SEAC and the Start of Image Processing at the National Bureau of Standards

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The National Bureau of Standards Electronic Automatic Computer, SEAC, completed in 1950, was the first electronic computer with an internally stored program in the U.S. government. This paper describes how scanning and computer processing of images began at the National Bureau of Standards in 1956 and how the use of SEAC made possible experiments that led to the widespread use of image processing and many other computer innovations.

Introduction

On the occasion of the 25th anniversary of Siggraph, it is useful to recall that computer processing of images began at the National Bureau of Standards (NBS, now National Institute of Standards and Technology, NIST) some 15 years earlier than the organization of Siggraph. This paper describes these beginnings of image processing and the construction of the early National Bureau of Standards Electronic Automatic Computer (SEAC), which made possible the experiments that led to image processing.

NBS, as part of its mission, offers scientific and technological assistance to other government agencies. This is in addition to its original fundamental mission of support for the National Measurement System. As we will see below, these two missions had a fortuitous coalescence in the NBS work on the development of electronic computers.

SEAC was the first electronic computer in the U.S. government with an internally stored program (see Fig. 1). It was the first of three computers built at NBS.[1] (A later machine, the SWAC, built after SEAC but before DYSEAC, is described in Huskey et al.[30]) It was designed, built, and operated at NBS by engineers, scientists, and mathematicians (there being no such thing as computer scientists until about a decade after the completion of SEAC in 1950).

Originally, SEAC was developed as an interim facility while NBS was awaiting the delivery of the first commercial computer to be used by the Bureau of the Census and subsequently by the Army and the Air Force. Its successful completion made computation possible at NBS both for the sponsors and for many other government agencies a year before any commercial computer was delivered. Notwithstanding the original interim nature of SEAC, this successful resource, with all its subsequent enhancements, continued to function usefully for the government for more than 13 years.

There were many engineering innovations introduced by SEAC. These included:

- the use of new input–output mechanisms,
- an early example both of time-sharing and the interconnection of two computers (the SEAC and the DYSEAC) in 1954,
- the development of marginal checking,
- new memory mechanisms, and
- a graphical display.

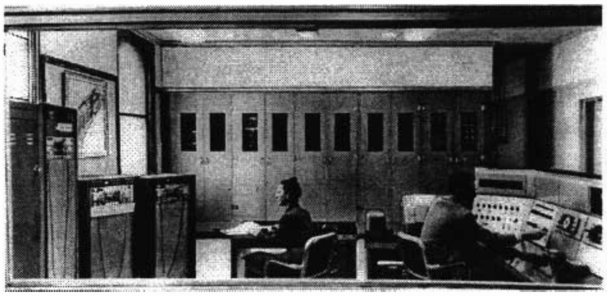

Fig. 1. Overall view of the SEAC computer. Half of the equipment racks and none of the memory cabinets are visible. SEAC contained 20,000 germanium diodes and 1,200 vacuum tubes housed in 20 racks of equipment. The memory of 1,024 45-bit words occupied cabinets approximately the same size as the racks visible in the figure.

Many such innovations are described in the *National Bureau of Standards Circular 551*,[1] which is a collection surveying work until 1953 but not published until 1955. An outstanding group of mathematicians also made major contributions to the field of numerical analysis. Much of this work was later collected in the very popular *Handbook of Mathematical Functions*.[2]

Many problems of science, mathematics, engineering, and government operation lent themselves naturally and obviously to assistance by rapid computational methods. The diversity of these uses is indicated in a list of representative examples of actual computations done on SEAC (see Table 1), as given in the *National Bureau of Standards Circular 551*,[1] mentioned above.

But the most important contributions made with SEAC were in the development of entirely new uses for computers. There was a

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fortunate correlation (causation?) between an expanding economy and an expanding technology that made it possible to develop uses that were previously unknown. Furthermore, the unique status of NBS enabled a kind of exploratory operation free from commercial constraints. Many of the new applications of SEAC to problems of science, mathematics, engineering, and government operation were neither anticipated nor, indeed, requested by the intended beneficiaries. It was usual for the NBS engineers to understand not only possible new goals for the computer but, of course, the technical way to achieve these goals. So, commonly, the benefiting agency would allow NBS the flexibility of exploring its own areas of research. Only after NBS developed prototype applications on the SEAC for these agencies was there a demand for "more of the same, whatever that is."

TABLE 1
COMPUTATIONS DONE ON SEAC

- Mathematics and Statistics
    - *Tables of Jacobi elliptic functions*
    - Monte Carlo methods for differential equations
    - Optimum sampling plans for the Census Bureau
- Physics and Chemistry
    - Crystal structure
    - Relative abundance of the elements
    - Wave functions for He and Li
- Engineering
    - Optical system design
    - Synchrotron design
    - Transient behavior of an oscillator
    - Stresses in aircraft structures
    - Plastic deformation of eccentric columns
- Business and Economics
    - Air Force program planning
    - Social Security accounting

Evangelism

In the early days of electronic computation, a primary question, and one that posed considerable anxiety, was whether computers could be made to function flawlessly and for a sufficiently long period of time to do useful computation. The ENIAC provided some encouragement, and, by 1952, sufficient experience had accumulated at NBS to bolster that encouragement with a measure of confidence.[3] Consequently, NBS was able to encourage the use of computers in areas for which there was no previous experience with automation. As a scientific and engineering agency of high reputation for integrity within the government, NBS made proposals for innovative uses of the SEAC that were received with a more generous response by other agencies than would have been possible in a more competitive commercial environment. In fact, there was a widely held feeling that "nothing will be restrained from them which they have imagined to do."[4]

There were special conditions associated with the operation of the SEAC that encouraged such evangelism. Everybody on the staff shared in the onerous task of playing nursemaid to the computer 24 hours each day. There was a nominal maintenance crew, of which I was a member, and we were augmented by the rest of the staff. The maintenance crew had extraordinary powers. This was the power to take the machine away from the so-called productive users, based entirely on our own judgment. The rationale behind this—a rationale that I still think is admirable, but very seldom practiced nowadays—was that we needed to keep the computer in almost flawless operation to be able to use it as a self-diagnostic tool. Such a diagnostic tool would be of no use unless one could make the assumption that there was *at most* one fault in the machine at any one time. Consequently, any time that we suspected that there was a fault, we would take the computer away from the users to try to track it down, for fear that *another* fault might occur before we had located the first one. Typically, we would find a memory error, and we would use one half of the memory for the diagnostic program while we checked the other half. If there were two errors in the memory at the same time, we could not reliably load the diagnostic program. Then the problem of finding the trouble would be very hard. So we were very scrupulous about keeping the computer fault-free.

> **After reconnecting the computer, I discovered, to my horror, that there was a wiring error in the original design that had survived about a decade of our scrupulous diagnostic checking.**

We were prepared to claim several years of fault-free operation of the SEAC when we moved the computer to a different part of the NBS campus. This required disassembling the hardware and reconnecting it according to the design diagrams (and the excellent memory of some of the staff). After reconnecting the computer, I discovered, to my horror, that there was a wiring error in the original design that had survived about a decade of our scrupulous diagnostic checking and would have resulted in a definitive error every time a suitable program was run. It had never occurred in a decade of round-the-clock operation. From this, we may conclude that a faultless computer has probably never been built, since all computers have always had known malfunctions with associated "workarounds" in the software, if not in the hardware.

Such assiduousness in tracking down malfunctions is seldom, if ever practiced today. But in the process of testing the computer after a suspicious fault had been detected, I would confirm the correct operation by running some of my own research programs. It turns out that in the early days of computing, many people had this same practice. For example, Arthur Samuel at IBM, who wrote the first artificial intelligence program for playing checkers, was the manager of the Poughkeepsie, New York, plant. He had masses of IBM 701 computers playing checkers every night, supposedly in order to check out the computers, but of course really to accumulate learning experience on his program. This was also the source of similar computer time that I used to accumulate my own artificial intelligence research results.

These modes of operation allowed us to try ideas for which there were not necessarily any stated applications. And the great size of what we eventually considered the "government market" enabled any innovative computer use to be successfully placed somewhere in a government agency.

Among these innovative uses of computers were the searching of chemical structures,[5] artificial intelligence,[6] information retrieval,[7] language processing,[8] and many others during SEAC's

14 years of productive computation. Below I discuss the four decades of one of these applications—image processing—as it developed at the NBS.

The Earliest Image Processing

By 1957, computers were in common use in many laboratories and commercial establishments. Originally, they were devoted exclusively to numerical, algebraic, and geometric computation. Later, the symbol manipulation capability of computers became recognized, leading to so-called business data processing, in which alphanumeric processing became routine. The alphanumeric data presented the obvious problem of inputting the vast quantity of data needed for business. This created activity in developing character recognition machinery.[9] It occurred to me that a general-purpose computer could be used to simulate the many character recognition logics that were being proposed for construction in hardware. This would require an input device that could transform a picture (of a character) into a form suitable for storage in the memory of a computer.

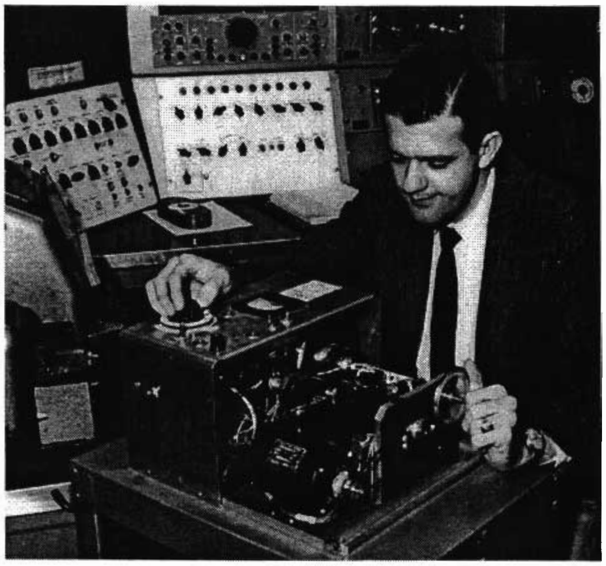

Fig. 2. Richard B. Thomas at the SEAC scanner.

A further important advantage of building such a device was that it would enable programs to be written to simulate the multifarious ways in which humans view the visible world. A tradition had been building in which simple models of human structure and function had been studied, for example, in neuroanatomy and neurophysiology.[10] The emphasis on binary representations of neural functions led us to believe that binary representations of images would be suitable for computer input. This serious mistake, discussed below, was implemented in the first picture scanner built. We connected it to the SEAC in 1957, and it enabled us to experiment with algorithms that launched the fields of image processing and image pattern recognition.[11]

The scanner (Fig. 2) used a rotating drum and a photomultiplier to sense reflections from a small image mounted on the drum. A mask interposed between the picture and the photomultiplier tessellated the image into discrete pixels.

We experimented with several classes of algorithms. The first was of homogeneous transformations. Once an image was acquired, we used the great speed of SEAC to transform it with edge-enhancement filters. These have become important in recent years as highly parallel methods of processing became common in neural network simulations, for example. They also provided the basis for the large class of image-enhancement methods that developed. We also wrote algorithms to take measurements on objects in an image. By showing that these objects could have multiple connectivity and still be measured correctly, we encouraged the development of specialized machines for image analysis.

A staticizer connected to the SEAC memory enabled a stored image to be displayed on a cathode-ray oscilloscope. This made it possible for us to see what the computer "saw." And when we could see binary images, we realized the limitations of binary representation. So we experimented with superimposing multiple scans at different scanning thresholds and the use of time-varying thresholds for pulse density modulation to represent multiple gray levels in an image.

A feel for the age and maturity of the image-processing field can be seen from the fact that one of the first pictures ever scanned and redisplayed was of my newborn son (see Fig. 3). Today, his face is scanned nightly and digitally processed to appear on the nightly news as a TV reporter. Recently, he showed his newborn daughter on the evening news (see Fig. 4). "Plus ça change...."

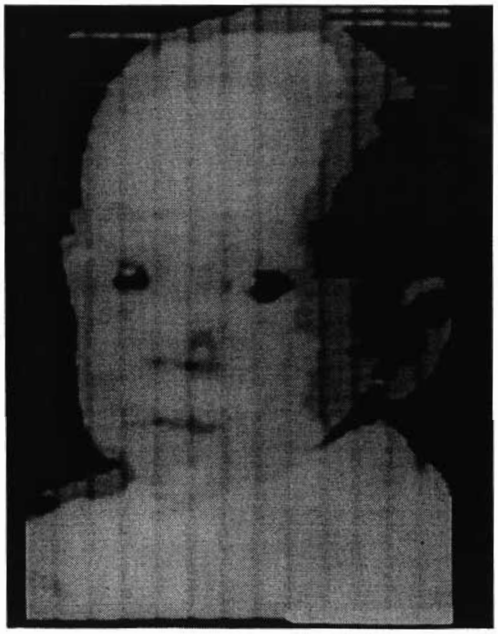

Fig. 3. The first computer picture made from two successive binary scans of size 176 × 176 pixels. The first scan made on the SEAC scanner was a picture of my baby son. With two superimposed binary scans, it was possible to approximate sufficient gray levels to make the image recognizable, though not satisfactory to grandparents.

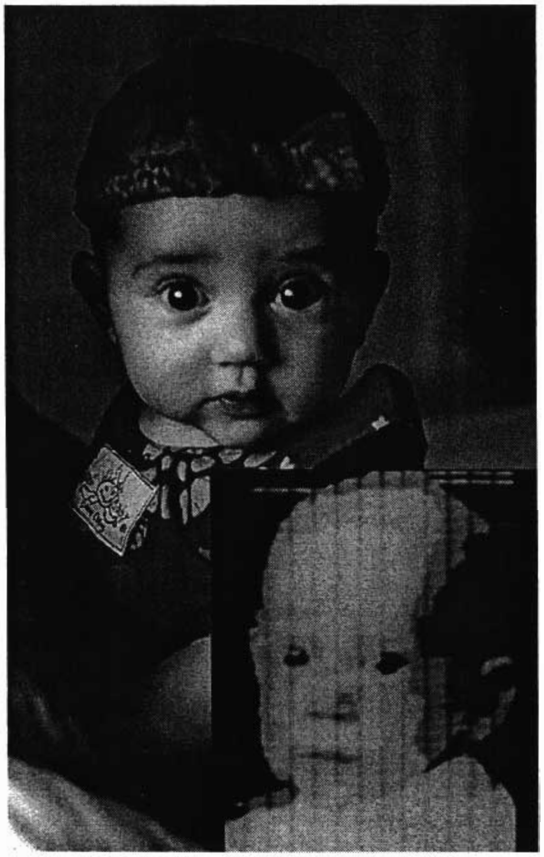

Fig. 4. Two scans separated by 40 years. The two scans show father and daughter separated by 40 years, 24 bits per pixel, and memory requirements in the ratio of 1,600:1.

The Consequences of Early Engineering Decisions

Several decisions made in our construction of the first scanner have been enshrined in engineering practice ever since. Perhaps the most insidious was the decision to use square pixels. Simple engineering considerations as well as the limited memory capacity of SEAC dictated that the scanner represent images as rectangular arrays of size 176 × 176 square binary pixels, each of size 0.25 mm × 0.25 mm. No attempt was made to predicate the digitization protocol on the nature of the image. Every image was made to fit the Procrustean requirement of the scanner. That this was unnecessarily restrictive would have been obvious to us had we known about the methods used 1,400 years previously by the artists who made mosaics in Ravenna, Italy.[12] Fig. 5 shows a mosaic made in Ravenna in the sixth century. It contains about 80 × 46 tesserae, each carefully chosen both in shape and in color to represent the structure of the image at that location. If we recreate this mosaic with even more (100 × 58) square pixels, in the common engineering manner, each having multiple colors, we get the much inferior image in Fig. 6. The practice that we initiated with the SEAC scanner survives today, much to the disadvantage of economical storage of images.

Our binary thinking was quickly supplanted as research progressed in the pattern recognition field. Over a period of many years, attempts to design vision systems have successively expanded image representation to include multiple gray levels, color, texture, motion, and stereo. Today, researchers in vision systems realize that a unimodal approach to image understanding systems is unnecessarily limited. Other sensory modalities such as touch must supplant vision if image understanding is to be achieved.

Fig. 5. A sixth-century mosaic from Ravenna, Italy.

Fig. 6. The mosaic of Fig. 5 represented with 100 × 58 pixels.

One particular expected consequence of early decisions never occurred. In 1957, computer storage capacity was very expensive compared to computation speed. On the SEAC, we had the equivalent of 6,000 bytes of storage—that is, *bytes*, not megabytes. The basic operation time for a simple addition operation was 48 microseconds. It would appear logical that we would have investigated image compression algorithms for economical storage of images. But, in fact, the widespread development of such algorithms did not occur until recent years, when megabytes of memory, gigabytes of nonvolatile storage, and operation times of a few nanoseconds became common. With storage so expensive in 1957, it was unrealistic to consider storage of large quantities of images. Only when storage became cheap compared to computation time was it reasonable to look for even cheaper methods of storage, hence image compression.

Development at the National Bureau of Standards

The pioneering start of image processing at NBS led to many pioneering applications of image processing. The earliest was the creation of the field of quantitative metallography. In the early 1960s, G.A. Moore of the NBS Metallurgy Division, having heard of our scanner, asked me whether he might use it for stereology applications. It was common practice at that time to determine the size distribution of particles in metallurgical photomicrographs by drawing random chords through such images. The length of the intersections with the particles could be tabulated to give a statistical estimate of particle size. I explained to G.A. Moore that no such statistical estimate was necessary. We could "pick up" each particle from a scanned image in the computer, measure it, and tabulate an exact count of particle sizes. G.A. Moore recognized the radical nature of this departure and proceeded to create the field of quantitative metallography as we now know it.[13] Most commercial machines used today in quantitative metallography can be traced back to this fundamental work.

The image-processing field has spawned research in various kinds of vision systems. These include vision systems that robots could use in navigating the world.

In the NBS Standard Reference Materials program, precise measurements of standard materials were necessary. In later work, C.G. Interrante and G.E. Hicho[14] used scanned images to calibrate such materials.

Much of the research at NBS was concerned with measurement science, as in the above examples. Another kind of measurement more related to image pattern recognition was for the recognition of fingerprints. In an attempt to automate fingerprint processing for the Federal Bureau of Investigation, J.H. Wegstein,[15] G.A. Moore, and John Rafferty developed recognition algorithms.

A more orthodox class of image measurements was made to support the study of surface topography using interferometry.[16] In some of this work, laser interferograms were scanned, and the measurements made on them produced precise descriptions of surface roughness.

An important source of energy conservation is the use of recycled fibers in the manufacture of paper. But, before such fibers can be used, they must be characterized in terms of their dimensional properties. E.L.Graminski and I showed that by scanning photomicrographs of paper fibers, measurements could be made on them that would predict their properties when used to make recycled paper.[17]

The image-processing field has spawned research in various kinds of vision systems. These include vision systems that robots could use in navigating the world. A group at NBS has been exploring robot vision systems since 1979.[18,32] Much of this work is concerned with robots for use in manufacturing.

In the early 1960s, the National Institutes of Health began considering the automation of cytology, the measurement of cell structure in biological microscopy. Only the simplest kinds of cell analyses were available at the time. The NBS image-processing experience was useful in designing an ambitious program in automated cytological analysis that resulted in a large laboratory program at the National Institutes of Health.[19,33,34] This program included a general plan for cell analysis as well as the development of specific methods for analysis of cell images.

As image processing began to be seen as useful in areas outside the physical sciences and outside the narrowly construed field of metrology, it became apparent to me that assigning structure to images was a generalization of the kinds of numerical measurement that we had been doing for many years. The success of architects[20] in describing the structure of design objects led me to investigate the use of image processing in the fine arts.[21,35,36] The tools that architects had used were applied to the structural analysis of painting style.[22,37,38,39] One consequence of this structural representation was an economical representation of paintings.[23] Finally, I recently applied these tools to the study of archaeological objects such as rock engravings.[24,40]

Development of New Image-Processing Tools

While new applications of image processing were being developed at NBS, new tools, both physical and conceptual, were being developed. I have stated that "the best way to store a photograph is in its original form."[11] This implied that for many photographs, a larger scanner than the first SEAC scanner would be necessary if the computer was to have access to such images. In 1964, R.T. Moore, M.C. Stark, and L. Cahn at NBS built a precision scanner that could accommodate a much larger image.[25] This scanner was built around a commercial lathe body offering dimensional precision of 1/200 inch. It had sufficient accuracy that repeated scans could serve the purpose of avoiding the prohibitively large memory requirements that would be needed to store a scanned image as large as 10 inches square.

In 1957, we thought that pattern recognition could proceed monotonically forward from scanning to processing to recognition. It was many years before we understood that models of the visual world would have to exist in the computer before scanned images could be effectively used. By 1964, we showed that one could summarize the information about the visual world in the form of a picture grammar.[26] Such a grammar would precede the image-scanning operation and aid in pattern recognition. Much of this work was theoretical in nature and resulted in a large literature on syntactic image processing. Only in 1978 did this understanding get reformulated elsewhere[20] in the context of architecture and applied to practical problems in the representation of architectural designs.

Among the tools developed were programming languages for processing images. G.A. Moore describes a subroutine library for the SEAC, written by R.B. Thomas, that made it convenient to invoke processing operations on metallurgical photograph images.[31] Later, K. Kloss adapted, for the IBM 709 computer at NBS, a simulator written at the University of Illinois. This simulator was for the Pattern Articulation Unit of the Illiac III computer. It was a homogeneous processor of the kind that became common with parallel processing. Kloss embedded the program in the Lisp language, and I used it both at NBS and remotely on the CTSS Time Sharing System at the Massachusetts Institute of Technology, where I would send images over telephone lines at

300 baud from Maryland to Massachusetts. We also installed the system on the ANFSQ32 computer at System Development Corp. in California and used it, again remotely, on slow telephone lines. D.J. Orser, I. Rhodes, and A.H. Meininger, all of NBS, also developed a Lisp-based image-processing system installed on the DEC-10 computer at the National Institutes of Health that was used remotely at NBS.

The most recent, powerful member of this class of Lisp-based image-processing languages is the MacLispix language that David S. Bright developed at NIST.[27] MacLispix uses the Macintosh Common Lisp language on the Macintosh computer. This is a Lisp compiler and interpreter, with the full symbol manipulation capability of Lisp, in which Bright has embedded efficiently coded routines for the most common image-processing operations. It is available as a public domain language with extensive documentation.

Conclusion

When we started the field of computer image processing, we could not have anticipated applications worldwide in such diverse areas as satellite imaging, computed tomography, desktop publishing, manufacturing inspection, and atomic physics. One such application, that of the CAT scanner, resulted in a Nobel Prize for Sir Godfrey Hounsfield and Alan Cormack in 1979. An application of R. Young was used in the development of the scanning tunneling microscope, in 1972 at NBS,[28] in support of another Nobel Prize. The Nobel Prize for Physics in 1997 was awarded to William D. Phillips of NIST,[29] who used a computer analysis of video images to determine how a cloud of atoms spreads out as it is being laser cooled.

Thus, we see that the collective imagination of the computer community took up the challenge raised by this new powerful tool and extended it "far beyond our poor powers to add or detract."

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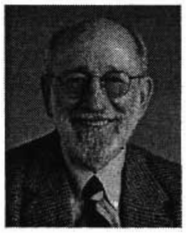

Russell A. Kirsch received his scientific training from the Bronx (New York) High School of Science in 1946, with refinements occurring at New York University (BEE, 1950), Harvard University (SM, 1952), American University, and the Massachusetts Institute of Technology. He was a member of the group that first designed and built digital computers in the U.S. National Bureau of Standards, where he was responsible for computer design, operation, training, programming, and research for 33 years, from 1951 until he retired as head of artificial intelligence research, becoming director of research of the Sturvil Corporation, but still maintaining an affiliation with the National Bureau of Standards. His research started the computer fields of image processing, syntactic pattern recognition, and chemical structure searching. He was among the early computer workers in natural language processing, library science, time-sharing, biomedicine, artificial intelligence, and security printing. He is a past advisory editor of the *IEEE Transactions on Pattern Analysis and Machine Intelligence* and advisory editor of *Languages of Design*. He is a member of the ACM, a life member of the IEEE, and a fellow of the AAAS. His current research interests are using computers in the fine arts and studying ancient petroglyphs.

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