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Abstract

Airplanes were invented by hobbyists and experimenters, and some personal computers were as well. Similarly, many open-source software developers are interested in the software they make, and not focused on profit. Based on these cases, this paper has a model of agents called tinkerers who want to improve a technology for their own reasons, by their own criteria, and who see no way to profit from it. Under these conditions, they would rather share their technology than work alone. The members of the agreement form an information network. The network's members optimally specialize based on their opportunities in particular aspects of the technology or in expanding or managing the network. Endogenously there are incentives to standardize on designs and descriptions of the technology. A tinkerer in the network who sees an opportunity to produce a profitable product may exit the network to create a startup firm and conduct focused research and development. Thus a new industry can arise.

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Some important technologies have been advanced by open sharing among innovators who were not motivated mainly by prospective profits. For example, many hobbyists around the world tried to make aircraft in the late 1800s, before there were what we now call airplanes. Personal computers were advanced greatly by hobbyists who met in groups, notably at the Homebrew Computer Club (Freiberger and Swaine (1984) and Levy (2001)). Many open-source software projects make source code publicly available. The airplane, personal computer, and open-source software cases are examples of “open source” technology development processes.

Allen (1983) introduced the related term *collective invention* to describe firms sharing technical information. Schrader (1991), Nuvolari (2002), and von Hippel (2005) offer other examples. Harhoff, Henkel, and von Hippel (2003) model this phenomenon. In this literature, the technology is known to deliver useful outputs, and the profit-minded firms exchange information. By contrast, this paper describes situations in which a novel technology appears *first* because of the combined efforts of people who do not expect to sell anything.

This paper places open source technology development in an abstract, deductive model. Three key assumptions are necessary. First, agents called tinkerers are interested in advancing the technology for some reason, such as their own inherent interest. Second, each tinkerer sees how to improve the technology using his own criteria for improvement. Third, the tinkerers believe the technology is so immature and uncertain that current actions do not significantly affect future opportunities for commercialization. Under these conditions, tinkerers share their technologies with one another, forming an an open-source network.

Within the model, a new industry appears when a tinkerer envisions a way to profit from the technology, and leaves the network to try that. In the cases described, amateur tinkerering eventually led to increases in commercial output and productivity.

I Examples of open-source technology development

I.A Before the airplane

For decades before there were functional airplanes, there was an international discussion about wings and flying machines. By the 1890s several journals and societies in France, Britain, Germany, and the United States were devoted to this topic. Important experiments by Otto Lilienthal, Samuel Langley, and Lawrence Hargrave advanced the field.

A Chicago railroad engineer named Octave Chanute was inspired by the possibility that by cooperating, experimenters around the world could make winged flying machines a reality. He visited many of them, and corresponded with many more. Chanute's speeches and writings were "noteworthy for fostering a spirit of cooperation and encouraging a free exchange of ideas among the world's leading aeronautical experimenters" (Stoff, 1997, p. iv). In his optimistically titled 1894 book *Progress in Flying Machines*, Chanute summarized and commented on hundreds of kites, gliders, experimenters, authors, and theorists of aerial navigation. Newly interested people learned about the subject from this important book. Wilbur and Orville Wright read it and contacted Chanute.

Like many others, the Wrights discussed their experiments openly. Chanute visited them and invited colleagues to participate in their effort. At Chanute's invitation, Wilbur Wright made a speech about their experiments at the Western Society of Engineers. Wilbur Wright published in British and German aircraft journals. In other words, the Wrights took an open source perspective on their technology as they advanced it.

In 1902 and 1903, the Wrights developed better wings and propellers than their predecessors, partly because of the uniquely accurate and precise measurements they got from their wind tunnel and its instrumentation. They began to withdraw from processes of open sharing as they believed they were near to a successful powered glider flight. (Crouch, 2002). They planned to protect their rights to patent and license their technology. This led to permanent conflicts with Chanute, who was devoted to open-source processes of invention.

I.B The beginning of personal computers

In the 1970s many clubs of hobbyists were working on microcomputers. The Homebrew Computer Club which met in Menlo Park and Palo Alto, California, starting in March, 1975 was particularly central. Most of the people who attended were interested in making computers for their own home use. At the first meeting, "it turned out that six of the thirty-two had built their own computer system of some sort, while several others had ordered Altairs" (Levy, 2001, p. 202). The Altair was a new kit for making a hobbyist computer.

Meetings were informal. "The group had no official membership, no dues, and was open to everyone. The newsletter, offered free . . . became a pointer to information sources and a link between hobbyists." (Freiberger and Swaine, 1984, p. 106) "They discussed what they wanted in a club, and the words people used most were 'cooperation' and 'sharing'." (Levy, p. 202). Homebrew meetings included a presentation, often of a demonstration of a club member's latest creation. Then there was "the Random Access session, in which everyone scrambled around the auditorium to meet those they felt had interest in common with them. . . . . [M]uch information had to be exchanged; they were all in unfamiliar territory" (Freiberger and Swaine, 1984, p. 106).

The information flow was a cause and also an effect of the fact that they often used similar parts, attempted similar projects, and read the same newsletters and magazines. Members were drawn to the hands-on experience of making computers and understanding the component parts, not theories of computing, or the social effects of computing. (Levy, 2001)

The Homebrew club of hobbyists had an important effect in moving personal computer technology forward. There were many other places for hobbyists to get involved in this exciting area. There were a series of (U.S.) West Coast Computer Faires which gathered tremendous interest and attendance. Hobbyists ran bulletin board personal computer systems to which people could dial in and send email, and engaged in Usenet discussions on the Internet. Hobbyists did this activity, mostly not for profit.

At one Homebrew meeting, Steve Wozniak demonstrated a new board which could do many things a computer would do. He did not intend to start a company or sell anything, but his entrepreneurial friend Steve Jobs convinced him to cofound a company and to sell this product as a computer, which they called the Apple I. Only computer hobbyists could use it, but among them it was quickly in demand. The personal computer industry took off with this device.

Apple Computer, and perhaps twenty other companies, were started by Homebrew attendees. But the club started because of an interest in computers, not business.

I.C Open source software projects

In open-source software, human-readable source code files are made widely available on a computer network. Source code, in computer languages, is fed as input to specialized development tool programs, such as interpreters, compilers, assemblers, and linkers, which generate the instructions which a computer eventually executes.

Sharing source code makes it possible for many programmers to experiment and improve the code in parallel. A user may also alter the program for a particular purpose. Sponsors of open source projects usually copyright the software in a way that allows a wide spectrum of uses. Revisions are published under the same license. This is a powerful mechanism to support collective invention because it is common knowledge that some later improvements will become part of the shared code.

The owners of a chunk of source code moderate the final choices in released versions of the software. Users may make a version different from a released one. The owners try to avoid the project's source code "forking" into permanently divergent, partly-incompatible versions. If that were to happen, the project's members would lose some of the benefits of having one code base which improved along many dimensions over time.

Several roles and institutions support sharing in open source projects:

- Web servers store the source code.
- Intellectual property claims are explicitly preempted by special open copyrights.
- The relevant programmers have similar development tools and skills.
- Source control programs keep records of who changed the software and how.
- Moderators or "owners" control which of those changes are published.
- Culturally, experimentation is welcome and unrestricted.

Such projects have been started by individuals with many different interests. The operating system Linux, for example, was started, sponsored, and organized by a student, Linus Torvalds. Now it is a core product of firms with hundreds of millions of dollars in revenue annually. Many other projects such as Apache and Firefox also have this form. Open source software projects often have an explicit copyright condition to keep the core technology in the public domain.

II Motivation and psychology

The model which follows is meant to describe the airplane experimenters and also hobbyists, hackers, and innovators of the computer age such as Steve Wozniak (developer of the Apple I personal computer), Richard Stallman (a defining programmer of the free-software movement), Tim Berners-Lee (inventor of the World Wide Web's browsers and servers), and Linus Torvalds (the founding programmer of the Linux operating system). These innovators created important technologies without intending to sell them.

Such innovators have various motivations. They may find a project inherently absorbing and enjoyable. They may benefit from some service it provides. These are sometimes called *intrinsic* motivations. They may anticipate receiving honors, prestige, wealth, or career benefits from the project, which are *extrinsic* motivations. They may anticipate that the project could improve the human condition apart from themselves, which is an *altruistic* motivation. The model to follow directly incorporates intrinsic or altruistic motivations, and demonstrates how certain network behaviors emerge.

Important aircraft experimenters referred to their intrinsic or altruistic motivations:

- "A desire takes possession of man. He longs to soar upward and to glide, free as the bird . . . " (Otto Lilienthal, 1889).
- "The glory of a great discovery or an invention which is destined to benefit humanity [seemed] . . . dazzling. . . . Otto and I were amongst those [whom] enthusiasm seized at an early age." (Gustav Lilienthal, 1912 introduction).
- "The writer's object in preparing these articles was . . . [to ascertain] whether men might reasonably hope eventually to fly through the air . . . [and] To save . . . effort on the part of experimenters . . . " (Chanute, 1894).
- "I am an enthusiast . . . as to the construction of a flying machine. I wish to avail myself of all that is already known and then if possible add my mite to help on the future worker who will attain final success" (from Wilbur Wright's 1899 letter to the Smithsonian Insitution requesting information).
- "Our experiments have been conducted entirely at our own expense. At the beginning we had no thought of recovering what we were expending, which was not great . . . " (Orville Wright, 1953, p. 87).

The motivation of hardware hackers was often instrinsic or altruistic too. After the first meeting of the Homebrew Club, Steve Wozniak reports (Wozniak, 2006, pp 156-7):

> I started to sketch out on paper what would later come to be known as the Apple I. . . . I did this project for a lot of reasons. For one thing, it was a project to show the people at Homebrew that it was possible to build a very affordable computer . . . with just a few chips. In that sense, it was a great way to show off my real talent, my talent of coming up with clever designs, designs that were efficient and affordable. By that I mean designs that would use the fewest components possible.
>
> I also designed the Apple I because I wanted to give it away for free to other people. I gave out schematics for building my computer at the next meeting I attended.
>
> This was my way of socializing and getting recognized. I had to build something to show other people. And I wanted the engineers at Homebrew to build computers for themselves . . .

Open source developers have a similar mix of motives. Lakhani and Wolf (2003) show based on surveys that many programmers participate in open source projects because of the creative enjoyment and the value of using the output, not explicit rewards. Pavlicek (p. 146) reports that ”Open Source people are used to doing work on a project because they perceive its value to the community.”

It is difficult to define in output or engineering terms what the tinkerers, hobbyists, or hackers are accomplishing in the short run. The devices or software do not work well, and they are not clearly commensurable, because they are qualitatively different attempts to make a desirable design. In the model to follow, progress is therefore not measured by attributes of the artifacts, but by the individual’s own satisfaction with it, that is, in terms of utility.

III A tinkerer

Let us define an individual called a tinkerer who enjoys a technological activity A. The notation A stands for aircraft or some other hobbyist activity such as building a computer or writing a computer program at home. A has no market value, and no honors or profits are associated with it. The tinkerer may imagine that there may someday be honors or profits, but thinks this is unlikely and assigns a low expected value to such possibilities.

The tinkerer receives a periodic flow of positive utility a_t directly from the existence of A in period t. Let $a_0 \geq 1$ be a parameter defining the utility received in period zero, the present period, and treat the choice about tinkering separately from all other utility decisions. The tinkerer values alternative choices in a risk-neutral way according to the net present sum of expected future utility payoffs. Utility to be received in future periods is discounted by a $\beta \in (0,1)$ for each intervening period. Using a standard time series summation ($(1-\beta)(\sum_{t=0}^{\infty} \beta^t) = 1$), expected utility at time zero can be put into a closed form:

$$EU_{t=0} = a_0 + \beta a_0 + \beta^2 a_0 + \cdots = a_0 \sum_{t=0}^{\infty} \beta^t = a_0 (\sum_{t=0}^{\infty} \beta^t)(\frac{1-\beta}{1-\beta}) = \frac{a_0}{1-\beta} \quad (1)$$

The tinkerer can choose to invest in ("tinker with") A in order to raise future benefits a_t. An investment costs one utility unit in the present period representing the effort, expenses, and the opportunity costs of time involved. The agent anticipates that tinkering will raise his future utility by p units in each time period in the future. The notation p stands for progress which the agent experiences subjectively. We assume p is fixed, positive, and that the tinkerer's forecast is correct.

A tinkerer chooses whether to tinker based on the estimated costs and benefits. The utility benefits from one effort to tinker have the value p in each subsequent period. The discounted payoffs to tinkering in the present period are

$$p\beta + p\beta^2 + p\beta^3 + p\beta^4 + \ldots = \frac{p\beta}{1-\beta}$$

The investment required to receive this payoff is one utility unit at time zero so the net payoff to tinkering in period zero is $\frac{p\beta}{1-\beta} - 1$. Benefits exceed cost when $p > \frac{1-\beta}{\beta}$. For example, if

$\beta = 0.95$ and $p = 0.07$, tinkering in the current period brings a positive surplus of $\frac{.07*.95}{.05} - 1 = .33$.

Unless parameters or conditions change, any tinkerer who finds it worthwhile to tinker once will find it worthwhile to tinker again and again. As long as $p > \frac{1-\beta}{\beta}$, the agent will tinker in every period, receiving payoff of $a_0 - 1$ in the current period, $a_0 + p - 1$ in period one, and in general $a_0 + pt - 1$ in period t. The associated payoff stream is

$$\begin{aligned} EU_{t=0} &= \sum_{t=0}^{\infty} \beta^t (a_0 + pt - 1) \\ &= (a_0 - 1) \sum_{t=0}^{\infty} \beta^t + p \sum_{t=0}^{\infty} \beta^t t \\ &= \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + p \sum_{t=0}^{\infty} \beta^t t \end{aligned}$$

The last term can be expressed in closed form using this derivation:

$$\begin{aligned} \sum_{t=0}^{\infty} \beta^t t &= \beta + 2\beta^2 + 3\beta^3 + \cdots \\ &= \left(\beta + \beta^2 + \beta^3 + \cdots\right) + \left(\beta^2 + \beta^3 + \beta^4 + \cdots\right) + \left(\beta^3 + \beta^4 + \beta^5 + \cdots\right) + \cdots \\ &= \frac{\beta}{1-\beta} + \beta\frac{\beta}{1-\beta} + \beta^2\frac{\beta}{1-\beta} + \beta^3\frac{\beta}{1-\beta} + \cdots \\ &= \frac{\beta}{1-\beta}\left(1 + \beta + \beta^2 + \beta^3 + \cdots\right) \\ &= \frac{\beta}{1-\beta}\left(\frac{1}{1-\beta}\right) \\ &= \frac{\beta}{(1-\beta)^2} \end{aligned}$$

With that substituted in, the tinkerer's overall expected utility at time zero is:

(2) $$\mathrm{EU}_{t=0} = \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + \frac{p\beta}{(1-\beta)^2}$$

The first term of equation 2 expresses the present value of expected utility from A in its original state. The second term is the present value of the costs of endless tinkering. The third term is the present value of the benefits expected from endless tinkering.

For a tinkerer characterized by $\beta = 0.95$ and $p = 0.07$, the gain in expected utility from tinkering forever is the sum of the second and third terms:

$$\frac{p\beta}{(1-\beta)^2} - \frac{1}{1-\beta} = \frac{.07 * .95}{(0.05)^2} - 20 = \frac{1.33}{.05} - 20 = 6.6$$

So, for these parameters (which will be used throughout the paper to facilitate comparison), endless tinkering increases the tinkerer's utility by 6.6 times the cost of a one-time investment. This self-motivated tinkerer is a perpetual innovation machine.

IV A network of tinkerers

To get to the main proposition quickly, we make simple and extreme assumptions. Later sections relax the underlying assumptions.

Let there be two tinkerers with identical utility functions working on similar projects A_1 and A_2 whose innovative tinkerings could be useful to one another. Each tinkerer believes that the other cannot profit from the project using any foreseeable version of the existing technology. Let the subjective rate of progress of the first player be p_1, and the subjective rate of progress of player two be p_2.

Suppose the two tinkerers can make a verifiable and enforceable agreement to share a well-defined set of the functional design changes in A_1 and A_2 and their experimentally discovered effects. This agreement forms a *network* for future information. At any time, either partner can depart from the network, and then ceases to share his subsequent innovations and ceases to learn from the other tinkerer.

Let fraction $f \in (0, 1)$ of each tinkerer's innovation be perceived as useful to the other one's project, so that knowing tinkerer two's most recent innovation would benefit tinkerer one by fp_2 each turn. The remaining fraction $(1 - f)$ does not carry over because the projects are not identical and perhaps there are costs to interacting.

If the tinkerers expect each other to produce a positive flow of innovations, they are always better off by joining in a network. If they tinker and share with these parameters forever, tinkerer one's expected utility is:

(3) $$EU_0 = \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + \frac{p_1\beta}{(1-\beta)^2} + \frac{fp_2\beta}{(1-\beta)^2}$$

The new fourth term expresses the benefits player one receives from the flow of information coming from player two. Because of this free good, utility is greater in equation (3) than in equation (2). The tinkerer prefers joining a network rather than working alone. Thus *under these assumptions, rational agents generate open-source technology networks.* This is the central analytical result of this paper.

V Standardizing, specializing, and consensus redesign

Only a fraction $f \in (0, 1)$ of the experimental discoveries made by player two are usable to player one. Suppose that for cost c_s, a tinkerer can adjust some elements of his project to look more like the other one's project, and that doing so would raise the fraction of innovations of the other tinkerer which apply to his own project from f to f_2. If tinkerer one pays this cost to standardize on an element of tinkerer two's design, expected utility changes to

$$EU_0 = \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + \frac{p_1\beta}{(1-\beta)^2}4 + \frac{fp_2\beta}{(1-\beta)^2} - c_s + \frac{(f_2-f)p_2\beta}{(1-\beta)^2}$$

Comparing this to equation 3, a tinkerer would pay the standardization cost if:

$$\frac{\beta p_2(f_2-f)}{(1-\beta)^2} > c_s$$

In words, a player benefits more from standardization if, holding other things constant: (a) other tinkerers produce a large flow of innovations p_2; (b) the cost of standardization, c_s, is small; (c) the increase in usable innovations ($f_2 - f$) is large; and (d) the tinkerer is patient for results (β is close to 1). Intuitively, these are the conditions under which it makes sense for a software developer to replace a working piece of code by a standard library of code written by others.

The same argument can explain why experimenters tend to develop a common technical language to describe their technologies. This can reduce communication costs and also clarify thinking. For example, Wilbur Wright published a journal article (Wright, 1902) asking other experimenters to cease using "angle of incidence" to mean the angle between a wing (or other airfoil) and the ground. The better definition, he argued, was the angle between the airfoil and the flow of air coming at it; the angle with respect to the ground was not relevant. This request was an effort both to improve the thinking processes of other experimenters and to lower frictional losses in communication. In a more important example, Lawrence Hargrave's experiments showed that a box-shaped kite was more stable than a flat kite in a gust of wind. This specialist contribution helped glider flyers standardize on a biplane (two wing) design for gliders.

Both kinds of standardization partly explain why tinkerers would agree to publish their findings. The fewer differences between experiments there are, the lower future communication and adoption costs will be. It benefits player one in communication if his preferred language and concepts are available to both players. If a tinkerer anticipates adopting part of another's tinkerer's technology at some time in the future, he lowers the future cost of that adoption by giving the other tinkerer a chance to use his own technology now. It also means they would be able to compare options for standardization and choose the best one, in the sense of moving the project forward or raising f more. This incentive could be formalized by making $f()$ a decreasing function of a player's own history of making new findings public. An experimenter who publishes more makes it easier for other players to communicate with him or to learn from his design choices. If f is a declining function of the number of findings a player has shared, it partly substitutes for the enforcement of the rule that players should share all their findings. Each one has an incentive to share in order to get the others to learn from his own findings, and to standardize on his own choices (rather than having to pay the costs of standardizing on the choices of others).

A tinkerer may invest in redesign to make the device easier to learn or easier to use, because it represents progress p or makes it easier to exchange information, raising f. This is important in the software context where a project can "fork" (split over time into incompatible versions used by different people) if the contributors do not agree to standardize enough. In the history of Unix there was a painful fork, and programmers refer to this history to convince others to keep projects unified even as they work independently. In this model, they are willing to pay some price to maintain the large network on the project. A redesign to achieve a consensus and avoid forking is therefore rationalized by the flow of future exchanges that are possible if the players can avoid forking.

For $f = 0.5$, $f_2 = 0.54$, $p_1 = 0.07$, and $\beta = 0.95$, the payoff to standardization is $\frac{p_2\beta(f_2-f)}{(1-\beta)^2} = \frac{.07*.95*.04}{.05*.05} = 1.064$. In this illustration, if the cost of the standardization investment were one utility unit, like the cost of a normal investment, it would be just worth undertaking.

Thus standardization and specialization are natural outcomes of exchanging information to develop a technology. They can occur without any necessary reference to competition or market exchange. The network is a search technology which provides the tinkerer with information he values and does not obtain by experiment.

VI Joining, searching, or matching costs

Perhaps there are costs to finding a match partner or joining together once a match is found. Let c_j be the immediate cost in utility terms to a tinkerer for joining a sharing institution or starting one with a known partner. The gross benefits of joining the group are again $\frac{fp_2\beta}{(1-\beta)^2}$, and if c_j is less than this, the tinkerer would prefer to join than to work alone.

So the model predicts the tinkerer joins, ceteris paribus, if (1) costs of joining, c_j, are small enough, (2) the flow of innovations from the others in the group, p_2, is large enough, (3) the innovations are relevant enough to his own project, as measured by f, and (4) the tinkerer's valuation of future events, β, is high enough.

The same comparison applies if c_j is the cost for a tinkerer to search for a network or candidates to join an existing network. This parameter can incorporate the real-world problem that usually few people know a network exists and how to communicate with it. The problem is addressed in the real world by members who write books, edit journals, make speeches, talk about their hobby to outside people, or broadcast emails.

There might be many tinkerers, working in isolation, making almost no progress because they do not share. Here we have a situation in which an information failure alone prevents a Pareto-improving institution from appearing. Probably there are many situations in which tinkerers *would* join a network, but the search costs are such that they do not find one another. If one thinks of tinkerers as a natural resource, institutional attributes of the environment (like the presence of the Internet) affect whether they can find one another and work together and their speed of progress.

An individual tinkerer might specialize in expanding the network, e.g. through speech-making, book-writing or other publicity. Tinkerers who make A easier to learn or easier to use can also lower search costs by making it easier for others to see the virtues of A.

We do see such editor/moderators in the cases of interest:

- Aircraft experimenter and author Octave Chanute had a strong interest in open sharing of information. He expressed affection for the point of view of Lawrence Hargrave, who on principle published all his results and patented nothing, with the idea that this open-source approach would maximize the speed of collective progress.
- In the Homebrew computer club, Lee Felsenstein, who usually moderated the meetings, established a ”Random Access” interaction time for people to talk to whoever could help them.
- In the open source software cases, charismatic founders or charismatic projects draw in interest, and the programmers are explicitly and routinely encouraged to share innovations, sometimes by the licensing agreement.

VII Intellectual property

Some of the innovators discussed preferred to avoid formal intellectual property claims and institutions, such as patents, which might get in the way of using a technology. Pioneering aircraft experimenter Lawrence Hargrave and programmer Richard Stallman are examples. This behavior can be rationalized in this model. Effort devoted to establishing intellectual property rights in an unprofitable technology may not pay off as well as sharing which pushes the technology forward.

One can formally illustrate this. For simplicity, consider a two-tinkerer case. Assume all the utility functions are linear in money and have been normalized to the money metric, and that none of them expect to be make a commercial product. Suppose each tinkerer has property rights to his designs and can charge a price to use the design information he transmits to the network. He may impose a cost c_1 for each information transmission on each network member who makes use of it. With one network partner, a tinkerer receives c_1 times fp_1 in copyright payments, and pays out c_2 times fp_2. This pattern of zero-sum exchanges is profitable to the tinkerers who produce the greatest flow of innovations, but some of the others may find it too expensive enough to stay in the network, which slows overall progress.

More realistically, if there are many partners and frictional costs to defining, managing, or enforcing intellectual property rights, private ownership may bring the tinkerers greater social costs than social benefits. For both reasons, tinkerers in the model are better off and more willing to participate in networking if the rules of the game do not include the definition and protection of intellectual property.

That changes when commercialization to a broader market, beyond the tiny population of tinkerers, is likely. So far the model has not considered the mixed incentives faced by a tinkerer who anticipates selling a product some day. That tinkerer faces a perceived opportunity cost if he does not create a barrier to competition. In one useful example, the Wrights changed their behavior once they believed they were about to invent the airplane.

VIII Entrepreneurial exits from the network

Starting in late 1902, after they had run tests on wings in a wind tunnel, the Wrights were decreasingly willing to share information. From Crouch (2002), p. 296:

> The brothers had been among the most open members of the community prior to this time. The essentials of their system had been freely shared with Chanute and others. Their camp at Kitty Hawk had been thrown open to those men who they had

> every reason to believe were their closest rivals in the search for a flying machine. This pattern changed after fall 1902.
>
> The major factor leading to this change was the realization that they had invented the airplane. Before 1902 the Wrights had viewed themselves as contributors to a body of knowledge upon which eventual success would be based. The breakthroughs accomplished during the winter of 1901 and the demonstration of . . . success on the dunes in 1902 had changed their attitude.

They applied for a patent in March 1903, received it in 1906, and started an airplane business. Chanute had criticized others who kepts secrets before, and he began to have conflicts with the Wrights. These conflicts grew severe and in the end, Chanute and the brothers were no longer on speaking terms.

This kind of split also occurred in the Homebrew club, whose attendees had tended to follow what Levy (2001) called the Hacker Ethic – that information should be freely available. After Apple and other companies were founded by its members, the experience at the club changed. Members who had started companies stopped coming, partly because keeping company secrets would be uncomfortable at Homebrew. From Levy (2001), p. 269:

> No longer was it a struggle, a learning process, to make computers. So the pioneers of Homebrew, many of whom had switched from building computers to *manufacturing* computers, had not a common bond, but competition to maintain market share. It retarded Homebrew's time-honored practice of sharing all techniques, of refusing to recognize secrets, and of keeping information going in an unencumbered flow. . . . Now, as major shareholders of companies supporting hundreds of employees, they had secrets to keep.
>
> "It was amazing to watch the anarchists put on a different shirt," [former Homebrewer] Dan Sokol later recalled. "People stopped coming. Homebrew . . . was still anarchistic: people would ask you about the company, and you'd have to say, 'I can't tell you that.' I solved that the way other people did—I didn't go. I didn't want to go and not tell people things. There would be no easy way out where you would feel good about that. . . ."
>
> It no longer was essential to go to meetings. Many of the people in companies like Apple, Processor Tech, and Cromemco were too damned busy. And the companies themselves provided the communities around which to share information. Apple was a good example. Steve Wozniak and his [friends and employees] Espinosa and Wigginton, were too busy with the young firm to keep going to Homebrew.

In the open source software world, analogous tensions arise between programmers who think a particular program should be freely modifiable and reusable, and those who would allow a business or person to have intellectual property rights over it. The subject of licensing is complicated and philosophical, but the Free Software Foundation classically defines and defends the free software concept, and private businesses take an interest in ownership of software code, and there are a spectrum of views regarding various programs.

VIII.A Modeling entrepreneurial exits

In each of the historical episodes, firms burst out from networks of tinkerers to create an industry. The transition is complicated. One altered assumption can make it happen mechanically in the model. Earlier the assumption was made that the tinkerer could not see how to implement a marketable form of the technology. One might say that a veil blocks the tinkerer's view of better forms of the technology. If that veil were to lift, the tinkerer might see how to produce a product. Substantively, the new perception or belief about making an implementable product might be caused by advances in the technology, or changes externally, or by internal reflection. For simplicity, in this section the probability that the veil lifts each turn is fixed, exogenous, and known to the agent.

A generic derivation will help incorporate this into the model. Consider a one-time utility payoff which arrives with probability π at the beginning of each future period. Denote the unknown random period in which it arrives by s. We can compute the mean discount factor to apply to this payoff, $E[\beta^s]$. It is the probability-weighted average of the appropriate discount rates for each possible s. The time series summation trick is used again:

$$
\begin{aligned}
E[\beta^s] &= \sum_{t=0}^{\infty} Pr(s == t)\beta^t \\
&= 0 + \pi\beta + \pi(1-\pi)\beta^2 + \cdots + \pi(1-\pi)^{t-1}\beta^t + \dots \\
&= \pi\beta + (1-\pi)\pi\beta^2 + (1-\pi)^2\pi\beta^3 + \dots \\
&= \pi\beta[1 + (1-\pi)\beta + (1-\pi)^2\beta^2 + \dots] \\
&= \pi\beta\sum_{t=0}^{\infty}[\beta(1-\pi)]^t \\
&= \frac{\pi\beta}{1-\beta(1-\pi)} = \frac{\pi\beta}{1-\beta+\beta\pi}
\end{aligned}
$$

Suppose at some point a tinkerer (or an entrepreneur advising the tinkerer) envisions a directed research and development process which would result in a profitable product or service based on project A. Suppose further that if the tinkerer were to continue to share experimental findings universally, this would reduce the utility of the resulting monopolistic profits by more than the utility of staying in the network, so the tinkerer wishes to drop out of the tinkerer's network. Dropping out means entering a new game, in exchange for losing the payoffs a_0, ceasing to tinker with A, and ceasing to receive inflows of information from the other tinkerers, but continuing to use information from past investments and inflows.

Let M be the present utility payoff of a large monopoly profit minus the utility cost of directed research and development, capital costs, risks, and the value of the future inflows of information that would have come from the network of tinkerers, all computed at the instant the tinkerer exits the network. Let π_1 be the probability each turn that this tinkerer sees a opportunity to take M, and π_2 be the probability that the partner tinkerer does. Assume that these events cannot occur in the same period. For intuition, assume these are small probabilities.

The time-zero present value of this prospective exit in unknown period s, is M discounted by

$E[\beta^s]$, which is M times $\frac{\pi\beta}{1-\beta+\beta\pi}$ as calculated above. The utility value of tinkerering up until s is $\frac{a_0}{1-\beta} - E[\beta^s]\frac{a_0}{1-\beta} = (1 - \frac{\pi\beta}{1-\beta+\beta\pi}) * (\frac{a_0}{1-\beta}) = (\frac{1-\beta}{1-\beta+\beta\pi}) * (\frac{a_0}{1-\beta}) = \frac{a_0}{1-\beta+\beta\pi_1}$

The mean utility cost of tinkering each period until s, falls analogously to $\frac{1}{1-\beta+\beta\pi}$. The mean benefits expected from tinkering each period until s fall to $\frac{p_1}{(1-\beta)^2} - E[\beta^s]\frac{p_1}{(1-\beta)^2} = \frac{p_1\beta}{(1-\beta)(1-\beta+\beta\pi_1)}$. The inflow of information from the partner is cut off if either partner exits, so s arrives with probability $(\pi_1 + \pi_2)$ each turn until the end. Putting that into the generic derivation, the capital value of inflows from other tinkerers falls to $\frac{fp_2\beta}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)}$. Combining these pieces, the overall expected utility from joining the network is now

(4)

$$EU_0 = \frac{a_0 - 1}{1-\beta+\beta\pi_1} + \frac{p_1\beta}{(1-\beta)(1-\beta+\beta\pi_1)} + \frac{fp_2\beta}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)} + \frac{\pi_1\beta M}{1-\beta+\beta\pi_1}$$

The first three terms now incorporate the possibility that these streams of utility will end, and the fourth term incorporates the new payoff of leaving the network to take payoff M.

The previous results extend forward analogously with this adjusted discounting. The net benefit of redesigning, standardizing, or specializing to raise communication efficiency to f_2 becomes $\frac{p_2\beta(f_2-f)(1-\pi_1-\pi_2)}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)} - c_s$. The net benefit of joining the network is $\frac{fp_2\beta(1-\pi_2)}{(1-\beta)(1-\beta+\beta\pi_2)} - c_j$.

For the tinkerer to prefer to exit the network when offered M, M must be at least as great as the right side of equation 4, since at that level the tinkerer is indifferent between taking it or continuing in the network. For the story to hold together, the exit value parameter M must satisfy:

$$M \geq \frac{a_0 - 1}{1-\beta+\beta\pi_1} + \frac{p_1\beta}{(1-\beta)(1-\beta+\beta\pi_1)} + \frac{fp_2\beta}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)} + \frac{\pi_1\beta M}{1-\beta+\beta\pi_1}$$

from which one can derive the minimum value of M:

$$M \geq \frac{a_0 - 1}{1-\beta} + \frac{p_1\beta}{(1-\beta)^2} + \frac{fp_2\beta(1-\beta+\beta\pi_1)}{(1-\beta)^2(1-\beta+\beta\pi_1+\beta\pi_2)}$$

Using the previous parameters $\beta = .95$, $a_0 = 1$, $f = .5$, $f_2 = .54$, and $p_1 = p_2 = .07$, here is how the payoffs change when the possibility of exits is included in a tinkerer's forecasts:

Concept	Expression	Without exits $(\pi_1 = \pi_2 = 0)$	With exits $(\pi_1 = \pi_2 = .01)$
Utility cost of future investments	$\frac{1}{1-\beta+\beta\pi_1}$	-20	-16.81
Present value of own future progress	$\frac{\beta p_1}{(1-\beta)(1-\beta+\beta\pi_1)}$	26.6	22.35
Present value of future inflows	$\frac{\beta f p_2}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)}$	13.3	9.64
Present value of standardizing	$\frac{\beta p_2(f_2-f)}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)}$	1.064	.771
Minimum payoff worth exiting for	minimum M	39.9	38.07

The payoffs of being in the network are thus somewhat lower if the tinkerers expect members to exit. Still, they are positive, so tinkerers would be willing to network in the near run if the entry price is low enough. Even if the tinkerers expect to be in competition with one another, the network might still hold up, depending on the parameters. To include this aspect would complicate the model and is not attempted here. It does not seem to be very important in the historical cases under consideration. The Wright Flyer Company did not compete mainly with others who had previously been connected to Chanute. The early Apple Computer did not compete mainly with other Homebrew Computer Club alumni. Open source software companies are in practice cooperating as well as competing with the same network their founders were in before they started their company. In these empirical cases, progress is more important than competition in the mind of the tinkerer.

There are also more differentiated outcomes in real open source software situations than the binary choice of exiting or staying in the network which was modeled. For example, the source code to the operating system Linux is freely available on the Internet, but companies such as Red Hat and SuSE/Novell develop and distribute it, and offer complementary products and services. There are a variety of licenses for open source software which keep some of the source code in the public domain. These nuanced arrangements reduce the conflict inherent in the choice as it was modeled.

The model makes explicit how tinkerers make progress *before* the industry starts, according to utility maximization, not market criteria.

IX Relaxing the assumptions

IX.A Rates of progress

The assumption that each tinkerer achieves a high, steady, known rate of progress can be relaxed in some cases, and still allow a tinkerer's network to hold.

First, the assumption that progress occurs at a known fixed rate is stronger than necessary, although it is a useful simplification. A more realistic description is that tinkerers see some stream of opportunities to achieve progress as they define it. They have informed expectations about experiments, based on their knowledge and experience. A tinkerer tries experiments, whose outcomes are random. Tinkerers quit if dissatisfied with their progress. By self-selection, the population of tinkerers tends to consist of those who can make effective progress, and the p in the model is a long-run average for each member of this selected population. Modeled in this way, the present value of utility could not be so readily computed analytically. The complexity thereby introduced would distract from the main points of this model.

Second, the assumption that each tinkerer achieves a high enough rate of progress alone to motivate his own efforts is not always necessary. Tinkerers could play other roles in a network. Here are two examples:

- Suppose a tinkerer is in two networks which address different kinds of projects but occasionally some idea in each one is useful to tinkerers in the other. As an information broker transmitting these cross-cutting ideas, a tinkerer may contribute enough to maintain membership in both networks.

- A family member or friend of a tinkerer may encourage a tinkerer, express interest in the project, and bounce ideas back and forth with the tinkerer. This helpful person would not need to make any specific rate of progress or pay any joining cost to in essence become part of the network, learn about the project, and seize on useful opportunities to help the tinkerer. the progress that the tinkerer makes. Among the aerial experimenters there were several pairs of brothers among the aerial experimenters. At least in the case of the Wrights, the close collaboration helped the Wrights stick with the project through bad patches in which there was not much success. Thus other relationships can support a network's relationships.

Thus the assumption that every individual's progress outpaces a discount rate is not strictly necessary. The essential assumptions are that tinkerers are interested in common projects and can make mutually helpful progress on them according to their own judgement.

IX.B Technological uncertainty

The model assumes an agent cannot sell the technology at a profit, and cannot foresee how such possibilities could occur in the future. This is an extreme version of *technological uncertainty*, described in Tushman and Anderson (1986), Dosi (1988), and Rosenberg (1996). If there is no technological uncertainty, and the path to a marketable design is clear, then, by perfect foresight arguments, a profit-seeking firm would do that immediately. So if tinkerers lead the way technologically to a profitable industry, there must have been technological uncertainty.

The model assumed that tinkerers operate under technological uncertainty and so could not see how to make a version of A for which there would be enough demand to make a profit. In casual conversation one might say that he does not see a version of A that is "good enough" to sell, but with radically new products, both supply and demand may be hard to foresee. Several early aircraft developers did not expect the rapid military adoption of aircraft. Early personal computer makers dramatically underestimated demand. Tushman and Anderson (1986) used errors in forecasts by industry analysts as a metric of technological uncertainty.

Because of this, investment and payback for tinkerers are unavoidably subjective in this model. The experimenters do not know future forms of the output (whereas we can look *back* at a well-defined "invention of the airplane"). The improvements include qualitative redesign and "failed" experiments. A tinkerer may expect to have a better understanding of the activity after an experiment, whether or not it improves A in functional terms, and it may benefit other tinkerers to know about that experiment. Therefore the model incorporates subjective progress, and does not measure progress by engineering or market attributes of A.

IX.C Scale and population size

The model has only one relationship between two tinkerers, but each can be connected to groups or networks beyond. So the network model can scale up. As modeled, all participants contribute information to create a positive sum interchange, potentially having positive externalities. There is positive feedback, because fast progress makes a network more appealing to join. Its expansion is limited because experimenters in frontier technologies are rare.

For tinkerers of a given level of interest and capability, a larger network makes faster progress than a small one. So members have an incentive to reduce barriers to communication within the network, or with people who might join the network. This benefit of scale implies that networks with fewer barriers will address technical problems better or more quickly than networks with more barriers. For example, the use of English to discuss an open source project may improve the speed of development if more potential programmers can participate in English.

This suggests that, holding other things constant, open source innovation will tend to be more successful when tinkerers communicate in a language many people know, and in locations with less restriction on printing or association with other people. If there are many tinkerers, the network will probably have greater internal friction, and require administrative structures of information sharing (as in open source software), which are not modeled here.

IX.D Motivation

The tinkerer is imagined to have intrinsic or altruistic motivations. But a network can form in support of a profit-making or career effort of the tinkerer too, as long as the other tinkerers do not see it as a zero-sum competition. So for example a government laboratory's programmers may contribute to an open source software development effort if it is useful to their project, or a cost-reducing effort could be co-sponsored by competing firms.

A tinkerer's motivation could include not only the possible honor of making a major invention, but also the possible second-best prize of being recognized and cited by the final inventor. Such streams of payoffs can be viewed as a portion of a rate of progress p. The model also excludes any payoffs experienced in sharing what one has done with others, although innovators report the opportunity to share is beneficial and satisfying.

In the examples that motivate this model, the tinkerers do not yet know much about how to make a good A because the technology cannot yet be usefully implemented. The number of tinkerers who can make experimental progress on a particular type of project is limited to those with the knowledge, wealth, and tools to attempt it. Many people could value experimenting with new aircraft, but few like it enough, and are good enough at it, and have the resources, to bother. Those few have opportunities to make something that looks like progress to them. One might imagine that values of a_0, the original payoff of activity A, were drawn from a distribution, and the few people with a sufficiently positive value for a_0 would be tinkerers. In the aircraft case, even successful experimenters considered quitting, and many did.

Once a technology is established and competitively produced, the basic uncertainties have been resolved, so the model loses relevance. Today, there is an established spectrum of technologies for making aircraft and personal computers and delivering services to and from them. Technological uncertainty still exists within narrower domains that could be relevant for the model.

IX.E Enforceability

In the model, tinkerers would be willing to agree to an enforced open-source contract rather than work alone. But in the case of gliders leading to the airplane, there was no exogenous enforcement. There are several sources of incentive besides technological progress to support an open-source pattern which were not modeled here.

- Innovators may feel an obligation to share with the group, so enforcement is internal to each tinkerer. Meyer (2003) discusses some examples.
- Innovators may want their peers to see their work because they are proud of it and will be favorably recognized for it, as discussed in Raymond (2001) and Levy (2001). Unlike a_0 in the model, this payoff directly supports open-source relationships, and does not depend on an information flow back from the other person.
- If an invention delivers more output when it has more users, inventors may benefit more by giving it away than by keeping it secret or charging a fee to examine or use it. For example, since Web browsers were invented, many have been given away to make collaboration and information tracking easier (Berners-Lee, 1999).
- In the model of Bessen and Maskin (2006), profit-making firms are willing to share innovation information openly with one another if they are following different paths of

research or if the innovations they expect to make will be useful to achieving future ones. For tinkerers, one might model this by raising the rate of progress each tinkerer expects if more sources of information are available.

- Tinkerers may gain more from interaction if they are familiar with one another's work. Adapting this model, f could rise over time as the network's members develop longer histories together.

- To a tinkerer who anticipates someday selling a product or service, the population of tinkerers inside the network may be the natural market of early adopters for it. Interaction with others helps the tinkerer know what customers will want, and creates an opportunity to earn their trust. At first only specialists could understand and appreciate the aircraft, personal computers, and new types of software discussed earlier.

Given incentives like these, sustaining the agreement can be rational for each individual participant. The enforceable contract in this paper is a modeling shortcut. More accurate stories may require a more complex model.

IX.F Frictions, diseconomies of scale, or other costs

As written, the model incorporates the extreme assumption that there are no economies or diseconomies of sharing with more and more people. For example, it is implicitly assumed that there is no time constraint in keeping up with the relevant literature, nor cost for communicating to yet another person, nor changing marginal cost to enforce the sharing agreement. One could incorporate such influences by making f a function of the number of participants to generate increasing returns to scale (encouraging evangelism) or decreasing returns to scale (inducing pressure to reduce or exclude members).

Many aspects of the environment affect f. If, for example, communication between the tinkerers are noisy or clogged with unhelpful communication, such as email spam, f is lower. If the languages of technical communications are different, f is lower. An American experimenter working on gliders may naturally choose not to read a French journal about balloon developments, even if the balloon work is productive in its own terms (measured by p_2), either because he cannot read French, or because he thinks balloon innovations are unlikely to apply to gliders.

The model implies there are no expensive capital or training requirements. In the examples, tinkering was not usually capital-intensive. It appears that once expensive equipment is necessary for some activity, that activity falls beyond the boundaries of a network of tinkerers, except perhaps inside an organization. Also, tinkering tends to arise in environments where not much specialized training is required.

X Conclusion

A network of tinkerers model applies to innovative processes in which:

- Individuals communicate novel technical findings and designs about a technology to one another without explicit compensation.
- Experimenters do not have extrinsic rewards, largely because they are working on something that has no obvious price or does not fit into an existing, standard product market at the time they enter the field.
- Some participants specialize in managing or expanding the network.
- The activity evolves over time, in response to events that participants interpret as *progress*, such as discoveries or inventions. For example, when Hargrave reported results from his box kite experiments, other aeronautical experimenters learned and adapted to the findings

without imitating his experiments. Thus they behaved as if they were responding to a discovery of a natural law or invention, not performing for others or engaging in a sport.

Given such a situation, the model predicts that participants specialize in aspects of the technology, and standardize on some tools, as opportunities permit. The framework assumes predictions about the future form or importance of the technology are diverse and uncertain in the sense of Dosi (1988) and Rosenberg (1996). It predicts that members who do not plan to sell a related product quickly will object to intellectual property impositions. And it predicts the kind of ferment which can lead participants to jump out into entrepreneurial ventures, whose value is difficult to predict in the sense used by Tushman and Anderson (1986). The model predicts progress would be slowed by high costs to invest in experimentation or to find and join networks.

Examples of this process occurred in the invention of the airplane, the invention of the personal computer, and in the development of open source softare programs. There is a spectrum of similar kinds of innovative development:

- Shared creative content can be like open-source software. The Wikipedia, for example, is a public domain encyclopedia written principally by unpaid users. The collection of video content at YouTube.com is donated by users. In these cases the pooled content is not made up of functional engineering achievements. Instead the developers are sharing text, reasoning, and media. The library grows with contributions from many users to advance in a direction they more or less agree upon. Such shared content is similar to open source software.
- Open science. The rise of "open science" institutions which motivate, support, and enforce open publication of scientific findings, was supported by competition between patrons to employ prestigious and effective scientific innovators (David, 1998). Through the network of tinkerers story, open science would also be supported by people who wish to speed the progress of science.

- User innovation, in which a company produces a product and its users generate *user innovations*, as defined and discussed in von Hippel (2006), which also provides many examples.

- “Skunkworks”, projects of creative engineering inside corporations in which engineers work around an employer’s hierarchy, rather than obeying it. Their goal may be for the organization to succeed despite its managers. The model offers a way to think of such actors less as shirking, and more like visionaries, as they think of themselves.

- The British Industrial Revolution after 1750 occurred in a place and time when printers were allowed more freedom about what to print than printers elsewhere. This helped support an estimated 1020 technical and scientific societies (Inkster, 1991, pp 71-79). Workshops of the time were often open to visitors, and they generated, by one account, ”a wave of gadgets [which] swept [over] Britain” (Mokyr, 1993, p. 16, citing Ashton). Mokyr (1993, p. 33) concluded: “The key to British technological success was that it had a comparative advantage in microinventions.”

- The Internet and the Web expand the opportunities for technological discussion.

This model provides a formal structure to describe developers of radically new technology. Some innovators make fast progress on their own, although it may not look like progress to other people. Others make sufficient progress to perservere, if they have exogenous links to one another. Independent innovators have an incentive to join networks and share flows of information. An innovator with comparative advantages in recruitment, publicity, moderating conversation, publishing, or editing journals may end up doing those things because that moves the project forward faster than if this person worked directly on the technology. Much of this can be understood and discussed in terms of progress rates p, fractional flows of useful information f, and differentiated opportunities for each person. Players may imagine profitable future exit opportunities but if these are remote or improbable enough, joining the network makes sense until participants actually see those opportunities.

Tinkerers in the model choose to combine their information to maximize the combined flow of useful innovations. The speedup in the flow of innovations is therefore endogenous. In the model, purposeful choice generates flows of innovation that other economic models of technological change often take as given. When technological uncertainty is great, tinkerers networks can eventually form an industry, once enough tinkerers can anticipate commercial possibilities from their activities.

The desire of people to make their world a better place is a kind of natural resource. The environment affects their effectiveness. If publishing a journal, forming an association, and traveling are costly or officially discouraged, innovators facing technological uncertainty would be less effective. In this model that would reduce their utility. In the real world they might respond by reducing effort, keeping innovations secret, or emigrating to a location where the environment was more favorable. So noisy or restricted communications channels can reduce the flow of innovations both by reducing the flow of communication, and by driving tinkerers away.

In this model, innovation is generated by individuals not organizations. One benefit of modeling innovation this way is that the predictions and intuitions often apply outside the context of businesses and hierarchies, as in production prior to capitalism, or communications inside or between organizations.

XI Bibliography

Allen, R.C., 1983. Collective invention. *Journal of Economic Behavior and Organization* 4, 1-24.

Bessen, James, and Eric Maskin. 2007. Sequential Innovation, Patents, and Imitation. Institute of Advanced Study School of Social Science Working Paper 25. 2007. Forthcoming *RAND Journal of Economics*.

Berners-Lee, Tim. 1999. *Weaving the Web*. HarperCollins.

Chanute, Octave. 1997. *Progress in Flying Machines*. Dover, Toronto.

Cringely, R.X. 1992. *Accidental Empires*. HarperCollins edition, 1996.

Crouch, Tom. 2002. *The Dream of Wings: Americans and the airplane, 1875-1905*, second edition. Norton.

David, Paul A. 1998. Common Agency Contracting and the Emergence of ”Open Science” Institutions. *American Economic Review*, May 1998, 15-22.

Dosi, Giovanni, 1988. Sources, Procedures, and Microeconomic Effects of Innovation. *Journal of Economic Literature* 26:3 (Sept.), 1120-1171.

Freiberger, Paul, and Michael Swaine. 1984. *Fire in the Valley: the making of the personal computer*, first edition. McGraw-Hill.

Harhoff, Dietmar, Joachim Henkel, and Eric von Hippel. 2003. Profiting from voluntary information spillovers: How users benefit from freely revealing their innovations, *Research Policy* vol 32, No.10 (Dec), 1753-1769.

Inkster, Ian. 1991. *Science and Technology in History*. Rutgers University Press.

Jakab, Peter. 1990. *Visions of a Flying Machine*. Smithsonian Institution.

Lakhani, Karim R., and Bob Wolf. 2005. Why hackers do what they do: Understanding motivation and effort in free/open source software projects. In *Perspectives on Free and Open Source Software*, edited by J. Feller, B. Fitzgerald, S. Hissam, and K. R. Lakhani, 2005, MIT Press. Available at `http://opensource.mit.edu/papers/lakhaniwolf.pdf`

Levy, Stephen. 2001. *Hackers: Heroes of the Computer Revolution*. Penguin edition.

Meyer, Peter B. 2003. Episodes of collective invention. BLS Working paper WP-368. Available on Web at `http://www.bls.gov/ore/abstract/ec/ec030050.htm`.

Mokyr, Joel. 1990. *The Lever of Riches: technological creativity and economic progress*. Oxford University Press.

Mokyr, Joel. 1993. Editor’s introduction. *The British Industrial Revolution: an economic perspective*. Westview Press.

Nuvolari, Alessandro. 2002. Open Source Software Development: Some Historical Perspectives. ECIS working paper.

Pavlicek, Russell C., 2000. *Embracing Insanity: Open Source Software Development.* Sams Publishing.

Raymond, Eric S., 2001. *The Cathedral & the Bazaar: Musings on linux and open source by an accidental revolutionary*. O’Reilly.

Rosenberg, Nathan. 1996. Uncertainty and technological change. In *Mosaic of Economic Growth*, edited by Ralph Landau, Timothy Taylor, and Gavin Wright. Stanford University Press.

Schrader, Stephan. 1991. Informal technology transfer between firms: cooperation through information trading. *Research Policy* 20:153-170.

Tushman, Michael L., and Philip Anderson. 1986. Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly* 31 (Sept.): 439-465

von Hippel, Eric. 2005. *Democratizing Innovation*. MIT Press.

Wozniak, Steve, with Gina Smith. 2006. *iWoz*, Norton and Company, New York.

Wright, Orville. 1953. *How We Invented the Airplane*.

Wright, Wilbur. 1901. Angle of Incidence. *The Published Papers of Orville and Wilbur Wright*, edited by Peter L. Jakab and Rick Young, 2000.