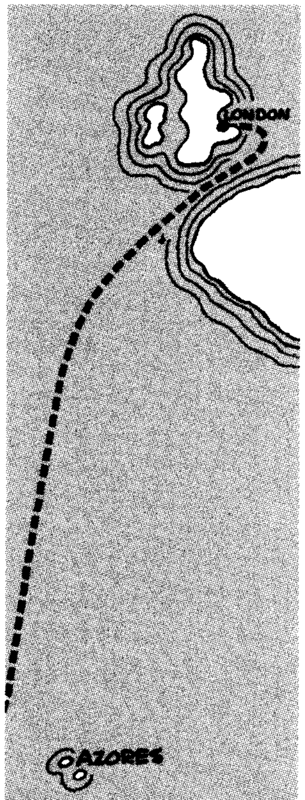
By Harrison's time, astronomers had made much progress in mapping the skies. The clock in the sky continued to look encouraging, although the necessary computations required several hours while, with Harrison's clock, the computations were relatively simple and could be done in a matter of minutes.

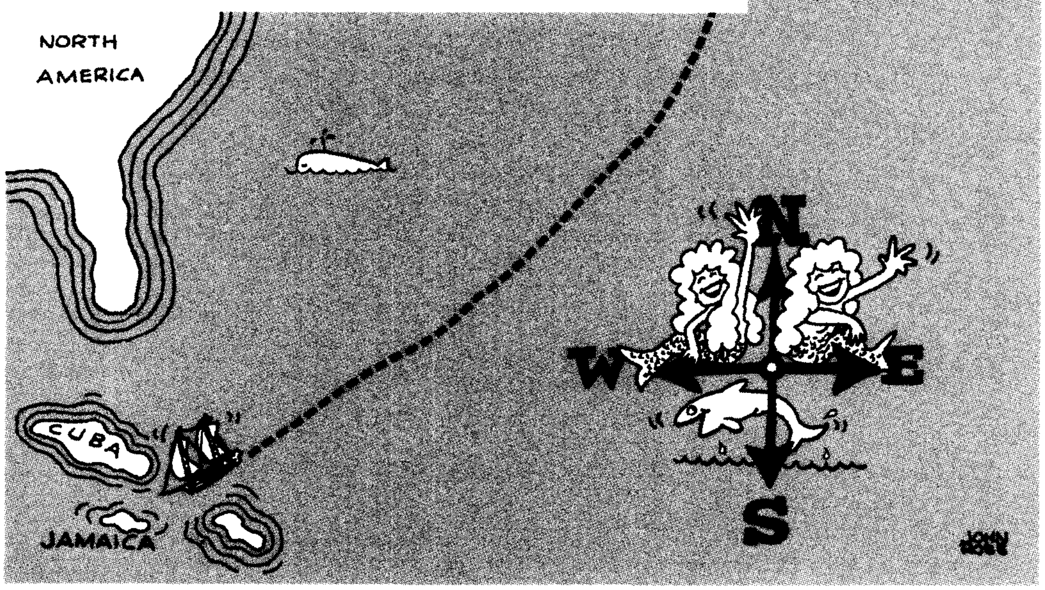
Unfortunately for Harrison, one of the members of the prize committee was a strong advocate of the astronomical method and was the Astronomer Royal to boot. Finally, Harrison appealed directly to King George III, who, sympathetic to Harrison's plea, applied pressure on Parliament to award the balance of the prize money. Technically, Harrison never did receive the full prize since he never received the approval of the prize committee.

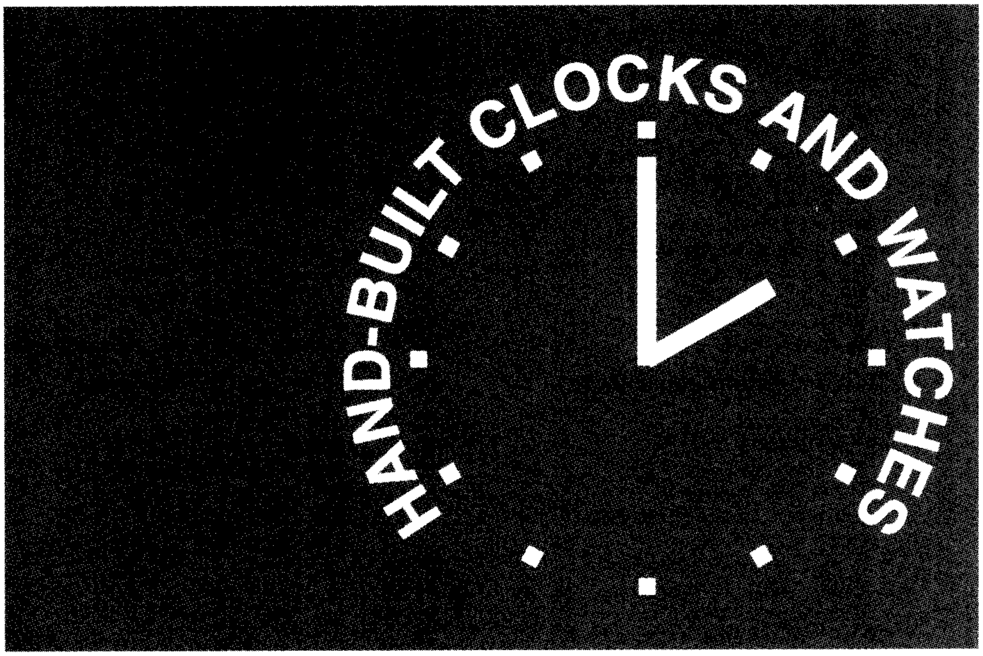
To this day, the struggle between the astronomers and the clock makers continues—although in a considerably friendlier fashion. We shall take up this matter again when we discuss the atomic definition of the second.

For more than half a century after Harrison's chronometer was accepted, an instrument of similar design—each one built entirely by hand by a skilled horologist—was an extremely valuable and valued piece of equipment—one of the most vital items aboard a ship. It needed very careful tending, and the one whose duty it was to tend it had a serious responsibility.

Today there may be almost as many wrist watches as crew members aboard an ocean-going ship—many of them more accurate and dependable than Harrison's prized chronometer. But the ship's chronometer, built on essentially the same basic principles as Harrison's instrument, is still a most vital piece of the ship's elaborate complement of navigation instruments.




HAND-BUILT CLOCKS AND WATCHES

# II.

# HAND-BUILT CLOCKS AND WATCHES

## Chapter 3

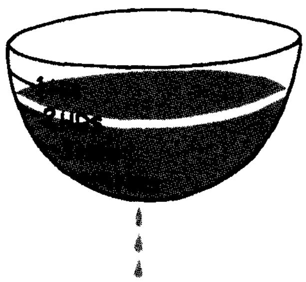
# EARLY CLOCKS

Three young boys, lured by the fine weather on a warm spring day, decided to skip school in the afternoon. The problem was knowing when to come home, so that their mothers would think they were merely returning from school. One of the boys had an old alarm clock that would no longer run, and they quickly devised a scheme: The boy with the clock set it by a clock at home when he left after lunch at 12:45. After they met they would take turns as timekeeper, counting to 60 and moving the minute hand ahead one minute at a time!

Almost immediately two of the boys got into an argument over the rate at which the third was counting, and *he* stopped counting to defend his own judgment. They had "lost" the time—crude as their system was—before their adventure was begun, and spent most of their afternoon alternately accusing one another and trying to estimate how much time their lapses in counting had consumed.

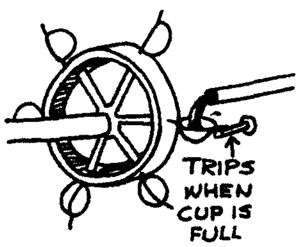
"Losing" the time is a constant problem even for timekeepers much more sophisticated than the boys with their old alarm clock. Regulating the clock so that it will "keep" time accurately, even with high-quality equipment, presents even greater challenges. We have already discussed some of these difficulties, in comparison with the relatively simple keeping of a device for measuring length or mass, for example. We've talked about what a clock is and have mentioned briefly several different kinds of clocks. Now let's look more specifically at the components common to all clocks and the features that distinguish one kind of clock from another.

### SAND AND WATER CLOCKS



The earliest clocks that have survived to now were built in Egypt. The Egyptians constructed both sundials and water clocks. The water clock in its simplest form consisted of an alabaster bowl, wide at the top and narrow at the bottom, marked on the inside with horizontal "hour" marks. The bowl was filled with water that leaked out through a small hole in the bottom. The clock kept fairly uniform time because more water ran out between hour marks when the bowl was full than when it was nearly empty and the water leaked out more slowly.

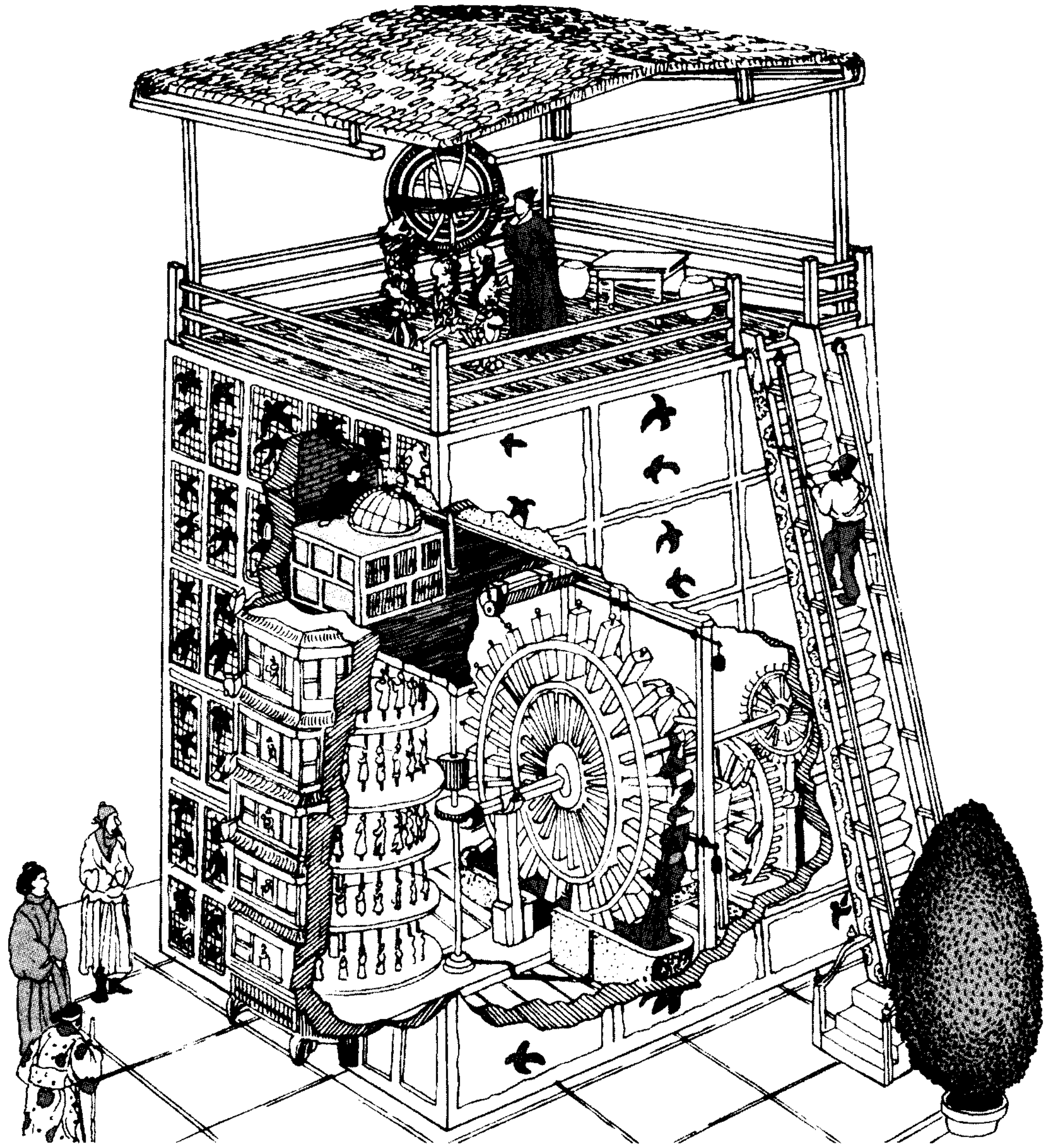
The Greeks and Romans continued to rely on water and sand clocks. Sometime between the 8th and 11th centuries A.D. the Chinese constructed a clock that had some of the characteristics of later "mechanical" clocks. The Chinese clock was still basically a water clock, but the falling water powered a water wheel with small cups arranged at equal intervals around its rim. As a cup filled with water it became heavy enough to trip a lever that allowed the next cup to move into place; thus the wheel revolved in steps, keeping track of the time.



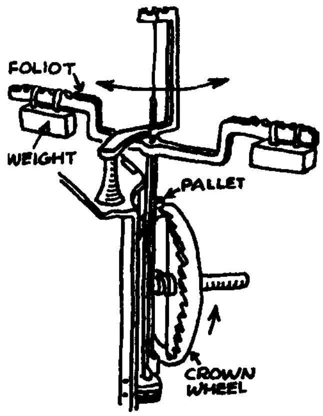

EARLY CHINESE WATER CLOCK

Many variations of the Chinese water clock were constructed, and it had become so popular by the early 13th century that there was a special guild for its makers in Germany. But aside from the fact that the clock did not keep very good time, it often froze in the western European winter.

The sand clocks introduced in the 14th century avoided the freezing problem. But because of the weight of the sand, they were limited to measuring short intervals of time. One of the chief uses of the hour glass was on ships. Sailors threw overboard a log with a long rope attached to it. As the rope played out into the water, they counted knots tied into it at equal intervals, for a specified period of time as determined by the sand clock. This gave them a crude estimate of the speed—or "knots"—at which the ship was moving.

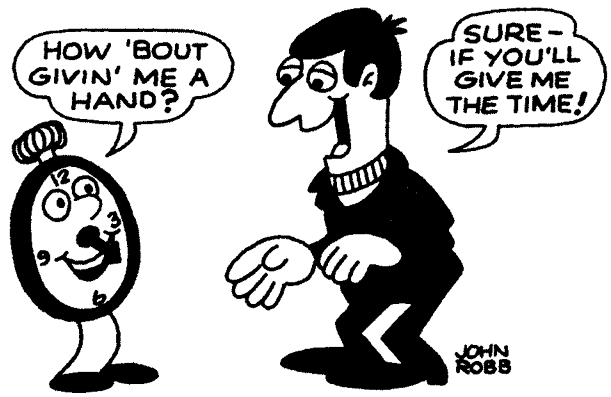


14TH CENTURY CHINESE WATER CLOCK




## MECHANICAL CLOCKS

The first mechanical clock was built probably sometime in the 14th century. It was powered by a weight attached to a cord wrapped around a cylinder. The cylinder in turn was connected to a notched wheel, the *crown wheel*. The crown wheel was constrained to rotate in steps by a vertical mechanism called a *verge escapement*, which was topped by a horizontal iron bar, the *foliot*, with movable weights at each end. The foliot was pushed first in one direction and then the other by the crown wheel, whose teeth engaged small metal extensions called *pallets* located at the top and bottom of the crown wheel. Each time the foliot moved back and forth, one tooth of the crown wheel was allowed to escape. The rate of the clock was adjusted by moving the weights in or out along the foliot.

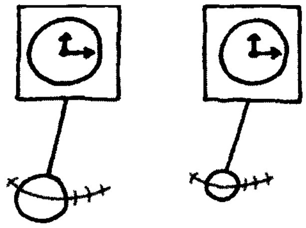



Since the clock kept time accurately within about 15 minutes a day, it did not need a minute hand. No two clocks kept the same time because the period was very dependent upon the friction between parts, the weight that drove the clock, and the exact mechanical arrangement of the parts of the clock. Later in the 15th century the weight was replaced by a spring in some clocks, but this was also unsatisfactory because the driving force of the spring diminished as the spring unwound.

### The Pendulum Clock

As long as the period of a clock depended primarily upon a number of complicated factors such as friction between the parts, the force of the driving weight or spring, and the skill of the craftsman who made it, clock production was a chancy affair, with no two clocks showing the same time, let alone keeping accurate time. What was needed was some sort of periodic device whose frequency was essentially a property of the device itself and did not depend primarily on a number of external factors.

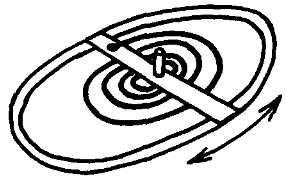
A pendulum is such a device. Galileo is credited with first realizing that the pendulum could be the frequency-determining device for a clock. As far as Galileo could tell, the period of the pendulum depended upon its length and not on the magnitude of the swing or the weight of the mass at the end of the string. Later work showed that the period does depend slightly upon the magnitude of the swing, but this correction is small as long as the magnitude of the swing is small.



Apparently Galileo did not get around to building a pendulum clock before he died in 1642, leaving this application of the principle to the Dutch scientist Christian Huygens, who built his first clock in 1656. Huygens' clock was accurate within 10 seconds a day—a dramatic improvement over the foliot clock.

### The Balance-Wheel Clock

At the same time that Huygens was developing his pendulum clock, the English scientist Robert Hooke was experimenting with the idea of using a straight metal spring to regulate the frequency of a clock. But it was Huygens who, in 1675, first successfully built a spring-controlled clock. He used a spiral spring, whose derivative—the "hair spring"—is still employed in watches today. We have already told the story of John Harrison, the Englishman who built a clock that made navigation practical. The rhythm of Harrison's chronometer was maintained by the regular coiling and uncoiling of a spring. One of Harrison's chronometers gained only 54 seconds during a five-month voyage to Jamaica, or about one-third second per day.



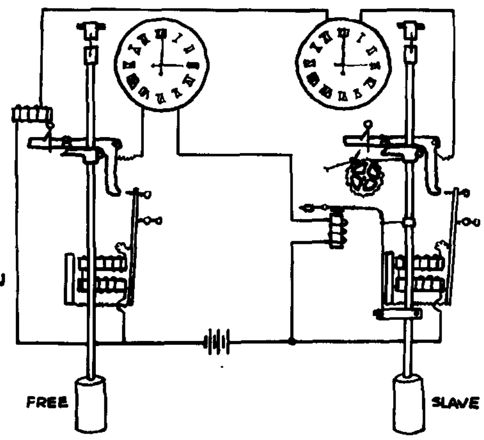
### Further Refinements

The introduction of the pendulum was a giant step in the history of keeping time. But nothing material is perfect. Galileo correctly noted that the period of the pendulum depends upon its length; so the search for ways to overcome the expansion and contraction of the length of the pendulum caused by changes in temperature was on. Experiments with different materials and combinations of metals greatly improved the situation.

As the pendulum swings back and forth it encounters friction caused by air drag, and the amount of drag changes with atmospheric pressure. This problem can be overcome by putting the pendulum in a vacuum chamber, but even with this refinement there are still tiny amounts of friction that can never be completely overcome. So it is always necessary to recharge the pendulum occasionally with energy, but recharging slightly alters the period of the pendulum.

Attempts to overcome all of these difficulties finally led to a clock that had two pendulums—the "free" pendulum and the "slave" pendulum. The free pendulum was the frequency-keeping device, and the slave pendulum controlled the release of energy to the free pendulum and counted its swings. This type of clock, developed by William Shortt, kept time within a few seconds in five years.

SCHEMATIC DRAWING OF AN EARLY TWO-PENDULUM CLOCK. THE SLAVE PENDULUM TIMES THE RELEASE OF ENERGY VIA AN ELECTRIC CIRCUIT TO THE FREE PENDULUM, THUS AVOIDING A DIRECT MECHANICAL CONNECTION BETWEEN THE FREE AND SLAVE PENDULUM.



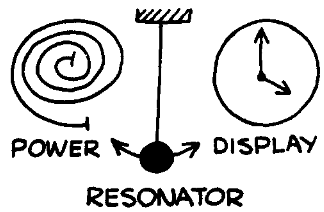

## THE SEARCH FOR EVEN BETTER CLOCKS

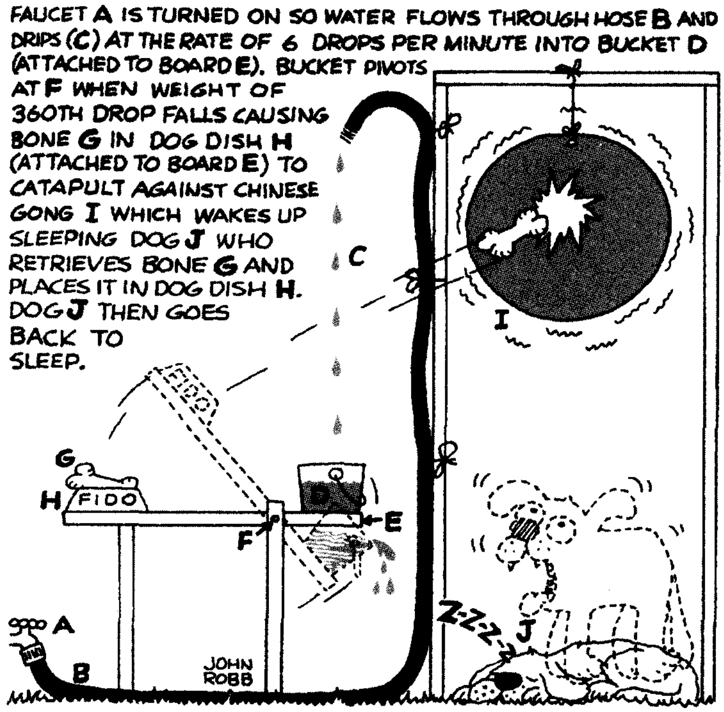
If we are to build a better clock, we need to know more about how a clock's major components contribute to its performance. We need to understand "what makes it tick." So before we begin the discussion of today's advanced atomic clocks, let's digress for a few pages to talk about the basic components of all clocks and how their performance is measured.

From our previous discussions we can identify three main features of all clocks:

- We must have some device that will produce a "periodic phenomenon." We shall call this device a *resonator.*
- We must sustain the periodic motion by feeding energy to the resonator. We shall call the resonator and the energy source, taken together, an *oscillator.*
- We need some means for counting, accumulating, and displaying the ticks or swings of our oscillator—the hands on the clock, for example.

All clocks have these three components in common.




HOUR CLOCK

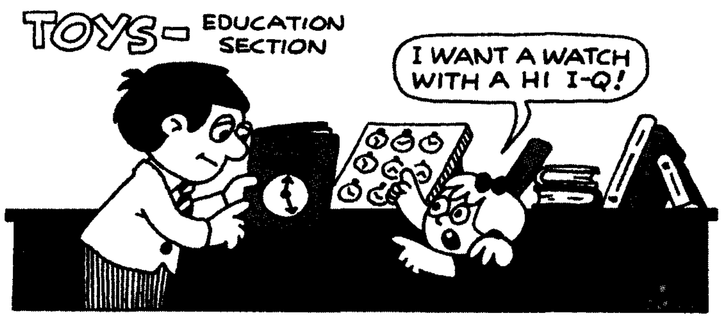
# Chapter 4

# "Q" IS FOR QUALITY

An ideal resonator would be one that, given a single initial push, would run forever. But of course this is not possible in nature; because of friction everything eventually "runs down." A swinging pendulum comes to a standstill unless we keep replenishing its energy to keep it going.

Some resonators, however, are better than others, and it is useful to have some way of judging the relative merit of various resonators in terms of how many swings they make, given an initial push. One such measure is called the "Quality Factor," or "*Q*." *Q* is the number of swings a resonator makes until its energy diminishes to a few percent of the energy imparted with the initial push. If there is consider-

Q=QUALITY FACTOR



| TYPE | Q |
|---|---|
| INEXPENSIVE BALANCE WHEEL WATCH | 1000 |
| TUNING FORK WATCH | 2000 |
| QUARTZ CLOCK | $10^5 - 10^6$ |
| RUBIDIUM CLOCK | $10^6$ |
| CESIUM CLOCK | $10^7 - 10^8$ |
| HYDROGEN MASER CLOCK | $10^9$ |

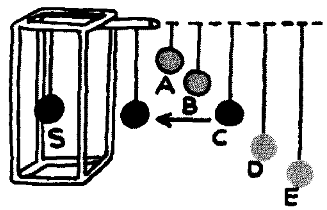
able friction, the resonator will die down rapidly, so resonators with a lot of friction have a low Q, and vice versa. A typical mechanical watch might have a Q of 100, whereas scientific clocks have Q's in the millions.

ACCURACY
STABILITY

One of the obvious advantages of a high-Q resonator is that we don't have to perturb its natural or *resonant* frequency very often with injections of energy. But there is another important advantage. A high-Q resonator won't oscillate at all unless it is swinging at or near its natural frequency. This feature is closely related to the *accuracy* and *stability* of the resonator. A resonator that won't run at all unless it is near its natural frequency is potentially more *accurate* than one that could run at a number of different frequencies. Similarly, if there is a wide range of frequencies over which the resonator can operate, it may wander around within the allowed frequency range, and so will not be very *stable*.

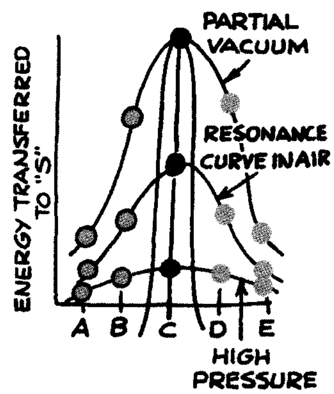
## THE RESONANCE CURVE

To understand these implications better, consider the results of some experiments with the device shown in the sketch. This is simply a wooden frame enclosing a pendulum. At the top of the pendulum is a round wooden stick to which we can attach the pendulums of various lengths shown in the sketch.




Let's begin by attaching pendulum C to the stick and giving it a push. A little bit of the swinging motion of C will be transmitted to the pendulum in the frame, which we shall call S. Since S and C have the same length, their *resonant frequencies* will be the same. This means that S and C will swing with the same frequency, so the swinging energy of C can easily be transferred to S. The situation is similar to pushing someone on a playground swing with the correct timing; we are pushing always *with* the swings, never working against them.

After a certain interval of time we measure the amplitude of the swings of S, which is also a measure of the energy that has been transferred from C to S. The sketch shows this measurement graphically; the black dot in the middle of the graph gives the result of this part of our experiment.




Now let's repeat the experiment, but this time we'll attach pendulum D to the stick. D is slightly longer than S, so its period will be slightly longer. This means that D will be pushing S in the direction it "wants" to swing part of the time, but at other times S will want to reverse its direction before D is ready to reverse. The net result, as shown on our graph by the gray dot above D, is that D cannot transfer energy as easily as could C.

Similarly, if we repeat the experiment with pendulum E attached to the stick, there will be even less transference of energy to S because of E's even greater length. As we might anticipate, we obtain similar diminishing in energy transfer as we attach pendulums of successively *lesser* length than S. In these cases, however, S will want to reverse its direction at a rate *less* than that of the shorter pendulums.

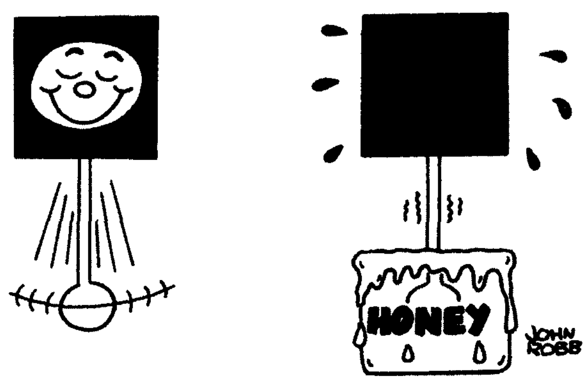
The results of all our measurements are shown by the second, or middle, curve on our graph; and from now on we shall call such curves *resonance* curves.

We want to repeat these measurements two more times, first, with the frame in a pressurized chamber, and second with the frame in a partial vacuum. The results of these experiments are shown on the graph. As we might expect, the resonance curve obtained by doing the experiment under pressure is much flatter than that of the experiment performed simply in air. This is true because, at high pressure, the molecules of air are more dense, so the pendulum experiences a greater frictional loss because of air drag. Similarly, when we repeat the experiment in a partial vacuum, we obtain a sharper, more peaked resonance curve because of reduced air drag.

These experiments point to an important fact for clock builders: the smaller the friction or energy loss, the sharper and more peaked the resonance curve. $Q$ is related to frictional losses; the lower the friction for a given resonator, the higher the $Q$. Thus we can say that high-$Q$ resonators have sharply peaked resonance curves and that low-$Q$ resonators have low, flat resonance curves. Or to put it a little differently, the longer it takes a resonator to die down, or "decay," given an initial push, the sharper its resonance curve.

## ENERGY BUILD-UP AND THE RESONANCE CURVE —AN ASIDE ON Q

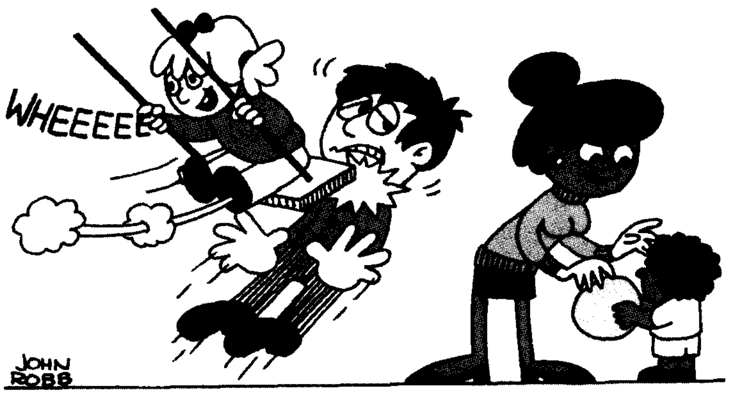
Why do resonators with a long "decay" time resist running at frequencies other than their natural frequency? A pendulum with a high $Q$ may swing for many minutes, or even hours, from just a single push, whereas a very low-$Q$ pendulum—such as one suspended in honey—may hardly



make it through even one swing after an initial push; it would need a new push for every swing and would never accumulate enough energy to make more than the single swing.

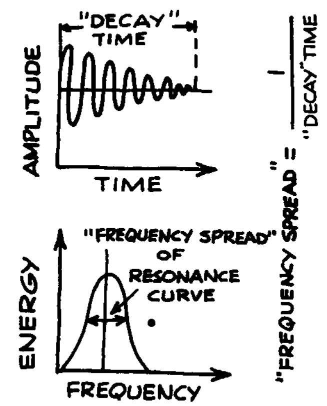
But if we push the high-Q pendulum occasionally in step with its own natural rhythm or frequency, it accumulates or stores up the energy imparted by these pushes. Thus the energy of the pendulum or oscillator may eventually greatly *exceed* the energy imparted by a single push or injection. We can observe this fact by watching someone jumping on a trampoline. As the jumper matches her muscular rhythm to that of her contact with the trampoline, it tosses her higher with each jump; she stores up the energy she puts into it with each jump.

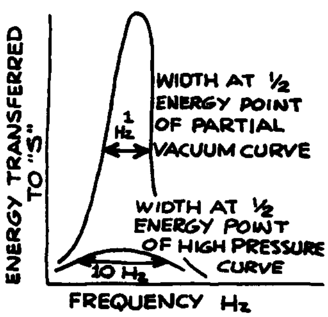
The same principle governs a person swinging on a playground swing. He "pumps up" by adding an extra shot of energy at just the right moment in the swing's natural rhythm or frequency. When he does this, the swing carries over extra energy from his pushes. The rhythm of the swing becomes so strong, in fact, that it can resist or "kick back" at the energy source if it applies energy at the wrong time-as anyone who has pushed someone else in a swing well knows!




In just such a way, a high-*Q* resonator can accumulate or pile up the energy it receives from its "pusher," or oscillator. But a low-*Q* resonator cannot accumulate appreciable energy; instead, the energy will constantly "leak out" at about the same rate it is being supplied, because of friction. Even though we feed the resonator with energy at its natural frequency, the amplitude will never build up. On the other hand, if we replenish its energy at a rate other than the natural frequency, the resonator won't have accumulated appreciable energy at its natural frequency to resist pushes at the wrong rate.

Thus the shape of the resonance curve is determined by the $Q$ of the resonator that is being pushed or driven by some other oscillator, and the transferral of energy from the oscillator to the driven resonator depends upon the similarity between the natural frequency of the resonator and the frequency of the oscillator.



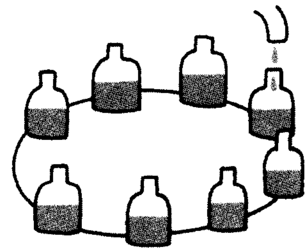

## THE RESONANCE CURVE AND THE DECAY TIME

We have already observed that resonators with a high $Q$ or long decay time have a sharp resonance curve. Careful mathematical analysis shows that there is an exact relation between the decay time and the sharpness of the resonance curve, if the sharpness is measured in a particular way. This measurement is simply the *width* of the resonance curve, in hertz, at the point where the *height* of the curve is half its maximum value.

To illustrate this principle we have redrawn the two resonance curves for our resonator in a pressure chamber and in a partial vacuum. At the half-energy point of the high-pressure curve, the width is about 10 hertz, whereas for the partial vacuum curve the width is about 1 hertz at the half-energy point. With this measurement of width the mathematical analysis shows that the width of the resonance curve at the half-energy point is just the reciprocal of the decay time of the resonator. As an example, let's suppose it takes a particular resonator 10 seconds to die down, or decay. Then the width of its resonance curve at the half-energy point is one over 10 seconds, or 0.1 hertz.

We can think of the width of the curve at the half-energy point as indicating how close the pushes of the driving oscillator must be to the natural frequency of the resonator before it will respond with any appreciable vibration.

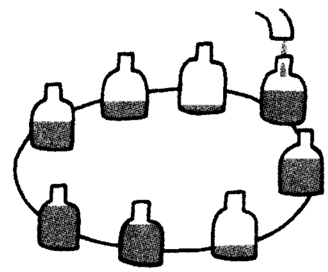
## ACCURACY, STABILITY, AND Q



ALL BOTTLES HALF FULL

Two very important concepts to clockmakers are *accuracy* and *stability*; and, as we suggested earlier, both are closely related to $Q$.

We can understand the distinction between accuracy and stability more clearly by considering a machine that fills bottles with a soft drink. If we study the machine we might discover that it fills each bottle with almost exactly the same amount of liquid, to better than one-tenth of an ounce. We would say the filling *stability* of the machine is quite good. But we might also discover that each bottle is being filled to only half capacity—but very precisely to half capacity from one bottle to the next. We would then characterize the machine as having good stability but poor *accuracy*.



EACH BOTTLE CONTAINS DIFFERENT AMOUNT

However, the situation might be reversed. We might notice that a different machine was filling some bottles with an ounce or so of extra liquid, and others with an ounce or so less than actually desired, but that *on the average* the correct amount of liquid was being used. We could characterize this machine as having poor *stability*, but good *accuracy* over one day's operation.

Some resonators have good stability, others have good accuracy; the best, for clockmakers, must have both.

### High Q and Accuracy

We have seen that high-$Q$ resonators have long decay times and therefore sharp, narrow resonance curves—which also implies that the resonator won't respond very well to pushes unless they are at a rate very near its natural or resonant frequency. Or to put it differently, a clock with a high-$Q$ resonator essentially won't run at all unless it's running at its resonant frequency.

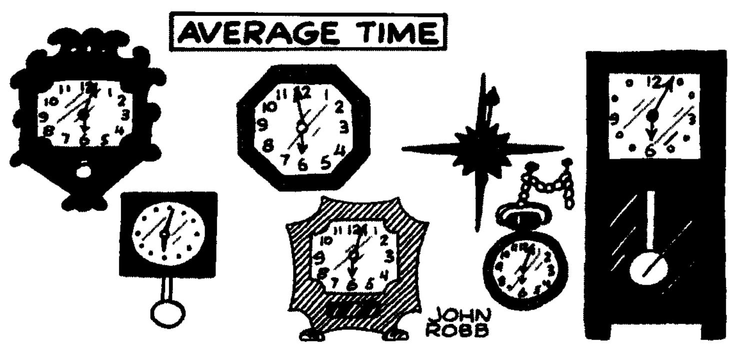
Today, the second is defined in terms of a particular resonant frequency of the cesium atom. So if we can build a resonator whose natural frequency is the natural frequency of the cesium atom—and furthermore, if this resonator has an extremely high $Q$—then we have a device that will *accurately* generate the second according to the definition of the second.

### High Q and Stability

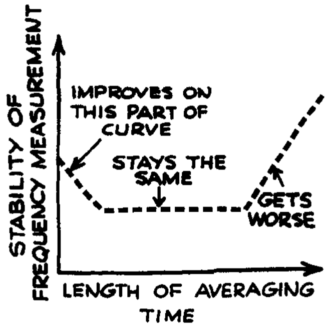
We saw that a low-stability bottle-filling machine is one that does not reliably fill each bottle with the same amount of liquid and further, that good stability does not necessarily mean high accuracy. A resonator with a high-$Q$, narrow resonance curve will have good stability because the narrow resonance curve constrains the oscillator to run always at a frequency near the natural frequency of the resonator. We could, however, have a resonator with good stability but whose resonance frequency is not according to the definition of the second—which is the natural frequency of the cesium atom. A clock built from such a resonator would have good stability but poor accuracy.

### Waiting to Find the Time

In our discussion of the bottle-filling machine, we considered a machine that did not fill each bottle with the desired amount, but that on the average over a day's operation used the correct amount of liquid. We said such a machine had poor stability but good accuracy averaged over a day. The same can be said of clocks. A given clock's frequency may "wander around" within its resonance curve so that for a given measurement the frequency may be in error. But if we average many such measurements over a long time—or average the time shown by many different clocks at the same time—we can achieve greater accuracy—assuming that the resonator's natural frequency is the correct frequency.



It may appear that clock error can be made as small as desired if enough measurements were averaged over a long time. But experience shows that this is not true. As we first begin to average the measurements, we find that the fluctuations in frequency decrease, but then beyond some point the fluctuations no longer decrease with averaging, but remain rather constant. And finally, with more measurements considered in the averaging the frequency stability begins to grow worse again.



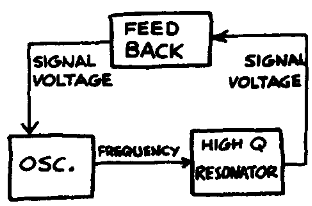

The reasons that averaging does not improve clock performance beyond a certain point are not entirely understood. One reason, called "flicker" noise, has been observed in other electronic devices—and interestingly enough, even in the fluctuations of the height of the Nile River.

**PUSHING Q TO THE LIMIT**

You may wonder whether there is any limit to how great $Q$ may be. Or in other words, whether clocks of arbitrarily high accuracy and stability can be constructed. It appears that there is no fundamental reason why $Q$ cannot be arbitrarily high, although there are some practical considerations that have to be accounted for, especially when $Q$ is very high. We shall consider this question in more detail later, when we discuss resonators based upon atomic phenomena, but we can make some general comments here.

Extremely high $Q$ means that the resonance curve is extremely narrow, and this fact dictates that the resonator will not resonate unless it is being driven by a frequency very near its own resonant frequency. But how are we to generate such a driving signal with the required frequency?

The solution is somewhat similar to tuning in a radio station—or tuning one stringed instrument to another. We let the frequency of the driving signal change until we get the maximum response from the high-Q resonator. Once the maximum response is achieved, we attempt to maintain the driving signal at the frequency that produced this response. In actual practice this is done by using a "feedback" system of the kind shown in the sketch.




We have a box that contains our high-$Q$ resonator, and we feed it a signal from our other oscillator, whose output frequency can be varied. If the signal frequency from the oscillator is near the resonant frequency of the high-$Q$ resonator it will have considerable response and will produce an output signal voltage proportional to its degree of response. This signal is fed back to the oscillator in such a way that it controls the output frequency of the resonator. This system will search for that frequency from the oscillator which produces the maximum response from the high-$Q$ resonator, and then will attempt to maintain that frequency.

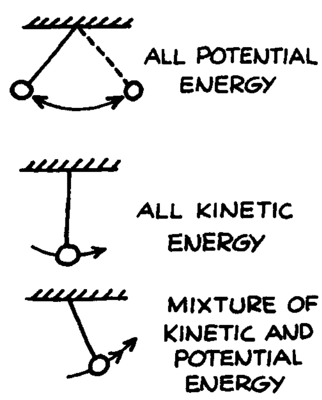
In the next chapter, where we discuss resonators based upon atomic phenomena, we shall consider feedback again. With a fair notion of what $Q$ is all about and how it describes the potential stability and accuracy of a clock, we are in a position to understand a number of other concepts introduced later in this book.

# Chapter 5

# BUILDING EVEN BETTER CLOCKS

The two-pendulum clock, developed in 1921 by William Hamilton Shortt, squeezed just about the last ounce of perfection out of mechanical clocks. If significant gains were to be made, a new approach was needed. As we shall see, new approaches became available as people increased their understanding of nature, particularly in the realms of electricity, magnetism, and the atomic structure of matter. In one sense, however, the new approaches were undertaken within the framework of the old principles. The heart of the clock is today, as it was 200 years ago, some vibrating device with a period as uniform as possible.

Furthermore, the periodic phenomena today, as before, involve the conversion of energy to and from, between two different *forms*. In the swinging pendulum we have energy being transferred back and forth repeatedly from the maximum energy of motion—*kinetic* energy—at the bottom of the swing, to energy stored in the pull of the Earth's gravity—or *potential* energy—at the top of the swing. If the energy does not "leak out" because of friction, the pendulum swings back and forth forever, continually exchanging its energy between the two forms.

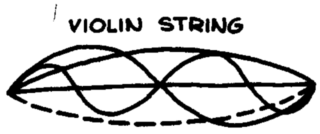



Energy appears in many forms—kinetic, potential, heat, chemical, light ray, electric, and magnetic. In this discussion we shall be particularly interested in the way energy is transferred between atoms and surrounding fields of radio and light waves. And we shall see that resonators based on such phenomena have achieved $Q$'s in the hundreds of *millions.*

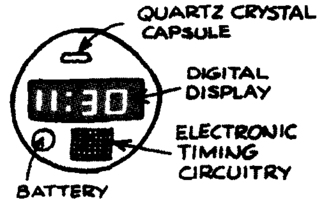
### THE QUARTZ CLOCK—$Q = 10^5 - 2 \times 10^6$

The first big step in a new direction was taken by the American scientist Warren A. Marrison with the development of the quartz-crystal clock in 1929. The resonator of this clock is based on the "piezoelectric effect." In a sense, even the quartz-crystal clock is actually a mechanical clock because a small piece of quartz crystal vibrates when an alternating electric voltage is applied to it. Conversely, if the crystal is made to vibrate it will generate an oscillatory voltage. These two phenomena together are the . The internal friction of the quartz crystal is so very low that the $Q$ may range from 100 000 to more than 2 000 000. It is no wonder that the quartz resonator brought such dramatic gains to the art of building clocks.

The resonant frequency of the crystal depends in a complicated way on how the crystal is cut, the size of the crystal, and the specific resonant frequency that is excited in the crystal by the driving electric voltage. That is, a particular crystal may operate at a number of frequencies in the same way that a violin string can vibrate at a number of different frequencies called *overtones.* The crystal's vibration may range from a few thousand to many millions of cycles per second. Generally speaking, the smaller the crystal the higher the resonance frequency at which it can vibrate. Crystals at the high-frequency end of the scale may be less than 1 millimeter thick. Thus we see that one of the limitations of crystal resonators is related to our ability to cut crystals precisely into very small bits.




The crystal resonator is incorporated into a feedback system that operates in a way similar to the one discussed earlier. The system is self regulating, so the crystal's output frequency is always at or near its resonant frequency. The first crystal clocks were enclosed in cabinets 3 meters high, 2½ meters wide, and 1 meter deep, to accommodate the various necessary components. Today quartz-crystal *wrist*




*watches* are available commercially—which gives some indication of the great strides made in miniaturization of electronic circuitry over the past few years.

The best crystal clocks will keep time within less than 1 millisecond per month, whereas lower quality quartz clocks may drift a millisecond or so in several days. There are two main causes of drift in a quartz oscillator. First, the frequency changes with temperature; and second, there is a slow, long-term drift that may be due to a number of things, such as contamination of the crystal with impurities, changes inside the crystal caused by its vibration, or other aspects of "aging."

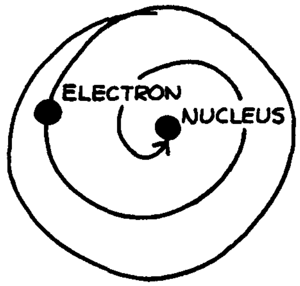
Elaborate steps have been taken to overcome these difficulties by putting the crystal in a temperature-controlled "oven" and in a contamination-proof container. But just as in the case of Shortt's two-pendulum clock, a point of diminishing returns arrives where you must work harder and harder to gain less and less.

## ATOMIC CLOCKS—$Q = 10^7 - 10^8$

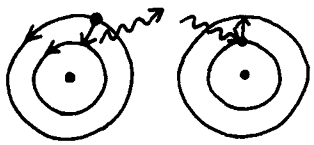
The next big step was the use of *atoms* (actually, at first, *molecules*) for resonators. We can appreciate the degree of perfection achieved with atomic resonators when we are told that these resonators achieve $Q$'s over *100 million*.

To understand this we must abandon Newton's laws, which describe swinging pendulums and vibrating materials, and turn instead to the laws that describe the motions of atoms and their interactions with the outside world. These laws go under the heading of "quantum mechanics," and they were developed by different scientists, beginning about 1900. We shall pick up the story about 1913 with the young Danish physicist, Niels Bohr, who had worked in England with Ernest T. Rutherford, one of the world's outstanding experimental physicists. Rutherford bombarded atoms with alpha particles from radioactive materials and came to the conclusion that the atom consists of a central core surrounded by orbiting electrons like planets circling around the Sun.

But there was a very puzzling thing about Rutherford's conception of the atom: Why didn't atoms eventually run down? After all, even the planets as they circle the Sun




gradually lose energy, moving in smaller and smaller circles until they fall into the Sun. In the same manner, the electron should gradually lose energy until it falls into the core of the atom. Instead, it appeared to circle the core with undiminished energy, like a perpetual motion machine, until suddenly it would jump to another inner orbit, releasing a fixed amount of energy. Bohr came to the then revolutionary ideas that the electron did not *gradually* lose its energy, but lost energy in "lumps" by jumping between definite orbits and that the energy was released in the form of radiation at a particular *frequency*.




Conversely, if the atom is placed in a radiation field it can *absorb* energy only in discrete lumps, which causes the electron to jump from an inner to an outer orbit. If the radiation field has no frequency that corresponds to the energy associated with an allowed jump, then energy can be absorbed. If there is such a frequency, then the atom can absorb energy from the radiation field.

The frequency of the radiation is related to the lump or quantum of energy in a very specific way: The bigger the quantum of energy, the higher the emitted frequency. This energy-frequency relationship, combined with the fact that only certain quanta of energy are allowed—those associated with electron jumps between specific orbits—is an important phenomenon for clockmakers. It suggests that we can use atoms as *resonators,* and furthermore that the emitted or resonance frequency is a property of the atom itself.

This is a big advance because now we don't have to be concerned with such things as building a pendulum to an exact length or cutting a crystal to the correct size. The atom is a natural resonator whose resonance frequency is practically immune to the temperature and frictional effects that plague mechanical clocks. The atom seems to be approaching the ideal resonator.

But we are still a long way from *producing* an atomic resonator. How are we to count the "ticks" or measure the frequency of such a resonator? What is the best atom to use? How do we get the electron in the chosen atom to jump between the desired orbits to produce the frequency we want?

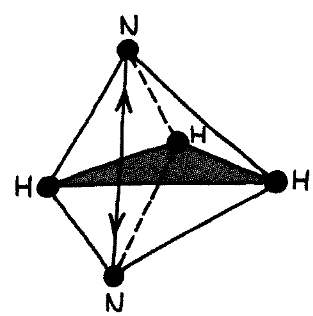
We have partially answered these questions in the section on "Pushing $Q$ to the Limit." There we described a feedback system consisting of three elements—an oscillator, a high-$Q$ resonator, and a feedback path. The oscillator produces a signal that is transmitted to the high-$Q$ resonator, causing it to vibrate. This vibration in turn, through suitable electronic circuitry, generates a signal proportional to the magnitude of the vibration that is fed back to the oscillator to adjust its frequency. This process goes around and around until the high-Q resonator is vibrating with maximum amplitude; that is, it is vibrating at its resonance frequency.

In the atomic clocks that we shall discuss, the oscillator is always a crystal oscillator of the type discussed in the previous section, whereas the high-$Q$ resonator is based upon some natural resonant frequency of different species of atoms.

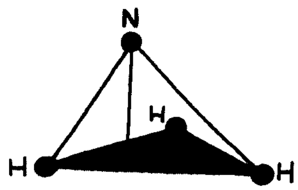
In a sense, atomic clocks are the "offspring" of Shortt's two-pendulum clock, where the crystal oscillator corresponds to one pendulum and the high-$Q$ resonator to the other.

### The Ammonia Resonator—$Q = 10^8$

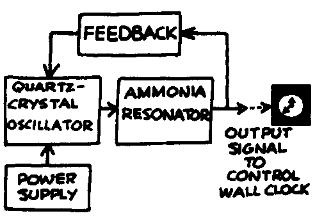
In 1949, the National Bureau of Standards (NBS) announced the world's first time source linked to the natural frequency of atomic particles. The particle was the ammonia molecule, which has a natural frequency at about 23 870 megahertz. This frequency is in the microwave part of the radio spectrum, where radar systems operate. During World War II, great strides had been made in the development of equipment operating in the microwave region, and attention had been focused on resonant frequencies such as that of the ammonia molecule. So it was natural that the first atomic frequency device followed along in this area.




The ammonia molecule consists of three hydrogen atoms and one nitrogen atom in the shape of a pyramid, with the hydrogen atoms at the base and the nitrogen atom at the top. We have seen how the rules of quantum mechanics require that atoms emit and absorb energy in discrete quanta. According to these rules, the nitrogen atom can jump down through the base of the pyramid and appear on the other side, thus making an upside-down pyramid. As we might expect, it can also jump back through the base to its original position. The molecule can also spin around different axes of rotation: The diagram shows one possibility. Each allowed rotation corresponds to a different energy state of the molecule. If we carefully inspect one of these states, we see that it actually consists of two distinct, but closely spaced, energy levels. This splitting is a consequence of the fact that the nitrogen atom can be either above or below the base of the pyramid. The energy difference between a pair of levels corresponds to a frequency of about 23 870 megahertz.



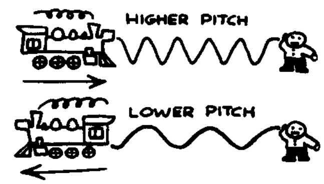

To harness this frequency a feedback system consisting of two "pendulums" is employed: a quartz-crystal oscillator and the ammonia molecules. The quartz-crystal oscillator generates a frequency near that of the ammonia molecule. We can think of this signal as a weak radio signal being broadcast into a chamber of ammonia molecules. If the radio signal is precisely at the resonant frequency of the ammonia molecules, they will oscillate and strongly absorb the radio signal energy, so little of the signal will pass through the chamber. At any other frequency the signal will pass through the ammonia, the absorption being roughly proportional to the difference between the radio signal frequency and the resonant frequency of the ammonia. The radio signal that gets through the ammonia is used to adjust the frequency of the quartz-crystal oscillator to that of the ammonia's resonance frequency. Thus the ammonia molecules keep the quartz-crystal oscillator running at the desired frequency.




The quartz-crystal oscillator in turn controls some display device such as a wall clock. Of course, the wall clock runs at a much lower frequency—usually 60 hertz, like an ordinary electric kitchen clock. To produce this lower frequency, the crystal's frequency is reduced by electronic circuitry in a manner similar to using a train of gears to convert wheels running at one speed to run at another speed.

Although the resonance curve of the ammonia molecule is very narrow compared to previously used resonators, there are still problems. One is due to the collision of the ammonia molecules with one another and with the walls of the chamber. These collisions produce forces on the molecules that alter the resonant frequency.

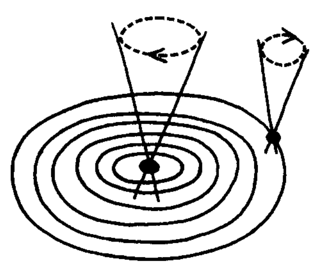
Another difficulty is due to the motions of the molecules—motions that produce a "Doppler shift" of the frequency. We observe Doppler frequency shifts when we listen to the whistle of a train as it approaches and passes us. As the train comes toward us, the whistle is high in pitch, and then as the train passes by, the pitch lowers. This same effect applies to the speeding ammonia molecules and distorts the results. Turning to the cesium atom instead of the ammonia molecule minimizes these effects.



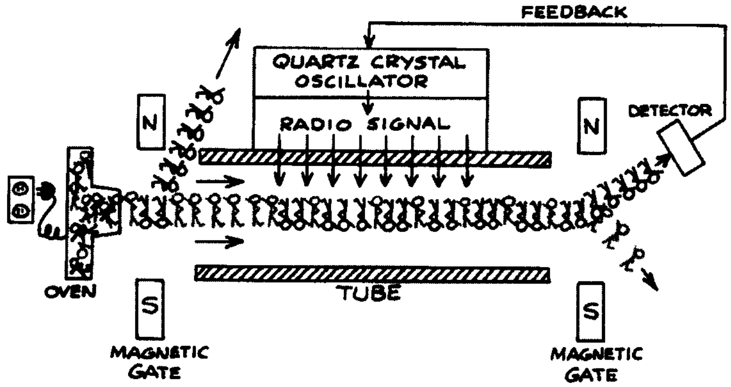

### The Cesium Resonator—$Q = 10^7 - 10^8$

The cesium atom has a natural vibration at 9 192 631 770 hertz, which is, like that of the ammonia molecule, in the microwave part of the radio spectrum. This natural vibration is a property of the atom itself, in contrast to ammonia's natural frequency, which results from the interactions of four atoms. Cesium is a silvery metal at room temperature. The core of the atom is surrounded by a swarm of electrons, but the outermost electron is in an orbit by itself. This electron has a magnetic field as though it were spinning on its axis. The core or nucleus of the cesium atom also spins, producing another miniature magnet, each magnet feeling the force of the other.

These two magnets are like spinning tops wobbling around in the same way the Earth wobbles because of the pull of the Moon. (This wobbling motion of the Earth is discussed more fully in Chapter 7.) If the two magnets are aligned with their north poles in the same direction, the cesium atom is in one energy state; if they are aligned in opposite directions, the atom is in a different energy state. The difference between these two energy states corresponds to a frequency of 9 192 631 770 hertz. If we immerse the cesium atoms in a "bath" of radio signals at precisely this frequency, then the outside spinning electron can "flip over," either absorbing energy or emitting energy.



The next figure illustrates the operation of the cesium-beam frequency standard. On the left is a small electric "oven" that heats the cesium atoms so that they are "boiled out" through a small opening into a long, evacuated tube.




The atoms travel down the tube like marching soldiers, thus avoiding collisions with each other—which was one of the difficulties with the ammonia resonator. As the atoms pass along the tube they come to a "gate," which is in reality a special magnetic field that separates the atoms into two streams according to whether their electron is spinning in the same direction as the nucleus or the opposite direction. Only one kind of atom is allowed to proceed down the tube, while the others are deflected away. The selected beam then passes through a section of the tube where the particles are exposed to a radio signal very near 9 192 631 770 hertz. If the radio signal is precisely at the resonant frequency, then large numbers of atoms will change their energy state, or "flip over."

The atoms then pass through another magnetic gate at the end of the tube. Those atoms that have changed energy state while passing through the radio signals are allowed to proceed to a detector at the end of the tube, while those that did not change state are deflected away from the detector. When the radio frequency is equal to the resonant frequency, the greatest number of atoms will reach the detector. The detector produces a signal that is related to the number of atoms reaching it, and this signal is fed back to control the radio frequency through a crystal oscillator so as to maximize the number of atoms reaching the detector—which, of course, means that the radio signal is at the cesium atom's resonance frequency. In this way the crystal oscillator's frequency is tied to the resonance frequency of the cesium atom. The whole process, which is automatic, is much like carefully tuning in a radio so that the receiver gets the loudest and clearest signal; when this happens, the receiver is exactly "on-frequency" with the signal sent.

We have seen that one of the difficulties with the ammonia resonator is avoided by having the cesium atoms march down the tube with as little interaction as possible. The spread in frequency caused by the Doppler shift is minimized by transmitting the radio signal at right angles to the beam of the cesium atoms, as shown in the figure; the cesium atoms are never moving toward or away from the radio signal, but always across it.

### One Second in 10 000 000 Years

Carefully constructed cesium-beam-tube resonators maintained in laboratories have $Q$'s over 100 million, whereas smaller, portable units, about the size of a piece of luggage, have $Q$'s of about 10 million. In principle, laboratory oscillators keep time within about *one second in 10 000 000 years*—if we could build one that would last that long.

What accounts for this high $Q$ of a cesium resonator? In our discussion of $Q$ we saw that the frequency spread of the resonance curve decreases as the "decay" time increases. In fact, the spread is just the reciprocal decay time $\left(\frac{1}{\text{decay time}}\right)$. In the case of the cesium-beam tube, the decay time is the time it takes the cesium atoms to travel the length of the tube. Laboratory beam tubes may be several meters long, and the cesium atoms boiling out of the electric oven travel down the tube at about 100 meters per second, so the cesium atom is in a 1 meter long tube, for example, about 0.01 seconds which is equal to 100 hertz. But the $Q$ is the resonant frequency divided by the frequency spread, or 9 192 631 770 hertz/100 hertz, or about 100 million.

$$\text{TIME IN TUBE} = \frac{\text{LENGTH OF TUBE}}{\text{SPEED OF ATOMS}} = 0.04 \text{ SEC.}$$

$$\text{FREQUENCY SPREAD} = \frac{1}{\text{TIME IN TUBE}} = \frac{1}{0.04} = 25 \text{ Hz}$$

### Pumping the Atom

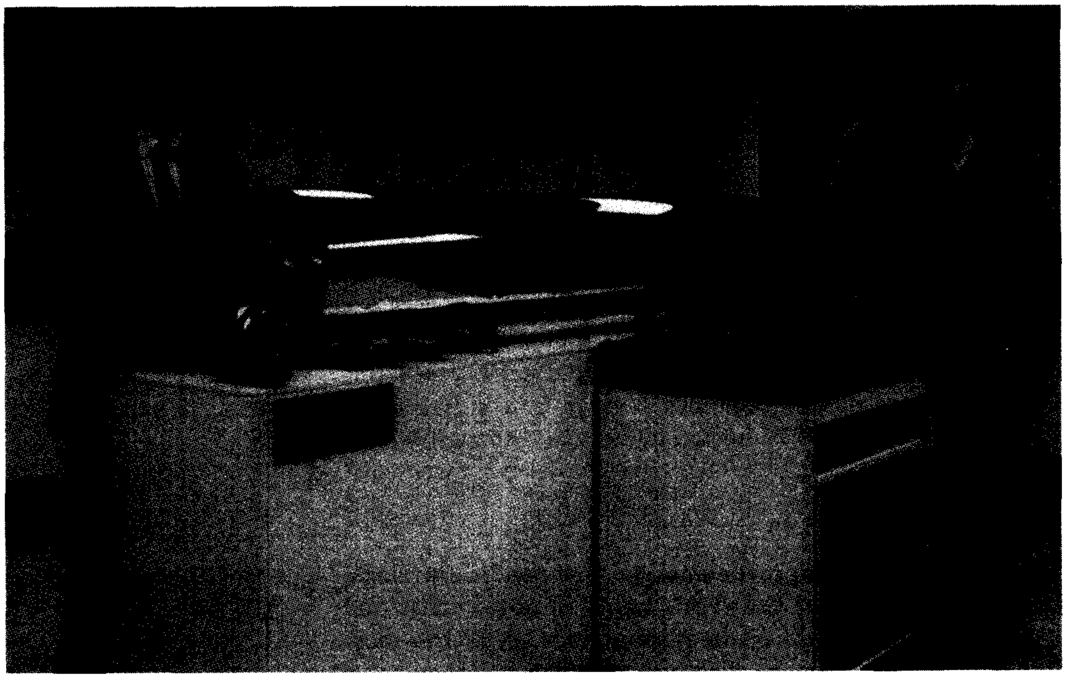
Like Shortt's improvements to the pendulum clock, there have been, over the years, many improvements and refinements of cesium beam resonators. One of the most important advances came with replacing the magnetic gates

## LASERS REPLACE MAGNETS

by "light" gates. In this method a laser light beam, which we shall revisit in Chapter 7, drives (or pumps) the cesium atoms into the desired energy state. After the atoms have passed though the beam tube they are radiated by a second laser beam. Only the atoms at the desired energy level absorb this light, which is reradiated almost immediately. A light-sensitive detector measures the reradiated light intensity. As with the earlier cesium resonator with magnetic gates, the reradiated light is at maximum strength when the bathing radio frequency equals the natural frequency of the atoms.

The pumping scheme has a big advantage over the earlier method. Here all the atoms in the beam are pumped into the desired energy level unlike the magnetic gate method which simply screens out the undesired atoms. The immediate benefit is that the signal strength from pumping is much higher.

In 1993, NIST replaced its primary frequency standard with one employing optical pumping yielding, almost at once, a large gain in accuracy.



NIST-7 Primary Frequency Standard with NIST Scientists.

### Atomic Definition of the Second

Because of the smoothness with which the cesium resonator "ticks," the definition of the second based on astronomical observation was abandoned in 1967, and the second was redefined as the duration of 9 192 631 770 vibrations of the cesium atom.

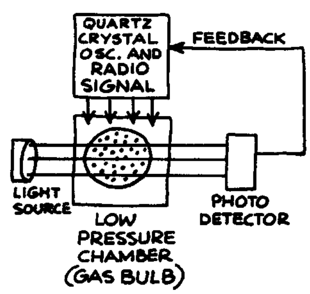
This is an example of the continuing tug of war between the astronomers and clockmakers we mentioned earlier.

In Chapter 9, there is a much fuller discussion of the events that led to the atomic definition of the second. As we shall also see in that chapter, national laboratories responsible for the ultimate generation of time information do not literally have a large atomic clock with a face and hands like a wall clock, but rather the "clock" consists of a number of components, one of which is a set of atomic oscillators whose job it is to provide accuracy and stability for the entire clock system.

### The Rubidium Resonator—$Q = 10^7$

The rubidium resonator, although of lower quality than the cesium resonator, is nevertheless important because it is relatively inexpensive compared to cesium resonators and because it is more than adequate for many of today's needs. The device is based on a particular resonance frequency of rubidium atoms contained as a gas at very low pressure in a specially constructed chamber.

Atoms, like crystals, have more than one resonant frequency. One of the rubidium resonance frequencies is excited by an intense beam of light, and another resonant frequency is excited by a radio wave in the microwave frequency region. As the light shines through the glass bulb containing rubidium gas, atoms in the "correct" energy state will absorb energy. (The situation is similar to the cesium atoms passing through the radio signal, where only those atoms with the outer electron spinning in the proper direction could absorb the radio signal and flip over to produce a different energy state.)



RUBIDIUM OSCILLATOR

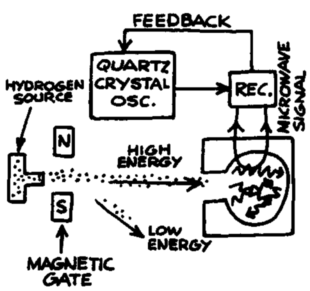
The microwave radio signal, when it is at the resonance frequency of the rubidium atom, converts the maximum number of atoms into the "correct" kind to absorb energy from the light beam. As more of the atoms in the bulb are converted into the correct kind, they absorb more of the energy of the light beam; thus when the light beam is most heavily absorbed, the microwave signal is at the desired frequency. Again, as in the cesium-beam tube, the amount of light intensity that shines through the beam is detected and used to generate a signal that controls the microwave frequency to make the light beam reach minimum value.

The best rubidium oscillators have $Q$'s of around 100 million, and they keep time within less than one millisecond in a few months. But like crystal oscillators, they drift slowly with time and must occasionally be reset with reference to a cesium oscillator. This drift is due to such things as drift in the light source and absorption of rubidium in the walls of the storage bottle.

### The Hydrogen Maser—$Q = 10^9$

In the three atomic resonators we have discussed—ammonia, cesium, and rubidium resonators—we observe the resonant frequency indirectly. That is, in the cesium oscillator, we measure the number of atoms reaching the detector. In the ammonia and rubidium devices, we measure the signal absorbed as the signal passes through atoms and molecules. Why not observe the atomic radio or optical signal directly? The next device we shall discuss—the hydrogen maser—does just that.

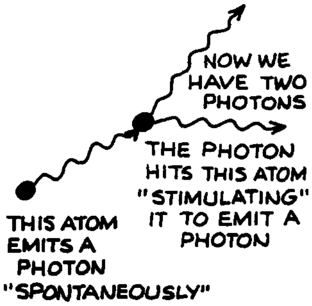
Charles H. Townes, an American scientist who developed the maser, was not working on an oscillator at all; rather he was seeking a way to amplify microwave radio signals. Hence the name *maser,* which is simply an acronym for Microwave Amplification by Stimulated Emission of Radiation. But as we have seen, anything that oscillates or swings with a definite period or frequency can become the basis of a timekeeping device or clock. The resonator in the hydrogen maser is the hydrogen atom, which has, among others, a particular resonant frequency of 1 420 405 752 hertz.




HYDROGEN MASER OSCILLATOR

In a manner similar to that of the cesium-beam tube, hydrogen gas drifts through a magnetic gate that allows only those atoms in an energy-emitting state to pass. Those atoms making it through the gate enter a quartz-glass storage bulb several centimeters in diameter. The bulb is coated inside with a Teflon material similar to that used on nonstick cookware. For reasons not entirely understood, this coating reduces the frequency-perturbating actions caused by collisions of the hydrogen atoms with the wall of the bulb. The atoms stay in the bulb about one second before leaving; thus their effective decay time is about one second, as opposed to 0.01 second for the cesium-beam tube. This longer decay time results in a $Q$ about 10 times higher than that of the cesium beam oscillator, even though the resonant frequency is lower.

If the bulb contains enough hydrogen atoms in the energy-emitting state, "self-oscillation" will occur in the bulb. According to the laws of quantum mechanics, an atom in an energy-emitting state will, eventually, *spontaneously* emit a packet of radiation energy. Although it is not possible to know in advance which atom will emit energy, if there are enough atoms in the quartz bulb, eventually one of them spontaneously emits a packet of energy, or *photon*, at the resonant frequency. If this photon hits another atom in an energy-emitting state, that atom may be "stimulated" to release its energy as another photon of exactly the same energy—and therefore the same frequency—as the photon that started the process. The remarkable thing is that the "stimulated" emission is in step with the radiation that produced it. The situation is similar to that of a choir in which all members are singing the same word at the same time, rather than the same word at different times.




We now have two photons bouncing around inside the bulb, and they will interact with other energy-emitting atoms, so the whole process escalates like a falling house of cards. Since all of the photons are in step, they constitute a microwave radio signal at a specific frequency, which is picked up by a receiver. This signal keeps a crystal oscillator in step with the resonance frequency of the energy-emitting hydrogen atoms. Energy is supplied by a constant stream of hydrogen atoms in their high-energy state, and thus, a continuous signal results.

Although the $Q$ of the hydrogen resonator is higher than that of the cesium-beam resonator, its accuracy is not as great today because of the unsolved problem of accurately evaluating and minimizing the frequency shift caused by the collisions between the hydrogen atoms and the wall of the quartz bulb.

## CAN WE ALWAYS BUILD A BETTER CLOCK?

DECAY TIME DECREASES WITH INCREASING FREQUENCY

We have seen that the $Q$ of the resonator is related to its decay time. For the atomic resonators we have discussed, the decay time was largely determined by the length of time the atom spends in some sort of container—a beam tube or a bulb. Historically, the trend has been toward resonators with higher and higher resonance frequencies. But this turns out to have an impact on the decay time. As we said, atoms in energy-emitting states can, given sufficient time, release spontaneously a burst of energy at a particular frequency. According to the rules of quantum mechanics, the decay time decreases rapidly with increasing frequency. At such high frequencies, the average time for spontaneous emission—or natural lifetime—may be considerably smaller than the time that the atom spends in the container.

The history of better clocks has always been one of steady improvement of existing technologies—the first pendulum clock to Shortt's two-pendulum clock, for example—followed by a spurt in clock performance underwritten by some new insight into nature such as a better understanding of the nature of the atom.

The 1989 Nobel Prize in physics demonstrates both aspects of this historical march toward better clocks. Part of the prize was awarded to Norman Ramsey of Harvard University for his many achievements over a lifetime of work. Ramsey's work led to significant improvements in cesium beam resonators and he was a pioneer in exploring the implications of masers for timekeeping.

The other part of the prize was awarded jointly to Hans Dehmelt of the University of Washington and Wolfgang Paul of the University of Bonn in Germany. Their work set the stage for one of those dramatic spurts in improved timekeeping. Whereas cesium beam resonators require millions of atoms for their operation, Paul and Demelt's achievements point toward clocks based on a handful of atoms or even just one atom. We shall have much more to say about this in Chapter 7.

For the present, the only limit to building better and better clocks appears to be the upper reaches of human ingenuity in coping with the problems that inevitably arise when a particular path is taken. So it is our imagination, not nature, that dictates the possibilities for the future.

The atomic resonators we have discussed are far too cumbersome and expensive for any but scientific, laboratory, and similar specific uses, and their operation and maintenance require considerable expertise. But a few years ago the same would have been said of the quartz-crystal oscillator which is now common in clocks and watches. Who is to say that there may not be some breakthrough that will make some sort of atomic clock much more practicable and widely available than it is today?

Chapter

1 2 3 4 5 **6** 7
8 9 10 11 12 13 14
15 16 17 18 19 20 21
22 23 24 25 26 27 28
29 30 31

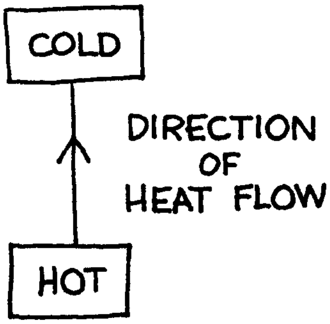
# A SHORT HISTORY OF THE ATOM

In this chapter, we temporarily leave our main theme to fill in a bit of background. We do this for several reasons. First, we need to deepen our understanding of quantum mechanics because it remains a primary tool in the clock maker's arsenal, pointing the way to ever-better clocks. In addition, quantum mechanics, coupled with astronomical observations, has revolutionized our understanding of the birth and evolution of the universe. As we shall see, in Chapter 18, this new understanding has prompted us to rethink the nature of time and the role it plays in the physical universe.

QUANTUM MECHANICS + ASTRONOMICAL OBSERVATIONS

Today, the degree to which we understand the anatomy of the atom verges on the miraculous, given that scientists at the end of the 19th century still debated the atom's very existence. The story of how the atom prevailed is an important part of our background story because we shall see how the motions of atoms led to a profound understanding of the concept of temperature—a subject not only important for future clock development, but also a subject that helps clarify the character of time and the early moments of the universe. We start by briefly reviewing the historical development of the notions of "hot" and "cold" and how they led to the atom.

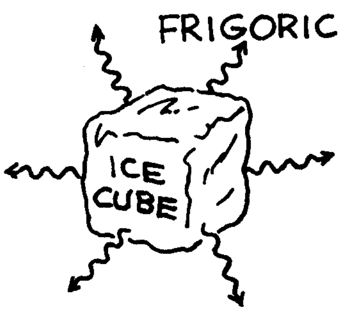
## THERMODYNAMICS AND THE INDUSTRIAL REVOLUTION




Until the last 20 years or so, the techniques for cooling were understood in terms of the laws of thermodynamics, the physical laws dealing with the gross properties of heat, energy and temperature. One of these laws, the Second Law, says that heat will not flow naturally from a cold to a hot place. In other words, we must do work to make a cold place colder—build a refrigerator for example.

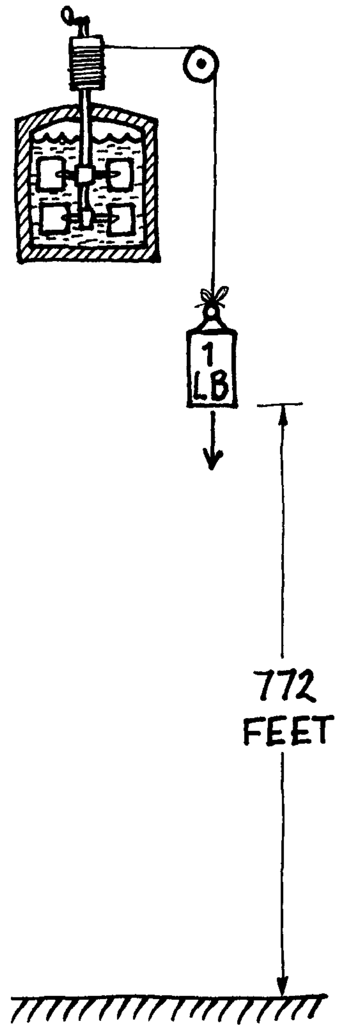
Surprisingly, these laws were discovered by studying idealized models of the steam engines that powered the industrial revolution, well before the true nature of heat was understood. As we shall see, heat is a form of energy and the temperature of an object is related to the motions of its atoms. But let's begin at the beginning where many of the important concepts of the nature of heat and cold were developed, without benefit of the atom. Later, we shall see how our understanding of the atomic nature of heat has allowed us to develop new techniques for cooling substances to almost unimaginably low temperatures—just the ticket to better clocks.

We begin by considering what it means to cool or, for that matter, heat something. For most of us, heating and cooling mean stoves and refrigerators. Earliest humans knew how to build fires and heat their food. Cooling was more problematic, but those who lived near glaciers or snow banks were in luck. However, it was not clear until the last century that heating and cooling are two variations on the same theme.

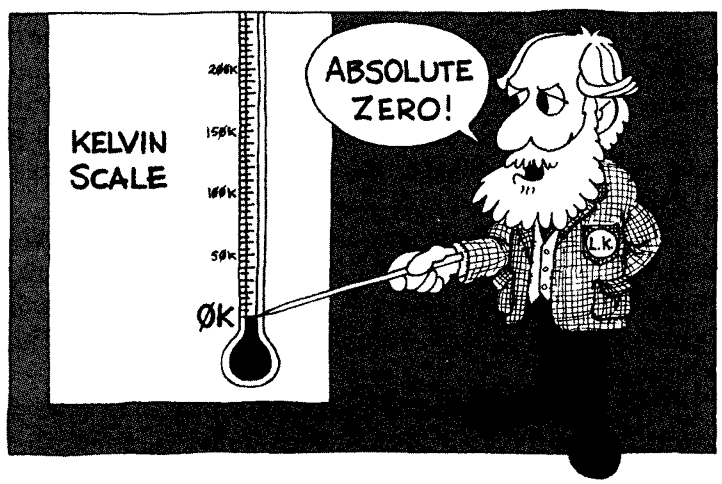



One early idea was that heat and cold are produced by fluid-like substances called "caloric" and "frigoric." The thought was that when ice melted, frigoric was released, cooling nearby objects. On the other hand, when you bored a hole in brass to make a cannon, the ground-up bits of brass released the caloric, so the cannon became hot. Others pointed out that you could warm your hands by rubbing them together with no tangible evidence of powdered skin at your feet.

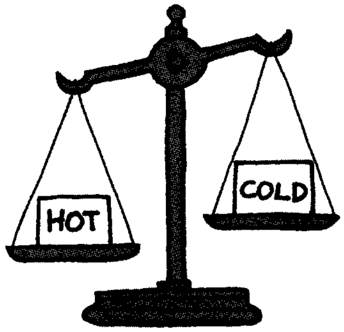
Finally, the British physicist, James Prescott Joule, born in 1818, showed that heat is a form of energy. His proof was clever. He placed a small churning paddle wheel in an insulated vessel of water. The paddle wheel was turned, through an ingenious mechanism, by a falling weight similar to the weights powering a grandfather clock. After years of experimentation, Joule concluded that a 1 pound weight needed to fall 772 feet to raise the temperature of 1 pound of water 1 degree Fahrenheit. His result was remarkably close to today's accepted value, 778 feet.




Joule's experiment killed the notion that heat and cold are different substances—it was now clear that cold was simply the lack of heat. But just how the energy of a churning paddle wheel heated water remained a mystery. Nevertheless, this new outlook generated some interesting ideas. One of the most fascinating ideas was that if cold is the lack of heat then there must be some point where an object contains no heat. Whatever that point, it must represent the coldest possible temperature. By 1848, this notion was so refined that a new temperature scale emerged. On this, the Kelvin scale, zero represents the lowest possible temperature. The scale is named after the great English physicist, Lord Kelvin, and, appropriately enough, zero kelvins, 0 kelvin, is called "absolute zero." We shall return to the Kelvin scale a little later.




The question of the exact nature of heat was a centuries-long debate that was not settled until the last hundred and thirty years or so. Joule's demonstration that cold was




simply the lack of heat did not diminish the idea that heat was still some kind of fluid—it now seemed that there was just one fluid, not two.

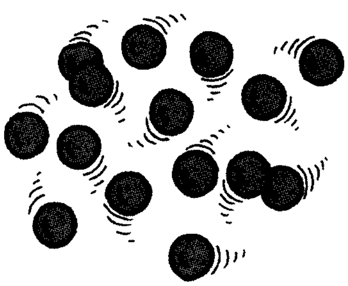
That heat was a fluid had many attractive features. Even today we say that "heat flows." But there were some problems. Why didn't a hot object filled with caloric weigh more than a cold one, for example.

### COUNT RUMFORD'S CANNON

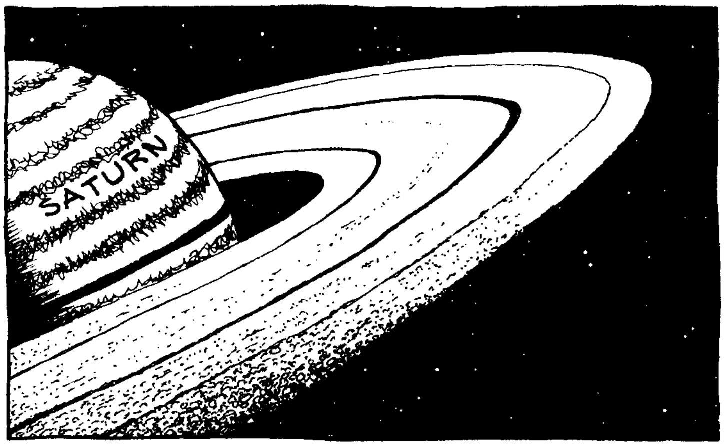
There was a growing belief that, in some unknown way, heat was a property of matter itself. One common opinion was that heat was somehow related to motion. Credence was lent this idea by the turncoat American, Benjamin Thompson, who left the Colonies for England and eventually became Count Rumford in recognition for services rendered to the Elector of Bavaria. Among the Count's duties was the supervision of the boring of brass cannon for the Bavarian army. Rumford, skeptical of a "caloric fluid," performed an experiment during the boring of one of the cannons. He rammed a revolving, blunt steel shaft into the cannon's muzzle and placed the tip of the cannon in a container of water. As the turning shaft rubbed against the cannon's bore-hole, the cannon heated, which in turn heated the water to boiling after two and a half hours. Rumford pointed out this heating was accompanied by no accumulation of brass filings and that the cannon continued to produce heat as long as the shaft turned. He concluded that heat was a product of motion and that there was no caloric fluid.

MOTION = HEAT?

But Rumford's suggestion presented a problem: Why does an object, such as a heated cannon, remain hot after the boring stops? Where is the motion in a stationary cannon? Is it possible that a stationary cannon is not in fact stationary?



This puzzle resurrected an old idea proposed as early as the 5th century B.C. by the Greek philosopher, Democritus. Democritus speculated that solids were not really solids, but that they were composed of countless, independent, infinitesimal balls he called "atomoi." If this were true, then a stationary cannon is not really stationary—it consists of continually moving invisible bits of matter. The hotter the cannon, the greater the frenzy of the bits.




**SATURN'S RINGS AND THE ATOM**

The suggestion that the universe was composed of atoms captured the imagination of the brilliant 19th century physicist, James Clerk Maxwell. Born in Edinburgh in 1831, Maxwell continually pestered his father with the question, "What's the go o' that?" when he discovered something that interested him. A gifted student, Maxwell so impressed his teachers that two of his papers were presented before the Royal Society of Edinburgh, even though he was only 17 years old at the time.

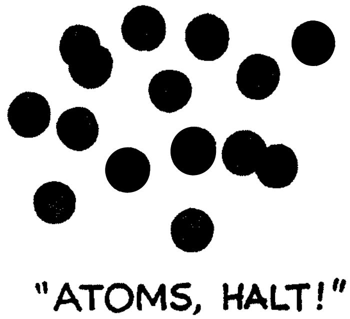
As a student at Cambridge University in England, Maxwell investigated the rings of Saturn and concluded that they were not solid, as most scientists believed, but were in fact disconnected particles. His further investigations of the "flight of brickbats" led him to propose that any substance consists of "minute particles. . . in rapid motion, the velocity increasing with temperature [so] that the precise nature of this motion becomes a subject of rational curiosity." Maxwell extended his investigation to include collisions between particles and eventually worked out how the average speed of particles is related to temperature. He also calculated the distribution of particle speeds for a particular temperature.

Thus it is the motion of particles, atoms and molecules, that produces the sensation of heat—the hotter an object the quicker its particles move. At room temperature, molecules of air move at speeds ranging from nearly zero to over 3000

MOTION = HEAT

kilometers per hour with an average speed near 1500 kilometers per hour.

### BRINGING ATOMS TO A HALT



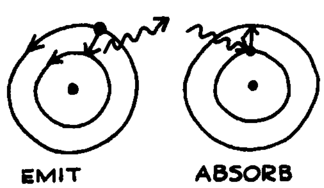

This brings up an interesting question: "Is it possible to cool an object to the point that its atoms stop moving altogether?" If this were possible, we could say that we had reached the lowest possible temperature—absolute zero on the Kelvin scale.

But how are we to cool an object to 0 kelvin, to completely stop its atoms? One step toward the answer we know: Put the object in a freezer where the temperature is around 0 degrees on the Fahrenheit scale, about 273 kelvin—a long way from 0 kelvin. Still, by doing the refrigeration in steps, scientists have attained temperatures a few hundredths of one kelvin. However, beyond a certain point even the most sophisticated refrigeration techniques reach their limit.

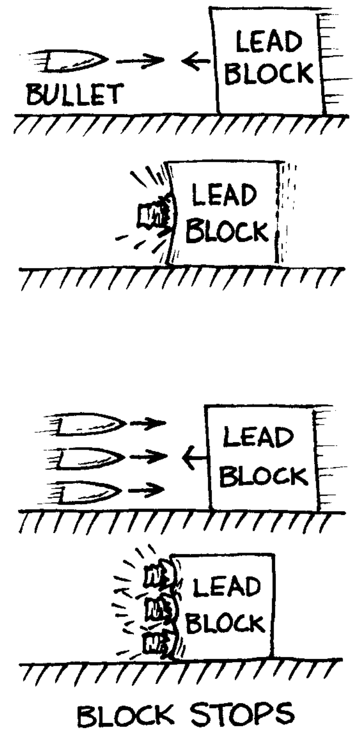
The problem is something like getting a group of young children to stand still. We can address the children as a group, asking them to sit in their chairs, for example. But, eventually, approaches aimed at the group don't work-there are always a few who will not sit down and most of the rest continue to wiggle in their chairs. What is needed is some way to attack the problem more directly—perhaps a seat belt for each chair.

The laws of thermodynamics are akin to addressing a group of children, because they are concerned with the average, gross properties of matter and cannot deal with individual "children." What is needed is a better understanding of the nature of matter and the tools to take advantage of that better understanding. As we shall see, the quantum theory of matter provides that understanding and the laser is one tool to fashion "seatbelts" for atoms.

### ATOMS COLLIDE



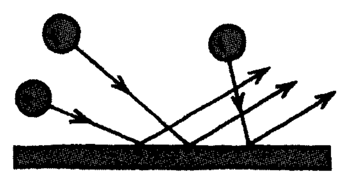

As we learned in the last chapter, atoms are not the hard spherical balls that Democritus imagined, but are like miniature solar systems with electrons circling a dense nucleus. We also learned that an atom absorbs or emits a photon when an electron jumps upward or downward between two allowed orbits—the energy absorbed or emitted is directly related to the photon frequency. Furthermore, for an atom to absorb a photon, the frequency of the photon must equal the resonant frequency associated with one of the allowed jumps. Finally, we learned that an atom may emit a photon by spontaneous or stimulated emission.




We can think of the absorption process as a kind of collision between a photon and an atom. What happens when two bodies collide depends on the respective speeds and masses of the bodies. Suppose, as the figure shows, a bullet is shot into a heavy block of lead which slides slowly along a smooth surface in the direction of the oncoming bullet. After the bullet smashes into it, the block slows slightly in the direction of its motion. The amount it slows depends on its mass and the mass and speed of the bullet—the greater the bullet's speed and mass, the more the block slows. If we fire a number of bullets into the sliding block we can bring it to near standstill. In much the same way, shooting photons at an atom slows its motion—in other words, cools the atom.

In the real world, no one is a perfect shot so a few of the bullets may miss the block, and the bullets that miss do nothing to slow its motion—a near miss does not count. As Sir Walter Scott wrote in his *Journal* on a December day in 1825, "A miss is as good as a mile." But, in the quantum world of photons and atoms, a miss is *not* as good as a mile. Even the wildest shot may slow the atom. How can that be?

Although Democritus' belief that atoms were small, hard balls gave way to the notion that atoms were built of nuclei surrounded by swarming electrons there was still a Democritian ideal at work—if atoms were not small hard balls, then at least the electrons and their nuclei were. And thus it appeared in the early explorations of the atom's structure. But then a strange thing happened.



Two American scientists, Clinton Davisson and Lester Germer, investigating the way electrons bounced off polished nickel, found that the electrons ricocheted in random directions, and then their apparatus unexpectedly blew up. Painstakingly, they rebuilt the shattered equipment and resumed their experiment. But now they obtained a new result—the electrons bounced from the nickel in only certain directions. This was very peculiar. It was as though a rubber

**BALL OR WAVE ? ANSWER: "BOTH"**

ball thrown at the ground at any arbitrary angle always bounced back at specific angles.

One of the first things Davisson and Germer discovered was that the heat from their exploding apparatus had crystallized their nickel. Now the atoms were no longer randomly arranged but were neatly lined up. But this shouldn't have mattered much if the electrons were really tiny hard balls.

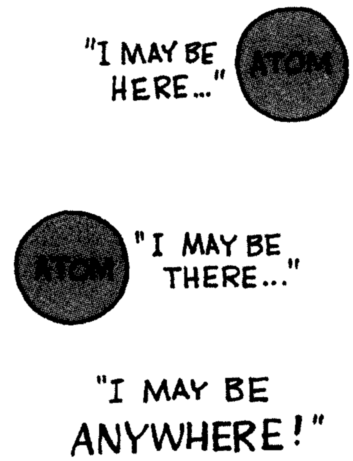
After months of further investigation, it appeared more and more likely that the electrons weren't hard balls at all—it appeared that they were waves. This would explain why the electrons reflected only at certain angles from the nickel. In some directions the electron waves are in step and so reinforce each other as they reflect from the lined-up atoms, while in other directions they are out of step and so cancel each other as the drawing shows. But there was still one big problem. Other experiments clearly showed that electrons behaved like tiny hard balls. How could matter be both particle and wave? It violates the adage, "You can't have it both ways." But in the world of atomic particles, as it turns out, you can.

The notion that atoms can be both waves and particles is contrary to common sense. Yet theories built on this belief provide the most complete description of nature that we know. It appears that electrons, photons, and other elementary particles are in a new category—neither particles nor waves but something beyond our everyday comprehension.

Now we are beginning to understand why a miss is not as good as a mile where atomic particles are concerned. When a photon and an atom collide we do not have a collision between one small and one large hard ball. We have rather an interaction between two wave-like particles, an interaction that cannot be understood in terms of the laws of motion that Newton uncovered. Instead, we must use the rules of quantum mechanics, which were worked out, in large measure, during the first few decades of this century.

Although the philosophical implications of quantum mechanics and the wave-particle nature of matter continue to be hotly debated, the German physicist, Max Born, finally provided an interpretation of the wave aspect of matter. The matter wave, he said, does not represent a kind of smeared-out particle but rather determines the probability of finding the particle at a particular spot. This probability interpretation of matter waves provides a link between the wave and particle natures of matter.

When an electron lights up a spot on a TV screen, the screen reveals the presence of an individual electron but the matter wave determines the probability that the electron will actually strike the screen in a particular spot. When we use the laws of quantum mechanics, we calculate using the matter waves the likely path of the electron. According to current thinking, backed up by many careful experiments, this is the best we can hope for. In fact, the idea that an atomic particle even *has* a path until it is detected is, according to quantum mechanics, a meaningless notion.




Now, that we are armed with a better understanding of temperature and the atomic nature of matter, we return to the main theme of our book.

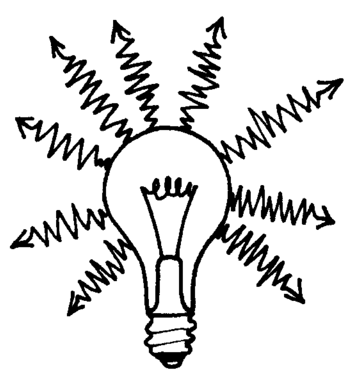
# Chapter 7

# COOLING THE ATOM

As we know, Democritus's hard spherical "atomoi" eventually yielded during the first part of this century to the Bohr atom with its compact nucleus and circling electrons. Further refinements of the Bohr atom led to quantum mechanics which, as we learned in the last chapter, prohibits us from thinking of colliding atoms, electrons, and photons as so many bouncing balls.

PROBLEMS:
- DOPPLER SHIFTS
- COLLISIONS

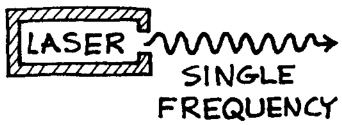
In Chapter 5, we learned that the motions and collisions of atoms are a primary obstacle to building better clocks: Motions produce Doppler shifts and collisions increase the frequency spread of the resonance curve. What we need is a tool to slow, or cool, atoms and molecules which, at room temperatures, move at speeds averaging 1500 kilometers per hour. As we hinted in the last chapter, lasers are such a tool.



JUMBLE OF WAVES

## PURE LIGHT

Ordinary light from a table lamp or a fluorescent bulb is a jumble of waves at different frequencies. Many people realized how useful it would be to have a device that generated light at a single frequency. Such an apparatus had been available for decades at radio frequencies—the radio transmitter. With a "light" transmitter, one could send information at rates vastly exceeding those supported by the lower frequency radio waves.




The first "light transmitters," lasers, were developed in the 1960s. As it turned out, there were myriad uses for lasers—everything from drilling holes to manipulating atoms, just the thing to cool atoms and thus build better clocks.

Lasers operate in a way remarkably similar to the hydrogen maser frequency standard we discussed in Chapter 5—in fact, the first lasers were called "optical masers." The cavity of the hydrogen maser is filled with hydrogen atoms in an energy emitting state. Eventually, one of these atoms *spontaneously* emits a photon which hits another atom *stimulating* it to emit another photon which strikes another atom and so on. The extraordinary thing is that each new stimulated emission is in step with the one that produced it, so these emissions eventually culminate in a signal strong enough for a receiver to detect. The primary difference between a maser and a laser is that the maser generates microwave radio signals while the laser generates light signals.

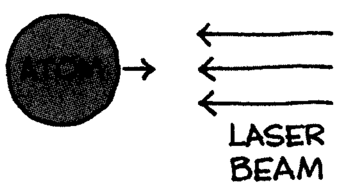
MASER:
- MICROWAVE RADIO SIGNALS

LASER:
- LIGHT SIGNALS

The first lasers were expensive and generated only short bursts of light at a few frequencies. But, by the 1970's, tunable lasers with continuous output became available. Nowadays, lasers are cheap, reliable, and used in everything from compact disk players to fiber-optical communication systems.

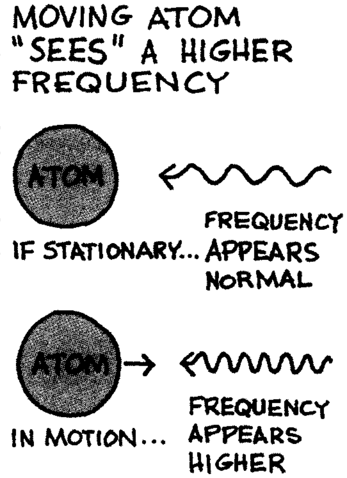
### SHOOTING AT ATOMS

Let's consider, now, how we might cool an atom with a laser. We begin by considering a very simple, idealized case.

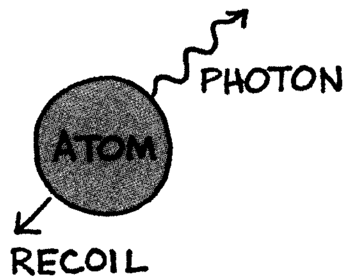



The drawing shows an atom moving toward a beam of laser light. Every time our idealized atom, with only two possible orbits—energy levels as they are called—absorbs a photon, it gets a little kick in the direction opposite to its motion. We want the atom to absorb as many photons as possible, so we adjust the frequency of the laser beam to equal the resonant frequency of our two-level atom. This seems straightforward enough, but there is a slippery point here.

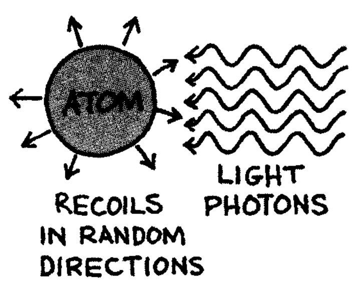
In Chapter 5 we learned that the frequency of a radio signal from an approaching atom appears high (the Doppler effect). We could achieve the same effect by moving toward a stationary atom because it is only the relative motion that counts. In the same way, the moving atom "sees" a laser frequency that is higher than the frequency a motionless atom sees. In other words, we need to retune the laser frequency by just the right amount to overcome the Doppler effect, so that the moving atom sees its resonant frequency. As the atom slows under bombardment, we continually tune the laser frequency so that it stays in step with the atom's resonant frequency.



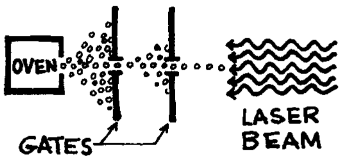

When our atom absorbs a photon, its electron jumps into the upper orbit. However, because of spontaneous emission, the electron eventually jumps back to its original orbit. At that instant a photon is emitted kicking the atom, much like a gun's recoil when a shot is fired in the direction opposite the photon's motion. The kick speeds up the atom by the amount that it was slowed down when it first absorbed a photon.




At first glance it appears that these kicks, due to absorption and spontaneous emission, cancel so that there is no net slowing of the atom. Fortunately, this is not the case. The kicks slowing the atom are in the direction opposite to the incident laser beam while, on the other hand, the spontaneously emitted photons leave the atom, as the figure shows, in all directions. The result is that the kicks due to spontaneous emission cancel while each kick due to absorption slows the atom. Thus, the velocity of the atom in the direction opposite to the incident laser beam is reduced at the expense of a much smaller increase in velocity in the other direction.




Immediately after an atom absorbs a photon it cannot absorb another until it spontaneously emits a photon to make "room" for another photon. The average time required for spontaneous emission depends on the type of atom—gold, mercury, hydrogen, or whatever—and the orbits involved. When the spontaneous emission times are long, it takes considerable time to cool the atom since the rate at which it absorbs photons is low. On the other hand, if the spontaneous emission time is short, the atom cools relatively quickly.



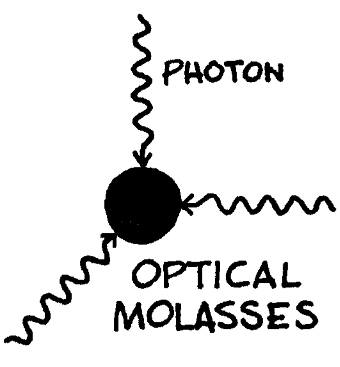

Let's consider, as a specific example, the cooling of cesium atoms. Imagine atoms boiling out of a 100 degree centigrade oven at 270 meters per second. As the figure shows, a couple of gates weed out the atoms not moving directly to the right. We illuminate the atoms with a strong laser beam so there will be plenty of photons to slow the atoms. Each time an atom absorbs a photon its speed decreases around 3.5 millimeters per second, so a little arithmetic shows that an individual atom stops after about 80 000 collisions.

CESIUM ATOMS STOP AFTER ABOUT 0.025 SECONDS

After an atom absorbs a photon it must await spontaneous emission, about 32 nanoseconds on average for cesium atoms, before it can absorb another photon and thus be further slowed. The total time it takes the atom to stop is 32 nanoseconds times 80 000, or about 0.025 second. It also will have traveled about 1.3 meters during that time.

## OPTICAL MOLASSES

In general, atoms may move in any direction, so we need three pairs of lasers, as the figure shows, to slow an atom. The figure suggests that there is no overall slowing of the atoms since there are apparently equal and opposite forces acting in all directions. But this is true only for a stationary atom. A moving atom sees different forces in different directions due to the Doppler shift, as we learned earlier. If all the lasers are tuned slightly below the resonance frequency of the atoms, then they always encounter a slowing force, whenever they move, whatever their direction of motion. It is as though the atoms are moving through a thick liquid and, in fact, scientists have dubbed the effect "optical molasses."

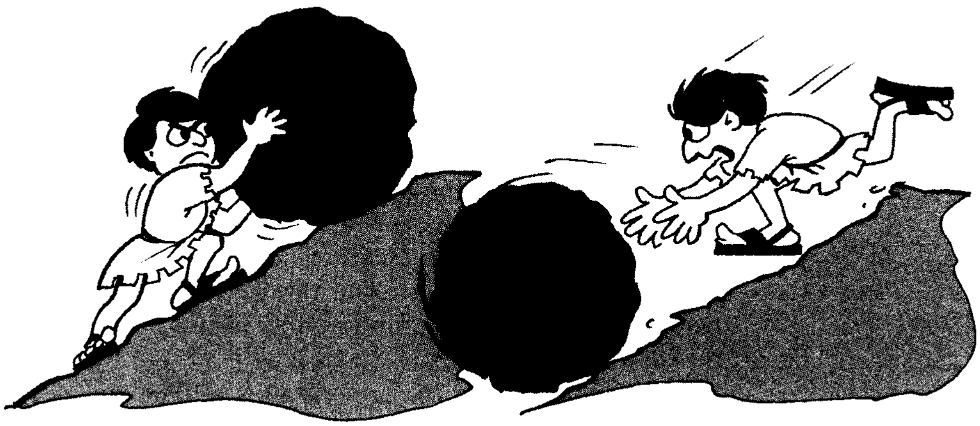



Although optical molasses is a very effective way to cool atoms, the quantum mechanical nature of the processes involved means that the atoms never completely stop—in other words 0 kelvin is not possible. This occurs because the times of absorption and direction of photon reemission are random. That is, the random absorption and reemission kick the atom hither and yon, as the figure shows, generating a small residual motion that cannot be overcome by optical molasses.

LASER COOLING... A COMPLICATED PROCESS

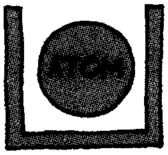
After experimenters gained some experience with laser cooling, they began to notice that the temperatures were much lower than they thought possible—a happy result considering that the opposite is usually the case. Some head-scratching finally provided some answers. As it turned out, the laser-cooling mechanism was much more complicated than originally imagined. A more complete analysis, using the full rigor of quantum mechanics, where hits and misses are always problematic, revealed that the laser beam altered the atom's energy levels so that cooling was actually several different processes involving a number of steps.

One of the processes has come to be called the "Sisyphus" effect after the cruel Corinthian king in Greek mythology who was forever condemned to roll a giant stone up a hill in Hades, only to have it roll down again as it neared the top. The net result was that Sisyphus was always pushing the stone up hill.



THE SISYPHUS EFFECT

The analogy in the atomic cooling process is that the atom is always moving uphill due to its altered energy states. When the atom gets to the top of the hill, it is pumped with laser light (analogous to our earlier description of light gates in the discussion of cesium resonators) to the bottom of the hill again. Thus the atoms are always moving up hill, like Sisyphus, losing energy, and thus cooling, in the process.

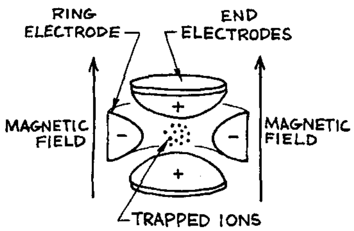



TRAPPING AN ATOM IN A BOX

## TRAPPING ATOMS

Optical molasses is somewhat like a rough and tumble game in which a small group of players are continually slowed by other players who continually push and shove them. A more restrictive game is to put the players in a box: The deeper and steeper the sides of the box, the greater the difficulty to escape. Scientists have assembled traps of the "box" type for atoms using electromagnetic fields. We begin by discussing the trapping of ions, or atoms that have lost one or more of their orbiting electrons and so are positively charged.

### Penning Traps

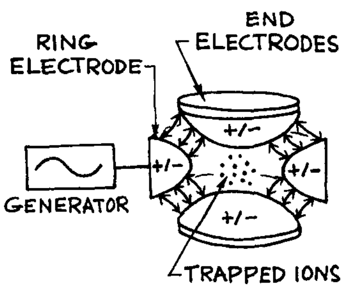



PENNING TRAP

Several kinds of traps have been investigated, but we shall discuss only two that are particularly attractive. The "Penning" trap, as the figure shows, consists of three electrically charged parts: one of them, negatively charged and ring-shaped, and the other two, positively charged and shaped like the two halves of a ball. A short gap, about 10 millimeters between the curved faces or end caps of the two balls, is the trapping area. The positively charged end caps repel the positively charged ions, confining them between the two caps while the negatively charged ring attracts the ions. A vertical, static, magnetic field, as the figure shows, prevents the ions from moving toward the ring. The net result of all this pushing and pulling is that the ions are confined near the center of the trap.

Penning traps, which may contain a million ions or so, are operated in very high vacuums, so that the ions won't be knocked out of the trap by stray gas molecules.

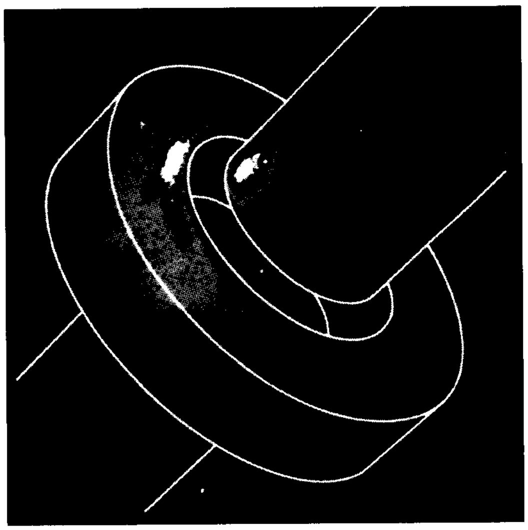
### Paul Traps




PAUL TRAP

In the other trap, the "Paul" trap, ions are confined by a radio frequency signal. The design is similar to the Penning trap but there is no static magnetic field. A high-frequency alternating current, operating between the end caps and the ring, causes the end caps and ring to rapidly switch their electrical polarities. When the end caps are positive they repel the ions into the plane of the ring. When the ring is positive it holds the ions along the vertical axis; thus the ions become trapped as they move first one direction and then another.

In 1978, researchers at NBS in Boulder, Colorado, cooled magnesium ions to less than 40 kelvins in an electromagnetic trap. In another two years they were down to half of one kelvin above absolute zero. Single ions, because there are no collisions, have been cooled even further, almost to the theoretical limit. The white dot in the photo shows the location of a single ion caught in the center of an electromag-

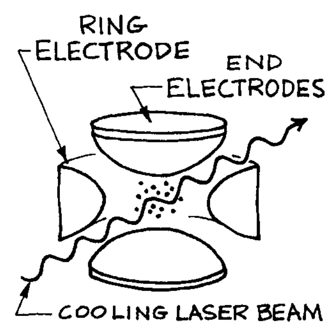


netic trap. The trap itself, in the adjacent photo, is portrayed against the backdrop of an American penny.

## REAL COOL CLOCKS

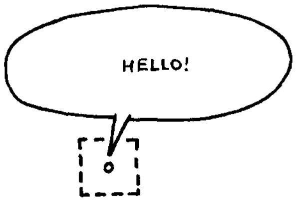
Let's consider how cooled ions might lead to better clocks. It is probably evident that the two main impediments to building better atomic clocks, collisions, and Doppler shifts, are materially reduced when atoms are cooled.

Although a number of different strategies have been employed to reduce and contain the motions of ions, we shall discuss a particular case that involves both laser cooling and trapping. The idea is to laser-cool an ion snared in an electromagnetic trap.



PAUL OR PENNINGTRAP

The figure shows ions, trapped in either a Paul or Penning trap, illuminated by a laser beam. As we have explained, the laser is tuned slightly below the ion's resonance frequency, so the ions are slowed whenever they move toward the laser.




SINGLE IONS GENERATE WEAK SIGNALS

Ideally, we would like a single, stationary ion resting comfortably, forever, in the center of its trap. But, as always, there are practical problems.


TOO MANY IONS DEGRADE SIGNAL QUALITY

One problem with a single-ion frequency standard is that the signal produced by a solitary ion is too weak to serve as a reliable reference for the electronic circuitry needed to generate a suitable output signal. To generate a stronger signal we need the cumulative signal of many ions. But now the kinds of problems we have been trying to avoid creep back, because with more than one ion we reintroduce the possibility of ion-ion interactions. Although the ions do not actually collide, their associated fields Doppler-shift the very resonance frequency we seek, consequently degrading the signal. Thus, the clock builder must employ enough ions to create a sufficiently strong signal, but not so many as to overly compromise the purity of the desired resonance frequency.

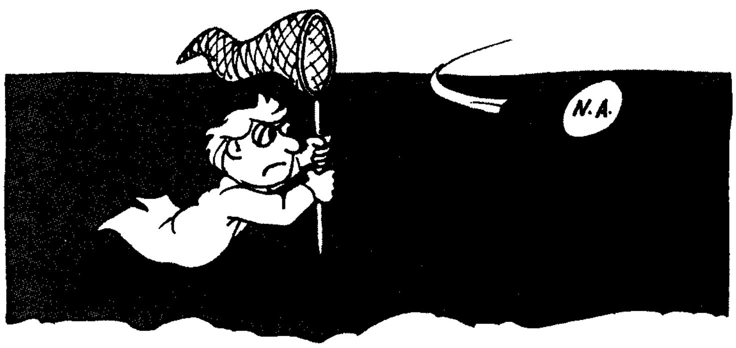
Once the ions have been laser-cooled in the trap the reference frequency is generated pretty much along the lines described in the operation of ordinary atomic standards. That is, for example, some suitable resonance frequency in the microwave part of the radio spectrum is selected for excitation. The excited ions then decay. It is the cumulative decaying of these many ions from the excited state that creates a detectable signal. However, when the process occurs with cooled atoms, $Q$'s thousands of times greater than those available from current cesium atomic clocks are possible.


MARRIAGE OF OPTICAL TRAPPING WITH OPTICAL RESONANT FREQUENCIES YIELDS HIGH Qs.

As we know from Chapter 5, $Q$ depends on the resonant frequency: The higher the resonant frequency the higher the $Q$, other things being equal. This suggests looking for resonant frequencies in the optical part of the electromagnetic spectrum where frequencies are many thousands of gigahertz. This marriage of optical resonant frequencies with ion trapping and cooling would yield $Q$'s well beyond those possible with just trapping and cooling alone.

One experiment based on a resonant frequency in the ultraviolet with a single trapped ion achieved a $Q$ of $10^{13}$, the highest $Q$ ever achieved in the microwave or optical frequency regions. We can appreciate the significance of this result when we recall from Chapter 5 that $Q$'s for even the best cesium beam clocks are around $10^9$.

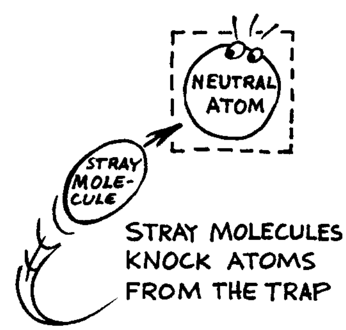
A principal problem with the optical frequency standard is that it is difficult to count its cycles. (Today's atomic clocks are based on cesium beam frequency standards whose cycles are relatively easy to count at the lower microwave frequencies.) Nevertheless, the never-ending demand for better clocks will doubtless produce a practical solution to the counting problem.




## CAPTURING NEUTRAL ATOMS

After the early success in cooling trapped ions, workers, desiring to explore other possibilities, began to focus on cooling and trapping neutral atoms. Here the problem is more difficult because neutral atoms are scarcely affected by electric and magnetic fields. But "scarcely" is not the same as "not at all."

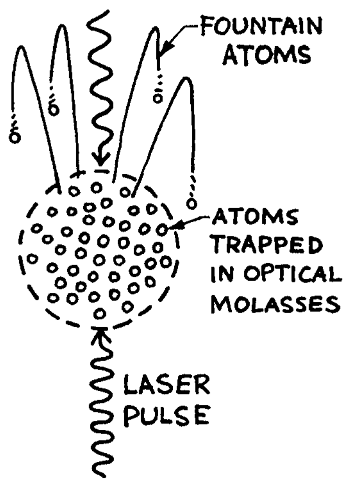
As with ions, a number of cooling and trapping methods have been investigated. Here we shall discuss a method that depends on the fact that atoms, although neutral, behave like tiny bar magnets. By far the most efficient trap for neutral atoms is the "magnetooptic trap" or "MOT." This trap combines the optical molasses slowing action with a magnetic field which regulates the optical forces to not only cool, but also force the atoms to a particular point in space. With



MOTS, researchers have trapped and cooled millions of atoms in regions as small as a BB.

Nevertheless, because the MOT is so weak, an atom can easily be knocked from the trap by a stray atoms. Even so, tens of millions of atoms have been trapped in a BB-sized volume for a second or more.

A practical difficulty with neutral atoms for frequency standards is that their resonance frequencies are altered by the cooling laser beams and by the fields composing the traps. One promising technique for overcoming these difficulties is to build an "atomic fountain."



ATOMIC FOUNTAIN

### ATOMIC FOUNTAINS

We start with a group of atoms trapped in a MOT and cooled with optical molasses. Next, two laser beams, one shining up and the other down, illuminate the bed of optical molasses for a millisecond or less. The frequency of the downward beam is slightly less than the upward beam's frequency, so the neutral atoms are propelled upward out of the molasses with a speed of about a quarter of a meter per second. As the atoms ascend, gravity slows their motion until they finally stop and then fall back. During the up-and-down journey the atoms are outside the perturbing laser beams so that their resonance frequencies remain unchanged, and thus they can serve in that interval as reference oscillators for frequency standards. Since the total journey time exceeds the time it takes for cesium atoms to drift the length of a conventional beam tube, much higher $Q$s are possible.

Impressive as the results are for ions and neutral atoms we may not soon see a new generation of commercial atomic clocks. As with most innovations, it takes substantial time and effort to transform laboratory results into practical everyday devices. Nevertheless, today's challenges are no greater than those faced by the first scientists who dreamt of clocks forged from atoms.

### QUANTUM MECHANICS AND THE SINGLE ATOM

Aside from the interest of laser cooling for building better clocks, studying and manipulating nearly stationary atoms, small groups, or even single atoms allow scientists to investigate some of the basic ideas of quantum mechanics that had, before, been out of reach.

LASER-COOLED ATOMS MAY BE STUDIED ONE-BY-ONE.

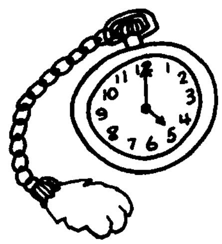
In this book, for example, we have discussed electrons jumping between orbits, emitting or absorbing energy in the process. With laser-cooled atoms, scientists at NIST and other laboratories have studied this process atom by atom. One of the founders of quantum mechanics, Erwin Schrödinger, doubted that quantum jumps in individual atoms even had meaning. In 1952, he wrote, "We never experiment with just one electron or atom or molecule. In thought experiments we sometimes assume that we do; this invariably entails ridiculous consequences." Now we know that Schrödinger was wrong.

# Chapter 8

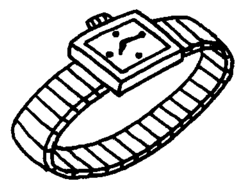
# THE TIME FOR EVERYBODY

Thus far, we have concentrated on the technical developments that led to improved timekeeping, and we have seen how these developments were used in scientific and national standards laboratories, where the utmost accuracy and stability are required. Now we shall turn to the more pedestrian timepieces, which we operate in a manner similar to their laboratory cousins, but which are less accurate for reasons of economy, size, and convenience.

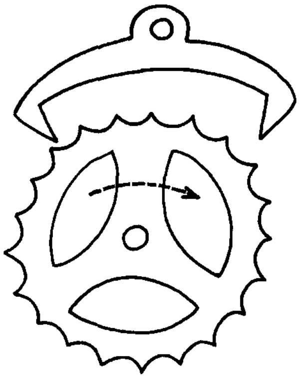
## THE FIRST WATCHES



The word *watch* is a derivation from the Anglo-Saxon *wacian* meaning "to watch," or "to wake." Probably it described the practice of the man keeping the "night watch," who carried a clock through the streets and announced the time, as well as important news—or simply called out, "Nine o'clock and all's well."



Early clocks were powered by weights suspended from a rope or chain—an impractical scheme for portable timepieces. The breakthrough came in about 1600, when Robert Henlein, a German locksmith, realized that a clock could be powered by a coiled brass or steel spring. The rest of the clock was essentially the "foliot" mechanism discussed earlier,




which was very sensitive to whether it was upright in position or lying on its side.

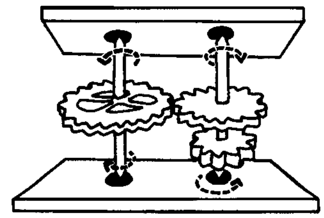
In 1660, the English physicist Robert Hooke toyed with the idea that a straight metal spring could act as a resonator in a clock; and in 1675 the Dutch physicist and astronomer Christian Huygens employed this principle in the form of a metal spiral spring connected to a rotating balance wheel; energy flowed back and forth between the moving wheel and the coiled spring.

Hooke is also credited with development of a new kind of escapement, the "anchor" escapement—so called because of its shape—which with the help of its "escape wheel" delicately transferred energy to the resonator of the clock. With these developments, the accuracy of clocks improved to the point where the minute hand was added in the latter part of the 1600's.

The history of watches up until about the middle of the 17th century was essentially one of gradually improving the basic design of the first watches—most of which were so large that today we would call them clocks. As Brearley explains in "Time Telling through the Ages": "Back in 1650 it was some job to figure out the number of teeth in a train of wheels and pinions for a watch, to determine their correct diameters, to ascertain the number of beats of the escapement per hour, and then design a balance wheel and hair spring that would produce the requisite number; to determine the length, width, and thickness of a main spring that would furnish enough and not too much power to drive the mechanism; and finally, with the very crude and inadequate tools then available, to execute plans and produce a complete watch that would run and keep time—even approximately."

One significant development occurred in 1701, when Nicholas Facio, of Basel, Switzerland, introduced the jeweled bearing. Up to that time, the axles of the gears rotated in holes punched in brass plates—which considerably limited the life and accuracy of the watch.

Before the middle of the 17th century, the production of clocks and watches was largely the work of skilled craftsmen, principally in England, Germany, and France, although it was the Swiss craftsmen who introduced nearly all of the basic improvements in the watch. The watchmaker—or "horological artist," as he was called—individually designed, produced, and assembled all parts of each watch, from the jeweled bearings and pinioned wheels to the face, hands, and case. In some cases, a horologist might take an entire year to build a single timepiece.



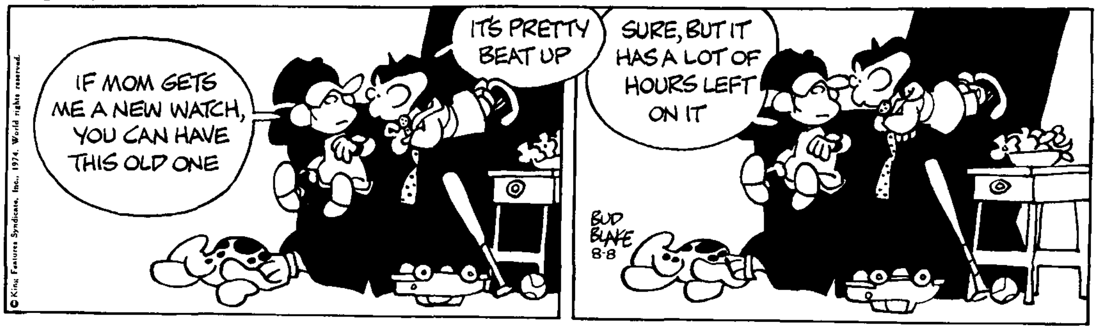
In Switzerland, however, and later in the United States, watchmakers became interested in ideas that the industrial revolution was bringing to gunsmithing and the making of other mechanisms. The manufacture of identical and interchangeable parts that could be used in making and repairing watches made possible the mass production of both expensive and inexpensive watches. Turning to this kind of standardization, Switzerland rapidly became known throughout the world as the center for fine watchmaking. About 6000 watches were produced in Geneva in 1687, and by the end of the 18th century Geneva craftsmen were producing 50 000 watches a year. By 1828, Swiss watchmakers had begun to make watches with the aid of machinery, and mass production of watches at a price that the average person could afford was assured.

But it was in the United States that the idea of machine-produced interchangeable parts finally resulted in a really inexpensive watch that kept good time. After many false starts and efforts by various persons that met with little success, R.H. Ingersoll launched the famous "dollar watch" around the end of the 19th century. A tremendous success, it sold in the millions throughout the next quarter century or more. The first were pocket watches encased in a nickel alloy, but as the wrist watch gained acceptance and popularity in the 1920's, Ingersoll also manufactured both men's and ladies' wrist watches.

### MODERN MECHANICAL WATCHES

It was style consciousness that was largely responsible for continued changes and improvements in the watch mechanism. The challenge of producing watches small and light enough to be pinned to the sheer fabrics of ladies' daytime and evening dresses without pulling the dress out of shape resulted in the dainty, decorative pendant watches popular in the early 1900's. Designing works that would fit into the slim, curved wristwatch case that became increas-

TIGER






ingly popular with men was a major achievement after World War I.

Accuracy, stability, and reliability also remained important goals. The multiplying railroad lines, with their crack trains often running only minutes apart by the latter half of the 19th century, helped to create a strong demand for accurate, reliable watches. Every "railroader," from the station manager and dispatcher to the engineer, conductor, and track repair crew with their motorcar, had to know the time, often to the part of a minute. A railroad employee took great pride in his watch—which he had to buy himself and which had to meet specified requirements.

Before electronic watches entered the scene, the Union Pacific Railroad required that all watches have 21 jewels and that they be a certain minimum size. Today electronic wristwatches are allowed, but whatever the type, each morning a railroader's watch must be checked against a time signal coming over a telegraph wire or the telephone, and it must be within 5 seconds of the correct time. As an additional safety measure, watches are checked on the job by watch inspectors, who appear unannounced. Time, to the railroads, is still a very serious matter.

Today's mechanical watch is a marvel of the art of manufacturing and assembling of tiny parts. The balance wheel in a ladies' wrist watch has a diameter about the same as that of a matchhead, and the escapement ticks over one hundred million times a year, while the rim of the balance wheel travels over 11 200 kilometers in its back-and-forth journey. The balance wheel is balanced and its rate adjusted by over a dozen tiny screws around its rim. Some 30 000 of these screws would fit into a thimble, and the jewels may be as small as specks of pepper. It's no wonder that the tiniest piece of dust can stop a watch or seriously impair its motion.

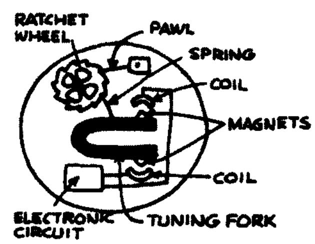
Even oiling a watch is a delicate operation. A single drop of oil from a hypodermic syringe is enough to lubricate over a thousand jeweled bearings. An amazing variety of substances have been used for lubrication, ranging from porpoise-jaw oil to today's modern synthetic oils.

*"Every night, when he winds up his watch, the modern man adjusts a scientific instrument of a precision and delicacy unimaginable to the most cunning artificers of Alexandria in its prime."*

—Lancelot Hogben

### ELECTRIC AND ELECTRONIC WATCHES

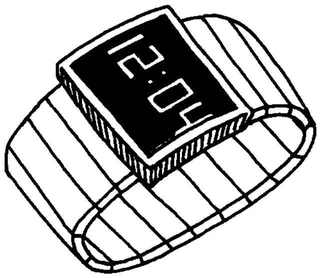
A very big step in the development of the watch occurred in 1957 with the introduction of the electric watch. This watch was essentially the same as its mechanical predecessor, except that it was powered by a tiny battery instead of a spring. Two years later, in 1959, a watch was introduced with the balance wheel replaced by a tiny tuning fork. Historically, we have seen that the quality factor, or $Q$, of resonators increases with resonance frequency. The balance wheel in mechanical watches swings back and forth a few times a second, but the tuning fork vibrates several hundred times a second, with a $Q$ around 2000—20 times better than the average balance wheel resonator. Such watches can keep time within a minute or less in a month. The tuning fork's vibrations are maintained by the interaction between a battery-driven, transistorized oscillating circuit and two tiny permanent magnets attached to the ends of the tuning fork.




THE VIBRATING FORK PUSHES A SMALL SPRING AGAINST THE RATCHET WHEEL WHICH MOVES THE HANDS OF THE WATCH. THE PAWL KEEPS THE RATCHET WHEEL FROM MOVING BACKWARDS. THE TWO COILS, CONTROLLED BY AN ELECTRONIC CIRCUIT, INTERACT WITH THE TWO MAGNETS TO KEEP THE TUNING FORK VIBRATING.

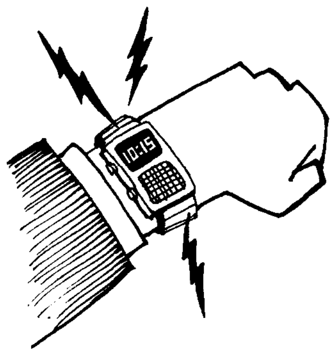
### THE QUARTZ-CRYSTAL WATCH

The quartz-crystal wrist watch, which is a miniature version of the quartz-crystal clock discussed earlier, is the latest step in the evolution of watches. Its development was not possible until the invention of the integrated circuit—the equivalent of many hundreds of thousands of transistors and resistors in an area only a centimeter or less on a side. These circuits can carry out the many complex functions of a watch, one of the most important being the electronic counting of the vibrations of the quartz-crystal resonator.




The first quartz wrist watches used the "hands" type of display, adapted from existing watches. But later versions with no moving parts at all became available. The hands were replaced by digital time "readouts" in hours, minutes, and seconds formed from small luminous elements that are entirely controlled by electrical signals. Quartz watches today are accurate to within one minute a year, but improvements are still being made, such as automatic compensation for changes in body temperature.

### WATCHES AND COMPUTERS




It has been decades since Dick Tracy's radio wrist watch first appeared in the comic strips. With this marvel of ingenuity, Tracy could not only find the time but he could call headquarters to talk to the Chief. The radio wrist watch has still not become a practical reality for mass consumers, but what we might call the computer wrist watch has.

As integrated circuits became ever smaller, it eventually became feasible to put computer chips in watches. With the new computer wrist watches, you can find the local date and time of any location in the world, time races, set a reminder or wake-up alarm, do math calculations, store frequently used telephone numbers and addresses. In fact, what can be done is mostly limited by the ingenuity of the watchmaker.


And the Dick Tracy watch may be just around the corner. There are already commercially available watches automatically set by radio time signals.

### HOW MUCH DOES "THE TIME" COST?

Clocks and watches are big business. Hundreds of millions of clocks and watches are sold, worldwide, every year. But all these timepieces, from the most basic to the most elaborate, must be set initially to the correct time and occasionally updated. So how much does "the time" cost?

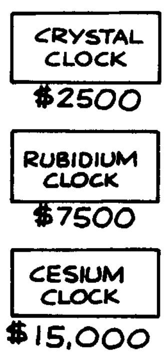
For about 99 percent of the people who want to know what time it is—or to clock the duration of time—a clock or watch that "keeps time" within a minute or so a day is acceptable. The familiar and inexpensive wall or desk clock driven by the electric current supplied by the power company is completely adequate for the vast majority of people; few persons recognize a need for a more "refined" time. Using only their eyes and fingers, human beings have not the manual dexterity to set a clock or watch to an accuracy of better than a second or so, even if they have the time and patience to do it.

"Losing" the time altogether, when a clock or watch stops, is no problem to most people; they simply dial the telephone company time service or consult another of the many possible suppliers of the "correct" time. In short, for nearly everyone, in nearly all circumstances, the wide choice of clocks and watches available in the local drug or department store at prices of a few dollars and up is sufficient to meet everyday needs.

But let's suppose you are going into a remote area on a trip, where there will be no radio receiver and no contact with other people for three or four weeks. If it's a fishing trip, you probably don't care whether your watch loses or gains a few minutes a day. You still probably make connections with the pilot who is flying in to pick you up at the end of the period.

Now suppose that you are to make certain observations at certain times of day, and that a scientific laboratory is depending on the information you gather, and it's important to the laboratory that the time the information is recorded be correct within a tolerance of one minute. Or perhaps you have a radio transmitter and are only one of several people in the field, each of whom is to send in a report at certain times each day. Then you will need a more accurate and dependable—and more expensive—watch. A $300 to $400 watch that's waterproof and shockproof, and that has proved to keep time without resetting—losing, say, no more than 30 seconds in six months or so—should serve nicely. Especially if you have a radio receiver with which you can pick up a time broadcast occasionally, and so check the time once in awhile and reset your watch if you need to.

But then there is a surprising array of very common time users for whom any kind of watch or clock that can be read by the human eye or ear is as useless as a meter stick is to a lens grinder. Communications and power company engineers, scientific laboratory technicians, and many other special users of time and frequency information read this information with the help of electronic timing equipment connected to sophisticated receiving instruments. Their clock may be driven by a quartz-crystal oscillator, which, although accurate to one millisecond per month, must be checked when more accurate time is required—often several times a day. A quartz-crystal oscillator may cost as much as a few hundred dollars, depending on its quality. It must have a special housing with controlled temperature and humidity, and it may require someone with special training in its care and use to look after and regulate it. Often a team of technicians read it, chart its performance, and adjust it as needed, every day.



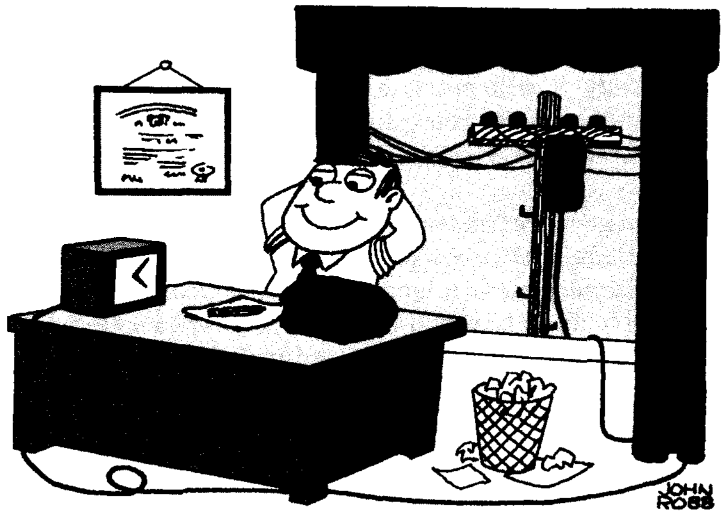
These individuals, obviously, must have an even better time source than their quartz-crystal clocks in order to keep them telling the time accurately. This will be an atomic clock of some kind. Perhaps a rubidium frequency standard, which will likely cost thousands of dollars, or a cesium standard with a price tag of several tens of thousands of dollars. When a portable cesium standard is hand carried from its "home" to be checked and adjusted against another, similar standard—or against the NIST atomic frequency standard or the official standard in another nation—it travels, usually by airplane, attended by a technician who sees that it is plugged into an electric circuit whenever possible, and that its batteries are kept charged for use when this is not possible.

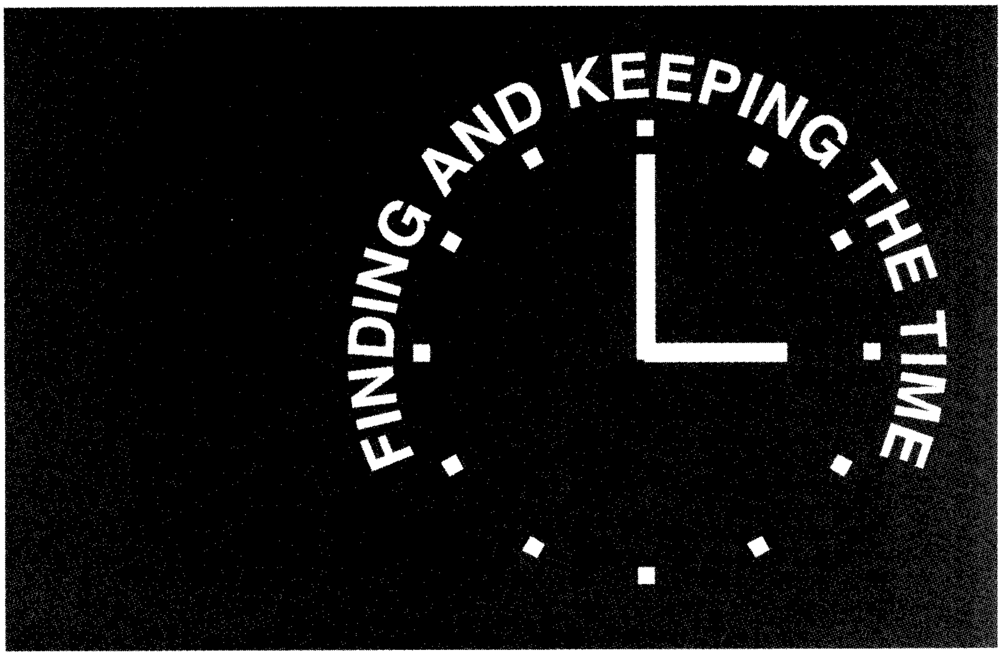
A portable cesium standard weighs about 90 kilograms, and occupies about one-third of a cubic meter. Characteristically, it will not lose or gain one second in a few thousand years. Such atomic standards are found in scientific laboratories, electronics factories, and even a few TV stations.

The primary frequency standard, at the laboratories of the National Institute of Standards and Technology in Boulder, Colorado, is much larger than the portable standards. Housed in its own special room, it is about two meters long. The present model was completed in 1993 and would cost about one million dollars to duplicate. It is used in conjunction with a number of other atomic clocks that monitor each other constantly and are the basis of the NIST time and frequency services. It is accurate to one second in over 10 000 000 years.

So who needs the million dollar clock? We all do. We need it to set our $15 watch. Everyone who uses a television set, a telephone, electric shaver, record player, vacuum cleaner, or clock depends ultimately on the precise time and timing information supplied by this million dollar clock. Not to mention everyone whose daily activities are more or less regulated by and dependent on the working of hundreds of computers plugged into each other all across the nation—everything from airplane and hotel reservations to stock market quotations and national crime information systems.

"The time" is very inexpensive and easy to come by for many millions of average users, simply because relatively *few* users must have very expensive and much more refined, precise time. The remarkable accuracy and dependability of the common electric wall clock can be bought very cheaply only because very much more expensive clocks make it possible for the power company to deliver electricity at a very constant 60 cycles per second, or 60 hertz, day in and day out. The "time" as most of us know it is simply inexpensive crumbs from the tables of the few rich "gourmet" consumers of time and frequency information.




FINDING AND KEEPING THE TIME

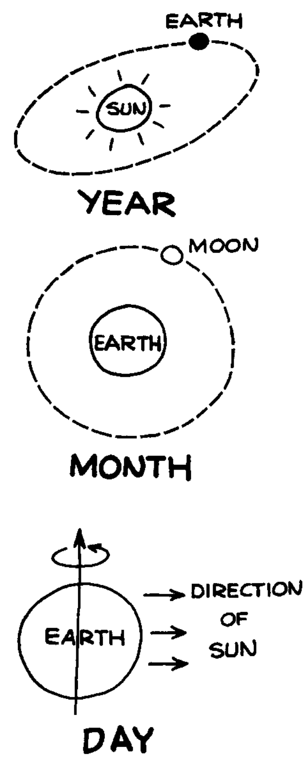
# III

# FINDING AND KEEPING THE TIME

# Chapter 9

# TIME SCALES

Length scales may measure inches or centimeters, miles or kilometers. Scales may be read in ounces or grams. When we speak of an ounce, we sometimes have to specify whether we mean avoirdupois weight or apothecaries' weight, for each is measured by a different *scale.* Nautical miles are not measured by the same scale as statute miles. Time, too, is measured by different scales for different purposes and by different users, and the scales themselves have been modified throughout history to meet changing needs or to gain greater accuracy.

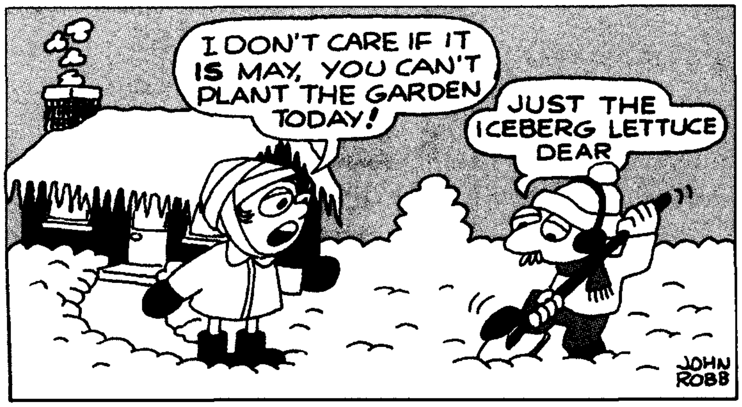



## THE CALENDAR

The year, the month, and the day are natural units of time derived from three different astronomical cycles:

- The year—solar year—is the period of one complete revolution of the Earth about the Sun.
- The month is the time between two successive new moons.
- The day is the time between two successive "high" noons.

As humans became more sophisticated in their astronomical measurements, they noticed that there was not an




even number of days and months in the year. Early farmers in the Tigris–Euphrates Valley had devised a calendar with 12 months per year, each month being the average time between two new moons, or 29½ days. This adds up to 354 days per year, 11 days short of the year we know. Before long, the farmers noticed that their planting times were getting out of step with the seasons. To bring the calendar into conformity with the seasons, extra days and months were added, at first irregularly, and later at regular intervals over a 19-year cycle.

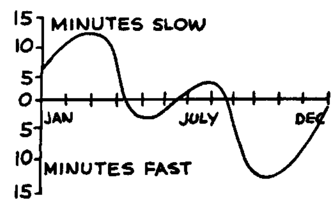
The Egyptians were the first to recognize that the solar year was close to 365 days and that even this calculation needed adjustment by adding one extra day every four years. However, the Egyptian astronomers could not persuade the rulers to add the extra day every fourth year, so the seasons and the calendar slowly drifted out of phase. It was not until some two centuries later that Julius Caesar, in 46 B.C., instituted the 365-day year adjusted for leap years. But even this adjustment isn't quite correct; a leap year every four years amounts to an overcorrection on the average of 12 minutes every solar year. About one thousand years after Julius Caesar established his calendar, this small yearly error had accumulated to about six days, and important religious holidays such as Easter were moving earlier and earlier into the season.

By 1582, the error had become so great that Pope Gregory XIII modified the calendar and the rules for generating it. First, years initiating a new century, but not divisible by

400, would not be leap years. For example, the year 2000 will be a leap year because it is divisible by 400, but the year 1900 was not. This change reduces the error to about one day in 3300 years. Second, to bring the calendar back into step with the seasons, October 4 of 1582 was followed by October 15, removing 10 days from the year 1582.

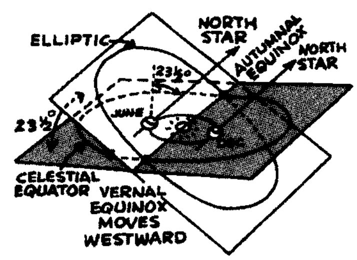
With the adoption of the Gregorian Calendar, the problem of keeping the calendar in step with the seasons was pretty well solved. But we still have the awkward fact that the numbers of days and months in the year are not commensurate with the period of the Earth's rotation around the Sun. Thus, as long as we base our calendar upon these three astronomical cycles we will always be stuck with the kind of situation we have now, with different numbers of days in the months and the years.

### The Solar Day



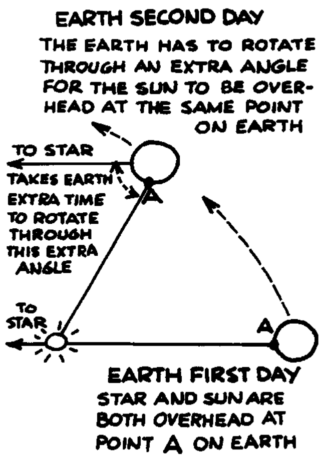

We have just seen that because there is not an integral number of days or months in the year we have a ragged calendar. But there are more problems. As humans improved their ability to measure time, they noticed that the time of day as measured by a sundial could vary from the "norm" as much as 15 minutes in February and November. There are two primary reasons for this:

- The Earth does not travel around the Sun in a circle, but in an ellipse. When the Earth is nearer the Sun—in winter, in the northern hemisphere—it travels faster in orbit than when it is farther away from the Sun—in summer.
- The axis of the Earth's rotation is tilted at an angle of about 23½ degrees with respect to the plane which contains the Earth's orbit around the Sun.




Together, these two facts account for the discrepancies in February and November. Because of this variation, a new day called the "mean solar day" was defined. The mean solar day is the average duration of all of the individual solar days throughout the year. The sketch shows how the length of the solar day leads and lags behind the mean solar day throughout the year.

## The Stellar or Sidereal Day




We have defined the solar day as the time between two "high" noons, or upper transits of the Sun. But what if we measured the time between two upper transits of a star? Does the "star" day equal the solar day? No. A star appears at upper transit a little earlier the second night. Why? Because the Earth, during the time it is making one rotation about its axis, has moved some distance, also, in its journey around the Sun. The net effect is that the mean solar day is about four minutes longer than the day determined by the star. The day determined by the star is called the *sidereal day.*

Unlike the solar day, the sidereal day does not vary in length from one time of the year to another; it is always about four minutes shorter than the *mean* solar day, regardless of the time of year or season.

Why is its length so much more nearly constant? Because the stars are so far away from the Earth that the tilt of the Earth's axis and the elliptical orbit of the Earth around the Sun can be ignored. To put it differently, if we were looking at the Earth from some distant star, we would hardly be able to discern that a tilted Earth was moving around the Sun in an elliptical orbit. In fact, the mean solar day itself can be more easily measured by observing the stars than it can by observing the Sun.

## Earth's Rotation

There still remains one final area of uncertainty in the astronomical time scale. Does the Earth itself rotate uniformly? There were suspicions as early as the late 17th century that it does not. The first Astronomer Royal of England, John Flamstead, suggested in 1675 that since the Earth is surrounded by water and air, whose distribution across the surface of the Earth changes with time, its rotation rate might change from season to season.

A more definitive clue was obtained by the British astronomer Edmund Halley, after whom the famous comet was named. In 1695, Halley noticed that the Moon was ahead of where it should have been. Either the Earth was slowing down in its rotational rate or the Moon's orbit had not been properly predicted. The Moon's orbit was carefully recalculated, but no error was found.

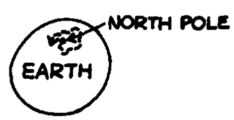
The evidence continued to mount. Near the beginning of the 20th century, Simon Newcomb, an American astronomer, concluded that during the past two centuries the Moon had been at times ahead of, and at times behind, its predicted position. By 1939, it seemed clear that the Earth's rotation was not uniform. Not only was the Moon not appearing where it was supposed to be, but the planets, too, were not in their predicted places. The obvious explanation was that the Earth's rotation was not uniform.


B.C. BY PERMISSION OF JOHNNY HART AND FIELD ENTERPRISES, INC.

With the development of atomic timekeeping in the early 1950's, it was possible to study the irregularities in Earth rotation more carefully, for time obtained from atomic clocks is more uniform than Earth time. These studies, along with observations such as those just mentioned, indicate that there are three main types of irregularities:

- *The Earth is gradually slowing down*; the day is about 16 milliseconds longer now than it was 1000 years ago. This slowing is due largely to frictional tidal effects of the Moon on the Earth's oceans. Indirect evidence from the annual growth bands on fossil corals suggests that six hundred million years ago, the Earth day was about 21 hours.
- *The positions of the North and South poles wander around by a few meters from one year to the next.* Precise measurements show that this wandering may produce a discrepancy as large as 30 milliseconds. This polar

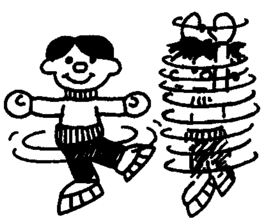

TIDAL SLOWING



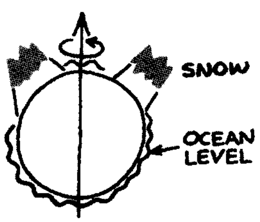

POLE WANDERS

effect may be due to seasonal effects and rearrangements in the structure of the Earth itself.

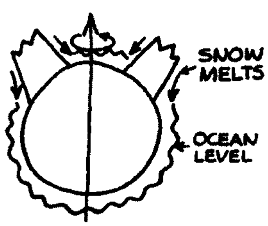
- *Regular and irregular fluctuations are superimposed on the slow decrease in rotation rate.* The regular fluctuations amount to a few milliseconds per year. In the spring the Earth slows down, and in the fall it speeds up, because of seasonal variations on the surface of the Earth, as first suspected by John Flamstead.



This variation can be understood by recalling the figure of a skater spinning on one toe. As the skater draws his outstretched arms in toward his body, he spins faster. When he extends them, he slows down. This is so because rotational momentum cannot change unless there is some force to produce a change. The skater is an isolated spinning body with only a slight frictional drag caused by the air and the point of contact between the ice and the skate. When he pulls in his arms, his speed increases, so that his rotational momentum remains unchanged, and vice versa.




WINTER SLOWS DOWN




SUMMER SPEEDS UP

The Earth is also an isolated spinning body. During the winter in the northern hemisphere, water evaporates from the ocean and accumulates as ice and snow on the high mountains. This movement of water from the oceans to the mountain tops is similar to the skater's extending his arms. So the Earth slows down in winter; in the spring the snow melts and runs back to the seas, and the Earth speeds up again.

You might wonder why this effect in the northern hemisphere is not exactly compensated by the opposite effect in the southern hemisphere during its change of seasons. The answer is that the land mass north of the equator is considerably greater than the mass south of the equator; and although there are compensating effects between the two hemispheres, the northern hemisphere dominates.

All of these effects that conspire to make the Earth a somewhat irregular clock have led to the development of three different scales of time that are called *Universal Time*: UT0, UT1, and UT2.

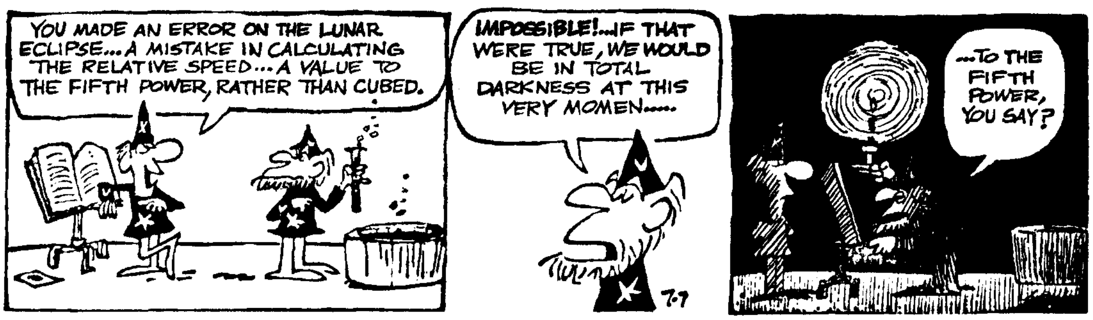
- UT0 is the scale generated by the mean solar day. Thus UT0 corrects for the tilted Earth moving around the Sun in an elliptical orbit.
- UT1 is UT0 corrected for the polar motion of the Earth.
- UT2 is UT1 corrected for the regular slowing down and speeding up of the Earth in winter and summer. Each step from UT0 to UT2 produces a more uniform time scale.

## THE CONTINUING SEARCH FOR MORE UNIFORM TIME: EPHEMERIS TIME

As we have seen, time based upon the Earth's rotation about its axis is irregular. Because of this irregular rotation, the predicted times of certain astronomical phenomena such as the orbits of the moon and the planets are not always in agreement with the observations. Unless we assume that the Moon and all of the planets are acting in an unpredictable, but similar, fashion, we must accept the only alternative assumption—that the Earth's rotation is not steady.

Since this assumption seems the more reasonable—and has indeed been substantiated by other observations—we assume that the astronomical events occur at the "correct" time, and that we should tie our time scale to these events rather than to Earth's rotation. This was in fact done in 1956, and the time based on the occurrence of these astronomical events is called *Ephemeris Time*.

### THE WIZARD OF ID




THE WIZARD OF ID BY PERMISSION OF JOHNNY HART AND FIELD ENTERPRISES, INC.

## HOW LONG IS A SECOND?

The adoption of Ephemeris Time had an impact on the definition of the second, which is the basic unit for measuring time. Before 1956, the second was 1/86 400 of the mean solar day, since there are 86 400 seconds in a day. But we know that the second based on solar time is variable; so after 1956 and until 1967 the definition of the second was based upon Ephemeris Time. As a practical matter it was decided that the Ephemeris second should closely approximate the mean solar second, so the Ephemeris second was defined as very near the mean solar second for the "tropical" year 1900. (Tropical year is the technical name for our ordinary concept of the year; it is discussed more fully later.) Thus two clocks, one keeping Ephemeris Time (ET) and the other Universal Time (UT), would have been in close agreement in 1900. But because of the slowdown of the Earth's rotation, UT was about 30 seconds behind ET by the middle of the century.

Ephemeris Time has the advantage of being uniform, and as far as we know it coincides with the uniform time that Newton had in mind when he formulated his laws of motion. The big disadvantage of Ephemeris Time is that it is not readily accessible because, by its very definition, we must wait for predicted astronomical events to occur in order to make a comparison. In other words, to obtain the kinds of accuracies that are required in the modern world, we must spread our astronomical observations over several years. For example, to obtain ET to an accuracy of 0.05 second requires making observations over a period of nine years!

UT seconds, by contrast, can be determined within a few milliseconds in one day because UT is based upon daily observations of the stars. But the fact remains that the UT second is a variable because of the irregularities in the Earth's rotation rate. What was needed was a second that could be obtained accurately in a short time.

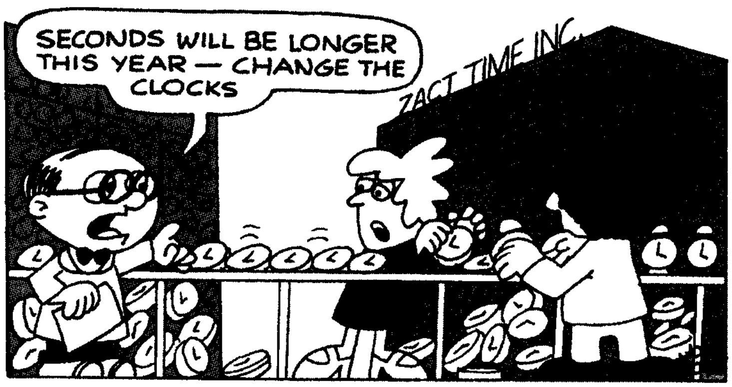

### "Rubber" Seconds

By the early 1950's, scientists had developed workable atomic clocks with accuracies never before realized. The problem was that even with the refinements and corrections that had been made in UT (Earth Time), UT and Atomic Time will get out of step because of the irregular rotation of the Earth. The need persisted for a time scale that has the smoothness of Atomic Time but that will stay in approximate step with UT.

Such a compromise scale was generated in 1958. The de facto definition of the second was based on atomic time, but the time scale itself, called Coordinated Universal Time (UTC) was to stay in approximate step with UT2. It was further decided that there would be the same number of seconds in each year.

But this is clearly impossible unless the length of the second is changed periodically to reflect variations in the Earth's rotation rate. This change was provided for, and the "rubber" second came into being. Each year, beginning in 1958, the length of the second, relative to the atomic second, was altered slightly, with the hope that the upcoming year would contain the same number of seconds as the one just passed. But as we have previously observed, the rotation rate of the Earth is not entirely predictable, so there is no way to be certain in advance that the rubber second selected for a given year will be right for the year or years that follow.

In anticipation of this possibility it was further agreed that whenever UTC and UT2 differed by more than 1/10 second, the UTC clock would be adjusted by 1/10 second to stay within the specified tolerance.




But after a few years many people began to realize that the rubber-second system was a nuisance. Each year clocks all over the world had to be adjusted to run at a different rate. The problems were similar to those we might expect if each year the length of the centimeter was changed slightly, and all rulers—which were made of rubber, of course—had to be stretched or shrunk to fit the "centimeter of the year." Not only was it a nuisance to adjust the clocks, but in cases where high-quality clocks had to be adjusted, it was a very expensive operation. The rubber second was abandoned in favor of the atomic second.

### Atomic Time and the Atomic Second

**BEFORE 1956**
ONE SECOND = $\frac{\text{MEAN SOLAR DAY}}{86,400}$
CALLED THE MEAN SOLAR SECOND

**1956–1967**
ONE SECOND = $\frac{\text{TROPICAL YEAR FOR 1900}}{31,556,925.9747}$
CALLED THE EPHEMERIS SECOND

**1967–**
ONE SECOND = 9,192,631,770 OSCILLATIONS OF THE "UNDISTURBED" CESIUM ATOM
CALLED THE ATOMIC SECOND

The development of atomic frequency standards set the stage for a new second that could be determined accurately in a short time. In 1967, the second was defined in terms of the frequency of radiation emitted by a cesium atom. Specifically, by international agreement, the standard second was defined as the elapsed time of 9 192 631 770 oscillations of the "undisturbed" cesium atom. Electronic devices associated with an atomic clock count these oscillations and display the accumulating counts in the way that another clock counts the swings of a pendulum.

Now the length of the second could be determined accurately, in less than a minute, to a few billionths of a second. Of course, this new definition of the second is entirely independent of any Earth motion, so we are back to the same old, now-familiar problem: Because of the irregularity of the Earth's rotation, Atomic Time and Earth Time (UT) will get out of step.

### The New UTC System and the Leap Second

To solve the problem of Atomic Time and Earth Time getting out of step, the "leap second" was invented in 1972. The leap second is similar to the leap year, when an extra day is added every fourth year to the end of February to keep the number of days in the year in step with the movement of the Earth around the Sun. Occasionally an extra second, the leap second, is added—or possibly subtracted—as required by the irregular rotation rate of the Earth. More precisely, the rule is that UTC will always be within 0.9 second of UT1. The leap second is normally added to or subtracted from the last minute of the year, in December, or the last minute of June; and timekeepers throughout the world are notified by the International Earth Rotation Serv-


ice, in Paris, France, that the change is to be made. The minute during which the adjustment is made is either 59 or 61 seconds long.

In 1972—a leap year—two leap seconds were added, making it the "longest" year in modern times. Since that time, more years have had leap seconds than those that haven't.

### THE LENGTH OF THE YEAR

Up to this point we have defined the year as the time it takes for the Earth to make one complete journey around the Sun. But actually there are two kinds of year. The first is the *sidereal year*, which is the time it takes the Earth to circle around the Sun with reference to the stars, in the same sense that the sidereal day is the time required for one complete revolution of the Earth around its axis with respect to the stars. We can visualize the sidereal year as the time it would take the Earth to move from some point, around its orbit, and back to the starting point—if we were watching this motion from a distant star. The length of the sidereal year is about 365.2564 mean solar days.

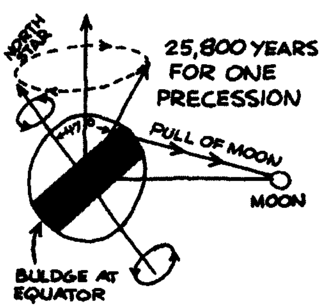
SIDEREAL YEAR = 365.2564 MEAN SOLAR DAYS

TROPICAL YEAR = 365.2422 MEAN SOLAR DAYS

The other kind of year is the one we are used to in everyday life—the one that is broken up into the four seasons. This year is technically known as the *tropical year*, and its duration is about 365.2422 mean solar days, or about 20 minutes shorter than the sidereal year. The reason the two years have different durations is that the reference point in space for the tropical year moves slowly itself, relative to the stars. The reference point for the tropical year is the point in space called the *vernal equinox*, which moves slowly westward through the background of stars. The earlier sketch shows how the vernal equinox is marked.

The celestial equator is contained in the plane that passes through the Earth's equator, whereas the "ecliptic" is in the plane that passes through the Earth's orbit around the Sun. The vernal equinox and the autumnal equinox are the two points in space where the ecliptic and celestial equators intersect. The angle between the ecliptic and the celestial equator is determined by the tilt of the Earth's axis of revolution to the plane of the ecliptic.

But why does the vernal equinox—as well as the autumnal equinox—move slowly in space? For the same reason that a spinning top wobbles as it spins. The top wobbles because the Earth's gravitation is trying to pull it on its side, while the spinning motion produces a force that attempts to keep the top upright. Together the two forces cause the top to wobble, or "precess."

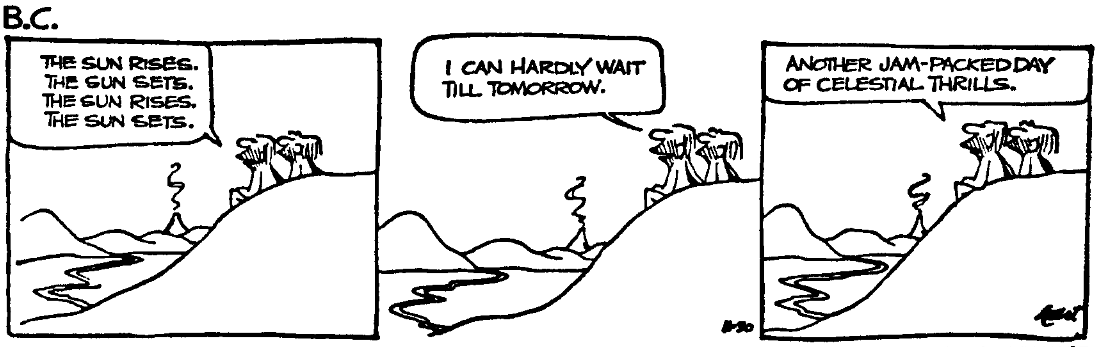



In the case of the Earth, the Earth is the spinning top and the forces trying to topple it are the pulls of the Moon and the Sun; the Moon produces the dominant force. If the Earth were a perfect sphere with uniform density, there would be no such effect by the Moon because all of the forces could be thought of as acting at the center of the Earth. But because the Earth spins, it bulges at the equator, and so there is an uneven distribution of mass, which allows the Moon's gravitational field to get a "handle," so to speak, on the Earth. The time for one complete precession is about 25 800 years, which amounts to less than 1 minute of arc per year. (One degree equals 60 minutes of arc.) But it is this slight yearly motion of the vernal equinox that accounts for the tropical year being about 20 minutes shorter than the sidereal year.

### THE KEEPERS OF TIME

Whatever the time scale and its individual advantages or idiosyncrasies, it is, of itself, simply a meter stick, a basis for measurement. Before it's of any value, someone must put it to use and someone must maintain and tend the instruments involved in the measurements. For as we've noted before, time is unique among the physical properties in that it is forever changing, and the meter stick that measures it can never be laid aside or forgotten about, to be activated only when someone wishes to use it.

You can measure length or mass or temperature of an isolated entity, without consideration of continuity or needing to account for all of the space between two isolated entities. But every instant of time, in a sense, must be accounted for. If a month, a year, or a century doesn't "come out right" with respect to astronomical movements, it won't do simply to stop the clocks for the needed period of time—or move them ahead a certain amount—and start over. Every single second has its name on it, and each one must be accounted for, day after day, year after year, century after century. There has to be a general agreement among people and among nations on which time scale is to be used, and when alterations are to be made in "the time." This is a much greater and more elaborate undertaking than most persons realize.



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The keepers of time make an important contribution to society, and even in days past they were held in high esteem. Ancient legends of early peoples often portray the great position of honor and trust occupied by the tender of the clock—also the tedious and sometimes irksome sense of responsibility felt by the tender, and the ignominy and condemnation heaped upon him by his fellow tribesmen when he failed in his duties. "The more things change, the more they are the same." The clock tender today is in much the same position, for although what passes for the "correct time" is all around us, all this information is of little value to those responsible for maintaining the accuracy of "the clock"—or frequency standard. They must realize that each clock is an individual, unique in all the world, and that many operations involving time, money, and other people depend upon how well they tend their clock.

Whether the clock in question regulates the activities of a radio or television station, tells the power company when it's putting out electricity at exactly 60 hertz, or providing location information on a ship at sea, the clock's keeper depends on a broader authority for *his* information. These authorities are both national and international.

**World Time Scales**

As we know from earlier chapters, timekeeping was initially a local affair—the ring of a church bell, the comforting voice of the town crier, even the crowing cock at sunrise. But with the discovery of the New World and the rising tide of global navigation, we learned how worldwide, accurate time became essential to solving the longitude problem. But this was only the beginning. The 19th century Industrial Revolution brought planetary communication and commerce. And, the twin workhorses of that era were trains and ships. The speeding interstate and intercontinental trains fostered the birth of time zones and, as we know, ships navigators had for many years needed accurate time.

But if the industrial revolution accelerated the need for better, worldwide time, it also provided many of the answers: the mass production of cheap clocks and watches, the telegraph, and later radio, to name only three. Timekeeping in the past, driven by the natural rhythms of the heavens and often structured by religious authority, was rapidly being replaced by the secular authority of mechanical timepieces.

In the early 1840's Great Britain replaced the local time systems in England, Scotland, and Wales with Greenwich standard time. The Royal Greenwich Observatory, the source of so many of Hamilton's problems, was the center of this operation. Greenwich Mean Time (GMT) remained the official world standard until 1972.

In 1830, the United States established the U.S. Naval Observatory (USNO) to join Great Britain and other world observatories in determining time based on astronomical observations. Later, with the development of atomic clocks, timekeeping, as we have seen, had both astronomical and atomic clock components. Today dozens of nations contribute both astronomical and atomic clock data to the Bureau International des Poids et Mesures (BIPM), the organization responsible for calculating the present-day universal time scale, UTC.

TIME SCALES

1. ASTRONOMICAL COMPONENT
2. ATOMIC COMPONENT
   a. ACCURACY
   b. STABILITY

**Bureau International des Poids et Mesures**

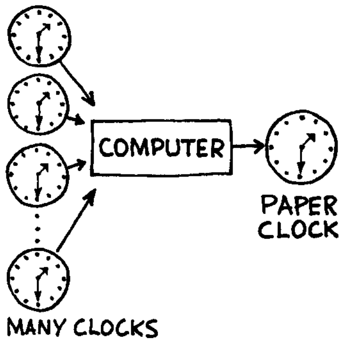
The BIPM, located in Sèvres, France, near Paris, is the international headquarters for timekeeping. There, from the contributions of many nations throughout the world, it constructs UTC.


There is an old joke among professional timekeepers: If you have one clock you know what time it is; if you have two clocks you don't know what time it is. If you have three clocks you know what time it is.

The point is that if there is only one clock and everybody uses it, then it makes no difference how well the clock keeps time, since everybody keeps in step with that clock. With two clocks you face the likely possibility that the clocks will show different times. Now you don't know which one is right and which one is wrong. With three clocks, you assume that if one clock shows time A, and the other two both show time B, then the latter two clocks provide the correct time. The joke doesn't trouble itself with the possibility that all three clocks show different times.

For the BIPM and other timekeeping organizations, the problem is usually the one the joke doesn't cover: none of the clocks shows the same time. This presents thorny technical and at times political problems. In an attempt to sort out the technical problems, at least, the BIPM and other timekeeping organizations have made a great effort to construct mathematical procedures to sort out the good clocks from the not-so-good clocks. These procedures often involve lengthy computations which are only practical with computers. In fact, the computer has become an indispensable tool of professional timekeepers.

Computers automatically record the time from large ensembles of clocks, process the data to identify faltering clocks, establish pecking orders of clock stability, and per-




form numerous other data and maintenance-related tasks. Finally, the computer puts all this information together to generate a time scale. Thus, the ultimate clock is, ironically enough, a paper clock.

In the next chapter we shall learn how time, generated by many clocks throughout the world, is communicated to the BIPM.

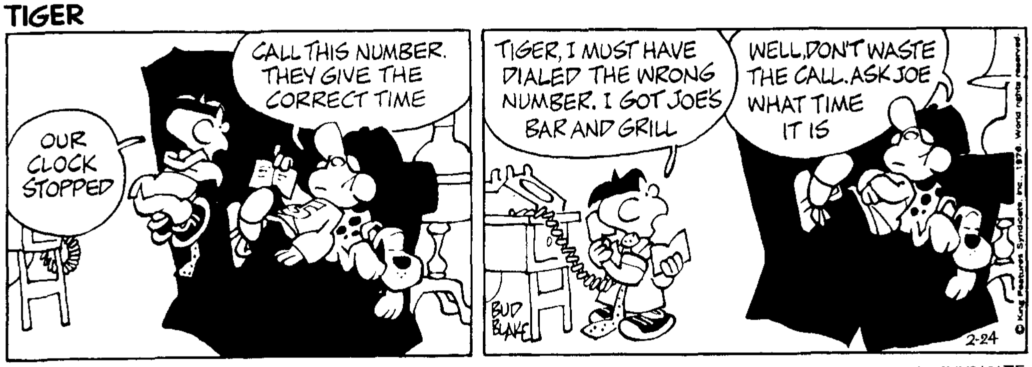
Chapter

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 8 | 9 | **10** | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 29 | 30 | 31 | | | | |

# THE CLOCK BEHIND THE CLOCK

A great many people carry "the time" around with them, in the form of a wrist watch. But what if the watch stops? Or what if two wrist watches show different time? How do the wearers know which is right—or whether either one is correct?

TIGER






They may ask a friend with a third watch—whose timepiece may or may not agree with one of the first two. Or one may dial the telephone company time service, or perhaps set her watch when she hears the time announcement on radio or television. The "correct time" seems to be all around us—on the wall clock at the drug store or court house, the outdoor time-and-temperature display at the local bank or shopping center. But a bit of observation will show that these sources are not always in agreement, even within a minute or so of each other, not to mention seconds or a fraction of a second. Which one is right? And where do *these* sources get the time? How do radio and television station managers know what time it is?

The answer is that there are, throughout the world, special radio broadcasts of accurate time information. Most of these broadcasts are at frequencies outside the range of ordinary AM radio, so you need a special radio receiver to tune in the information. Many of these short-wave receivers are owned by radio and television stations, as well as by scientific laboratories in industry and government, and even by private citizens, such as boat owners, who need precise time information to navigate by the stars.

Finally, we come to the ultimate question: Where do these special broadcast stations go to find the time? And the answer is that many nations maintain the time by using very accurate atomic clocks combined with astronomical observations, as we discussed more fully in the previous chapter. All the time information from these various countries is constantly compared and combined by, as we know, BIPM to provide a kind of "average world time," UTC, which is then broadcast by the special time and frequency radio stations located in various parts of the world.

## FLYING CLOCKS

Keeping the world's clocks synchronized, or running together, is an unceasing challenge. One of the most obvious ways to do it is simply to carry a third atomic clock between the master clock and the users' clocks. The accuracy of the synchronization depends primarily on the quality of the clock carried between the two locations and the time it takes to transport it. Usually the clock travels by airplane carefully tended at all times by a technician. Typically, the best quality portable atomic cesium clocks might drift less than 0.1 microsecond per day. In the past, carrying portable atomic clocks was one of the main methods for comparing the time and frequency standards of the various nations with BIPM. However, as we shall see, new methods are replacing portable clock comparisons.

### TIME ON A RADIO BEAM

As early as 1840, it occurred to the English inventor Alexander Bain that it would be possible to send time signals over a wire. Bain obtained several patents, but it was not until a decade or so later that any serious progress was made in this direction. But before the middle of the 19th century the railroads were spreading everywhere, and their need for better time information and dissemination was critical. As the telegraph system developed by Samuel F.B. Morse grew with the railroads, systems were developed to relay time signals by telegraph, which automatically set clocks in all major railroad depots.

During the early part of the 20th century, with the development of radio, broadcasts of time information were initiated. In 1904, the United States Naval Observatory experimentally broadcast time from Boston, and by 1910, time signals were being broadcast from an antenna located on the Eiffel Tower, in Paris. In 1912, at an international meeting held in Paris, uniform standards for broadcasting time signals were discussed.

RADIO TIME BROADCASTS

1904 - UNITED STATES NAVAL OBSERVATORY TRANSMITS FROM BOSTON

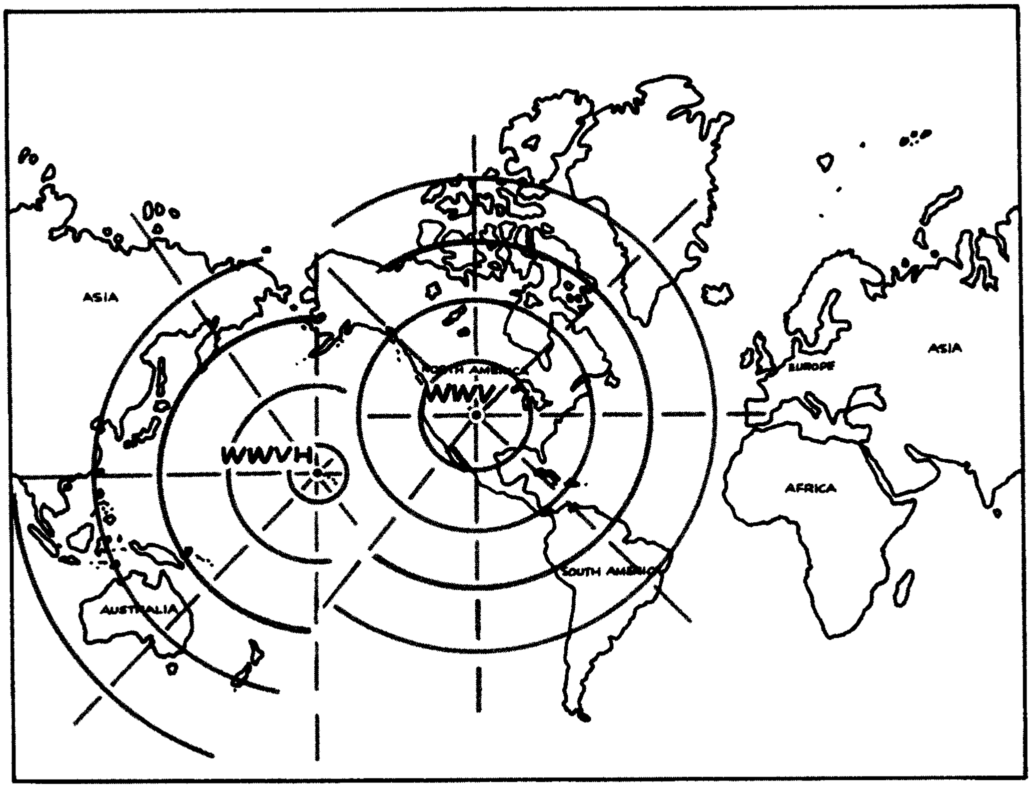
1910 - TRANSMISSIONS FROM EIFFEL TOWER IN PARIS

1923 - NATIONAL BUREAU OF STANDARDS TRANSMITS FROM WASHINGTON, D.C.

In March of 1923, the National Bureau of Standards began broadcasting its own time signal. At first there were only standard radio frequencies, transmitted on a regularly announced schedule from short-wave station WWV, located originally in Washington, D.C. One of the main uses of this signal was to allow radio stations to keep on their assigned frequencies, a difficult task during the early days of radio. In fact, one night in the 1920's the dirigible *Shenandoah* became lost in a winter storm over the eastern seaboard, and it was necessary for the New York radio stations to suspend transmissions so that the airship's radio message could be detected.

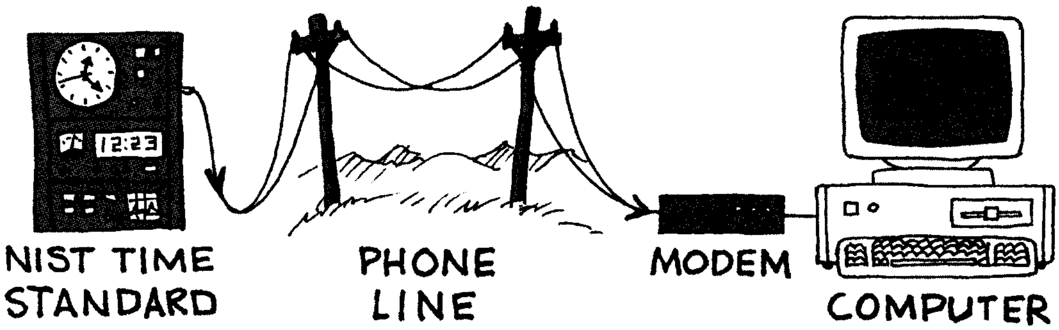
WWV was later moved outside Washington, D.C., to Beltsville, Maryland, and in 1966 to its present home near Fort Collins, Colorado, about 80 kilometers north of Boulder.

A sister station, WWVH, was installed in Maui, Hawaii, in 1948, to provide similar services in the Pacific area and




western North America. In July 1971, WWVH was moved to a site near Kekaha on the Island of Kauai, in the western part of the Hawaiian Island chain. The 35 percent increase in area coverage achieved by installation of new and better equipment extended WWVH service to include Alaska, Australia, New Zealand, and Southeast Asia.

Throughout the years NIST has expanded and revised the services and format of its short-wave broadcasts to meet changing and more demanding needs. Today signals are broadcast at several different frequencies in the short-wave band 24 hours a day. The signal format provides a number of different kinds of information, such as standard musical pitch, standard time interval, a time signal both in the form of a voice announcement and a time code, information about radio broadcast conditions, and even weather information about major storm conditions in the Atlantic and Pacific areas from WWV and WWVH, respectively. The broadcasts of WWV may also be heard by telephone by dialing (303) 499-7111 (Boulder, Colorado). You will hear the live broadcasts as received by radio in Boulder. Considering the instabilities and variable delays of propagation by radio and telephone combined, do not expect accuracy of these telephone time signals to better than 1/30 of a second, which, in any case, exceeds your physiological response time by an ample margin.



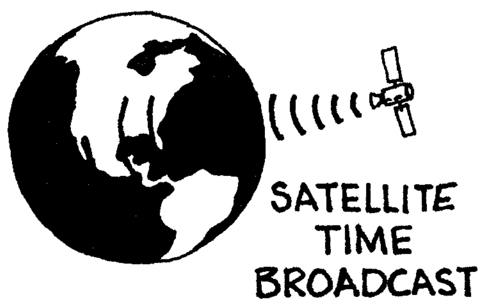

NIST also offers more advanced telephone time services called ACTS (Automated Computer Time Services through both telephone and the Internet). In this system, a digital time signal is delivered to a computer which displays UTC time and the date. With appropriate software, the computer's clock can be set automatically. In the most advanced telephone version of ACTS, telephone time delays are automatically compensated for providing time accurate to a few milliseconds.

NIST also broadcasts a signal at 60 kilohertz from radio station WWVB, also located in Fort Collins, in the form of a time code, which is intended primarily for domestic uses. This station provides better quality frequency information because atmospheric propagation effects are relatively minor at 60 kilohertz (see Chapter 11). The time code is also better suited to applications where automatic equipment is used. The USNO provides time and frequency information by a number of U.S. Navy communication stations, some of which operate in the very low frequency (VLF) range. Over 30 different radio stations throughout the world now broadcast standard time and frequency signals.

## TIME IN THE SKY

One problem with shortwave time broadcasts is that no single broadcast provides worldwide coverage. So there is always the question: How well are the various time broadcasts synchronized to each other? For example, suppose a global study of earthquakes requires recording the onset of particular seismic events. If observers in one part of the world, location A, depend on a time broadcast in their local area while observers in another area, B, depend on a different time broadcast, then the two broadcasts must be synchronized. If they are not, erroneous conclusions may be drawn.

Suppose, for example, that both observers record the same seismic event. Observers at A say the event occurred at time T while those at B say the event occurred 3 milliseconds after T. The fact that the event occurred first at A and then later at B is important information because it suggests the order of a chain of seismic events. But, if the two time broadcasts are not synchronized, it may be that the apparent order of events is reversed—that the event actually occurred at B before it did at A. Such an error could completely invalidate the results of the earthquake study.




One solution to the problem of multi-shortwave time broadcasts is to broadcast time from a satellite. A single satellite positioned high above the equator provides coverage to nearly one third of the Earth's surface so that three satellites, appropriately spaced, can provide nearly worldwide coverage.

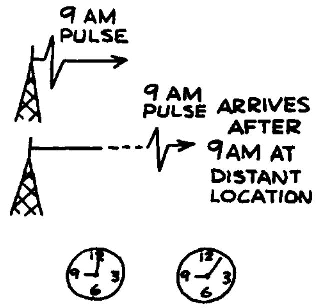
There are a number of time signals originating from satellites, the most notable of which emanate from the US military navigation satellites that are part of the Global

Positioning System (GPS). A similar system known as GLONASS is operated by Russia. We shall return to the topic of satellite time broadcasts and GPS.

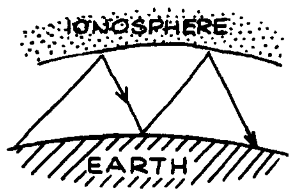
Let's consider now what makes a good time signal.

### Accuracy

The basic limitation in short-wave radio transmission of time information is that the information received lacks the accuracy of the information broadcast. The signal broadcast takes a small but definite time to reach each listener; when you hear that the time is 9:00 a.m., it is really a very small fraction of a second after 9:00 a.m. If you know how long it takes for the radio signal to reach you, you can allow for the delay and correct this reading accordingly. But where extremely accurate time information is needed, determining the delay precisely is a difficult problem because the signal does not normally travel in a direct line to the listener. Usually it comes to him by bouncing along a zig-zag path between the surface of the Earth and the ionosphere, which is a layer of the upper atmosphere that acts like a mirror for radio waves.



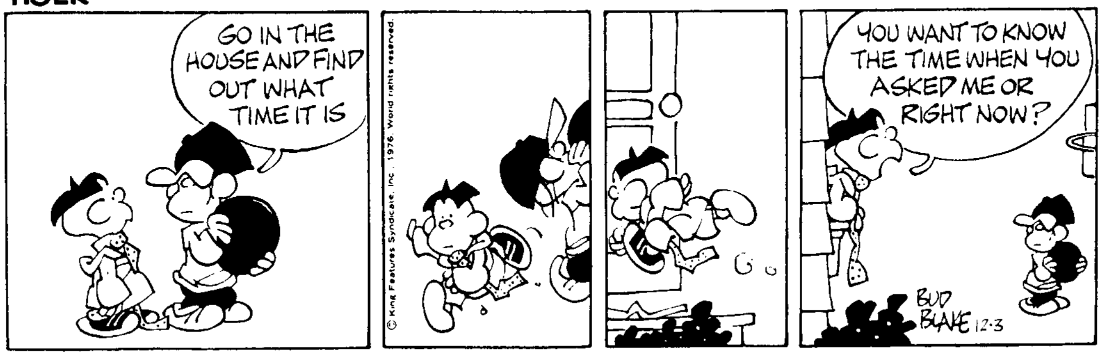

The height of this reflective layer depends in a complicated way upon the season of the year, the sunspot activity on the Sun, the time of day, and many other subtle effects. So the height of the reflective layer changes constantly in a way that is not easy to predict, and thus the path delay in the signal is also difficult to predict or evaluate.



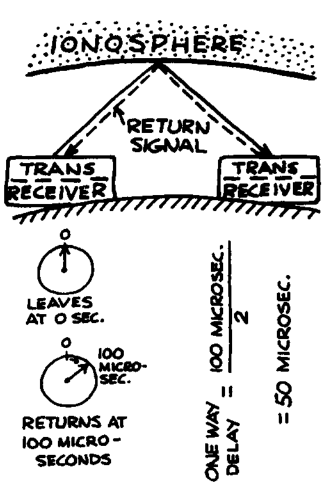

Because of these unpredictable effects, it is difficult to receive time by short-wave radio with an uncertainty less than one-thousandth of a second. For the everyday activities of about 98 percent of time information users, this accuracy is more than adequate. But there are many vitally important applications—such as the high-speed communications systems discussed in Chapter 14—where time must be known to one-millionth of a second, or even better.

The need for greater accuracy has led to several schemes for overcoming the problem of the unpredictable path delay. Instead of trying to predict or calculate the delay, for example, we measure it. One of the most common ways to do this is to transmit a signal from the master clock, at a known time, to the location we wish to synchronize. As soon as the

TIGER






signal is received at the remote location, it is transmitted back to the master clock. When the signal arrives back at its point of origin, we note its arrival time. Then by subtracting the time of transmission from the time of return, we can compute the round-trip time, and the one-way-trip time by dividing this figure by 2.

As is usually the case, however, we don't get something for nothing; we've had to install a transmitter at the receiver's location to make the measurement. One of the most important applications of this particular approach has been to use a satellite to relay signals back and forth between the locations we wish to synchronize.

We shall return to this subject again when we consider the ways time information is communicated to the BIPM.

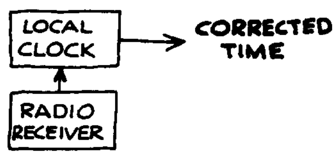
### Coverage

Accuracy is only one of the requirements for a usable time-information system. Obviously, an extremely accurate time source that could make its information known only a hundred miles away would be of limited use; sometimes it's important to make the same information simultaneously available almost throughout the world as we saw when we considered the problem of world wide earthquake measurements. As an actual illustration, scientists, during the International Geophysical Year starting in July of 1957, wanted to know how certain geophysical events progressed as a function of time over the surface of the Earth. They wanted to find out, among other things, how a large burst of energy from the Sun affected radio communications on Earth, as a function of time and location. Such information not only has practical importance for local and worldwide communications, but it also provides data to develop theories and to decide between proposed theories.

**Reliability**

Reliability is another important factor. Even if the transmitting station is almost never down because of technical difficulties, radio signals often fade in and out at the receiver. Most of the well-known standard time and frequency broadcast services are in the short-wave band, where fading can be a severe problem. To return to our scientists of the Geophysical Year, they may want to make a crucial measurement during, say, an earthquake, and discover that there is no available radio time signal.


Of course, most users are aware of this difficulty, so they try to protect themselves against such loss of information by maintaining a clock at their own location, to interpolate between losses of radio signals. Or more usually they routinely calibrate their clocks once a day when reliable radio signals *are* available.




At the broadcast station an attempt is made to overcome loss of its signals by broadcasting the time on several different frequencies at once. The hope is that at least one signal will be available most of the time.

### Other Considerations

*Percent of time available* refers mainly to systems that are not particularly subject to signal fading but are off the air part of the time. For example, if we broadcast time over a commercial TV station, say, once every half hour, we can be pretty certain that the signal will be there when it is supposed to be. But since many TV stations are off the air during late-night and early-morning hours, the information will not be available 100 percent of the time.

*Receiver cost* is another factor that you must consider in your choice of system. No system is ideal for all users or in all circumstances. And as is generally the case in most choices, you have to accept some limitations in order to get the advantages most important to you.

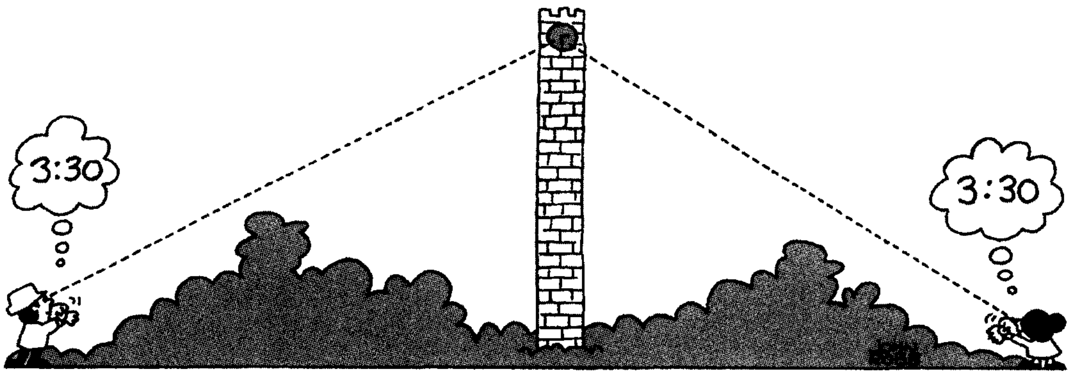
*Ambiguity* refers to the degree to which the time signal is self-contained. For example, a time signal that consisted of ticks at one-minute intervals would allow you to set the second hand of your watch to 0 at the correct moment, but it wouldn't tell you at what minute to set the minute hand. On the other hand, if the minute ticks were preceded by a voice announcement that said, "At the tick the time is 12 minutes after the hour," then you could set both your second hand and your minute hand, but not your hour hand.

For the most part, short-wave radio broadcasts dedicated primarily to disseminating time are relatively unambiguous in the sense that they broadcast day, month, year, hour, minute, and second information. In some other services we assume that the user knows what the year, month, and day it is. Other systems, particularly navigation systems that are sources of time information, are usually more ambiguous because their signals are primarily ticks and tones, the user must have access to some other time signal to remove the ambiguity.

## OTHER RADIO SCHEMES

In addition to the widely used short-wave broadcasts of time information are radio systems that can be used to retrieve such information. Low-frequency navigation systems, for instance, although they were built and are operated for another purpose, are good sources of time information because their signals are referenced to high-quality atomic frequency standards and to "official" time sources.

At the other end of the frequency spectrum, television broadcasts provide a source of extremely sharp, strong pulses that can readily be used to synchronize any number of clocks. Actually, *any* kind of radio signal with some identifiable feature that is "visible" at two or more places can be used to synchronize clocks, as we shall see in the next chapter. Of course, clocks can be synchronized without necessarily telling the "correct" or standard time. But if any one of the clocks being synchronized has access to standard time (date), all other clocks—given the necessary equipment—can be synchronized to it.




The broadcast *frequency* of a radio signal has a great deal to do with its usefulness. Systems other than the shortwave system have certain advantages—but also distinct disadvantages. We shall say more about this in the next chapter.

# Chapter 11

# THE TIME SIGNAL ON ITS WAY

We've already realized that information about the "correct time" is useless unless it's instantly available. But what, exactly, do we mean by "instantly," and how is it made available to everyone who wants to know what time it is? What can happen to this information on its way to the user, and what can be done to avoid some of the bad things that can and do happen?

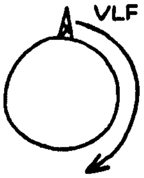
## CHOOSING A RADIO FREQUENCY

The *frequency* of a radio signal primarily determines its *path*. The signal may bounce back and forth between the ionosphere and the surface of the Earth, or creep along the curved surface of the Earth, or travel in a straight link depending on the frequency of the broadcast. We shall discuss the characteristics of different frequencies, beginning with the very low-frequencies and working our way up to higher frequencies.

### Very Low Frequencies (VLF)—3 to 30 kilohertz

The big advantage of VLF signals is that one relatively low-powered transmitter provides wide coverage. A number of years ago, a VLF signal broadcast in the mountains near Boulder, Colorado, was detected in Australia, even though the broadcast signal strength was less than 100 watts. The VLF signal travels great distances because it bounces back and forth between the Earth's surface and the lowest layer of the ionosphere, with very little of its energy absorbed at each reflection.

In addition, VLF signals are not strongly affected by irregularities in the ionosphere, which is not true in the case of short-wave transmissions. This is so because the size of the irregularities in the ionosphere "mirror" is generally small compared to the length of the VLF radio waves. For example, at 20 kilohertz the radio frequency wavelength is 15 kilometers. The effect is somewhat the same as the unperturbed motion of a large ocean liner through slightly choppy seas.




But VLF also has serious limitations. One of the big problems is that VLF signals cannot carry much information because the signal frequency is so low. We cannot, for example, broadcast a 100 kilohertz tone over a broadcast signal operating at 20 kilohertz. It would be like trying to get mail delivery 10 times a day when the mailman comes only once a day. More practically, it means that time information must be broadcast at a very slow rate, and any schemes involving audio frequencies, such as voice announcement of the time, are not practical.

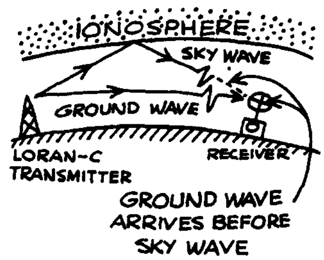
We mentioned that VLF signals are not particularly affected by irregularities in the ionosphere, so the path delay is relatively stable. Another important fact is that the ionospheric reflection height is about the same from one day to the next at the same time of day. Unfortunately, though, calculating the path delay at VLF is a complicated and tedious procedure.

One last curious thing about VLF is that the receivers are better off if they listen to signals from a distant station than from nearby stations. The reason is that near the station they get two signals—one that is reflected from the ionosphere (sky wave) and another that is propagated along the ground. And what they receive is the sum of these two signals. This sum varies in a complicated way as a function of time and distance from the transmitter. So you want to be so far from the transmitter that for practical purposes the ground wave has died out, and you don't have to deal with this complicated interference pattern.

### Low Frequencies (LF)—30 to 300 kilohertz

In many respects, LF signals have properties similar to VLF. The fact that the carrier frequencies are higher means that the information-carrying rate of the signal is potentially higher also.

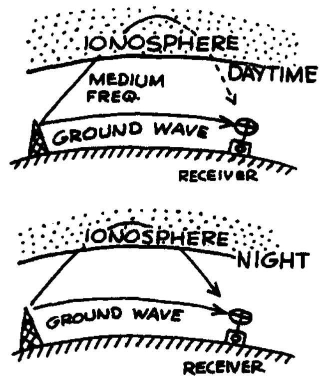
These higher carrier frequencies have allowed the development of an interesting trick to improve the path stability of signals. The scheme was developed for the Loran-C (LOng RAnge Navigation) navigation system at 100 kilohertz, which is also used extensively to obtain time information. The trick is to send a pulsed signal instead of a continuous signal. A particular burst of signal will reach the observer by two different paths. The observer will first see the ground-wave signal that travels along the surface of the Earth. And a little later she will see the same burst of signal arriving via reflection from the ionosphere.




At 100 kilohertz, the ground wave arrives about 30 microseconds ahead of the ionospheric wave, and this is usually enough time to measure the ground wave, uncontaminated by the sky wave. The ground wave is stable in path delay, and the path-delay prediction is considerably less complicated than when one is working with the sky wave.

Beyond about 1000 kilometers, however, the ground wave becomes so weak that the sky wave predominates; and at that point we are pretty much back to the kind of problems we had with VLF signals.

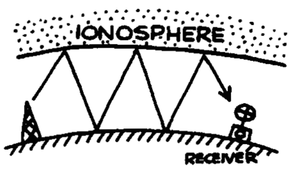
### Medium Frequencies (MF)—300 kilohertz to 3 megahertz




We are most familiar with the medium-frequency band because it contains primarily the AM broadcast stations. During the day the ionospheric or sky wave is heavily absorbed, as it is not reflected back to Earth, so for the most part, during the daytime we receive only the ground wave. At night, however, there is no appreciable absorption of the signal, and these signals can be heard at great distances.

One of the standard time and frequency signals is at 2.5 megahertz. During the daytime, when the ground wave is available, the Japanese report obtaining 30 microsecond timing accuracy. At night, when we receive the sky wave, a few milliseconds is about the limit. It is fair to say, however, that this band has not received a great deal of attention for time dissemination, and there may be future promise here.

### High Frequencies (HF)—3.0 to 30 megahertz



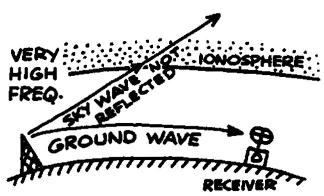

MANY HOPS MAKES DELAY DIFFICULT TO PREDICT. SIGNAL FADES.

The HF band is the one we usually think of when we speak of the shortwave band. Signals in this region are generally not heavily absorbed in reflection from the ionosphere. Absorption becomes even less severe as we move toward the upper end of this band. Thus the signal may be heard at great distances from a transmitter, but it may arrive after many reflections, so accurate delay prediction is difficult. Another difficulty is that in contrast to VLF waves, HF wavelengths can be of the same order, or smaller, than irregularities in the ionosphere. And since these irregularities are constantly changing their shape and moving around, the signal strength at a particular point will fade in and out in amplitude. Because of the fading and the continuous change in path delay, accuracy in timing is again restricted to about 1 millisecond, unless we are near enough to the transmitter to receive the ground wave.

Most of the world's well-known standard time and frequency broadcasts are in this band.

### Very High Frequencies (VHF)—30 to 300 megahertz

VHF signals are often not reflected back to the surface of the Earth, but penetrate through the ionosphere and propagate to outer space. This means that we can receive only those stations that are in line of sight and explains why we do not normally receive distant TV stations, since TV signals are in this band. It also means that many different signals can be put on the same channel, and there is little chance of interference as long as the stations are separated by 300 kilometers or more.




LIMITED TO LINE OF SIGHT. HAS HIGH ACCURACY. CAN SEND SHARP PULSES.

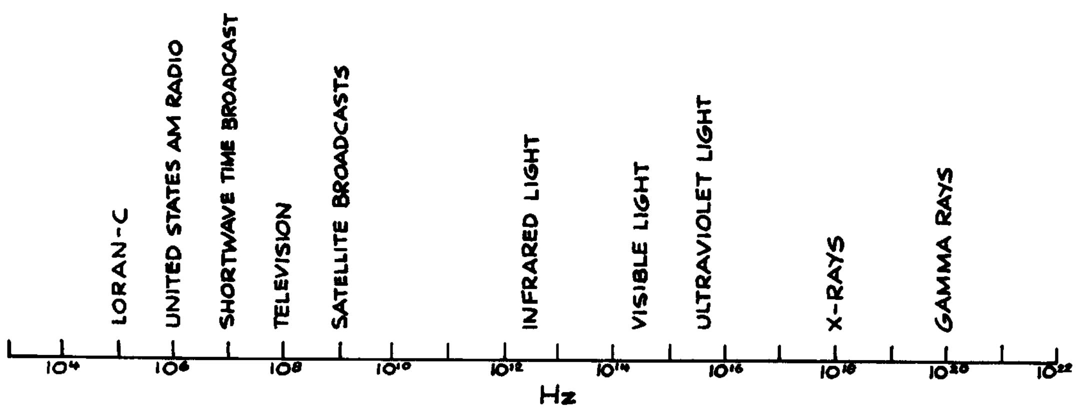
From a timing point of view, however, this is bad, for if we want to provide worldwide—or even fairly broad—coverage, many stations are required, and they must all be synchronized. On the other hand, there are advantages to having no ionospheric signals because this means that we can receive a signal uncontaminated by sky wave. We can also expect that once we know the delay for a particular path, it will remain relatively stable from day to day.

A third advantage is that because carrier frequencies are so high, we can send very sharp rise-time pulses, and thus can measure the arrival time of the signals very precisely. Because of the sharp rise time of signals and the path stability, timing accuracies in this region are very good. Microsecond timing is relatively easy; if care is taken, accuracy of 0.1 microsecond can be achieved.

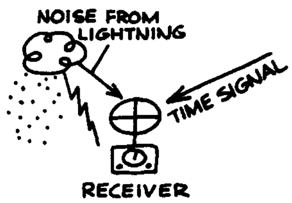
### Frequencies above 300 megahertz

The main characteristic of these frequencies is that like VHF frequencies the signals penetrate into outer space, so systems are limited to line of sight. There may be problems caused by small irregularities in the path—or "diffraction effects," as they are commonly called—similar to such effects at optical wavelengths. Nevertheless, if a straight shot to the transmitter is available, we can expect good results.

Above 1000 megahertz weather may produce problems; this is especially significant in broadcasting time from a satellite, where we wish to minimize both ionospheric and lower atmosphere effects. We'll say more about satellite time broadcasts later.



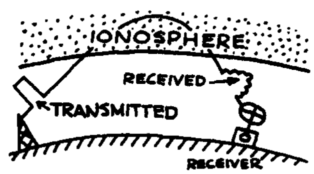
## NOISE—ADDITIVE AND MULTIPLICATIVE



ADDITIVE NOISE

We have been discussing different effects that we should expect in the various frequency bands. We should differentiate explicitly between two types of effects on the signals. They are called "additive noise" and "multiplicative noise." "Noise" is the general term used to describe any kind of interference that mingles with or distorts the signal transmitted and so contaminates it.

Additive noise is practically self-explanatory. It refers to *noise that is added to the signal and reduces its usefulness.* For example, if we listen to a time signal perturbed by radio noise caused by lightning or automobile ignition noise, we would have an additive noise problem.



MULTIPLICATIVE NOISE

Multiplicative noise is noise in the sense that something happens to the signal to distort it. A simple illustration is the distortion of your image by a mirror in a fun house. None of the light or signal is *lost*—it is just rearranged so that the original image is *distorted.* The same thing can happen to a signal as it is reflected by the ionosphere. What was transmitted as a nice, clean pulse may, by the time it reaches the user, be smeared out or distorted in some way. The energy in the pulse is the same as if it had arrived cleanly, but it has been rearranged.


How can we overcome noise? With additive noise, the most obvious thing to do is to increase the transmitter power so that the received signal-to-noise ratio is improved. Another way is to divide the available energy and transmit it on several different frequencies at once. One of these frequencies may be extremely free from additive noise. Another possibility—quite often used—is to "average" the signal. We can take a number of observations, average them, and improve our result. This works because the information on the signals is nearly the same all the time, so the signal keeps building up, but the noise is, in general, different from one instant to the next; therefore, it cancels out.

With multiplicative noise, it doesn't help to increase the transmitter power. To return to our previous illustration, the image from a fun-house mirror will be just as *distorted* whether you are standing in bright light or in dim light. Most of the strategies for overcoming multiplicative noise come under the general heading of *diversity*—specifically space diversity, frequency diversity, and time diversity.

- **Space diversity** means that we measure the incoming signal at several different *locations*, but not just any locations. The locations must be far enough apart that we are not seeing the same distortion; what we are attempting to do is to look for elements in the signal that are common to all signals. In other words, if we look at the fun-house mirror from several different locations, it is the distortion that changes, not our body. And maybe by looking at the mirror from several different locations we can get the distortions to cancel out, leaving the true image.
- **Frequency diversity** means simply that we send the same information on several different *frequencies*, again hoping that the signal distortion on the different frequencies will be sufficiently different so that we can average them out and obtain the true signal image.
- **Time diversity** means that we send the same message at different *times*, hoping that the distortion mechanism will have changed sufficiently between transmissions for us to reconstruct the original signal.

## THREE KINDS OF TIME SIGNALS

We can use three different kinds of signals to get time information. The most obvious is, of course, a signal that was constructed for this very purpose, such as a broadcast from WWV, or perhaps the time announcement on the telephone. The obvious utility of this method is that the information comes to us in a relatively straightforward way, and we have to do very little processing.

STANDARD TIME BROADCASTS

RADIO NAVIGATION SIGNALS

TV SIGNALS

A second way is to listen to some signal that has time information buried in it. A good example is the Loran-C navigation system. In this system the pulses emitted for navigation are related in a very precise way to atomic clocks that are all coordinated throughout the system. Although we may not get a pulse exactly on the second, minute, or hour, the emission times of these signals are related precisely to the second, minute, and hour. So to use Loran-C for time information we must make a measurement of the arrival time of a pulse or pulses with respect to our own clock. And we must also have information that tells us how the pulses are related to the controlling clock. This information about Loran-C is, in fact, available from the United States Naval Observatory.

Finally, we can use a radio signal for synchronization without any specific effort by those operating the transmitter to provide such information—or even knowing that it is being so used. The process is called the "transfer standard" technique; it was in the past used, for example, to keep the radio emissions from the standard time and frequency short-wave radio stations WWV and WWVB near Fort Collins, Colorado, referenced back to the atomic clock system and National Frequency Standard at the NIST laboratories 80 kilometers away, in Boulder.

Let's see how the method works for this example. A TV signal consists of a number of short signals in quick succession, with each short signal responsible for one line of the picture on the TV screen. Each such signal is about 63 microseconds long, and each is preceded by a pulse that, in effect, tells the TV set to get ready for the next line of information. Let's suppose now that we recorded the arrival time of one of these get-ready pulses—or "synchronization pulses,"—with respect to our clock in Boulder. Let's suppose that someone at the WWV station also monitors the arrival time of this same pulse with respect to the clock.

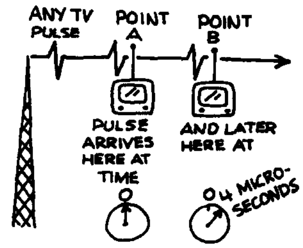
The TV stations in this area are near Denver, which is closer to Boulder than to Fort Collins. So we will see a particular "sync pulse" in Boulder before it is seen at WWV, because of the extra distance it must travel to reach WWV. If we assume that we have measured or calculated this extra path delay, we see that we are in a position now to check the clocks in Boulder and WWV against each other.

It could work like this: The person who made the measurement in Boulder could call the measurer in Fort Collins, and they could compare readings. If the two clocks are synchronized, then the Boulder time-of-arrival measurement subtracted from the Fort Collins time-of-arrival measurement should equal the extra path delay between Boulder and Fort Collins. If the measurement is either greater or smaller, then the two clocks are out of synchronization, and by a known amount that can be found simply by subtracting the known path delay from the measured difference.

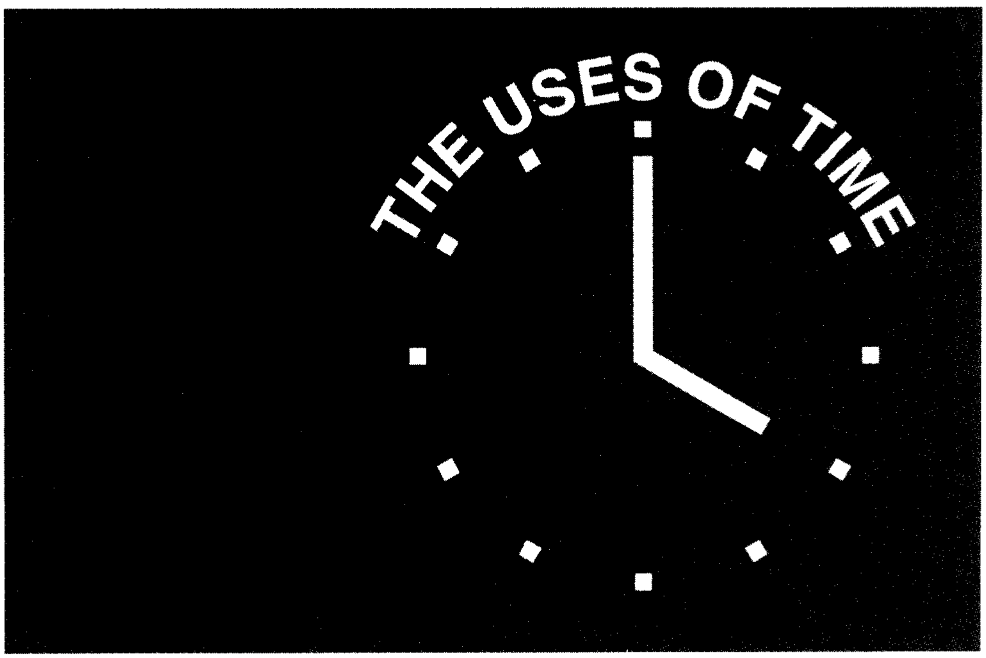
Any kind of radio signal with some identifiable feature that is visible at two or more places can be used in this way to synchronize clocks. As we've mentioned, though, a TV signal provides a remarkably sharp, clear signal, free from problems inherent in any system that bounces signals off the unpredictable ionosphere. But its coverage is limited to a radius of about 300 kilometers from the TV station.

In Chapter 13 we shall see how application of the transfer standard technique to satellite signals has become an important method for international time coordination and, in particular, for transferring time information from the world's standards laboratories to the BIPM.

Finding out what time it is can be very simple, or very complicated, depending on *where* you are when you need to know the time, and how accurate a time you need to know.




FROM PREVIOUS MEASUREMENTS, OPERATORS AT A AND B KNOW THAT IT TAKES A SIGNAL FOUR MICROSECONDS TO TRAVEL FROM POINT A TO POINT B. TO CHECK THE SYNCHRONIZATION OF THEIR CLOCKS, EACH RECORDS THE ARRIVAL TIME OF THE SAME PULSE AS IT ARRIVES FIRST AT CLOCK A AND THEN AT CLOCK B. IF THE CLOCKS ARE SYNCHRONIZED THEIR TWO ARRIVAL TIME READINGS WILL DIFFER BY 4 MICROSECONDS. IF NOT, THEY CAN USE THE DISCREPANCY TO DETERMINE THE AMOUNT OF SYNCHRONIZATION ERROR BETWEEN THE TWO CLOCKS.


THE USES OF TIME

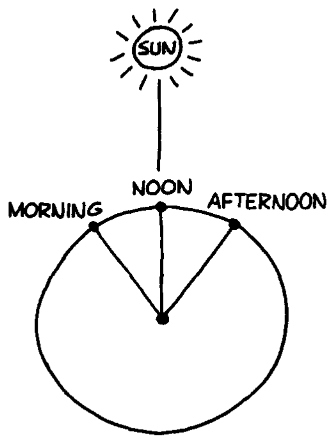
# IV.

# THE USES OF TIME

# Chapter 12

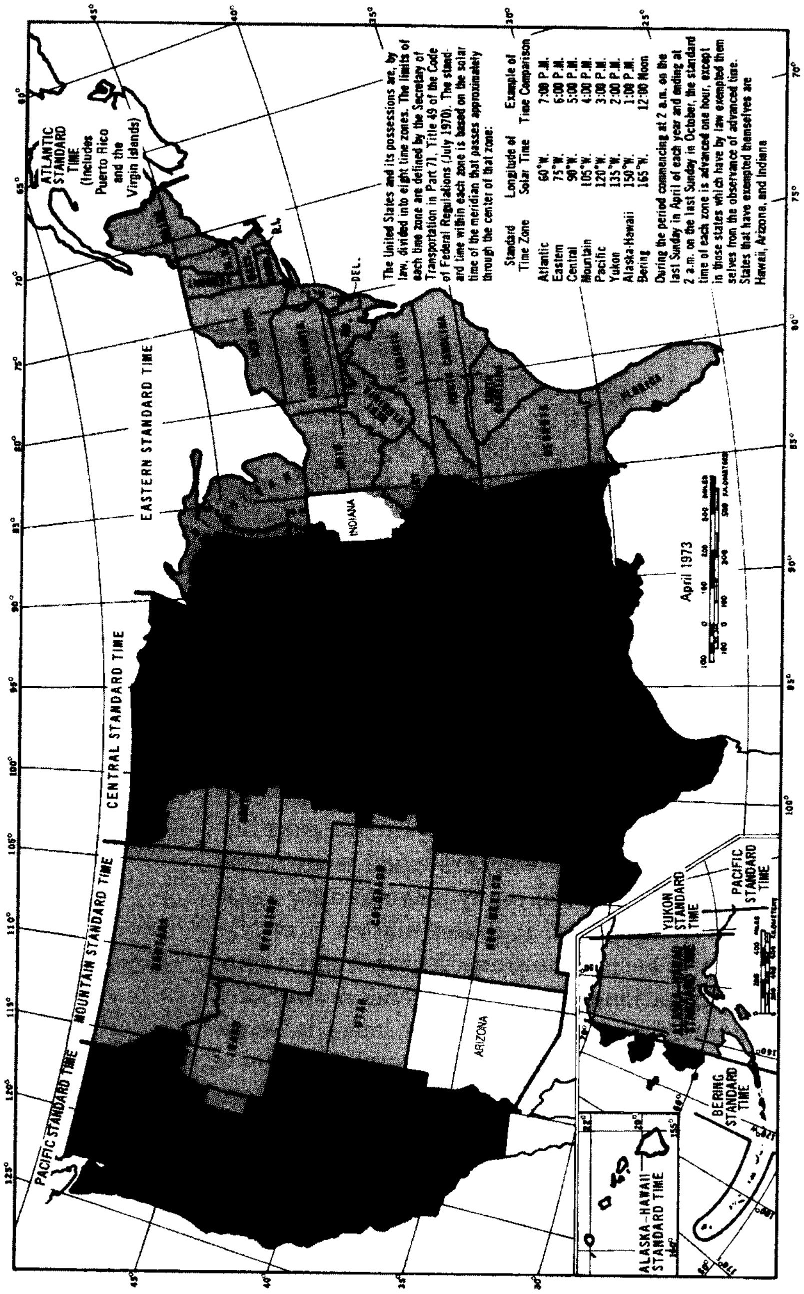
# STANDARD TIME

Our discussions of time have shown that "the time" when something happened or the "length" of time it lasted depends on the scale used for measurement. "Sun time" is different from "star time," and both differ from "atomic time." Sun time at one location is inevitably different from sun time only a few kilometers—or even a few *meters*—east or west. A factory whistle blown at 7:00 in the morning, Noon, 1:00, and 4:00 p.m. to tell workers when to start and stop their day's activities served many a community as its time standard for many years. It didn't matter that "the time" was different in each community. But in today's complex society, with its national and international networks of travel and communications systems, it's obvious that some sort of universal *standard* is essential. The establishment of *Standard Time* is much more recent than many persons realize.




## STANDARD TIME ZONES AND DAYLIGHT-SAVING TIME

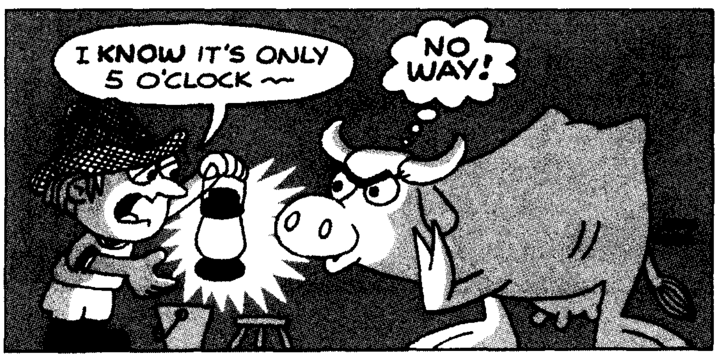
In the latter part of the 19th century, a traveler standing in a busy railroad station could set his pocket watch to any one of a number of clocks on the station wall; each clock indicated the "railroad time" for its own particular line. In some states there were literally dozens of different "official"




STANDARD TIME ZONES OF THE UNITED STATES OF AMERICA times—usually one for each major city—and on a cross-country railroad trip the traveler would have to change his watch 20 times or so to stay in step with the "railroad time." It was the railroads and their pressing need for accurate, uniform time, more than anything else, that led to the establishment of *time zones* and standard time.

One of the early advocates of uniform time was a Connecticut school teacher, Charles Ferdinand Dowd. Dowd lectured railroad officials—and anyone else who would listen—on the need for a standardized time system. Since the continental United States covers approximately 60 degrees of longitude, Dowd proposed that the nation be divided into four zones, each 15 degrees wide—the distance the sun travels in one hour. With the prodding of Dowd and others, the railroads adopted in 1883 a plan that provided for five time zones—four in the United States and one covering the *maritime* provinces of Canada.

The plan was placed in operation on November 18, 1883. There was a great deal of criticism. Some newspapers attacked the plan on the grounds that the railroads were "taking over the job of the Sun," and said that, in fact, the whole world would be "at the mercy of railroad time." Farmers and others predicted all sorts of dire results—from the production of less milk and fewer eggs to drastic changes in the climate and weather—if "natural" time was interfered with. Local governments resented having their own time taken over by some outside authority. So the idea of a standard time and time zones did not gain popularity rapidly.




STANDARD TIME ZONES OF THE WORLD

But toward the end of the second decade of the 20th century, the United States was deeply involved in a World War. On March 19, 1918, the United States Congress passed the Standard Time Act, which authorized the Interstate Commerce Commission to establish standard time zones within the United States; at the same time the Act established "daylight-saving time," to save fuel and to promote other economies in a country at war.

The United States, excluding Alaska and Hawaii, is divided into four times zones; the boundaries between zones zigzag back and forth in a generally north-south direction. Today, for the most part, the time-zone system is accepted with little thought, although some people near the boundaries still complain and even gain boundary changes so that their cities and towns are not "unnaturally" separated from neighboring geographical regions where they trade or do business.

The idea of daylight-saving time has roused the emotions of both supporters and critics—notably farmers, persons responsible for transportation and radio and television schedules, and those in the evening entertainment business—and continues to do so. Rules governing daylight-saving time have undergone considerable modification in recent years. Because of confusion caused by the fact that some cities or states chose to shift to daylight-saving time in summer and others did not—with even the dates for the shifts varying from one place to another—Congress ruled in the Uniform Time Act of 1966 that the entire nation should use daylight-saving time from 2:00 a.m. on the first Sunday in April until 2:00 a.m. on the last Sunday in October. Any *state* that did not want to conform could, by legislative action, stay on standard time. Hawaii did so in 1967, Arizona in 1968 (though Native American reservations in Arizona—which are under Federal jurisdiction—use daylight-saving time), and Indiana.

In a 1972 amendment to the Uniform Time Act, those states split by time zones may choose to keep standard time in one part of the state and daylight-saving time in the other, Indiana has taken advantage of this amendment so that only the western part of the state observes daylight-saving time. When fuel and energy shortages became acute in 1974, it was suggested that a shift to daylight-saving time throughout the nation the year around would help to conserve these resources. But when children in some northern areas had to start to school in the dark in winter months and the energy savings during these months proved to be insignificant, year-round daylight-saving time was abandoned, and the shifts were returned to the dates originally stated by the 1966 Uniform Time Act. In the long run, the important thing is that the changes be uniform and that they apply throughout the nation, as nearly as possible.

The whole world is divided into 24 standard time zones, each approximately 15 degrees wide in longitude. The zero zone is centered on a line running north and south through Greenwich, England. The zones to the east of Greenwich have time later than Greenwich time, and the zones to the west have earlier time—one hour difference for each zone.

With this system it is possible for a traveler to gain or lose a day when crossing the International Date Line, which runs north and south through the middle of the Pacific Ocean, 180 degrees around the world from Greenwich. A traveler crossing the line from east to west automatically advances a day, whereas one traveling in the opposite direction loses a day.

Both daylight-saving time and the date line have caused a great deal of consternation. Bankers worry about lost interest, and lawsuits have been argued and settled—often to no one's satisfaction—on the basis of whether a lapsed insurance policy covered substantial loss by fire, since the policy was issued on standard time and the fire in question, had it occurred during a period of standard instead of daylight-saving time, would have been within the time still covered by the policy. The birth or death date affected by an individual's crossing the date line can have important bearing on anything from the child's qualifying for age requirements to enter kindergarten to the death benefits to which the family of the deceased are entitled. The subject continues to be a lively issue and probably will remain so.

TIME INTERVAL - LOCAL

SYNCHRONIZATION - REGIONAL

DATE - UNIVERSAL

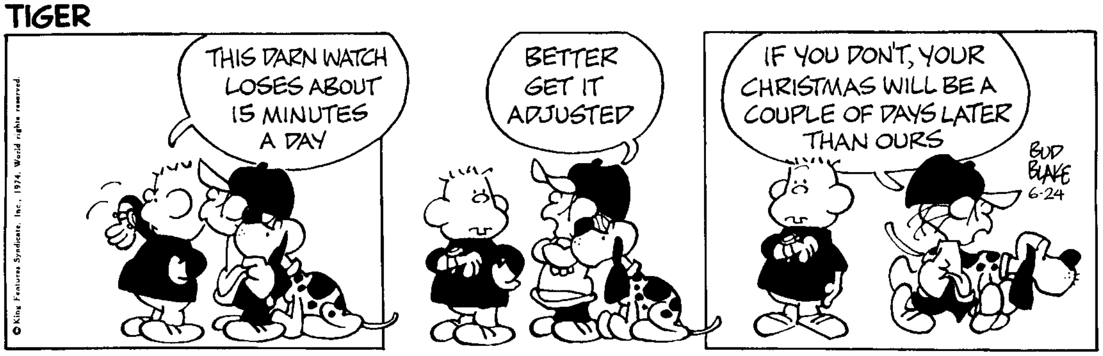
### TIME AS A STANDARD

The disarray in railroad travel caused by the lack of a standard time system in the late 19th century illustrates one of the primary benefits of standardization—standards promote better understanding and communication. If we agree on a standard of time or mass, then we all know what a "minute" or a kilogram" means.

In time and frequency, we have standardization at various levels. With the development of better clocks, people began to see the need for defining more carefully the basic units of time—since the minutes or seconds yielded by one clock were measurably different from those yielded by another. As early as 1820, the French defined the second as "1/86 400 of the mean solar day," establishing a standard time *interval* even though town clocks ticking at the same rate would show different local time—that is, a different *date* for each town.

In our first chapter, we discussed briefly the concepts of *time interval, synchronization*, and *date*. In a sense, these three concepts represent different levels of standardization. Time interval has a kind of "local" flavor. When someone is boiling a three-minute egg, the time in Tokyo is of little concern to her. What she needs to know is how long three minutes is at her location.

**TIGER**






Synchronization has a somewhat more cosmopolitan flavor. Typically, if we are interested in synchronization we care only that particular events start or stop at the same time, or that they stay in step. For example, if people on a bus tour are told to meet at the bus at 6:00 p.m., they need only synchronize their watches with the bus driver's watch to avoid missing the bus. It is of little consequence whether the bus driver's watch is "correct" or not.

Date has the most nearly universal flavor. It is determined according to well-defined rules discussed earlier, and it cannot be arbitrarily altered by people on bus tours; they do it only at their own peril, for they may well be late for dinner.

There has been a trend in recent years to develop standards in such a way that, if certain procedures are followed, the basic units can be determined. For example, the definition of the second, today, is based upon counting a precise number of oscillations of the cesium atom. This means that if you have the means and materials necessary, and are clever enough to build a device to count vibrations of the cesium atoms, you can determine the second. You don't have to travel to France.

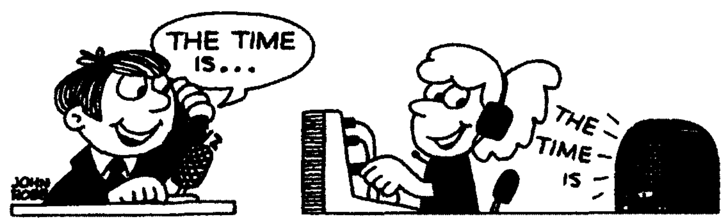
Concepts such as date, on the other hand—built from the basic units—have an arbitrary starting point, such as the birth of Christ, which cannot be determined by any physical device.

In Chapter 22 we shall return to these issues.

### IS A SECOND REALLY A SECOND?

In our development of the history of timekeeping, we saw that the spinning Earth makes a very good timepiece; even today, except for the most precise needs, it is more than adequate. Nevertheless, with the development of atomic clocks we have turned away from the Earth definition of the second to the atomic definition. But how do we know that the atomic second is uniform?

One thing we might do to find out is to build several atomic clocks, and check to see if the seconds they generate "side by side" are of equal length. If they are, then we will be pretty certain that we can build clocks that produce



uniform intervals of time at the "same" time. We have already discussed how this approach is used at the BIPM and other standards laboratories.

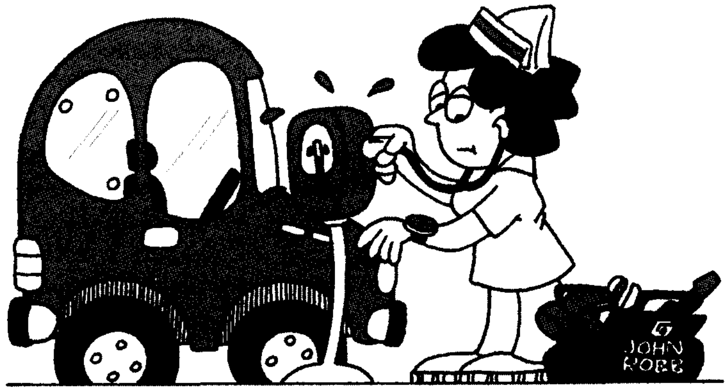
But then how can we be certain that the atomic second itself isn't getting longer or shorter with time? Actually there is no way to tell, if we are simply comparing one atomic clock with another. We must compare the atomic second with some other *kind* of second. But then if we measure a difference, which second is changing length and which one is not? There would seem to be no way out of this maze. We must take another approach.

Instead of trying to prove that a particular kind of clock produces uniform time, the best we can do is agree to take some device—be it the spinning Earth, a pendulum, or an atomic clock—and simply say that the output of that device helps us define time. In this sense, we see that time is really the result of some set of operations that we agree to perform in the same way. This set of operations produces the standard of time; other sets of operations will produce different time scales.

But, we may ask, what if our time standard really does speed up at certain times and slow down at others? The answer is that it really doesn't make any difference, because all clocks built on the same set of operations will speed up and slow down together, so "we will all meet for lunch at the same time"—it's a matter of definition.

## WHO CARES ABOUT THE TIME?

Every day hundreds of thousands of people drop nickels, dimes, and quarters into parking meters, coin-operated washers, dryers and dry-cleaning machines, and "fun" machines that give their children a ride in a miniature airplane or on a mechanical horse. Homemakers trust their cakes and roasts, their clothing, and their fine china to timers on ovens, laundry equipment, and dishwashers. Businesses pay thousands of dollars for the use of a computer's time or for minutes—sometimes fractions of minutes—of a communication system's time. We all pay telephone bills based on the number of minutes and parts of minutes we spend talking to Aunt Martha halfway across the nation.



The pumps at the gas station and the scales at the supermarket bear a seal that certifies recent inspection by a standards authority, and assurance that the device is within the accuracy requirements set by law. But who cares about the devices that measure time? What's to prevent a company from manufacturing equipment that runs for 9 minutes and 10 seconds, for instance, instead of the 10 minutes stated on a label? Are there any regulations at all for such things?

Yes indeed. In the United States, NIST has the responsibility for developing and operating standards of time interval (frequency). It is also given the responsibility of providing the "means and methods for making measurements consistent with those standards." As a consequence of these directives, NIST maintains, develops, and operates a primary frequency standard based on the cesium atom, and it also broadcasts standard frequencies based on this primary standard as we have already discussed.

The state and local offices of weights and measures deal with matters of time interval and date, generally by reference to NIST publications that deal with such devices as parking meters, parking garage clocks, "time in–time out" clocks, and similar timing devices. The lowest uncertainties involved in these devices are about ±2 minutes on the date, and about 0.1 percent on time interval. Typically, the penalty for violating this code is a fine, a jail sentence, or both, for the first offense.

State standards laboratories seek help from NIST for such duties as calibrating radar "speed guns" used by traffic officers and other devices requiring precise timing. In addition to NIST, more than 250 commercial, governmental, and educational institutions in the United States maintain standards laboratories; 65 percent of these do frequency and/or time calibrations. So the facilities for monitoring the timing devices that affect the lives of all of us are readily available throughout the land.

In the United States, the United States Naval Observatory collects astronomical data essential for safe navigation at sea, in the air, and in space. The USNO maintains an atomic time scale based on a large number of commercial cesium-beam frequency standards. And like NIST, it disseminates its standard, or time scale, by providing time information to several U.S. Navy broadcast stations. The Department of Defense (DOD) has given the USNO the responsibility for the time and frequency needs of the DOD. As a practical matter, however, both the USNO and NIST have a long history of working cooperatively together to meet the needs of a myriad of users.

The responsibility for enforcing the daylight-saving time changes and keeping track of the standard time zones in this country is held by the U.S. Department of Transportation (DOT). And yet another organization—the Federal Communications Commission (FCC)—is involved in time and frequency control through its regulation of radio and television broadcasts. Its *Code of Federal Regulations—Radio Broadcast Services* describes the frequency allocations and the frequency tolerances to which various broadcasters must conform. These include AM stations, commercial and noncommercial FM stations, TV stations, and international broadcasts. The NIST broadcast stations are references which the broadcaster may use to maintain assigned frequency, but the FCC is the enforcing agency.

The development, establishment, maintenance, and dissemination of information generated by time and frequency standards are vitally important services that most of us take for granted and rarely question or think about at all, and they require constant monitoring, testing, comparisons, and adjustment. Those responsible for maintaining these delicate and sensitive standards are constantly seeking better ways to make them more widely available, at less cost to more users. Each year, the demand for better, more reliable, and easier-to-use standards grows; each year scientists come up with at least some new concepts and answers to their problems.

# Chapter 13

# TIME, THE GREAT ORGANIZER

Time is so basic a part of our daily lives that we take it for granted and overlook the vital part it plays in industry, scientific research, and many other activities of our present-day world. Almost any activity today that requires precision control and organization rests on time and frequency technology. Its role in these activities is essentially the same as in our own mundane affairs—providing a convenient way to bring order and organization into what would otherwise be a chaotic world.

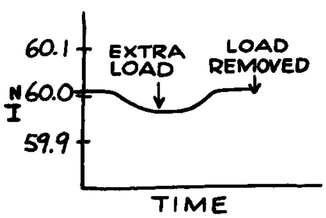
The difference is mainly one of degree; in our everyday lives we rarely need time information finer or more accurate than a minute or two, but modern electronic systems and machines often require accuracies of one microsecond and better. In this chapter, we shall see how the application of precise time and frequency technology helps to solve problems of control and distribution in two key areas of modern industrial society—*energy* and *transportation*—plus a few other usual and unusual uses of time and frequency information. In the next chapter, we shall continue our discussion with an examination of the crucial role time and frequency technology plays in the evolving world of digital communication.

ENERGY
COMMUNICATION
TRANSPORTATION

## ELECTRIC POWER

Whether it is generated by nuclear reactors, fossil-fuel-burning plants, or a hydroelectric system, electric power is delivered in the United States and Canada at 60 hertz, and at 50 hertz in a good part of the rest of the world. For most of us it is in this aspect of electric power that time and frequency plays its most familiar role. The kitchen wall clock is not only powered by electricity, but its "ticking" rate is tied to the "line" frequency maintained by the power company.

The power companies carefully regulate line frequency, so electric clocks keep very good time. The motors that drive tape and compact disk players operate at rates controlled by the line frequency, so that listeners hear the true sound, and electric toothbrushes and shavers, vacuum cleaners, refrigerators, washing and drying machines operate efficiently.




Nevertheless, slight variations in frequency cannot be overcome. If the line load unexpectedly increases in a particular location—as when many people turn on their television sets at the same time to see a local news flash—power generators in the area will slow down until input energy to the system is increased or until the load is removed. For example, the line frequency may drop to 59.9 hertz for a time and then return to 60.0 hertz when the extra load is removed.

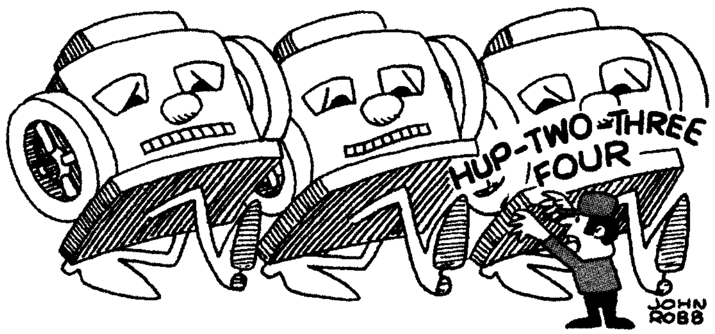
During the period when the line frequency is low, electric clocks will accumulate a time error that remains even though 60 hertz is restored at some later point. To remove this time error, the power companies increase line frequency above 60 hertz until the time error is removed—at which time they drop back to 60 hertz. Generally the time error never exceeds two seconds; in the United States this error is determined with respect to special time and frequency broadcasts of the National Institute of Standards and Technology.

But frequency plays a greater role in electric power systems than merely providing a convenient time base for electric clocks. Frequency is a basic quantity that can be measured easily at every point of the system, and thus provides a way to "take the temperature" of the system.

We have seen that frequency excursions are indicative of load variations in power consumption. These variations are used to generate signals that control the supply of energy to the generators, usually in the form of steam—or water at hydroelectric plants. To provide more reliable service, many power companies have formed regional "pools," so that if power demands in a particular region exceed local capability, neighboring companies can fill in with their excess capacity.

Frequency plays an important part in these interconnected systems from several standpoints. First, all electric power in a connected region must be at the same frequency. If an "idle" generator is started up to provide additional power, it must be running in step with the rest of the system before being connected into it. If it is running too slowly, current will flow into its windings from the rest of the system in an attempt to bring it up to speed; if it is running too fast, excessive current will flow out of its windings in an attempt to slow it down. In either case, these currents may damage the machine.

Besides running at the same electrical frequency as the rest of the system, the new generator must also be in step or in *phase* with the rest of the system. Otherwise, damaging currents may again flow to try to bring the machine into phase.




We can understand the distinction between phase and frequency by considering a column of soldiers marching to a drummer's beat. If the soldiers step in time to the beat, they will all be walking at the same rate, or *frequency*, but they will not be in *phase* unless all left feet move forward together. Power companies have developed devices that allow them to make certain that a new generator is connected to a system only after it is running with the correct frequency and phase.

In power pools, frequency helps to monitor and control the distribution and generation of power. Members of power pools have developed complex formulas based on customer demand and the efficiency of various generating components in the system, for delivering and receiving electric power from one another. But there are unexpected demands and disruptions in the system—a fallen line, for example—that produce alterations of these schedules. To meet scheduled as well as unscheduled demands, electric power operators use a control system that is responsive both to electric energy flow between neighboring members of a pool and to variations in system frequency. The net result of this approach is that variations in both frequency and scheduled deliveries of power are minimized.

Time and frequency technology is also a helpful tool for fault location—such as a power pole toppled in a high wind. The system works somewhat like the radio navigation systems described later in this chapter. At the point in the distribution system where the fault occurs, a surge of electric current will flow through the intact lines and be recorded at several monitoring stations. By comparing the relative arrival time of a particular surge as recorded by the monitors, operators can determine the location of the fault.

The East Coast blackout a number of years ago brought to attention the vital role that coordination and control—or the lack of them—play in the delivery of reliable electric power. Today many power companies are developing better and more reliable control systems. One of the requirements of such improved systems will be to gather more detailed information about the system—information such as power flow, voltage, frequency, phase, and so forth—which will be fed into a computer for analysis. Much of this information will have to be carefully gathered as a function of *time*, so that the evolution of the power distribution system can be carefully monitored. Some members of the industry suggest that time to a microsecond or better will be required in future control systems.

## TRANSPORTATION

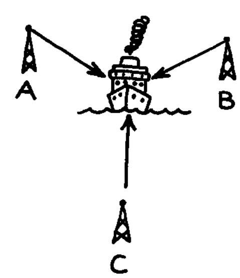
In Chapter 2 of this book we discussed the important part time plays in navigation by the stars. But time is also an important ingredient in modern electronic navigation systems, in which the stars have been replaced by radio signals.

Just as a road map is a practical necessity to a cross-country automobile trip, so airplanes and ships need their "road maps" too. But in the skies and on the oceans there are very few recognizable "signposts" to which the traveler can refer. So some artificial signpost system has to be provided. In the early days of sailing vessels, fog horns, buoys, and other mechanical guides were used. Rotating beacon lights have long been used to guide both air and sea travel at night. But their ranges are comparatively short, particularly in cloudy or foggy weather.

Radio signals seem to be the answer. Radio waves can be detected almost at once at long distance, and they are little affected by inclement weather. The need for long-range, high-accuracy radio navigation systems became critical during World War II. Celestial navigation and light beacons were virtually useless for aircraft and ships, especially in the North Atlantic during wintertime fog and foul weather. But time and frequency technology, along with radio signals, helped to provide some answers by constructing reliable artificial sign posts for air, sea, and land travelers.

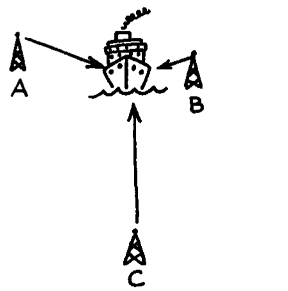
### Navigation by Radio Beacons

To understand the operation of modern radio navigation systems, let's begin by considering a somewhat artificial situation. Let's suppose we are on a ship located at exactly the same distance from three different radio stations, all of which are at this moment broadcasting a noontime signal. Because radio waves do not travel at infinite speed, the captain of our ship will receive the three noon signals a little past noon, but all at the same time. This simultaneous arrival of the time signals tells him that his ship is the same distance from each of the three radio stations.




SIGNALS LEAVE ALL 3 TRANSMITTERS AT 12 NOON AND ARRIVE SIMULTANEOUSLY SHORTLY PAST NOON AT SHIP

If the locations of the radio stations are indicated on the captain's nautical map, he can quickly determine his position. If he were a little closer to one of the stations than he



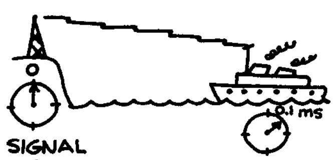

SIGNAL B ARRIVES FIRST.
SIGNAL A ARRIVES SECOND.
SIGNAL C ARRIVES LAST.

is to the other two, then the closer station's signal would arrive first, and the other two at later times, depending upon his distance from them. By measuring this difference in arrival time, the captain or his navigator could translate the information into the ship's position.

There are a number of navigation systems that work in just this way. One such system is Loran-C, which broadcasts signals at 100 kilohertz. Another is the Omega navigation system, which broadcasts at about 10 kilohertz. Operating navigation systems at different radio frequencies provides certain advantages. For example, Loran-C can be used for very precise navigation at distances out to about 1600 kilometers from the transmitters, whereas Omega signals can easily cover the whole surface of the Earth, but the accuracy of position determination is reduced.

What has time to do with these systems? It is crucially important that the radio navigation stations all have clocks that show the same time to a very high accuracy. If they don't, the broadcast signals will not occur at exactly the right instant, and this will cause the ship's navigator to think that he is at one position when he is really at another. Radio waves travel about 300 meters in one microsecond, so if the navigation stations' clocks were off by as little as one-tenth of one microsecond, the ship's navigator could make an error of many meters in plotting the position of his ship.

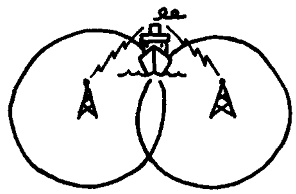
Clocks and radio signals can be combined in another way to indicate distance and position. Let's suppose that the captain has on board his ship a clock that is synchronized with a clock at his home port. The home-port clock controls a radio transmission of time signals. The ship's captain will not receive the noon "tick" exactly at noon because of the finite velocity of the radio signal, as we mentioned earlier. Because the captain has a clock synchronized with the home-port clock, he can accurately measure the delay of the signal. If this delay is one-tenth of one microsecond, then he knows that his distance or *range* from the home port is about 30 meters.




SIGNAL LEAVES SHORE AT THIS TIME AND...

...ARRIVES AT SHIP 0.1 ms LATER

With two such signals the captain could know that he was at one of two possible points determined by the intersection of two circles, as shown in the sketch. Usually he has a coarse estimate of his position, so he will know which point of intersection is the correct one.

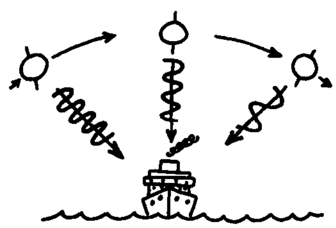


## Navigation by Satellite

We have described a navigation scheme that requires broadcasting signals from three different Earth stations. There is no reason, however, that these stations need be on Earth; the broadcasts could be from three satellites.

Satellites offer various possibilities for navigation systems. An interesting early example is the *Transit* satellite navigation system, in which the navigator can determine position by recording a radio signal from just a single satellite as it passes overhead.

In a sense, receiving a signal from one satellite as it passes by is like measuring signals from many different satellites strung out across the sky, looking at one at a time. The operation of the system depends upon a physical phenomenon called the *Doppler effect*, which we have discussed in other connections in this book. We are most familiar with this effect, as we have said, when we hear the whistle of a passing locomotive. As the locomotive approaches, the tone of the whistle is high in pitch, or is "sharp"; then as it passes and moves away, the pitch lowers, or is "flat."



SIGNAL FREQUENCY GOES FROM HIGH TO LOW AS SATELLITE PASSES OVER

In a similar way, a radio signal from a passing satellite appears high as the satellite approaches, and then lower as the satellite disappears over the horizon. A listener standing at some location other than ours would observe the same phenomenon, but the curve of rise and fall would be different for her. In fact, all observers standing at different locations would record slightly different curves. The position of the satellite is tracked very accurately, so that we could, if time allowed, calculate a catalog of Doppler signals for every point on Earth. The navigator, to find her location, would record the rising and falling Doppler signal as the satellite passed overhead, and then find in the catalog the "Doppler curve" that matched her own—and thus could identify her location.

Of course, this is not a very practical approach because of the enormous number of calculations that would be required for the entire Earth. In practice, navigators record the Doppler curve as the satellite passes over, and the position of the satellite as broadcast by the satellite itself. Generally, navigators have at least a vague notion as to their location. They feed estimates of their position, along with the satellite location, into a computer, which calculates the Doppler curve navigators should be seeing if they are where they think they are.

This calculated curve is compared, by the computer, with the recorded curve. If they are the same, the navigators have correctly guessed their position. If they are not, the computer makes a new "educated guess" as to their location and repeats the process until there is a good fit between the calculated and the recorded curves. This "best fit" curve is then the curve that yields the best guess as to the navigator's position.

Scientists in different organizations are working constantly to develop simpler, less expensive methods for keeping track of ships at sea, planes in the air, and even trucks and buses on the highways, through applying time and frequency technology.

## THE GLOBAL POSITIONING SYSTEM

The U.S. Navy developed the Transit system in the 1960's, shortly after the Soviet Union launched *Sputnik* in 1957. Although a fundamental breakthrough in navigation technology, it had some shortcomings. The electronic equipment needed to process the signals was expensive and often required recording at least two satellite Doppler curves before an adequate position could be obtained. This could take an hour and a half or more.

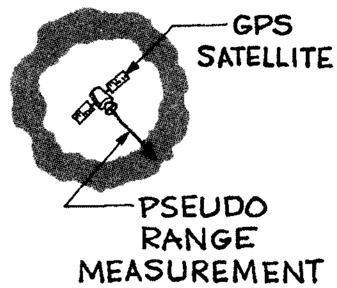
Before Transit's launch, a number of people had thought that a better solution would be to build a kind of "Loran-C" in the sky.

One immediate benefit would be that positions could be obtained almost instantaneously. This was important—especially for fast moving aircraft. Thus it was that the U.S. Air Force started planning a system using the ranging concept discussed a few paragraphs back. The system is now operational and is called the "Global Positioning System," or more usually "GPS."

The problems were formidable. First the ranging system requires that both the user and the satellite signals be synchronized or, what amounts to the same thing, be offset by a known amount. Furthermore, to be useful to aircraft and space vehicles, position determinations needed to be made in three-dimensional space—you could not assume that the we are on the Earth's surface.

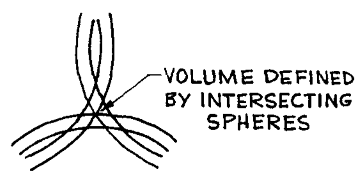
The solution chosen to solve these problems requires that we observe at least four satellites followed by a number of computations not feasible without computers. It works like this.

First, the user makes range measurements to four satellites. These measurements will likely be in error, because it cannot be assumed that your receiver clock is synchronized to the clocks on the satellites. The range measurements at this stage are called "pseudo-range" measurements.



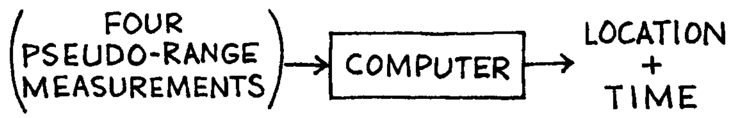

You will recall from the ranging system described earlier that a single range measurement placed the observer on the circumference of a circle whose center coincided with the transmitter location. In space, however, a single range measurement places the observer on the surface of a sphere of uncertain radius, as the figure shows, because the measurement is a pseudo-range measurement.

Further pseudo-range measurements to three more satellites place the observer on the uncertain surfaces of three more intersecting spheres. If the range measurements had been exact, the observer would know that she was located where all four spheres intersect just as, in the earlier discussion, the observer knew that she was located at the intersection of two circles.




Nevertheless, even though the observer doesn't know her exact location, she does know, as the figure shows, that she is in the volume of space defined by the blurred intersecting surfaces. The dimension of the volume depends on how much the observer and satellite clocks are out of synchronization.

The next steps are where the computer comes in. The computer takes the approximate location of the observer, established by the four pseudo-range measurements, and computes the volume of the region containing the observer. Next, it adjusts the observer's location and recomputes the volume of the region containing the observer. If the volume




has decreased, the computer knows it is moving in the right direction. If the volume has increased, the computer knows it is moving in the wrong direction. By successively making many calculations of this kind, the computer zeroes in on the correct location.

We can look at this process in a slightly different way. The fact that the computer eventually finds a location where all four spheres intersect is the same as the computers knowing the offset between the observer and the satellite clocks. In other words, we could say that what the computer does in its search for the observer's location is to continually adjust the clock offset until the spheres coincide. Thus the four pseudo-range measurements not only determine the user's location but also the offset between the user and satellite clocks. Here, then, is another way to coordinate clocks.

The ranging signals are another aspect of the GPS system that depends on computers. Making the range measurements with the required precision necessitates a computer-generated signal. The signal is reminiscent of the signals generated by radio stars which have been used for several decades by astronomers and geodesists to measure the shapes of radio stars and to study continental drift—a subject we shall return to in Chapter 17.

Radio star signals are noise-like emissions that sound much like static on an ordinary radio receiver. As astronomers realized, these noise-like signals are ideal for precisely measuring the difference in arrival time of the same radio star signal at two different antenna locations—a requirement for the continental drift and radio-star-shape determinations.

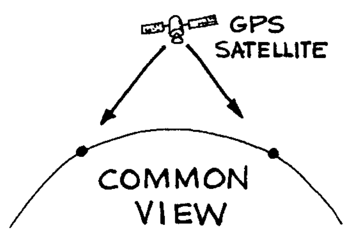
## SIGNALS BASED ON RANDOM NUMBERS

What the GPS designers wanted was also a noise-like ranging signal which, they recognized, could be generated by a computer. These computer-generated noise-like signals have some advantages beyond precise range measurements. First they allow inexpensive GPS receivers to be built. The GPS signals are based on sequences of random numbers which are unique from one satellite to the next. The offshoot of this is that all GPS satellites can transmit at the same radio frequency without interfering with each other. This allows inexpensive, single-frequency receivers to be built.

The random sequences also helps solve another problem. The ranging signals must pass through the Earth's ionosphere on their way to the observer. The ionosphere introduces a path delay, in addition to the normal path delay, whose value depends on the exact frequency of the signal, thus contaminating the range measurements.

To overcome this ionospheric component of path delay, each GPS receiver transmits signals on two different radio frequencies but each signal has the same random signal structure. The random signals on the two frequencies are in step as they leave the satellite, but gradually separate in time as they pass through the ionosphere. The GPS receiver measures this time separation and uses this information to calculate the delay introduced by the ionosphere, thereby correcting for the ionospheric delay.

To make sure that users can determine their location anytime, anywhere on or near the surface of the Earth, 21 satellites and 3 spares orbit the Earth at altitudes of about 20 000 kilometers.




As so often in the past, a navigation system has once again proved a boon to timekeepers. As we have seen, time can be obtained directly from GPS measurements. But another time coordination scheme based on GPS measurements has proved more effective than direct time recovery. The scheme, called "common view," is simply a satellite version of the transfer standard technique we discussed in Chapter 11 with reference to TV signals.

Suppose observers at two different locations wish to compare their clocks. They select a satellite that they can both "see" at the same—the satellite is in common view. Both observers measure the arrival time of the signal, from the selected satellite, relative to their local clocks. Knowing their own locations and that of the satellite, which each satellite continually broadcasts, they compute the signal time delay to each of the respective locations from the satellite. With this information they know what the respective arrival times should be. Just as with the TV signals, the difference between the expected arrival-time separation and the measured-time separation equals the offset between the two clocks.

There are a couple of interesting points here. First, the common view measurement is completely independent of the clock time on the satellite. Second, when the two observers make their expected delay calculations, they depend on the satellite to broadcast its own position correctly. Although the GPS satellites are tracked very carefully, there are still errors, however small, in their broadcast locations. Some of this position error drops out with common view measurements, so satellite location error does not translate fully into clock comparison error. What all this adds up to is that widely separated clocks can be compared within a few nanoseconds so that carrying atomic clocks is largely a thing of the past.

At the present time, GPS common view measurements are now the backbone of international time comparisons as well as the primary method for delivering clock information from the various standards laboratories throughout the world to the BIPM.

## SOME COMMON AND SOME FAR-OUT USES OF TIME AND FREQUENCY TECHNOLOGY

The makers of thermometers, bathroom scales, and tape measures have a fair idea of how many people use their product, who the users are, and what the users do with their measuring devices. But the suppliers of time and frequency information are like the poet who "shot an arrow into the air." There is no good way of knowing where the "arrows" of their radio broadcasts fall, who picks them up, or whether the "finders" number in the thousands or the tens of thousands. The signal is available everywhere at all times, and remains the same whether ten receivers pick it up or ten thousand. And except for inquiries, complaints, and suggestions for improvements—mostly from users already well known to the broadcasters—those who go to great effort and expense to make their time-measuring meter sticks available to the public hear from only a small percentage of those who pick up their wandering "arrows."

They would like to know, however, so that they might make their product more useful and more readily available to more people. So occasionally they make special efforts to survey their "public," and invite users to write to them.

Several such invitations from NIST have brought many thousands of responses from the usual power company and communication system users; the scientific laboratories, universities, and observatories; the aviation and aerospace industries; manufacturers and repairers of radio and television equipment and electronics instruments; the watch and clock manufacturers; the military bases. There were scores of responses from private aircraft and yacht and pleasure-boat owners. Many ham radio operators responded, as did a surprising number of persons who classified themselves simply as hobbyists—astronomy or electronics buffs.

Among the specific uses mentioned by these respondents were such things as "Moon-radar-bounce work and satellite tracking," "Earth tide measurements," "maintenance of telescope controls and instrumentation," "timing digital clocks," "setting time of day on automatic telephone-toll-ticketing systems," "synchronizing timecode generators," and "calibrating and synchronizing outdoor time signals in metropolitan areas."

Data processing and correlation, calibration of secondary time and frequency standards, and seismic exploration and data transmission were all very familiar uses. And as more electronic instruments are being developed for use in hospitals and by the medical profession, it was not surprising to have a growing number of users list "biomedical electronics," "instrument time-base calibration for medical monitoring and analyzer equipment," and similar specific medical applications.

Greater use of electronic systems in automobiles has brought automobile mechanics into the ranks of time and frequency technology users. And the proliferation of specialized cameras that take pictures under water, inside organs of the body, or from a thousand kilometers out in space—pictures from microscopic to macroscopic proportions—as well as sophisticated sound recording systems, has greatly increased the need for time and frequency technology among photographic and audiovisual equipment manufacturers and repairers. Oceanography is another rapidly developing science that is finding uses for time and frequency technology.

Time information—both date and time interval—is vitally important to both manufacturers and repairers of clocks and watches. With the growing availability and lower prices of fine watches capable of keeping time to a few seconds in a month, more and more jewelers and watch repairers need more precise time than they can get from the electric clock driven by the power company line. A jeweler on the east coast reported that he telephones the NIST time and frequency information service in Colorado daily to check the watches he is adjusting. The same information is available via short-wave radio from NIST stations WWV and WWVH, but getting the information by telephone may be simpler and less time consuming, and the signal comes through with little distortion or noise.


Some musicians and organ and musical instrument makers reported use of the standard 440 hertz audio tone—the "A" above "middle C" in the musical scale—to check their own secondary standards or to tune their instruments.

Several scientists working on thunderstorm and hailstorm research reported their need for time and frequency information. One specified "coordination of data recordings with time-lapse photography of clouds." Another explained that he used the information to tell him where lightning strikes a power line.

Other responses came from quartz crystal manufacturers, operators and repairers of two-way radio systems, and designers of consumer products—everything from microwave ovens and home entertainment systems to the timers on ranges, cookers, washers, and other home appliances. Even toy manufacturers stated their needs for precise time and frequency technology.

Then there were a few what might be called less serious uses—except to the users, who seemed to be dead serious. An astrologer declared he needed precise time information to render "dependable" charts. Pigeon racers reported using WWV broadcast as a reference point for releasing birds at widely separated locations at the same instant. And persons interested in sports-car rallies and precise timing of various kinds of races and other sporting events stated their needs.

Miniaturization and printed circuits have brought a great many pieces of inexpensive and useful electronic equipment within easy reach of the average consumer. Electric guitars, radio-controlled garage-door closers, "white-sound" generators to shut out disturbing noises and soothe you to sleep—who knows what designers and manufacturers will think of next? With these and many other consumer products has come a growing need—even for the person on the street—for better time and frequency technology. This need can only continue to expand, and scientists keep busy working constantly to meet demands.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Chapter 14

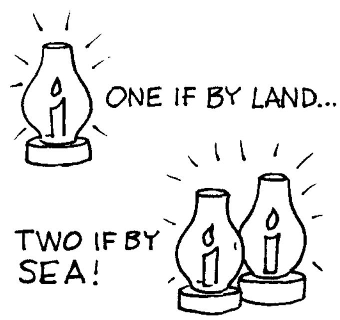
# TICKS AND BITS

*"Talk is cheap."*
-Sam Spade

Dashiell Hammett's acerbic detective didn't have electronic communication in mind when he made that remark, but it still fits. Talk has never been cheaper. The cost of sending the basic packet of information, the bit, is the lowest it's ever been, and there is every indication the trend will extend into the indefinite future. Time and frequency technology has played no small role in that fact. But we are getting ahead of our story.

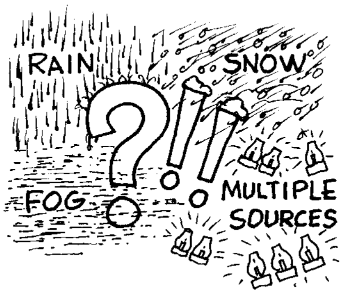
## DIVIDE AND CONQUER

It is Revolutionary America and Paul Revere awaits a lantern signal from a fellow patriot in the Belfry of the Old North Church in Boston. The scheme is simple: if the British land by sea, two lanterns are to be hung in the belfry, if by land, one. As the message flashed to Revere, he sped off to Lexington to tell the undermanned American troops where the British would attack.




This rudimentary signaling strategy is the basis of modern communication systems. We can extend Revere's scheme to fit today's situation: one flash means land, two flashes mean sea, and three flashes mean by air. And, for good measure, we could let four flashes mean the invasion was proceeding on all three fronts.

However, an indefinite expansion of this scheme leads to problems: Was one flash "by sea" or "by air"? And suppose it is foggy—what then? Well, then there needs to be a backup plan—one ring of the belfry bell means by sea and two means by land. But then wouldn't English sympathizers hear the bell?




The problems facing these early, Revolutionary communicators are no different from those modern communicators face: How shall we make certain that the signal gets through? How can we code the message so the enemy won't know its meaning? What is the best way to make sure the signals don't get mixed up? And suppose several people want to communicate at the same time, what then? As we shall see, the solution to all these problems is highly indebted to time and frequency technology.

As we said, Revere's scheme, one if by land, two if by sea, contains the essence of modern communication systems. The basic unit of information, the bit, can deliver one of two messages—it is either "this" or "that"—either by land or by sea. It is common to represent these two possibilities with the numbers "1" and "0" which in turn are often interpreted as "yes" or "no." Of course we are at liberty to reverse the meanings—0 means "yes" a 1 means "no." The important thing is to remember whichever alternative we chose.


A BIT DELIVERS ONE OF TWO MESSAGES

With this simple 0 or 1 system we can create complex messages, encrypt them so only those who "need to know" can read them, and develop tactics to overcome the primary enemy of unobstructed communication, noise. Noise can be nature's creation—static generated by lightening flashes—or man-made radio signals transmitted by the enemy to jam the radio signals of the good guys.

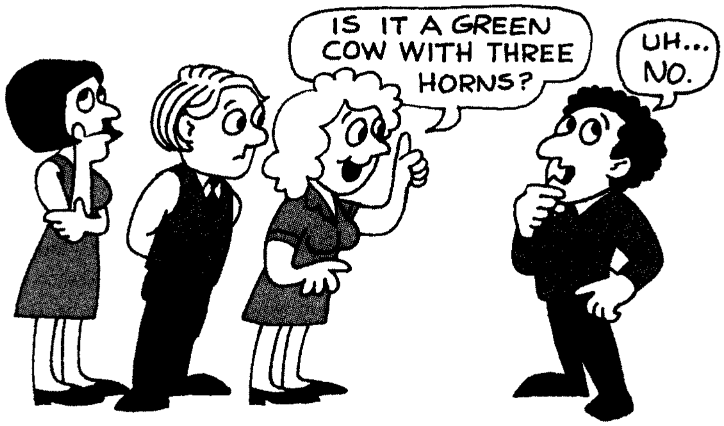
Let's see how we can create complex or simple messages from bits. Most written languages require an alphabet and some punctuation marks. In English we have:

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
and several punctuation marks. For our purposes, we'll say there are six: the period (.), the comma (,), the question mark

(?), the semicolon (;), the colon (:), and the exclamation point (!). These 32 symbols constitute our written communication system. To convert our symbols to bits we'll play a game similar to "Twenty Questions." In that game, you'll recall, one player thinks of an object, usually obscure, and it is up to the other players to identify the object in 20 questions or less. The players ask questions that can be answered "yes" or "no." The player who selected the object must answer each question truthfully.

CREATING COMPLEX MESSAGES WITH MANY BITS

"YES NO YES YES NO YES NO NO YES NO NO NO YES"...




Suppose the player selects as his "object" the letter "H." (We'll assume the players already know the object is one of the 32 symbols listed above.) Since the object might, with equal probability, be any one of 32 symbols, a good strategy is to discover the number with a divide-and-conquer approach.

Here, the first player asks, "Is the symbol among the first 16? Answer: "Yes." (H occupies the eighth position in the list.) Second player: "Is the symbol among the first 8 symbols? Answer: "Yes." Third player: "From the first two questions, I know the symbol occupies a position 1 through 8. Is it in the first half of these positions? Answer: "No." Fourth player: "Since the symbol must be somewhere in positions 5 through 8, is it in the last half of this set? Answer: "Yes." Fifth player: From what I've heard, I know the answer is either the letter "G" or "H." Is it "H." Answer: "Yes."

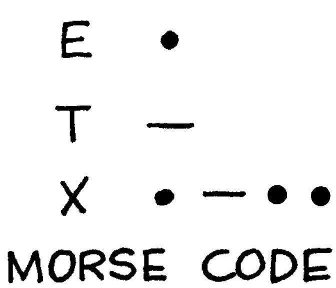
The answers, yes, yes, no, yes, and yes eliminate all the symbols but "H." Indeed any one of the 32 symbols is

"H" = 11011

uniquely identified by a string of five choices of yes and no. Remember earlier we said that "yes" and "no" are often represented by "1" and "0." With this in mind the letter "H" becomes "1 1 0 1 1." This, then, is the letter "H" in bits.

Obviously, by building up words from letters, we can represent any message we like with a sufficiently long string of 0's and 1's. As you might imagine, messages are often millions of bits and longer. This sounds like a bookkeeper's nightmare. How are we to keep track of all these bits?—make sure they stay in the proper order and arrive at the proper destination? You have probably already guessed, time and frequency technology is a big part of the answer.

## SENDING MESSAGES THE OLD FASHIONED WAY, ONE BIT AT A TIME

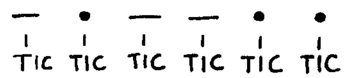



The early explorers of electrical and magnetic phenomena realized that messages could be sent by currents over wires, but the first practical system was put together by the American portrait painter, Samuel F.B. Morse in the early decades of the last century. Morse's idea was to code the letters of the alphabet as a series as dots and dashes. A visit to a local newspaper gave him the clue he needed to code his messages efficiently. Typesetters showed Morse that they needed more letters of one kind than another. From the typesetters trays, Morse discovered that the "e" compartment contained the most letters, "t" was next, with the "x" compartment containing the fewest letters. With this information, Morse decided that the letter "e" should be represented by a dot—the shortest and easiest signal to produce—and "t" by a dash, the next easiest, and "x" by dot-dash-dot-dot.

Dots and dashes were sent manually, one after the other, by depressing a knob on a telegraph key. The rate at which messages could be sent largely depended on the skill of the telegraph operators who both sent and received the messages. By 1860, most of the major cities in the United States were linked by telegraph wires.

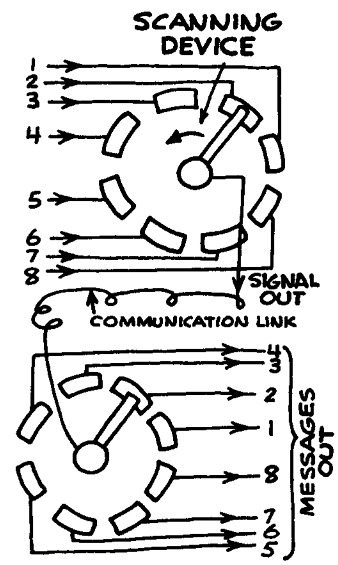
## AUTOMATED TELEGRAPHY

As good as telegraph operators were, it was clear that some mechanized telegraph system would be even better. A mechanized system offered a number of advantages. One advantage was that all transmissions could be sent at a standard rate that could be decoded by standardized receiving and decoding machine at the reception end. Here then is an early hint of the importance of clocks in communication stems—a clock is needed to "clock out" the dots and dashes at some fixed rate.




But clocks in telegraph systems suggested the possibility of new ways of communicating that were totally unfeasible with human telegraph operators. By 1914 a new device, called the "synchronous distributor," was in use over most of the telegraph trunk lines in the United States. With synchronous distributors it was possible to *multiplex* messages—to send several telegraph messages over the same line at the same time. More generally, we can think of multiplexing as allowing us to divide a communication channel into several channels.

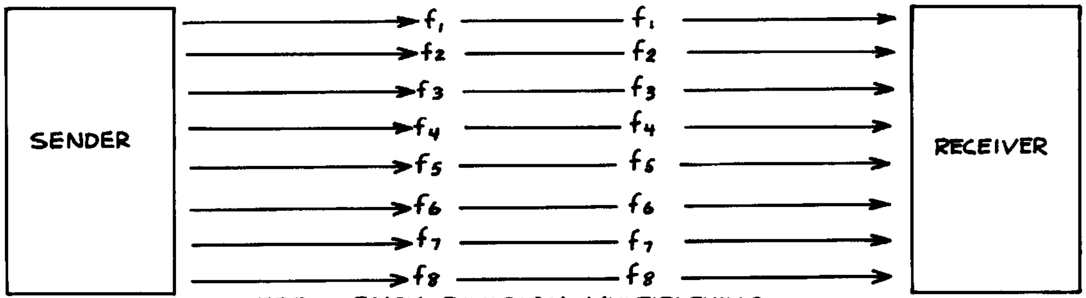
Suppose we want to multiplex eight separate channels of information over a single communication link—this might be a telegraph wire or it could be a modern optical fiber. We might use these channels to connect eight pairs of people, each pair consisting of a person at the sending end of the link and another at the receiving end. At the sending end we have a device that scans each of the eight channels in a round-robin fashion. At any instant, only the message from one channel is leaving the scanning device, but during the time that it takes the pointer of the scanner to make one complete revolution, the output signal will be made of the parts of eight different messages interleaved together. The interleaved messages travel down some communication link—a telegraph line—and are then fed into another scanning device that sorts the interleaved messages into their original forms. As the sketch shows, the scanning devices at the two ends of the communication link must be synchronized. If they are not, the messages leaving the scanning device on the receiving end will be garbled. In some very high-speed communication systems, the scanning devices must be synchronized within microseconds or less. This kind



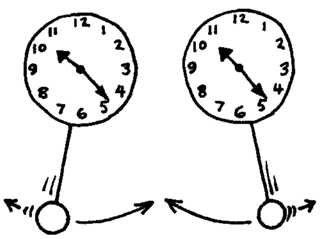

TIME DIVISION MULTIPLEXING

of communication system, where the signals are divided into time slots, is called *time division multiplexing*.

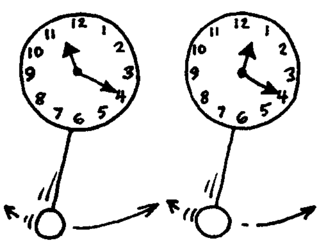
**FREQUENCY DIVISION MULTIPLEXING**




FREQUENCY DIVISION MULTIPLEXING



SYNCHRONIZE
CLOCK HANDS SHOW SAME TIME, BUT PENDULUMS MAY DIFFER.



SYNTONIZE
PENDULUMS SWING AT THE SAME RATE, BUT CLOCKS MAY SHOW DIFFERENT TIME.

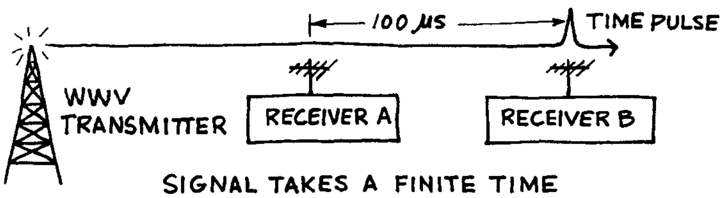
One familiar application depending on frequency for message identification is "tuning" our radio or TV set to a desired station. What we are really doing is telling the set to select the correct frequency for the station we wish to tune in. When we turn the dial to channel 5, for example, the TV set internally tunes to the frequency that is the same as channel 5's broadcast frequency; the set thus selects one specific frequency from all of those coming in, displaying its program and screening out all others.

We can think of television transmission as another form of multiplexing, but this time we are sending several channels of information at the same time by assigning each channel to a different frequency. This kind of scheme is called "frequency division multiplexing."

Before we end this section, we need to make an important distinction between synchronizing clocks in time and *syntonizing* them in frequency. Strictly speaking, when we synchronize clocks we are only adjusting them so that they show the same time of day. If we were synchronizing two wall clocks we would set the hands on both faces to show the same time—10:23 for example.

When we *syntonize* two clocks, we are only adjusting them so they "tick" at the same rate. For example, if we wanted to syntonize two grandfather clocks, we would adjust the lengths of their respective pendulums so that they swung back and forth at the same rate. Syntonized clocks don't necessarily present the same time. To go back to our grandfather clocks, they might be syntonized but one clock face might show 11:20 while the other showed 12:20. However, as long as they stay syntonized, they always show a constant time difference of one hour.

In communication systems, it is important to decide whether the systems need to be syntonized or synchronized, or both. The reason these distinctions are important is because it is much easier to syntonize clocks than it is to synchronize them.




SIGNAL TAKES A FINITE TIME TO TRAVEL FROM TRANSMITTER TO RECEIVER.

As we know from Chapter 11, radio time signals travel with finite speed. If we want to synchronize two clocks to, say, a time signal from WWV, we must know how long it takes the same time signal reference mark—the pulse at noon for example—to reach the two clocks, because, unless the two clocks are the same distance from WWV, the reference pulse will reach the clocks at different times. If the pulse arrives at the first clock 100 microseconds before it arrives at the second, then the clocks will be out of synchronization by 100 microseconds. Only by calculating or measuring this difference in arrival time can we adjust the two clocks to assure they are synchronized.

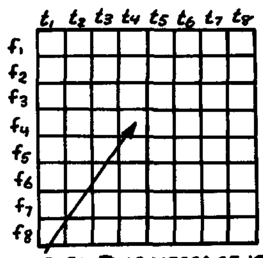
DETERMINING THE SIGNAL DELAY IS USUALLY THE HARDEST PROBLEM.

Determining the arrival time difference is often a very difficult problem, particularly when it is necessary to synchronize clocks to a few microseconds or better.

When we need only syntonize clocks, the situation is considerably simplified. Suppose we want to syntonize a grandfather clock to the one-second time ticks on WWV. Luckily for us, this grandfather clock has a pendulum whose period is nearly one second. We just need to adjust it slightly to bring it into step with WWV's one-second ticks. The important point to notice is that the distance to WWV from the grandfather clock is of no significance—the seconds ticks arrive at the same rate whatever the distance to WWV.

With these background comments, we see frequency division multiplexing needs only syntonized clocks while time division multiplexing requires synchronized clocks.

## SIMULTANEOUS TIME AND FREQUENCY MULTIPLEXING

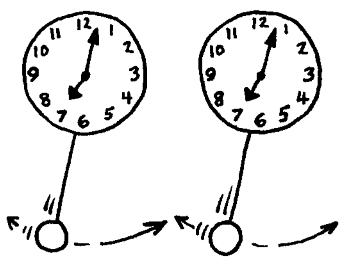



EXAMPLE: THIS MESSAGE IS TRANSMITTED AT TIME $t_4$ AT FREQUENCY $f_4$
TIME AND FREQUENCY DIVISION MULTIPLEXING

Systems can combine time and frequency division multiplexing, so that the senders and users need clocks synchronized and syntonized. An easy way to visualize time and frequency multiplexing is to divide "signal space" into a pattern much like the pattern of a checker board, as the figure shows. The columns of our pattern are labeled with times $t_1, t_2, \ldots, t_8$ while the rows are labeled $f_1, f_2, \ldots, f_8$. Each square has a unique identity or coordinates in terms of f and t. For example, the square in the third column, second row down has coordinates $t_3$, $f_2$. Each square represents a packet of information. Since there are 64 squares or cells, the figure schematically depicts 64 possible messages.

By visualizing the messages as occupying different cells in signal space, we can consider some powerful communication techniques. This power comes through a marriage of computers and time and frequency technology. We will assume, for the moment, that all the clocks in our hypothetical communication system are both syntonized and synchronized.

We have already noted that each package has unique coordinates in terms of the t's and f's. This has an advantage from an "addressing" point of view. Normally, when we send a message we must provide an address. However, with time-and-frequency multiplexed messages this is not always true. If I want to send a message to you, all we need to do is agree ahead of time that I will send my message to you at a particular frequency and at a particular time. For example we agree that your message will be designated by cell $f_6$, $t_2$. This means that, as the messages go by, you must pick out the one with these time and frequency coordinates.



CLOCKS MUST BE BOTH SYNCHRONIZED AND SYNTONIZED.

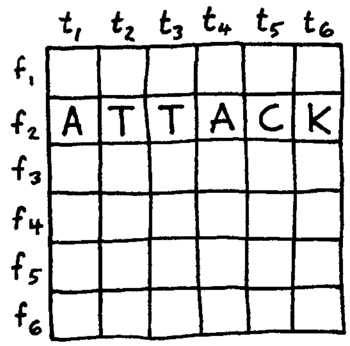
This only works if our clocks are both synchronized and syntonized. If they are not, then I, as the sender, may send your message at the wrong time and frequency, or you, as receiver will select the wrong message, or, if your clock is really off, will likely detect no message at all.

In today's high-speed communications systems, millions of bits per second can be delivered and messages may only be microseconds long, or even less; so, without exacting clock coordination, the system won't work.

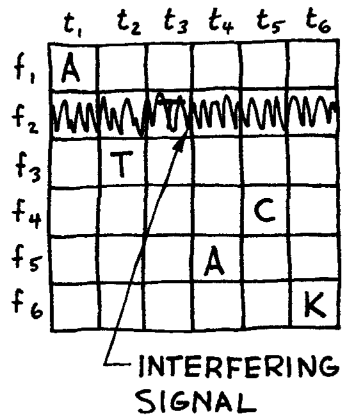
### DON'T PUT ALL YOUR MESSAGES IN ONE BASKET

When we look at communication from the point of view of signal space we see, as the figures show, that time division multiplexed signals occupy the rows while frequency division-multiplexed signals occupy the columns. And, of course, time and frequency division-multiplexed signals occupy both, as the figure shows.

Let's see now how message multiplexing works by considering a specific example—we want to send the message "ATTACK."

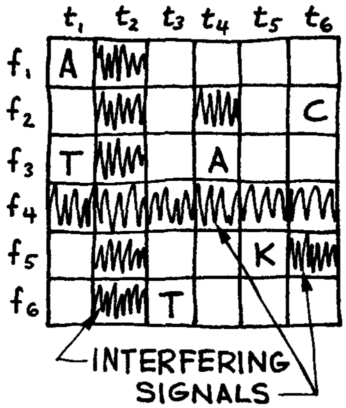



First we shall time-division-multiplex this message using all the messages cells centered at frequency $f_2$. This is shown in the figure by filling in the first six cells with the letters A, T, T, A, C, and K along the row labeled $f_2$. Suppose now that there is some signal, also at $f_2$, that interferes with our signal. The interfering signal might be due to a neighbor running his electric drill or it might be intentional on the part of some bad guy who is trying to jam our signal. What can we do?




Well, with our syntonous and synchronous communication system there are many things we can do. We could randomly place our message in different rows of message space, as the figure shows. With this scheme, the interfering signal is no problem except when the message happens to occupy a cell in row $f_2$. Jumping around in frequency is particularly effective against someone who is intentionally jamming our signal, since the protagonist doesn't know, from one message to the next, what frequency to jam.

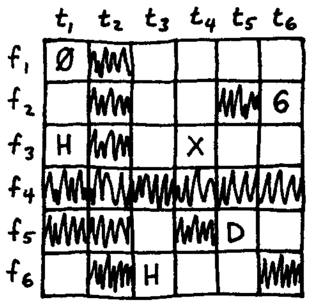
Schemes where the transmission frequency changes from moment to moment go under the generic heading "frequency hopping." In practical systems, the sequence of frequency hops is determined by a computer program, and, the intended recipient of the message must have the same program, so that she can program her receiver to switch




frequencies in step with the transmitted signals. Since the whole system is under computer control, the switching can be exceedingly fast, making it almost impossible for a jammer, who does not have the program, to keep up. If we can frequency-hop a message, we can also time-hop it, as the figure shows. Now the message is broken up so that it appears in a random sequence along a time column. Just like frequency hopping, computer-controlled time hopping can be exceedingly fast.

The ultimate, as the figure shows, is to both time and frequency hop a message. With such a scheme we can defend against several kinds of noise: continuous noise at a single frequency, noise across all frequencies that is intermittent in time, and noise that is both intermittent in frequency and time.

## SENDING SECRET MESSAGES




SENDING SECRET MESSAGES:
- RANDOMLY TIME AND FREQUENCY HOP
- ENCRYPT MESSAGE

As you might have guessed, not only are frequency and time hopping a good defense against noise, but they also provide a large degree of privacy. A listener who does not have the appropriate program will find it very difficult to detect a message. At best all he will receive are random bits of signal here and there as he chances to have his receiver tuned to the right frequency at the right time. But even greater privacy can be achieved by randomizing the message—send TATCKA instead of ATTACK, for example. The ultimate privacy is achieved by encrypting the message before it is sent—by replacing the letters A, T, T, A, C and K with other letters—so that, even if the message is intercepted, it must be decoded by the interceptor—a very difficult job with modern coding.

## KEEPING THE CLOCKS IN STEP

Since no clocks are perfect, they will gradually drift away from each other; it is necessary, from time to time, to reset all the clocks in the communication system.

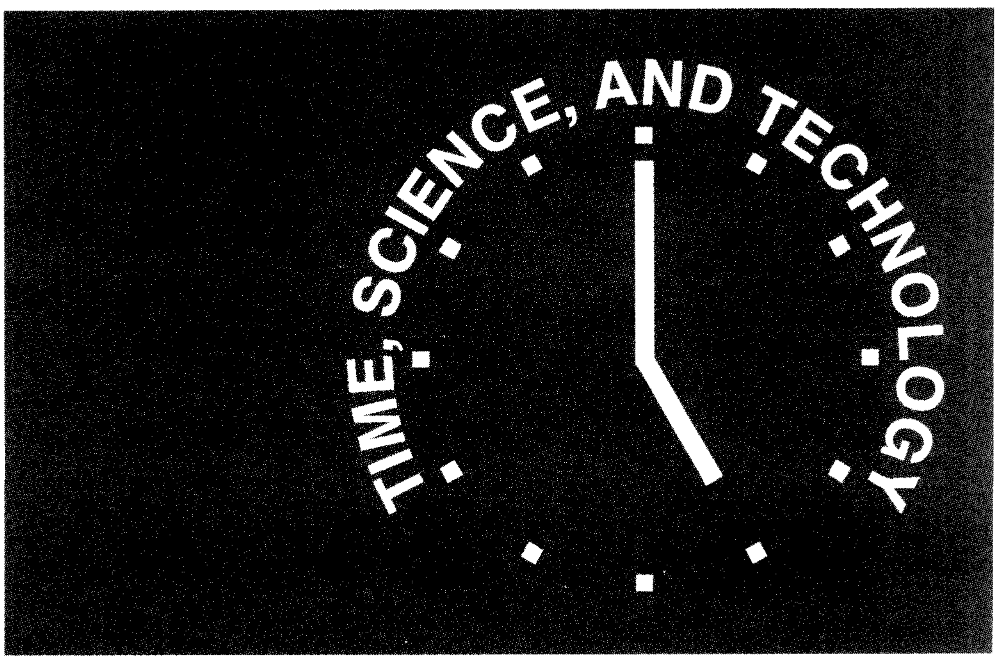
One way this can be done is for one user in the system to send a pulse that leaves his location at some particular time—say 4:00 p.m. Another user at a different location notes the arrival time of the 4:00 p.m. signal with respect to her clock. The signal should arrive at a later time, which is exactly equal to the delay time of the signal. If the listener at the receiving end records a signal that is either in advance of or after the correct delay time, she will know that the sender's clock has drifted ahead of or behind her own clock, depending upon the arrival time of the signal. All the clocks in a system can be reset by expanding on this scheme.

How often the readjustment must be made depends upon the quality of the clocks in the system and the rate at which the information is delivered. In a very familiar example, the television broadcast that we receive in our homes, there are about 15 000 synchronization pulses every second, a few percent of the communication capacity of the system. We shall discuss this example more fully in Chapter 21.

BETTER CLOCKS MEAN MORE COMMUNICATION CAPACITY.

If we want to optimize the time that the system is used to deliver messages and minimize time devoted simply to the bookkeeping of coordinating the clocks, then we must use the best clocks available. This is one big reason for the continuing effort to produce better clocks and better ways of disseminating their information.

An alternative to using the system itself for time coordination is to acquire time from some external system such as WWV or the Global Positioning System we discussed in some detail in Chapter 13. The advantage of this approach is that the communication system can be used almost exclusively for delivering information; it is not tied up sending messages to adjust its clocks.


TIME, SCIENCE, AND TECHNOLOGY

# V.
# TIME, SCIENCE, AND TECHNOLOGY

# Chapter 15

# TIME AND MATHEMATICS

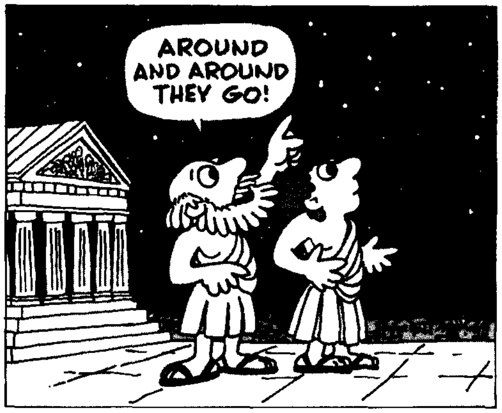
## A NEW DIRECTION

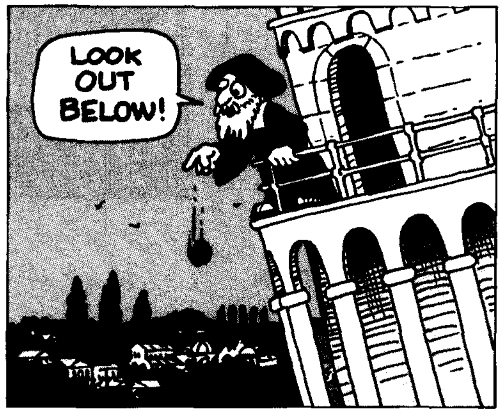
Until now we have concentrated on how time is measured, how it is broadcast to almost every point on the surface of the Earth, and how it is used in a modern industrial society. In the remainder of this book we shall turn away from the measurement, distribution, and practical uses of time and dip into a number of somewhat unrelated subjects in science and technology where time plays many different roles.

In this chapter for example, we shall explore 17th and 18th Century developments in mathematics, particularly calculus, which provided a new language uniquely qualified to describe the motions of objects in concise and powerful ways. Motion, too, is intimately related to time as is indicated by such questions as, what is the period of rotation of the Earth, or how long does it take an object to fall a certain distance on the surface of the Moon? Then there are always the intriguing and mind-boggling questions concerning the age and evolution of the universe, where the very words "age" and "evolution" connote time.

These and other subjects discussed in the last chapters of this book are developed so as to cast the spotlight on time, but there are many other characters on stage, and time is not the only important player. Modern scientific theories are rich in a variety of concepts and applications, which you will quickly discover if you pursue in any depth the subjects which we have examined primarily as they pertain to time.

As a final point, many of these subjects are by no means closed to discussion, but are on the very boundary of research and controversy. In fact, it does appear that every step which leads us toward a better understanding of the nature of time also brings into view new, uncharted territory.




## QUALITY QUANTITY

It is often said that mathematics is the language of science. But it hasn't always been so. Greek scientists and philosophers were more interested in qualitative discussions of ultimate causes than they were in precise quantitative descriptions of events in nature. The Greeks wanted to know why the stars seemed to circle endlessly around the Earth. Aristotle provided an answer—there was an "Unmoved Mover." But Galileo was more interested in *how long* it took a stone to fall a certain distance than he was in why the stone fell toward the center of the Earth. This change in the thrust of science from the *qualitative why* to the *quantitative how long* or *how much* pushed the need for precise measurement. Along with this shift in emphasis came the development of better instruments for measurement and a new mathematical language, calculus, to express and interpret the results of these measurements.

One of the most important measurements in science is the measurement of time. Time enters into any formula or equation dealing with objects changing or moving in time. Until the invention of calculus there was no mathematical language expressly tailored to the needs of describing motion and change. We shall describe in some detail in this chapter how the interaction between mathematics—especially calculus—and measurement allows us to construct theories which deeply illuminate the fundamental laws of nature. As we shall see, time and its measurement are crucial elements in the structure of these theories.

## TAKING APART AND PUTTING TOGETHER

People have always been preoccupied with the past and the future. An understanding of the past gives us a feeling of identity, and knowledge of the future, insofar as this is possible, helps us chart the most efficient and rewarding course. Much human effort is directed toward trying to see into the future. Whether it's a fortune teller gazing into a crystal ball, a pollster predicting the outcome of an election, or an economist projecting the future of inflation or the stock market, any "expert" on the future has a ready audience.


Science, too, has its own peculiar brand of forecasting. Two of the underlying assumptions of a science are that the complex can be understood in terms of a few basic principles, and that the future unfolds from the past according to strict guidelines laid down by these principles. One of the tasks of scientists, therefore, is to strip their observations down to their bare essentials—to extract the basic principles and to apply them to understanding the past, the present, and the future. The extraction of the principles is usually a "taking apart," or *analysis*; and the application of the principles is a "putting together," or *synthesis*. One of the scientist's most important tools in both of these efforts is mathematics. It helps uncover the well-springs of nature, and having exposed them, helps predict the course of their flow.

### SLICING UP THE PAST AND THE FUTURE—CALCULUS

DIFFERENTIATION = TAKING APART

INTEGRATION = PUTTING TOGETHER

As we know, in nature everything changes. The stars burn out and our hair grows gray. But as obvious as this fact is, people have difficulty grasping and grappling with change. Change is continuous, and there seems to be no way of pinning down a particular "now."

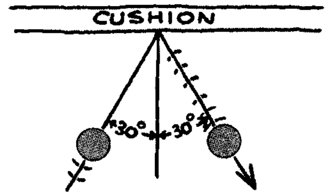
This struggle is clearly reflected in the development of mathematics. The mathematics of the Greeks was "stuck" in a world of constant shape and length—a world of geometry. The world of numbers continued to be frozen in time until 1666, when Isaac Newton invented the mathematics of change—the *calculus*. With his new tool he was able to extract an "essential quality" of gravitation from Galileo's experimentally discovered law for the distance a rock falls in a given time.

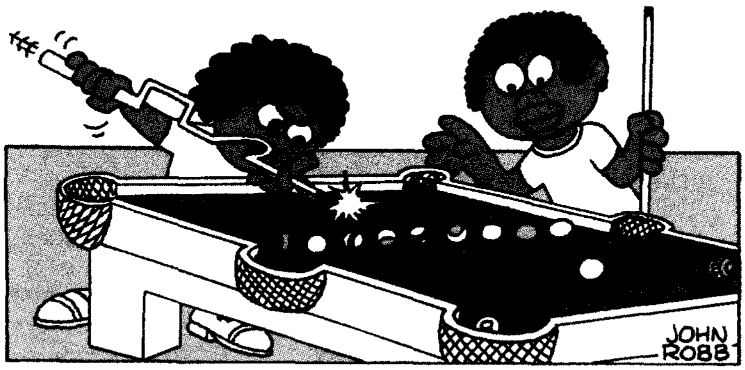
Newton's tool for sifting gravitation from Galileo's formula is called *differentiation*, and differentiation and *integration* are the inverses of each other in the same sense that subtraction is the inverse of addition and division is the inverse of multiplication. Differentiation allows us to pick apart and analyze motion, to discover its instantaneous essence; integration allows us to synthesize the instantaneous, revealing the full sweep of motion. We might say that differentiation is seeing the trees and integration is seeing the forest.

#### Conditions and Rules

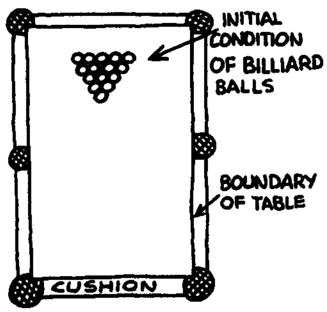
Before we get into a more detailed discussion of differential and integral calculus, let's back up a bit and discuss, in general terms, how the mathematical physicist views a problem. Suppose, for example, she wants to analyze the motion of billiard balls. First, she recognizes some obvious facts:

- At any instant, all of the balls are moving with certain speeds and directions at particular points on the table.
- The balls are constrained to move within the cushions that bound the table.
- The balls are subject to certain rules that govern their motion—for instance, a ball colliding with a cushion at some angle will bounce off at the same angle, or a ball moving in a particular direction will continue in that direction until it strikes a cushion or another ball. The latter is a form of one of Newton's laws of motion, and the former can be *derived* from Newton's laws of motion.



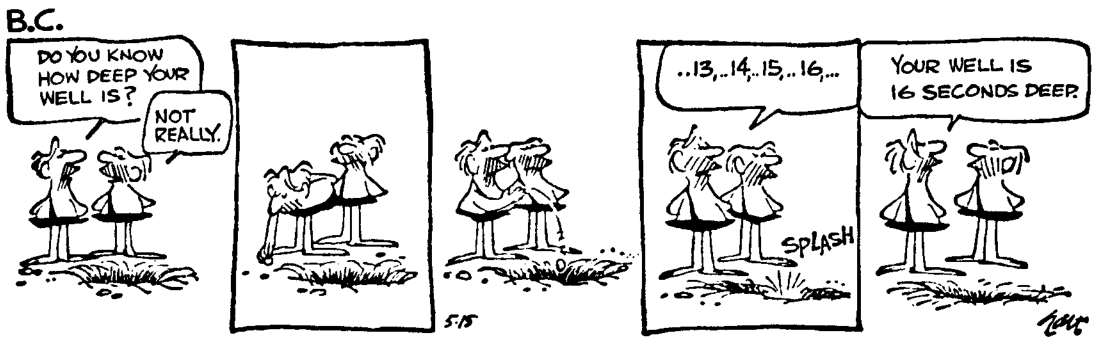

With all this information, the physicist can predict the motions of the balls. Mathematicians call the statements that characterize the locations and motions of the balls at an instant the *initial conditions*. And they call the statements that describe the allowable area of motion—in this case the plane of the table bounded by the cushion on four sides—the *boundary conditions*. Obviously the future location of the balls will be very dependent on the shape of the table. A round table will give a result entirely different from a rectangular table.




Thus with a set of initial conditions, boundary conditions, and rules governing the motion, we can predict the locations, speeds, and directions of the balls at any future time. Or we can work backward to determine these quantities at any earlier time. It's easier if we have a computer!

Having stated that the future and past are related to the "now" of these conditions, how do we proceed? In our example, the boundary conditions are simply obtained by measuring the table. Getting the initial conditions is somewhat trickier. From a photograph we determine the locations of the balls at the instant the picture is taken, but we also need to know the *speeds* and *directions* of the balls.

It might occur to us that if we take *two* pictures, one very slightly later than the other—say one-tenth of a second later—we can determine *all* of the initial conditions. From the first photograph we determine the locations of the balls; from the second, compared with the first, we determine the directions of the balls, as well as their speeds, by measuring the change of position each ball makes in 0.1 second. Changes in boundary conditions and initial conditions will alter the future course of events; it is one of the challenges of physics to deduce from a set of observations which part is due to initial and boundary conditions, and which part is due to the laws governing the process.

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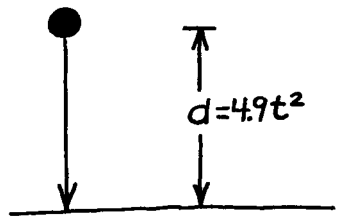
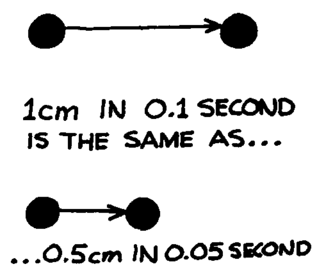
Let's apply these ideas now to Galileo's problem of the falling rock. According to legend, Galileo dropped objects from the leaning tower of Pisa and measured their time of fall. But according to his own account, he measured the time it took for bronze balls to roll down a smooth plank—probably because he had no reliable way to measure the relatively short time it takes a rock to fall the length of the tower of Pisa. In any case, Galileo ultimately came to the conclusion that a freely falling object travels a distance proportional to the time of fall squared, and that the fall time does not depend upon the object's mass. That is, if a rock of any mass falls a certain distance in a particular time interval, it falls four times as far in twice that time interval. More precisely, he discovered that the rock falls a distance "d" in meters equal to about 4.9 times the fall time squared, in seconds—or $d = 4.9t^2$.




Is this simple formula a law of motion, or is it some combination of laws, boundary conditions, and initial conditions? Let's explore this question.

### Getting at the Truth with Differential Calculus

The method of differential calculus is similar to the scheme we developed for determining the locations, speeds, and directions of the billiard balls at a specified time. Let's look more carefully at the particular problem of determining the speed of a billiard ball.




To get the data we needed, we took two pictures of the moving balls, separated by 0.1 second, and we determined the speed of a ball by measuring the distance it had moved between photos. Let's suppose that a specific ball moved 1 centimeter in 0.1 second. We easily see that its speed is 10 centimeters per second.

Suppose, however, that we had taken the pictures 0.05 second apart. Then between photos the ball moves half the distance, or 0.5 centimeter. But of course the speed is still 10 centimeters per second, since 0.5 centimeter in 0.05 second is the same as 1.0 centimeter in 0.01 second.

In differential calculus we allow the time between photos to get closer and closer to 0. As we have seen, halving the time between photos does not give us a new speed, because the distance moved by the ball decreases proportionately; so the *ratio* of distance to time between photos always equals 10 centimeters per second. The essence of differential calculus is to divide one "chunk" by another—in our example, distance divided by time—and allow the two chunks to shrink toward 0. This sounds like very mysterious business, and you might think that the end result of such a process would be dividing nothing by nothing. But this is not the case. Instead, we end up with the rate of motion at a particular instant and point.

This process of letting the chunks shrink toward 0, mathematicians call "taking the limit." By taking the limit we reach the answer we are seeking, the magnitude of the motion at a *point* not contaminated by what happened over a *distance*, even though the distance was very small. *Integration* is the reverse process; we take the instantaneous motion and convert it back to distance.

In our example, since the billiard ball moves with constant speed, we get the same results with photos that taking the limit produces: 10 centimeters per second. But in fact, the ball won't move with constant speed, but will slow down ever so slightly because of friction. If we wanted to be really accurate in our measurement, we would want our two photos to be separated by the shortest possible time, which approaches the idea of taking the limit.

$d = 4.9t^2$

Let's go back now to Galileo's formula for falling bodies: $d = 4.9t^2$. We would like to reduce this formula to some number that does not change with time—a quantity that characterizes the rock's motion independent of initial and boundary conditions. As Galileo's formula stands, it tells us how the *distance fallen* changes with time. Putting a different time in the formula gives a different distance; this formula certainly is not independent of time.

We might think, well, since the distance changes with time, maybe the velocity remains constant. Perhaps the rock falls with the same speed on its journey to the ground.

Differential calculus gives us the answer. It allows us to go from *distance traveled* to *speed of travel*. We can think of this process as putting our formula $d = 4.9t^2$ into a "differentiating machine" which produces a new formula showing how speed, s, changes with time. The process performed by the machine is somewhat akin to the two-photo procedure we discussed in earlier paragraphs. (See also "What's Inside the Differentiating Machine? An Aside on Calculus.") Let's see what happens now:

In goes $\left(d = 4.9t^2\right) \rightarrow \boxed{\text{DIFFERENTIATING MACHINE}} \rightarrow$ out comes $\left(s = 9.8t\right)$.

To our disappointment we see that the speed $s$ is not constant; it increases continually with time. For every second the rock falls, the speed *increases* by 9.8 meters per second.

Well, perhaps then the *rate* at which the speed changes, the *acceleration, a*, is constant. To find out, we run our formula for speed through the differentiating machine:

In goes $(s = 9.8t) \rightarrow \boxed{\text{DIFFERENTIATING MACHINE}} \rightarrow$ out comes $(a = 9.8)$.

At last we've found a quantity that does not change with time. The acceleration of the rock is always the same. The speed increases at the constant rate of *9.8* meters per second every second. We have hit rock bottom; *9.8* is a number that does not change, and it tells us something about nature because it does not depend upon the height of the tower or the way we dropped the rock.

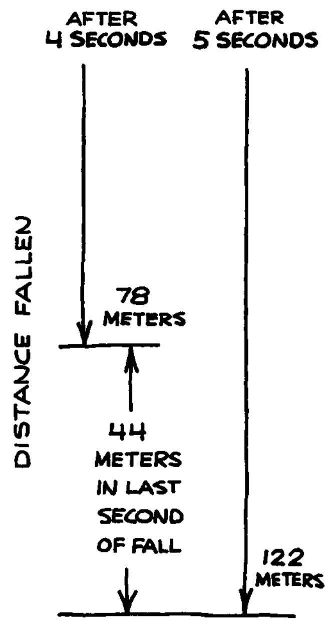
## WHAT'S INSIDE THE DIFFERENTIATING MACHINE?—AN ASIDE ON CALCULUS

To understand how the differentiating machine works, let's consider a specific example. We'll suppose a rock hits the ground after falling for 5 seconds, and we would like to know the speed at impact. We start with Galileo's formula that says

$$y = 4.9t^2,$$

where $y$ is the distance fallen and $t$ is time. From the formula, we find that the rock has fallen 78 meters after 4 seconds and 122 meters after 5 seconds, or that the rock falls 44 meters in its last second before impact. (During this last second, the average speed is 44 meters per second, although at the beginning of the second the rock's true speed is less than this and at the end it is greater.) We repeat this procedure several times, always using Galileo's formula, to obtain the *average* speed during the last ½ second, the last ¼ second, and so forth down to the 1/16 000 second. The results are shown in the table on the following page.

| TIME INTERVAL (SECONDS) | 1 | $\frac{1}{2}$ | $\frac{1}{4}$ | $\frac{1}{16}$ | $\frac{1}{32}$ | $\frac{1}{64}$ | $\frac{1}{160}$ | $\frac{1}{1600}$ | $\frac{1}{16{,}000}$ |
|---|---|---|---|---|---|---|---|---|---|
| DISTANCE FALLEN (METERS) | 44 | 23 | 12.00 | 3.03 | 1.52 | 0.76 | 0.30 | 0.03 | 0.003 |
| AVERAGE SPEED (METERS PER SECOND) | 44 | 46 | 47.50 | 48.50 | 48.60 | 48.69 | 48.73 | 48.76 | 48.767 |




If we scan along the bottom row of the table, it appears that the final speed is 49 meters per second, although with this approach we can never quite prove it. However, with calculus we can prove it. Let's see how.

What we want to do is apply calculus to Galileo's formula for distance and turn it into a formula that gives speed for any arbitrary fall time. Since we want a general formula, we shall use symbols, rather than numbers, to derive our new formula.

First, we shall let $t$ stand for the fall time, and $\Delta t$ (delta t) stand for any short interval of fall time. Thus, we might say that the rock falls for a time t and then falls an additional small interval of time $\Delta t$. Similarly, we shall let $\Delta y$ stand for the distance the rock falls during the short interval of time $\Delta t$.

Next, using Galileo's formula, we want to find a formula for $\Delta y$, the distance the rock falls in $\Delta t$ seconds.

We start with $y = 4.9t^2$.

Then it follows that

$$y + \Delta y = 4.9\,(t + \Delta t)^2 = 4.9t^2 + 9.8t\Delta t + 4.9(\Delta t)^2.$$

Subtracting the first formula for $y$ from the second formula for $y + \Delta y$, we see that

$$\Delta y = 9.8t\Delta t + 4.9\,(\Delta t)^2.$$

Since the distance $\Delta y$ is covered in a time $\Delta t$, the average speed over the distance is $\Delta y / \Delta t$.

$$\Delta y \,/\, \Delta t = \frac{9.8\Delta t + 4.9(\Delta t)^2}{\Delta t} = 9.8t + 4.9\Delta t\,.$$

Finally, what we want to know is not the average speed over the distance $\Delta y$, but the instantaneous change of distance with respect to time or, equivalently, the speed at a point. We do this by letting $\Delta t$ approach zero; or as the mathematicians say, we "take the limit" as $\Delta t$ approaches zero, which is

instantaneous speed = $\underset{\Delta t \to 0}{\text{limit}}\,(9.8t + 4.9\,\Delta t) = 9.8t$ or speed, $s = 9.8$.

Let's see how this new formula works. We put 5 seconds into our formula and we obtain $s = 9.8 \times 5, = 49$ meters per second, which is precisely what we anticipated from our table.

The instantaneous change of distance y with respect to time $t$ is called the "derivative" of $y$ with respect to $t$. It is written $dy/dt$, which is just in our example a shorthand notation for the process, $\underset{\Delta t \to 0}{\text{limit}}$.

In compact mathematical symbols, the derivative with respect to time t of the distance fallen, $y$ $(= 4.9t^2)$, is expressed as:

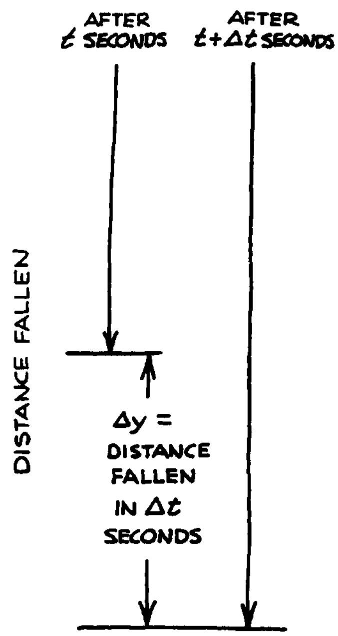
$$\frac{d(y)}{dt} = \frac{d(4.9t)^2}{dt} = 9.8t = s\,.$$

Or, as we said earlier:

$$\text{in goes } \left(d = 4.9t^2\right) \rightarrow \boxed{\text{DIFFERENTIATING MACHINE}} \rightarrow \text{out comes } (s = 9.8t)\,.$$

That part of calculus which is devoted to taking derivatives is called "differential calculus" and the inverse is called "integral calculus." If we had an "integrating" machine for integral calculus, it would take the formula for speed and turn it back into the formula for distance:

$$\text{In goes } (s = 9.8t) \rightarrow \boxed{\text{INTEGRATING MACHINE}} \rightarrow \text{out comes } \left(y = 4.9t^2\right).$$

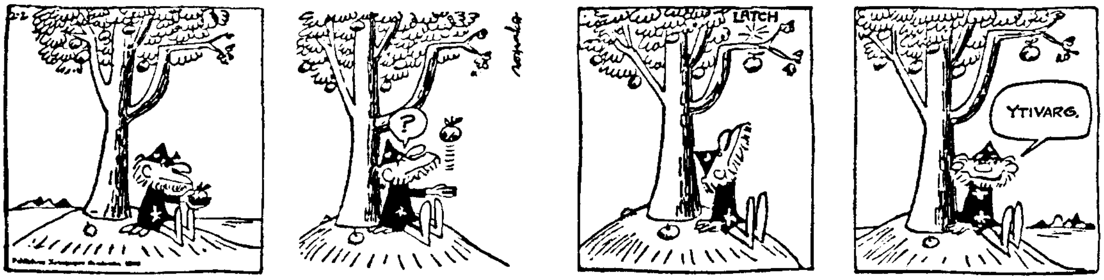


We shall not go into the details here, but the process of going from ($s = 9.8t$) to ($y = 4.9t^2$)—that is, integrating speed with respect to time—is somewhat similar to the exercise we have just completed. The difference is that instead of using Galileo's formula to compute the average speed over each small interval of time, we use our new formula for speed ($s = 9.8t$) to determine the distance fallen over many short consecutive intervals of time: then we add up all of these intervals to obtain the total distance fallen, and finally, let the intervals of time approach 0 (take the limit) to obtain the exact result. To complete the integration process correctly for a particular problem, we must know the initial and boundary conditions. For example, we can compute correctly the speed of a rock after it has fallen for 10 seconds from the formula $y = 4.9t^2$ only if the rock starts its fall from rest. If it has an initial downward motion—such as would result if we threw the rock downward instead of simply releasing it from our hand—then we must include this fact in our calculation if we are to obtain the correct answer. That is, we must know the initial condition at which the rock left our hand at, say 14 kilometers per hour, as well as the formula $y = 4.9t^2$.

## NEWTON'S LAW OF GRAVITATION

Of course, nature might have been different; we might have found that the acceleration increased with time and that the rate of increase of acceleration with time was constant. But this is not the case. After two "peelings," Newton had discovered that *gravitational pull* produces constant acceleration independent of time. Armed with calculus and Galileo's and others' measurements, he was able to develop his famous *law of gravitation*. He demonstrated that this law applied not only to falling rocks, but also to the solar system and the stars. The latter step required the application of *integral* calculus. By working the whole process backward—*integrating* the instantaneous motions of the planets—he proved that they had to move around the Sun in ellipses. By looking through the "microscope" of differentiation, Newton was able to discover the essence of falling

THE WIZARD OF ID

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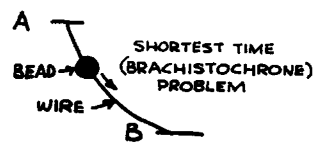
bodies; by looking through the "telescope" of integration, he was able to see the planets circling the Sun.

For whatever reasons, Newton kept his invention of calculus to himself, and it was invented again some 10 years later by Gottfried Wilhelm von Leibnitz, a German mathematician. Even then, Newton did not publish his version for another 20 years. Leibnitz's symbolism was easier to manage than Newton's, so calculus developed at a faster rate on the Continent than it did in England. In fact, a rivalry developed between the two groups, with each group trying to stump the other by posing difficult mathematical questions.




One problem posed by the Continental side concerned the shape a wire should have (not straight up and down) so that a bead sliding down it would reach the bottom in the shortest possible time. Newton spent an evening working out the solution, which was relayed anonymously to the Continent. One of Leibnitz's colleagues, who had posed the problem, received the solution and reportedly said, "I recognize the lion by his paw."

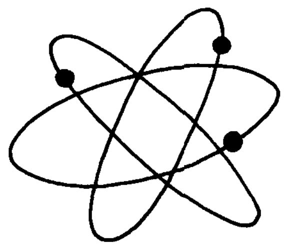
Although Newton's laws of motion and gravitation can be summed up in a few simple mathematical statements, it took many great applied mathematicians—men such as Leonhard Euler, Louis Lagrange, and William Hamilton—another 150 years to work out the full consequences of Newton's ideas. Rich as Newton's work was, even he realized that there was much to be done in other fields, especially electricity, magnetism, and light. It was 200 years after

Newton before substantial progress was made in these areas.

Even later, Newton's laws were overturned by Einstein's *relativity*; most recently quantum mechanics, with its rules governing the microscopic world, has come into play. Each new understanding of nature has led to dramatic gains in the search for perfect *time*.

Chapter 16

# TIME AND PHYSICS



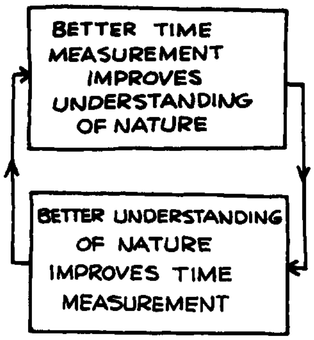
Although much of the early interest in time sprang from religious activities, the "high priests" of time had worked out remarkable schemes for predicting various astronomical events such as the summer solstice, the winter solstice, and motions of the constellations in the sky throughout the year. In later times, with the development of commerce and naval activities on the seas and the need for improved navigation methods, the interest in time turned somewhat from the religious to the secular. But it makes little difference what the application, religious or secular, the tools for "unraveling" the fabric of time are the same.

As we have seen, time measurement has been intimately connected with astronomy for many centuries, and within our own lifetime we have begun to look at the atom in connection with the measurement of time. It is curious that we have made a quantum jump from one end of the cosmological scale to the other—from stars to atoms—in our search for the perfect clock. The motions of pendulums, planets, and stars are understood in terms of Newton's laws of motion and gravity—or with even greater refinement in terms of Einstein's General Theory of Relativity; the world of the atom is understood in terms of the principles of quantum mechanics. As yet, however, no one has been able

to come up with one all-encompassing set of laws that will explain our observations of nature from the smallest to the largest—from the atoms to Andromeda. Perhaps the ultimate goal of science is to achieve this unified view. Or in the words of the artist-poet William Blake, the task of science is

*To see a world in a grain of sand*
*and a heaven in a wild flower,*
*Hold infinity in the palm of your hand*
*And eternity in an hour.*
Auguries of Innocence

Until this goal is reached, the science of physics will continue to ask many difficult questions about the big and the small, and short and the long, the past and the future.




As we saw in our discussion of clocks, the developments of scientific knowledge and of time measurement have moved forward hand in hand; more accurate time measurements have led to a better understanding of nature, which in turn has led to better instruments for measuring time. Improvements in the measurement of time have made it possible for the science of physics to expand its horizons enormously; because of this, modern physics has several very important things to tell us about time:

- Time is relative, not absolute.
- Time has direction.
- Our measurement of time is limited in a very fundamental way by the laws of nature.
- A time scale based upon one particular set of laws from physics is not necessarily the same time scale that would be generated by another set of laws from physics.

### TIME IS RELATIVE

Isaac Newton stated that time and space are absolute. By this he meant that the laws of motion are such that all events in nature appear to proceed in the same fashion and order no matter what the observer's location and motion.

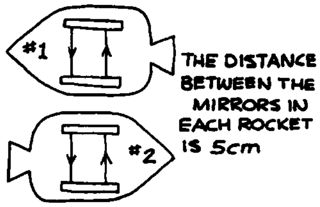
This means that all clocks synchronized with each other should constantly show the same time.

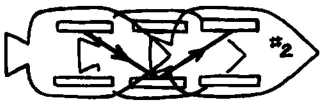
Albert Einstein came to the conclusion that Newton was wrong. Certain peculiar motions in the movement of the planet Mercury around the Sun could not be explained according to Newton's ideas. By assuming that space and time are *not* absolute, Einstein was able to formulate new laws of motion that explained the observed orbit of Mercury.

But what have Einstein's ideas to do with clocks not all showing the same time? First, Einstein stated that if two spaceships approach each other, meet, and pass in outer space, there is no experiment that can be performed to determine which spaceship is moving and which is standing still. Each ship's captain can assert that his ship is standing still and the other's is moving. Neither captain can prove the other wrong. We've all had the experience of being in a train or other vehicle that is standing still, but feeling sure it is in motion when another vehicle close beside us moves past. Only when we look around for some other, stationary, object to *relate* to can we be sure that it is the vehicle beside us, and not our own, that is in motion.

We must emphasize here that we are not attempting to prove Einstein's idea true; we are merely stating what he had to assume in order to explain what happens in nature. Let's suppose now that each of our two spaceships is equipped with a clock. It's a rather special kind of clock that consists simply of two mirrors, facing each other and separated by a distance of 5 centimeters. The period of the clock is determined by a pulse of light that is simply bouncing back and forth between the two surfaces of the mirrors. Light travels about 30 centimeters in $10^{-9}$ seconds (one nanosecond), so a round trip takes 1/3 nanosecond.

The captain traveling on Ship One would say that the clock on Ship Two is "ticking" more slowly than his because its pulse of light traveled more than 10 centimeters in its round trip. But the captain in Ship Two would be equally correct in making the same statement about the clock on Ship One. Each captain views the other's clock *relative* to his. And since, according to Einstein's statement, there is no way to tell which ship is moving and which is standing still, one captain's conclusion is as valid as the other's. Thus, we




AS THE TWO ROCKET SHIPS PASS EACH OTHER, THE CAPTAIN OF #1 SAYS THAT THE LIGHT PULSE IN #2 TRAVELS MORE THAN 10 cm IN ITS BACK AND FORTH JOURNEY

see that time is relative—that is, the time we see depends on our point of view.

To explore this idea a little further, let's consider the extreme case of two spaceships meeting and passing each other at the speed of light. What will each captain say about the other's clock? We could use the mathematics of relativity to solve this problem, but we can also go straight to the answer in a fairly easy way:

When we look at a clock on the wall what we are really seeing is the light reflected from the face of the clock. Let's suppose that the clock shows noon, and that at that moment we move away from the clock at the speed of light. We will then be moving along with the *light image* of the noon face of the clock, and any later time shown on the clock will be carried by a light image that is also moving at the speed of light. But that image will never catch up with us; all we will ever see is the noon face. In other words, for us time will be frozen, at a standstill.

There are other interesting implications in this concept of time as relative to one's own location and movement. The fact that each captain of our two spaceships sees the other's clock "ticking" more slowly than his own is explained by Einstein's "Special Theory of Relativity," which is concerned with *uniform* relative motion between objects. Sometime later, Einstein developed his "General Theory of Relativity," which took gravitation into account. In this case, he found that the ticking rate of a clock is influenced by gravitation. He predicted that a clock in a strong gravitational potential, as is the case near the Sun, would appear to us to run slow.

To see why this is so, we go back to our two rocket ships. This time, let's suppose that one of the ships is stopped a certain distance from the Sun. At this point, there will be a gravitational field "seen" by the spaceship and its contents, including the mirror clock. Let's suppose the other spaceship is falling freely in space toward the Sun. Objects in this spaceship will float around freely in the cabin as though there were zero gravitational field—just as we have seen from televised shots of the astronauts on their way to the Moon.

Let's suppose now that the falling spaceship passes the stationary spaceship on its journey toward the Sun, in such a way that the captain in the free-falling spaceship can see the clock in the other spaceship. Because of the relative motion, he will again say that the other clock is running more slowly than his own. And he might go on to explain this observation by concluding that the clock where there is a gravitational field runs more slowly than one where there is zero gravitational field.

We can use these observations about clocks from the theories of Special Relativity and General Relativity theories to obtain an interesting result. Suppose we put a clock in a satellite. The higher the satellite is above the surface of the Earth, the faster the clock will run because of the reduced gravitational potential of the Earth. Furthermore, there will also be a change in the rate of the clock caused by the *relative motion* of the satellite and the Earth. The difference in relative motion increases as the height of the satellite increases. Thus these two relativistic effects are working against each other. At a height of about 3300 kilometers above the surface of the Earth, the two effects cancel each other, a clock there would run at the same rate as a clock on the surface of the Earth.

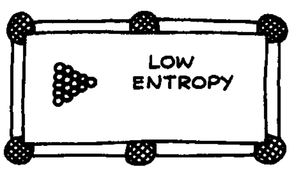
## TIME HAS DIRECTION

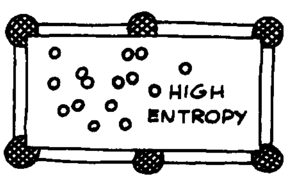
If we were to make a movie of two billiard balls bouncing back and forth on a billiard table, and then show the movie backward, we would not notice anything strange. We would see the two balls approaching each other, heading toward the edges of the table, bouncing off, passing each other, and so forth. No laws of motion would appear to have been violated. But if we make a movie of an egg falling and smashing against the floor, and then show *this* film backward, something is clearly wrong. Smashed eggs do not in our experience come back together to make a perfect egg and then float up to someone's hand.

In the egg movie there is very much a sense of *time direction*, whereas in the billiard ball movie there is not. It appears that the sense of time direction is somehow related to the probability or improbability of events. If we film the billiard balls over a longer period of time, for example, so that we see the balls slowing down and finally coming to rest—and then show the movie backwards, we would realize


that it was running backward. Billiard balls don't start moving from rest and gradually increase their motion—at least not with any great probability.

Again the direction of time is determined by the probable sequence of events. The reason the balls slow down is that friction between the balls and the table gradually converts the ordered rolling energy of the balls into the heating up of the table and balls ever so slightly. Or more precisely, the ordered motion of the balls is going into disordered motion. A measure of this disordered motion is called *entropy*. Entropy involves *time* and the fact that time "moves" in only one direction.




Systems that are highly organized have low entropy, and vice versa. To consider our billiard table further, let's suppose we start by racking up the balls into the familiar triangular shape. At this point, the balls are highly organized and remain so until we "break" them. Even after the break, we can perceive a certain organization, but after a few plays the organization has disappeared into the random arrangement of the balls. The entropy of the balls has gone from low to high.

Now let's suppose that we had filmed this sequence from the initial break until well after disorder had set in. Then we run the film backward. During the first part of the showing, we are watching the balls' motion during a period when they are completely randomized, and in this interval we cannot tell the difference between showing the film forward or backward. In the physicist's jargon, after the entropy of a system is maximized we cannot detect any direction of time flow.

As we continue to watch the film, however, we approach the moment when the balls were highly organized into a compact triangle. And as we come nearer to this moment we can certainly detect a difference between the film running forward or backward. Now we can assign direction to "time's arrow."

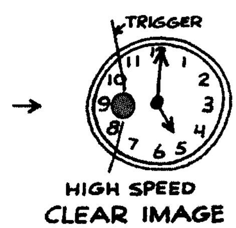
We can bring another point out by comparing this observation with our earlier discussion of two balls. We noticed that with two balls we were not able to detect a time direction, but with many balls we can assign a meaning to time direction. With just *two* balls we are not surprised when they collide with each other and move off, but when *many* balls are involved it is highly improbable that they will eventually regroup to form a compact triangle—unless we are running the film backward.

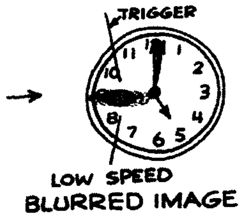
## TIME MEASUREMENT IS LIMITED

We have discussed why it was necessary for Einstein to modify Newton's laws of motion. Some years later, scientists discovered that it was necessary to modify Newton's laws to explain observations of objects at the other end of the size scale from planets and stars—atoms. But the modifications were different from those that Einstein made.

One of the implications of these modifications is that there is a limit to how precisely time can be measured under certain conditions. The implication is that the more we want to know about *what* happened, the less we can know *when* it happened, and vice versa. It's a kind of "you can't eat your cake and have it" type of law.

We can get a feeling for it by considering the following problem: Let's suppose we would like to know the exact instant when a BB, shot from an air rifle, passes a certain point in space. As the BB passes this point, we could have it trigger a fine hair mechanism that sets off a high-speed flash photo. Behind the BB is a wall clock whose picture is taken along with the BB's picture. In the high-speed photo we would see the BB suspended in motion, and the wall clock would indicate the time at the moment the picture was taken.





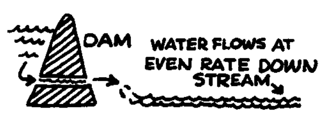

But let's suppose we wanted to know something about the *direction* the BB is moving, but we were still limited to one picture. We could take a slower picture, which would show a blurred image of the BB, and from this image we could determine the direction of movement. But now the second hand on the clock would be blurred also, and we could not know the exact *time* when the BB crossed the mark.

Both the time when an event happens and the duration of time it occupies can be measured quite precisely. But the greater the degree of precision, the less other information can be gathered. This fact, which scientists call the "uncertainty principle," seems to be a fundamental feature of nature.

From quantum mechanics a more precise expression of the uncertainty principle is that the more we know about the "energy" of a process, the less we know about when it happened, and vice versa. We can apply this statement directly to an atom such as a hydrogen atom in a hydrogen maser emitting a photon of radiation. According to the uncertainty principle, the more precisely we know the energy emitted by the atom, the less we know about when it happened.

In Chapter 5 we found that the frequency of the radiated energy is related in a precise way to the "quantum" of energy emitted: The bigger the quantum of energy, the higher the frequency emitted. But now we see that there is another application of this frequency–energy relationship. If we know the magnitude of the quantum of energy quite accurately, then we know the frequency radiated quite accurately, and vice versa.

But the uncertainty principle tells us that to know the energy precisely—and thus the frequency precisely—means that we won't know very much about *when* the emission took place.





The situation is somewhat like water flowing out of a reservoir. If the water runs out very slowly, we can measure its rate of flow accurately, but this flow will be spread over a long period of time, so we have no distinct notion of the process having a precise beginning and ending. But if the dam is blown up, a huge crest of water will surge downstream; as the crest passes by, we will have no doubt that something happened and when it happened—but we will have great difficulty in measuring the rate at which the water flows by.

In the case of the atom, the energy leaking away slowly means that we can measure its frequency precisely. We have already observed a similar idea in Chapter 5, in our discussion of the cesium-beam tube resonator. We said that the longer the time the atom spends drifting down the beam tube, the more precisely we could determine its resonance frequency; alternatively, the longer the time the atom spends in the beam tube, the higher the $Q$ of the resonator. Thus, both from our discussion of resonators in Chapter 5, and also from quantum mechanics, we come to a conclusion that makes sense: The longer we observe a resonator, the better we know its frequency.

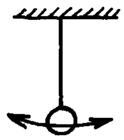
As a final comment, we can relate our discussion here to the spontaneous emission of an atom, which we also discussed in Chapter 5. Atoms, we observed, have a "natural" lifetime. That is, left alone they will eventually spontaneously emit a photon of radiation, but this lifetime varies from atom to atom and also depends upon the particular energy state of the atom. If an atom has a very short natural lifetime, we will be *less* uncertain about when it will emit energy than if it had a very long lifetime. Invoking the uncertainty principle, atoms with short lifetimes emit uncertain amounts of energy, and thus the frequency is uncertain; atoms with long lifetimes emit packets of energy whose values are well known, and thus the frequency is well established.

We see in a sense, then, that each atom has its own natural $Q$. Atoms with long natural lifetimes correspond to pendulums with long decay times, and thus high $Q$; and atoms with short natural lifetimes correspond to pendulums with short decay times, and thus low $Q$.

We should emphasize, however, that although a particular energy transition of an atom may correspond to a relatively low $Q$ as compared to other transitions of other atoms, this of itself is not necessarily a serious obstacle to clock building. For example, atomic beam resonators contain many millions of atoms, and what we observe is an "average" result, which smooths out the fluctuations associated with emissions from particular atoms. The only limitation appears to be the one that we have already pointed out in Chapter 5, in our discussion of the limitations of atomic resonators.

## ATOMIC AND GRAVITATIONAL CLOCKS

No single theory in science explains both the macroscopic world of heavenly bodies and the microscopic world of the atom. Gravity governs the motions of the stars, galaxies, and pendulums; atoms come under the jurisdiction of quantum mechanics.



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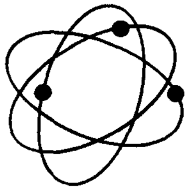
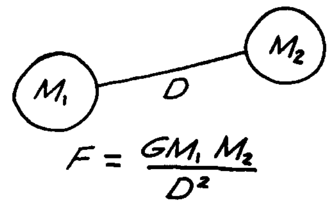


In our history of the development of clocks, we have seen that there has been a dramatic change in the last several decades. We have gone from clocks whose resonators were based on swinging pendulums—or other mechanical devices—to resonators based on atomic phenomena. We have gone from the macroworld to the microworld with a concomitant change in the laws that govern the clocks' resonators.

This diversity raises an interesting question: Do clocks, understood in terms of Newton's law of motion and gravitation, keep the same time as those based on quantum theory? The atomic second was defined as nearly equal to the ephemeris—or "gravity"—second for the year 1900. But will this relationship be true a million years from now—or even a thousand? Might not the atomic second and the gravitational second slowly drift apart?

The answer to this challenging question is embedded in the deeper question of the relationship between the laws describing the macroworld and those describing the microworld: In the laws of both there are numbers called *physical constants*, which are assumed not to change in time. One such constant is the velocity of light; another is the gravitational constant $G$. $G$ appears in Newton's law of gravitation, according to which the gravitational attraction between two objects is proportional to the product of their masses and inversely proportional to the square of the distance between them. Thus, if we write $M_1$ and $M_2$ for the two masses, and the distance between them $D$, Newton's law reads

$$\text{FORCE} = F = G\frac{M_1 M_2}{D^2}.$$




To get the correct answer for the force $F$ we have to introduce $G$; $G$ is a number that we must determine experimentally. There is no scientific theory that allows us to calculate $G$.

We have a similar situation in quantum mechanics. We have already learned that energy $E$ is related to frequency $f$; mathematically the expression is $E = hf$, where $h$ is another constant—Planck's constant—which must be determined experimentally. If in some unknown way, $G$ or $h$ is changing with time, then time kept by gravitational clocks and atomic clocks will diverge. For if $G$ is changing slowly with time, a pendulum clock under the influence of gravitation will slowly change in period. Similarly, a changing $h$ will cause the period of an atomic clock to drift. At present, there is no experimental evidence that this is happening, but the problem is being actively investigated.

If $G$ and $h$ diverge in just the "right" way, we could get some strange results. Let's suppose gravitational time is slowly decreasing with respect to atomic time. We can't really say which scale is "correct"; one is just as "true" as the other. But let's take the atomic time scale as our reference scale and see how the gravitational scale changes with respect to it.

We'll assume that the rate of the gravitational clock doubles every thousand million years—every billion years—with respect to the atomic clock. To keep our example as simple as possible, let's assume that the rate of the gravitational clock does not change smoothly but occurs in jumps at the end of each billion years. Thus, one billion years ago the pendulum or gravitational clock was running only half as fast as the atomic clock. As we keep moving into the past, in billion-year intervals, we could tabulate the total time as measured by the two kinds of clocks as follows:

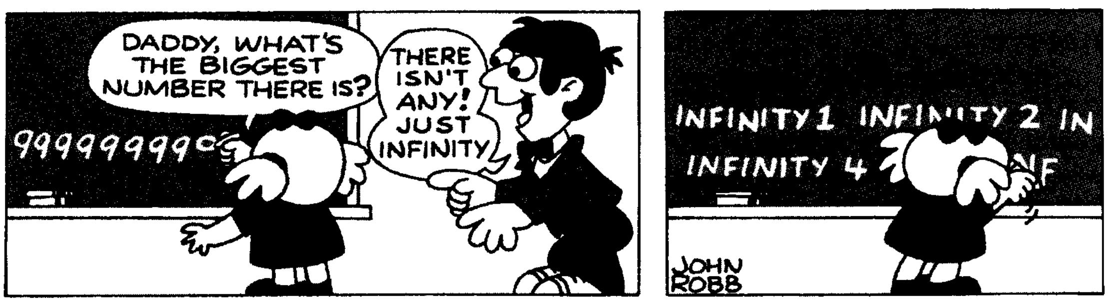
> Accumulated Atomic Clock Time = 1 billion years + 1 billion years + 1 billion years + and so forth indefinitely.
>
> Accumulated Pendulum Clock Time = 1 billion years + 1/2 billion years + 1/4 billion years + 1/8 billion years + and so forth indefinitely.

As we go further and further into the past, the accumulated atomic time approaches infinity, but the accumulated pendulum clock time does not; it approaches 2 billion years:

$$1+\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}+\frac{1}{32}+\frac{1}{64}\ldots=2$$

The arithmetic is similar to the problem we discussed earlier, where we saw that the speed of a rock hitting the ground approached 49 meters per second, as we kept computing its average speed at intervals successively closer to the ground. Thus, in our example, gravitational time points to a definite *origin* of time, and atomic time does not.

The example we have chosen is just one of many possibilities, and we picked it for its dramatic qualities. But it illustrates that questions relating to the measurement of time must be carefully considered. To ask questions about time and not specify how we will measure it is most probably an empty exercise.




## THE DIRECTION OF TIME AND SYMMETRIES IN NATURE—AN ASIDE

We can relate this discussion of the billiard balls and time's direction to what was said about mathematics and time earlier. We recall that a mathematician-scientist characterizes a problem by the initial conditions, the boundary conditions, and the laws that govern the process she is investigating. The direction of time's arrow is a consequence of initial conditions and not a consequence of the laws governing the motions of the balls. The initial condition that all of the balls start from a triangular nest and proceed toward random positions over the surface of the table gives a sense of time's direction.

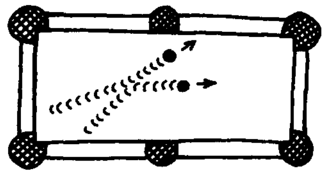
If the balls had started out randomly—that is, if the initial condition had been a random placement of the balls, with random speeds and directions of motion—then we would have no perception of time's direction. But the *laws* governing the motion are the same whether the balls are initially grouped or scattered over the surface of the table.

These observations bring up a very interesting question: Is there no sense of time direction in a random universe? From preceding discussion, it would appear that there is not. But we cannot give a final answer to this question. Until 1964, it appeared that there was no law in nature that had any sense of time direction, and that time's arrow is simply a consequence of the fact that nature is moving from order to disorder. That is, in the distant past the universe was compact and ordered, and we are now some 10 to 20 billion years down the path to disorder. We shall discuss this again later, in connection with the "big bang" theory of the universe.

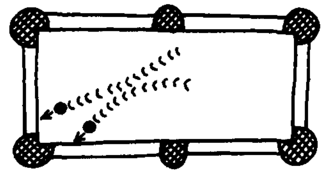
## THE STRUGGLE TO PRESERVE SYMMETRY

To dig deeper into this question of time's direction, we move into an area of physics that is on the frontier of experimentation and theoretical development. This means the subject is highly controversial and by no means resolved. All we can do at this point is attempt to describe the present state of affairs, and our guess as to what the future will bring to light is perhaps as good as anyone's.

As we have said, there was no evidence until 1964 that the laws of nature contained the least indication of the direction of time. But 10 years before that, in 1954, two physicists, T.D. Lee and C.N. Yang, of the Institute for Advanced Study, at Princeton, inadvertently opened up new speculation on this subject.



THIS IS A MOVIE OF TWO BALLS COLLIDING



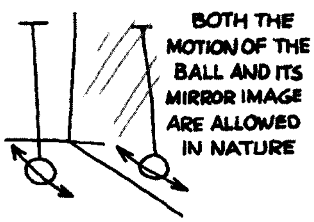
THIS IS THAT MOVIE SHOWN BACKWARD

BOTH THE MOVIE AND ITS BACKWARD VERSION CAN OCCUR IN NATURE

TIME INVARIANCE

A very powerful notion in physics is that there is a certain symmetry inherent in nature and that the detection of symmetries greatly clarifies our understanding of nature. Let's return to our two billiard balls for an example. We found that there was no way to determine the direction of time by running the film forward and backward—assuming that the table is frictionless. The laws governing the interactions and motions of the balls are not sensitive to time's direction. We could extend this test to any of the laws of nature that we wished to investigate by making movies of processes governed by the law under consideration. As long as we could not tell the difference between running the film backward and forward, we could say that the laws were insensitive to time's direction, or in the language of physics, time "invariance"—or $T$ invariance—is preserved.

But $T$ invariance is not the only kind of symmetry in nature. Another kind of symmetry is what we might call left–right symmetry. We can test for this kind of symmetry by performing two experiments. First, we set up the apparatus to perform a certain experiment, and we observe the result of *this* experiment. Then we set up our apparatus as it would appear in the mirror image of our first experiment and observe the result of this experiment. If left–right symmetry is preserved, then the result of our second experiment will be just what we observe by watching the result of our first experiment in a mirror. If such a result is obtained, then we know that left–right symmetry is preserved—or as the physicist would say, there is *parity* between left and right, or $P$ invariance is preserved.

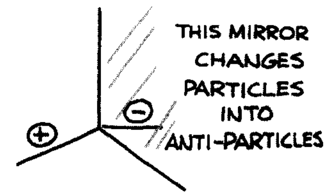



LEFT-RIGHT INVARIANCE OR "P" INVARIANCE

Until 1956, everyone believed that left–right parity was always preserved. No experiment gave any evidence to the contrary. But Lee and Yang, in order to explain a phenomenon that was puzzling scientists studying certain tiny atomic particles, proposed that parity is not *always* preserved.

The issue was settled in 1957 by an experiment performed by Chien-Shiung Wu of Columbia University. In this experiment she lined up the nuclei of radioactive atoms in a magnetic field so they all spun in the same direction. What she observed was that more electrons were given off in one direction than in another. The implication was that left–right parity was violated as Lee and Yang had predicted.

The violation of parity—*P* invariance—greatly disturbed physicists, and they looked for a way out. To glimpse the path they took we must consider a third kind of symmetry principle in addition to *T* and *P* invariance. This is called *charge conjugation*, or *C* invariance. In nature every kind of particle has an opposite number called an *antiparticle*. These antiparticles have the same properties as their counterparts except that their electric charges, if any, are opposite in sign. For example, the antiparticle for the *electron*, which has a negative charge, is the *positron*, which has a positive charge. When a particle encounters its antiparticle they can both disappear into a flash of electromagnetic energy, according to Einstein's famous equation $E = Mc^2$. Antiparticles were predicted theoretically by the English physicist Paul Dirac in 1928, and were detected experimentally in 1932 by American physicist Carl Anderson, who was studying cosmic rays.




CHARGE CONJUGATION OR "C" INVARIANCE

But what has all of this to do with the violation of parity—and of even more concern to us—*time reversal*? Let's deal with the parity question first. As we have said, experiments demonstrated that parity was violated were performed with a very disturbing result. But physicists were able to salvage symmetry in a very ingenious way: If the mirror is replaced by a new kind of mirror, which not only gives a mirror image but also transforms the particles in the experiment into their corresponding antiparticles, symmetry is preserved. In other words, we obtain a result that does not violate a new kind of symmetry. We could say that nature's mirror not only changes right to left, but also reverses matter into antimatter. Thus charge invariance and parity invariance taken together are preserved—*CP* invariance is preserved—and physicists were much relieved.

SYMMETRIES
TIME INVARIANCE
LEFT RIGHT
CHARGE CONJUGATION

This inner peace was short lived, however. In 1964 J. H. Christenson, J. W. Cronin, R. Turley, and Val Fitch performed an experiment that gave a result that could not be accounted for even by a mirror that replaced matter by antimatter, and *CP* symmetry was broken. But this turns out to have an implication for time invariance, or *T* invariance. From relativity and quantum mechanics, cornerstones of modern physics, comes a super-symmetry principle that says: If we have a mirror that changes left to right, exchanges matter for antimatter, and on top of all this, causes time to run backward in the sense of showing a movie backward—then we get a result that should be allowed in nature. Cronin and Fitch, somewhat belatedly, received the 1980 Nobel prize for their part in this work.

We must underline here that this super-symmetry principle is not based on a few controversial experiments undertaken in the murky corners of physics, but is a clear implication of relativity and quantum mechanics; to deny this super principle would be to undermine the whole of modern physics. The implication of the 1964 experiment that demonstrated a violation of *CP* invariance requires that time invariance symmetry—*T* symmetry—be broken, if the super principle is to be preserved. Nobody to date has actually observed *T* invariance symmetry violated. It is only inferred from the broken *CP* symmetry experiment combined with the super-symmetry principle.

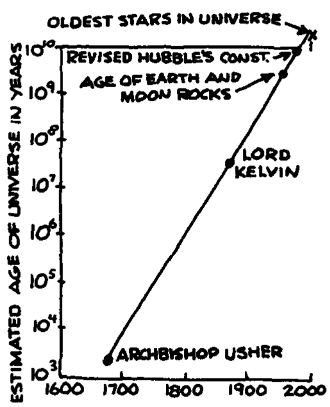
It is not clear what all of these broken symmetries mean for people in their everyday life. But such difficulties in the past have always created a challenge leading to new and unexpected insight into the underlying processes of nature. The violations of the symmetry principles we have discussed represent only a very few exceptions to the results generally obtained, but such minute discrepancies have many times led to revolutionary new ways of looking at nature.

Chapter

1 2 3 4 5 6 7
8 9 10 11 12 13 14
15 16 **17** 18 19 20 21
22 23 24 25 26 27 28
29 30 31

# TIME AND ASTRONOMY

We have seen that the measurement and determination of time are inseparably related to astronomy. Another facet of this relationship, which sheds light on the evolution of the universe and the objects it contains, has been revealed over the past few decades. In this chapter, we shall see how theory combined with observations has allowed us to estimate the age of the universe. We shall discuss some stars that transmit signals like "clockwork," and we shall discuss a peculiar kind of star to which the full force of relativity theory must be applied if we are to understand the flow of time in the vicinity of such a star. And finally, we shall discuss a new technique of radio astronomy that became possible only with the development of atomic clocks and has interesting applications outside of radio astronomy.




## MEASURING THE AGE OF THE UNIVERSE

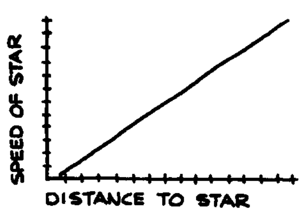
In 1648, Irish Archbishop Usher asserted that the universe was formed on Sunday, October 23, 4004 B.C. Since then there have been numerous estimates of the age of the universe, and each new figure places the origin back in a more distant time. In the 19th Century, Lord Kelvin estimated that it had taken the Earth 20 to 40 million years to cool from its initial temperature to its present temperature.

In the 1930's, radioactive dating of rocks settled on two billion years, and the most recent estimates for the age of the universe lie between 8 and 16 billion years.

These newest estimates are developed along two lines of thought and observation: The first relates the age of the universe to the speeds, away from the Earth, of distant galaxies. The second is obtained from observations of the makeup of the universe that peg it as being at a particular point in *time* along its evolutionary "track."

### The Expanding Universe—Time Equals Distance

Throughout much of history, people have tended to think of the universe as enduring "from everlasting to everlasting." But in 1915, Einstein applied his theory of general relativity to the problem of the evolution of the universe and reluctantly came to the conclusion that the universe is dynamic and expanding. In fact, he was so dubious about his conclusion that he introduced a new term into his equations—the "cosmological term"—to prevent his equations from predicting this expansion. Then in 1929, some 14 years later, the American astronomer Edwin Hubble discovered that the universe was indeed expanding, and Einstein is reported to have said that the cosmological term was "the biggest blunder of my life."



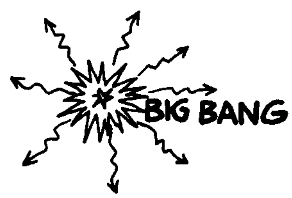
HUBBLE'S DISCOVERY

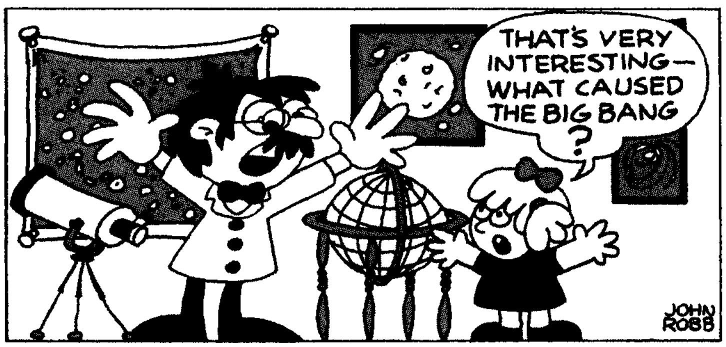
We have already encountered the technique used by Hubble to discover the expanding universe. It is based on the Doppler effect, whereby the whistle of an approaching train seems to have its frequency shifted upward and then shifted downward as the train moves away. Hubble was investigating the light from a number of celestial objects when he noticed that certain aspects of the light spectrum were shifted to lower frequencies, as though the radiating objects were moving away from the Earth at high speeds. Furthermore, the more distant the object, the greater its speed away from the Earth.

With Hubble's discovery of the relationship between distance and speed, it was possible to estimate an age of the universe. The fact that all objects were moving away from the Earth meant that all celestial objects had at some time in the distant past originated from one point. The observed distance to the objects, with their corresponding recessional speeds, when extrapolated backward in time, indicated an origin about 20 billion years ago. We might suspect that the recessional speeds have been slowing down with time, so the age of the universe could be less than that derived from the presently measured speeds. In fact, using the evolutionary line of reasoning to estimate the age of the universe, we find that this seems to be the case.

### Big Bang or Steady State?

Scientists have developed theories for the evolution of the universe. According to these theories, the universe evolves in a certain way, and the constitution of the universe at any time is unique. Observations to date suggest that the universe is about ten billion years old, which fits in with the notion that the universe was, at an earlier date, expanding at a greater rate than it is today. This theory is known popularly as the "big bang" theory. It postulates that at the origin of time, the universe was concentrated with infinite density and then catastrophically exploded outward, and that the galaxies were formed from this primordial material.




Competing with this theory is the "steady-state" theory, which is more in line with the philosophical thought that the universe endures "from everlasting to everlasting." But the great bulk of the astronomical observations today agrees with the big bang theory rather than the steady-state theory, and the steady-state theory has been largely abandoned.

We are still faced with the unsettling question of what was before the big bang. We do not have the answer. But perhaps you will have realized by this point that time has many faces, and perhaps in the long run questions of this sort, relating to the ultimate beginning and end of the universe, are simply projections of our own micro experience into the macroworld of a universe that knows no beginnings and no ends.

We shall investigate these questions again in Chapter Eighteen.

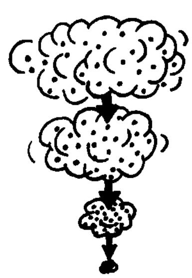
### STELLAR CLOCKS

Often in science, a project that was intended to explore one area stumbles unexpectedly upon interesting results in another. Several years ago, a special radio telescope was built at Cambridge University's Mullard Radio Observatory in England, to study the twinkling of radio stars—stars that emit radio waves. The twinkling can be caused by streams of electrons emitted by the Sun. It may be very fast, so equipment was designed to detect rapid changes.

PULSAR SIGNAL

In August of 1964, a strange effect was noticed on a strip of paper used to record the stellar radio signals: A group of sharp pulses was bunched tightly together. The effect was observed for over a month and then disappeared, only to reappear. Careful analysis indicated that the pulses were coming with incredible regularity at the rate of 1 337 301 13 per second, and each pulse lasted 10 to 20 milliseconds. Such a uniform rate caused some observers to suspect that a broadcast by intelligent beings from outer space had been intercepted. But further observations disclosed the presence of other such "stellar clocks" in our own galaxy—the Milky Way Galaxy—and it did not seem reasonable that intelligent life would be so plentiful within our own galaxy.

It is generally believed now that the stellar clocks, or *pulsars*, are neutron stars, which represent one of the last stages in the life of a star. According to the theory of the birth, evolution, and death of stars, stars are formed from interstellar dust and gas that may come from debris left over from the initial big bang or from the dust of stars that have died in a violent explosion or *super nova*.

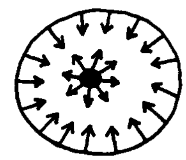


FORMATION OF STAR

A particular cloud of gas and dust will begin to condense because of the mutual gravitational attraction between particles. As the particles become more compact and dense, the gravitational forces increase, forming a tighter and tighter ball, which is finally so dense and hot that nuclear reactions, like a continuously exploding H bomb, are set off in the interior of the mass.

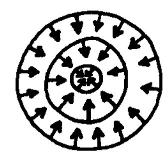
### White Dwarfs

In a young star, the energy of heat and light is produced by the nuclear burning of hydrogen into helium. The pressure generated by this process pushes the stellar material outward against the inward force of gravitation. The two forces struggle against each other until a balance is reached. When the hydrogen is exhausted, the star begins to collapse gravitationally upon itself again, until such a high pressure is reached that the helium begins to "burn," creating new and heavier elements. Finally, no further burning is possible, no matter what the pressure, and the star begins to collapse under its own weight.



STRUGGLE BETWEEN GRAVITY AND OUTWARD PRESSURE PRODUCED BY NUCLEAR FURNACE

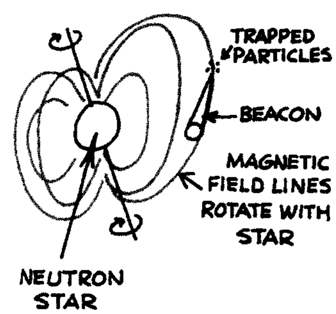
At this point, what happens to the star depends upon its mass. If its mass is near that of our own Sun, it collapses into a strange kind of matter that is enormously more dense than matter organized into the materials we are familiar with on Earth. One cubic centimeter of such matter weighs about 1000 kilograms. Such a collapsed star is called a "white dwarf," and it shines faintly for billions of years before becoming a "clinker" in space.



NUCLEAR FURNACE BURNS OUT AND STAR COLLAPSES ON ITSELF

### Neutron Stars

For stars that are slightly more massive than our Sun, the gravitational collapse goes beyond the white dwarf stage. The gravitational force is so great and the atoms are jammed together so closely that the electrons circling the core of the atom are pressed to the core, joining with the protons to form neutrons with no electrical charge. Normally, neutrons decay into a proton, a particle called a neutrino, and a high-speed electron, with a half-life of about 11 minutes—that is, half of the neutrons will decay in 11 minutes. But given the enormous gravitational force inside a collapsed star, the electrons are not able to escape, and thus we have a "neutron star"—a ball about 20 kilometers in diameter, having a density a hundred million times the density of a white dwarf. Such an object could rotate very fast and not fly apart, and it looks as though the neutron star is the answer to the puzzling "stellar clocks."

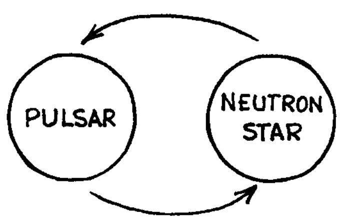


But where do the pulses come from? Such a neutron star will have a magnetic field that rotates with the star, as the Earth's magnetic field rotates with the Earth. Electrically charged particles near the star will be swept along by the rotating magnetic field; the farther they are from the star, the faster they will have to rotate—like the ice skater on the end of a "crack the whip" chain.

The most distant particles will approach speeds near that of light. According to the relativity theory no particle can exceed the speed of light, so these particles will radiate energy to "avoid" exceeding the speed of light. If the particles are grouped into bunches, then each time a bunch sweeps by, we will see a burst of light or radio energy as though it were coming from a rotating beacon of light. Thus, the pulses we detect on Earth are in reality the signals produced as the light sweeps by us. If such an explanation is correct, then the star gradually loses energy because of radio and light emission, and the star will slow down. Careful observations show that pulsar rates *are* slowing down gradually, by an amount predicted by the theory.

### Pulsars and Gravitational Waves

A remarkable discovery in the 1970's turned out to be a case study in the importance of time and frequency technology to astronomy. Russell A. Hulse and Joseph H. Taylor, Jr., in the course of a systematic survey of the sky for pulsars, discovered a pulsar that did not fit the normal pattern. It emitted pulses at a rate of about 17 per second, but the period of the pulses changed by about 80 microseconds from one day to the next. This was an entirely unforeseen result.




Further investigation showed that the signal pattern varied in a regular way, repeating itself at intervals of 7 hours and 45 minutes. Hulse and Taylor speculated that the pattern could be explained if the pulsar were orbiting a companion star—probably a neutron star. This unexpected pairing of a neutron star with a pulsar suggested to Hulse and Taylor that here was an ideal situation to test an important prediction of the General Theory of Relativity that had never been tested.

According to the theory, any accelerating body should emit gravitational waves—ripples in spacetime that propagate with the speed of light—in analogy to accelerated electrons emitting radio waves. But the gravitational waves would be exceptionally weak except for the most massive bodies.

Calculations suggested that the gravitational waves generated by the neutron-pulsar pair were carrying off energy at the rate of about one-fifth the total radiation from the Sun—an extraordinary amount of energy. One implication of this energy loss is that the distance between the neutron star and pulsar should slowly decrease by a few meters a year. But how do we measure such a minute change at such a great distance?

Further calculations showed that the slow approach of the two stars translated into a detectable variation in the pulsar's radio emissions. By carefully measuring the radio pulses over a period of years, Taylor and his colleagues determined that the change in the pulse pattern was in almost exact agreement with the General Theory of Relativity.

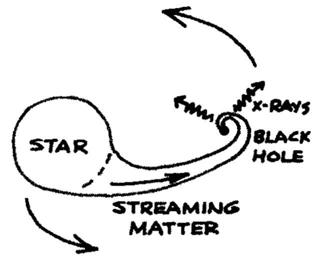
For their efforts, Hulse and Taylor received the 1993 Nobel prize in physics.

### Black Holes—Time Comes to a Stop

Stars with masses about that of our own Sun or smaller collapse into white dwarfs; slightly more massive stars collapse into neutron stars. Now let's consider stars that are so massive that they collapse into a point in space.

In the case of the neutron star, complete collapse is prevented by the nuclear forces within the neutrons, but with more massive stars, gravitation overcomes even the nuclear forces; according to the theories available today, the star continues to collapse to a point in space containing all of the mass of the original star, but with zero volume, so that the density and gravity are infinite—gravity is so strong near this object that even light cannot escape; hence the term *black hole*.

These fantastic objects—black holes—were postulated theoretically, within the relativity theory, in the late 1930's. Over the years, evidence has steadily accumulated indicating that they do indeed exist. One important observation reveals a star circling around an invisible object in space. In

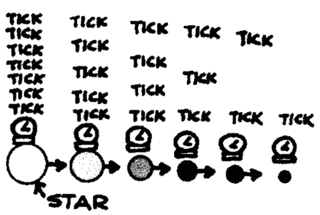



the vicinity of this unseen star, or black hole, strong x-rays are emitted, and it is suspected that these x-rays are generated by matter streaming into the black hole, matter that the gravity field of the black hole pulls away from the companion star.

Launching of the Hubble telescope seems to have clinched the matter. Photos of the universe, undistorted by the Earth's intervening atmosphere, reveal dozens of probable locations for black holes—including the center of our own Milky Way Galaxy.

How would time behave in the vicinity of such a strange object? We recall from our section on relativity that as the gravitational field increases, clocks run more slowly. Let's apply this idea to a black hole. Suppose we start out with a massive star that has exhausted all fuel for its nuclear furnace and is now beginning to undergo gravitational collapse.

Suppose that on the surface of this collapsing star we have an atomic frequency standard whose frequency is communicated to a distant observer by light signals. As the star collapses, the frequency of the atomic standard, as communicated by the light signal, would decrease as the gravitational field increases. Finally, the diameter of the star reaches a critical value where the gravitational pull is so strong that the light signal is not able to leave the surface of the star. Our distant observer would notice two things as the star approaches this critical diameter: First, the clock on the surface of the star is running more and more slowly; at the same time, the image of the star is getting weaker. Finally, we are left with only the "Cheshire cat smile" of the star.




FORMATION OF BLACK HOLE

A careful mathematical analysis of the situation shows that for the distant observer, it appears to take infinite time for the star to reach this critical diameter; but for an observer riding with the clock on the surface of the star, the critical size is reached in a finite length of time.

What does all of this mean? No one knows for sure. The equations indicate that the massive star just keeps collapsing on itself until it is merely a point in space. Mathematicians call these points in space *singularities*; when a singularity is encountered in a mathematical law of nature, it usually means that the theory has broken down and scientists start looking for a more powerful theory that will lead them into new pastures. It has happened many times before in physics. For example, when Niels Bohr postulated that an electron could circle around an atom without spiraling into the nucleus, he provided a stepping-stone toward a whole new concept of the microworld. Perhaps the "black hole" is the doorway connecting the microworld to the macroworld.

## TIME, DISTANCE, AND RADIO STARS

In Chapter 13 we described systems for determining distance and location from synchronized radio signals. Here we shall discuss a new technique for relating time to distance via observations of radio stars—a technique that has grown out of the relatively new science of *radio astronomy*.

RESOLUTION
AREA OF ANTENNA
RADIO FREQUENCY

One of the problems of astronomy is to determine the directions and shapes of distant celestial objects. Astronomers call this the "resolution" problem. The resolution of a telescope is primarily determined by two factors—the area of the device that collects the radiation from outer space, and the radiation frequency at which the observation is made.

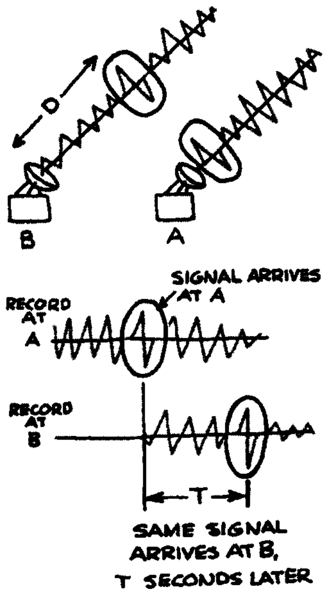
As we might expect, the bigger the collecting area, the better the resolution; but not so obvious is the fact that resolution decreases as we make observations at lower frequencies. For optical astronomers, the area of the collecting device is simply the area of the lens or mirror that intercepts the stellar radiation. And for radio astronomers, it is the area of the antenna—often in the shape of a dish—that figures in the determination of resolution.

Because of the dependence of resolution on frequency, an optical telescope lens with the same area as a radio telescope dish yields a system with much greater resolution because optical frequencies are much higher than radio frequencies. The cost and engineering difficulties associated with building large radio antennas to achieve high resolution at radio frequencies fostered alternative approaches. A system consisting of two small antennas separated by a large distance has the same resolution as one large antenna whose diameter is equal to the separation distance. Thus, instead of building one large antenna 10 kilometers in diameter, we can achieve the same resolution with two smaller antennas separated by 10 kilometers.

But as always, this advantage is obtained at a cost. The cost is that we must very carefully combine the signals received at the two smaller dishes. For large separation distances, the signals at the two antennas are typically recorded on magnetic tape, using high-quality tape recorders.

The two signals must be recorded very accurately with respect to time. This is achieved by placing at the two antenna sites synchronized atomic clocks that generate time signals recorded directly on the two tapes along with the radio signals from the two stars. With the time information recorded directly on the tapes, we can at some later time bring the two tapes together—usually at a location where a large computer is available—and combine the two signals in the time sequence in which they were originally recorded. This is important, for otherwise we will get a combined signal that we cannot easily disentangle.

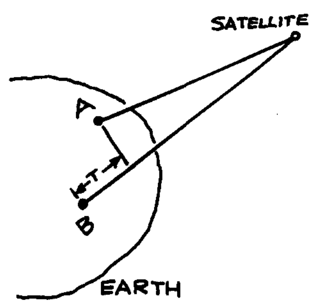
It is also important that the radio-star signals be recorded with respect to a very stable frequency source; otherwise, the recorded radio-star signals will have variations, as though the radio telescopes were tuned to different frequencies of the radio-star "broadcast" during the measurement. The effect would be similar to trying to listen to a radio broadcast while someone else was continually tuning to a new station. The atomic standard provides this stable frequency-reference signal. These requirements for time and frequency information are so stringent that the two-antenna technique, with large separation, is not practical without atomic clocks.




To understand the implications of this technique, called "long baseline interferometry," for synchronization and distance measurement, we need to dig a little more deeply. In the sketch, we see a signal coming from a distant radio star. Signals from radio stars are not at one frequency, but are a jumble of signals at many frequencies, so the signal has the appearance of "noise," as shown in the sketch. We have already discussed this feature of radio star signals in Chapter 13.

Let's now consider a signal that is just arriving at the two antennas. Because the star is not directly overhead, the signal arriving at antenna A still has an extra distance $D$ to travel before it reaches antenna B. Let's suppose that it takes the signal a time $T$ to travel the extra distance, $D$, to antenna B. Thus we are recording the signal at A, a time $T$ before it is recorded at B. The situation is similar to recording a voice transmission from a satellite at two different locations on the Earth. Both locations record the same voice transmission, but one transmission lags B behind the other in time.

Let's replace the radio star with a satellite. Suppose we know the locations of the satellite and the two Earth sites, A and B, as shown in the sketch. We record the two voice transmissions on tape and later bring the two recordings together and play them back simultaneously. We hear two voices, one the "echo" of the other.




Now suppose that we have a device that allows us to delay the signal coming out of tape recorder A by an amount that is accurately indicated by a meter attached to the delay device. We adjust the delay from tape recorder A until the two voice signals are synchronized—that is, until the echo has disappeared. The delay required to bring the two voices into synchronism is precisely the delay $T$ corresponding to the extra distance the signal must travel on its way to antenna B, with respect to antenna A.

We stated that we knew the locations of the satellite and of A and B. This is enough information to calculate $T$. Suppose $T$ is calculated to be 100 nanoseconds, but that the delay we measure to get rid of the echo is 90 nanoseconds. We are now confronted with a problem. Either the locations of the satellite and of A and B that we used to calculate T are in error, or the atomic clocks at A and B are not synchronized.

We recheck and find that the ground stations and satellite positions are not in error. Therefore, we conclude that the 10 nanoseconds error is due to the fact that the clocks are not synchronized. In fact, they must be out of synchronization by 10 nanoseconds. We now have a new means of synchronizing clocks.

We can also turn this situation around. Suppose we know for certain that the clocks are synchronized, and we also know the position of the satellite accurately. By combining signals recorded at A and B, we can determine what the A–B separation must be to give the measured time lag. Work is now underway using both satellites, GPS for example, and radio stars to measure the distance between distant parts of the surface of the Earth to a few centimeters. Such measurements give new insight into Earth crust movements and deformations that may be crucial for the prediction of earthquakes.

The uses to which the relationships of time, frequency, and astronomy may be put are far reaching, and we probably have seen only the beginning.

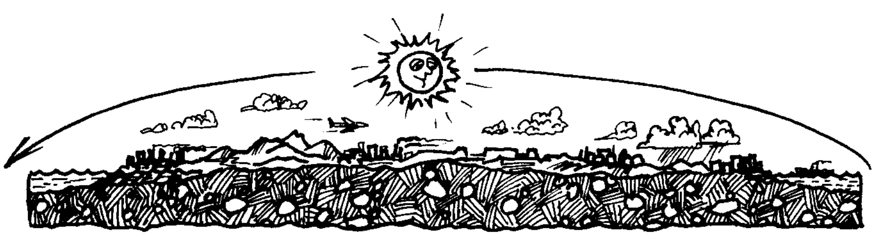
# Chapter 18

# UNTIL THE END OF TIME

*You're searching, Joe*
*For things that don't exist.*
*I mean beginnings*
*Ends and beginnings*
*Ends and beginnings—there are*
*no such things*
*There are only middles.*
Robert Frost

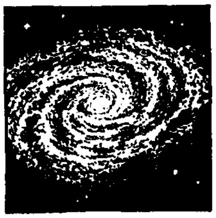
## PARADOXES

Common-sense observation is all too often an unreliable guide to the nature of the universe. What could be more obvious than that the Earth is flat and circled by the Sun? Yet, nothing could be further from the truth.



THE FLAT EARTH

ATOM



GALAXY

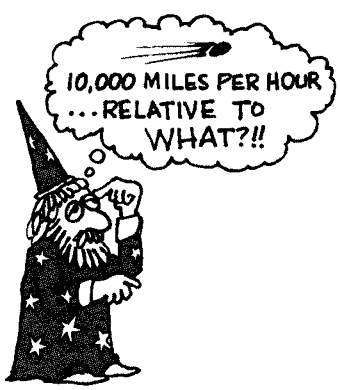
Part of the problem is the universe's immense scale—from subatomic particles to vast spiral galaxies. Humans, being neither subatomic nor galactic in scale, have only firsthand knowledge of other similarly sized objects: horses, marbles, bricks, automobiles, and so on. Even some of our own handiwork embraces scales beyond human comprehension. Who can fathom, standing on the sidewalk below, a 100 story skyscraper or grasp the meaning of millions of circuit connections on a postage-stamp-sized computer chip?

Common-sense notions of the Earth, its position in space and time and its relation to other matter in the universe were, under close scrutiny, troublesome long before Einstein. If the Earth was flat, did it have a boundary? And if it did, would you fall at the boundary, and to where?

WRONG IDEAS → PARADOXES

It was hard to imagine a bounded Earth, so, perhaps, the Earth was not bounded. But that was hard to believe too. How could space be infinite? The idea of a flat Earth, bounded or otherwise, leads to paradoxical questions. Often beliefs that generate paradoxes suggest that something is wrong with the belief that generates them. For example, when we abandon a flat Earth and substitute a spherical Earth, suspended in space, the paradoxes go away. (Now we have to wonder how something can float in space, which leads to a whole new set of questions.)

Perhaps, in the some way, paradoxical questions about time, whether it has a beginning and an end, arise because we have faulty beliefs about the underlying nature of time. We shall return to this question.



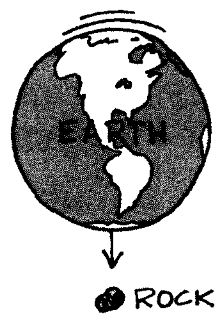

One common-sense truth is that the universe is filled with objects occupying space and existing in time. Yet this common-sense universe generates some fascinating questions. For example, early philosophers and scientists wondered what motion meant in a universe containing a single object. How could one measure the speed of a solitary object? Speed is measured relative to something—the surface of the Earth or perhaps the distant stars. But in a one-object universe there is no "something else."

Newton was considerably perplexed by these problems, especially as they related to his own formulation of the laws of motion. One problem he found particularly vexing had to do with space—more particularly "absolute" space. The problem stemmed directly from his belief that the laws of motion are the same for all uniformly moving reference systems. In other words, it didn't matter, for example, whether you played billiards at your favorite parlor or on a ship moving steadily across the sea—the balls, given identical collisions, moved the same in both settings. In fact, if you were placed blindfolded on a smoothly sailing ship containing an exact replica of your favorite billiard parlor, you would never know from the motion of the balls whether you were on ship or shore.

But therein lies the problem. If the laws of motion are identical for all uniformly moving platforms, how is one to pick one over the other, to say one represents absolute space and the others do not? Newton never resolved that dilemma.

However, he had no trouble believing that all clocks kept the same time whether on his mantle or a moving ship. The extent to which clocks did not keep the same time simply reflected the inability to perfect clocks accurately mirroring the relentless, uniform flow of time throughout the universe.

But, as we saw in Chapter 16, the notion of absolute time was eventually abandoned. We explored this idea by considering how time, as kept by a photon bouncing between two mirrors, does not "tick" at the same rate for observers who are stationary relative to the mirrors and those who move at uniform velocities relative to the mirrors.




EARTH FALLS TOWARD ROCK ?!!

"TIME IS NOT ABSOLUTE"
- A. EINSTEIN

### TIME IS NOT ABSOLUTE

The seeds of the downfall of absolute time were planted in 1676 when the Danish astronomer, Ole Christensen Roemer, discovered that light travels with finite speed—not with infinite speed as many at the time believed. By making some clever measurements of the instants when Jupiter eclipsed its moons, he concluded that light travels at about 225 000 kilometers per second, not too far from the modern value, 299 000 kilometers per second.

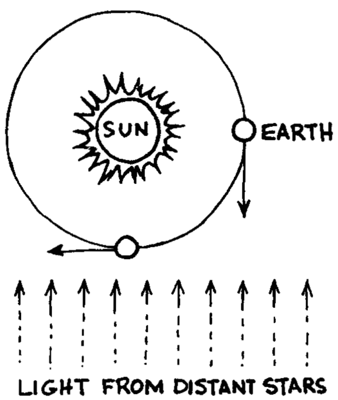
Incidentally, Roemer made this discovery serendipitously since his primary mission was related to Galileo's suggestion of using the eclipse times of the Jovian moons as a master clock for navigation.


RECIPE FOR LIGHT:
1 PART ELECTRICITY
PLUS
1 PART MAGNETISM

However, a satisfactory theory for the propagation of light didn't appear until 1865. In that year, the British mathematician and physicist, James Clerk Maxwell—the same Maxwell who concluded that gases consisted of atoms—succeeded in combining two partial theories of electricity and magnetism into one complete theory, which, among other things, predicted a new kind of wave, the electromagnetic wave. Curiously enough, as Maxwell pointed out, this new wave travelled at the speed of light and exhibited all the other known characteristics of light. It was a small step to conclude that light was, indeed, an electromagnetic wave.

LIGHT SIGNAL SPEEDS THROUGH ETHER AT 186,000 MILES PER SECOND.

Since the theory predicted that light moved at 299 000 kilometers per second, the question naturally arose "299 000 kilometers per second relative to what?" The general consensus at the time was that light traveled through a substance called "ether," much as sound waves travel through the air, and it was this ether that the 299 000 kilometers per second referred to. Thus, an observer moving through the ether toward a light source should observe the light traveling at a speed greater than 299 000 kilometers per second while one moving away from the light source should observe a lesser speed. Some onlookers at the time noted that this "ether" sounded suspiciously like the "absolute space" Newton's laws couldn't locate.




MICHELSON - MORLEY EXPERIMENT

In any case, two American scientists, Albert Michelson and Edward Morley, carried out a number of carefully designed experiments at the Case School of Applied Science in Cleveland, aimed at observing the variation in the speed of light depending on the direction of motion of the observer relative to the light source. With the Earth as their measuring platform, they measured the speed of light emitted by distant stars in the direction of the Earth's motion as well as at right angles to the Earth's motion. Much to their surprise, and that of the scientific world, they could detect no variation. The speed of light remained firmly at 299 000 kilometers per second whatever the observer's motion. It was as though two automobiles approaching each other at 100 kilometers per hour observed each other's relative speeds as 100 kilometers per hour—not 200 kilometers per hour. Common sense had, once again, been a false guide.

## GENERAL THEORY OF RELATIVITY

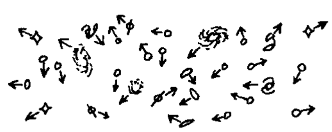
As we know from previous chapters, one of the cornerstones of Einstein's Special Theory of Relativity was that the speed of light was the same for all observers independent of their relative motions. Thus, what had been an enigma to Michelson and Morley became a foundation of Einstein's new version of the laws of motion. Later Einstein, in his General Theory of Relativity, included gravity. One of the essential conclusions of his new theory was that space, time, and matter no longer led independent lives, the kind they enjoyed in Newton's universe, but were now inextricably intertwined, mutually defining each other. So absolute space, time, and matter fell by the way in a new vision of the universe.

"THE SPEED OF LIGHT IS THE SAME FOR ALL OBSERVERS."
-A. EINSTEIN

But still, powerful as General Relativity was, the infinitude, or finiteness, of time was undetermined as a consequence of the intertwining of matter, space, and time. In other words, time and space depended on the distribution of matter throughout the universe, an issue to be decided by astronomers, not theoretical physicists with only pen and paper at hand.

Einstein was the first to explore the nature of time with his new General Theory of Relativity. The common-sense belief in the first part of this century, when Einstein formulated his General Theory of Relativity, was that the universe was essentially static. From that starting point we could assume that the universe had either existed forever or that it had somehow appeared in its present form at some instant in the finite past. But under General Relativity a static universe was not possible. Unfortunately, Einstein was so influenced by the notion of a static universe that he modified General Relativity by adding a new repulsive force, the "cosmological constant," that kept the universe from collapsing. But even with this repulsive force, Einstein's universe was unstable.

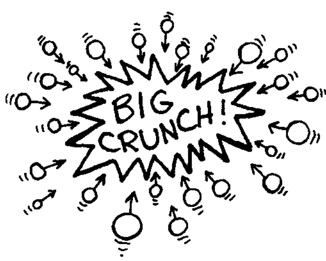
STATIC UNIVERSE
OR...
MOVING UNIVERSE



Had Einstein stuck by his original theory of General Relativity he would have made one of great predictions of all time—that the universe was collapsing, or alternatively, expanding. But at the time of the birth of his theory, there was no evidence of the universe doing either.

In 1922 the Russian mathematical physicist, Alexander Friedman, proposed the first realistic model of the universe. He scrapped Einstein's cosmological constant and proceeded on the basis of a simple assumption: the universe appears the same in every direction no matter where in the universe the observations are made. With this assumption he was able to show that there are only three possibilities: either the universe expands, or contracts, or expands at a critical rate just fast enough to avoid recollapse. Which of these possibilities held up depended on the distribution of mass throughout the universe. However, with any of these models the universe had to have a beginning. So, if Friedman's analysis was correct, one of the puzzles about time had been resolved—time had a beginning; it began with the creation of the universe. It was no longer possible to think of time as something that predated the universe, and that the universe came into existence at some moment in preexisting time.

"TIME HAS A BEGINNING"
-A. FRIEDMAN




But there was still the question of whether time had an end, which in turn depended on the ultimate fate of the three possible universes. If the universe continued to expand forever, then time extended indefinitely into the future. But if the universe eventually recollapsed, then time ended at the instant of what is called "the big crunch."

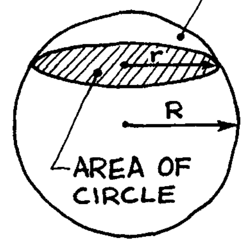
Although Einstein's application of General Relativity to the problem of time led him astray, it did nevertheless contain some key ingredients. As we stated earlier, General Relativity demands that space, time, and matter be intimately connected. More specifically, space and time are altered by matter. We have already learned how the ticking rate of a clock is altered in the presence of matter—in the presence of a gravitational field. But space is also altered by matter: it curves.

IN FLAT SPACE, THE VOLUME OF A BALL EQUALS $4/3\pi r^3$.

IN CURVED SPACE, THE VOLUME OF A BALL MAY BE LESS THAN $4/3\pi r^3$.

Curved space is a difficult notion to grasp and we can only imagine it by analogy. In flat space, the volume of a sphere is $4/3\ \pi r^3$, the formula we learned in high school geometry. But in curved space the volume of a sphere can be less. For example, in Einstein's static model of the universe, the gravitation of the stars causes the volume of a sphere of radius r to be less than $4/3\ \pi r^3$.

We can, perhaps, understand the impact of the curvature of space on geometric figures by considering the following circumstance. First, we draw a circle of radius, r, on the two-dimensional surface of the sphere of radius, R, shown in Figure 1. The figure shows that the area enclosed by the circle is less than the corresponding area enclosed by the circle on the surface of the sphere—that area depends on R. As R increases, for example, the area of the circle approaches the familiar $\pi r^2$. Or said differently, as R increases the surface of the sphere becomes increasingly flat.




In this two-dimensional analogy, we can think of the radius R of the sphere as a measure of the curvature of space; so as R increases, the space becomes flatter and thus the area enclosed by the circle on the surface of the sphere approaches the familiar result.

Einstein's static model of the universe, because it contained mass, was curved in on itself, so its volume was finite. This means that, in principle, an astronaut could completely explore Einstein's universe without ever encountering an edge or boundary, just as a two-dimensional creature could explore the surface of a sphere without encountering an edge or boundary.

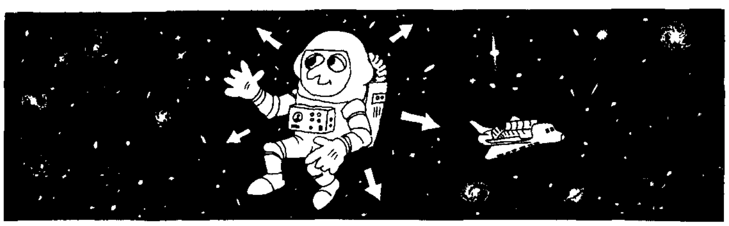
EINSTEIN'S STATIC UNIVERSE CURVED IN ON ITSELF.

Although Einstein's static universe proved untenable, it nevertheless contained an ingredient key to all three versions of Friedman's universe—it was finite and bounded.

Unfortunately, little attention was paid to Friedman's work until Edwin Hubble discovered, as we learned in Chapter 17, that, in fact, the universe was expanding.

#### A BANG OR A WHIMPER?

Friedman's assumption that the universe looked the same in all directions definitely is not true in the vicinity of the Earth. The Earth resides on the edge of a galaxy whose stars are much more dense in the center than they are on the edge. And if we look at greater distances we see clumps



THE UNIVERSE APPEARS TO LOOK THE SAME IN ALL DIRECTIONS of galaxies contained within ever greater clumps of galaxies. Nevertheless, there is compelling evidence that, on a large enough scale, the universe is smooth.

In 1964, two American scientists, Arno Penzias and Robert Wilson, discovered a faint radio noise whose origin they could not, at first, identify. Further investigation revealed that the radiation had a cosmic origin and that the intensity of the radiation was the same in whatever direction they looked. After a few inquiries, the scientists learned that certain theoretical considerations suggested that intense radiation should have been present in the early universe and that a much weaker version of that radiation should be visible today.

As it turned out, this relic radiation was the key piece of evidence that the universe and been born in a colossal convulsion, the "big bang."

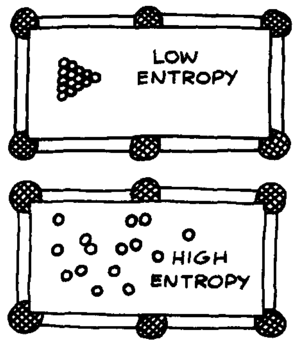

The microwave radiation that Penzias and Wilson found covered a range of radio frequencies that travel through the universe, largely unabsorbed, so it reached us from the very edges of the universe. Nevertheless, any large-scale irregularities in the universe would have had some detectable effect on the radiation, so it would have appeared stronger in some directions than in others. Early Earth-based observations could detect no irregularities but more recent satellite observations have revealed small, but significant, irregularities. These new observations allowed astronomers to breathe a sigh of relief, because in an absolutely smooth universe stars and galaxies would never have formed.

So, will the universe, and time with it, end in the big crunch, or will time go on forever as the universe expands everlastingly? The jury is still out. The direct astronomical evidence indicates that matter is not dense enough throughout the universe to bring about the big crunch. But indirect evidence suggests there is much invisible "dark" matter in the universe which, taken together with the visible matter, might lead to the big crunch. But the odds-on favorite, at the moment, is that there is just enough matter in the universe to lead to Friedman's third model, the one with the universe expanding at the critical rate barely avoiding the big crunch. If this is true, then time had a beginning but has no end.

# Chapter 19

# TIME'S DIRECTION, FREE WILL, AND ALL THAT

In Chapter 16, we considered the idea that the apparent forward motion of time is a consequence of the fact that the universe moves, overall, from organization to disorganization. We considered specifically the case of a billiard game where the balls are initially organized in a triangular pattern, but become increasingly disorganized as the game proceeds. We pointed out that a movie of such a game would clearly not look the same shown forward and backward, that we would easily detect which way the film should be shown to depict the natural, forward flow of time. This view, that the directionality of time is born of increasing disorganization, suggests that, as the universe becomes increasingly disorganized, the directionality of time fades away. Or, if we think of our earlier discussion of temperature in Chapter 6, we could say that when all parts of the universe reach temperature equilibrium, then time's direction ceases.




### TIME'S DIRECTION AND INFORMATION

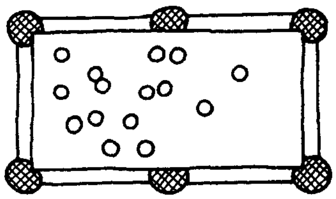
One of the puzzles that led to our "billiard ball" explanation of time's direction was that the underlying laws of physics are time reversible. It makes no difference in Newton's laws, Maxwell's equations of electromagnetism, the equations of quantum physics, Einstein's Relativity, and so

THE BASIC LAWS OF PHYSICS WORK EQUALLY WELL INDEPENDENT OF THE DIRECTION OF TIME.

"THE PAST AND THE FUTURE ARE ONE"
- I. NEWTON

on whether time runs backward or forward. In Newton's laws, for example, we can let time run forward to predict the future course of the moons of Jupiter or we can let time run backward to determine where they were in the past. In a sense, on this view, there is no future or past. But in our common everyday experiences, the future and past are firmly divided between the past, which is known and completed, and the future, which is unknown and yet to happen. But in Newton's universe the future is as knowable as the past and thus time collapses, because there is no profound distinction between present and past. How can we reconcile the reversibility of time at the level of the basic laws of physics with the irreversibility of time we encounter in actual life?

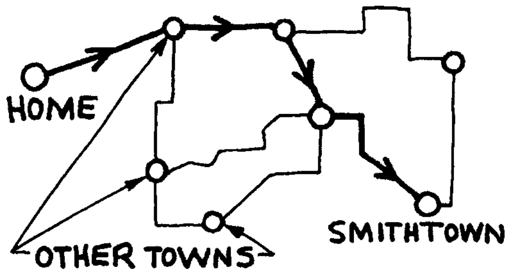
### DISORGANIZATION AND INFORMATION



In one sense, disorganization is simply a lack of information suggesting that we can look at time's direction from an informational point of view. For example, suppose we examine a billiard game after the play has gone on for some time. We see the balls in a certain pattern on the surface of the table. We cannot specifically say how the balls came to occupy these positions. Any number of games viewed at various times might have looked the same, or very nearly the same, as the pattern we see. In other words, the pattern we see does not have a definite history. The balls might have come to occupy their present positions in any number of ways. Only by keeping track of the game (filming the game for example) from the beginning to the present would we know in detail how the balls had come to the present configuration.

This business of keeping track of the game versus not keeping track of the game is reminiscent of our discussion of thermodynamics. There we said that concepts like temperature referred to the gross properties of matter, glossing over the details of the exact positions and motions of the particles making up matter. If we could make a movie of the motions of gas particles in a gas, which we can't with present technology, then we would know, as we did with the billiard game, how the gas particles had come to occupy their positions at any moment in time.

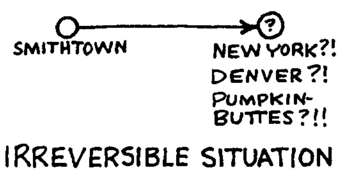
All this is to suggest that if time's direction is a result of increasing disorganization, then it, like temperature, is a property that arises because we gloss over the details of what is going on in particular circumstances, just as temperature arises out of glossing over the exact details of particulate motion.




We can put this matter in better focus by considering an analogous situation. Suppose you want to travel from your home to some distant city, Smithtown. You start by consulting your bus schedule to see what buses go to Smithtown. Normally, there will be many possibilities so you select the connections that minimize your total travel time. We shall assume, as is generally the case, that the number of buses running back and forth between any pair of cities on the way to Smithtown is the same. In other words, you can go back and forth with equal ease between any two cities. We shall call this *"microscopic reversibility."*


After you have completed your business in Smithtown you consult your bus schedule and retrace your steps back home.

Suppose now, on some other trip to Smithtown, you can't find your schedule when it is time to return home. All the numbered gates, with their arriving and departing buses, are still there. The only thing that has changed is your knowledge of the destinations and departure and arrival times of the buses. Without this information, even with a bagful of money, your chances of getting home are pretty slim. You may end up in New York or Denver or Pumpkin Buttes. But notice the only thing that has changed is your information about what is going on. The physical situation remains unchanged—the buses come and go as before. Yet,

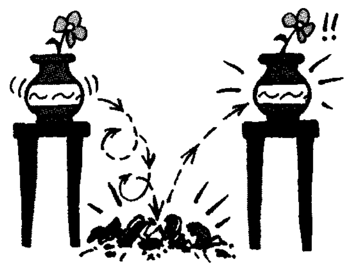


what was once a reversible situation has become an irreversible situation.

The time-reversal symmetry that we see in the basic laws of physics refer to microscopic reversibility where every occurrence can be undone by reversing whatever caused the occurrence—by letting time run backwards. Only in very special circumstances we can undo what has been done, because, like the balls on the billiard table, we don't know what has been done to bring about the present situation. We simply cannot mark and keep track of every atom and molecule, every subatomic particle and photon. In all but the simplest phenomena we have to employ gross concepts, like temperature, which are averages over innumerable, unmarked, microscopic particles. This leads to what is called "*macroscopic irreversibility*" and it is macroscopic irreversibility that gives time its direction.

GROSS CONCEPTS LEAD TO MACROSCOPIC IRREVERSIBILITY.

Before we leave the subject of macroscopic irreversibility we should point out that there is some possibility, however small, that you might find your way back home without a bus schedule. By the same token there is some slight possibility that a vase that has fallen to the floor and smashed to bits might reassemble itself. This would require all the bits and pieces of the vase at the microscopic level to retrace their steps. Although possible, calculations show that it would not likely happen over a period of time equal to the age of the universe, some fifteen billion years, or even over many millions of such lifetimes. Yet, if it did happen, we could say that time had run backward, at least for the vase. Or, in the words of W.S. Gilbert from *H.M.S. Pinafore*,



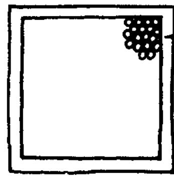
TIME RUNS BACKWARDS

*What never? No, never!*
*What never? Well, hardly ever!*

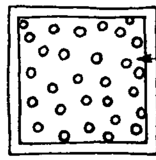
If time's direction is a manifestation of the relentless march from order to disorder, then we have to wonder how it was that the big bang produced an organized universe that could become increasingly disordered to give time a direction? This, as we shall see, is not an easy question to answer—the central problem being, "How can we explain the exquisite detail of the early universe necessary to explain the universe as we see it today?" This result can be approached in a number of ways, but we shall attack it based on some of the thermodynamic ideas we developed in Chapter 6.

In our billiard ball explanation of time's direction, we assumed that someone had initially racked up the balls into a neat, triangular pattern. But who or what "racked up the balls" at the universe's genesis?

We can get some notion of the problems raised by this question by returning to the idea introduced by Maxwell, in Chapter 6, that a gas consists of minute particles continually colliding with each other and the walls of their container.



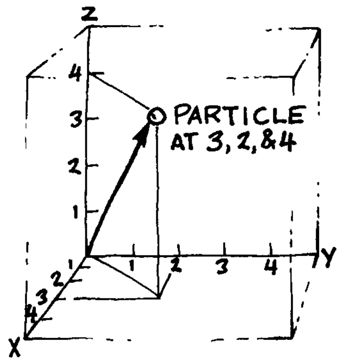

Imagine a gas-filled container in which most of the gas particles reside in some corner of the container. That seems an unlikely state of affairs. It seems far more likely that the particles would be thoroughly, randomly mixed throughout the container. As you will recall from Chapter 16, entropy is a measure of disorder—the greater the disorder, the greater the entropy. In other words, a container in which the particles are all bunched together has lower entropy than does one where the particles are mixed throughout the container—a considerably more likely state of affairs. In fact, this circumstance gives maximum entropy and is called "thermal equilibrium."



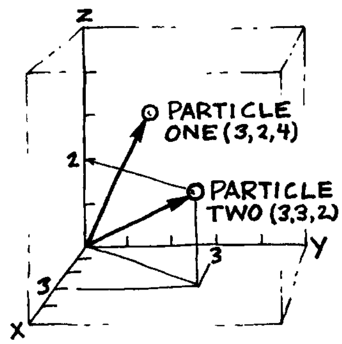

If we think about entropy in terms of the origin of the universe, then we require that entropy in the early universe was low. If this were not the case, then we would have no mechanism for understanding the directionality of time which depends on the universe evolving from low to high entropy. But why should the universe have low entropy at its origin any more than all the particles in a container of gas would be bunched together? There are many more ways in which the universe can start out in a disorganized way than there are in an organized way, just as there are many more ways in which a pack of cards can be disorganized than organized. If this were not the case, then a "winning" hand would be the norm, not the exception.

Since there are so many possible configurations of the early universe, we need some way to represent this fact without having to consider each possibility, case by case. In the last century the American physicist, Willard Gibbs, conceived of a way to do just that.

## PHASE SPACE

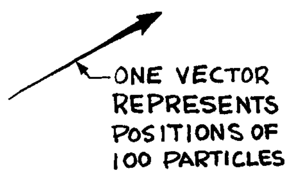



To understand his method consider a box-shaped vessel containing just one particle. We can locate this particle, as the figure shows, by its coordinates, 3, 2, and 4 on the x, y, and z axis. We could also designate the particle's position by drawing an arrow from the origin of our coordinate system to the particle, as the figure also shows. This arrow is called a "vector." This particular vector for the particle is also completely specified by the three coordinates 3, 2, and 4, again shown by figure.




Suppose now we want to specify the positions of two particles. As the figure shows, we could do this with two vectors where a new particle has coordinates 1, 1, and 2. In a more general way, we could specify the positions of as many particles as we liked by associating each particle with the appropriate vector. Let us notice something however. It takes three numbers (3, 2, and 4) to specify the location of one particle and 6 numbers (3, 2, 4 and 3,3, 2) to specify two particles in our three-dimensional coordinate system.

Consider now that we use, instead of a three-dimensional coordinate system, a six-dimensional coordinate system. We can't visualize such a coordinate system since we are creatures of a three-dimensional world, but there is no problem doing it mathematically. In this six-dimensional coordinate system we represent both particles by a single vector whose coordinates along the six axes are 3, 2, 4,3, 3, and 2. If we have 100 particles, we can represent all their positions by a single vector in a coordinate system with 300 dimensions. In principle, then, we can represent as many particles as we like with a single vector as long as we use a coordinate system with enough dimensions.

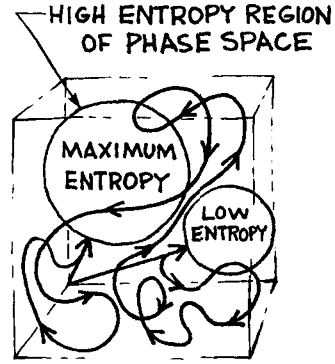



300 DIMENSIONAL SPACE

We can extend this idea to specifying each particle's velocity by assigning another three numbers to each particle. We need three additional numbers, not one, because velocity gives both the speed and direction of motion of the particle. If we put all this together, we see that we can specify both the location and velocity of n particle in a (six times n) dimensional space with a single vector. This multidimensional space is called "phase space." Although this procedure seems fanciful, it has proved, from a mathematical point of view, to be extremely powerful. Let's see, now, how that might work.

IN PHASE SPACE SIX DIMENSIONS ARE NEEDED TO SPECIFY THE LOCATION AND VELOCITY OF EACH PARTICLE.

We return to our container with all the particles bunched in the corner—a low entropy state. With our new multidimensional space we can represent this entire collection of particles with a single vector. Similarly, we can represent the same group of particles in their maximum entropy (thermal equilibrium) state by another vector. Even more interestingly, we can follow the transition from the low entropy to the thermal equilibrium by following the path traced out by the tip of the vector; because, this path represents each stage of the gas as it diffuses throughout the container.




The figure suggests how this might look. The vector starts in a part of phase space labeled low entropy. There are a good many arrangements of the particles that could be in this part of phase space. For example, any bunched arrangement of particles, not just in a corner of the container, would be in this part of phase space.

If this figure represented the phase space of a deck of playing cards, then any orderly arrangement of cards would be in this region of phase space. The volume of phase space occupied by these orderly arrangements is a measure of the entropy associated with these arrangements.

As the gas spreads throughout the container, we see the vector wander through phase space finally coming to rest in the portion of phase space labeled "maximum entropy." Notice how much bigger the maximum entropy volume is than the low entropy volume. This simply reflects the fact that high entropy is a much more probable state than low entropy.

Our figure poorly represents just how different in size these two volumes are. Suppose our box is a cube one meter on a side. If the gas were ordinary air, then there would be about $10^{25}$ molecules in the box. Suppose these molecules were bunched in a corner that occupied one-tenth of the box's total volume. A simple calculation shows that the volume in phase space occupied by the particles represents only 1/10 times $10^{-25}$ of the total phase space. This dramatically illustrates why it is exceedingly unlikely that the particles will, by chance, bunch up in some corner of the box. If we saw such a bunching, we would strongly suspect that some human agent was responsible.

Considering the enormously different volumes in phase space that different entropies can require, we need a more manageable system. So, instead of saying that entropy is directly proportional to phase space volume, we say that entropy is proportional to the logarithm of the volume. That is

entropy = k log volume,

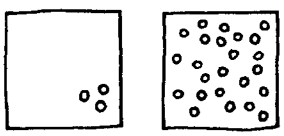
where k is a constant number called Boltzmann's constant.

The logarithm is the power to which one number, the base, must be raised in order to obtain another number. For example, 3 is the logarithm of the number 1000 with respect to the base 10 since $10^3 = 1000$.

### PHASE SPACE FOR THE UNIVERSE

But what does this have to do with the flow of time in our universe? The answer is that with phase space we can estimate how well the universe needed to be organized at the big bang to reflect the conditions we see today.

The microwave radiation created at the big bang is the best clue we have to the degree of organization—or lack of it, in the early universe. As it turns out, the entropy at the big bang is approximated by the number of photons of big-bang radiation in the universe at the present.



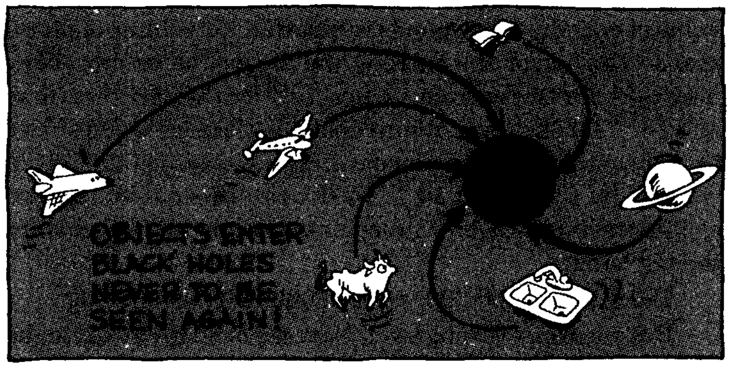
FOR THE SAME SIZE BOX, MORE PARTICLES MEAN GREATER POTENTIAL ENTROPY.

This may seem odd at first, but if we think of our gas-filled container again we can see why this is true. The entropy of the gas in the container depends not only on how particles are arranged in the container but also on how many particles the container holds. If the container held only two or three particles, the entropy would always be small compared to the same container with many particles simply because there are many more ways to arrange numerous particles than there are to arrange only two or three particles. Thus, we see, entropy is a function of particle number as well as particle arrangement.

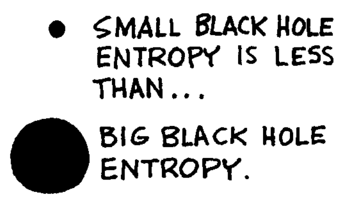
Measurements indicate the big-bang radiation consists of about $10^{88}$ photons. As we shall see in a moment, even if the measurement is grossly in error, it affects the final conclusion very little.

Now that we have an estimate of entropy at the time of the big bang, we need to estimate the entropy of the present universe.

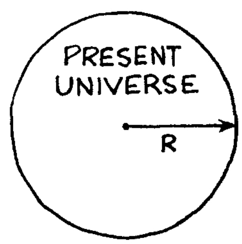
## BLACK HOLES AND ENTROPY




We showed earlier, in our discussion of the bus journey, how entropy and information are two sides of the same coin—that if you know one you can determine the other. A black hole is the ultimate shredder—the ultimate destroyer of information. Any object—book, space ship, wandering planet, whatever—approaching a black hole too closely will be gravitationally pulled into the black hole never to be seen again. Whatever information associated with these objects is lost forever. This suggests that if black holes are destroying information, they are, at the same time, generating entropy. And that is the case.




A careful analysis shows that the entropy of a black hole is proportional to its surface area. Or, alternatively, the maximum information that can be contained in some volume depends on the surface area of the volume. Put this way, the result makes more sense because we are used to the notion that the more information we store, the more room we need whether it is a library or computer memory. In any case the result is the clue to estimating the entropy of the present universe. From astronomical measurements we know the radius of the present universe, some 15 billion light years. Therefore, the area of the universe is proportional to this number squared. If we carry through the relevant




R= 15 BILLION LIGHT YEARS

calculations we find that the present universe could have an entropy as high as $10^{123}$. As before, the final conclusion is little affected even if this estimate is grossly in error.

Let's see where we are so far. First, we have an estimate of the entropy of the universe at the time of the big bang. Second, we have an estimate of the present entropy (or (information) of the universe. In phase space, a particular value of entropy corresponds to a particular volume of phase space—the bigger the entropy, the bigger the volume. Now if we take our two entropy values, $10^{88}$ for the early universe and $10^{123}$ for the present universe, a little calculation shows that the entropy of the present universe exceeds the initial entropy by a factor of $10^{35}$. We'll write this out so that we can appreciate just how much entropy has increased since the big bang:

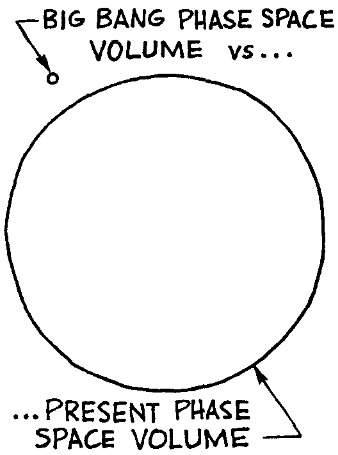
ENTROPY OF THE EARLY UNIVERSE WAS ABOUT $10^{88}$

ENTROPY OF THE PRESENT UNIVERSE IS ABOUT $10^{123}$

$$\frac{10^{123}}{10^{88}} = 10^{35}$$

100 000 000 000 000 000 000 000 000 000 000 000.

But we aren't through yet. Next we need to calculate the volumes in phase space that correspond to the initial and present entropies of the universe. When we remember that the entropies are proportional to the logarithms of the volumes, we find that the phase space volume of the present universe is a factor $10^{10^{123}}$ greater than the initial volume at the big bang. We won't even attempt to write out this number. There aren't enough atoms in the universe on which we could record the zeroes—one zero per atom. Furthermore, even if our estimates on which this number is based are in error by many hundreds of millions, we still get a number whose magnitude is beyond comprehension.




So what does this all mean in terms of the direction of time? Imagine one vast phase space representing the entire universe. As we know from the preceding discussion, the part of this total volume that represents the big bang is unimaginably smaller than the total volume. More specifically, since the total phase space of the universe represents all the conceivable ways that the universe could have started, the odds that it could have started the way it did are one in $10^{10^{123}}$.

These odds are so overwhelming that we are inclined to look, as we did in the case of the gas particles bunched in one corner of the vessel, for some explanation other than pure chance.

The most consistent suggestion is that our knowledge of the laws of nature is not advanced enough to explain how the universe could have been so delicately organized at its beginning. At the present we have the General Theory of Relativity for understanding the large-scale features of the universe and quantum mechanics to explain the small-scale features, the universe of atomic and subatomic particles. As long as these two universes don't overlap, quantum mechanics and General Relativity work exceedingly well. But the early moments of the big bang represent a period where we have scales appropriate to quantum mechanics and gravitational forces fitting to General Relativity. What we need is a theory that marries quantum mechanics to relativity.

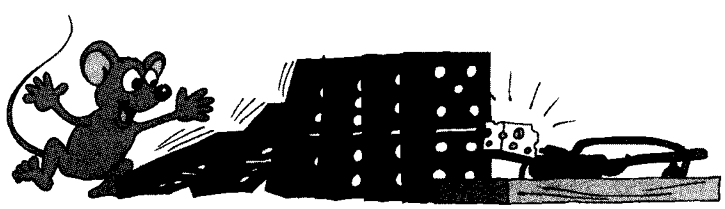
AT THE BIG BANG, WE NEED A THEORY COMBINING QUANTUM MECHANICS AND GENERAL RELATIVITY.

Einstein spent the last 30 years of his life looking for such a theory, and some of the best minds of the last half of this century have continued Einstein's search. There are some tantalizing possibilities—but they remain just that—tantalizing possibilities.

## THE PROBLEM OF FREE WILL

We end this chapter addressing a subject whose content is more philosophical than scientific—free will. We do this because, whatever the true nature of free will, its explication is tangled inextricably with time.

With Newton's laws came an unparalleled advance in humanity's understanding of the natural universe. But these advances brought problems, especially for philosophers. In Newton's universe there is strict cause and effect, like so many dominoes tumbling one into another, domino after domino. If everything is determined, how can there be free will? Since man is made of the same stuff as the rest of

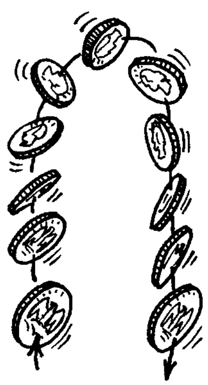


the universe, is man not subject to Newton's laws like the meanest dust particle or the noblest comet?

One explanation is that man is more than a complex arrangement of atoms and molecules, that man has a spiritual side beyond the material world. For many this was, and remains, sufficient explanation. But if we are to look for an explanation of free will within the bounds of natural law, then escaping through the "spiritual door" is not playing the game fairly.

As we know from the last two chapters, time does not exist independently of the rest of the universe. As St. Augustine said, "The Universe was born with time, not at some time." Time's intimate connection with the material universe seems to have determined that time had a beginning, may or may not have an end, and has direction.

Of these chief characteristics, it is the directional aspect that is most important for free will. The very idea of time's direction means that we know the past but the future remains uncertain, and, to the extent that the future is uncertain, we have the option to exercise free will.



FLIPPING A COIN IS ONLY AN ILLUSION OF RANDOMNESS IN NEWTON'S WORLD.

Our uncertainty about the future might spring from one or more sources. If we believe in Newton's strictly causal world, then we have to conclude that there is no such thing as free will. Free will is an illusion springing from the fact that the future depends on so many factors, known and unknown, that we, with limited intellectual capacity, can never know it. The situation is analogous to flipping a coin. We say the coin comes up randomly. But that is only because we don't have complete information on the spin rate and trajectory of the coin as it leaves the hand. If we did, we could, in principle, predict whether the coin comes up heads or tails. In Newton's world, uncertainty about the future is simply lack of knowledge and the inability to process adequately the knowledge we do have.

Nevertheless, the idea of free will in Newton's world may represent a convenient fiction. It embodies a mode of thought that allows us to rationalize many of the circumstances of our lives: if you commit a crime you will be punished; if you put on your seatbelt you will live longer; if you work hard you will prosper. The deterministic cynic, regarding the latter, might be more inclined toward John

Paul Getty's formula for success: "Get up early. Work hard. Strike oil!"

Until the first part of this century, there seemed to be no room for free will. But then radioactive elements, like radium and uranium, were discovered and out of these discoveries grew quantum mechanics which embodied notions like the *"Heisenberg Uncertainty Principle,"* which, as we know, said that the universe was at heart, random, that at the atomic level things happened with no cause whatsoever.


RADIATION IS EMITTED AT RANDOM TIMES

Quantum mechanics gave philosophers renewed hope that there was room, after all, for free will. If the future is truly indeterminate, then perhaps we do have some influence over our lives. The problem is there is little or no evidence that quantum mechanics operates at the level of living organisms, living organisms being creatures of the macroworld, not the microworld.

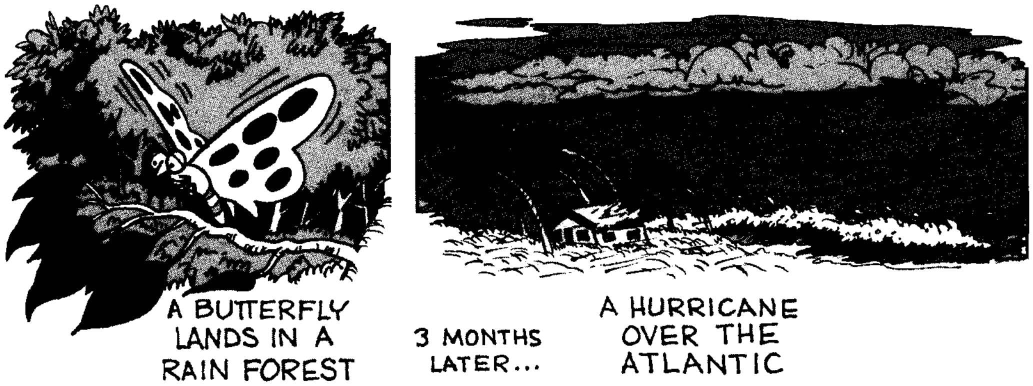
### Cleopatra's Nose

We have discussed in some detail the deterministic nature of Newton's world. But we need to make a distinction between what is deterministic and what is predictable. But more about that later. First, we turn to Cleopatra's nose.

The famous 17th century mathematician, Blaise Pascal, the inventor of the first calculating machine with cogged wheels, is said to have wondered how different the history of the world might have been had Queen Cleopatra's nose been less fetching.

Pascal's question was prophetic because we now know that the most minor occurrences in nature can produce profound and completely unexpected events later on. Scientists today call this the *butterfly effect* because a butterfly landing in the Brazilian rain forests could spawn a hurricane months later over the Atlantic ocean.

How can this be? Surprisingly enough, this kind of behavior springs out of Newton's clocklike universe. In Chapter 15 we discussed how changes in initial conditions alter the subsequent chain of events—how the initial direction of a billiard cue ball determines the future course of its trajectory as well as the trajectories of the balls it hits. What we didn't mention was that the calculations to predict these




trajectories are, for all practical purposes, impossible when a handful of balls, or more, are involved.

The billiard ball calculation in Chapter 15 was for an idealized situation—we assumed the table was perfectly flat, the balls were perfectly round and so on. But if we are to make realistic long range predictions, these simplifying assumptions and others can not be ignored. One effect we ignored was the mutual gravitational attraction between the balls. Incredibly small as this attraction is, it leads to a whole new set of problems that first bedeviled Newton.

Newton, with his newly minted laws of gravitation and motion, was able to account for the elliptical orbits of the planets around the sun. Encouraged by this success he tackled a more difficult problem—accounting for the motion of the moon around the earth. It was known that the moon's orbit contained small irregularities, irregularities Newton suspected were due to the mutual interactions between the Earth, the Moon and the Sun—the so called "three-body problem." Newton, with all his mathematical genius, was unable to arrive at a satisfactory solution. We now know that Newton's efforts were doomed from the beginning, that when three or more bodies are involved, there is no simple solution of the kind Newton found for two bodies. The mutual interactions between three or more bodies leads to equations of motion that cannot, except in very special circumstances, be solved to provide reliable long range predictions of the future positions of the bodies.

This kind of behavior is an example of what today is called *chaotic motion*, and the whole subject is treated under a relatively new discipline called *chaos theory*. The primary feature of chaotic motion is that the most minute changes in the initial conditions lead to drastic differences at later times. If the direction of the cue ball is changed by an amount that is vanishingly small, the long-term trajectories of all the balls are completely unpredictable.

There is another aspect of this problem we need to consider. To determine the trajectories of the balls we must first know the direction and speed of the cue ball. But we can obtain this information only by making measurements, and measurements are always subject to error, however small, be it in the hundredth decimal place or the millionth or the billionth. There is always some error, and this error leads to a complete breakdown in our knowledge of the ball's trajectory at some point in the future. Thus, both lack of information—did the butterfly land or not land in the rain forest?—and noisy measurements conspire in a chaotic world to keep us from knowing the future.

THERE IS ALWAYS MEASUREMENT ERROR

Weather forecasting is another example of truly unpredictable, chaotic behavior. Since we can never make error-free measurements of temperature, humidity, wind speed, and so on, our forecasts always break down at some time in the future. Even the best possible measurements coupled with unimaginable computing power will never lead to forecasts that are reliable beyond a few months.

There is a fundamental difference between the uncertainty generated by chaos and the kind associated with the Heisenberg Uncertainty Principle. Where chaos is involved, the future is deterministic in a Newtonian sense—although we cannot predict the trajectories of the balls very far into the future, each collision is governed strictly by Newton's laws of motion. If the balls were subject to the Uncertainty Principle, the collisions would not be bound by strict Newtonian cause and effect.

### Computing The Future

Now that we have discussed the difference between deterministic and predictable processes, we need to consider one last concept, *computability*.

To start our discussion we go back to the work of the early 20th century mathematician, David Hilbert, who be-

MATHEMATICS IS BUILT ON A FIRM FOUNDATION OF LOGIC

lieved that mathematics was the one sure stronghold of unqualified certainty in a time when quantum mechanics had placed uncertainty at the deepest levels of nature. After all, mathematics was built on a foundation of pure logic. How could doubt creep into a system laboring along these lines? If Bill is older than Mary and Mary is older than Tom, then Bill is older than Tom.

But it did. And not in a small way. Even worse, where does this leave science if its most important tool, mathematics, is suspect?

But back to Hilbert. Hilbert believed that mathematics was unassailable, and he believed he had a plan to prove it. Few doubted Hilbert's assertion because he was the premier mathematician of his time.

Kurt Gödel, a young mathematician in the 1930's, was one of the mathematicians who believed in Hilbert and he set out to prove Hilbert right. But what Gödel found instead was that Hilbert was wrong.

Gödel's discovery involved a long mathematical line of reasoning, but what he uncovered is not hard to understand. He discovered that there are always some mathematical truths in any mathematical system of sufficient complexity, algebra is an example that can't be proved true within that system. This was not only a loose end but a gigantic hole.

We can get a sense of Gödel's discovery by considering the questions of a young child. The typical vocabulary of a young child is a few hundred words—enough vocabulary to ask hard questions but not enough vocabulary to understand the answers. So it is with mathematics, Gödel found. The mathematics is there to ask the questions but its "vocabulary" is not always rich enough to answer them.

If this is the problem, why not go to a mathematics with a richer vocabulary? We can probably do that, but now we can ask even more difficult questions which the new system is not rich enough to answer. And so it goes, on without end.

Let's return now to our billiard table. We have already seen that predicting the paths of even a handful of balls is not possible into the indefinite future. Suppose now we change the shape of the table—change the boundary conditions as we described it in Chapter 15. It turns out that with certain table shapes the future paths of the balls are *non-computable*.

We want to emphasize that the ideas of *unpredictable* and *noncomputable* are not the same. Unpredictability stems from the chaotic motion of the balls while noncomputability stems from Gödel's result. In other words, with certain table shapes, a computer can never decide what the future paths of the balls will be. It just goes on computing forever and never provides an answer. It's not that the balls don't have definite paths as the future unfolds, it's just that the computer can't decide what they are, just as certain mathematical statements can never be proved true even though they are.

CHAOS → UNPREDICTABILITY

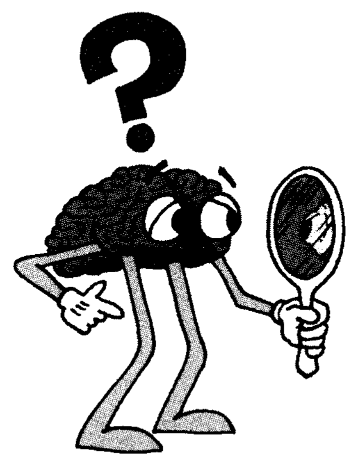
GÖEDEL'S THEORY → NONCOMPUTABILITY

This could be bad news for physics, because it might be that the ultimate, basic laws of the universe, or even a good approximation to them, are such that some events, although possible in nature, will never be accommodated in our calculations.

Perhaps free will is akin to a circumstance that is deterministic but is neither predictable nor computable.

### The Brain Problem

Another problem with free will is that it requires us to contemplate our own thinking process, which brings up the question "Can the brain, with limited capacity, understand itself?"



Perhaps it would be best to end this discussion with the words of the Nobel Prize winning novelist, Isaac Bashevis Singer:

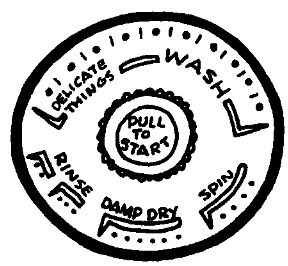
*"We have to believe in free will.*
*We don't have any choice."*

Chapter

1 2 3 4 5 6 7
8 9 10 11 12 13 14
15 16 17 18 19 **20** 21
22 23 24 25 26 27 28
29 30 31

# CLOCKWORK AND FEEDBACK

Automation is a cornerstone of modern industrial society. In a sense the clock planted the seed of automation, since its mechanism solves most of the problems associated with building any kind of mechanical device whose sequence of steps is controlled by each preceding step.




A good example is the automatic washing machine. Most such machines have a "timer" that initiates various phases of the wash cycle and also controls the duration of each phase. The timer may "instruct" the tub to fill for 2 minutes, wash for 8 minutes, drain, perform various spray-rinse operations, fill again and rinse, and finally spin-dry for 4 minutes. In most machines the operator can exercise some control over the number and duration of these phases. But unless there is some such interference, once the wash cycle is started, the timer and its associated control components are oblivious to happenings in the outside world.

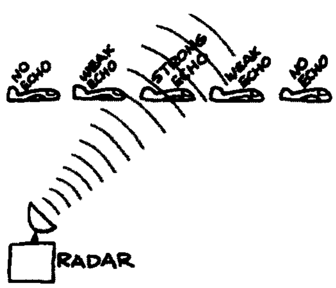
## OPEN-LOOP SYSTEMS

A control system such as that in an automatic clothes- or dish-washer is called an "open-loop" system, whose main characteristic is that once the process is started, it proceeds through a preestablished pattern at a specified rate. Other examples of devices utilizing open-loop control systems are peanut-vending machines, music boxes, and player pianos. Each such machine is under the control of a clockwork-like mechanism that proceeds merrily along, oblivious to the rest of the world—like the broom in the story, "The Sorcerer's Apprentice," which brings in bucketful after bucketful of water, even though the house is inundated.

## CLOSED-LOOP SYSTEMS

Another important kind of control system, called a "closed-loop" system, employs feedback. An example is a furnace which is activated by a signal from a thermostat. When the room temperature falls below the temperature set on the thermostat, the thermostat produces a signal which is "fed back" to a controlling mechanism at the furnace which turns the furnace on. When the room temperature reaches the value set on the thermostat, the thermostat "instructs" the controlling mechanism to turn the furnace off. This system with its feedback automatically keeps the room near the temperature set on the thermostat. We have already encountered other systems with feedback, or self-regulating systems, in Chapter 2, and again in Chapter 5, in the discussion of atomic clocks.

Systems that use feedback are dependent upon time and frequency concepts in a number of ways. We shall explore these in some depth by considering the operation of a radar system that tracks the path of an airplane. Such tracking systems were developed during World War II and were used for the automatic aiming of anti-aircraft guns. Today, tracking radars are used extensively in a variety of ways—such as tracking storms, civilian aircraft, and even bird migrations.




The operational principle of the tracking system is simple. A "string" of radar (radio) pulses is transmitted from a radar antenna. If a pulse of radio energy hits an airplane, it is reflected back to the radar antenna, now acting as a *receiving* antenna. This reflected signal, or radar echo, indicates to the radar system the presence of an airplane. If the echo signal strength increases with time, the airplane is moving in toward the center of the radar beam; if the echo signal strength is *decreasing,* the airplane is moving out of the radar beam.

This change of echo signal strength with time is fed back to some device—perhaps a computer—which interprets the echo signal and then "instructs" the radar antenna to point toward the airplane. It all sounds very simple, but, as usual, there are problems.

### The Response Time

The antenna does not respond immediately to changes in the direction of the airplane's flight, for a number of reasons. The inertia associated with the mass of the antenna keeps it from moving at an instant's notice. It also takes time for the computer to interpret the echo signal; and for the radar signal itself to travel the airplane and back.

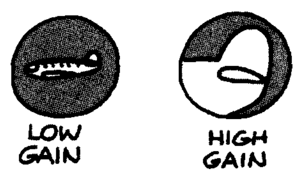
These difficulties bring out an important time concept related to feedback systems—the "system-response time." Even human beings are subject to this delayed response time, which is typically about 0.3 second. In dinosaurs the problem was particularly serious; a dinosaur 30 meters long would take almost a full second to react to some danger near its tail—if it weren't for an "assistant brain" near the base of its spine!

In our own example, if the system-response time is too long, the plane may move out of the radar beam before the antenna takes a corrective action. The best information in the world is of little use if it is not applied in time.

### System Magnification or Gain

The accurate tracking of an airplane really depends upon the interplay between two factors—the response time just mentioned, and the magnification or *gain* of the feedback system.

We can easily understand this interplay by considering the problem of looking at an airplane through a telescope. At low magnification, or low telescope "gain," the airplane covers only a small portion of the total field of view of the telescope. If the plane takes a sudden turn, we can easily redirect the telescope before the plane disappears from view.




But with high telescope magnification, the plane will cover a larger portion of the total field of view. In fact, we may be able to see only a portion of the plane, such as the tail section, but in great detail. With high magnification, then, we may not be able to redirect the telescope before the plane disappears from view.

These observations bring us to the conclusion that if we want to track an airplane successfully with a high-magnification or high-gain telescope, we must be able to react quickly. That is, we must have a short *response time.* With lower magnification, we don't have to react so quickly. The obvious advantage of high magnification, from the point of view of tracking, is that we are able to track the airplane with greater accuracy than with low magnification. With lower magnification there is a certain latitude in pointing the telescope while still keeping the plane in view—which means that the telescope may not be pointed squarely at the plane.

These principles of the telescope apply to a radar tracking antenna. The radar radio signal spreads out as a beam from the radar antenna. Depending upon the construction of the antenna, the beam may be narrow or wide, just as a flashlight beam may be narrow or wide. With a narrow beam, all of the radio energy is concentrated and travels in nearly the same direction. If the beam strikes an object, such as the metal surface of an airplane, strong echoes are reflected back to the radar antenna.

WIDE BEAM = LOW MAGNIFICATION

NARROW BEAM = HIGH MAGNIFICATION

On the other hand, we will get no reflections at all from objects in the *vicinity* of the airplane, since they are missed by the narrow radar beam. With a *wide* radar beam, the energy is more dispersed, so we will get only weak reflections, but from objects located throughout a larger volume of space.

Thus the narrow-beam radar corresponds to the high-magnification telescope, since it gives good information about a small volume of space, whereas the *wide-beam* radar corresponds to the low-magnification telescope, since we get less detailed information about a larger volume of space. With the narrow-beam radar, the tracking system must react quickly to changes in direction of the airplane; otherwise the plane may fly out of the beam. And with the wide-beam antenna, more time is available to redirect the antenna before the echoes stop.

Obviously, the narrow-beam, high-gain tracking antenna does a better job of following the path of the airplane, but the price to be paid is that the system must respond quickly to changes in direction of the plane; otherwise, the airplane may be lost from view.

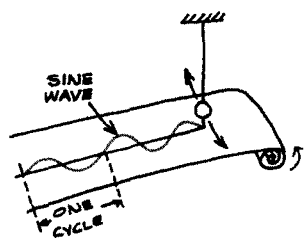
### Recognizing the Signal

The radar tracking system may encounter another difficulty. Not all signals reaching the radar antenna are return echoes from the airplane we are interested in tracking. There may be "noise" from lightning flashes, or reflections from either other airplanes or perhaps from certain kinds of cloud formations. These extraneous signals all confuse the tracking system. If the antenna is to follow the plane accurately, it must utilize only the desired echo signals and screen out and discard all others.

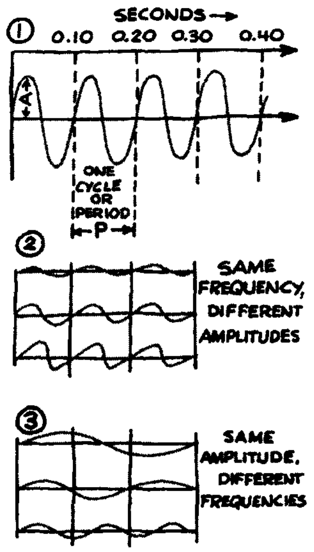
At this point another time and frequency concept, primarily mathematical in nature, comes to our aid. As we shall see, this mathematical development allows us to dissect the radar signal—or any other signal—into a number of simple components. The dissection gives us insight into its "inner construction," and such information will be invaluable in our task of separating the desired signal from extraneous signals and noise.

### Fourier's "Tinker Toys"

The mathematician most responsible for the development of these ideas was the Frenchman J.B.J. Fourier, who lived in the early part of the 19th Century. Fourier's development led to a very profound idea—that almost any shape of signal that conveys information can be dissected into a number of simpler signals called *sine waves*. We have already encountered sine waves a number of times in this book, but we haven't called them that. Sine waves are very intimately related to devices that vibrate, or swing back and forth. For example, if we trace out the swinging motion of a pendulum on a moving piece of paper, we have a sine wave.

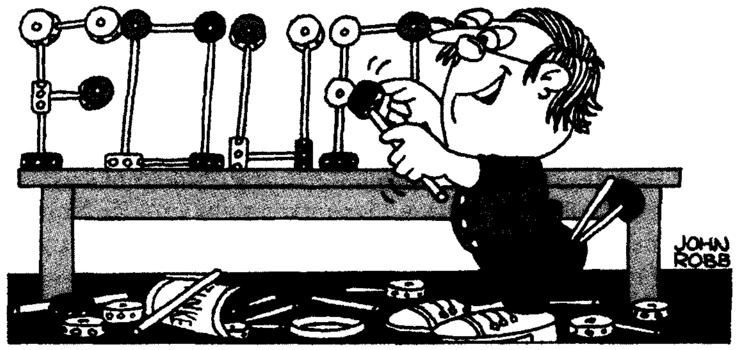


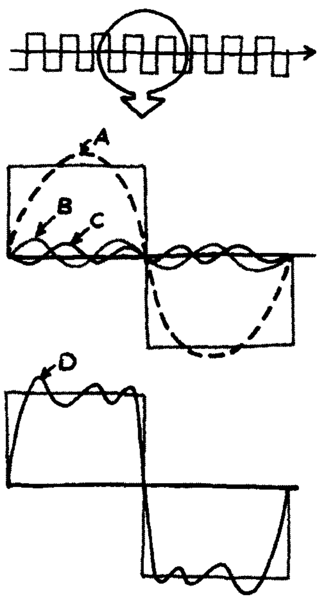

This sine wave has two important characteristics. First, it has an amplitude indicated by the length of the arrow marked A; and second, it has a pattern that repeats itself once each cycle. The number of cycles per second is the *frequency* of the sine wave, and the duration of a particular cycle, in seconds, is the period of the sine wave. In our




example there are 10 cycles each second, so the frequency is 10 cycles per second, or hertz. And the *period* is, therefore, 0.1 second. We can have sets of sine waves all with the same frequency but with differing amplitudes; sets with differing frequencies, but all with the same amplitude; or sets with differing amplitudes and differing frequencies.

Fourier discovered that with the proper set of sine waves of differing amplitudes and frequencies, he could construct a signal of almost any shape. We can think of sine waves as the "tinker toys" out of which we can construct different signals. Let's see how this works.

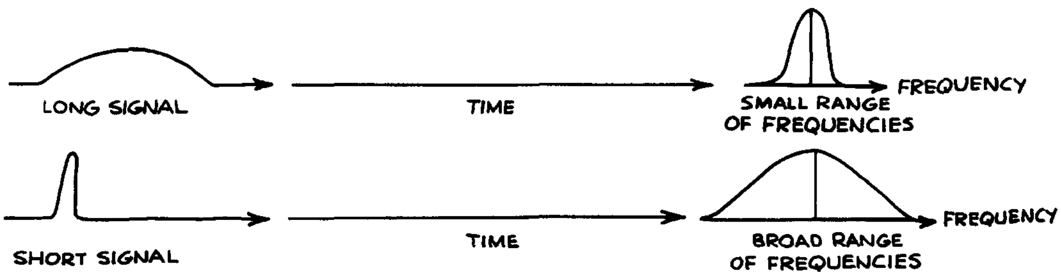



Suppose we'd like to construct a signal with a square wave shape, like the one shown in the sketch. Since each cycle of the square wave is identical to its neighbors, we need consider only how to build *one* square-wave cycle; all others will be constructed from the same recipe. The sketch shows one cycle of the square wave magnified. The sine wave marked "A" approximates the shape of the square wave, and if we were for some strange reason restricted to only one sine wave in our building of the square wave, this is the one we should pick.

In a sense, this sine wave represents to the communications engineer what a roughed-out piece of marble represents to the sculptor, and further additions of sine waves represent refinements of the square wave in the same sense that further work on the marble brings out details of the statue. By adding the sine waves B and C to A, we get the signal marked D, which, as we see, is an even closer approximation to the square wave. This process of adding or superimposing sine waves is similar to what happens when ocean waves of different wave lengths come together; the merging ocean waves produce a new wave, whose detailed characteristics depend upon the properties of the original constituent ocean waves.

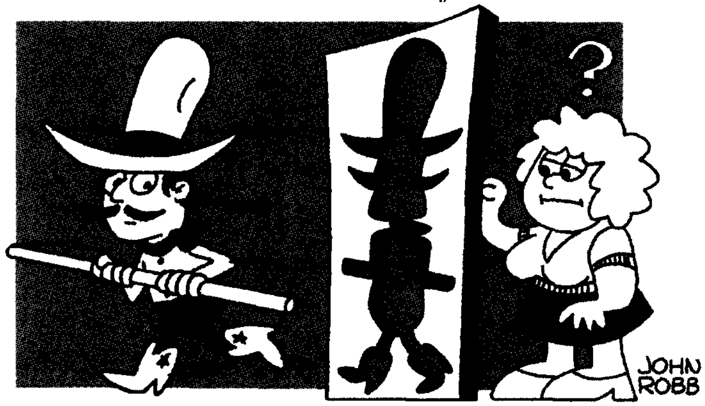
If we wished, we could add even more sine waves to A, besides B and C, and obtain an even closer approximation to a square wave. Fourier's recipe tells us precisely what sine waves we need to add. We shall not go into the details here, but as a rule of thumb, we can make a general observation: If our signal is very short—such as a pulse of energy one microsecond long—then it takes many sine waves covering a wide range of frequencies to construct the pulse. If, on the other hand, the signal is long and does not change erratically in shape, then we can get by with fewer sine waves covering a narrower range of frequencies.




This concept of relating pulse length to range of frequencies is also the mathematical underpinning for the subject we covered in Chapter 4, decay time—which is the reciprocal of frequency width of the resonance curve. We recall that a pendulum with a long decay time, because of low friction, will respond only to pushes at rates corresponding to a narrow range of frequencies at or near its own natural frequency. In a similar mathematical sense, a radar signal that lasts for a long time—in a sense, that has a long decay time—can be constructed from sine waves covering a narrow range of frequencies. A radio pulse lasting only a short while—corresponding to a pendulum with a short decay time—requires sine waves covering a broad range of frequencies—in the same sense that a pendulum with a short decay time will respond to pushes covering a broad range of frequencies.

### Finding the Signal

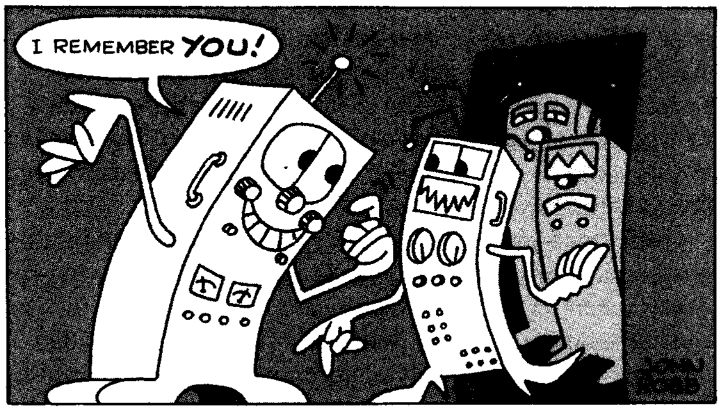
Now we must relate Fourier's discovery to the problem of extracting weak radar-echo signals from a noisy background. The problem is somewhat similar to building a cage to trap mice, where the mice play the role of the radar echo signal and the cage is the radar receiver. One of the most obvious things to do is to make the trap door into the cage only big enough to let in mice, and to keep out rats, cats, and dogs. This corresponds to letting in only that range of frequencies necessary to make up the radar signal we are trying to "capture." To let in a wider range of frequencies won't make our signal any stronger, and it may let in more noise—rats and cats—which will only serve to confuse us.



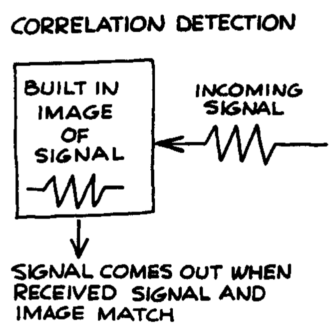

But Fourier's discovery suggests how we can build an even better radar receiver that will not only keep out rats and cats, but hamsters too, which are the same size as mice. That is, Fourier tells us how to separate signals of different *shapes*, even though they can be constructed from different "bundles" of sine waves covering the same range of frequencies.

The length of the signal primarily determines the frequency range of the sine waves that we need to build the signal, but within this range we can have many bundles of sine waves to construct many different kinds of signals simply by adding together sine waves with different frequencies, amplitudes, and phases. To go back to the tinker-toy analogy, we can build many different kinds of figures—signals—from tinker toys that are all restricted to a given range of lengths-a certain range of frequencies.

We construct our radar receiver system not only to let in the correct range of frequencies, but also to give favorable treatment to those sine waves that have the amplitudes, frequencies, and phases of exactly the set of sine waves that make up our radar signal; in this way we can separate the mice from the hamsters.




To complete the story, there is another approach to separating the mice from the hamsters, which is informationally equivalent to the approach just described, but which is different from an equipment point of view. It is called *correlation detection* of signals, and it simply means that the radar receiver has a "memory," and built into this memory is an image of the signal it is looking for. Thus it can accept signals that have the correct image and reject those that have not. It is equivalent to the system just described because all of the electronic circuitry required to give favorable treatment to the correct bundle of sine waves is equivalent, from an information point of view, to having an image of the desired signal built into the receiver.




In most cases, the electronic processing circuits can be replaced by a computer with the appropriate program. The big advantage here is that it is easier to change the program to accommodate new signal shapes than it is to alter the circuitry.

## CHOOSING A CONTROL SYSTEM

We have discussed two kinds of control systems—the open-loop system, which churns along mindlessly in the face of any changes in the outside world, and the closed-loop system, which responds to changes in the outside world. As we have seen, both systems are intimately related in one way or another to time and frequency concepts. But in terms of operation they are almost at opposite ends of the pole.

We might wonder why the open-loop approach is used in some applications and the closed-loop in others. Perhaps the most crucial test relates to our completeness of knowledge of the process or mechanism that we wish to control. Washing clothes is straightforward and predictably the same from one time to the next. First wash the clothes in detergent and water, then rinse, then spin-dry. This predictability suggests the simpler, less expensive, open-loop control system, which, as we know, is what is used.

OPEN LOOP OR CLOSED LOOP?
ECONOMICS
TECHNOLOGY
ADVANTAGES
LIMITATIONS

But some processes are very sensitive to outside influences that are not predictable in advance. Driving to work every morning between home and office building is very routine—almost to the point of being programmable in advance—but not quite. If an oncoming car swerves into our lane, we immediately appreciate the full utility of closed-loop control because we can, we hope, take action to avoid a head-on collision.

Sometimes the question of closed-loop versus open-loop control reduces to one of simplicity and economy. Thus, often we elect to use a closed-loop control, even though, in principle, there are no unknowns that might affect the desired goal. All factors, including available technology that could be included as part of a system, must be considered, and costs and other considerations balanced against benefits. Each kind of system has its advantages and limitations. Both depend upon applications of time and frequency information and technology for their operation.

# Chapter 21

# TIME AS INFORMATION

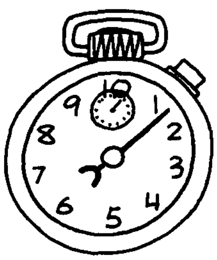
Many questions in science and technology seek answers to such details as: When did it happen? How long did it take? Did anything else happen at the same time, or perhaps at some related time after? And finally, Where did it happen? We have already seen from the point of view of relativity that questions of when and where have no absolute answers; particularly at speeds approaching the speed of light, the separation between space and time becomes blurred. But in our discussion here we shall assume that speeds are low, so the absolute distinction between space and time that Newton visualized holds.

## THREE KINDS OF TIME INFORMATION REVISITED


The question of "when" something happened is identified with the idea of *date*. The question of "how long" it took is identified with time *interval*. And the question of "simultaneous occurrence" is identified with *synchronization*—as we discussed more fully in Chapter 1.

In science, the concept of date is particularly important if we are trying to relate a number of diverse events that may have occurred over a long period of time. For example, we may be taking temperature, pressure, wind speed, and direction measurements at a number of points both upon and above the surface of the Earth. For weather forecasts, the concept of date is very convenient because a number of persons gather information at different times of the day, month, and year, scattered over many continents. Not to have one common scheme for assigning times to measurements is at least a very troublesome bookkeeping problem and at worst could lead to complete uselessness of the time measurements.

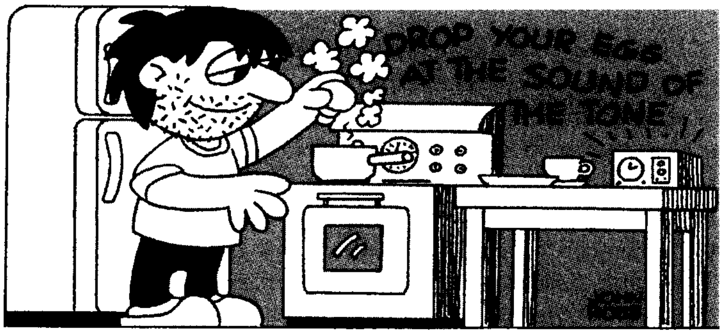
On the other hand, we are often content to know simply whether some event occurred simultaneously with another event, or after some regular delay. For example, the fact that a car radio always fades when we drive under a steel overpass suggests some cause-and-effect relationship which, at first glance at least, does not appear to be related to date. Although the fading and the passing under the steel structure occur simultaneously, we notice the same effect at 8:20 on the morning of January 9 that we do at 6:30 in the evening on April 24. An important point is that the amount of time information needed to specify synchronism is generally less than that required to specify date, and we may be able to achieve some economies by realizing the distinction between the two.




Finally, as we have noted before, time *interval* is the most localized and restricted of the three main concepts of time—date, synchronization, and time interval. For example, we are often concerned only about controlling the duration of a process. A loaf of bread baked for 45 minutes in the morning is just as good as one baked for 45 minutes at night, and a loaf baked for 3 hours in the morning is just as burned as one baked for 3 hours at night.

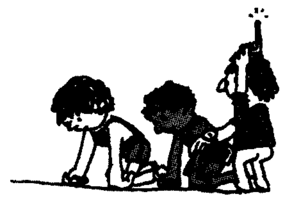
To get a better handle on the information content of the three kinds of time, let's return to the problem of boiling an egg. Suppose we have a radio station that broadcasts a time tick once a minute, and nothing else. If we want to boil an egg for three minutes, such a broadcast is adequate. We simply drop an egg into boiling water upon hearing a tick, and take it out after three more ticks.

But let's suppose that a next-door neighbor would like to prepare a three-minute egg, and for some strange reason he would like to boil his egg at the same time we are boiling ours. He can use the radio time signal to make certain that

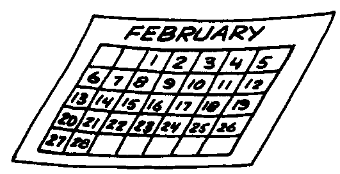



he boils the egg for three minutes, but he can't use the signal to assure himself that he will start his egg when we start ours. He needs some added information. We might arrange to flash our kitchen lights when we start our egg, which will signal him to start his.

But this wouldn't be a very practical solution if, for some even stranger reason, everyone in the whole town would like to boil eggs when we boil ours. At this point, it would be more practical to include a voice announcement on the radio time signal, which simply says, "When you hear the next tick, drop your egg into the water."



We have now solved the *simultaneity* problem by adding extra information to the broadcast, but even this solution is not altogether satisfactory, for it means that everyone in the whole town must keep his radio turned on all the time waiting for the announcement saying, "Drop your egg into the water." A much more satisfactory arrangement is to announce every hour that all eggs will be dropped into the water on February 13, 1997, at 9:00 a.m.—and to further expand the time broadcasts to include announcements of the date, say every five minutes. Thus, as we progress through the concepts of time interval, simultaneity or synchronism, and date, we see that the information content of the broadcast signal must increase. In a more general sense, we can say that as we move from the localized concept of time interval to the generalized concept of date, we must supply more information to achieve the desired coordination. And as usual, we cannot get something for nothing.



## TIME INFORMATION—SHORT AND LONG

Generally speaking, we associate time information with clocks and watches. Time interval—if the interval of interest is shorter than half an hour or so—is often measured with a stop watch. Where greater precision is required, we can use some sort of electronic time-interval counter. But some kinds of time information are either too long or too short to be measured by conventional means. In our discussion of Time and Astronomy, we deduced an age for the universe from a combination of astronomical observations and theory. Obviously, no clock has been around long enough to measure directly such an enormous length of time.

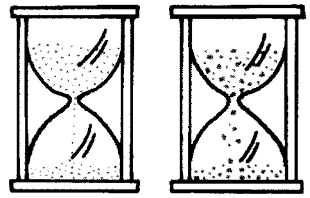
There are also intervals of time that are too short to be measured directly by clocks—even electronic counters. For example, certain elementary atomic particles with names like *mesons* and *muons* may live less than one billionth of a second before they turn into other particles.

TRACK LENGTH IS A MEASURE OF PARTICLE LIFETIME

If we cannot measure such short times with existing clocks, how do we come to know or speak of such short intervals of time? Again, we *infer* the time from some other measurement that we *can* make. Generally, these particles are traveling at speeds near the speed of light, or about 30 centimeters in a nanosecond ($10^{-9}$ second). When such a particle travels through a material like photographic film, called an emulsion, it leaves a track, whose length is a measure of the lifetime of the particle. Tracks as short as 5 millionths of a centimeter can be detected, so we infer lifetimes less than $10^{-15}$ second. But we must restate that we have not actually measured the time directly—we have only inferred it.

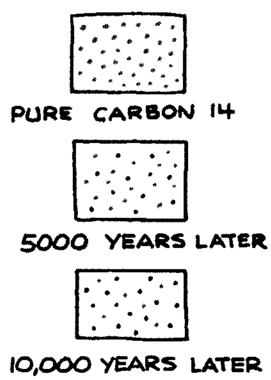
We can imagine even shorter periods of time, such as the time it would take a light signal to travel across the nucleus of a hydrogen atom—about $10^{-24}$ second. Of course, we can *imagine* even shorter times, such as $10^{-1000}$ second. But no one knows for sure what such short periods of time mean, because no one has measured directly or indirectly such short times, and we are on very uncertain ground if we attempt to extrapolate what happens over intervals of time that we can measure to intervals well beyond our measurement capability.

The question of whether time is continuous or comes in "lumps" like the jerky motion of the second hand on a mechanical watch has occupied philosophers and scientists since the days of the Greeks. Some scientists have speculated that time is continuous, and that we can divide it into as small pieces as we like, as long as we are clever enough to build a device to do the job, but there is not yet sufficient evidence to decide between the two points of view.



## GEOLOGICAL TIME


We have already seen how cosmological times have been inferred. Here we shall discuss a technique that has shed a good deal of light on the evolution of the Earth and the life it sustains. Again, as always, we want to tie our time measurements to some mechanism or process that occurs at a regular and predictable rate, and has done so for a very long time. If we want to measure something over a long period of time, we should look for some phenomenon that occurs at a very low rate, so that it won't have consumed itself before our measurement is complete.




One such process is related to carbon-14, which is a radioactive form of carbon. Carbon-14 has a "half-life" of 5000 years. This means that if we took a lump of pure carbon-14 and looked at it 5000 years later, we would find that half of the original lump would still be radioactive, but the rest would have "decayed" to become ordinary carbon-12. After another 5000 years the half that was radioactive would have been reduced again to half radioactive and half non-radioactive carbon. In other words, after 10 000 years the lump would be one-fourth radioactive carbon, and three-fourths ordinary carbon.

Thus we have a steady process where half of the radioactive carbon present at any particular time will have turned into ordinary carbon after 5000 years. Radioactive carbon-14 is produced by cosmic rays striking the atmosphere of the Earth. Some of this carbon-14 will eventually be assimilated by living plants in the process of photosynthesis, and the plants will be eaten by animals. So the carbon-14 eventually finds its way into all living organisms. When the organism dies, no further carbon-14 is taken in, and the residual carbon-14 decays with a half-life of about 5000 years. By measuring the amount of radioactivity, then, it is possible to estimate the elapsed time since the death of the organism, be it plant or animal.

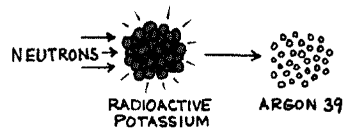
Other substances have different half-lives. For example, a certain kind of uranium has a half-life of about $10^9$ years. In this case the uranium is turning not into nonradioactive uranium, but into lead. By comparing the ratio of lead to uranium in certain rocks, scientists have come to the conclusion that some of these rocks are about five billion years old.

In the last decade or so lasers have revolutionized radioactive dating. We shall explore this revolution in connection with potassium–argon dating.

Radioactive potassium decays into argon-40, one of argon's isotopes. The dating procedure depends on determining the relative amounts of radioactive potassium and argon-40 in a sample. The usual method is to divide the sample into two pieces and determine the amount of potassium in one piece and the amount of argon in the other. This is not without problems.

First, there is no assurance that the ratio of potassium to argon is the same in both pieces. Second, the techniques for determining the amount of potassium, a solid, in one piece differ from the technique for determining the amount of argon, a gas in the other. What one would like is a technique that does not require two pieces and that is the same for both potassium and argon.

A relatively new technique does just that. First, the sample is bombarded with neutrons turning the potassium into argon-39. Now what needs to be determined is the ratio of argon-39 to argon-40, both gases.




Second, a minute sample is heated with a laser, which boils off the argon for both isotopes of argon. It is not necessary to boil off all the argon since the ratio of the two isotopes remains the same no matter how much gas is boiled off.

This procedure is also advantageous when rare materials, such as Moon rocks, require dating, since so little material is needed. In fact this procedure was applied to Moon rocks establishing that the oldest were around 4.4 billion years—near the age of the oldest rocks found on Earth—suggesting that the Earth and the Moon were formed about the same time.

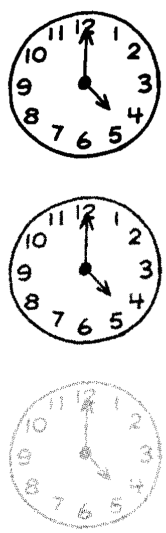
## INTERCHANGING TIME AND LOCATION INFORMATION

As we have said, often scientists are interested in *where* something happens, as well as *when* it happens. To go back to our weather measurement, knowing where the weather data were obtained is as important as knowing when they were obtained. The equations that describe the motion of the atmosphere depend upon both location and time information, and an error in either one reduces the quality of weather forecasts.

As a simple illustration, let's suppose that a hurricane is observed moving 100 kilometers per hour in a northerly direction at 8:00 a.m. and has just passed over a ship 200 kilometers off the coast of Louisiana. Assuming that the storm keeps moving in the same direction at the same speed, it should arrive over New Orleans two hours later, at 10:00 a.m. But the warning forecast could be in error for either or both of two simple reasons: The ship's clock may be wrong, or the ship may be either nearer to or farther from the shore than its navigator thought. In either case, the storm would arrive at New Orleans at a time other than forecast, and the surprised citizens would have no way of knowing which of the two possible errors was responsible for the faulty forecast.


In actual practice, of course, there are other factors that could cause a wrong forecast; the storm might veer off in some other direction, or its rate of movement might slacken or accelerate. But the example illustrates how errors in time or position or both can contribute to faulty predictions; and naturally, the difficulty described here also applies to any process that has both location and time components. Thus, we see another kind of interchangeability between time and space that is distinct from the kind that concerned Einstein.

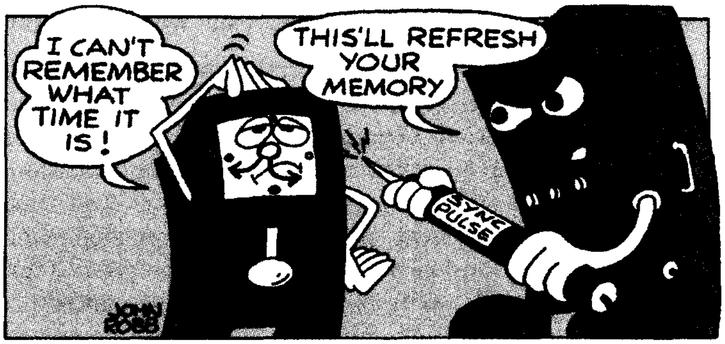
### TIME AS STORED INFORMATION



An important element in the progress of people's understanding of their universe has been their ability to store and transmit information. In primitive societies, information is relayed from one generation to the next through word of mouth and through various ceremonies and celebrations. In more advanced societies, information is stored in books, compact disks and tape, microfilm, computer memories, and so forth. This information is relayed by radio, television broadcasts, and other communication systems.

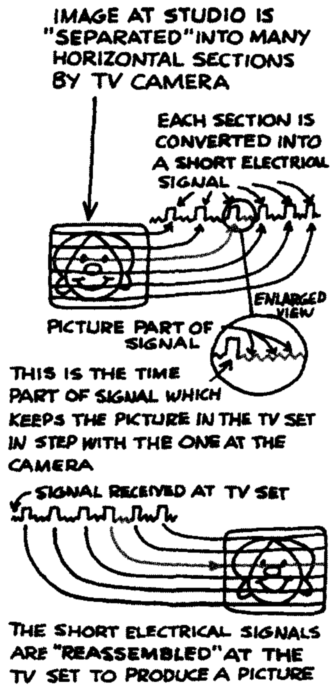
We have seen that time is a form of information, but it is also perishable because of its dynamic nature. It does not "stand still," and therefore cannot be stored in some dusty corner. We must maintain it in some active device, which is generally called a clock. Some clocks do a better job of maintaining time than others. As we have seen, the best atomic clocks would not be in error by more than a second in 10 million years—whereas other clocks may lose or gain several minutes a day, and may refuse to run altogether after a few years.

Any clock's "memory" of time fades with time, but the rate of the fading differs with the quality of the clock. Radio broadcasts of time information serve to "refresh the clock's memory." We have already hit upon this point in our discussion of communication systems in Chapter 14. We discussed high-speed communication systems in which it is necessary to keep the various clocks in the system synchronized, so that the messages do not get lost or jumbled with other messages. We also stated that often the communication system itself is used to keep the clocks synchronized. But the transmission of time to keep clocks synchronized is really a transmission of *information*, so if the clocks in a communication system are of poor quality, a good bit of the




information capacity of the system must be used just to keep the clocks synchronized.

A particularly good illustration of this process occurs in the operation of television. The picture on a black-and-white television screen really consists of a large number of horizontal lines that vary in brightness. When viewed from a distance, the lines give the illusion of a homogeneous picture.

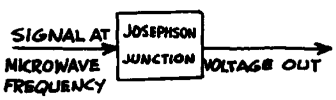



The television signal is generated at the TV studio by a TV camera, which converts the image of the scene at the studio into a series of short electrical signals—one for each line of the picture displayed on the screen of the TV set. The TV signal also contains information that causes that portion of the TV picture being displayed on the screen to be "locked" to the same portion of the scene at the studio that is being scanned by the TV camera. That is, the signal in the TV set is *synchronized* to the one in the camera at the studio. Thus the TV signal contains not only picture information, but time information as well. In fact, a small percentage of the information capacity of a TV signal is utilized for just such timing information.

In principle, if TV sets all contained very good "clocks," which were synchronized to the "clock" in the TV camera at the studio, it would be necessary only occasionally to reset the TV receiver "clock" to the camera "clock." But as a practical matter, such high-quality clocks in TV sets would make them very expensive. So as an alternative there is a clock which must be reset with a "synchronization pulse," every 63 microseconds, to keep the clocks running together.

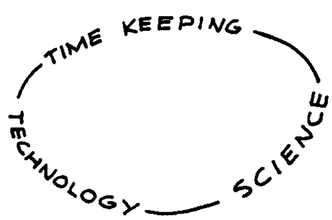
## THE QUALITY OF FREQUENCY AND TIME INFORMATION

There is at present no other physical quantity that can be measured as precisely as frequency. Since time interval is the total of the periods of many vibrations in the resonator in a clock, it too can be measured with very great precision. Because of these unique qualities of frequency and time among all other physical quantities, the precision—and accuracy—of any kind of measurement can be greatly improved if it can be related in some way to frequency and time. We have already seen an example of this fact in the operation of navigation systems in which time is converted to distance. Today considerable effort is being devoted to translating measurement of other quantities—such as length, speed, temperature, magnetic field, and voltage—into a frequency measurement. For example, in one device frequency is related to voltage by the "Josephson effect," named for its discoverer Brian Josephson, at the time a British graduate student at Oxford, who shared a 1973 Nobel prize for the discovery. A device called a "Josephson junction," which operates at very low temperatures, can convert a microwave frequency to a voltage. Since frequency can be measured with high accuracy, the voltage produced by the Josephson junction is known with very high accuracy.




In the next chapter we shall discuss in some detail the conversion of standards to frequency measurements.

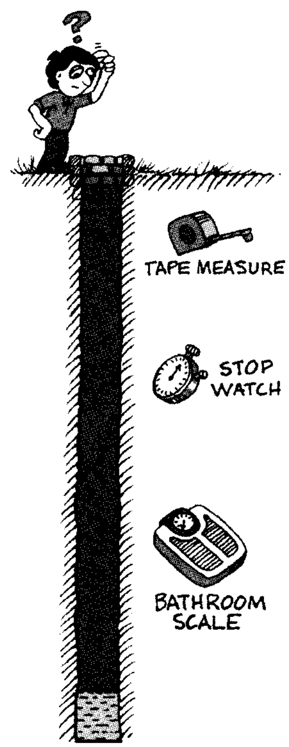
In this and the previous chapters we have been able to mention only a few of the many associations between science and technology, on the one hand, and time on the other. It is clear, however, that the progress and advancement of science, technology, and timekeeping are intimately bound together, and at times it is not even possible to make a clear distinction between cause and effect in the advancement of any one of the three. For the most part, we have attempted to emphasize those aspects of the development of science, technology, and timekeeping that are clearly established or at least well down the road toward development.



## Chapter 22

# HOW MANY SECONDS IN A METER?

There is an old story of a teacher who posed the following question to his beginning physics students: How would you measure the depth of a well if the only items you possessed were a measuring tape, a stop watch, and a bathroom scale? All but one student answered: "Measure the well's depth with the measuring tape."



HOW DEEP IS THE WELL?

There was a little more to the teacher's question than appears at first glance. Notice that the three available items—a tape, a watch, and a scale—represent the three most common units of measurement: length, time, and mass. Most likely the teacher was trying to make the broader point that we perceive length, time, and mass to be the primary, measurable characteristics of our world, and that we have built special instruments to make these measurements.

But perhaps the situation is not quite so simple. By now we know that length, mass, and time are intrinsically related as clarified by the General Theory of Relativity. And even at the more mundane level, there is usually more than one way to skin a cat—which brings us back to our story. How did the dissenting student propose to measure the depth of the well? "I would," he said, "measure with the stop watch how long it took the bathroom scale to hit the bottom of the well. Then, knowing the acceleration due to gravity, I would compute the depth from the fall time."

At first we are amused by this answer. But as we shall see a bit later, measuring the fall time probably gives the best answer.

In the rest of this chapter we want to discuss a number of related issues: How should we make measurements? Does nature dictate our measurement units or do we have some choice in choosing the best units to suit our purpose? And, finally, is there a relation between our measurement units and nature's constants?

## MEASUREMENTS AND UNITS

TWO FARDELS = ONE NOOKE

ONE FOOT = 36 BARLEYCORNS

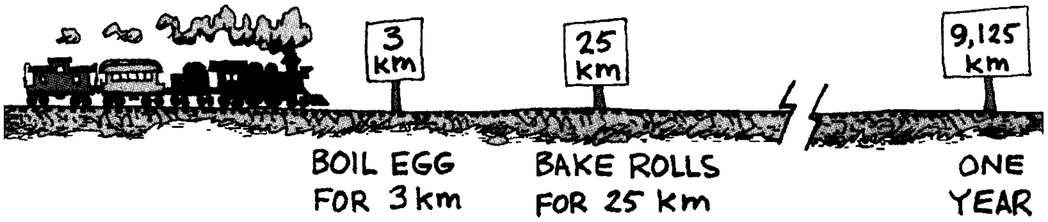
SPEED = 16 FURLONGS PER FORTNIGHT

The story of the invention and evolution of units of measurement is long and often uncertain. We can only wonder how it came to be that two fardels equal one nooke and a fathom was the distance a Viking could encircle in a hug. Or why the foot was defined as 36 barleycorns laid end to end, which in turn seems to have been derived from a statue of England's Henry I. On the other hand, some measurements make eminent sense: an acre is the area that can be plowed by a team of two oxen in a day.

Units of length, mass, and time often are called fundamental because it is not obvious how we could break them down into more fundamental units. However, once again there is more than one way to skin a cat.

Consider a universe where all trains travel at 60 kilometers per hour. (It's not clear how you would get on and off such trains, but that is another problem.) The fact that all trains travel at the same speed seems to be a fact of nature, something to count on. This curious fact does not escape the notice of the people of this universe, so they decide to make it a basis of their measurement system. Their basic measurement is distance or length [L]. They don't have a unit of time measurement [T], but it's not a problem because of their peculiar trains. Their recipe books say things like "For a soft-boiled egg, boil it in water for 3 kilometers" and "Take the rolls out of the oven after 25 kilometers," and their astronomy books say the year is "9125 kilometers long."

In terms of our understanding, what they meant was boil the egg for the duration of time it takes the train to




travel 3 kilometers, take the rolls out of the oven after the train has traveled 25 kilometers, and every time the train has traveled 525 600 kilometers, one year has elapsed. Although this system sounds awkward, it is not too far removed from what we often do. We say it's 20 minutes to downtown and 2 hours to the seashore. These assertions imply some assumed reference speed—like the train.

What these illustrations show is that we can go back and forth between two of our fundamental measurement units, length and time, if we have some way to link them—the speed of a train in this case. Furthermore, we can even dispense with a fundamental unit if we are willing to use the link to convert measurements in one kind of unit into measurements of the other kind.

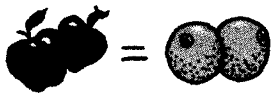
TIME AND LENGTH ARE RELATED BY SPEED

In our universe, the most common speed for converting back and forth between length and time is the speed of light, some 300 000 kilometers per second. Like the train, the speed of light is a constant of nature, again something to count on. In fact, not only is it a constant, it is, as far as we know, the same for all observers whatever their speed relative to each other.

As an example, astronomers measure the distance to stars in light years. When they say Alpha Centauri is about four light years away they mean it would take a rocket ship, traveling the speed of light, four years to reach it. But aside from the utilitarian nature of this example, there is a deeper reason for converting distance to time. As we have seen on a number of occasions by now, Einstein showed that space and time are two sides of the same coin. In fact, in relativity, space, and time have been combined and put on an equal footing (no pun intended) and replaced with one concept, "spacetime."

EINSTEIN REPLACED SPACE AND TIME WITH ...SPACETIME!

## RELATIVITY AND TURNING TIME INTO SPACE



APPLES EQUAL ORANGES?

It is convenient in spacetime, from a mathematical point of view, to convert all coordinates in spacetime to the dimensions of length [L]. This seems nonsensical. How can time equal length? It would be like saying that apples equal oranges. The answer is, as you might have guessed, the speed of light, which is usually designated by the letter "c." With c we can convert oranges into apples.

To understand this, we need to look at the dimensions of the various quantities. Time has the dimension of time or [T], while distance has the dimension of length or [L]. On the other hand, speed has the dimensions of distance divided by time (10 kilometers per hour, for example) so that the dimensions of speed are [L]/[T]. As we know, speed and time are linked by the equation

[L] = SPEED x [T]

distance = speed multiplied by time.

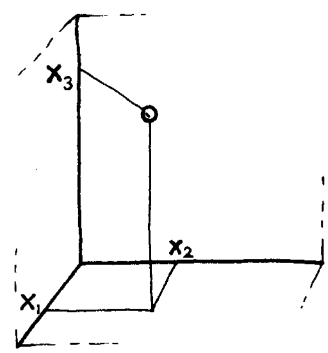
In any equation, the parts of the equation on either side of the equal sign have to represent the same quantity—apples equal apples, to use our fruit analogy. Another way of saying this is that the two sides of the equation have to have the same dimensions. For our equation, we have distance on the left side, with dimension [L], and speed and time on the other side with dimensions [L]/[T] and [T]. But speed and time are multiplied together so that the dimensions on the left side are really

$$\frac{[L]}{[T]}\text{times}[T]\text{, or}$$

simply [L] because the [T]s cancel out ([T]/[T] = 1). So from a dimensional point of view our equation is

$$[L] = [L],$$

which is exactly what we want—we want apples to equal apples. And what has performed the trick? It is c because its dimensions [L]/[T] neatly merge with the dimension of time [T] leaving [L]. Now we return to spacetime.




It is common in physics parlance, as the figure shows, to designate the three spatial dimensions (east-west, north-south, and up-down for example) with the symbols $x_1$, $x_2$, and $x_3$, while time is designated by "t." With these four symbols we can designate where and when some event, an airplane crash, for example, occurs, as the figure shows. But, from the mathematical point of view of relativity, we would rather represent time by the symbol $x_4$ which, like the other three x coordinates, should have the dimension of length [L]. We know how to do this. We multiply t by c and set this quantity, c times t, equal to $x_4$. Now, the quantities $x_1$ through $x_4$ all have dimensions [L], which is what we wanted. You might say that we have incorporated c into time to obtain $x_4$.

The reader may think we have gone to a lot of work to accomplish what? Well, for one thing all the x coordinates have the same dimension, [L]—one of our stated goals. But more importantly, we have removed the distinction between space and time which relativity shows do not lead separate lives. Furthermore, when we do calculations we don't have to bother with the speed of light; we don't have to carry it along in our equations like a pack of useless rocks on our back.

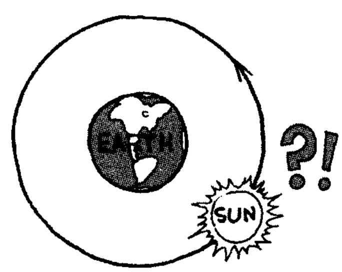
$x_4 = ct$

$x_1, x_2, x_3$, AND $x_4$ ALL HAVE THE DIMENSION [L]

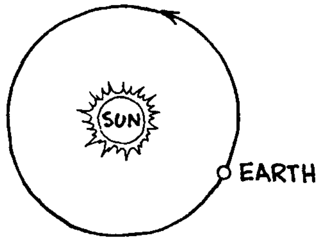
All of this is to say that we choose the quantities in our equations and formulate our problems as best we can to make life as simple as possible. But we need to do this in such a way that we get the correct answer. We have to be careful that our symbol manipulation doesn't lead us astray.

## NATURE'S CONSTANTS AND THE NUMBER OF BASE UNITS

Choosing the right symbols and the right point of view is extremely important in science. Before Copernicus, people believed that the Sun and all the planets circled the Earth. Elaborate schemes, based on this model of the solar system, were erected to explain and predict the motions of the Sun, Moon, and planets. From the point of view of the Earth-centered solar system, the planets and the Sun moved in complicated paths called epicycles. These were paths generated by small circles whose centers moved on the circumference of larger, Earth-centered, circles. The circumference of these



circles coincided with the orbits of the planets of the Earth. Surprisingly enough, this system allowed astronomers to make accurate predictions of planetary motions and eclipses.




COPERNICUS SIMPLIFIED THINGS

When Copernicus replaced the Earth-centered model with a Sun-centered one, the predictions weren't any better, but the calculations were considerably simplified and it was much easier to visualize what the calculations meant.

How we choose our units of measurements is also predicated on the conviction that they should be useful and easy to measure. There is nothing in nature that dictates that we must set up a measurement system in one particular way and not another. To be sure, some measurement systems, given the nature of our universe, make more sense than others, but ultimately the choice is ours, for better or for worse.

EPHEMERIS SECOND WAS HARD TO MEASURE.

The ephemeris second, adopted in 1956 and abandoned in 1967, is an example of a time standard that is not particularly useful from a measurement point of view. As we know from Chapter 9, the ephemeris second was adopted to overcome the irregular nature of the second based on Earth's rotation. In that respect, it was a success. The trouble was that astronomical measurements had to be made over a nine-year period just to achieve an accuracy of 0.05 second.

As we have already said, mass, time, and length seem to be basic, measurable properties of the universe that can't be broken down into more fundamental units. But on the other hand, we have also seen how to get rid of the time dimension by suitably "folding" it into length, as we did in relativity theory.

"$\varepsilon$"
HERE TODAY-GONE TOMORROW

This possibility is not new. There is a constant $\varepsilon_0$, which is called the permittivity of free space. This constant tells us how well free space transmits an electric field. $\varepsilon$ has appeared and disappeared over the years depending on the fashion of the time. A law, Coulomb's law, gives us the force F between two electric charges, $q_1$ and $q_2$, as a function of their separation d. In SI units (the International System of Units, which are in fashion today) the law takes the form

$$F = \frac{q_1 q_2}{4\varepsilon_0 \pi d^2}.$$

In an earlier time, when electrostatic units (esu) were in fashion, Coulomb's law read

$$F = \frac{q_1 q_2}{d^2}.$$

You will notice, there is no $\varepsilon_0$. What happened?

The answer is that in SI units, charge is regarded as a different concept that cannot be defined in terms of [L], [M], and [T], while in esu units charge is not a fundamental unit. In fact, its dimensions in esu units are

$$\frac{[M][L]}{[T]},$$

ELECTRICAL CHARGE HAS UNITS OF

$$\frac{M \quad L}{T}$$

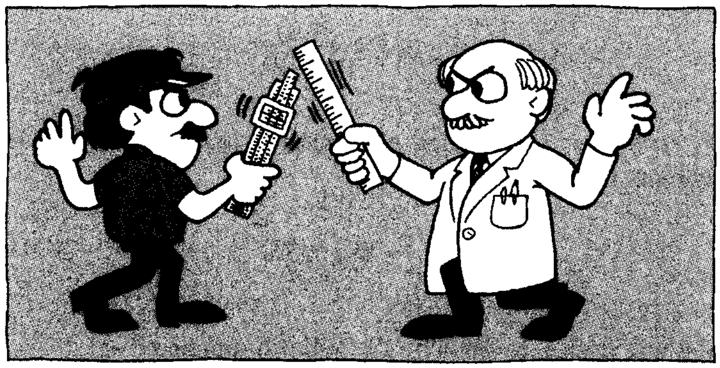
IN ESU UNITS

while in SI it is defined in terms of amperes and seconds which do not involve the units of mass and length.

In summary, what has happened is that in esu units $\varepsilon$ has been absorbed into charge so that it ends up having the dimensions shown above. In SI units $\varepsilon$ is a conversion factor that we need because of our choice of base units. In other words, you can't get something for nothing. If you want to have a lot of base units then you avoid quantities, like charge, having dimensions involving mass, length, and time. That's the good news. The bad news is that you need constants, like $\varepsilon$, to show you how all these base units relate to each other.

Ultimately, if all base units were reduced to frequency measurements, then all the constants of nature would be reduced to numbers like $\varepsilon$, "scale factors" as they are called. But the final point is, whatever is done is largely at the discretion of the user and should be guided by whatever simplifies her struggles.

To some extent, scientists' choice of units and other measurable quantities depend on their point of view. Often the point of view turns on whether a scientist is an experi-



THEORETICIAN VERSUS EXPERIMENTALIST
THE BATTLE OF THE UNITS!

mentalist or a theoretician. We have already seen the advantage of folding time into space from the point of view of the theoretical physicist doing relativistic calculations. But what is good for theory is not necessarily good for measurement. In fact, from a standards-measurement point of view it is better to focus on time rather than space.

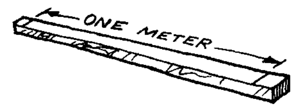
TIME CAN BE MEASURED WITH THE MOST ACCURACY

The reason for this is easy to understand. Of all the basic measurements, time is, by far, the one that can be measured with the most accuracy. This suggests that we should, as much as possible, relate all basic measurements to time measurements. The best example of this, one that took place officially in 1987, is the redefinition of the length standard. We shall explore next how this came about.

### LENGTH STANDARDS

In the 1790's, revolutionary France tried to bring order to the mishmash of existing measurement systems. At that time, they proposed that the world adopt the metric system and that the meter be defined as 1/10 000 000 of the distance between the North Pole and the equator. Like ephemeris time, the concept was easy to grasp, but the measurement required to realize the "standard" meter was excruciating. Who knew exactly where the equator was, let alone the North Pole—a place no one had ever seen!

A few years earlier Voltaire, regarding a doomed Norwegian expedition to measure the distance to the North Pole, had quipped "These Norwegians have lost life and limb to measure what Newton figured out in his armchair." In the spirit of Voltaire, what was needed was an armchair definition of the meter. But that didn't happen until 1889 when scientists defined the meter as the distance between two marks on a platinum-iridium bar kept under constant conditions near Paris. This length standard provided an accuracy of about one part in a million, which by 1960, was entirely unsatisfactory. In that year, the meter was redefined as 1 650 763.73 wavelengths of the reddish-orange light emitted by the gaseous rare element, krypton-86.




PLATINUM - IRIDIUM BAR

With this standard, errors were reduced to about four parts per billion—which translated into an error of about two meters for Earth–Moon distance measurements. As good as this was, it raised problems for the ever-growing space-age industry and for scientists who were exploring the subtleties of relativity theory and the movements of continents.

In 1983 in Paris, the General Conference on Weights and Measures adopted a new definition of the meter based on a time measurement. Conceptually, the new definition was easy as pie: the meter was the distance that light travels in 1/299 792 458 of a second. At the time of the new definition, atomic clocks were accurate to about 1 part in $10^{13}$ while the

AS OF 1983, ONE METER EQUALS THE DISTANCE LIGHT TRAVELS IN $\frac{1}{299,792,458}$ OF A SECOND.


accuracy of the krypton length standard was about 4 parts in $10^9$, so the potential improvement was by a factor of about 5000.

Unfortunately, implementation of the new length standard was easier said than done. As we know, the second is defined in terms of a microwave frequency, with a wave-

IT'S DIFFICULT TO RELATE LENGTH AND MICROWAVE RADIO FREQUENCY MEASUREMENTS.

length of about 3.3 centimeters, while length metrology is most easily done with optical devices, such as interferometers, where the wavelengths are much shorter than 3.3 centimeters. One way to realize directly the definition of the meter would be to build an interferometer that operated at microwave frequencies. But such a device would be impractically large.

A better alternative is to link frequency measurements in the microwave region to frequency measurements in the optical region. The main approach to this problem is to build a chain of frequency sources, starting with the cesium standard microwave frequency signal and work up, step by step, to the optical frequency range. This task has proved to be about as much art as science. Nevertheless, impressive gains have been made since the new definition of the meter in 1983.

SPEED OF LIGHT IS A DEFINED QUANTITY.

One fallout of this new definition was that the speed of light was no longer a measured quantity; it became a defined quantity. The reason is that, by definition, a meter is the distance light travels in a designated length of time, so however we label that distance—one meter, five meters, whatever—the speed of light is automatically determined. And measuring length in terms of time is a prime example of how defining one unit in terms of another removes a constant of nature by turning c into in a conversion factor whose value is fixed and arbitrary.

### MEASURING VOLTS WITH FREQUENCY

RELATE ALL MEASUREMENTS TO TIME

It is the hope of some metrologists that eventually all seven base standards—time, length, mass, current, temperature, amount of substance, and luminous intensity—will be replaced with a single base standard, time. This possibility is being explored to one degree or another by public and private standards laboratories throughout the world. It is not feasible to review all this work, but we shall conclude our discussion of this topic by describing one area that has been particularly fruitful—the voltage standard. Voltage is not one of the base units, but it could easily be and its story conveys the general concept.

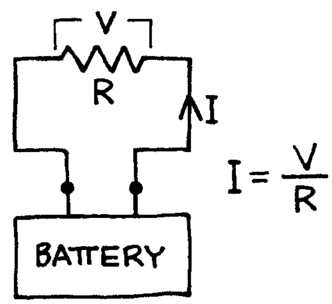
In our discussion of the atomic clock, we pointed out that one of the great advantages of an atomic definition of time is that it is based on a natural resonant frequency of the cesium atom. This frequency is provided by nature, so all we have to do is figure out how to measure it. This is very much unlike time based, say, on a pendulum clock where the reference frequency depends on how well we can fabricate a pendulum of the desired length. It would be desirable if all the units of our measurement system were related to natural phenomena, leaving humanity out of the picture as much as possible.

MOVE MEASUREMENTS FROM THE MACROWORLD TO THE MICROWORLD.

We might say that a time standard based on a pendulum clock is a macroworld approach to the problem while one based on an atomic resonance frequency is a microworld approach. From this point of view, we would like all our base measurements to be derived from microworld phenomena.

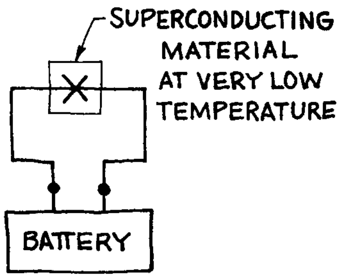
The ampere, the basic unit of current, is the foundation of all electrical measurements. It is defined in terms of the amount of current that's required to flow between two parallel wires, one meter apart in a vacuum, to produce a certain force, per meter, between the wires. Obviously, this is a macroworld definition.

The volt, in turn, is defined as the difference in electric potential between two points on a conducting wire carrying a constant current of one ampere where the power dissipated between the points is 1 watt—obviously, another macroworld definition. What we would like is some connection between volt and frequency that depends on a phenomenon in the microworld.




The figure shows a simple electrical circuit consisting of a battery with voltage V and a resistor with value R. There is a simple, intuitively satisfying relation between V and R and the amount of current I that flows in the circuit. The relation simply says that the current flow depends on the battery voltage V and the resistor's resistance R. If you increase the voltage the current goes up and if you decrease the voltage the current goes down. With resistance, just the opposite is true: if you increase R the current goes down and if you decrease R the current goes up. This is all neatly summarized by the equation

$$I = V/R.$$




Now consider another circuit where, as the figure shows, we have removed the resistor leaving a gap—and just for good measure have placed an insulator in the gap. Since the circuit is broken and also insulated, we would not expect any current to flow in this circuit anymore than we would expect our toaster to toast bread if the toaster were unplugged.

But suppose we make the gap very small—say a few atoms across. And further suppose we place the gap in a superconducting material immersed in a very low temperature environment. Now would a current start to flow? The answer is, yes. This is just another example of how things in the microworld don't behave in expected ways.

The prediction that current would flow in such a device was made by the English physicist, Brian Josephson. Josephson's forecast was based on his analysis of the device using quantum mechanics—the appropriate theory for the microworld. The figure shows Josephson's device which is called, fittingly enough, a "Josephson junction." The figure shows the device consists of superconducting material interrupted by a small insulated gap.

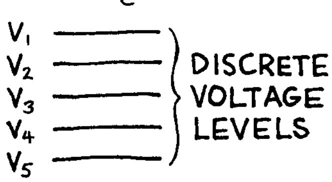
$$V = \left(\frac{h}{2e}\right) \times f$$

Josephson not only predicted that a current would flow in his junction, but said that under certain conditions the current would not be smooth, that it would alternate at a microwave frequency. This is called the AC Josephson effect and is related to voltage by the simple formula

$$V = \left(\frac{h}{2e}\right) \times f\,,$$

where f is the microwave frequency, e is the electrical charge of an electron, and h is Planck's constant. The formula is the key to measuring volts with frequency.

VOLTAGE INCREMENTS EQUAL MULTIPLES OF $\frac{h}{e} \times f$

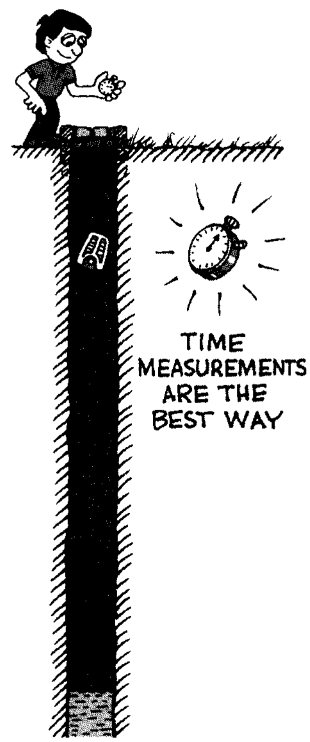



The junction, as is normal in the microworld, also works in reverse. That is, if you apply a microwave signal to the junction, then a voltage appears at the junction. These voltages increase in discrete steps as the current increases—a strong clue that we are dealing with the quantum world—and are related to the frequency in the formula above. Specifically, the voltage increments are equal to multiples of the quantity h/2e times f. So the accuracy of our knowledge of the voltage depends directly on how well we can measure f which, fortunately, we can measure very well with a cesium frequency standard.

One practical difficulty is that the value of 2h/e is only about 0.000 002 volts per gigahertz (one billion hertz) so it is difficult to make voltage calibrations with just one Josephson junction. However, with today's technology, it is possible to mass-produce the junctions, each only a few micrometers across, as thin films. By joining many such devices together we can generate enough voltage to make calibrations.

## STUDENT REDUX

At the beginning of this chapter, we made the point that the student who dropped the bathroom scale in the well to measure its depth may not have been too far off the mark. Although we don't recommend this as a routine procedure, it should be clear by now that if you want to make the most accurate measurements, time measurements are the way to do it.



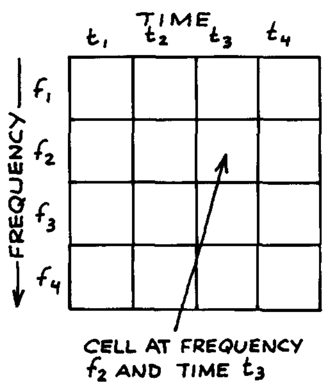
# Chapter 23

# THE FUTURE OF TIME

We have called time “the great organizer.” In a world that is rapidly depleting its known natural resources, it is mandatory that we use the resources we have efficiently. Central to efficient use are planning, information gathering, organizing, and monitoring. The support of these activities will make great demands on time and frequency technology.

## USING TIME TO INCREASE SPACE

We can think of time and frequency technology as providing a giant grid within which we can file, keep track of, and retrieve information concerning the flow of energy and materials. The higher the level of our time and frequency technology, the more we can pack into the cells of our grid. Improving time and frequency technology means that the walls separating the cells within the grid can be made thinner, thus providing more spacious cells. And at the same time we can identify more rapidly the location of any cell within the system. To explore this theme, we shall once again use transportation and communication as examples.




As a safety measure, airplanes are surrounded by a volume of space, into which other planes are forbidden to fly. As the speed of the plane increases, the volume of this space increases proportionately, in much the same way that a driver of a car almost automatically leaves a larger space between himself and other cars on the highway as he increases his speed. Over the years, the average speed and the number of planes in the air have increased dramatically, to the point that there are severe problems in maintaining safety in high-traffic areas.

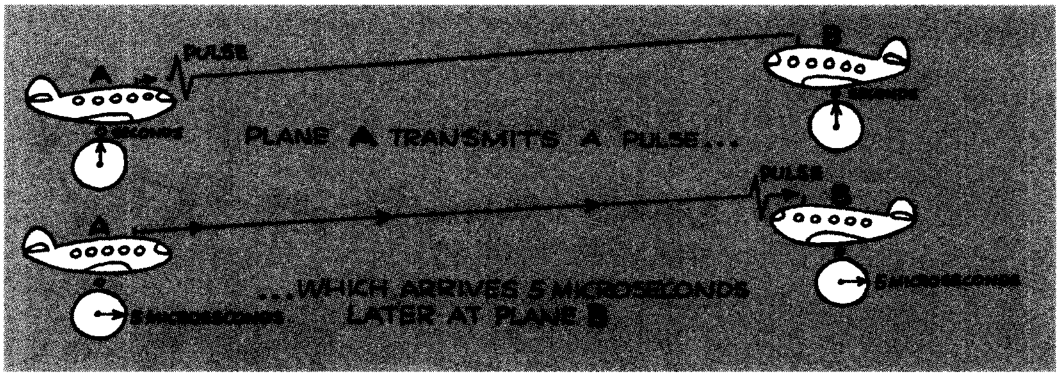
We have two choices: Either limit air traffic or institute better air traffic control measures—which, in effect, means reducing the size of the protective space around each plane. At present, new systems that will allow greater airplane density without diminishing safety are being explored.

There are a number of ways we might do this. One solution is for air traffic controllers to keep track, by radar or some other means, of all the aircraft in their vicinity. With this information they can warn aircraft of possible problems. (We can imagine that these control functions might, at some future date, be taken over by computerized, satellite monitoring stations.) This is a centralized approach to the problem.

A more localized approach requires planes to, in effect, notify other planes in the area of their presence. In one approach, planes continually emit pulses that are automatically received and retransmitted by transmitters in other planes—by transponders. The distance between any two planes, and therefore any constellation of planes, is obtained by dividing the round-trip path delay pulse time by two and thus obtaining the distance between pairs of planes. We shall return to this two-way technique, shortly, in connection with satellite time coordination.

Another system for collision avoidance relies on planes carrying synchronized clocks that "time" the transmission of the pulses. For example, plane A might transmit a pulse arriving 5 microseconds later at plane B. As we know, radio signals travel at about 300 meters in 1 microsecond, so planes A and B are separated by about 1500 meters.

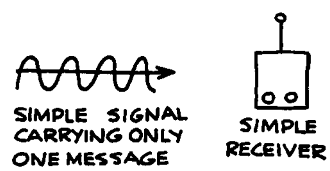
This system puts a severe requirement on maintaining interplane synchronization, since each nanosecond of clock synchronization error translates into 1/3 meter of interplane error. The clock and transponder approaches are classic examples of the tradeoff between synchronized and nonsynchronized systems. With nonsynchronized systems, the col-

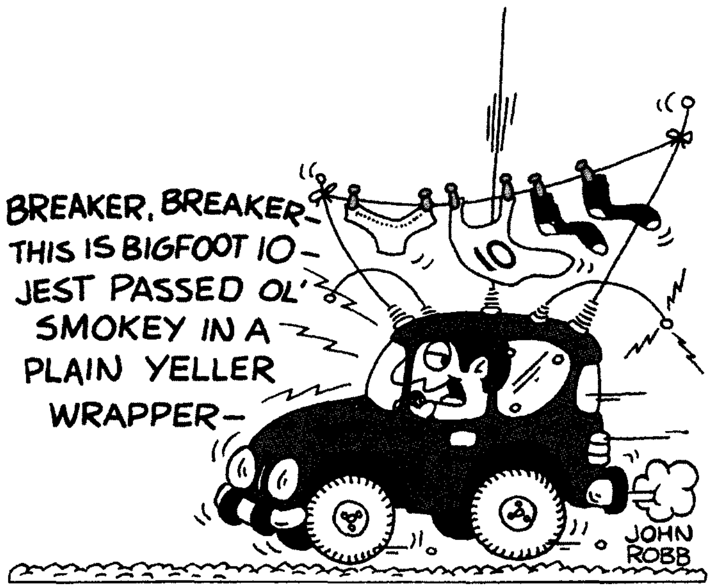



lision avoidance system using transponders, planes continually receive and transmit pulses, while with the synchronized system planes need only receive pulses from surrounding planes to know their ranges. As long as there is plenty of radio spectrum, the transponder approach is cheaper. But the radio spectrum is a limited natural resource which becomes more valuable each day as more and more demands are made on it. In the meantime, high quality clocks are becoming cheaper. At some point in the future, synchronized systems may become the economical solution.

In Chapter 11 we saw that high message-rate communication systems rely heavily on time and frequency technology so that messages can be both directed to and received at the correct destination. Many of these messages travel in the form of broadcast radio signals, with different kinds of radio "message traffic" being assigned to different parts of the radio frequency spectrum. Just as a protective space is maintained around airplanes, a protective frequency gap is maintained between radio channels. And further, just as air space is limited, so is radio "space." We cannot use the same piece of radio space for two different purposes at the same time.

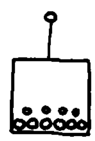
To get the best use from the radio space, we would like to pack as much information as possible into each channel, and we would like the protective frequency gap between channels to be as small as possible. Better frequency information means that we can narrow the gap between channels, since there is reduced likelihood of signals assigned to one radio channel drifting over into another. Better time and frequency information together contribute to the possibility






of packing more, almost error-free, information into each channel by employing intricate coding schemes.

COMPLEX SIGNAL CARRYING MANY MESSAGES



COMPLEX RECEIVER TO DETECT AND SEPARATE SIGNAL INTO DIFFERENT MESSAGES

The transportation and communication examples we have cited can work no better than the underlying technology that supports them. We may be able to generate high-rate messages and build high-speed airplanes by the hundreds, but we cannot launch them into the "air" unless we can assure that they will arrive reliably and safely at their appointed destinations.

In the past, the world has operated as though it had almost infinite air space, infinite radio space, infinite energy, and infinite raw materials. We are now rapidly approaching the point when the infinite-resource approximations are no longer valid, and our ability to plan and organize will be heavily strained. It is here, no doubt, that time and frequency technology will be one of man's most valuable and useful tools.

## TIME AND FREQUENCY INFORMATION—WHOLESALE AND RETAIL

The quality of time and frequency information depends ultimately upon two things—the quality of the clocks that generate the information and the fidelity of the information channels that disseminate the information. There is not much point in building better clocks if the face of the clock is covered by a muddy glass. In a sense, we might think of the world's standards labs as the wholesalers of time, and the world's standard time and frequency broadcast stations as the primary distribution channels to the users of time at the retail level. Let's explore the possibility of better dissemination systems for the future.

### Time Dissemination

At present, the distribution of time and frequency information is a mixed bag. We have broadcasts such as WWV, dedicated primarily to disseminating time and frequency information; and we have navigation signals such as Loran-C and GPS, which provide high-quality time information because the systems themselves cannot work without it. The advantage of a broadcast such as WWV is that the time information is in a form that is optimized for the users. The signal contains time ticks and voice announcements of time in a readily usable form. The formats of navigation signals, on the other hand, are optimized for the purposes of navigation, and time information is often somewhat buried, not so easily used.

From the viewpoint of efficient use of the radio spectrum, we would like to have one signal serve as many uses as possible. But such a multi-purpose signal puts greater demands on the user. He must extract from the signal only that information of interest to him, and then translate it into a form that serves his purpose.

In the past, the philosophy has generally been to broadcast information in a form that closely approximates the users' needs, so that processing at the users' end is minimized. This means that the receiving equipment can be relatively simple and therefore inexpensive. But such an approach is wasteful of the radio spectrum, which, as we have said, is a limited resource. Today, with the development of transistors, large-scale integrated circuits, and mini- and micro-computers, complicated equipment of great sophistication can be built at a modest cost. This development opens the door to using radio space more efficiently, since users can

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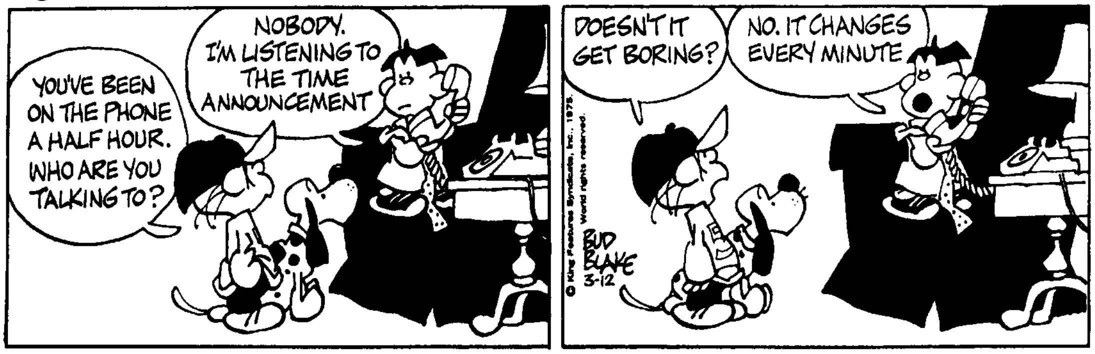





now afford the equipment required to extract and mold information to their own needs.

Thus there is a trade-off between receiver complexity and efficient use of the radio spectrum. But there is another aspect of efficient use that we need to explore. The information content of a time information broadcast is itself very low compared to most kinds of signals because the signal is so very predictable. A user is not surprised to hear that the time is 12 minutes after the hour when she has just heard a minute before that the time was 11 minutes after the hour. Furthermore, all standard time and frequency stations must broadcast the same information; we don't want different stations broadcasting different time scales and causing confusion. In fact, the nations of the world take great pains to see that all stations do broadcast the same time as nearly as possible. But from an information standpoint, the broadcasts are highly redundant.

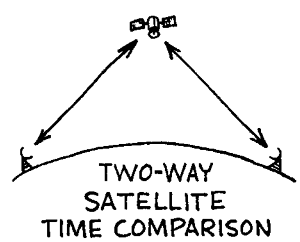
This redundancy also creeps in, in another way. We don't always readily recognize that there is a good deal of redundant time information in, say, a broadcast from WWV and from GPS, because the formats of the signals are so vastly different. This redundancy, of course, is not accidental, but intentional—so that, among other reasons, time information can be extracted from GPS signals. There are many other examples of systems that carry their own time information in a buried form. We have seen this in the operation of television, where a part of the TV signal keeps the picture in the home receiver synchronized with the scene being scanned by the studio TV camera.

We might ask whether it is necessary to broadcast, in effect, the same time information over and over in so many different systems. Why not have one time signal serve as a time reference for all other systems? There could be advantages in such a plan. But suppose that one universal time and frequency utility serves all, and it momentarily fails. Then all other dependent systems may be in trouble unless they have some backup system.

There is no easy answer to the question of universal time and frequency utility versus many redundant systems. Universal time is obviously more efficient for radio spectrum space, at the possible costs of escalating failure if the systems falter, whereas redundant systems are wasteful of radio spectrum space, but insure greater reliability of operation.

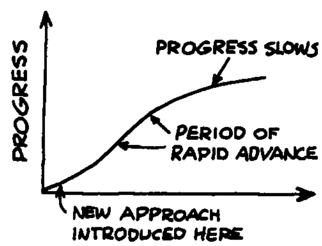
Satellite time broadcasts are vastly superior to ground-based broadcasts. Satellite time signals, like those from the Indian satellite, INSAT, provide wide geographic coverage with microsecond accuracy and with relatively little effort on the part of the user.

As we explained earlier, GPS has replaced carrying atomic clocks as the backbone of international time comparisons. Research is presently underway to develop an even better satellite comparison system. Here, signals are exchanged between pairs of locations, where clock comparisons are needed, via a communications satellite. Analogous to the two-way, transponder collision avoidance system, these two-way signal exchanges allow the signal path delay between pairs of stations to be measured directly with extreme accuracy—usually a few nanoseconds—with the promise that subnanosecond accuracy will eventually be achieved. Knowing the path delays with such high accuracy allows the best clocks throughout the world to be compared with little or no degradation.




The development of lasers and optical fibers provides yet another avenue for time coordination that equals, or may even surpass, satellite coordination systems. Fiber optic communications systems have ideal properties, as described in Chapter 11, for time coordination: wide bandwidth, good signal-to-noise performance, and stable path delay. Experiments over distances of several thousand kilometers, using the two-way signal technique, have already demonstrated time-transfer comparisons well below one microsecond.

### Clocks In the Future—The Atom's Inner Metronome




If we reflect for a moment on the history of the development of clocks, we notice a familiar pattern. First, some new approach such as the pendulum—or in more recent times the atomic resonator—is introduced. Because of the intrinsic qualities of the new resonator, a big step forward results. But no resonator is perfect. There is always some problem to be overcome, whether it is compensating for variations in the length of the pendulum caused by temperature fluctuations, or reducing frequency perturbations caused by collisions in atomic resonators. As each difficulty is systematically removed, further progress is gained only with greater and greater effort—we have reached a point of diminishing returns. Finally we reach a plateau, and a "leap forward" requires some radical new approach. But this by no means indicates that we are in a position to abandon the past when another innovation comes along. Usually the new rests on the old. The atomic clock of today incorporates the quartz-crystal oscillator of yesterday, and tomorrow's clock may well incorporate some version of today's atomic clock.

In the late 1970's the NIST primary atomic clock kept time accurate to a second in about 300 000 years. Today's standard, NIST-7, as we know from Chapter 5, keeps time to a second in over 10 million years. This twentyfold increase in accuracy was brought about by a parade of steady improvements over the years, one of the most recent and important being optical pumping, described in Chapter 5. But, as explored in Chapter 7, we are on the verge of a dramatic breakthrough in timekeeping with the development of clocks based on small numbers of atoms—or even a single atom.

In the early days, only a few laboratories explored these new kinds of standards, but in recent times effort has multiplied many times over and it is not clear which of the many approaches will emerge the victor. In fact, several approaches may well grow and prosper just as today we find room for and need a myriad of devices including crystal oscillators, hydrogen masers, and atomic beam resonance devices.

Our ability to build and improve clocks rests ultimately on our understanding of the laws of nature. Nature seems to operate on four basic forces. The Earth-Sun clock depends upon the force of gravity described within the framework of *gravitational theory*. The electrons in the atomic clock are under the influence of electric and magnetic forces, which are the subject of *electromagnetic theory*. These two forces formed the basis of classical physics.

**FORCES**
GRAVITATIONAL
ELECTROMAGNETIC
WEAK
NUCLEAR

Modern physics recognizes two other kinds of forces in nature. A complete understanding of the decay of radioactive elements into other elements requires the introduction of the so-called *weak force*. We encountered this force when we applied radioactive dating to determine the age of rocks and of ancient organic material. The fourth and final force, according to our present understanding, is the *nuclear* force, the force that holds the nucleus of the atom together. Many scientists suspect that the four forces are not independent—that there is some underlying connection. It has already been experimentally verified that the electromagnetic and weak forces are really variations on a united electromagnetic-weak force particularly between electromagnetic and weak forces, which will someday yield to a more powerful, universal theory. Good progress, in the theoretical arena, has been made in bringing the nuclear force into the fold. But a truly unified theory including the force of gravity has, so far, resisted real progress.

The technology of time and frequency will no doubt play an important part in unearthing new data required for the construction of such a theory. At the same time, the science of keeping time will benefit from this new, deeper insight into nature.

A technique that both gives insight into nature and points to possible new ways of building even better clocks is based upon a remarkable discovery, in 1958, by the German physicist, R.L. Mössbauer, who later received a Nobel Prize for his work. Mössbauer discovered that under certain conditions the nucleus of an atom emits radiation with extreme frequency stability. The emissions are called *gamma rays*, and they are a high-energy form of electromagnetic wave, just as light is a lower energy form of electromagnetism.

The *Q* of these gamma ray emissions is over 10 billion, as opposed to 10 million for the cesium oscillator described in Chapter 5. These high-*Q* emissions have permitted scientists to check directly the prediction of Einstein—that photons of light are subject to gravitational forces, even though they have no mass. (We encountered this effect when we discussed the operation of clocks located near black holes.)

A photon falling toward the earth gains energy just as a falling rock gains kinetic energy with increasing speed. However, a photon cannot increase its speed, since it is already moving with the speed of light—the highest speed possible, according to relativity. To gain energy the photon must increase its frequency because light energy is proportional to *frequency*. Using high-*Q* gamma rays, scientists have verified Einstein's prediction, even though the distance the photons traveled was less than 30 meters.

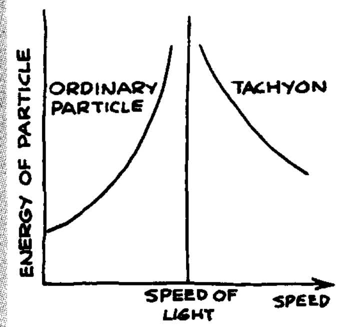

In Chapter 5 we stated that as we go to higher and higher emission frequencies produced by electrons jumping between orbits, the time for spontaneous emission—or natural lifetime gets smaller and that it might eventually get so small that it would be difficult to build a device to measure the radiation. The high-*Q* gamma rays are not produced by jumping electrons traveling in orbits around the nucleus of the atom. They come from the nucleus of the atom itself. The situation is similar to the radiation produced by jumping electrons in the sense that the nucleus of the atom undergoes an internal rearrangement, releasing gamma rays in the process. But the natural lifetime of these nuclear emissions is much longer than the equivalent atomic emissions at the same frequency. This suggests that nuclear radiations may be candidates for good frequency standards.

But there are two very difficult problems to overcome. First, as we stated in our discussion of the possible combined time-and-length standard, we are just now approaching the point when we can connect microwave frequencies to optical frequencies; and the ability to make a connection to gamma-ray frequencies—some 100 thousand to 20 million times higher in frequency than light—is not close at hand. Second, we must find some way to produce gamma-ray signals in sufficient strength and purity to serve as the basis for a resonant device. We cannot be certain at this time that such a gamma-ray resonator will form the basis for some new definition of the second, but the discussion points out that there are new avenues to be explored and that the possibility still exists for improving the $Q$ of clocks.

## PARTICLES FASTER THAN LIGHT—AN ASIDE

We have touched upon the four basic forces in nature and upon the theories associated with these forces. Relativity theory says that no object can be made to travel faster than the speed of light. Each small gain in the speed of an object requires greater energy input until, at the speed of light, the energy input is infinite.

But what about the possibility of particles that are already traveling at speeds greater than the speed of light? These particles were not *pushed across* the speed-of-light barrier; they have always been on the other side. Such particles have been named tachyons, and—if they exist—they must have some remarkable properties if they are to conform to man's present conception of the laws of nature. For example, tachyons gain in speed as they lose energy. Tachyons at rest have an "imaginary" mass—that is a mass which is multiplied by $\sqrt{-1}$. The symbol $\sqrt{-1}$ is well known to mathematicians and can easily be manipulated, but it does not correspond to something that can be measured. This does not present a problem for tachyons, since they are never at rest, so there is no imaginary mass to measure.



But what does all of this have to do with time? When tachyons were first discussed, they seemed to violate—for observers moving in a certain range of speed less than the speed of light—two cornerstones of physics: the law of causality—which says that cause always precedes effect (a timelike idea)—and the idea that something cannot be created out of nothing.

Suppose we have two atoms, A and B. For observers moving in a critical range of speeds it appears as though atom B absorbs a negative-energy tachyon before it is emitted by atom A—a clear violation of causality.

The negative-energy tachyon suggests that we can create particles out of nothing, so to speak. A cardinal rule of physics is that mass/energy is conserved. A system with net zero mass/energy must always have net zero mass/energy. But with negative-energy particles we can create energy out of nothing and not violate conservation of energy. For each new positive energy particle we create, we also create its negative energy cousin, so that, on balance, the net energy is zero.

Happily, a way out of this seeming dilemma was found. Let's suppose that for those observers moving in the critical speed range we interpret the observations differently. We say that instead of seeing a negative-energy tachyon being absorbed by atom B before being emitted by atom A, they see instead a positive-energy tachyon being emitted by B and then absorbed by A.

The search is now on for tachyons, but to date there is no concrete evidence that they exist. For the present, the best we can say is that tachyons are the product of enlightened scientific imagination.

## TIME SCALES OF THE FUTURE

The history of timekeeping has been the search for systems that keep time with greater and greater uniformity. A point was eventually reached with the development of atomic clocks where time generated by these devices was more uniform than that generated by the movement of the Earth around its own axis and around the Sun. As we have


seen, celestial navigation and agriculture depend for their timekeeping requirements upon the angle and the position of the Earth with respect to the Sun. But communication systems are not concerned about the position of the Sun in the sky. For them, uniform time is the requirement.

As we have pointed out, our present system for keeping time—UTC—is a compromise between these two points of view. But we seem to be moving in the direction of wanting uniform time more than we want Sun–Earth time. Even navigators are depending more and more on electronic navigational systems. The need for the leap second may be severely challenged at some future date. Perhaps we should let the difference between Earth time and atomic time accumulate, and make corrections only every 100 years—or perhaps every 1000 years. After all, we make adjustments of even greater magnitude twice every year, switching back and forth between standard and daylight-saving time. But before we conclude that pure atomic time is just around the corner, we can look back to other attempts to change time and be assured that no revolutions are likely.

### The Question of Labeling—A Second is a Second is a Second

More and more of the world is going to a measurement system based upon 10 and powers of 10. For example 100 centimeters equal a meter, and 1000 meters equal a kilometer. But what about a system where 100 seconds equal an hour, 10 hours equal one day, and so forth? Subunits of the second are already calculated on the decimal system, with milliseconds (0.001 second) and microseconds (0.000 001 second), for example. In the other direction, we might have the "deciday"—one deciday equals 2.4 hours; the "centiday"—14 minutes and 24 seconds; and the "milliday"—86.4 seconds.

The idea of the decimalized clock is not new. In fact, it was introduced into France in 1793, and, as we might imagine, was met with anything but overwhelming acceptance. The reform lasted less than one year.

Will we someday have decimal time? Possibly. But the answer to this question is more in the realm of politics and psychology—as well as economics—than in technology.

### Time Through the Ages

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|---|---|
| Reality is flux and change. | *"You cannot step twice into the same river, for fresh waters are ever flowing in upon you."*<br>Heraclitus 535–475 B.C. |
| Time involves measure and order. | *Time is the "numerical aspect of order motion with respect to its successive parts."*<br>Aristotle 384–322 B.C. |
| Time and space are absolute and separate. | *"Absolute, true and mathematical time, itself and from its own nature, flows without relation to anything external."*<br>Newton 1642–1727 |
| Time and space are relative. | *"There is no absolute relation in space, and no absolute relation in time between two events, but there is an absolute relation in space and time . . ."*<br>Einstein 1879–1955 |

## WHAT IS TIME—REALLY?

We have seen that there are almost as many conceptions of time as there are people who think about it. But what is time—really? Einstein pondered this problem when he considered Newton's statements about absolute space and absolute time. The idea of speed—so many kilometers per hour—incorporates both space, distance, and time. If there are absolute space and absolute time, is there then absolute speed—with respect to nothing? We know what it means to say that an automobile is moving at 80 kilometers per hour with respect to the ground; the ground provides a frame of reference. But how can we measure speed with respect to nothing? Yet Newton was implying just this sort of thing when he spoke of absolute space and time.

Einstein recognized this difficulty. Space and time are meaningful only in terms of some frame of reference such as that provided by measuring sticks and clocks, not by empty space. Without such frames of reference, time and space are meaningless concepts. To avoid meaningless concepts, scientists try to define their basic concepts in terms of operations. That is, what we think about time is less important to defining it than how we measure it. The operation may be an experimental measurement, or it may be a statement to the effect that if we want to know how long a second is, we build a machine that adds up so many periods of a certain vibration of the cesium atom.

For scientists, at least, this operational approach to definitions avoids a good deal of confusion and misunderstanding. But if history is our guide, the last word is not yet in. And even if it were, time may still be beyond our firm grasp. In the words of J.B.S. Haldane,

*"The universe is not only queerer than we imagine, but it is queerer than we can imagine."*

### Some suggestions for further reading

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