THE AIRPLANE AS AN OPEN-SOURCE INVENTION

Peter B. Meyer

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The Airplane as an Open-Source Invention

Peter B. Meyer*

Airplanes were invented after decades of experimentation in many countries through a process we can call open-source innovation. Experimenters, inventors, and writers contributed to the airplane's development by sharing information in publications, in clubs, by writing letters and by visiting. The hundreds of aeronautical patents before 1900 were treated like publications, not like claims to intellectual property. Inventors of modern airplanes copied earlier designs, analogously to advances in open-source software today. In 1908 airplanes were seen to fly in public exhibitions, and a new industry of airplane manufacturers started quickly in several countries based largely on public non-proprietary information. With the appearance of industrial airplane manufacturing, patents assumed a new importance in the context of commercial competition.

L'AVION COMME INVENTION OPEN-SOURCE

Les avions furent inventés après des décennies d'expérimentation dans plusieurs pays grâce à un processus que l'on peut appeler innovation en open-source. Des expérimentateurs, des inventeurs et des rédacteurs ont contribué au développement de l'aviation en partageant l'information dans des publications, des sociétés, en s'écrivant des lettres et en se rencontrant. Les centaines de brevets dans l'aéronautique avant 1900 peuvent être considérés comme des publications, et non pas comme des revendications de propriété intellectuelle. Les inventeurs d'avions copiaient des modèles précédents, de manière analogue aux progrès de l'open-source de nos jours. En 1908, les avions pouvaient être vus dans les expositions publiques, et l'industrie nouvelle de l'aviation a très vite commencé dans plusieurs pays où l'information était publique et non privatisée. Avec l'émergence de ce secteur manufacturier, les brevets acquirent une importance nouvelle dans un contexte de compétition commerciale.

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* Office of Productivity and Technology, U.S. Bureau of Labor Statistics. *Address:* Bureau of Labour Statistics, Division of Productivity Research and Program Development, 2 Massachusetts Avenue ne, Washington dc 20212-0001 usa. *Email:* meyer.peter@bls.gov

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INTRODUCTION

For thirty years before functioning airplanes appeared, there was serious discussion about how to design them. Over time, basic design ideas became established on how to make a fixed-wing, heavier-than-air powered glider that could carry a person on a controlled flight. Hundreds of experimenters, theorists, and other authors contributed to the relevant literature. New participants found there were journals, books, and clubs available to them, and they were never short of curious visitors. The open literature and the culture of curiosity and sharing contributed to technical progress, as experimenters were able to work from previous designs. This paper explores how the sharing of information among the early experimenters, hobbyists, and scientists led to the invention and subsequently the industry. This case exemplifies the recurrent phenomenon of *open-source innovation,* in which technological progress depends largely on information that is not secret and not proprietary.

Experimenters communicated actively and linked up across borders. By the mid-1890s, the active participants were aware of many other experimenters and their writings refer to work by others more often than before. Influential experimenters of that time were familiar with this literature and they imitated prior designs. Many distinct "firsts" followed, including controlled powered glider flights by the brothers Wilbur and Orville Wright in December 1903 and by Alberto Santo-Dumont in 1906. Major public exhibitions began in 1908 and scores of startup companies quickly appeared.

A staggering amount of original documentation and historical research is available on the developers of early airplane technology and their precursors. A *Bibliography of Aeronautics* (Brockett [1910]) lists more than 13,000 publications related to aircraft before 1909, principally from France, Britain, Germany, and the u.s. 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 beginning databases of this information.

One useful frame of reference is to envision the information that was available to the early twentieth-century inventors of working airplanes. 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, called *Progress in Flying Machines,* defined the field for many. We can trace some of the knowledge that was available to the Wrights and their contemporaries, where it came from, and the networks of innovators who produced it.

This sharing of information by aircraft experimenters has several parallels to open source software development. These attributes characterize open source innovation:

- Contributors were autonomous and geographically dispersed, with diverse objectives and projects;
- 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 openly without explicit exchanges or payoffs;

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- 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 matter most in fields where technological uncertainty is greatest. There is no established general economic model of open-source innovation, but data on the gradual invention of the airplane helps provide microfoundations for such a model.

NINETEENTH-CENTURY DEVELOPMENTS

Modern airplane designs are traceable back to George Cayley's visions of fixed-winged aircraft around 1800.[1] The fixed-wing idea is an important departure from the more natural and recognizable mechanisms of birds and balloons. Aircraft with flapping wings ("ornithopters"), though intuitively appealing, were flimsy, underpowered and difficult to construct.[2] Balloons could not be made to move quickly or in directionally controlled ways. It turned out to be more practical in engineering terms for fixed wings to provide lift while speed was provided in some other way –from a human, an engine and propellers, or, in a model, wound-up rubber bands. Separating the speed-generating system from the lift-generating system turned out to be an essential design idea.

Ballooning clubs promoted discussions on aerial *navigation,* which often meant a focus on fixed-wing, heavier-than-air designs, and new clubs with this orientation appeared. At least a dozen such societies were founded in the nineteenth century. Important ones included the Aeronautical Society of Great Britain, the Société française de navigation aérienne, and the Aéro-Club de France, with up to 400 members by 1865.[3] The societies or clubs were linked to regular journals of which the most important to aerial navigation were *L'Aéronaute* and *L'Aérophile*.

Key innovators in this period include Alphonse Penaud, Louis Mouillard, Lawrence Hargrave, Samuel Langley, Otto Lilienthal, and Octave Chanute. These were self-motivated men, coming from a variety of backgrounds and locations.

1. Cayley's attention was drawn to aircraft by the recent success of balloons and helicopter designs (Gibbs-Smith [1962]).
2. Cayley used flapping wings for propulsion but not for lift. Several experimenters were convinced by evidence that flapping wings could not be as efficient as fixed ones. This is confirmed by later aerodynamic science. Other metaphors existed, such as rockets and helicopters, but these were not central to the fixed-wing discussion. The line of thought that turned out to work proceeded from kites to gliders to powered gliders.
3. Marck [2009], p. 37.

They did not have a joint plan. They did not have the same vision of what they were trying to make, although some aspects of the basic design was similar.

Alphonse Penaud made winged flying models powered by wound-up rubber bands in the 1870s. He studied how their stability in the air depended on the location of the wings with respect to the center of gravity of the craft and how the tail's horizontal surface should best be angled to the oncoming air flow. Afterward a tail with both vertical and horizontal surfaces was sometimes called a Penaud tail. Toys with Penaud designs were widely available afterwards including to the Wright brothers.

Louis Mouillard lived in Algeria and then Egypt in the 1870s and 1880s. He studied birds at great length and measured their weight and their wings. He experimented with wooden wings to carry himself on glides from hills. His writings became well known among experimenters and members of interested societies.

Lawrence Hargrave of Sydney, Australia, retired young and devoted many years to the design of flying machines. He took a specific interest in box kites, which are shaped like boxes but with no top or bottom, so that wind can flow through. In the early 1890s Hargrave demonstrated that box kites were more stable in the air than flat kites. This turned out to be a useful fact; the "box" also gave strength to the structure. Gliders of the time were made of light materials – usually wood covered by cloth. They were unstable in the wind, and flimsy. With one wing on top of the other, the biplane configuration, they made a box structure which is more stable and strong.[4] In related experiments Hargrave showed that the lift from several connected box kites could lift him into the air.

After an effort to patent an aircraft design, Hargrave decided to publish results from all his experiments and patent nothing. He wrote that there would be plenty of credit and money in the field once the key achievement of making a flying machine was achieved, and until then it was expensive and unhelpful to place stakes around intellectual property. He took an open-science kind of view: "Workers must root out the idea that by keeping the results of their labors to themselves a fortune will be assured to them. Patent fees are so much wasted money. The flying machine of the future will not be born fully fledged […]. Like everything else it must be evolved gradually. The first difficulty is to get a thing that will fly at all. When this is made, a full description should be published as an aid to others. Excellence of design and workmanship will always defy competition."[5]

Steam engine engineer Otto Lilienthal conducted twenty years of experiments on wings with his brother Gustav to demonstrate whether and how curvature could help wings produce lift. He demonstrated repeatedly that a wing which has a lower front and rear edge can generate more lift in an air flow than a flat one can. He settled on a relatively symmetrical shape which looked like bird's wings. He published detailed data about his experiments in his 1889 book *Birdflight as the Basis of Aviation*.

In 1891, Lilienthal began to make hang gliders and to fly them from hills in and near Berlin. Over time he drew an audience. Hundreds of people saw him fly, and he became a celebrity. This brought glamour and charisma to the

4. This structural advantage is nowadays generally irrelevant because jet airplanes are made of stronger materials and biplanes experience much more drag than monoplanes.

5. Quoted from Chanute [1894], p. 218.

otherwise quirky and obscure field of aerial navigation. Lilienthal built hang gliders with one and two levels of wings. He began small scale manufacture of hang gliders at his company and offered them for sale.[6] Lilienthal planned to attach a motor to a glider but did not get the chance. After a crash in 1896 his spine was broken and he died of this injury.

Samuel Langley conducted four years of experimental research on the lift and drag of rectangular planes moving in the air while he was a professor at the University of Pittsburgh. His 1891 book *Experiments in Aerodynamics* carefully described the equipment he used to measure lift and drag. He later became the director of the Smithsonian Institution in Washington, DC, and in the 1890s conducted studies of model gliders with engines, sometimes with the backing of the War Department, whose interest was in reconnaissance from the air. Unlike other aeronautical experimenters, Langley therefore had great financial resources for research.

In the early 1900s Langley and his staff made a powered experimental aircraft large enough to carry a person. By his reckoning it had to have a strong, heavy, frame and therefore required a powerful engine. The airframe, engine and the houseboat which held the craft were expensive. To reduce the danger from crashing, Langley's craft was to fly over a river and would not be able to land except in water which meant it could not be tested in rapid iterations. After some crashes in 1903, the trustees of the Smithsonian asked him to stop experimentation. Wilbur Wright later wrote, "I cannot help feeling sorry for him. The fact that the great scientist, Prof. Langley, believed in flying machines was one thing that encouraged us to begin our studies. [He] recommended [readings] to us […] [and] started us in the right direction in the beginning." (Crouch [1989], p. 293).

Langley's design choices were like those for a modern passenger jet –strong steel materials, large wings, and powerful engines. But these choices prevented quick iterative tinkering and the pilot was really a passenger, with no prior experience in the air.

THE MOTIVATION OF EXPERIMENTERS

These experimenters and others had various motives, but mainly they were strongly drawn to flying, itself. From their writings we know they hoped to participate in making a great invention, and some of them imagined getting prestige and fame (though their actual experience was that most people did not believe that what they were doing was practical or feasible). Some also wanted to change the world; one recurring idea was that quick easy travel across borders would increase contact and comfort with foreigners and help bring peace. In an economic model, their progress toward these internal or altruistic goals can be represented by utility functions. Some had an interest in selling a product eventually but except perhaps for Lilienthal they did not have a clearly-defined plan or profit incentive.

6. Ten sales are known, according to Bernd Lukasch, director of Otto-Lilienthal Museum in Anklam, Germany (in a 2011 conversation). From letters and other sources some of the buyers are known.

Their economic and social environments provided enough support to allow some of these experimenters to publish, travel, and work creatively, although the aerial navigation activity was not widely respected. There was no general agreement that the activity was likely to succeed in a predictable way. In economic language, they faced *technological uncertainty*. Understanding this environment in a model can help characterize how creative individual actions, over decades, lead to the appearance of new industries. An important dynamic discussed in the next section is that they got in touch with one another, building an informational network through correspondence, visits, clubs, and journals.

When technological development is so often justified by future revenue streams, why would individuals develop technology on their own, at their own expense, without having a plausible plan to sell it? As with the open source software developers surveyed by Lakhani and Wolf [2005], there were a variety of motivations. Some experimenters found the project inherently absorbing and challenging. Some looked forward to being able to fly themselves. These are sometimes called *intrinsic* motivations. Some experimenters anticipated receiving honors, prestige, career benefits, credit for having made something useful, and perhaps somehow wealth from their own success at addressing the problem of flight. These are *extrinsic* motivations. Some experimenters anticipated that flight would improve the human condition or their nation's security, which are *altruistic* motivations. Several thought that since airplanes would increase human contact across borders, they would help bring about peace.

Specifically regarding extrinsic motivations, Otto Lilienthal invented the modern hang glider, and sold a few in kits from his steam engine firm. Samuel Langley had research funding from the Smithsonian and from the War Department which was interested in using aircraft for reconnaissance. Many experimenters patented their inventions, though until the Wrights demonstrated the feasibility of flight aircraft patents brought no substantial revenue. In the airplane case, the prospects for extrinsic rewards were not great for most of the experimenters. Progress took decades, and several experimenters died in crashes. None became rich from aircraft until after 1903. They were not rewarded as professional engineers for their quixotic attempts to fly, and many left the activity even after some success, in order to do something more rewarding. The experience of experimenters did not suggest that they would expect extrinsic rewards to outweigh costs.

Instead, aircraft experimenters referred directly to 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 [1912], introduction).
- "The writer's object in preparing these articles was [to ascertain] whether men might reasonably hope eventually to fly through the air […] and to save effort on the part of experimenters…" (Chanute [1894]).
- "I am an enthusiast […] as to the construction of a flying machine. I wish to avail myself of all that is already known and then if possible add my mite to

help on the future worker who will attain final success" (from Wilbur Wright's 1899 letter to the Smithsonian Institution requesting information).

- "Our experiments have been conducted entirely at our own expense. At the beginning we had no thought of recovering what we were expending, which was not great…" (Orville Wright [1953], p. 87).
- "[I offer] experimental demonstration that we already possess in the steam-engine as now constructed… the requisite power to urge a system of rigid planes through the air at a great velocity, making them not only self-sustaining, but capable of carrying other than their own weight… [My experiments required] a great amount of previous trial and failure, which has not been obtruded on the reader, except to point out sources of wasted effort which future investigators may thus be spared…" (Samuel Langley [1891], on pp. 5-6 of 1902 edition)

The experimenters who devoted their time to the subject seem rational if they had intrinsic motivations. If they were motivated only by a long shot possibility of getting rich, their behavior seems poorly informed, or irrational, because it was time-consuming, dangerous, and unlikely to pay off financially sufficiently well to repay their expenses.

In a world of millions, perhaps a few hundred tried to contribute specifically to making heavier-than-air, fixed-wing aircraft. Early aeronautical experimenters were unusual, self-selected by their distinctive interest in the project of flight and their belief that they could contribute to it. They had an interest in the end goal. This helps explain why they would share their findings and innovations in clubs and journals and networks.

OCTAVE CHANUTE AND THE OPEN INFORMATION NETWORK

After becoming independently wealthy from railroad work, Octave Chanute became a writer and experimented with flying machines. He wrote a series of articles about the efforts toward flight and combined them into a book with the optimistic title *Progress in Flying Machines* [1894]. It had an important effect by surveying and organizing a dispersed literature. By contrast, the earlier works of Langley and Lilienthal, for example, are insightful and detailed, but they are one-way broadcasts about particular sets of experiments, with very few citations to others. By taking a global perspective, Chanute served as a kind of technology information broker or moderator, identifying key persons and technologies and evaluating them. He would put aircraft builders in touch with one another, either via his book or through personal correspondence. He was infused with the idea that by communicating and cooperating, experimenters around the world would make success possible. 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."[7]

7. Stoff [1997], p. iv. Similar technology moderators, with similar ideologies, appear in other cases of collective invention. They organize networks of creative technologists which supports later entrepreneurship. Examples include Joel Lean, the steam engine builder who ran a newsletter in the

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Progress in Flying Machines cited 190 experimenters from around the world. The frequency with which the book referred to various persons, a kind of citation count, provides a proxy measure of their significance and contribution according to Chanute's vision of the network of airplane creators. Table 1 ranks the men Chanute cited or quoted most often, according to the number of pages on which they appeared.

Table 1. *Most-cited authors and experimenters in Octave Chanute,* Progress in Flying Machines [1894]

Experimenter / group	Pages referring to, or quoting, that person	Location (background)
Hiram Maxim	33	Britain (us)
Otto Lilienthal	31	Germany
Alphonse Penaud	22	France
Louis Mouillard	21	Algeria, Egypt (Fr)
Lawrence Hargrave	19	Australia (Br)
Thomas Moy	19	Britain
Jean-Marie Le Bris	17	France
Samuel Langley	16	us
Francis Wenham	15	Britain
H. F. Phillips	14	Britain

These "citation counts" come from a book finished before the Wrights or other twentieth-century airplane builders had even begun experimentation. Thus the list was not selected or ordered on the basis of later successes. The people on it were, however, significant by other criteria, and connected to personal networks of information.

Chanute visited and corresponded with many of the key experimenters cited in his book and in later years. The letters were gracious and personal in style, and almost always referred to experiments, experimenters, or related technical subjects. In research for her biography of Chanute, author Simine Short located 29 letters between Chanute and Lawrence Hargrave, 26 between him and Francis Wenham, and 12 to or from the Lilienthals. Thanks to her work and others, 175 letters between Chanute and Mouillard are online.[8] Once the Wrights contacted him, Chanute maintained a strong relationship with them too, sending

early nineteenth-century in Cornwall (Nuvolari [2004]); Alexander Holley, a consultant, frequent author and journal editor at the time that Bessemer steel plants were being built in the u.s.; Lee Felsenstein, who moderated the Homebrew Computer Club from which Apple and a dozen other Silicon Valley startups spun out in the 1970s; Tim Berners-Lee, who invented the World Wide Web and made its standards public; Richard Stallman, who founded and organized the gnu free software efforts; Linus Torvalds, who founded and organized the development of Linux; other open source software projects also had charismatic founders who encouraged openness and did not seize chances to keep the technology secret and extract maximum profit. For more details on these comparisons, see Meyer [2003].

8. "The Chanute-Mouillard Correspondence," from 1890 through 1897, translated from French into English, is at http://invention.psychology.msstate.edu/i/Chanute/library/Chanute-Mouillard/Chanute-Mouillard.html.

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at least 230 letters to them and receiving at least 177 from them, which have been published by McFarland. Short has identified another 50 unpublished items of their correspondence.[9]

Other bibliographies were published around the same time, and there was a general upturn in the size of the common pool of information and the number of publications. The environment had changed. While Lilienthal [1889] and Langley [1891] cited almost no one else, successful experimenters in the mid-1890s were clearly aware of a broad range of past experiments. It is convenient to mark 1894 as the beginning of a global search for a better technology informed by a connected technical literature; what may be described as a pool of aeronautical knowledge.

Some of the correspondence of the Lilienthal brothers also survives. Schwipps [1985] has collected this correspondence. Otto was sometimes aided by his brother Gustav who knew English and who traveled more. They corresponded with dozens of other experimenters.

After-the-fact citation counts can be constructed too. In a collection of the indexes from 15 published books with histories of aviation, across languages and countries, I found that they cite the Wrights, Chanute, Lilienthal, Louis Blériot, Langley, and Glenn Curtiss most frequently.[10] Blériot and Curtiss were later pilots, not nineteenth century experimenters.

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. As a result, the Smithsonian developed a large library on aeronautics and an associated bibliography, which systematically included references to works that were not in its own collection. Smithsonian librarian Paul Brockett, published a series of books of aeronautical bibliography. The first, *Bibliography of Aeronautics* [1910] lists more than 13,000 publications related to aeronautics before 1910, including many which were not held at the Smithsonian.

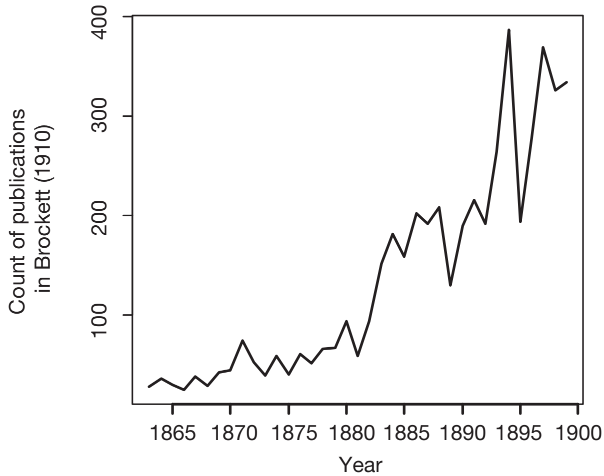
This bibliography has been scanned and put online at archive.org by Cornell University and the University of Michigan. After cleaning up the electronically scanned text, we have for most of these publications a title, author(s), year of publication, a journal of publication, the language of the text, and country of publication. Excluding entries for which these data elements are not complete, it has been possible to compile a database which can track the evolution of this technical literature.

From a preliminary analysis of this bibliographical data (figure 1), we can see there was a substantial literature, which grew sharply in the 1880s to over 200 titles per annum and again in the 1890s to nearly 400, several years before the airplane was a proven technology. French was the most common language in this literature, followed by English and German. Over time, a growing fraction of the articles in this selected sample were about kites or gliders, not balloons.

9. McFarland [1953], Short [2011], and personal communications from Simine Short.

10. Meyer, "A Pre-History of the Airplane," presented at Columbia University. Counts excluded references to events after 1909.

Figure 1. *Count of publications in Paul Brockett (Bibliography of Aeronautics [1910])*



PATENTS IN THE AERIAL NAVIGATION FIELD

Patents are publications which make claims of intellectual property. Nineteenth-century aeronautical patents were used as publications but with no traction as rent-seeking instruments. I am not aware of any fixed-wing aircraft patent through 1905 which earned any license revenue. There are several national collections from which to draw inferences. Researchers Simine Short, Gary Bradshaw, and colleagues compiled a list of early u.s. patents related to aircraft.[11] Patentees who filed more than two aircraft-related u.s. patents through 1906 were E. Falconnet with six, W. Quinby with five, and W. Beeson, A. Blackman, S. Cairncross, C. Fest, and A. O'Brate with three each. None of these inventors had any publication listed in Brockett's *Bibliography*. Chanute's book refers to work by Quinby and by Beeson but did not treat it as valuable. Nor did the Wrights' publications refer to these inventors, who are usually absent from modern histories of the airplane.

The Otto Lilienthal Museum has collected a database of German patents by aircraft experimenters.[12] It is not perfectly comparable to the u.s. table because it includes patents on other subjects by the same people. In particular, most of Otto and Gustav Lilienthal's many patents were for steam engines, and they were well represented both in the patent count and in the open literature. Apart from the Lilienthals, the names of the most frequent patentees on this list were little referenced by Chanute or the Wrights, and they do not appear in any conventional

11. The list is available at http://invention.psychology.msstate.edu/PatentDatabase.html.
12. It is online at http://www.lilienthal-museum.de/olma/pat_ar.htm.

history of the invention of the airplane. British patentees fared only slightly better. A collection of 250 British patent abridgments, published in 1893, was meant to "be of benefit" to "those interested in the subject of aeronautics" and expressed hope that "failures will not deter inventors from still striving to master the great problem of aerial navigation."[13] Several of these patentees and patents were referred to in Chanute's book and in the literature of the 1900s.

This casual environment changed after the Wrights filed their wing-warping patent in March 1903, which was granted finally in 1906. Their patent was interpreted broadly by the u.s. courts and the Wrights enforced it vigorously. Courts in other countries interpreted the patent narrowly. Yearly patent counts related to aeronautics rose immediately starting in 1907, because the basic technological uncertainty had been resolved. Specialists then knew that airplanes could work and anticipated a market for relevant inventions.

THE WRIGHT BROTHERS AND THEIR INVENTIONS, 1900-1906[14]

Wilbur and Orville Wright enter the story in 1899 when, inspired partly by Lilienthal, Wilbur took a specific interest in the possibilities of winged aircraft. He wrote to the Smithsonian Institution for information and was rewarded with a reply that contained substantial reading material and advice on the prior literature that he should study. The Wrights followed these leads and wrote also to Chanute for information. They continued a long correspondence with Chanute for years afterward, and these exchanges of letters have been studied by many historians to describe what happened technologically.

The Wrights began their research with kites and gliders designed in imitation of Chanute's design of 1896.[15] They studied flights of this kite at length. Sticking with the same basic design, they made a series of larger, heavier, stronger kites and gliders which a pilot could ride. These were inexpensive until 1903, when they felt sure of success and added an engine (and filed their first patent). The wings were like Lilienthal's and Chanute's, made of canvas stretched over a wooden frame. Their aircraft were not designed to be intrinsically stable, but rather depended on frequent adjustments of the wingtips by a pilot. Professionally the Wrights made bicycles, whose riders make similar adjustments. Progress like Lilienthal's required experience in the air, and the development of a skill of piloting this kind of aircraft. The Wrights were proficient toolsmiths, and measured more precisely what they intended to measure than other experimenters did. Among their key technological achievements was the development of a small but precise wind tunnel which made better wings and propellers possible.

Until 1903, the Wrights had participated in the open, collective inventive process in ways similar to those who had advanced the field previously. They

13. Brewer and Alexander [1893].
14. This section draws from Jakab [1990] and Crouch [2002].
15. Wilbur's first letter to Chanute in 1900 said so: "[T]he 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."

frequently discussed technical issues and previous work with Chanute, hosted visitors to their experimental flights, helped others to test their wings and aircraft, and took advice (Crouch, p. 249 and p. 253). Wilbur gave a public speech to engineers, at Chanute's invitation, and published two papers in European journals in 1901.[16] The published papers of the Wright brothers refer often to Chanute, Lilienthal, and Langley[17] and less often to other individuals, although they were familiar with previous work.

TRANSITION FROM "OPEN SOURCE" DYNAMICS TO INDUSTRIAL COMPETITION

Within the context of this unorthodox activity of aeronautics, imitations were rife: the most successful and influential designers copied from others and this was considered normal. Cayley's design started the field; many experimenters copied Penaud's design; Chanute's 1896 gliders depended on many predecessors including the work of Penaud, Hargrave, and Lilienthal; the Wrights explicitly copied Chanute's design. Moreover, before the Wrights achieved their success, Ferdinand Ferber had already imitated the same design, based on Chanute's enthusiastic descriptions and pictures. Ferber's work was central to the later successes of European aviation.[18] Copying in early aeronautics was fuzzy and imprecise, not precise and bit-for-bit as it is in software. Imitators usually worked from verbal or photographic descriptions, and learned more details by personal collaborations. Patents existed only in the background.

Successes came from the open literature but there were also many attempts at secrecy. After 1901, Langley prepared for a large scale experiment and became more secretive.[19] The Wrights did too starting in 1902. Crouch (p. 296) infers that this was because they foresaw success:

– 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 [successful demonstrations] in 1902 had changed their attitude.

16. Anderson ([2004], pp. 110-111) argues that one of these was an important contribution to the field of aeronautics.

17. Jakab and Young [2000].

18. Gibbs-Smith [1966], pp. 54-60.

19. Langley felt pressure not to conduct his experiments too publicly because of the need to protect the Smithsonian Institution's reputation from exotic failures, but secrecy was not entirely feasible since his craft flew from a giant houseboat with a hangar on the Potomac river near Washington, d.c.

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Chanute had criticized others, such as Clément Ader, who kept designs secret before, and he had conflicts with Langley and with the Wrights. Analogous conflicts occur today between open source programmers; some take the view that computer code must be freely available, and others would allow it to be owned and licensed.

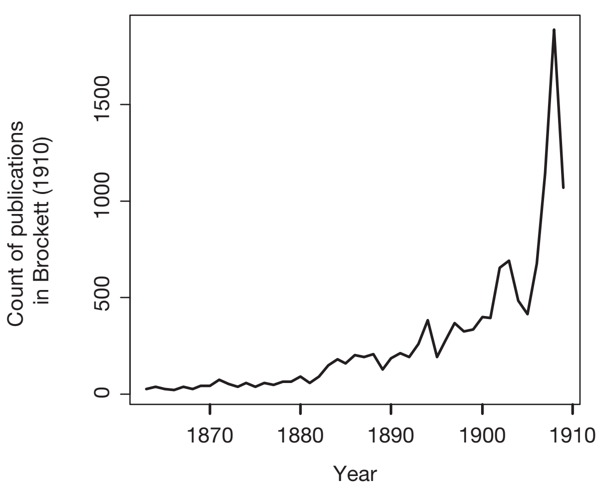
In 1906, the Wrights received their key patent and Alberto Santos-Dumont flew a powered glider in Europe. The Wrights contacted the military in various countries in attempts to make long-term large contracts, and they founded a company to manufacture airplanes. In short order other companies were also making airplanes and these companies competed both over intellectual property and in an infant market for airplanes.

1907-1910: NEW DYNAMICS AND THE RISE OF A NEW INDUSTRY

In 1907, the annual number of aeronautical patents filed increased sharply in the u.s. and German data, and continued to rise thereafter. The annual number of publications also rose sharply and permanently. In the Brockett [1910] data, publications from the second half of 1909 are not included which explains the apparent drop at the end of the period in figure 2.

In 1908 there were large public demonstrations of airplanes for the first time. It quickly became clear to newspaper readers in all the industrial countries that such flying machines were possible; many thousands witnessed their flights in 1908-9. The public mindset or beliefs changed, from thinking that fixed-wing aircraft was improbable and useless, to thinking that it was a feasible activity and industry. In the language of Hannan *et al.* [1995], the new industry was perceived suddenly as legitimate.

Figure 2. *Count of annual publications, 1860-1909*



Source: Brockett [1910].

Starting in 1908, a burst of airplane-making firms appear across the industrialized countries, and research is underway to organize a data set on them. Fewer than a dozen were founded in 1907, but from 1908 to 1914 there were more than thirty a year. Differences across countries seem relatively small; the timing of the initial burst and subsequent flow looks similar in Britain, France, Germany, and the u.s., and several companies appeared in Austria-Hungary, Russia, and elsewhere. A spectrum of related privately provided services also arose: exhibition companies, flying schools, makers of engines, propellers, other parts, and of models, consultants, and service firms offering maintenance and repair.

Few of the founders of these new firms were experimenters in the period 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 none 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 seems to result from the combination of great technological uncertainty and open-source/tinkering behavior before the transition, and the need for capital-intensive manufacturing after the transition. This rapid takeoff of the industry, unmoored from the original inventors, suggests that much of the key knowledge was widely available. There were great patent battles after 1906 in the u.s. (and after 1910 in Europe) and industrial competition, but the key knowledge necessary to fly was not in fact licensed from one place or closely tied to any particular patent. Many of the new firms spun off from existing firms in another line of business and from other new aircraft firms, or licensed the technologies of the earliest firms. This is analogous to findings in early u.s. automobile companies around the same time (Klepper [2009]).

Rapid growth followed. Chadeau ([1987], p. 435) estimates that there were 57 airplanes and 95 airplane motors produced in France in 1909; 316 and 1,050 in 1912; 796 and 2,355 in 1914; and even faster growth in the first World War. Industry growth in the u.s. started more slowly. The first private sale of an airplane in the u.s. and the Wrights' first contract with the u.s. military both occurred in 1909 (Head [2008]). Demand in both countries came from the military, from private buyers, and from exhibitions ticket sales. In these years there was not yet substantial revenue from passenger service, mail delivery, or freight transport.

MODELING THE OPEN SOURCE PERIOD AND THE NEW INDUSTRY

Largely, then, the invention of the first airplanes was based on open-source information and networks of enthusiasts. 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 decentralized copying of designs and the transition which created a new industry are elements of special interest here.

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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 generally not competing against one another. 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"[20]) is necessary to explain why existing firms do not directly seize the opportunity with their own research and development. If no market were established and the technical problems were 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, standardization of designs and terminology, evangelism, editing and moderation of joint journals, clubs, and interaction. These are "networks of tinkerers" in the model of Meyer [2007].[21]

A private company might share private knowledge without payment, for several reasons discussed in the collective invention literature (including Allen [1983], Nuvolari [2004], Meyer [2003], and von Hippel [1987] which discusses know-how trading which is similar). Among the reasons companies would share such information are: (1) better public technology would raise the value of their assets, as among the nineteenth century British blast iron furnace firms (Allen [1983]); (2) innovating firms garner favorable publicity by making their successes known; (3) organizations may not find it worth the effort or expense to keep privately developed information secret (which is infeasible if, for example, 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) establishing engineering standards can be justified by network effects even if it upgrades a competitor's technology (Meyer [2003]); (6) the firms conduct research in different directions and expect future innovations to depend on advances made outside their particular firms (Nuvolari [2004]; Bessen and Maskin [2009]). Even recognizing all these dimensions, the collective invention literature does not describe the behavior of networks of individuals operating outside organizations; some kind of user innovation or open science story is still needed to characterize the airplane case.

In early aeronautics, some experimenters, such as Chanute, devoted energy to surveying and documenting the work of the others. One can explain why a tinkerer would do this in terms of his 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 designed to meet the same objective. When we observe that information travels quickly and freely among the

20. For other, similar characterizations of technological uncertainty, see Tushman and Anderson [1986], Dosi [1988], and Rosenberg [1996]. In the airplane case the technology advanced quickly and crystallized into workable designs by 1909.

21. Meyer [2007] formally models the case of tinkerers who choose to form such networks. These tinkerers trade their time and investments to achieve engineering standardization, modularization, and specialization to facilitate working together and reduce costs. They would be willing to evangelize to bring others into the inventive network. In this context, voluntary technical situations call for specialization, without reference to market phenomena (contrary to Adam Smith's assertion that "the division of labour is limited by the extent of the market").

interested participants, we can treat it as a pool and set aside the shape of linkages within the network (the dimension analyzed by social network analysis).

Other experimenters, such as Hargrave, decided against any attempt at rent-seeking through patents. 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. An experimenter who never enters such a network or who 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 [1894] stated that such time saving was a motive for publishing his book.

We can think of a tinkerer as a person working on a technology whose future 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. The tinkerer could choose to leave the network, stop giving and receiving information, and start directed research and development to make a product. In the model, the network can continue on if others keep it going. However in that model, the tinkerers depart from the network to create the new industry. Preliminary findings from the airplane case suggest that the new industries are mainly populated and started by others, not the early experimenters.

CONCLUSIONS

The modern precise legal definition of open-source software does not apply to the pre-history of the airplane though Pénin [2011] among others treats the legal aspect as central to the analogy. However, the mode of technological advance in flying machines in the nineteenth century has similarities to open-source software:

- Experimenters are autonomous (not in a hierarchy or cult) and from around the world.
- Many of the experimenters have intrinsic or altruistic motives. They are drawn to their topic –pulled by desire, not pushed.
- The experimenters regularly share technological information.
- Within the network, experimenters specialize in improving specific aspects of the technology.
- At least one (Chanute) specializes in communicating –collecting information from other experimenters and authors, and inviting new people into the network.
- Some experimenters (such as Hargrave and Santos-Dumont) avoid intellectual property institutions which would delay progress.
- The Wrights used publicly known knowledge and technology. The patent system was not relevant to advances in the field until 1903.

Such open processes supported industry among steam engine makers in the early decades of the nineteenth century (Nuvolari [2004, 2005]) and during

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the invention of the personal computer (Levy [2001]). In the British Industrial Revolution, progress in science and technology was supported by a relatively free press and the flowering of many scientific and technical societies with hundreds of thousands of members (Inkster, [1991], p. 71-9; Mokyr [1990]; Mokyr [1993], p. 34).

In the airplane case there were several phases of development. Dispersed experimenters had the basic design idea from about 1800. By 1870, there were institutions, such as clubs and journals, that treated this vision as a recognizable and legitimate topic of discussion. Around 1895, there appeared unified global surveys of the field and design platforms which could be copied –a kind of information platform for future developers– and all the relevant experimenters know of it. Powered glider flights occurred around 1905. Startup companies appeared in recognizable numbers on both sides of the Atlantic in 1908 and quickly industrial dynamics appeared, including patent litigation, substantial capital investment in manufacturing and revenues.

Such dynamics appear also in the cases of shared content, such as the Wikipedia sites, where the Internet, Web, and distinctive software help support easy collaboration. Future new-technology industries may relate to their scientific and experimental forerunners in the same way, but start more quickly.

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