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 technologies are a key ingredient of new industries. These new technologies may be developed for profit by firms, or may be developed by networks of hobbyists, scientists, and others who are not oriented toward profiting from the technology. The model in this paper characterizes technology development of the second type, by modeling developers of open source

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technologies as rational economic actors who do not expect pecuniary rewards from their innovations on the technology. Acting in their own interest, these developers form networks to share technical designs.

We generalize from three episodes of innovation. In the late 1800s, before modern airplanes existed, flying machine experimenters around the world shared designs and experimental findings. In the 1970s, hobbyists who met in clubs started part of the personal computer industry. And in recent years open source software developers systematically keep their software source code publicly available.

This paper models such open source technology developers in a deductive, analytically solvable way without assuming that they expect extrinsic rewards. Three key assumptions about the productive environment are necessary. First, individuals, called tinkerers here, develop the technology mainly for intrinsically satisfying reasons. Second, each tinkerer sees how to improve the technology by his own criteria. Third, the tinkerers believe the technology is so immature and uncertain that revealing it does not significantly affect their future commercial opportunities.

Under these conditions, tinkerers find it optimal to share technology designs with one another. They form a network. Then, network effects support the redesign of the technology to specialize, standardize, and modularize its subsystems and to make the technology easier to learn and use. Since the network is achieving the purposes of its members they wish to sustain it, and a tinkerer may optimally specialize in improving its internal communications or in expanding the network by evangelizing the technology to outsiders. We see these behaviors in the airplane, personal computer, and open source software cases.

In the model, a tinkerer may envision a way to profit from the technology and then leave the network to start a firm. A new industry can arise this way, and the network may then dissolve. Amateur efforts did eventually lead to the appearance of manufactured airplanes, commercial personal computers, and firms built around open source software technology. There is a tendency after the fact to recognize the industry and its productive effects without remembering the earlier networks of innovators which made the industry possible.

Allen (1983) introduced the closely 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 the collective invention literature, the technology is known to deliver useful outputs, and the profit-minded firms share information in lieu of organized research.

By contrast, the model in this paper shows how a useful industrial technology can be *invented* by the combined efforts of people who do not expect to sell anything. No such model seems to be established. This model makes explicit how technologists oriented to quality criteria, not market criteria, work together make progress before the technology is industrially useful. The discussion helps frame the economics of open source software, where the network of tinkerers may survive indefinitely.

1 Examples of open source technology development

1.1 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 advanced the field. Alphonse Penaud showed how it was easier to control a flying winged craft if it had a tail with control surfaces. Lawrence Hargrave tried designs with flapping wings and also showed that box kites with stacked wings were stable in an air flow. Samuel Langley whirled angled plane surfaces on an arm to see how much lift the airflow would give them, and flew a powered model. Otto Lilienthal ran many years of experiments to determine how much lift various curved wing shapes generated, and flew hang gliders with the shapes of bird wings. These results became well known and led to the early 1900s standard design of a glider, with stacked curved wings and a tail.

A Chicago railroad engineer named Octave Chanute was inspired by the possibility that experimenters around the world could cooperate to make winged flying machines a reality. He visited and corresponded with many of them. 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 optimistic 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 the instrumentation in their wind tunnel. They began to withdraw from processes of open sharing as they believed they were near to a successful powered glider flight (Crouch, 2002). They secured 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.

1.2 The beginning of personal computers

Around 1975 it became possible for a person to build a simple computer at home. The basic set of parts for an Altair computer could be ordered by mail. Clubs of computer hobbyists appeared, such as the Homebrew Computer Club in Menlo Park, California. Of those who came to the first Homebrew meeting, “six of the thirty-two had built their own computer system of some sort, while several others had ordered Altairs” (Levy, 2001, p. 202).

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).

These hardware hackers used similar parts, attempted similar projects, and read 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. Early attendees were drawn to the hands-on experience of making computers and understanding the component parts, rather than to theories of computing, or the social effects of computing. (Levy, 2001, and Meyer, 2003) Many computer hobbyists attended the (U.S.) West Coast Computer Faires. Some of them operated their own dial-in electronic bulletin board systems or discussed computers on the Usenet bulletin boards on the Internet. Most of this activity was not for profit.

The Homebrewers made a number of novel devices. At one meeting, Steve Wozniak demonstrated a new board which could do many things a minicomputer could 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.

Homebrew attendees founded perhaps twenty companies, including Apple Computer, Cromemco, and Osborne. But the club started because of an interest in computers, not business.

1.3 Open source software development

Open source software developers share source code on computer networks. Source code files written in a programming language are fed through specialized development tool programs such as compilers, assemblers, interpreters, and linkers, to create the binary form of the program that a computer can run.

Many programmers can experiment and improve the shared source code in parallel. A programmer may also alter the program for a new purpose. Sponsors of open source projects usually preempt intellectual property conflicts by copyrighting and licensing the software in a way that protects the rights of others to freely use, change, share, and republish it. Revisions are published under the same license. This mechanism encourages and coordinates development efforts, because it is common knowledge that the shared code will improve and they can all use the improved versions.

Administrators of the project select from the submitted source code when they release a new version of the software. Experimentation is usually welcome and unrestricted, and users may make a version different from a released one. The administrators 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 improving on many dimensions.

Open source software projects can have complicated roles and structures internally. The relevant programmers may use different platforms and tools. Version control software running on computer servers keeps records of who changed the source code and when. Large projects have established roles and powers for translators, legal specialists, documenters, and release managers. Much of this work is not engineering work.

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.

2 Motivation and psychology

The model which follows describes 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 benefit from some service the project provides, and they may find a project inherently absorbing and enjoyable. These are sometimes called *intrinsic* motivations. [1] They may anticipate that the project could improve the human condition apart from themselves, which is an *altruistic* motivation. Innovators may also anticipate receiving honors, prestige, or career benefits from the project, which are *extrinsic* motivations distinct from selling the technology. [2]

Economic models have naturally focused on cases with extrinsic motivations, but the cases described above point our attention in a different direction. For example, important aircraft experimenters wrote of their 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)

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[1] When innovators benefit from using the technology but not by selling it, they can be called "user innovators" (von Hippel, 2005). A computer programmer absorbed in a project may experience a creative "flow state" of the mind, or satisfy curiosity in answering a question. (Lakhani and Wolf, 2005). These are categories of intrinsic motivation.

[2] 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 as emphasized by Lerner and Tirole (2002) or because it raises the price of a complementary good the developer controls as in Allen (1983).

- "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).

Hardware hackers were not usually motivated financially 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.

3 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 circuit board which doesn't work yet, 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 $0 < \beta < 1$ for each intervening period. By substituting in a standard geometric series identity ($(1-\beta)(\sum_{t=0}^{\infty} \beta^t) = 1$), we can put expected utility at time zero into closed form:

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

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 be 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 $p > \frac{1-\beta}{\beta}$. 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:

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

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

$$\mathrm{E}U_{t=0} = \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + \frac{p\beta}{(1-\beta)^2} \tag{2}$$

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.

4 A network of tinkerers

To get to the main proposition quickly, we make simple and extreme assumptions. Later sections consider alternative 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 rates of progress of the two tinkerers be p_1 and p_2.

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. At any time either tinkerer can exit from the network, meaning he no longer shares information nor sees information from the other tinkerer.

Let $0 < f < 1$ be the fraction of tinker two's progress that tinkerer one recognizes as useful to his own project. So tinkerer one benefits by fp_2 in every period after learning of an innovation or finding from tinkerer two. Symmetrically let f be the value in tinkerer one's innovations that benefit tinkerer two. The remaining fraction $(1 - f)$ does not carry over for a variety of reasons: the projects are different; there are costs to interacting; and there are errors and limits in transmission and understanding.

If the tinkerers expect each other to produce a flow of relevant innovations, they are made better off by joining in a network. If they join and share forever, with fixed f and progress rates, tinkerer one's expected utility is:

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

The new fourth term expresses the benefits tinkerer one receives from the whole flow of information coming in from tinkerer two. Because of this free good, utility is greater in equation (3) than in equation (2). If $f > 0$, each tinkerer prefers to join the network rather than work alone. Thus under these assumptions, *rational agents without a profit motive form networks to share technology.* This is the central analytical result of this paper.

5 Standards, specialists, and consensus redesign

Now, we incorporate a technology *standardization* decision into the model. Thus far, a fixed fraction f of tinkerer two's progress has been useful to tinkerer one. Suppose that 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 tinkerer two's innovations which apply to tinkerer one's project rises from f to f'.

Let the cost of this redesign be c_s in the present period. This decision changes tinkerer one's expected utility to:

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

Comparing this to equation 3, a tinkerer would adopt another tinkerer's design element when:

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

So a tinkerer benefits more from standardization if: (a) other tinkerers produce a large flow of innovations p_2; (b) the cost of standardizing, c_s, is small; (c) the increase in the usable fraction $(f'-f)$ 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 criteria intuitively characterize the conditions under which it makes sense for a software developer to replace working code by a library of code written by someone else.

Anticipating more of these interactions, tinkerers will learn 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. Among the standardization decisions then is the overall specification of which elements are replaceable subsystems and how each one relates to the others (Baldwin and Clark, 2000).

In the example of the development of the airplane, Alphonse Penaud worked out how a lifting surface on an aircraft's tail would help to control its direction. 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. By 1905 these tail and wing features were common on gliders.

The same utility comparison above justifies why experimenters tend to develop a common technical language to describe their technologies. Precise technical language can reduce communication costs and also clarify thinking. Learning how the components have been labeled is a helpful education for the newcomer. Tinkerers may put focus and energy into the labels since that helps the network make progress.

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 could be formalized in the model by making the useful fractions of progress no longer symmetric between tinkerers, but rather an increasing function of the number of findings that the tinkerer has shared before. Sharing then brings two kinds of utility benefits.

First, by reducing the differences between the activities of the various tinkerers, standardization lowers communication costs. A tinkerer benefits if his preferred concepts, terminology, and notation are known to the others, just as academics in a specialized field save time and effort if they recognize the same language and notation. Standardized communication also makes it cheaper and easier for tinkerers to compare technical design alternatives.

Second, a tinkerer can avoid paying the standardization cost if he gets other tinkerers to standardize on his designs, rather than his having to pay the costs of adopting theirs. And sooner is better–he lowers his future costs of adopting other tinkerers' technologies if he can get them to adopt his own overall design or design elements 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 tinkerers tend to treat a past leader as a focal designer for the future, which gives this leader advantages in meeting his own design goals exactly.

These benefits of improving and standardizing both design and language partly explain why experimenters share their findings. To the extent that sharing is incentive-compatible, its benefits substitute for the model's assumption that the sharing agreement is enforceable.

For $f = 0.5$, $f' = 0.54$, $p_1 = 0.07$, and $\beta = 0.95$, the payoff to standardization is $\frac{p_2 \beta (f' - f)}{(1-\beta)^2} = 1.064$. 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' 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. If two tinkerers conduct identical experiments, they may see that there was an opportunity cost. This gives tinkerers a natural incentive to specialize in different design elements, which has the effect of raising f over what it would otherwise be.

A tinkerer may also optimally invest in a 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. These behaviors 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 and can generate a technological paradigm without the use of a price mechanism.

6 Joining and searching

Is a network worth joining? To model this decision, 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 that 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 parameter f is an interpersonal rate of substitution for progress, and c_j is an entry fee to receive it.

In the real world these matching decisions are facilitated by people who communicate about their network to outsiders in books, journals, speeches, email broadcasts, web sites, and conversations. 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 his results and patented nothing so as to aid collective progress.
- Lee Felsenstein, who usually ran the Homebrew club meetings, specifically designated “Random Access” interaction time for people to talk to whoever could help them.
- In open source software development, charismatic founders and projects draw in interest, and the programmers are explicitly and routinely encouraged and expected to share code.

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. The absence of information about one another may prevent a Pareto-improving appearance or growth of a network.

Knowing this, a tinkerer whose utility derives from technical progress might focus on reducing constraints or costs for finding or joining a network. Recruiting new members brings progress to the group indirectly. A tinkerer may choose whether to recruit a new network member by comparing the net benefit of tinkerering this period, $\frac{p\beta}{1-\beta} - 1$, to the net benefit of recruiting the new member, $\frac{fp_2\beta}{(1-\beta)^2} - c_j$.

Similarly, a tinkerer who makes the technology itself easier to learn or use, or who documents the technology in an effective way, makes it easier for others to see and benefit from it. 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. The costs and benefits of choices about these investments of time, effort, and expenses can be expressed in the same parameters.

7 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.

8 Entrepreneurial exits from the network

8.1 Examples of entrepreneurial exits

Starting in late 1902, after they had tested many wing shapes in their 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.

Open source software developers do not usually have to make such a high-stakes decision to exit the group when they start a firm, since they can offer related services or software while still participating in the development of the shared technology. However it can happen that 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.

8.2 Modeling entrepreneurial exit

In each of the historical episodes, firms arose from networks of tinkerers. The transition, which can create a new industry, can be complicated. One change in the modeled economic environment can make it happen mechanically.

Earlier it was assumed that in the environment of technological uncertainty, 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 an advance 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 then that a tinkerer in a network envisions a directed research and development process which would result in a profitable product or service based on project A. Suppose further that the focused research is not compatible with continuing to experiment and freely revealing the results. The tinkerer then evaluates dropping out of the network and entering a new decision environment. Dropping out means ceasing to tinker with A, losing benefits a_t, and receiving no more inflows of information from the other tinkerers. The tinkerer does not lose any information received by past tinkerings or inflows.

To evaluate the tradeoff, we will need 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:

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

Now let M be the net 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 possibility since the source of utility changes entirely at time s. The numerators stay the same while the denominators change to reflect the new discount factors. 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' becomes $\frac{p_2\beta(f'-f)(1-\pi_1-\pi_2)}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)} - c_s$. 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 $\beta = .95$, $a_0 = 1$, $f = .5$, $f' = .54$, and $p_1 = p_2 = .07$, 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	$\frac{\beta p_2(f'-f)}{(1-\beta)(1-\beta+\beta\pi_1+\beta\pi_2)}$	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 exits. Still, the tinkerers would be willing to share progress if the entry price is low enough. Even if the tinkerers expect to be in direct competition with one another in the distant future and this were incorporated into the exit value, they would share in the near term if progress were fast enough and the exit probabilities were low enough.

Theoretically the case of potential direct competition is interesting, but it does not seem to have been important in the historical cases under consideration. Few of Chanute's correspondents started companies. The competition for the Wrights for example came from established manufacturers who branched out into aircraft. Analogously, the early Apple Computer did not compete mainly with other Homebrew Computer Club alumni, but with established computer makers. In these cases it seems that with good foresight most tinkerers would find immediate progress to be more important to their utility than the prospect of industrial competition against others in the network.

In open source software, outcomes are more differentiated than simply staying in or exiting from the network. Open source software companies cooperate as well as compete with networks of outside developers. The source code is licensed so as to be available for wide use and sharing. For example, the main source code to the Linux operating system 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. These arrangements avoid the stark choice that was modeled above. More nuance and detail would be needed to model this outcome.

9 Issues and Extensions

9.1 Effort or investment choice

With an extension we can endogenize a networked tinkerer's decision about how much effort or investment to devote to tinkering. 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 for each period until the exit from the network. This affects only the first term of equation 4 so that expected utility now is:

(5)

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

Consider three effects that effort or investment might have on the outcomes – to speed progress, to speed the exit payoff, or to raise the value of the exit payoff. First, if a tinkerer's progress $p_1(e)$ is a positive function of effort, the tinkerer will maximize utility by increasing effort until meeting the first order condition $\frac{p_1^{'}(e)\beta}{1-\beta} = e$.

In the second case, let the exit payoff M be a function of e and assume $M'(e) > 0$ in the relevant range of e. In this situation, the tinkerer works on more valuable applications of the technology with more effort. Under this assumption, $\frac{d(EU_0)}{de} = \frac{\beta\pi_1 M'(e)-1}{1-\beta+\beta\pi}$. The tinkerer then maximizes utility by increasing effort until either $M'(e) = \frac{1}{\beta\pi_1}$ or e reaches its maximum.

For the third effect, suppose instead that more effort raises the chance that a good exit opportunity arrives, so that $\pi_1^{'}(e) > 0$ in the relevant range of e. Then with more effort, the payoff M is likely to come sooner. Since π_1 appears throughout equation 4 the math in this case is complicated, but the basic prediction is straightforward and intuitive. If M is large enough, the tinkerer is willing to put in the maximum 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 the 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 helps other tinkerers. In principle these investments can be empirically measured by the money and time experimenters spend on the technology.

9.2 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 know that other tinkerers will join in a network. Then the tinkerer starts to invest if the *combined* expected rate of progress exceeds the hurdle rate.
- Tinkerers could find information without expensive experimenting. Suppose a tinkerer is in two networks which address different projects, and occasionally a discovery or invention in one is useful to tinkerers in the other. By transmitting such cross-cutting information between the networks a tinkerer could benefit and contribute enough to stay in both networks without making experimental progress.
- Relationships outside a network can support its progress. Family members or friends for example may encourage a tinkerer, express interest in the project, and talk about it. Such helpful persons need not make any specific progress or pay any cost to learn about the project and help the tinkerer. Close collaboration and strong family support helped many of them stick with their glider projects through bad patches. Indeed among the aerial experimenters there were several pairs of brothers.
- The rate of progress need not be fixed or known. A more realistic description is that based on their knowledge and experience tinkerers see a stream of opportunities to achieve

> progress. They experiment, with occasionally surprising results. Tinkerers quit if dissatisfied with their progress. By self-selection, the population of tinkerers consists mainly of those who can make effective progress, and the p in the model is a long-run average for a member of the 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 assumes 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, the activity falls beyond the boundaries of a network of tinkerers, unless perhaps they are inside the same organization.

Empirical proxies for a tinkerer's rate of progress can come from the reports or publications by the experimenter, from the volume and timing of code shared ("posted") by a software developer, from the comments or reviews by others, or by evidence that others are using the tinkerer's work.

9.3 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 instead the path to a marketable design had been clear, then a profit-seeking firm would likely have taken it. If we observe instead that tinkerers led the way to creating the technology of a profitable industry, it is likely that there was great 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.

Once a technology is established and profitably produced, the basic uncertainties have been resolved, so the model loses relevance. Today, technologies for making, using, and maintaining today’s aircraft and personal computers are well established, but the model can be relevant to new frontier domains where technological uncertainty is still great.

9.4 Scale, frictions, and administration

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 with postitive externalities, creating a positive sum interchange. 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. Network members therefore have an incentive to reduce barriers to communication within the network, or with people likely to join it. Holding other things constant, open source innovation will tend to be more successful when tinkerers communicate in a language many people know, such as English, and in locations with few restrictions on publishing or associating with other people.

With many tinkerers, the network may have more internal friction, and require administrative roles and institutions typical of open source software projects. As written, the model incorporates the extreme assumption that there are no economies or diseconomies in the costs of sharing information with more people. But realistically, there are time constraints in keeping up with the relevant literature, and costs for communicating to more people, and changing marginal cost to enforce the sharing agreement, and costs of screening the contributions. To incorporate such constraints, f could be a function of the number of participants. This can generate increasing returns to scale (encouraging evangelism) or decreasing returns to scale (inducing pressure to fork the project or to reduce or exclude members).

Many aspects of the innovation environment affect f. If, for example, communication channels between the tinkerers are noisy, f is lower. If technical communications use incompatible terminologies or tools, 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.

9.5 Motivation for sustained sharing

As described above, the tinkerer is imagined to be an individual with intrinsic motivations. But a tinkerer might be pursuing a profit-making or career effort too, as long as the other tinkerers do not see it as significantly competing with their own goals. Even direct competitors may cooperate to co-sponsor technical standards that will lower costs for both. The model's mechanisms may apply.

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 tinkerers have started some important 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.

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 obligation to share with the group. Some such groups are called “communities of practice,” and the individual has internalized norms and ethics of the community. Then “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 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. This occurs explicitly if we see them agree on standards for their communication or their devices.
- The tinkerers in the network are a natural market of early adopters for new products. Interaction with others helps a tinkerer know what potential 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.

9.6 More networks of innovators

The network of tinkerers model of voluntary sharing of technical information to a network fits other cases of innovative development as well:

- The Industrial Revolution after 1750 occurred first in Britain, where there were an estimated 1020 technical and scientific societies (Inkster, 1991, pp 71-79). These societies had access to affordable printing presses and broad freedom to use them. The normative atmosphere also supported technical cooperation, and 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 existing technology. The tinkerers model shows how meetings and publications of technical societies could catalyze the appearance of new products, firms, industries, and growth. The model identifies some of the channels that enable economically progressive civilizations to be technologically creative (Mokyr, 1990).
- Scientific advances follow from personal commitment beyond pecuniary rewards. Centuries ago, patrons competed to employ prestigious and effective scientific innovators (David, 1998), and this helped create the "open science" institutions which motivate, support, and enforce publication of scientific findings. But these open science norms and institutions also meet an objective of the scientists to find satisfying answers through the model's mechanisms of standardization, specialization, and evangelism. In a survey, Stodden (2009) asked scientists why they had or had not invested the effort to make their results reproducible, and found that most of the scientists who did so wanted to advance the field and to draw in other researchers to the questions at hand. These are intrinsic or altruistic motivations, supporting the network effects discussed in the model.
- "Skunkworks" are engineering projects inside large organizations where engineers work around and across an employer's hierarchy, rather than obeying it. Their goal may be for the organization to succeed despite its managers. The tinkerers model frames them as visionaries, as they think of themselves, rather than as shirkers in a principal-agent relationship.
- Users of a product may modify it. Users applying the product in a new way or trying to satisfy new market trends are especially likely to modify manufactured products. In many cases, user innovations have been freely revealed. Von Hippel (2005) offers many examples. The tinkerers model emulates interactions between user innovators.

- The Internet and the Web expand 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. Altruistic motivations are especially able to find practical expression on the Web, where a developer who makes a new service or resource available not only can use it him or herself, but changes the state of the world for others who may then use it or refer to it.

10 Conclusions

Where did the first airplanes come from? They did not emerge from a series of profit-maximizing investments. Rather, they were developed from the work of hundreds of experimenters who invested time and money in a long term effort which they did not expect to be profitable. A very few became rich and famous, but more of them died in crashes. Collectively they advanced the technology until there were controlled, powered glider flights. By 1910, an industry of startup firms sold aircraft and related services. The tinkerers model provides microfoundations for the decades-long activity of inventing an airplane and the strange transition in which a an industry of competing manufacturing firms arose and the collegial network of experimenters gradually dissolved.

If the path to making the new invention had been clear in 1899, a profit-maximizing firm could have done it and patented it. But under extreme technological uncertainty, the organizational routines of firms do not deliver breakthrough inventions of unknown value. Instead, individual experimenters around the world dreamed of flying machines, tried to build them, and accumulated knowledge together. The tinkerers model takes as given that some innovators have an intrinsic interest in their particular field and the ability to make progress, since we observe that such innovators exist. In the model, tinkering is then a rational investment.

Tinkerers agree to share experimental information because this will improve their own technology. This explains basic open source behavior and some aspects of the work process. Tinkerers specialize on aspects of the technology, standardize the parts they use, and choose modular and usable designs so they can work more effectively together and bring in more participants. There are roles and tasks other than working directly on the technology. A tinkerer may recruit new members, evangelize the technology, publish a journal, or organize meetings.

Tinkerers form such links and institutions to share information because they want the technology to improve. These arrangements are not driven by prices or market processes but by network effects. Tinkerers align their efforts to benefit efficiently from the work of the others. Thus, the model decouples technological progress from competition and profit-seeking, which enables it to apply to cases where a research and development model does not apply. The tinkerer is a character unlike the standing economic models of consumers, producers, managers, and investors; these other models do not emulate important behavior we see in scientific and technological communities.

The inventive process will move more quickly if the societal and technological environment supports such networking. Noisy or restricted communications channels can reduce the flow of innovations both by reducing the effectiveness of communication and by driving tinkerer-types away. For example, intellectual property institutions may restrict participation or the flow of useful information in which case tinkerers tend to avoid them. With a global Internet, tinkerers can find one another rapidly and collaborate in new ways so we see an expansion of such activity.

A tinkerer may leave the network to focus on promising product-oriented research and development in a profit-oriented firm. The historical examples show that this behavior is at the heart of modern capitalist growth. Open source innovation is how radically new industries are born.

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