An Inventive Commons: sources of the airplane and its industry

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Abstract. This is a study of the experimenters, clubs, and publications associated with the gradual invention of airplanes from the 1860s to 1910. A growing number of experimenters worked out how to make fixed-wing aircraft that could be controlled in the air. They connected to one another in clubs and shared findings and designs in journals. These open institutions supported the literature which was put to use in the invention of the airplane and the creation of the associated new industries. These define a commons-space for work they found worthwhile, to cultivate a common opportunity. The experimenters readily shared information in publications and clubs, and by letters and visits. They treated aeronautical patent filings like publications, but not like intellectual property. They copied earlier designs in a way that is analogous to advances in open source software now.

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

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[1] Views expressed in this paper are those of the author and do not necessarily reflect the views or policies of the U.S. Bureau of Labor Statistics. This work is preliminary; please do not cite
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controlled flight. Hundreds of experimenters, theorists, and other authors contributed to the relevant literature. New participants found journals, books, clubs, and curious visitors. The open literature and culture of curiosity and sharing contributed to progress as experimenters were able to work from previous designs. This paper explores how the early experimenters, hobbyists, and scientists led to the invention and 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 and after that time were familiar with the literature and imitated prior designs. Many distinct "firsts" followed, including controlled powered glider flights by the Wright brothers in December 1903 and by Alberto Santo-Dumont in 1906. Major public exhibitions occurred in 1908 and scores of startup companies began in short order.

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 19th century, and hundreds of airplane-manufacturing establishments started before the First World War. From various sources we have preliminary databases of such publications, patents, clubs, and firms.

Early 20th century inventors of working airplanes knew a lot about the prior efforts. The Wright brothers, for example, read key works by experimenters 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, 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;
- 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; that is, in fields where it is not clear what a profit-minded firm should try to do. 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 trace back to George Cayley's vision for fixed-winged aircraft around 1800.[2] That was an important new idea, at a time when people found it natural to think of designs built around hot-air or hydrogen balloons, which were new at the time and much discussed, or with flapping wings like birds. Aircraft with flapping wings ("ornithopters"), though intuitively appealing, were flimsy, underpowered, and difficult to construct.[3] Balloons could not be made to move in quick controlled ways. It turned out to be more practical to provide lift in the air with fixed wings while speed is provided some other way – by gliding from a height, from human power, or from an engine and propellers, or in a model from wound-up rubber bands. Separating the speed-generating system from the lift-generating system turned out to be an essential design idea.

Nineteenth-century clubs on ballooning gradually incorporated discussions on *aerial navigation* and on *flying machines.* These terms were used by those who focused on fixed-wing, heavier-than-air designs, though the terms themselves also could apply to balloons and led to the creation of dirigibles which are ballons with rigid frames and can be steered more effectively than balloons can.

Ballooning clubs included sections on the fixed-wing activity, 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. One such society had 400 members in 1865.[4] The societies or clubs were linked to regular journals of which the most important to aerial navigation were *L'Aéronaute* and *L'Aérophile*.

[2] Gibbs-Smith, 1962. Cayley's attention was drawn to aircraft by the recent success of balloons and the first helicopter designs.
[3] 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 designs that turned out to work proceeded from kites, to gliders, to powered gliders.
[4] Marck, 2009, p.37.

Key innovators in this period, including Alphonse Penaud, Louis Mouillard, Lawrence Hargrave, Samuel Langley, Otto Lilienthal, and Octave Chanute, were self-motivated men, coming from a variety of backgrounds and locations. They did not have a joint plan or a common vision of what they were trying to make, although some aspects of the basic design were similar. It is helpful to look at some of the key experimenters before making further generalizations about them.

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 air flow. The tail, he found, must generate lift. 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, and wrote a book about this and the imagined extension to humans with wings which became well known among people interested in the aerial navigation problem. He experimented with wooden wings to carry himself on glides from hills, to the point of injury. He faced recurrent financial problems as he was distracted by his fascination with the subject. In 1889 the Aero-Club of France held a banquet for him where he met a number of interested persons.

Lawrence **Hargrave** of Sydney, Australia, retired young and devoted many years to the design of flying machines. He studied box kites, which are shaped like boxes but with no top or bottom so wind flows right through. In the early 1890s Hargrave demonstrated that box kites were more stable than flat kites in the air. 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, and were unstable in the wind. With one wing stacked on top of the other, in the "biplane" configuration, the wings mimic a box and were more stable and less flimsy.[5] 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 not to seek patents. He wrote that there would be plenty of credit and money once someone built a real flying machine, and until then it was expensive and unhelpful to place stakes around intellectual property. He took an open-science or information-commons 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."[6]

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[5] This structural advantage is nowadays generally irrelevant because jet airplanes are made of stronger materials and biplanes face much more resistance to forward motion ("drag") than monoplanes do.

[6] Quoted from Chanute, 1894, p. 218, and in biographies of Hargrave subsequently. In the language of the information commons he could foresee the problem of *enclosure* of information.

Steam engine engineer Otto **Lilienthal** and his brother Gustav conducted twenty years of experiments on wings shaped like those of birds to demonstrate whether and how their curvature could help produce lift. He examined how wings with a lower front edge and rear edge would generate more lift in an air flow than a flat one would. 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 fly them from hills around 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 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.[7] Lilienthal planned to attach a motor to a glider but died from a crash before he tried it. His death affected the thinking other experimenters greatly because he had been so successful at experimenting directly in the air.

While a professor at the University of Pittsburgh, Samuel **Langley** conducted four years of experimental research on the lift and drag of rectangular planes on a 30-foot rotating arm. His 1891 book *Experiments in Aerodynamics* carefully described the equipment he used to measure lift and drag. He became the director of the Smithsonian Institution in Washington, DC, where he conducted studies of model gliders with engines, sometimes with the backing of the War Department, whose interest was in reconnaissance from the air. Unlike most aeronautical experimenters, Langley therefore had substantial financial resources for research. His own library of aeronautics became the basis of the Smithsonian's library and the bibliography used later in this work.

In the early 1900s Langley and his staff made a powered aircraft large enough to carry a person. By his reckoning it had to have a strong, heavy, frame and therefore required a powerful engine. All this and the superstructure around it were unique and expensive, costing an estimated $50,000. It could not make a controlled landing so to reduce the damage from crashing, it was flown over a river. It would then be wet and so could not be tested and altered in rapid iterations. After public crashes in 1903, the trustees of the Smithsonian asked him to stop experimentation because it was bad publicity; newspapers excoriated the alleged waste of money. 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."[8]

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

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[7] Only nine sales are known, according to Bernd Lukasch, director of Otto-Lilienthal Museum in Anklam, Germany (in a 2006 conversation). From letters and other sources we can identify some of the buyers.
[8] Crouch, 1989, p. 293

Success would come more quickly to those using light gliders, who could experiment repeatedly and could use relatively light engines.

The motivation of experimenters

These experimenters 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 dreamed of prestige and fame (though their actual experience was that most people did not believe that what they were doing was practical or feasible). Some wanted to change the world; one recurring idea was that quick easy travel across borders easier would increase contact and comfort with foreigners and help bring peace. Their interest in selling a product is not clear; they did not have clearly-defined plans or products, and they do not seem to have discussed it much in writing.

Aerial navigation activity was not widely respected, but some of these experimenters had supportive enough economic and social environments that they could travel, work creatively, and publish. It was not commonly believed or predictable that the activity was likely to succeed. 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.

Why would individuals develop technology at their own expense and effort, 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 *social* or *altruistic* motivations. Several thought that since airplanes would increase human contact across borders, they would help bring about peace.

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)

Could there have been extrinsic motivations? Otto Lilienthal, who invented the modern hang glider, sold a few in kits from his steam engine firm. Samuel Langley had research funding from the Smithsonian and the War Department. Many experimenters patented their inventions, though until the twentieth century fixed-wing aircraft patents brought no revenue that I am aware of. 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 at least 1908. 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. Experimenters with intrinsic motivations could be viewed as rational agents pursuing a leisure interest. But any experimenters with extrinsic motivations do not appear to have been making rational well-informed choices, since their efforts were time-consuming, dangerous, and unlikely to pay for 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, “rare birds,” selected by their distinctive interest in the project of flight and their belief that they could contribute to it. They had an interest in an end goal, which helps explain why they shared their findings and innovations in clubs, journals, and networks.

To summarize: the experimenters were **self-selected** to have **intrinsic or altruistic motivation** to work on this particular topic, and to have the resources to try to make progress in a technologically uncertain situation.[9]   Part of the reason to emphasize this is that their work led to the creation of an industry however which like other industries was characterized by manufacturing production, competition between firms, and paid employment. One can forget that this did not follow from an early industrial mindset.

[9] 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 (2000), Polanski (2005), von Hippel (2006), Gambardella and Hall (2006), and Meyer (2007).

Such technically-focused and self-motivated individuals were willing to work alone and often did. Many also joined into clubs, societies, conversations, correspondence, exhibitions, conferences, and journals. There was a network of these experimenters. The research here involves building databases with evidence about this.

Clubs and societies

A number of societies and clubs formed around issues of ballooning and then the subject of controlled "aerial navigation" which focused more on heavier-than-air winged aircraft ("flying machines"). Among the most important of these were probably the Aeronautical Society of Great Britain (founded 1866), and the Societe francaise de navigation aerienne (1872). Membership fluctuated, but overall interest grew over time as is evidenced by a growing number of clubs with some attachment to aerial navigation. Some of these were locally oriented but they also developed connections between them.

The data below, gathered by over the course of years, describes the population of the relevant clubs and societies.

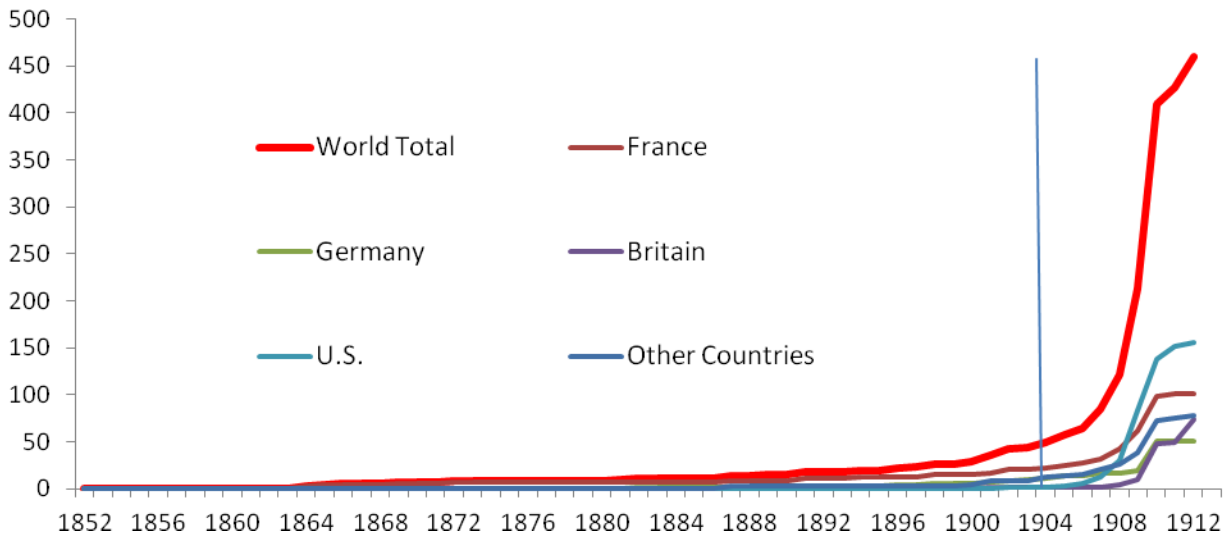
The earliest societies associated with "aerial navigation"

Name	started
Society for aerial navigation (Societe de Navigation Aerienne), France	1864
Society for the encouragement of aerial Locomotion by Heavier-than-air machines, France	1864
Aeronautic and Meteorologic Society of France (with a prior history)	1865
Aeronautical Society of Great Britain	1866
Aviation Society of Lyon, France	1869
French Society of Aerial Navigation (re-organized?)	1872
Russian Aeronautical Society	1880
Berlin Association for Aerial Navigation	1881
German Association for the Advancement of Aeronautics	1882
Vienna Flight Technical Association	1887
Emulation Aerostatic of the North	1887
Austrian Flight Technical Association (renamed and reorganized)	1887
Munich Association for Aerial Navigation	1889
Society of Aeronautic Pilots, France	1889

Sources: Author and researcher Ceceile Richter from many sources

Aeronautics-related clubs and societies

These are counts of these clubs which have ever been founded. It does not account for any exits, which were rare. Many clubs are first seen in 1910 Directory which partly accounts for the spike then.
Source: Author's list, based on many sources. Counts are in data appendix.
Counts only start dates, not accounting for end dates.



The number continued to grow after the airplane was convincingly invented. A writer in a 1914 Russian publication lamented that Germany had almost 100 aeronautical societies with 100,000 members, France had 80 with 40,000 members, and Russia had 10 with 2,000 members.[10] We do not know where these particular estimates came from, but they give a sense of scale.

Chanute and open networking

Octave Chanute became wealthy as a civil engineer, railroad manager, and real estate speculator then retired to write about and experiment with flying machines. He helped organized a major conference and exhibition at Chicago in 1893 on this topic, associated with the World's Fair. After publishing many articles he summarized the state of the art in an 1894 book with the optimistic title *Progress in Flying Machines*. By contrast, the earlier works of Langley and Lilienthal were insightful, detailed, one-way transmissions about particular sets of experiments, rarely citing others. By surveying the flying-machine activity broadly, Chanute connected others together, identifying key persons and explaining the relevant technologies. Chanute's many speeches and writings were "noteworthy for fostering a spirit of cooperation and encouraging a free exchange of

[10] *Dictatorship of the Air,* citing journal *Utro Rossii*

ideas among the world's leading aeronautical experimenters."[11] He believed this would make success possible.

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. This table shows the people cited or quoted on the most pages.

Most-cited authors and experimenters in *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" are a quirky measure but they have the advantage for analysis that they come from a book finished before the Wrights or other significant airplane builders had even begun experimentation. 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.

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; a pool of knowledge.

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

[11] 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: Joel Lean was the steam engine builder who ran a newsletter in the early nineteenth century in Cornwall (Nuvolari, 2002). Alexander Holley was a consultant, frequent author, and journal editor as Bessemer steel plants were built in the U.S. Lee Felsenstein moderated the Homebrew Computer Club from which Apple and a dozen other Silicon Valley startups spun out in the 1970s. Tim Berners-Lee invented the World Wide Web and made its standards public. Richard Stallman founded and organized the GNU free software efforts, Linus Torvalds founded and organized the development of Linux, and other open source software projects also have 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).

always referred to experiments, experimenters, or related technical subjects. Simine Short, who is writing a biography of Chanute, located 29 letters between Chanute and Lawrence Hargrave, 26 with Francis Wenham, and 12 to or from the Lilienthals.[12] Based on Short's work and others, 175 letters between Chanute and Mouillard are online.[13] Once the Wrights contacted him, Chanute maintained a strong relationship with them too, sending at least 230 letters to them and they sent at least 177 to him.[14] Short has identified another 50 unpublished letters with the Wrights.

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

In a preliminary collection of the indexes from 15 published books with histories of aviation, across languages and countries, I find they cite the Wrights, Chanute, Lilienthal, Louis Blériot, Langley, and Glenn Curtiss most frequently.[15] Blériot and Curtiss were later pilots, not nineteenth century experimenters.

Bibliography of Aeronautics, 1910

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 13,000 publications related to aeronautics before 1910, including many which 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, years 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, we have a database which can track the evolution of this technical literature.

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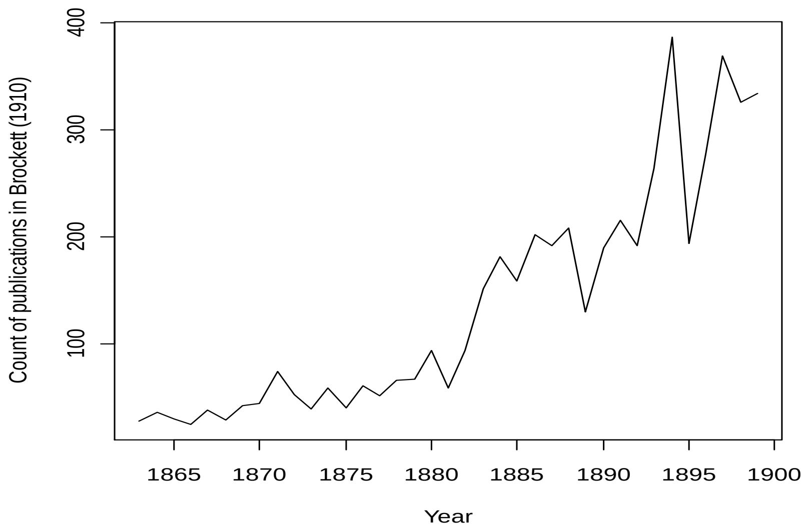
[12] Personal communications with Simine Short.
[13] "The Chanute-Mouillard Correspondence," from 1890 through 1897, translated from French into English, at http://invention.psychology.msstate.edu/i/Chanute/library/Chanute-Mouillard/Chanute-Mouillard.html.
[14] McFarland (1953) republished these.
[15] Meyer, "A Pre-History of the Airplane", presented at Columbia University. I excluded references to events after 1909.



The rough data at this early stage, graphed above, show a substantial and sharply growing literature in the 1880s and 1890s before the airplane was a proven technology. The most common language in this literature in this period was French, followed by English and German. Over time a growing fraction of the articles in this selected sample were about kites or gliders, not balloons.

In the next table we see the journals which were most represented in this bibliographical list.

Aeronautically relevant journals

These periodicals appear most frequently in the bibliography entries in Brockett (1910). The counts are approximate as the data is being cleaned up and organized. Sources: Brockett (1910) ; Library of Congress's *Aeronautical and Space Serial Publications* (1962) ; Wikipedia ; Hathitrust; archive.org; and other Web searches.

Journal	When	Where	Article count (Brockett 1910)
L'Aérophile	1893-	Paris	1390
Zeitschrift für Luftschiffahrt	1882-	Berlin; Vienna	1101
Illustrierte Aëronautische Mitteilungen	1897-1931	Strasbourg; Berlin	1065
L'Aéronaute	1868-1914	Paris	822
Wiener Luftschiffer Zeitung	1902-1914	Vienna	623
Bollettino della Societa Aeronautica Italiana	1904-	Rome	535
Aeronautics	1907-1921	London	441
Aëronautical Journal	1897-	London	415
Scientific American	1845-	New York	383
La Conquête de l'Air	1904-	Brussels	343
Aeronautical World	1902-1903	Ohio	315
Compte Rendus de l'Académie Sciences	1666-	Paris	191
Bulletin of the Aerial Experiment Association	1908-	Nova Scotia (AEA)	157
La Revue de l'Aviation	1906-	Paris	147
Flight	1909-1917	London; (Aero Club of UK)	130
American Magazine of Aeronautics	1907-1915	New York City	102
L'Aeronauta	1896-1899	Milan	95
Revue de l'Aeronautique	1888-95; 1900	Paris	87
American Aeronaut	1907-8; 1909	St. Louis; NYC	81
Aeronautical Annual	1895-1897	Boston	68
Ballooning and Aeronautics	1907-	London	63
Prometheus	1889-1921	Berlin	56
Report Board Smithsonian Inst	1846-	Washington DC	53
Nature	1869-	London	50
Dingler's Polytechnisches Journal	1820-	Stuttgart	38
Monthly Weather Review	1872-	Washington, DC: (US Army, US Dept of Agric.)	37
Mechanics' Magazine (and J. of Engineering)	1814-1871	London	44
Automotor Journal	1896-	London	26
Vozdukhoplavatel (Aerial Navigation)	1880-1889	St. Petersburg	24

What did they talk about in these articles? What would a scholar of "aeronautics" be indexing in the early 1900s? I have begun to classify the works based on their titles, or in rare cases from the contents. Thousands of these articles are available online at Archive.org, Hathitrust, or Google Books. Many more are available at the Library of Congress or other libraries and archives. It is too early to emphasize hard counts of articles by keyword, but many key identifying words, concepts, or themes are clear:

- Thousands were about **ballooning**, and include words such as balloon, aerostat, dirigible, airship, or Zeppelin in the title (or words that translate to these).
- Many articles were accounts of a **voyage**, trip, or ascent.
- Many say they are doing **science** with words such as science, research, theory, test; at least 330 refer specifically to meteorology or the upper atmosphere. Meteorology which was the field for which flying craft were most likely to be cited as being useful already.
- On the order of 410 refer to **experiments** or some near equivalent.
- More specifically, many refer to some **measurement** such as duration, weight, altitude, height, temperature. With this keyword we see much overlap between the more scientifically professional person and the hobbyist/experimenters who wished to do science and improve human knowledge. The attachment to precise and accurate measurement is noteworthy in many nineteenth-century technical works in other fields too.[16]
- Perhaps 500 refer to **motors**, engine, propulsion, or propellers
- The idea of a **machine** (or equipment) are referred to in the titles of perhaps 600.
- Examination of **birds**, animals, fish, insects – or references by metaphor – occur in perhaps 280 titles.
- The idea of **navigation**, control, steering comes up in over 400 titles, often in the phrase "aerial navigation". Aerial navigation sometimes included ballooning; the phrase "flying machine" was more focused on fixed-wing craft.
- Key developments, in retrospect, were focused on **wings, kites, gliders**, or soaring. On the order of 700 refer to these in the title**.** This is only about 6% of the total.

Research is continuing to analyze changes over time, especially of articles on wings and gliders, and to collect focused information on their authors.

Patents in the aerial navigation field

There are several national collections of patents related to aeronautics. Nominally patents are publications which make claims of intellectual property, but nineteenth century aeronautical patents seemed to have no traction as intellectual property. I do not

[16] I have noticed the tendency to over-report measurements in iron and steel journal articles in the 1860-1885 period. (Meyer and Johnson, 2007 presentation)

know of any fixed-wing aircraft patent through 1905 which earned any license revenue, and the Wrights seem not to have faced any patent infringement claims. However as a particular kind of engineering publications they are directly useful to track. A new combined database of 1200 patents before 1910 is under construction and being coded by content. It comes from several sources which have judged the patents as relevant to aeronautics. There are some differences in those judgments and the coverage across Germany, Britain, France and the U.S.; some analysis will be forthcoming shortly.

Researchers Simine Short, Gary Bradshaw, and colleagues have collected a list of early U.S. patents related to aircraft.[17] The patentees with more than two aircraft-related U.S. patents through 1906 were Eugene Falconnet with 6, Watson Quinby with 5, and William Beeson, Albert Blackman, Cairncross, Fest, and O'Brate with 3 each. None of these inventors had any publication listed in Brockett's *Bibliography*. Chanute's book refers to work of Quinby work and Beeson but did not treat it as valuable. The Wrights' publications do not refer to these inventors. Modern histories of the airplane do not normally mention any of them.

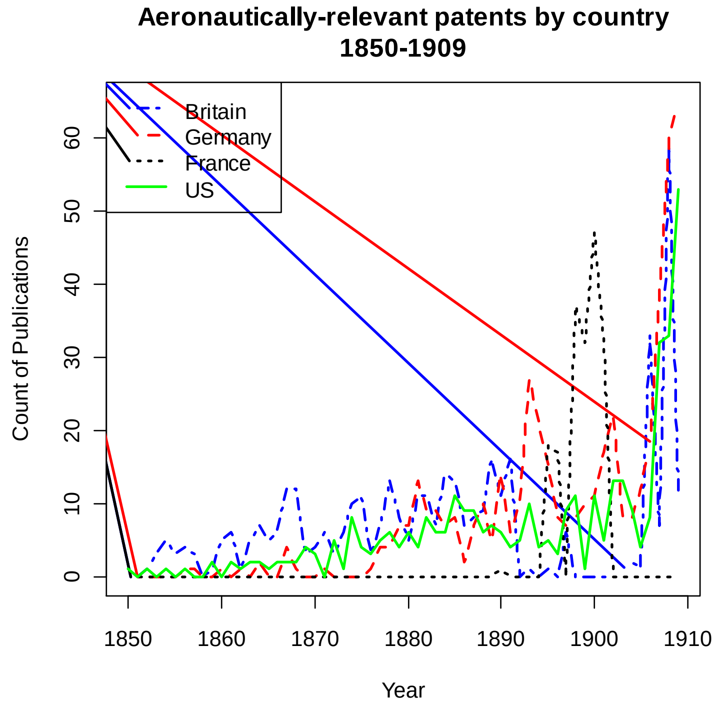
The Otto Lilienthal Museum has collected a database of German patents by aircraft experimenters.[18] It is not perfectly comparable to the U.S. table because it includes patents on other subjects by the same people. In particular, most of Otto and Gustav Lilienthal's many patents were for steam engines, and they were well represented both in the patent count and to the open literature. Apart from those two, the names of the most frequent patentees on this list were little referenced by Chanute or the Wrights and do not arise in a conventional history of the invention of the airplane.

An 1893 collection of descriptions of 250 British patent filings 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 stringing to master the great problem of aerial navigation."[19] Several of these patentees (and occasionally the patents themselves) were referred to in Chanute's book and in the literature of the 1900s.

Finally for France we have a number of patents reported on in the publication *L'Aerophile* from 1895 to 1901.

This casual environment changed after the Wrights' 1903 patent which was granted after much back and forth in 1906. Their patent was interpreted broadly by the U.S. courts and they 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 intellectual property.

[17] The list is available at http://invention.psychology.msstate.edu/PatentDatabase.html.
[18] It is online at http://www.lilienthal-museum.de/olma/pat_ar.htm.
[19] Brewer and Alexander (1893).



Patents sources:

- Simine Short and Gary Bradshaw data online, and Tom Nicholas dataset, for US
- Bernd Lukasch and Otto-Lilienthal Museum for Germany
- L'Aerophile and L'Aeronaute issues, for France
- Brewer and Alexander (1893), for Britain

Was this an information commons?

Hess and Ostrom (2006, pp 3-7) define an *information commons* or equivalently *knowledge commons.* Like other commons this is a resource of shared among a group of people, roughly analogous to a joint natural resource, but no one permanent unique right to it nor to keep it secret. Certain characteristic problems of commons can appear in this space, which they identify: congestion, free riding, enclosure, conflict, overuse, and pollution. One difference is that information is not a "subtractive" resource; unlike natural physical resources, the use by one person of information does not take it from others.

Can we think of the common institutions and literature of the aerial navigation experimenters as being a commons space? It fits some aspects of the definition but not others. The network's information was freely floating, not expensive, not subtractible, not particularly excludable, and de facto relatively free of intellectual property rights – meaning, critically in the engineering context, *free to copy*. In these ways the information in the literature was like a commons.

But unlike a formal commons, where some materials are explicitly shared, there is no overarching authority which recognizes it or enforces it. Explicit governance was occasional and sometimes anarchic.

Unlike other commons, the boundary of the aeronautical materials was not sharply defined, substantively or by journal. (Were examinations of bird weights and wing sizes in bounds or out? What about bats and snakes? Balloon voyages? Experiments with model helicopters and rockets? Kites? Gliders? Theories of wind flow? Meteorological equipment? Submarine propeller designs? The participants faced technological uncertainty and did not have a fully agreed on definition; all these were treated as relevant by somebody.) The commons metaphors also imply that the shared resource is useful or valuable. But the aeronautical works were of value to relatively few people at the time; it was a specialized hobby or professional activity and indeed they were not all trying to build what we now think of as an airplane. In one model of

Finally, there were not well-defined sanctions (punishments) for violating the norms of using the shared materials. There were formal rules within many of the clubs, journals, or national organizations, but across the world there were no common rules or common enforcement. The norms in the cultural context, which can be called "soft law"[20] had some characteristics:

- It was commonly knowledge that the participants believed in scientific progress, expected future machines to be useful, and believed it was appropriate for them to invest their own time in actively bringing this about. Participants would not need to justify their efforts to one another; it was self-evident what they wanted to do.
- This applied to a particular period (perhaps 1866-1910) and subject matter (flying machines). It did not apply to all activities of these individuals nor all times.
- It was often understood that if an experimenter was keeping key secrets of his findings, he was implicitly choosing not to support progress by the others. There were gentle criticisms of this, e.g. by Chanute against Clement Ader.[21]
- A participant in the commons, by implicit definition, was one who showed up at meetings, or wrote letters to the others, and especially published articles with new findings, discoveries, designs, or inventions. There were hundreds or more likely thousands of such persons; the others were non-participants.

[2020] An example of a soft law is "Academic works should footnote sources." The exact meaning is ambiguous and context dependent, the enforcing authority is not always clear, and enforcement is occasional and ad hoc.

[21] Ader was a successful inventor of telephones in France who with military financing made a series of large craft designed like a bat, with flapping wings and a powerful engine. Such craft were tested in 1891 and 1897, and the craft bounced into the air. Much later, claims were made that it had really flown but based on reports of the time and the design of the craft and the test this does not seem plausible. (Gibbs-Smith, *Clement Ader*). The relevance here is that in Chanute's 1894 book, it was already apparent that Ader was applying military levels of secrecy to the project and was also not learning the lessons from the commons. Thus he was not a participant in the commons,

- By that definition we can identify some aircraft-designers who were doing relevant technical work but did not participate in the commons: Chuhachi Ninomiya (Japan), and Richard Pearse (New Zealand) were far from the other experimenters and generally out of touch. Other experimenters did not know about them. Their work would have been of interest but they did not publish in ways the others could find. In retrospect they did not contribute to the actual invention of the airplane and its industry. Better communication capabilities (like the Internet) would have have improved the social efficiency of invention by letting them participate.

- Another set of nonparticipants were those who deliberately withdrew from the commons. Clement Ader did publish in the 1890s, but then became secretive as he worked for the French military. Some years later, Langley and the Wrights also became secretive when they were near critical experiments and optimistic about success.

- Presumably there were sanctions against dishonesty since this did not help progress. We know, afterwards, there were criticisms of Gustave Whitehead and Augustus Herring on this basis.

- Copying designs was permitted. The Wrights copied the Chanute-Herring 1896-7 craft.[22] Chanute copied a number of predecessors. Ferber et al copied the Wrights, imperfectly. This was an important norm which helped the technology progress.

- Similarly copying of text materials seemed to occur without much difficulty. Many of the articles in the Brockett bibliography were republished or reprinted, and it not clear what accommodations were made for copyright rules. (In Brockett's bibliography, some entries list multiple journals associate with the same author, date, and article title; these must be simple reprints. In other cases an author, and article title are in multiple journals or issues at about the same date, and each is its own entry in the bibliography. For quantitative work it is necessary to figure out if there are different meanings here or if they should be standardized the same way. Ongoing work will address this, slowly.)

- There was no norm against charging money for things, such as journal subscriptions, memberships, materials, and gliders (sold by Lilienthal).

A formal definition of an information commons also leaves out key effects of the communications among aeronautical experimenters. It required energy to participate and to experiment, and local support systems were naturally lacking – many or most people thought such efforts were *hopeless* or *useless* (wouldn't work; or might work but wouldn't accomplish anything) – and they knew for a fact it was *dangerous*. With journals, clubs, letters, one-on-one visits, exhibitions, and conferences, experimenters were *encouraged.* Chanute seemed to take it on as a mission to encourage others. The same is true of other episodes of collective invention, or open source innovation: Steve Wozniak invented the Apple I because *the other Homebrew Computer Club members*

[22] Evidence: Wilbur Wright's letter to Chanute in 1900. Also statements by Chanute later, and by Zahm later. The evidence became disputed only when there was a patent case, but the basic facts are clear.

would be impressed and interested. Linus Torvalds continued development of the Linux operating system because *other people asked him to and offered support, encouragement, and useful effort*. Richard Stallman started the GNU project to change the world and make software freedom possible, and sustains the effort for years because other people buy in and want it to work.[23] The point of this discursion is that the definition of information commons per se is flat and rulebound, as if it were not fundamentally important in an innovation context that the works and humans have an interactive life to them – whereas alternative models of open source innovation, collective invention, know-how-trading, and gift exchange can incorporate fundamentally the idea that participant A puts in effort and information *because he expects B to, also*; and that the result will be not only information but also joyful or useful.[24] Which models are achieving the first-order effects we need the most? The question is open for empirical research – from examples we may observe whether information commons have these interactively constructive effects. In the aerial navigation case, the experimenters were devoted and interested, and this was prior to their contact with one another.

The Wright brothers and their inventions, 1900-1906[25]

Wilbur and Orville Wright enter the story in 1899 when, inspired partly by Lilienthal, Wilbur takes a specific interest in the possibilities of winged aircraft. He wrote to the Smithsonian Institution for information and they replied with substantial reading material and advice on the prior literature 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 like Chanute's design of 1896.[26] The Wrights studied the behavior of this kite at length. Sticking with the same basic design, the Wrights 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. The wings were like Lilienthal's and Chanute's, made of canvas stretched over wood frame. Their aircraft were not designed to be very stable intrinsically, but rather to depend on frequent adjustments of the wingtips by the pilot; in this way their aircraft were like bicycles, which they knew well. Progress required (like Lilienthal's) experience in the air, and the development of a skill of piloting this kind of aircraft.

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[23] The literature of narratives is vast and similar anecdotes can be found in Levy (1984), Meyer (2003), Wozniak (), Torvalds and Diamond (), Stallman's book and essay in in DiBona ().
[24] Sources on these models, or accounts, include Allen (1982); Nuvolari (2004); Meyer (2007); Harhoff, Hinkel, and von Hippel (2002), von Hippel (1987), von Hippel and Schrader ().
[25] This section draws from Jakab (1990) and Crouch (2002).
[26] 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."

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 optimized wings and propellers possible.

The Wrights participated in the open, collective inventive process in ways similar to those who had advanced the field previously. They discussed technical issues and previous work with Chanute frequently. They 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 publications in 1901.[27] Published papers of the Wright brothers refer often to Chanute, Lilienthal, and Langley.[28] They refer much less often to other individuals, although they were familiar with previous work.

Transition from "information commons" or "open source" dynamics to industrial competition

Within the context of this unorthodox activity of aeronautics, 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 depend on many predecessors including Penaud, Hargrave, and Lilienthal; the Wrights explicitly copied Chanute's design. Before the Wrights' big success, Ferdinand Ferber has already imitated it based on Chanute's enthusiastic descriptions and pictures. Ferber's work was central to the later successes of European aviation.[29] Copying was fuzzy and imprecise, not precise and bit-for-bit in the software sense. Imitators usually worked from verbal or photographic descriptions, and learned more details by collaborating personally. Patents existed in the background. Sometimes an innovator had explicit permission to copy another one's work; often not, and in many cases we do not know. They do not seem to have discussed issues of intellectual ownership much in writing; this framing was not very relevant to what they were trying to do.

Successes came from the open literature but there were many attempts at secrecy too. After 1901 Langley prepared for a large scale experiment and became more secretive.[30] 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

[27] Anderson (2004, pp. 110-111) argues that one of these was an important contribution to the field of aeronautics.
[28] Jakab and Young (2000).
[29] Gibbs-Smith (1966), pp. 54-60.
[30] Langley felt pressure not to conduct his experiments too publicly to protect the Smithsonian Institution's reputation from being tied to any exotic failures. He could not keep his experiments entirely secret since they used a giant houseboat with a hangar on the Potomac river near Washington, D.C.

> 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.

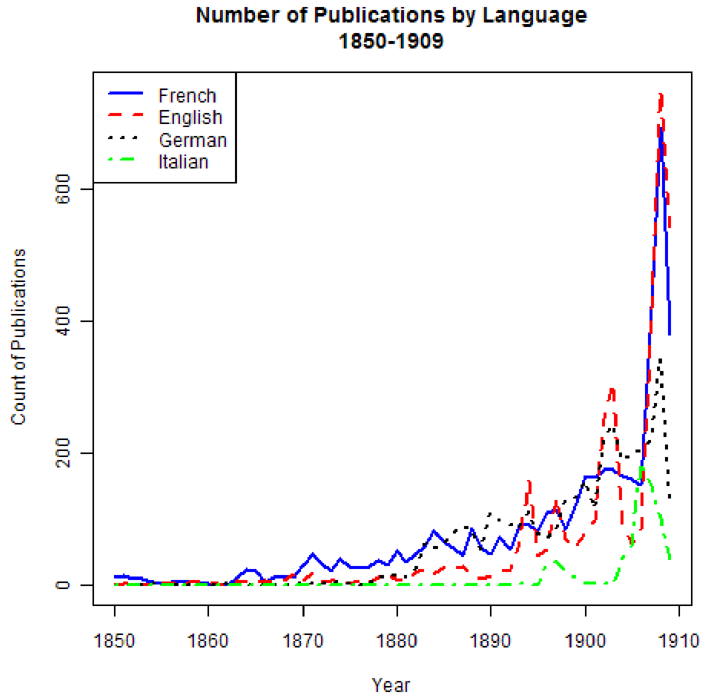
Chanute had criticized others (such as Clément Ader) who kept designs secret before, and he had conflicts with Langley and with the Wrights. Analogous conflicts occur between open source programmers, some of whom take the view that computer code must be freely available, and others who for various reasons 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 to make long term large contracts, and founded a company to manufacture airplanes. By the time they got going, other such companies were also making airplanes and they were in competition both over intellectual property and in an infant market for airplanes.

1907-1910: new dynamics and the rise of a new industry

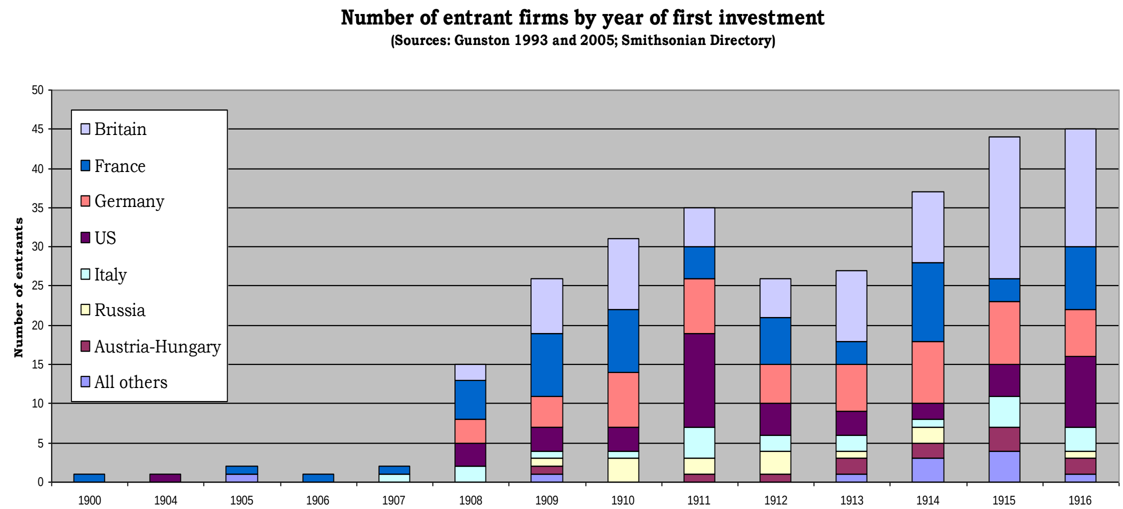
Several data series indicate the beginning of a new airplane industry – in which there were real firms, attempts to make a profit, and in a context where intellectual property means something. The annual number of aeronautical patents increased sharply in 1907 in U.S. and German data, and continued to rise afterward.

The number of publication annually also rose sharply and permanently. In the Brockett (1910) data, publications from the second half of 1909 are not included which is why there is a decline at the end of the graph; in fact the numbers of publications continued to boom and data from a later volume, Brockett (1921) will someday give us a count of the next years. The most common language of these publications, starting in 1908, was English, taking over from French.



In 1908 there were large public demonstrations of airplanes for the first time. It quickly became established to newspaper readers in all the industrial countries that such flying machines were possible; many thousands saw flights in 1908-9. For many people in the public the next years must have been a time when their mindset or beliefs changed, from thinking that fixed-wing aircraft was improbable and useless, to thinking that it was feasible activity and industry. In the language of Hannan, Carroll, Dundon, and Torres (1995), the new industry was perceived suddenly as legitimate.

In 1908, a burst of airplane-making firms appear across the industrial countries. Fewer than a dozen were founded in 1907, but in 1908 there were more than 30, and on the order of 60 a year after that. 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 arose also: exhibition companies; flying schools; makers of engines, propellers, other parts, and models; consultants; and service firms offering maintenance and repair. No single source creates a database of these companies; the author and assistants have collected preliminary lists, summarized in the next chart.



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 not one of the major contributors to the information stream in the 1890s was a central figure in the infant industry of 1910. The participants in the *commons* were different from the *entrepreneurs and managers*.

This sharp turn in the history of technology and industry seems to result from the combination of both (a) great technological uncertainty and open-source/tinkering behavior before the transition, and (b) 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 and industrial competition; but the key knowledge necessary to fly was not in fact licensed from one place or closely tied to any particular intellectual property.

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 automobile companies about the same time. In a study of automobile startups in the U.S. about the same time, Klepper (2009) defines *spinoffs* as a firm whose principal founder(s) came from another related firm, and defines a *diversifying* firm as one that has another line of business before it branches into the new field. Spinoffs by this definition make Detroit into a center of automobile production. Future research will evaluate the degree to which the new aircraft companies were spinoffs or diversifying firms.

Rapid growth followed. Chadeau (1987, p. 435) estimates that there were 57 airplanes and 95 airplane motors produced in France in 1909; 316 and 1050 in 1912;796 and 2355 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 were in 1909 (Head, 2008). Most of the demand in both countries came from the military, and there were also private buyers and revenues from ticket sales for exhibition. In these years there was not yet significant revenue from passenger service, mail delivery, or freight.

Modeling the open source period and the new industry

To an extent, then, the invention of the first airplanes 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 transition to industry is a essential new element.

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"[31]) 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, standardization of designs and terminology, evangelism, editing and moderation of joint journals, clubs, and interaction.[32]

A private company might share private knowledge without payment, for several reasons discussed in the collective invention literature.[33] However, that literature does not describe the behavior of networks of individuals operating outside organizations.

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[31] 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 a workable *dominant design*, as defined by Abernathy and Utterback (1978), by 1909.

[32] These are "networks of tinkerers" in the model of Meyer (2007) which formally models agents who choose to form such networks. These tinkerers willingly trade their time and investments to ease working together and lower costs by standardizing, modularizing, and specializing. They may evangelize to bring others into the inventive network. Such voluntary technical situations call for specialization, without reference to prices or markets, contrary to Adam Smith's assertion that "the division of labour is limited by the extent of the market."

[33] Collective invention is defined and discussed in Allen (1983), Nuvolari (2002), and Meyer (2003). Know-how trading (von Hippel, 1987) is similar. Among the reasons a company would do this: (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 does not expend the costs or effort necessary to keep its privately developed information secret (which is hard 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) To establish desirable engineering standards even if it requires upgrading a competitor's technology. Network effects of features can justify this, as documented in Meyer (2003). (6) The firms follow

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 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. 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 against any imposition 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.

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 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 the new industries are mainly populated and started by others, not the early experimenters.

Conclusions

The legal definition of open-source software does not apply to the pre-history of the airplane, when information was either freely shared or published and patented. However, the mode of technological advance in flying machines in the nineteenth century has other similarities with open-source software:

- Experimenters are autonomous (not subject to 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.

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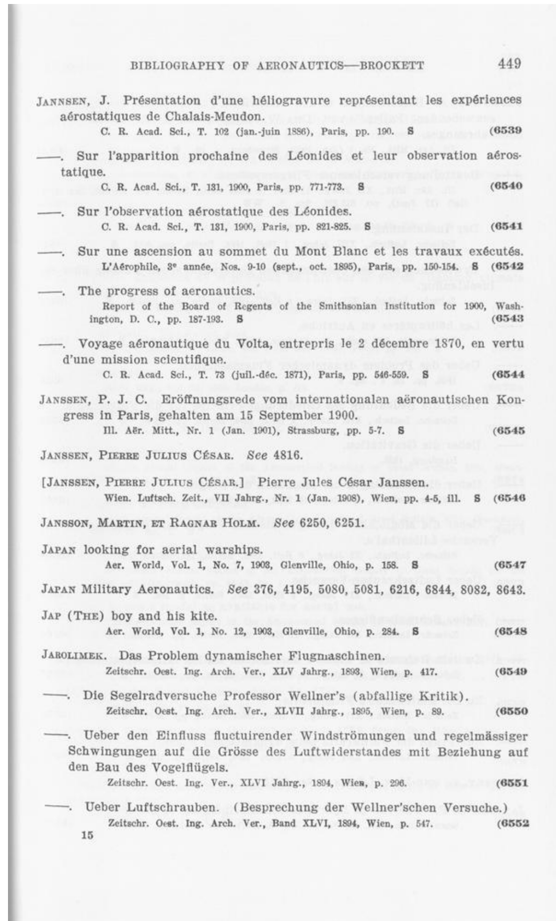
different paths of research and they expect future innovations to depend on some of the advances made outside their own firm, as in Nuvolari (2002) and Bessen and Maskin (2009).

- 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. Intellectual property 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) and during the invention of the personal computer (Levy, 2001). In Britain, during the Industrial Revolution, technical progress was supported by a relatively free press and a flowering of many scientific and technical societies with hundreds of thousands of members. (Inkster, 1991, pp 71-79; Mokyr, 1990; Mokyr, 1993, p.34; Mokyr, 2009). We see such dynamics also in the cases of shared content on the Web, such as the Wikipedia, where layers of software support easy collaboration.

In the airplane case there were phases of development. Dispersed experimenters have the basic design idea starting from about 1800. By 1870 there were institutions – clubs and journals – which treat this vision as a recognizable, legitimate, focal topic of discussion. Around 1895 there were 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 occur around 1905. Startup companies appear in numbers in 1908 and quickly industrial dynamics appear, including intellectual property claims, investments in manufacturing capital and revenues.

When there is no clear business model, because of technological uncertainty for example, open-source innovation naturally proceeds faster and more cheaply than directed research and development could. Therefore the phenomenon is recurrent, and future new-technology industries may relate to their scientific and experimental forerunners in the same way. Because the support infrastructure is better, they can start more quickly than in the past.



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Data appendix 1

Brockett (1910) has 940 pages of bibliography entries that look like the page at right.. These were digitized by several libraries, including the University of Michigan and Cornell University. The digital scans were dense with errors, notably because accented characters were rendered as English characters only. I have combined the files, corrected these characters, and converted the resulting file into a database in which we have, for most of these publications, the title, year, authors, and selected keywords coded.

Data appendix 2

Counts of aeronautical societies

	Aero clubs or societies started					world total
Year	France	Germany	Britain	US	all other	ever started
1887	1	0	0	0	2	14
1888	0	0	0	0	0	14
1889	1	1	0	0	0	16
1890	0	0	0	0	0	16
1891	2	0	0	0	0	18
1892	0	0	0	0	0	18
1893	0	0	0	0	0	18
1894	1	0	0	0	0	19
1895	0	0	0	1	0	20
1896	0	2	0	0	0	22
1897	1	0	0	0	0	23
1898	2	1	0	0	0	26
1899	0	0	0	0	0	26
1900	1	0	0	0	2	29
1901	1	1	1	0	4	36
1902	4	2	0	1	0	43
1903	0	1	0	0	0	44
1904	1	1	0	0	3	49
1905	3	3	0	1	2	58
1906	2	0	0	3	2	65
1907	5	3	0	7	5	85
1908	11	0	2	18	5	121
1909	19	2	6	53	12	213
1910	37	32	38	54	35	409
1911	2	0	1	13	2	427
1912	0	0	25	5	3	460
Total	101	51	74	156	78	

These include ballooning societies that included "aeronautical navigation" and "flying machine" sections at some point. Ten clubs started in Italy, ten in Switzerland, eleven in Austria-Hungary, and eight in the Russian empire.

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