Networks of Tinkerers: Examples and a Model of Open Source Technology Innovation

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Abstract

This paper models "tinkerers" who develop a technology with no market value. All benefit by sharing technological information through their network. Depending on opportunities, a network member contributes by specializing either in aspects of the technology, or in expanding and managing the network. To reduce costs, network members standardize on designs and descriptions of the technology. A tinkerer with an opportunity to create a sufficiently profitable product exits the network to conduct focused research and development, perhaps starting a new industry. The model characterizes open source software developers and key early inventors of airplanes and personal computers.

New industries based on science and new technology are a key ingredient in the growth of modern economies. Models of economic growth driven by technological change may depend on profit-maximizing firms to develop innovations.

But new industries have also emerged from hobbyists or scientists who were not oriented toward profit. This paper decouples the process of technological innovation from profit-maximizing firms by modeling open-source tinkerers as rational economic actors who do not expect pecuniary rewards. Acting in their own interest, they form networks of innovation in which technical designs are shared.

For example, in the late 1800s, before modern airplanes existed, flying machine experimenters around the world shared findings and designs. In the 1970s, hobbyists who met in clubs started part of the modern personal computer industry. Open source software developers keep their software source code publicly available, and license it so as to assure it will remain so. This paper treats the airplane, personal computer, and open source software cases as examples of "open source" technology development.

An individual may develop technology and donate it to a public place because of extrinsic financial rewards such as the prospect of signaling capabilities to a potential employer (Lerner and Tirole, 2002). A substantial literature shows that intrinsic or altruistic rewards also motivate this behavior (Lakhani and Wolf, 2005). Most such innovators benefit from using the technology and can be called "user innovators" (von Hippel, 2005). When the technology is too premature to be useful, neither extrinsic rewards nor usefulness rewards are available. Innovators who experiment then are likely be driven by scientific curiosity. Others are motivated by the appeal of having a creative outlet, and idealistic visions of changing the world.

This paper models open source technology developers in a deductive, analytically solvable model without assuming they expect to get extrinsic rewards. Three key assumptions are necessary. First, agents called tinkerers are interested in advancing the technology for intrinsically satisfying reasons. Second, each tinkerer sees how to improve the technology by his own criteria. Third, the tinkerers believe the technology is immature and uncertain so that current actions do not significantly affect future commercial opportunities or competition. Under these conditions, tinkerers find it optimal to share their technologies with one another, forming a network of information flows.

A tinkerer in the model may envision a way to profit from the technology, and then leave the network to form a firm. A new industry can arise this way, in which case the network is likely to dissolve. In airplanes and personal computers, amateur efforts did eventually lead to commercial outputs, the appearance of new industries, and productivity effects in other sectors. The model makes explicit how technologists oriented to quality criteria, not market criteria, made progress before an industry started. The discussion helps frame the economics of open source software and the industries appearing from it.

Allen (1983) introduced the related term *collective invention* to describe firms sharing technical information as in the example of iron blast furnaces in Britain in the late 1800s. Schrader (1991), Nuvolari (2005), and von Hippel (2005) offer other examples, and 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 share information in lieu of undertaking research. By contrast, the model in this paper shows how a useful industrial technology can *first* appear because of the combined efforts of people who do not expect to sell anything. No such model seems to be established.

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 filed for a patent and asserted their intellectual property rights in litigation. 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 mid-1970s the technologies became available for a technically skilled person to build a computer at home. Hobbyists working on computers formed many clubs. One club that turned out to be particularly important was the Homebrew Computer Club which met in Menlo Park and

Palo Alto, California, starting in March, 1975. Most of the people who came to Homebrew 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 kit for making a hobbyist computer had just become available.

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 from a spectrum of relevant newsletters and magazines. They were in touch outside of meetings, and sometimes shared equipment, or made relevant parts to sell to the others. 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, and Meyer, 2003)

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 dial-in electronic bulletin board systems for email exchanges, and they engaged in Usenet discussions on the Internet. Most of this activity was not for profit.

The Homebrewers made a number of novel devices. 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 found a company together and to sell this computer product. They called it the Apple I. Only computer hobbyists could use it, because it did not come with a monitor or a keyboard, but among hobbyists it was quickly in demand. The personal computer industry took off with this device.

Apple Computer, Cromemco, 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 development

Open source software developers make the source code files widely available on computer networks. Source code, written in computer languages, is fed as input to specialized development tool programs, such as interpreters, compilers, assemblers, and linkers, that generate the executable computer program.

Many programmers can experiment and improve the source code in parallel. A programmer may also alter the program for a new purpose. Sponsors of open source projects usually copyright and license the software in a way that forestalls intellectual property claims and protects its free availability for others to change and redistribute. Revisions are published under the same license. This is a powerful mechanism to coordinate, because it is common knowledge that later improvements will become part of the shared code and so the developers know they can all benefit by using later versions.

Administrative “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 prevent the project’s source code from “forking” into permanently divergent, partly-incompatible versions. If that were to happen, the project’s members would lose some of the benefits of having a single code base which improved along many dimensions over time.

Several roles and institutions support sharing in open source projects:

- Computer servers store the source code.
- Intellectual property claims are explicitly preempted by special copyrights, which keep the core technology available for others to use.
- The relevant programmers have similar development tools.
- 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. Other important programs such as the web server software Apache and the web browser Firefox are also open source programs. Tens of thousands of developers have contributed to programs like these.

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. Important aircraft experimenters spoke of intrinsic or altruistic motives:

- "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, 1911).
- "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 ..." (Octave 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" (Wilbur Wright's 1899 letter to the Smithsonian, included in McFarland, 2001, p.5)
- "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 not pecuniary either. Steve Wozniak wrote that, after the first meeting of the Homebrew Club (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 (2005) show based on surveys that many programmers participate in open source projects because of the creative enjoyment and the value of using the output. Pavlicek (2000, 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. If there is any dominant design, they are choosing to vary from it at their own cost. In the model to follow, progress is therefore measured not by attributes of the artifacts, but by the individual’s own satisfaction with it, that is, in terms of utility. By directly incorporating intrinsic or altruistic motivations, it demonstrates how certain network behaviors emerge.

III A tinkerer

Let us define an individual called a tinkerer who enjoys a private technological artifact or activity A. A might be a half-built aircraft in a barn, or a table with computer boards wired together, or a partly-written computer program. A has no market value, and is not useful yet, and the tinkerer derives no honors or profits from it. The tinkerer may imagine that there could someday be honors or profits, but 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 $\beta \in (0, 1)$ for each intervening period. Substituting in a standard geometric series identity ($(1 - \beta)(\sum_{t=0}^{\infty} \beta^t) = 1$), expected utility at time zero can be put into a closed form:

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

The tinkerer can choose to invest in (or "tinker with") the artifact 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. The agent anticipates that tinkering will improve A or replace it by something better, and therefore raise his utility by p units in each time period in the future. The notation p stands for progress which the agent experiences subjectively. Let p is fixed and positive.

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 $p > \frac{1-\beta}{\beta}$. This 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, a tinkerer who found it worthwhile to tinker once will find it worthwhile to tinker again and again. As long as p exceeds the hurdle rate $\frac{1-\beta}{\beta}$, 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 sums to

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

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:

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

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: $\frac{p\beta}{(1-\beta)^2} - \frac{1}{1-\beta} = 6.6$. 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 utility 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 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, and that the tinkerers forecast these correctly.

Suppose the two tinkerers can make an agreement to share all information about both projects including design changes and their experimentally discovered effects. This agreement forms a *network* for future information. For modeling simplicity, assume the agreement is costless and enforceable and that at any time either tinkerer 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 innovation be recognized 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 period. The remaining fraction $(1 - f)$ does not carry over because the projects are different, there are costs to interacting, and there are errors in interpretation by the innovator, transmission, and understanding by the other tinkerer.

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

(3) $$EU_{t=0} = \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + \frac{p_1\beta}{(1-\beta)^2} + \frac{fp_2\beta}{(1-\beta)^2}$$

The new fourth term expresses the benefits tinkerer one receives from the flow of information coming from tinkerer two. Because of this free good, utility is greater in equation (3) than in equation (2). The tinkerer prefers to join a network rather than work alone. Thus under these assumptions, *rational agents without a profit motive generate networks sharing open source technology.* This is the central analytical result of this paper.

V Standards, specialists, and consensus redesign

Now, we incorporate a *standardization* decision into the model. Thus far, only a fraction $f \in (0, 1)$ of player two's progress has been useful to player one.

Suppose that for cost c_s in the present period, tinkerer one can replace some element in his project by an element of tinkerer two's project. By making the components more compatible with one another in this way, the fraction of player two's innovations which apply to player one's project, rises from f to f_2. This decision changes tinkerer one's expected utility to:

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

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

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

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

Learning from these interactions and anticipating more of them, tinkerers will tend to design some elements in a modular way so that they can be replaced with less cost and impact on other elements of the design (Baldwin and Clark, 2000). Modular subsystems then appear through a planning process by each tinkerer which is educated by a path-dependent historical process of past development. Standardization can includes the list of things that are treated as modular subsystems.

For example, Alphonse Penaud worked out the benefits of an aircraft having a tail to control the direction of the aircraft better. Lawrence Hargrave's experiments showed that a box-shaped kite was more stable than a flat kite in a gust of wind, a lesson that could be incorporated into a glider design by having flexible wings stacked and connected by a rigid structure - a ”biplane” design. These design elements became common among glider experimenters.

The same utility comparison above justifies why experimenters tend to develop a common technical language to describe their technologies. This can reduce communication costs and also clarify thinking. Modularity in the technical design is often mirrored by modularity in the jargon the experimenters develop.

For example, in a journal article Wilbur Wright (1901) advised 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.

The benefits of standardizing designs and language partly explain why experimenters publish their findings. An experimenter who publishes more makes it easier for other experimenters to communicate with him and to work compatibly with his design choices. This incentive can be formalized in the model by making the fraction of another player’s progress which are useful to a particular tinkerer no longer symmetric between tinkerers, but rather an increasing function of the number of findings that the tinkerer has shared before. The sharer then benefits in two ways regarding future adoptions and communication.

First, each one would like to avoid paying the standardization cost, by getting the others to standardize on his own designs, rather than his having to pay the costs of standardizing on their designs. Furthermore, if a tinkerer anticipates adopting part of another tinkerer’s technology at some time in the future, he lowers his future cost of that adoption by getting the other tinkerer to adopt his own designs now. The one who designs first and shares thus gets a first-mover advantage. This can be a large benefit in the software context, where the designers of standards also receive recognition and the perception of leadership. Other players tend to treat a leader as a focal designer for future design elements, which gives the leader advantages in meeting his own design goals exactly.

Second, by reducing the differences between experiments, standardization lowers future communication costs. A tinkerer benefits if his preferred concepts, language, and notation are known to the others, in the same sense that academics in the same field save time and effort if they recogize the same lingo and notation. Better communication also makes it cheaper and easier for tinkerers to compare options for technical standards and choose the best ones.

These benefits of improving and standardizing both design and language partly explain why experimenters publish their findings. To the extent that sharing is incentive-compatible, its benefits substitute for the model’s artificial assumption that the agreement that players should share all their findings is enforced.

For $f = 0.5$, $f_2 = 0.54$, $p_1 = 0.07$, and $\beta = 0.95$, the payoff to standardization is $\frac{p_2\beta(f_2-f)}{(1-\beta)^2} = 1.064$. 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. Empirically, f and f_2 might be inferred from the similarity of the source code between computer system implementations, or from the communications interchanged between innovators.

If the tinkerers agree to work on separate components of of the technology, they can reduce duplication of effort. This is another way to raise f, and serves as a natural incentive towards specialization.

A tinkerer may also 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. In this model, they are willing to pay some price to maintain the large network on the project. A costly redesign to achieve a consensus can avoid the opportunity cost of forking, which loses some beneficial future exchanges.

Thus standardization, specialization, modularity and redesign for usability are natural outcomes of exchanging information to develop a technology. They can occur without competition or market exchange, despite the implication from Adam Smith that the extent of specialization is limited by the extent of the market. The network of tinkerers is a search technology which provides valuable information.

VI Joining and searching

Is a network worth joining? To model this, let c_j be the expected utility cost to start or join a sharing institution with known partners. It represents an investment or an opportunity cost. Balanced against this cost, the gross benefits of joining the network are again $\frac{fp_2\beta}{(1-\beta)^2}$. If c_j is less than this, the tinkerer would join.

So the model predicts a tinkerer joins, ceteris paribus, if

- (1) the costs of joining, c_j, are low enough,
- (2) the flow of innovations from the others, p_2, is large enough,
- (3) the innovations are mutually relevant enough, 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 find a network or candidates for an existing network. The problem is addressed in the real world by people who communicate about their network to outsiders in books, journals, speeches, email broadcasts, web sites, and conversations.

In the model, tinkerers working on similar projects make far more progress if they can connect together, but the absence of information about one another often prevents a Pareto-improving network from appearing. One can think of tinkerers as a natural resource, and institutional attributes of the environment (like the availability of the Internet) affect whether they find one another and work together effectively.

Knowing this, a tinkerer whose utility derives from technical progress might focus on lowering search or joining constraints or costs. A tinkerer who makes the technology itself easier to learn, or easier to use, or who documents the technology in a new way, makes it easier for others to see and benefit from its virtues. A member who recruits new members brings progress to the group indirectly. A member who eases internal communications about progress through a journal can lower interaction costs and thus indirectly increase future standardization within the group and its appeal to new members.

Such evangelists, editors, and moderators were essential in the motivating examples:

- Aircraft experimenter and author Octave Chanute corresponded widely and favored the 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, designated 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.

The model naturally emulates this preference. 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 neither tinkerer expects to 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 and simply give up on the activity or the network, which slows overall progress even for the most successful tinkerers.

If there are many partners and frictional costs to defining, managing, or enforcing intellectual property rights, the social costs of intellectual property further exceed the social benefits, so tinkerers in the model generally benefit more from networking if the rules of the game do not encourage the definition and protection of intellectual property.

That changes when commercialization to a broader market is likely. So far the model has not considered the mixed incentives faced by a tinkerer who anticipates selling a product some day, although part of the importance of this story is that new industries can start this way. The tinkerer who plans to enter the market wants to have a barrier to competition. In one memorable 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 less 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.

The Wrights applied for a patent in March 1903 and after their next experimental successes started an airplane business. Chanute had criticized others who kept secrets before, and he began to have conflicts with the Wrights. These conflicts grew severe and in later years 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. 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 software world, analogous tensions arise between developers who take the view that a particular program must 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 specific programs.

VIII.A Modeling entrepreneurial exit

In each of the historical episodes, firms arose from networks of tinkerers. The transition, which can create a new industry, is complicated. One change in the economic environment 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 of ignorance blocks the tinkerer's view of better forms of the technology. If that veil were to lift, the tinkerer might envision how to produce a product. The veil might lift because of introspection, accident, or systematic advances in the technology. For simplicity, in this section we model both the probability that the veil lifts each period, and the value of future profits, as fixed, exogenous, and known to the agent.

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 take the time and effort to experiment and to share findings universally, the utility of the resulting monopolistic profits would decline by more than the utility of staying in the network, so the tinkerer drops out of the network. Dropping out means ceasing to tinker with A, losing benefits a_t, and ceasing to receive inflows of information from the other tinkerers. The tinkerer does not lose any information received by past tinkerings or inflows.

Before specifying the parameters, we will need to make use of a generic calculation of the discount factor to apply to a one-time utility payoff which arrives with probability π at the beginning of each future period. Let s denote the unknown random period in which it arrives, and assume that the same discount factor β applies to this commercial outcome as to innovative events. The discount factor to apply to this payoff is $E[\beta^s]$. This is the probability-weighted average of the appropriate discount rates for each possible s. The geometric series summation trick applies again:

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

Now, 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 period that this tinkerer sees an opportunity to take M, and π_2 be the probability that the other tinkerer does. For computability, assume these probabilities are small and that both events cannot occur in the same period.

All the payoffs in the model must now incorporate that derivation since the source of utility changes entirely at time s. This means substituting in new denominators to represent the new discount factor. The time-zero present value of exiting in 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 tinkering 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 other tinkerer is cut off if either one exits, so s arrives with probability $(\pi_1 + \pi_2)$ each period until the end. Putting that into the generic derivation, the present 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 to this environment 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 a probability 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	38.67

The payoffs of being in the network are thus lower if the tinkerers expect other tinkerers to exit. Still, the payoffs 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 in the distance future, the network might still hold up, depending on the parameters. Including 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, Canonical, 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.

IX Extensions

IX.A Effort or investment choice

With an extension it is possible to endogenize a networked tinkerer's decision on how much effort or investment to devote to tinkering, instead of fixing it at 1. Let e denote the utility cost of an input of innovative effort or expense whose range is bounded by fixed known limits: $e \in [0, E]$. For notational simplicity, assume the level of e is fixed and comes every period until the exit from the network. This affects only the first term of equation 4 so that expected utility now is:

(5)

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

Assume first that only the exit payoff M, in the last term, is a function of e and $M'(e) > 0$ in the relevant range of e. In this situation, increased effort allows the tinkerer to work on more valuable applications of the technology, but does not speed the arrival of the exit event. Under this assumption, $\frac{d(EU_0)}{de} = \frac{\beta\pi_1 M'(e) - 1}{1-\beta+\beta\pi}$. So as modeled here, the tinkerer maximizes utility by increasing effort until either $M'(e) = \frac{1}{\beta\pi_1}$ or e reaches its maximum.

Similarly, if a tinkerer's progress is a positive function of effort, $p_1(e)$, the tinkerer increases effort until $\frac{p_1^{'}(e)\beta}{1-\beta} = e$.

Suppose instead that the probability of a good exit opportunity, π_1, is a function of effort and that $\pi_1^{'}(e) > 0$ in the relevant range of e. This models the idea that by putting in more effort the tinkerer can accelerate the arrival of the big discovery, invention, or entrepreneurial exit event.

Since π_1 appears throughout equation 4 the math is complicated, but the intuition is straightforward. When M is large enough, the tinkerer is willing to put in full effort. If M is only slightly greater than the value of staying in the network, the choice of effort makes little difference and the tinkerer puts in minimum effort.

So given this framework and the utility functions, the tinkerer will invest more or contribute additional effort if the extra effort raises the rate of progress or the value of exiting sufficiently. This extra investment or effort also helps other tinkerers. Empirically, investments can be measured in principle by the money and time spent by an experimenter on the technology.

IX.B Rates of progress

Above it was assumed that each tinkerer achieves a high, steady, known rate of progress exceeding the hurdle rate $\frac{1-\beta}{\beta}$. That simple assumption makes it clear how the network can start, but a tinkerer's network can arise when this assumption does not hold. Here are four such cases.

- Before beginning experimental work, a tinkerer may already know or believe that other tinkerers will join him in a network. The tinkerer then would start work if the combined rates of progress he expects to receive exceed the hurdle rate.
- Tinkerers could play other roles in a network besides experimenting. 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, even if his own experimental progress does not meet the hurdle rate.
- Exogenous relationships can support a network's progress. Family members or friends may encourage a tinkerer, express interest in the project, and talk about it. Such helpful persons need not make any specific progress or pay a joining cost to learn about the project and help the tinkerer. Among the aerial experimenters there were several pairs of brothers. Close collaboration and strong family support helped the Wrights stick with their glider project through bad patches during which they did not make much progress.
- The rate of progress need not be fixed or known. A more realistic description is that tinkerers see some stream of opportunities to achieve progress as they define it. They have informed expectations about potential experiments, based on their knowledge and experience. Outcomes of the experiments 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 this member

of a selected population. Modeled in this more complex way, the present value of utility would be harder to compute analytically.

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 judgments.

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, unless they are inside the same organization.

Empirical measures of the rate of progress can come from the reports or publications by the experimenter, and or from the volume and timing of code shared ("posted") by a software developer.

IX.C Technological uncertainty

The model assumes an agent cannot profit from the technology, and cannot foresee how to do so in the future. This is an extreme version of *technological uncertainty*, described in Tushman and Anderson (1986), Dosi (1988), and Rosenberg (1996). If there were no technological uncertainty, and the path to a marketable design were clear, then a profit-seeking firm would have done that. So if tinkerers are observed to 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, 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 technology (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.D Scale, population size, and frictions

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, however, by the supply of tinkerers in the relevant technology. 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, discussing an open source project in English rather than another language may improve the speed of development if more potential programmers know 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.

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 innovation environment affect f. If, for example, communication channels between the tinkerers is noisy, 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.

An empirical proxy for population size is the number of subscribers to the relevant journals or email broadcast lists, or the number of programmers who post source code. The complexity of the administrative structure could be measured by the number of roles within it.

IX.E Motivation for sustained sharing behavior

As modeled above, 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 significantly competing with their own goals. Even competitors can co-sponsor technical standards if it lowers costs for both.

A tinkerer's motivation can include not only the possible honor of making a major invention, but also the second-best prize of being recognized and cited by later inventors. Such streams of payoffs can be viewed as a portion of a rate of progress p. Innovators report the opportunity to share is beneficial and satisfying, but the model excludes direct utility from sharing because it would not explain why some tinkerers start projects alone.

In the examples that motivate this model, the earliest 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 profitably 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.

In the model, tinkerers would be willing to agree to an enforced open source contract rather than work alone. For brevity of argument, the existence of enforcement was a convenient assumption, but in the real world cases this is not common except insofar as the openness of open source software is legally protected by copyright rules. There are other incentives to sustain an open source agreement:

- Tinkerers may feel an ethical obligation to share with the group. So enforcement is internal to each tinkerer.

- 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 Cringely (1992), 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 price. Web browsers have usually been given away since their beginning, to make collaboration and information tracking easier and to establish standards. (Berners-Lee, 1999).

- In the model of Bessen and Maskin (forthcoming), 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 of communication.

- 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 participant. The enforceable contract in this paper is a modeling shortcut, and the point is that the tinkerers would be willing to agree to it. More accurate stories seem to require a more complex model.

X Conclusion

The network of tinkerers model provides a formal structure to describe the behavior of individuals who develop radically new technology. The inventive network mechanisms operate in addition to the well-established effects of price mechanisms. This model contains no price variable and does not model the supply and demand for innovations. It takes self-motivated innovators in the relevant field as given. This assumption in the model is legitimated first by the fact that we observe many such innovators and can see their words and behavior, and second because it helps explains open source behavior. The model characterizes situations in which:

- Individuals communicate novel technical findings and designs about a technology to one another without explicit compensation.
- These individuals work on something that has no obvious price and does not fit into an standard existing product market.
- Participants do not expect substantial extrinsic rewards.
- Some participants specialize in managing or expanding the network of communication.
- The activity evolves over time in response to discoveries, inventions, and other events that participants interpret as *progress*, rather than for example cyclical changes or changes in fashion.

In such situations, the model predicts that participants specialize in aspects of the technology, and standardize on some tools, as opportunities permit. The framework allows participants to hold varied predictions about the future form or importance of the technology. The technology is thus uncertain in the sense of Nelson and Winter (1982), Tushman and Anderson (1986), Dosi (1988), and Rosenberg (1996). The model then predicts that participants will tend to object to the imposition of intellectual property constraints. It also 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 that progress, as experienced subjectively by the tinkerers, will be slower if experimentation or networking are costly or constrained.

Such networks generated the first airplane, early personal computers, and many open source software programs. This model of voluntary sharing of technical information fits other cases of innovative development too:

- The Industrial Revolution after 1750 occurred first in Britain. There were an estimated 1020 technical and scientific societies there (Inkster, 1991, pp 71-79). This was supported by many printers who had more freedom print than printers outside Britain, both because of their legal freedom and the availability of relatively low-cost presses. The atmosphere supported some cooperation – craftsmen of the time routinely welcomed visitors to their workshops. These craftsmen made “a wave of gadgets [which] swept [over] Britain” (Mokyr, 1993, p. 16, citing Ashton). Mokyr (1993, p. 33) found that “The key to British technological success was that it had a comparative advantage in microinventions” – that is, small improvements on pre-existing technology. The network of tinkerers model shows how the capability to print, the permission to print, and the technical societies enable the appearance of new firms, industries, and growth. The mechanisms of the model can help analyze larger story that technological creativity distinguishes the economically progressive civilizations from others (Mokyr, 1990).

- Scientific advances tend to follow from personal commitment above and beyond pecuniary rewards. “Open science” institutions motivate, support, and enforce publication of scientific findings. Patrons competed to employ prestigious and effective scientific innovators (David, 1998). These institutions also catalyze scientific progress of science through the standardization, specialization, and evangelism mechanisms in the tinkerers’ network model.

- “Skunkworks” are engineering projects inside large organizations where 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 frames them as visionaries, as they think of themselves, rather than as shirkers. Under such circumstances, hierarchical and decentralized information flows coexist, and hierarchical, network, and evolutionary models of the organization all have some traction.

- Users of a product may modify it. “Lead users” working with new techniques for using the product or new market trends are especially likely to modify manufactured products. In many cases these innovations are freely revealed and in many cases they are commercialized. Von Hippel (2005) gives many examples of these user innovators and explains their thinking. The tinkerers model can characterize the interactions of user innovators without assuming that they begin with a plan to manufacture a product themselves.

- The Internet and the Web expanded the opportunities to discover niche interest groups and engage in distributed technological discussion. Creative content can be developed collaboratively online. The public domain Wikipedia, for example, is written, edited, and maintained mainly by unpaid users. The collection of video content at YouTube.com is donated by users. In these cases pooled content is made up partly of functional engineering achievements but mainly of text, reasoning, and media content. The library grows with contributions from many users to advance in a direction they more or less agree upon. The model's mechanisms apply to such shared content.

Some innovators make fast progress on their own, although it may not look like progress to other people. Others persevere partly because they have prior links to one another, such as the Wright brothers. 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 they find it optimal to participate in an institution of freely revealing their innovations until some specific opportunity appears.

Tinkerers in the model choose to combine their information to maximize the combined flow of useful innovations. Their choices generate endogenous unpriced flows of innovation which other economic models of technological change often take as given. Starting from a state of great technological uncertainty, networks of tinkerers can evolve generations of artifacts and eventually start commercial enterprises.

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 grappling with technological opportunity will have a harder road. In this model that would reduce their utility and progress. Given the option, they might respond by reducing effort, keeping innovations secret, or emigrating to a place where the environment is more favorable. Thus noisy or restricted communications channels can reduce the flow of innovations both by reducing effective communication, and by driving tinkerer-types away.

In this microeconomic model of scientific and technological progress, innovation is generated by individuals not organizations. One benefit of modeling innovation this way is that the predictions and intuitions apply outside the context of businesses and hierarchies, as in communications inside organizations, between organizations, or in historical contexts other than modern Western capitalism. However it describes behavior outside standard business hierarchies which is also the heart of the success of modern capitalist growth.

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