

THE CATAPULT OF RICHES

The Airplane as a Creative Macroinvention

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Technical progress usually comes from small changes to existing technologies. New computers for example are better than old computers insofar as their components are smaller and faster, they can run new software, and they connect to new devices. These improvements are driven by product-focused profit-oriented research and development, which is partly predictable. People remember the earlier generations of devices, and by asking people who know the subject one can often trace back many years of the process of imitation and improvement that brought the latest generation of devices into being. This is normal technological change, analogous to Kuhn's characterization of normal science. The technical innovations and improvements are *microinventions*, in the language of Mokyr (1990).

If one traces back far enough, one often finds a version of a technology for which the preceding generation, or variant, is not clearly identified. There was a first known vaccine, for smallpox, and no clear precedent for it. There was a first balloon that lifted into the air. These gaps, or larger steps, are called *macroinventions*. As defined by Mokyr (1990), these are novel epistemic steps that are complementary to a wave of microinventions that follow. By the broader definition in Meisenzahl and Mokyr (2011), they are economically influential.

The invention of the airplane was such a macroinvention by several of the overlapping definitions. The aircraft the Wright brothers developed in 1903–5 had radical novelty insofar as (1) they functioned, technically, in an unprecedented way to lift persons into the air and could be controlled and directed in a different and better way than balloons, gliders, or projectiles could; (2) a wave of technical improvements and applications followed quickly; and (3) a new industry with hundreds of start-up firms existed by 1911.

This case exemplifies the recurrent phenomenon of *open-source innovation* in which technological progress depends on the use of information that is not secret and not proprietary in practice (Meyer 2013). In the airplane's case, open-source information sharing generated waves of preparatory microinventions that *preceded* the key successful macroinvention.

Vast documentation and historical research are available on the developers of early airplane technology and their precursors. A *Bibliography of Aeronautics*

(Brockett 1910) lists more than thirteen thousand publications related to aircraft up to 1909, principally from France, Britain, Germany, and the United States. In these same countries, hundreds of patents were filed for aircraft in the nineteenth century, and hundreds of airplane-manufacturing establishments started before the First World War. From various sources we have data on such publications, patents, clubs, and firms. These databases are works in progress, from which some conclusions are now possible.

Early twentieth-century inventors of working airplanes knew a lot about the prior efforts. The Wright brothers, for example, read key works by Otto Lilienthal, Samuel Langley, and Octave Chanute. Chanute's 1894 survey book on the developing field of aerial navigation, *Progress in Flying Machines*, defined the field for many. We can trace the networks of innovators who produced this information and transmitted it. Detailed documentation is available on the publications, patents, exhibitions, conferences, clubs, and letters related to aeronautics and early aviation, and I am collecting and organizing databases of this information.

The data are useful to consider a research issue framed in Mokyr (1990): where do macroinventions come from? Some macroinventions were made quickly, by focused research and development in hierarchical organizations—for example, the atom bomb, and the rocket to the Moon. These have focused narratives. The airplane case is at a different extreme. Hundreds of literate people communicated about aeronautics for decades in writing. Thousands of publications, patents, and letters remain from that time, and dozens of books tell detailed narratives of how progress was made across the industrial countries, and they largely agree on matters of fact. So for the airplane case, there is a broad spectrum of fine-grained data and statistics on decentralized networks of technologists who made a macroinvention.

In the case of the airplane, substantial experimental and scientific effort occurred, and can be identified before the macroinvention worked. The participants are motivated by their own frank interest in the subject, and appear generally not to have expected to profit from it. They shared experimental information and designs frequently. I have called this pattern “open-source innovation” (Meyer 2013). If we make the assumption that they are interested in the problem intrinsically, not in external payoffs, and are not in competition, a model can be fashioned in which self-motivated agents—“tinkerers”—generate flows of innovation and perhaps ultimately a macroinvention. In economics language, they generate a *supply* of inventions, which may or may not match a market demand. This addresses the question partially: when tinkerers can or do form networks of shared information to address a possible invention, the invention is more likely to occur, and their intellectual descendants are more likely to eventually form such an industry.

I have argued elsewhere (Meyer 2013) that this sharing of information by aircraft experimenters has parallels to open-source software development. These attributes characterize open-source innovation:

- Contributors were autonomous, often with distinct visions, projects, and specializations
- Contributors were drawn to the activity because of the appeal and potential of the technology, not because of connections or similarities to the other participants
- Contributors routinely shared inventions and discoveries without explicit exchanges or payoffs
- Some contributors found intellectual property institutions detrimental to inventive progress
- Organizers, writers, and evangelists had roles beyond technical experimentation

Similar dynamics have occurred in other cases. Creative experimenters and hobbyists have advanced other technologies, in the computers, software, and online fields, for example, to the point that entrepreneurs could start businesses on the basis of open new technology. The open-source innovation dynamic sometimes outperforms the research and development mode in which the researchers are hierarchically authorized, funded, equipped, and motivated by explicit rewards. Open-source innovation seems to outperform best in fields where technological uncertainty is greatest.

This chapter offers a general economic model of open-source innovation, in which the ambitions of the experimenters—“tinkerers”—are the force driving technological change. Their technological creativity is not realistically sufficient if they were to work alone, but the network links the participants together into webs of knowledge and communities of practice. The catapult of this chapter’s title refers both to flight itself—and in fact some early aircraft were launched that way—and to these flexible webs of people and knowledge from which the new craft metaphorically sprang. Analogous communities of practice have supported other inventions to help them launch. The model here relates the enlightened minds described in Mokyr (2009) to the technological creativity described in Mokyr (1990) and thus leads to the knowledge economies of Mokyr (2002).

It is useful to begin by first illustrating the technological creativity of these individuals. They are the atoms of creativity in the model; a society has institutions that more or less efficiently tolerate and benefit from such individuals.

THEMES OF AERIAL NAVIGATION EXPERIMENTS

Modern airplanes trace back to British scientific experimenter George Cayley’s designs of fixed-winged aircraft around 1800. Cayley’s attention was drawn to flying by the recent invention of balloons and the first helicopter designs (Gibbs-Smith 1962). This fixed-wing idea was an important and necessary departure from the more natural and recognizable mechanisms of birds, balloons,

and rockets. Its success was slow, however, and thousands of experiments came between the idea and its practical application.

Significant innovators in the succeeding century came from a variety of backgrounds and locations. They include Alphonse Penaud and Louis Mouillard of France, Lawrence Hargrave of Australia, Americans Samuel Langley and Octave Chanute, and Otto Lilienthal of Germany. Below we lay out some of the technological dimensions they and others explored over the course of the century after Cayley's first publication. The larger point is to illustrate the great diversity of experimentation that came about without organized and directed research and development; and that much of this diversity was necessary to the eventual success.¹

FLAPPING WINGS The experimenters came to the topic of aircraft with a dream of flying like a bird. Cayley returned to the idea of propulsion by flapping wings again and again in his five decades of experimentation, and even after 1890 Hargrave and others did too. But aircraft with mechanical or human-powered flapping wings ("ornithopters"), though intuitively appealing, were flimsy, underpowered, and difficult to construct. Humans can power flapping wings, and did so in some of Cayley's experiments, but humans cannot provide enough power to keep themselves aloft in this way. Propellers would turn out to be more efficient and practical.

BALLOONS AND DIRIGIBLES Hot-air and hydrogen balloons had carried people since the 1780s. They improved throughout the nineteenth century. Powered steerable balloons (dirigibles), often with elongated shapes and skeleton frames, were developed. Still, balloons could not be made to move in quick controlled ways. Alberto Santos-Dumont was one of the few who made both piloted dirigibles and then airplanes. There were a variety of attempts to make compound craft with both a gas bag and wings.

RIGID FIXED WINGS Fixed wings with an upturned front edge can provide lift while speed is provided some other way. This was Cayley's central insight and a subject of many of his experiments. Cayley worked out, with partially correct logic, that an airplane can fly more stably if its wingtips are higher than the place where the wings attach to the fuselage.² Among the widely known later experiments of the nineteenth century was Louis Mouillard's effort to make wings of wood designed like birds' wings that he wore, then leaped from hills. Jean-Marie Le Bris created a large bird shape in wood and sat inside as it rested on a cart, pulled by a galloping horse, until the wooden bird lifted off. Mouil-

1 Most of the characterizations of these experimenters referred to in the list are in the Gibbs-Smith's (1966) masterful and concise *Invention of the Aeroplane*.

2 In modern language, the wings have a positive dihedral angle.

lard and Le Bris were not too seriously injured and were widely cited within the world of aerial navigation. At the end of the nineteenth century, Hiram Maxim demonstrated that with enough power, even entirely flat wings would be enough to launch an experimental flying machine. The overall theme is that the designs that turned out to work drew from soaring birds and kites, leading to gliders and then to powered gliders.

TAIL Cayley already had horizontal and vertical control surfaces—rudders—in his early designs. Alphonse Penaud extended this with experiments on small models powered by rubber bands. He showed that for the nose of the aircraft to stay lifted high enough the tail should have a lower angle with respect to the oncoming airflow than the wings do. This “Penaud tail” design feature was necessary for longitudinal stability and equilibrium in flight and was widely studied and imitated.

STACKED WINGS Since large wooden wings were structurally weak, Cayley put one wing on top of the other to achieve more lift on a smaller craft.³ This idea was explored with many variations. Hargrave in particular studied box kites and showed that they were able to remain stable in the air, and that the rigid box gave strength to the structure without much weight. Imitations of this led to the biplane configuration of many early airplanes.

CAMBERED WINGS Cayley worked out that a wing should not be flat but rather rise from the front edge then curve down to be lowest at the posterior edge. A wing with this shape is said to be “cambered.” The optimal shape differs depending on the speed and angle of the oncoming air flow. There were many experiments to determine why and how. A curved shape of this kind generates a partial vacuum above the wing and therefore lift, and also pushes air down at the posterior of the wing to generate further lift. These principles did not become entirely clear during the nineteenth century and good mathematical models of the magnitude were not available until after the first airplanes were working.

WING ASPECT RATIO Cayley and some successors made wings approximately square, which is a poor shape to achieve lift. More optimally for lift, the wingspan should be much longer than the width of the wing. Many shapes were explored, and the result was convincingly known only after wind tunnels were used in the 1870s. Progress required both propositional and prescriptive information, and both scientific and technological information (Mokyr 2009, 41–42).

³ Gibbs-Smith (1962, 113–14) discusses this invention, described by Cayley in an 1843 publication.

ENGINES Experimenters tried to fly models and gliders with steam engine power, despite the weight and the danger. John Stringfellow made tiny, precise award-winning engines for airplane models. Cayley sought another way, and made what may have been the earliest working hot-air engine, and gunpowder engines too. Samuel Langley, believing that a powerful engine was necessary to power a strong stable craft, invested tens of thousands of dollars in an advanced internal combustion engine.

PROPELLERS Most propellers for aircraft were designed like “water screws” used on ships, which were designed to push water backward. A critical insight waited until the Wrights found it in 1902—that an aircraft’s propeller should be cambered, like a wing, so that it generates “lift” in the forward direction.

PILOTING AND CONTROL With enough power, anything would fly. How could a pilot control the craft? Otto Lilienthal was the first to make gliders that he could fly for many minutes at a time, to learn the skill of being in the air and controlling the craft to some extent. After him, Octave Chanute and the Wrights followed this practice.

There are economic principles underlying such basic research. Here “production” includes experiments, voyages, publication, patents, letters—both doing and talking—about scientific and technological information that the participants think is related to the subject of aerial navigation. One of the crucial inputs is the experimenter’s own enthusiasm to understand the ideas, locate the resources, and perform experiments.⁴

THE OBJECTIVES OF EXPERIMENTERS

The experimenters did not often state their objectives clearly, but one can make inferences based on what they wrote. Most found bird flight absorbing and imagined flying themselves. The experimenters had a thorough prior belief in natural laws and that it was possible to make devices that depended on these laws. They allowed themselves to explore what it would mean to fly like a bird, to begin with, and to contrast soaring wings to flapping ones. The problem of how to make this work, if it ever could, was absorbing. These are said to be *intrinsic* objectives. Another recurring theme was the thought that the world would be a better place with flying machines—travel would be easier and contract between people would bring about peace. These are *social* or *altruistic* objectives.

Experimenters may think they can get external, or *extrinsic*, prizes. Several hoped to play a role in a great invention, either for pride or for fame or—I think principally—for the respect of others. More pecuniary career rewards

4 The phenomenon is associated with other new technologies too, illustrated in Meyer (2003).

were not obvious—it was widely thought that the search to make a flying machine was a hopeless effort, or that it might work but be useless, and in any case was certainly dangerous. One might suppose that they wished to manufacture a new kind of device and sell it, but I see few plausible references to this idea in the period under consideration. Given all the effort and little observed success, aircraft production was not a likely avenue of success; the technological uncertainty was extreme, more so than in other cases of invention that I have studied.

Ballooning, a parallel business, was mainly an expensive leisure activity with few practical applications. I am convinced that few of the important experimenters ever expected to deliver an aircraft product line. One cannot prove that, but few of them ever did even once it was technically possible. Otto Lilienthal, having invented a new kind of hang glider in his experimentation, attempted to sell them as sports equipment but may have sold only ten.⁵ The Wright brothers appear, from their quotes and actions, not to have expected to become financially successful in their first years of experimentation:

- “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, 1899 letter)
- “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, 87)

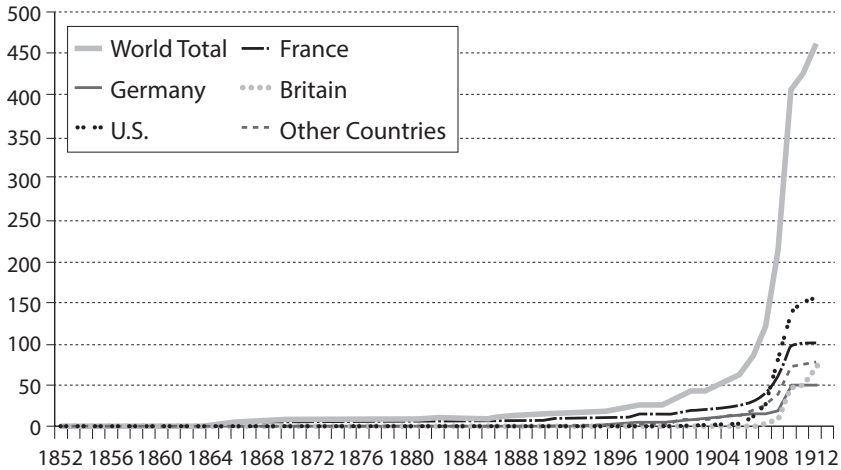
If their motivations were intrinsic, their actions seem rational. Thus it is plausible to describe the experimenters as having intrinsic or altruistic motivation. These particular ones had also various resources that were useful to make progress in a technologically uncertain situation.⁶ In the model to follow, we shall assume that intrinsically motivated experimenters exist.

CLUBS AND NETWORKING

Existing clubs on ballooning incorporated discussions on *aerial navigation*, which often meant a focus on fixed-wing, heavier-than-air designs for *flying machines*. New clubs with this navigation orientation also appeared. At least a

⁵ Bernd Lukasch, director of the Otto-Lilienthal Museum in Anklam, Germany, told me this in a 2011 conversation. The buyers were generally aerial navigation experimenters who did not focus on it as a sport.

⁶ Economists do not regularly refer to a standard model of such characters, with a shorthand for their utility functions, environments, and constraints. Partial models are in Harhoff, Henkel, and von Hippel (2003), Polanski (2007), von Hippel (2006), Gambardella and Hall (2006), and Meyer (2007).



8.1 Aeronautics-related clubs and societies.

Source: Author's list, based on many sources.

Note: These are counts of the clubs that have ever been founded. The figure does not account for any exits, which are rare. Many clubs are first seen in a 1910 directory, which partly accounts for the spike then.

dozen such societies were founded in the nineteenth century, sometimes with hundreds of members. Important ones included the Aeronautical Society of Great Britain and the Aéro Club de France. Several of these societies produced regular journals. Membership fluctuated, but overall interest grew over time as is evidenced by a growing number of clubs with some attachment to aerial navigation. The clubs and their members developed connections over time. Figure 8.1, showing club data gathered by over the course of years, describes the population of the relevant clubs and societies.⁷ The vertical bar in 1903–4 marks the Wright's first successful controlled powered flight. By that time there were more than forty clubs with an attachment to aerial navigation and flying machines.

The number continued to grow after the airplane's definite arrival. By 1914 tens of thousands of people had joined some kind of aeronautical society, and millions had seen an airplane fly (Meyer 2013). Most of the new clubs were locally oriented, and referred in their names to a city or region as well as a technology.

A particular organizer named Octave Chanute was a central figure. Having retired in Chicago after becoming wealthy as a railroad engineer and manager, he focused for years entirely on flying machines. He organized a conference at the Chicago World's Fair in 1893 on aerial navigation, and was in contact by letter with every experimenter he could find. He summarized the state of the art

⁷ The data are discussed further in Meyer (2014).

in an 1894 book with the optimistic title *Progress in Flying Machines*. By surveying the flying machine activity broadly, Chanute served as a social connector or moderator who identified key persons and technologies and incorporated them into his thinking. 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, iv),⁸ which he believed would make success possible. The individuals cited most often in *Progress in Flying Machines* are mentioned above in the section on the major technological themes. Almost all had substantial numbers of publications and most had patents (Meyer 2013).

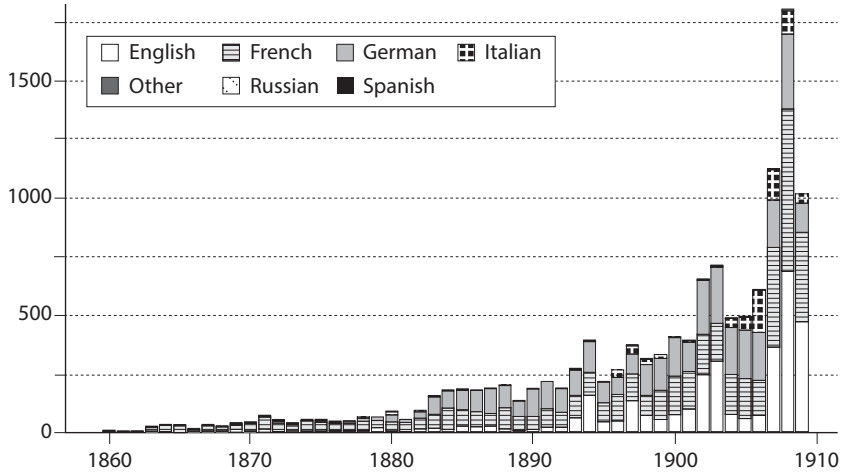
PUBLICATION AND PATENT DATA

The Smithsonian Institution in Washington, D.C., had been an early participant and publisher of works on aeronautics, and when experimenter Samuel Langley became the Smithsonian's director, he brought his collection of publications there. The Smithsonian developed a large library on aeronautics and an associated bibliography, systematically including references to works that were not in its own collection. Smithsonian librarian Paul Brockett published a series of books of aeronautical bibliography. The first lists more than thirteen thousand publications related to aeronautics before 1910, including many that were not at the Smithsonian. It has been scanned and put online at archive.org by Cornell University and the University of Michigan. After cleaning up the electronically scanned text, we have for most of these publications a title, authors, year of publication, journal of publication, language of the text, and country of publication. Excluding entries for which these data are not complete, we have a database that can track the evolution of this technical literature.

The rough data at this early stage, seen in Figure 8.2, show a substantial and sharply growing literature in the 1880s and 1890s before the airplane was a proven technology. French and English were the most common languages in this literature, followed by German. The literature in German grew more quickly over time than the other languages. I do not have a specific explanation for these comparative rates, though it could be associated with an expanding technical education system in Germany. With further extensions and refinements to the data it will be possible to study this question quantitatively.

The bibliography includes few patents per se. From a variety of sources, colleagues and I have collected thousands of early aeronautical and ballooning patents. These data cover on the order of half the relevant patents for the period up to 1910, and are not consistently coded for technology topic yet. Sources identifying a patent as relevant to ballooning or aeronautics are numerous and

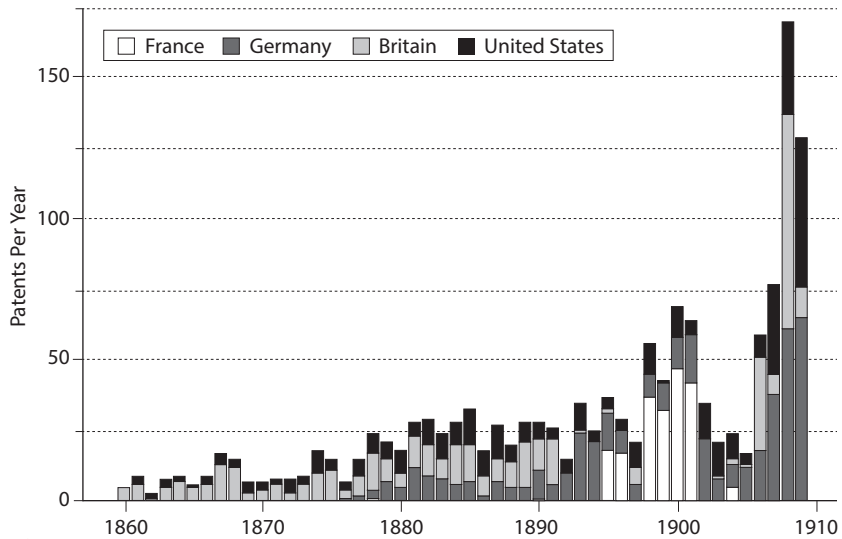
⁸ I have argued that analogous open-minded moderators played a similar role in the 1970s microcomputer revolution and in open-source software networks (Meyer 2003, 2013).



8.2 Sample of aeronautics-related publications by year.

Source: Brockett's *Bibliography of Aeronautics* (1910).

Note: For 1909 only half a year is included in the original data.



8.3 Sample of aeronautically-relevant patents by country.

Source: Brockett's *Bibliography of Aeronautics* (1910).

eclectic, and include some ex post facto classifications by the patent agencies. For examining the patents themselves, we have used Google Patents and espacenet.com. For source information and the latest data, please contact the author. The data are large, though not complete. Figure 8.3 displays the sample of aviation-related patents by country between 1860 and 1909.

The point here is that the patent counts are rising just as publications did. In principle, patents are intellectual property claims, but aeronautical patents seemed to have had no traction in this way until 1906; I do not know of any fixed-wing aircraft patent until then that was licensed or otherwise earned any revenue. This environment changed after the Wrights' main patent was granted in 1906. The U.S. courts interpreted their patent broadly, and the Wrights enforced it vigorously.

Yearly patent counts related to aeronautics rise immediately in 1907 and afterward, because the basic technological uncertainty had been resolved; specialists then knew that airplanes could work and believed there would be a market for new related inventions.

THE WRIGHT BROTHERS AND THE MACROINVENTION

Wilbur and Orville Wright were technically proficient mechanics who ran a bicycle shop and in 1899 took a specific interest in fixed-wing aircraft.⁹ Wilbur wrote to the Smithsonian Institution for information and received a list of relevant publications. The Wrights followed these leads, and began a long correspondence with Chanute. Nearly complete records of these letters exist (McFarland 1953).

The Wrights began their research with a kite designed like Chanute's glider of 1896,¹⁰ which they studied at length. Over the next years they made larger, heavier, stronger kites and gliders with similar basic designs made of canvas stretched over wood frames. During this time they participated in the open-source, collectively inventive process as other experimenters had done. They discussed technical issues and previous work with Chanute frequently. At Chanute's invitation, Wilbur gave a public speech to the Western Society of Engineers, and the Wrights published two journal papers in 1901, one of which has been characterized as an important contribution to the understanding of aeronautics (Anderson 2004, 110–11). They hosted visitors to their experimental flights, helped to test other people's wings and aircraft, and took advice from others (Crouch 2002, 249–53).

The Wrights had a control system that was better than anyone else's, and it enabled them to get more experience in the air than others had done. It came about from a creative insight. The story is told that Orville held a cardboard box for an inner tube in his hands, and twisted the box. It occurred to him, then, that a glider wing could be twisted the same way. A wing need not be soft like a balloon, or hard like a wooden board; it might twist. This was a useful, creative

⁹ This section draws from Jakab (1990), Crouch (2002), and Meyer (2013).

¹⁰ Wilbur's first letter to Chanute in 1900 said so: "The apparatus I intend to employ . . . is very similar to the 'double-deck' machine with which the experiments of yourself and Mr. Herring were conducted in 1896–7."

1 insight: the wing of a glider, a “hard” thing, might twist at its tip to impart a
2 small change in direction to the craft. This could be implemented with bicycle
3 wires attached from the wingtips to give some control to the pilot. The pilot
4 would then have direct and specific control of the craft and make rapid adjust-
5 ments analogous to those a bicyclist would make. Described this way the in-
6 sight is a three-dimensional technical vision, of a kind that can be diagrammed
7 on paper. It arrived as a tacit insight, however, insofar that the Wrights had ex-
8 perience in the air and had therefore ways to think about and process the issue
9 that were different from the insights of those working on paper alone (Jakab
10 1990, 51–57). They later extended this idea (when its first implementation was
11 unstable) and wired the wingtips to the rudder and elevator at the tail of the
12 plane in a way that made the aircraft more stable as it turned. This package of
13 design elements made up their major patent claim.

14 In 1902 the Wrights made a wind tunnel that was unusually precise for its
15 time, and this enabled them to make efficiently shaped wings, and then, having
16 been absorbed for months in the study of wings, they had the striking insight
17 that a propeller should be shaped like a wing so that it develops a partial vac-
18 uum ahead of itself and pulls the aircraft forward. In 1903 they added an en-
19 gine once they felt the other elements were finished, and December of that year
20 they flew several short controlled flights on the beach at Kitty Hawk, North
21 Carolina.

22 These internal moments of creativity are associated with substantial prepa-
23 ration. The Wrights had used a design platform of kites or gliders whose designs
24 they had chosen and partly inherited. They had extensive experience working
25 with these craft, and with other people on them. The technological creativity
26 of an economy depends on social constructions of the diffuse network kind. A
27 technologically creative society is not only one with technically competent per-
28 sons (as illustrated by Meisenzahl and Mokyr 2011) but also one with networks
29 of people who construct support systems for imagining technical futures. I
30 submit that the kinds of technically creative insights that break through tech-
31 nological uncertainty would be more rare for societies under social repression.

32 Was the Wright airplane a macroinvention? I think it fits the defining el-
33 ements well.¹¹ Like other macroinventions, the airplane did not appear in
34 response to microeconomic incentives; it arose in the context of particular
35 individuals and their genius and luck; and it required vast subsequent improve-
36 ments to work properly and a sympathetic environment to succeed technically
37 and economically. It did not have a large or even positive economic effect at
38 first; application was difficult. Most centrally it was a device that represented
39 a clear break from previous practice or technique, except for the practices of
40 aerial navigation experimenters that led to it.

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11 I draw these from Mokyr (1990, 13–14, 291–98).

INDUSTRIAL COMPETITION BEGINS

Successes came from the open literature; the macroinvention resulted from microinventions and copies of earlier designs.¹² The Wrights became more secretive as they believed they were near to making the first functioning, controllable, fixed-wing airplane (Crouch 2002).

The Wrights filed for a patent on their control system—the wiring of the wingtips to the tail and to a control lever—in 1903. After much back and forth with the U.S. Patent and Trademark Office, they were awarded their patent in 1906. Octave Chanute had encouraged the Wrights to file for a patent but was discouraged that they then enforced it vigorously with lawsuits, and the Wrights became unpopular with many American aviators.

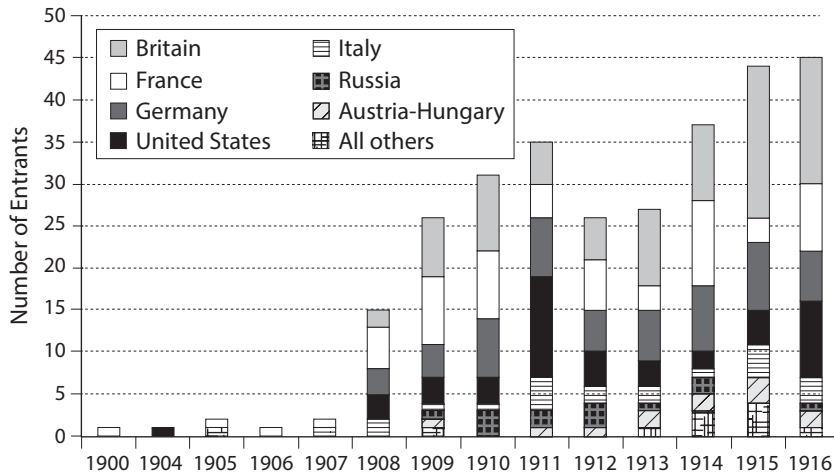
A new airplane industry began. In 1907 there was a sharp increase in the number of patent filings and of other publications. A wave of new firms appeared starting in 1908, in several industrial countries. From 1908 through 1911 there were large public exhibitions of airplane flights, and some of these exhibitions were very profitable. No single source creates a database of these companies; the author and assistants have collected entries from Gunston (1993, 2005), Bell (2002), and other sources. Figure 8.4 summarizes entry into the airplane industry.

The founders, investors, and aircraft designers of these new firms were from a different mold. Almost none of them were creative experimenters before 1900. The list of hundreds of nineteenth-century experimenters, authors, theorists, and patentees overlaps little with the list of founders, designers, and funders of the new companies in 1908 and afterward. Most strikingly, it seems that not one of the major contributors to the information stream in the 1890s was a central figure in the infant industry of 1910.

This sharp turn in the history of technology and industry results from the combination of both (1) great technological uncertainty and open-source/tinkering behavior before the transition and (2) the need for capital-intensive manufacturing and R&D in the new industry. The geographically widespread start to the industry, unmoored from the original inventors, tells us that the key knowledge was widely available, not in fact coming from one invention or one place.

Rapid growth followed. Revenues in the early years came from the military and from exhibition ticket sales as millions of people wanted to see the new aircraft. Only later were there significant revenues from passenger service, mail delivery, freight, or private buyers. Starting in 1910 there were substantial patent battles, and industrial competition of a conventional kind began.

12 This section draws from Meyer (2013).



8.4 Number of entrant firms by year of first investment.

Sources: Gunston (1993, 2005); Smithsonian directory.

MODELING THE DEVELOPMENT OF A MACROINVENTION

To an extent, then, the invention of the first airplanes—a macroinvention—was based largely on open-source information and networks of colleagues. How can we model a period of open hobbyist tinkerers and the transition into a new industry? The phenomenon overlaps with *open science* (David 1998), with *user innovation* (von Hippel 2006), and with *collective invention* (Allen 1983); but the dramatic result of a new capability of control in the air and the resulting appearance of a novel industry is an essential new element not characterized by the models or framings above.

This process matches a model of open-source technology development in which the participants care greatly about the advance of the technology itself or some other ideal, and are not mainly competing. It is helpful to assume also that the technology is not yet understood well enough for it to be clear how to generate profits from it. This assumption (a strong version of “technological uncertainty”¹³) is necessary to explain why existing firms do not directly seize the opportunity with their own research and development. If no market is established and the technical problems are too hard or unclear, existing profit-oriented firms would shy away from them. Under such conditions scientists or hobbyists will rationally share information and engage in specialization,

13 For similar characterizations of technological uncertainty, see Tushman and Anderson (1986), Dosi (1988), and Rosenberg (1996).

standardization of designs and terminology, evangelism, and editing and moderation of joint journals, clubs, and interaction.

Some experimenters, such as Chanute, devoted energy to surveying and documenting the work of the others, apart from his own experiments. We can explain why a tinkerer would do this in terms of his or her opportunities. If tinkering is rewarding because of the progress it generates, then maybe actively recruiting others to join the network brings faster progress, and is the preferred option. Thus we do not need to think of the experimenter and the author or speaker as having different interests; these are differentiated behaviors but are designed to meet the same objective. If we assume that information travels quickly among the interested participants, we can ignore the exact shape or linkages within the network.

Some experimenters, such as Hargrave, decided not to patent anything, that is, not to impose any claim of intellectual property. If there is no market of consumers, only other tinkerers, then restrictions on the flow of information between them is socially inefficient. A particular productive tinkerer may benefit, but the mechanism gets in the way of progress. Hargrave's choice was intended to help get quickly to the technological goal.

An experimenter who never joins into such a network or withdraws too soon may pour resources into a direction that other experimenters have demonstrated is a dead end. By being in the network, one has the exploration tree pruned by other experimenters. Chanute explicitly stated that such time saving was a motive for publishing his book.

We can think of all these tinkerers as working on a technology the future of which is shrouded behind a veil of technological uncertainty. The tinkerer may have an insight about what is behind the veil, and envision an implementable form of the technology, then choose to leave the network, stop giving and receiving information, and start directed research and development to make a product. Thus an industry can start, and this tinkerer leaves the network of open-technology sharing. The network can continue if others keep it going. A private company might share private knowledge without payment, for several reasons discussed in the collective invention literature.¹⁴ However, that

14 Collective invention is defined and discussed in Allen (1983), Nuvolari (2001, 2004), and Meyer (2003). Know-how trading (von Hippel 1987) is similar. Among the reasons a company would do this are the following: (1) better public technology may raise the value of assets owned by the innovator, as in Allen (1983); (2) the innovating firm garners favorable publicity by making its successes known; (3) an organization conserves on the costs or effort to keep its privately developed information secret (which would be hard if, say, many employees move between employers); (4) publications in an open environment give employers a useful way to judge the contributions, skills, or certifications of a specialized employee; (5) to establish desirable engineering standards even if it requires upgrading a competitor's technology (network effects of features can justify this, per Meyer, 2003); (6) the firms follow different paths of research and they expect future innovations to depend on advances made outside their own firm, as in Nuvolari (2001, 2004) and Bessen and Maskin (2009).

literature does not describe the behavior of networks of individuals operating outside organizations.

MODEL OF CREATIVE TINKERERS WHO PRODUCE A MACROINVENTION

With simple and extreme assumptions we can model self-motivated tinkerers of the kind who could conceivably invent an airplane or another macroinvention. Their progress toward internal or altruistic goals can be represented in their utility functions. This specification is drawn from Meyer (2007), which spells out the algebra more completely.

Define a *tinkerer* to be a person with a unique project, activity, or technology A . The notation A stands for an aircraft or anything related to it—a glider, a model airplane, an experiment on wings, or even a membership in a balloon club. The tinkerer enjoys A and may imagine that future honors and profits could derive from it. At present, there are no honors or profits, and future honors or profits are unlikely and uncertain. Assume A does not depreciate, and it has little market value, far less than what it is worth to the tinkerer.

The tinkerer receives a flow of positive utility from the existence or discussion of A . Let the tinkerer be risk-neutral, and value alternative choices according to the net present value of expected utility at time $t = 0$ in this equation,

$$U = \sum_{t=0}^{\infty} \beta^t a_t \quad (1)$$

where a_t is a positive scalar utility expected from A in each discrete time period t , and β is a discount factor between zero and one applied to utility anticipated in future periods. Each future a_t equals a fixed known a_0 unless A changes or circumstances change.

The tinkerer can choose to “tinker with” or “experiment on” A in some way that will raise his or her future benefits a_t . Tinkering in an investment, costing one unit of utility in the present period for the effort, expenses, and the opportunity cost of time spent. The agent believes that tinkering will raise his or her future utility by p units each time period in the future. The notation p stands for a rate of progress, which is subjectively experienced by the agent. For simplicity assume p is fixed and positive and that the tinkerer’s forecast is correct. We normalize the tinkerer’s outside option to have period utility of zero.

A tinkerer chooses to tinker if the expected utility benefits exceed the costs, which can be calculated based on the assumptions above. The gross utility benefits from one effort to tinker have a value of p in each subsequent period. The gross payoffs to tinkering in the present period can be compressed into a single fraction, by a standard series summation formula:

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

The investment required to receive this payoff was one utility unit at time zero.

So, the net payoff to tinkering in period zero is $\frac{p\beta}{1-\beta} - 1$. The benefits exceed this cost if $p > \frac{1-\beta}{\beta}$. An example makes this clearer: for a tinkerer who per-

ceives $\beta = .95$ and $p = .07$, tinkering is worth the effort. These parameter values are useful for illustration but are not drawn from any specific example.

The optimal choice about whether to tinker is not a function of the level of a_t at the time of the choice, unless it is so negative that the tinkerer should optimally abandon the project, which is not the case of interest. So if $p > \frac{1-\beta}{\beta}$, the agent will tinker in every period, and each $a_{t+1} = a_t + p$. Call an agent who meets these conditions a *classic tinkerer* on project A. For a classic tinkerer, the period utility value in each future time period will be $a_t = a_0 + pt$ and the investment's utility cost each period will be 1. The net expected utility (EU) payoff stream can be expressed in parameters which were known at time zero, as follows:

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

The last summation term can be put into closed form by simplifying its time series sums:

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

Substituting that back into the expected utility equation, the present value of utility at time 0 is:

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

Thus, simple assumptions about p (the payoff of progress to this tinkerer) and β (his or her discount factor)—parameters that could characterize his

fanatical obsession with a technical vision that others do not recognize—quickly lead to conclusions about his payoffs and behavior in common language. The first term of equation 2 is the present value of the expected utility from possessing A in its original state. The second term has the present value of the costs of endless tinkering. The third term has the present value of the benefits of endless tinkering.

Again using parameters $p=.95$ and $\beta=.07$, the second and third terms add up to 6.6. So, for these parameters, endless tinkering raises the tinkerer's present value utility by 6.6 times the cost of a one-time investment. *This self-motivated tinkerer is a perpetual innovation machine, of the kind who could make a macroinvention.*

TINKERERS WOULD BE WILLING TO SHARE

Suppose there are two tinkerers with identical utility functions working on similar projects A_1 and A_2 , and that their experimental findings and innovations could be useful to one another. Let each one believe that the other has no way to profit from the project using the existing technology or any likely foreseeable technology. Let the subjective rate of progress of the first player be p_1 , and the subjective rate of progress of player 2 be p_2 . Let fraction f , between zero and one, of player 2's innovations be useful to player 1's project, and the same fraction of player 1's innovations are useful to player 2. Because there are costs to interacting with others, let f be an inflow net of any costs. (So for some pairs of tinkerers, f could be negative, but in the cases of interest, f is positive.)

Suppose the two tinkerers have the option of making a costless, verifiable, enforceable agreement to share a well-defined set of the functional design changes in A_1 and A_2 and their experimentally discovered effects. This agreement forms a *network* for future information. At any time, either partner can depart from the network, and then does not learn about the subsequent innovations of the other and ceases to share his or her own.

The agreement does not require sharing everything the experimenters know or learn. They do not meld minds, memories, or objectives. For example, a tinkerer may discover or learn descriptive, propositional, or scientific knowledge which is not embodied in A , and an open-source agreement does not require sharing that.

If player 1 thinks player 2 will tinker and produce *any* positive flow of innovations, he or she is made better off by joining the sharing institution. It pays off when he or she receives any useful information from player 2. Player 2's subjectively determined rate of progress must have met the criterion $p_2 > \frac{1-\beta}{\beta}$ since he or she is a tinkerer, but the rate of innovations useful to player 1 might be small.

If player 1 expects both players to join, tinker, and share forever, his or her expected utility is

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

The new fourth term has the benefits player 1 receives from the flow of information coming from player 2. This addition to the expression in equation 2 tells us that the tinkerer prefers to join the network than to work alone. Thus *the classic tinkerer assumptions generate an individually rational model of groups conducting open-source technology development*. This is the central claim of this model.

TINKERERS WOULD BE WILLING TO STANDARDIZE AND SPECIALIZE

The fraction f of the usefulness of the findings and inventions made by player 2 are usable to player 1, but perhaps the players can coordinate to improve this communication flow. This models the choice to adopt an design or engineering standard from an external source.

Suppose for a cost c_s player 1 can adjust some arbitrary elements of his project A_1 to look more like A_2 , and that this would raise the fraction of player 2's innovations which applied directly to his own project to f_2 , where $f_2 > f$. If tinkerer one pays this cost, his or her expected utility is

$$EU_{t=0} = \frac{a_0}{1-\beta} - \frac{1}{1-\beta} + \frac{p_1\beta}{(1-\beta)^2} - c_s + \frac{f_2p_2\beta}{(1-\beta)^2} \quad (4)$$

Comparing this to equation 3, a player would find it optimal to pay the standardization cost if: $\frac{\beta p_2(f_2 - f)}{(1-\beta)^2} > c_s$.

So in the model, a tinkerer benefits more from adopting a standard if, holding other things constant: (1) the other tinkerers are producing a large flow of innovations p_2 ; (2) the cost of standardizing c_s is small; and (3) the gain in the fraction of useful innovations from the others that become useful ($f_2 - f$) is large. These are intuitively sensible, and the model formalizes them.

The same formal argument can explain why experimenters develop and try to standardize on their technical language for describing their new technologies. This can reduce communication costs and also clarify thinking. For example, Wilbur Wright published a journal article (Wright [1901] 2000) asking other experimenters to cease using "angle of incidence" to mean the angle between a wing (or other airfoil) and the ground. The better definition, he argued, was the angle between the airfoil and the flow of air coming at it; the angle

with respect to the ground was not relevant. This request was an effort both to improve the thinking processes of other experimenters and to lower frictional losses in communication. In a more important example, Lawrence Hargrave's experiments showed that a box-shaped kite was more stable than a single flat kite was in a gust of wind. This specialist contribution helped glider flyers standardize on a biplane (two-wing) design for gliders.

The standardization trade-off expressed in equation 4 explains partly why tinkerers would agree to publish their findings. The fewer unnecessary differences between experiments there are, the lower the future communication and adoption costs will be. A tinkerer may also take steps to make the device easier to learn or easier to use, which is a parallel pathway to delivering faster progress or the inflow of information.

These trade-offs are important in the software context where a project can "fork"—split over time into incompatible versions—if the contributors do not agree to standardize. In the history of UNIX there was a painful fork, and programmers can refer to this history to convince others to pay some price in effort to reunify a project on which people work independently. In this model, they are willing to pay some price to maintain the economies of scale of the project.

Standardization and specialization are intrinsic to technological and scientific development; they are a natural result of exchanging information, and *in this setting they can be explained without reference to competition or market exchanges*. It is useful and necessary here to escape Adam Smith's proposition that specialization is bounded by the extent of the market, because scientists and inventors do it without market-priced exchanges.

The network is itself a technology—a social or search technology for tinkerers to get possible valuable information that they do not obtain by their own experiments. Other aspects of the environment affect f also. If for example the tinkerers can upgrade from sending letters (which arrive slowly and some of which did not arrive at all) to email communication, f would rise, whereas if the email system became clogged with unhelpful spam, f would fall. Meyer (2007) discusses further examples of those like Chanute who manage the network itself, recruit new members, introduce them to one another, and moderate publications, all of which can be modeled as efforts to raise progress and information flows represented here by p and f .

ENTREPRENEURIAL EXITS

When they believed they were about to invent the airplane, the Wrights withdrew somewhat from their interpersonal network. They shared less. The model can incorporate the possibility that a tinkerer (or an entrepreneur who per-

suades the tinkerer) decides dynamically, as the Wrights did, to take activity *A* private. Even anticipating that possibility, the parameters may be such that a tinkerer might participate in a network while recognizing that he may later have an insight into how to implement something from activity *A* that could be provided to customers profitably, and then want to exit. Meyer (2007) shows this, and a relevant implication here is that tinkerers may optimally work together, even anticipating that one of them may want to break away when he or she suddenly sees an outside option to (perhaps) get rich. They are driven by subjective goals early in the process, and by market goals, perhaps, in a later phase.

TINKERERS MAY PURPOSEFULLY AVOID INTELLECTUAL PROPERTY

In the real-world episodes discussed some tinkerers preferred to avoid formal intellectual property institutions. Examples include pioneering aircraft experimenter Lawrence Hargrave and programmer Richard Stallman. This behavior can be rationalized in this model. Effort devoted to establishing intellectual property rights in a presently unprofitable technology may not seem worth it to them, compared to the benefits of pushing it forward to become better and perhaps profitable.

Suppose in the model that each tinkerer could charge for the flow of his or her own innovations that were used by others, and that there were small administrative costs to this. Many, probably most, tinkerers would find this to be net unprofitable. Social costs would exceed social benefits, so the establishment of this intellectual property institution would not have been Pareto optimal. This outcome could change if an entrepreneur developed a version of the technology that was profitable, because then there would be an inflow of external revenue.

This logic rationalizes why tinkerer types such as Hargrave and Chanute preferred to keep the information flow open, not secret, and generally unprotected by intellectual property institutions. The Wrights may also have held that view but changed their behavior in late 1902 to become protective because they had started to think they could manufacture airplanes for sale.

CONCLUSIONS

When the airplane appeared as a macroinvention, it already had an extensive and well-documented prehistory. A growing international scientific and technical literature was oriented toward the vision of a flying machine that could navigate through the air. Experimenters on the subject were generally

1 motivated intrinsically, and within both the history and the model we can see
 2 why they shared information and built common institutions given the tech-
 3 nological uncertainty they faced and the enthusiasm they shared. The sudden
 4 appearance of the new industry in many industrial countries at once shows
 5 that the main knowledge needed to make an airplane was widely held, not the
 6 private province of particular researchers.

7 The tinkers' network model is relevant to the airplane case, and to other
 8 cases of invention when certain kinds of evidence are present:

- 9 • Individuals communicate novel technical findings and designs to one an-
 10 other without explicit rewards.
- 11 • Experimenters do not all have extrinsic motivation, for example because
 12 they are working on something that has no obvious price or does not fit into
 13 an existing, standard product market when they enter the field.
- 14 • Some participants specialize in managing or expanding the network.
- 15 • The activity evolves over time, in response to events that participants in-
 16 terpret as *progress*, such as discoveries or inventions. For example, when
 17 Hargrave reported results from his box kite experiments, other aeronautical
 18 experimenters learned and adapted to the findings. They responded to and
 19 interpreted discoveries about natural law; they did not just imitate.

20
 21
 22 In such a situation the model predicts that participants would specialize in
 23 aspects of the technology, and standardize on some tools, as opportunities per-
 24 mit. It suggests that the latent predictions about the future form or importance
 25 of the technology are diverse and uncertain in the sense of Dosi (1988) and
 26 Rosenberg (1996). It predicts that members who do not expect to sell a related
 27 product will avoid imposing intellectual property constraints on the system.
 28 And it predicts this kind of ferment could lead to participants jumping out
 29 into entrepreneurial opportunities, whose value is hard to predict. Thus these
 30 behaviors can lead to a macroinvention.

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