A Pre-history of the Airplane Industry

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May 2010
Preliminary and incomplete – please do not cite[1]

Abstract. The airplane was invented after decades of effort by experimenters in many countries. The experimenters, inventors, and authors who contributed to the airplane's development shared information. Hundreds of relevant persons can be identified by citations in an 1894 survey book, a 1910 bibliography of aeronautics, and by the works of historians. Their importance can be inferred roughly by the frequency with which each one is cited by others and by historians. Many aircraft patents were filed in the 1800s and but they are not cited much and did not seem to be significant as intellectual property but rather as publications. The Wright brothers and other inventors depended heavily on publicly available information. Starting in 1908, around the time of the first large public airplane demonstrations, a wave of aircraft-making firms appeared. Few of the earlier experimenters started firms.

Introduction

For decades before there were functioning airplanes, there was serious discussion about how to do it. Over time, basic design ideas became established on how to make a controlled, fixed-wing, heavier-than-air powered flying machine that could carry a person. Hundreds of experimenters, theorists, and other authors contributed to a somewhat disconnected literatures on this topic. Journals, books, visitors, clubs, conferences, and visits welcomed and informed those who tried to make working aircraft starting in the 1860s.

They communicated actively and linked up across borders. In the 1890s, the most active participants become definitively aware of a large network of experimenters. In their writings, citations of work by others became much more common. If we have to pick one moment, it is convenient to date this change to 1894, when a well-known book called *Progress in Flying Machines* was published by Octave Chanute. It had a broad

[1] Views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Bureau of Labor Statistics. The author thanks, for valuable advice: Tomonori Ishikawa, Leo Sveikauskas, and participants at seminars at the BLS, the Midwest Economics Association, BEA, the Naval Postgraduate School, the 2006 International Economic History Congress, the OSSEMP 2007 conference, the 2007 SHOT conference, the 2007 Creativity and Entrepreneurship conference, the 2008 User and Open Innovation conference, and the U.S. National Air and Space Museum.

survey of the field, globally. After that point, the important experimenters were linked up to one another in what we can think of as a global network of information about the events, issues, and problems of controlled, fixed-wing, heavier-than-air craft.

In the decade of 1900-1909 there are many "firsts." Notably the Wrights have a controlled powered glider flight in December 1903 which is often considered the first flight. They obtain a key patent in 1906. Large public demonstrations occur starting in 1908-9, sometimes offering prize money.

An industry appears starting in 1907, with the beginnings of a long wave of startup companies appearing. Associated with this are legal battles over intellectual property, which had not previously been relevant in the fixed-wing aircraft field. By 1910 we have some statistics of revenues, which grow sharply over the years. The wave of startup companies looks in a statistical sense like other such technologically-enabled waves, with a big spike of entrants in just a few years, and a long slow process of exits. Our data ends in 1916 but the major shakeout does not occur until the 1920s.

The core questions to be addressed in this incomplete paper are about how much we can show statistically about how the new industry relates to the earlier period of experimenters, hobbyists, and scientists. It may be a useful example in which we have careful documentation over many years of the development of an open-source-type technology which led to an important industry. Scientific and hobbyist networks are in the pre-history of other industries, notably computer and software industries now.

Many perspectives on this are possible from data. From various sources Ceceile Richter and I have gathered a list of 350 firms founded before 1917. In most cases we expect to be able to identify their founders. A *Bibliography of Aeronautics* (Brockett, 1910) lists more than 13,000 publications related to aircraft before 1909. Furthermore, hundreds of patents were filed for aircraft in the 19^{th} century. These sources can be made into databases but the databases are incomplete at this point.

The airplane case is well understood historically. There is much clear and detailed original documentation and historical research concerning the Wright brothers and the world around them. The Wrights read key works by Otto Lilienthal, Samuel Langley, and Octave Chanute. Chanute's 1894 survey book of the developing field of aerial navigation describes the information flow available to developers of fixed-wing aircraft as it became increasingly feasible to build what we now think of as an airplane. We can trace some of the knowledge, where it came from, and the networks of innovators who produced it. A useful reference frame is to envision the information that was available to the Wright brothers.

This sharing of information, which supported progress toward making an airplane, has several parallels to open source software development:

- Contributors are autonomous and geographically dispersed, with their own objectives or projects. Individuals among them may be called experimenters, tinkerers, hobbyists, or hackers.
- Contributors are drawn to the activity or technology because of its charisma or potential, and did not previously know most of the other participants.
- Contributors shared inventions and discoveries without explicit payoffs.
- Some contributors found intellectual property institutions to be detrimental to inventive activity.

Creative experimenters and hobbyists have advanced some technologies to the point that entrepreneurs can start important businesses on the basis of the new technology. For example, hundreds of experimenters and researchers tried to advance aircraft technology long before the product was generally useful. Similar forces were in play among early personal computer developers in the 1970s, and in current open source software projects such as Linux, email transmission tools, browsers, and other Web software. This paper describes the network of individuals who gradually invented the airplane to provide support for an abstract model of open-source invention.

1860s to 1890s

A discussion about fixed-wings aircraft became about 1800 based on the early designs of George Cayley. The fixed-wing idea is an important change from designs that appeared more natural or intuitively plausible at that time – birds and balloons. Balloons were well known but could not be made to move in quick controlled ways. Designs with flapping wings ("ornithopters"), though appealing, were too weak and difficult to make.[2] It turned out to be more practical in engineering terms for fixed wings to provide lift while speed is provided some other way. For a glider, speed comes from gravity in the wind, and for a powered model it could come from propellers or (in theory) jets. The power system might be from the human, or from an engine, or in a model from wound-up rubber bands. Separating the speed-generating system from the lift-generating system turned out to be an important design idea, although for many of the thinkers of the time it was counterintuitive.

Local clubs on ballooning ("aerostatics") existed, and related clubs on the subject of fixed-wing craft formed in France and Britain starting in the 1860s. A society on aerial locomotion and navigation had 400 members in 1865 (Marck, 2009, p.37). Such societies continued in various forms for decades although they were not always so fashionable partly because there was not much technical success.

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[2] Several experimenters were convinced by evidence that flapping wings could never be nearly as efficient as fixed ones, and this is apparently correct according to later aerodynamic science. Other metaphors existed – rockets were known, and helicopter designs were known, but these were not central to the fixed-wing discussion. The line of thought that turned out to work proceeded directly from kites, to gliders, to powered gliders.

Key innovators in this period include Alphonse Penaud, Louis Mouillard, Lawrence Hargrave, Samuel Langley, Otto Lilienthal, and Octave Chanute. It is helpful to describe them a bit as individuals to understand the dynamics of innovation here, because it looks so different from hierarchically controlled research and development. These were self-motivated men, coming from a variety of backgrounds and locations. They did not have a joint plan, or even an agreed-on vision of what they were trying to make.

Alphonse **Penaud** was a young French engineer who in the 1870s made small winged flying models, powered by wound-up rubber bands. He demonstrated that for these to follow a stable trajectory in an air flow, they should have not only a set of wings for lift but also a tail with wings of its own for guidance. This was sometimes called a Penaud tail, afterward.

Louis **Mouillard** was a French man living in Algeria then Egypt in the 1870s and 1880s. He studied birds at great length and measured their weight and their wings. He thought about how which kinds of glider wings would best carry a person, and ran experiments from hills with his own sets of wooden wings. These did not work out well, but he wrote a book about the birds and his experiments which became well known among subsequent experimenters.

Lawrence **Hargrave** of Sydney, Australia, was able to retire young on the basis of his inheritance and devoted himself for decades to the development 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. Gliders of the time were made of light materials – usually wood covered by cloth. They were unstable in the wind. By designing them to have the structure of box kites, they could be more stable. This is part of the justification for the biplane configuration, with one wing on top of the other. (This structural advantage is nowadays generally irrelevant because jet airplanes are made of strong metals, and biplanes experience so much more drag than monoplanes that biplanes are no longer used.) Some researchers think biplane configurations were more common after Hargrave's experiment, and that Hargrave's results should be given the credit. In related experiments Hargrave showed that the lift from several connected box kites could lift him into the air.

Hargrave made one early effort to patent an aircraft design. He was advised that it was probably patentable, but that the design was not very practical and it would cost an estimated 150 pounds to do it. After this experience, Hargrave decided to publish results from all his experiments and patent nothing. He thought 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 just expensive and unhelpful to place stakes on intellectual property. He took an open-science kind of view (quoted in Chanute, 1894, p. 218): "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."

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 and engine were expensive, and the houseboat which held the aerodrome was 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 public 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, p. 293).

In some these decisions Langley made choices that the designer of a modern passenger jet would make – strong steel materials, large wings, and a powerful engines. But it meant he was also not able to tinker and iterate designs very much. His pilot, by definition, had almost no experience and was really only a passenger.

Engineer Otto **Lilienthal** rose from humble beginnings to start a company in Berlin to make steam engines. He also 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*.

Starting in 1891, Lilienthal began to make hang gliders and to fly them from hills in and near Berlin. He did not mind if people came to watch, and 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.[3] Lilienthal

[3] 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.

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.

A note on motivation and incentives of these experimenters

For characterizing this process of invention as economic history it is helpful to think about motivation and incentives. These and other experimenters had various motives, but mainly they seemed to be very 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, and make it a better place, e.g. by making travel across borders easier so that people would get along more easily and perhaps this could bring about 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.

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. A valuable additional fact discussed in the next section is that they got in touch with one another others, 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 nations, 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 including the Wrights patented their inventions, though until the Wrights aircraft patents brought no substantial revenue. Lerner and Tirole (2002) have taken the view that the contributions of open source developers can be explained by expectations of extrinsic rewards. 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.

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 or a few thousand were specifically trying to contribute to making a heavier-than-air, fixed-wing aircraft. The early experimenters are unusual, sharply selected by their distinctive interest in the project of flight and their belief that they can to contribute to it. It seems they have an interest in the end goal itself, whether they personally reach it or not. This helps explain why they would share their findings and innovations with others in clubs and journals and networks as discussed in the next section.

Octave Chanute and the open information network

After becoming independently wealthy from railroad work, Octave Chanute became a writer and experimented with flying machines. In a series of articles he wrote about glider flight. He combined these into book with the optimistic title *Progress in Flying Machines* which was published in 1894. It had an important effect by surveying and organizing an earlier literature together. While the books of Langley and Lilienthal are insightful and precise, 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 moderator, identifying key persons and technologies and evaluating them. He or his book would put aircraft builders in touch with one another. He was infused with the idea that by communicating and cooperating, experimenters around the world would make success possible. Describing Chanute's speeches and writings, Stoff (1997, p. iv) wrote that they were "noteworthy for fostering a spirit of cooperation and encouraging a free exchange of ideas among the world's leading aeronautical experimenters."[4]

Progress in Flying Machines cited almost 200 experimenters or kinds of aircraft from around the world. The frequency with which the book referred to various persons, a kind of citation count, provides a metric of their importance 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

[4] Similar technology moderators, with similar ideologies, appear in other cases of collective invention, summarized in Meyer (2003). 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 1800s in Cornwall (Nuvolari, 2002). Alexander Holley was a consultant and 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. Linus Torvalds founded and ran the Linux development project. 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.

These "citation counts" are a quirky measure but they have the advantage, for a disinterested analysis of such an invention process, that they come from a book finished before the Wrights or other significant airplane builders had even begun experimentation. Therefore the list does not depend on the pattern of future successes. Its members are not selected or ordered on the basis of later successes. But the list does look like people who were either significant or connected by other criteria.[5]

At the beginning of 1894 an influential book is published which reviews the field in a global way. Other bibliographies literature reviews are published around the same time, and there is a general upturn in the size of the common pool of information and the number of publications. It is convenient to mark 1894 as the beginning of a period in which the search is unambiguously understood to be global, and the most successful experimenters were informed about a range of past experiments internationally.

Chanute visited and corresponded with many of the key experimenters cited in his book. He had met Mouillard in France in the late 1880s and even sent money to him (Marck, 2009). Chanute visited Lilienthal, Langley, Santos-Dumont, Ferber, Huffaker, Herring, and Maxim. He corresponded by letter with Hargrave, Mouillard, Montgomery, Cabot, Zahm, Kress, Wenham, Moy, Pilcher, Means, the Lilienthals, and the Wrights. These letters almost always referred to experiments, experimenters, or related technical subjects. After such collegial or mentoring relationships he became a mentor himself. Once the Wrights contacted him, Chanute maintained a strong relationship with them as shown in the next table.

Counts of letters or telegrams between Octave Chanute and the Wright brothers

	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910
Wrights to Chanute	7	8	29	22	24	24	33	16	7	3	4
Chanute to Wrights	5	30	34	25	29	37	37	19	9	4	2

Source: McFarland (1953)

Who do aviation histories cite?

The next table comes from indexes of 15 books devoted to the history of fixed-wing aircraft and related developments from a variety of perspectives. These books make

[5] Such criteria include: the lists of works and people the Wright brothers read and referred to; the authors of the most publications on the subject of aerial naviation; the most-cited persons in histories of the invention of the airplane (discussed later). Another criterion is the frequency of references in the letters to and from Otto Lilienthal. Schwipps (1985) has collected this correspondence which was sometimes aided by brother Gustav who knew English and who traveled more. They corresponded with other experimenters such as Americans James Means and Octave Chanute. In the Schwipps book, the name Octave Chanute appears on 49 pages, James Means on 35, Augustus Herring on 29, Samuel Langley on 24, Robert W. Wood on 15, Karl Muellenhoff on 11, Carl Diestbach on 10, Samuel Cabot on 9, and Hiram Maxim on 8. Otto Lilienthal never knew the Wrights, who began experimentation after his death, but their names appear in the book too, for example because they sent $1000 to his widow in thanks for his great achievements.

approximately 9300 references to people, places, or institutions. This gives a kind of super-index of the set of views which primary historians have taken about who was relevant to these stories. It does not represent an individual historian or a consensus, but gives us a sort of frequency distribution of citations by observers who care and are well-informed. The table below lists the most-cited inventors, except that it excludes the Wrights because I have not standardized on how to count Wilbur, Orville, and "the brothers," and because some of the books are close to being biographies of the Wrights. This list overlaps heavily with the people most cited in Chanute's book. The list is restricted to people and institutions which were relevant to aircraft before 1909, although unfortunately it includes some references to events after 1909.

References to persons or institutions before 1909 in the books below, combined:

Last name	First name	Page references
Wright	Wilbur and Orville	*
Chanute	Octave	215
Lilienthal	Otto	167
Blériot	Louis	144
Langley	Samuel	135
Curtiss	Glenn	131
Stringfellow	John	117
Cayley	George	100
Voisin	Gabriel	80
Smithsonian Institution		80
Herring	Augustus	76
Patents		65
Manly	Charles	62
Bell	Alexander Graham	61
Zahm	Albert	60
Penaud	Alphonse	53
Ader	Clément	50
Maxim	Hiram	49
Means	James	44
Brearey	Frederick W.	44
Wenham	Francis Herbert	41
Hargrave	Lawrence	39
Mouillard	Louis	36

Sources:

Chadeau's *De Blériot À Dassault: Histoire de l'industrie aéronautique en France, 1900-1950*. (1987 pages 20-78) ; Chadeau *Le Rêve et la Puissance: l'avion et son siècle*. (1996, pages 11-78) ; Crouch's *A Dream of Wings* (1981/2002) ; Dale's *Early Flying Machines* (1992) Garber's *Wright Brothers and the Birth of Aviation* (2005) ; Gibbs-Smith's *The Invention of the Aeroplane*. (1966) ; Hallion's *Taking Flight* (2003) ; Head's *Warped Wings*, (2008, first sections) (mostly about patent battles with Wrights after 1909) ; Hoffman's *Wings of Madness* (2003) (biography of Alberto Santos-Dumont) ; Jakab's *Visions of a Flying Machine* (1990) ; Marck's *Passionnés de l'air: Petite histoire de l'aviation légère ;* Penrose's *An Ancient Air* (biography of John Stringfellow) ; Randolph's *Before the Wrights flew: the story of Gustave Whitehead*. (1966) ; Runge and Lukasch *Erfinder Leben* (2005) (biography of the Lilienthal brothers) ; Shulman's *Unlocking the Sky* (biography of Glenn Curtiss)

There are a variety of measurement issues not yet well addressed in this table:

- It does not screen out all references to people and events occurring after 1909.
- The indexes of biographies naturally either over-count, or under-count, the subject. (An undercount results if the index to the biography does not list its main subject; an

overcount is implicit in a biography which discusses the person's life history in detail apart from their specific role of contributing to a technical network.)

- Closely affiliated people are often referred to together, not separately. Notably, the Wright brothers are often cited as a team. The same measurement problem arises for other pairs of brothers to some extent (the Montgolfiers, Lilienthals, Tissandiers, and Voisins).

Fifteen turns out to be nowhere near enough to reach stability in the statistics, if stability will ever arise.[6] I am accumulating other sources (in different languages) are in the process of being incorporated into future drafts of this table. Part of the goal is to see what the overall population looks like, and not just emphasize the most-cited important people. Hopefully it will be possible to conduct analytical regressions in which we can predict the likelihood of a reference to an individual based on the book's language and country and whether the book is a designated biography of particular individual(s). By estimating these effects and adjusting for them it may become possible to produce less-nationalized measures of the significance of an experimenter, which should help give more stable results.

Future research: *Bibliography of Aeronautics*, 1910

A giant book by Smithsonian librarian Paul Brockett lists more than 13,000 publications related to aeronautics before 1910. The text was fortunately scanned online but with many errors (e.g. the absence of diacritical accents on characters). I am cleaning this up and making a database out of it. For each publication it will be possible to include as variables the author, year, publication, language, and country of publication. This will document the participation of these persons and others in an active open literature that contributed to the rise of the airplane, and again support the use of regression techniques.

Patents in the aerial navigation field

Patents are open publications, and they also represent claims of intellectual property. We can measure their relevance to an advancing technology in a variety of ways, such as (a) whether they are cited by other patents or other publications, (b) whether they earn license revenues, (c) whether their presence affects the stock market value or other measures of wealth by their owners; and (d) whether the specific persons who get patents are also important by other measures to later technological advances.

Imagine that the important advances in aircraft had been patented, over a period of decades, and built on one another until a final advance made the airplane viable. Then we would expect that the most important inventors would be well represented in the list of people who earned patents.

[6] Galenson's somewhat analogous work in *Historical Methods* drew from 40 sources in art history.

Researchers Simine Short, Gary Bradshaw, and colleagues have collected a list of early U.S. patents related to aircraft.[7] Here are the counts of those patents by those inventors who had more than two patents, excluding patents which were granted after 1907 and therefore did not contribute to the original invention of the airplane.

Inventors with the most aircraft-related U.S. patents before 1907

Inventor	Patent count
Falconnet	6
Quinby	5
Beeson	3
Bell	3
Blackman	3
Cairncross	3
Fest	3
O'Brate	3

The patent list provides a very different list of names from those cited by Chanute the Wrights, or by Chanute, or by historians of the invention of the airplane. Indeed the only one of these names to appear at all in standard histories of the invention of the airplane is that of Alexander Graham Bell who did take a detailed interest in aircraft, but before 1903 mainly as a friend and ally of Samuel Langley, and then as a conductor and organizer of experiments after 1903.

The Otto Lilienthal Museum in Anklam, Germany has collected a database of German patents by aircraft experimenters.[8] It is not perfectly comparable to the U.S. table because it includes patents on other subjects by the same people. Otto and Gustav Lillienthal had many patents on steam engines and on wings as well. My understanding is that four of these thirty or so patents had to do with aircraft, and almost all the rest had to do with steam engines. The Lilienthal brothers were well represented both in the patent count and to the open literature. Apart from those two, the names of the most frequent patenters on the German list do not arise in a conventional history of the invention of the airplane.

The central figures in the Wrights' perception of the field – Chanute, Langley, and Lilienthal, had written books providing technical information which was in essence in the public domain. Another experimenter, Hargrave, chose on principle to publish his experiments and not to patent his inventions. Chanute, an advocate of transparency, synthesized a summary of the state of the art. These accounts provide one perspective, that the airplane was invented through an open-source process, in which a patent might be important in the same sense a publication is, but it does not have importance as intellectual property, because its technology is uncertain and unproven. The airplane was not invented by a series of owned steps of intellectual property; rather, the key technologies were de facto in the public domain. I do not know of any case in which patents on fixed-wing aircraft granted up through 1905 earned any license revenue.

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

There would be a sharp change. The Wrights filed for a patent in 1903. Their patent application did not make direct reference to any previous inventor or patent. They did receive the patent, which was expansively interpreted and which was tremendously valuable and strongly affected the development of aircraft afterwards. It is clear that patents as intellectual property were important once an industry started. There was then a sharp rise in patenting of aircraft in data starting in and after 1907, but by then the basic technological uncertainty had been resolved because airplanes were known to work.

The Wright brothers and their inventions, 1900-1906[9]

Wilbur and Orville Wright of Dayton, Ohio had always been interested in mechanical matters. After trying a variety of enterprises, they started a bicycle shop in 1893. They never went to college, and apparently did not have much interest in establishing themselves as engineering professionals or academics. They did however have an active bicycle workshop, and became familiar with steam engines and other high tech activities of the time.

In 1899, Wilbur Wright took a specific interest in aircraft, and wrote to the Smithsonian Institution to ask about what he could read about this. The Smithsonian responded with substantial information, and the Wright brothers then searched the literature on the topic. The Wright brothers then maintained an interest in aeronautical problems partly because of the success of other people who had established so much about what a passenger aircraft should be, had gathered the necessary technical information, and defined and dramatized the prospects.

The Wrights wrote to Chanute for information, and continued a long correspondence with him for years afterward. These letters have helped historians describe what happened technologically. The Wrights also wrote the Smithsonian Institution for information about previous written work, and to the Weather Bureau to locate a windy location for flight tests.

The published papers of the Wright brothers, collected in Jakab and Young (2000 refer many times to Chanute, Lilienthal, and Langley. They refer much less often to other individuals, although they were quite familiar with previous work. Indirectly, the books by and interactions with these particular individuals contributed greatly to their invention.

Among aircraft experimenters, the Wrights were unusually proficient toolsmiths. They were able to measure precisely what they meant to measure, better than other experimenters could. They also debated different approaches, and also collaborated intensely. Furthermore, they gave one another support when it looked like the project was hopeless.

[9] This section draws heavily from Jakab (1990), Jakab and Young (2000), and Crouch (2002).

The Wrights began by designing and studying. Then they made larger, heavier, stronger kites which could also be flown as gliders, with a person on board. Until 1903, all their aircraft up to 1903 were light and relatively inexpensive. Their wings were not solid, but were made of canvas stretched over a wood frame. They did not add an engine until they understood well how to fly the same craft as a glider.

The Wrights were not secretive during most of their investigations. They corresponded frequently with Chanute, who identified them early on as serious and potentially successful aeronautical inventors. Chanute and other aeronautical hobbyists visited the Wrights in their flight testing location on the outer banks of North Carolina. The helped Chanute and Herring test their own aircraft (Crouch, p. 253). Impressed by the Wrights' glider experiments, Chanute invited Wilbur to give a speech to Society of Western Engineers, which Wilbur did in 1901. In the fall of 1901, Wilbur helped George Spratt set up a wind tunnel to test airfoils (Crouch, p. 249). In a visit, Spratt also helped the Wrights identify a particular problem which caused their gliders to stall. The problem was that if the center of the lifting forces on the aircraft was in front of its center of gravity, the aircraft tended to point upward, lose lift from its wings, and stall. Part of the reason that airplanes have tails is to control this kind of imbalance. The Wrights knew such a problem existed in theory but did not realize they faced it themselves.

Wilbur Wright also published two papers in 1901. In a British journal he published a paper stating an important relationship between the angle of an airfoil with respect to the flow of air and the area, weight, and speed of the airfoil.[10] In a German journal, Wilbur published an article which recommended that glider pilots lie flat rather than sit, to reduce drag.

The Wrights decided to have the pilot lie flat to reduce drag. They thought in detail about the control problems as they experienced them – what to do if the aircraft were to slide sideways, or rotate because of a gust of wind. Langley's answer, like that of many others, was that the aircraft should be strong and stable. The Wrights had a different instinct. They were intimately familiar with bicycles, which are intrinsically unstable – that is, if there is no rider, a bicycle falls down. It is the combination of the bicycle and an experienced rider which is stable, because the rider responds immediately to instability. The Wrights came up with an invention to apply the same kind of control to gliders. They attached wires from the wing tips to the pilot's cradle so that, by swiveling his body, the pilot could quickly adjust the wing tips to turn the craft a little toward the left or right. With his hands the pilot also had control of a rudder to raise or lower the attitude of the glider.

These choices took the Wrights down a technological trajectory different from Langley's. Their control mechanism was light and precise, as long as the pilot knew how to react. They became trained as pilots by gliding hundreds of times into the wind from hills near Kitty Hawk. They became trained, not only cognitively but also tacitly, to

[10] Wilbur Wright, "Angle of Incidence", 1901, republished in Jakab and Young, p. 109-112. Anderson (2004, pp. 110-111) argues this was an important contribution to the field of aeronautics.

respond quickly to gusts of wind or other problems that affected the glider. They invented the aircraft *and jointly the skill of piloting it*.

They received a patent on this "wing warping" technique in 1906, and it was interpreted broadly, giving them much control over other airplane makers. But in fact, shortly after, their wing warping technique was no longer in use. Wing flaps, called ailerons, now serve the same purpose. The wing warping technique was however good enough for gliders and the very first airplanes. It enabled a pilot to take some control whether or not the glider had an engine, even while moving on the ground. That meant the pilot could have real experience, in a sense that Langley's pilots could not.

Some aspects of efficient wing shapes were known. Kites, gliders, or wings in an air flow generate more lift, meaning upward force, if the leading edge is above the trailing edge so that the flow of air pressure would hit the underside. And Horatio Phillips, Otto Lilienthal, and others had shown that a curved shape generated more lift if the highest point of the airfoil (the wing or other object in the air flow) was between the leading edge and the trailing edge. Airfoils with this curvature are said to be "cambered."

Beyond this, the Wrights found to their surprise that there was not more scientific evidence on the matter. They conducted systematic investigations of precise wing shapes in late 1901. The Wrights designed and built a small wind tunnel, whose fan was powered by a moving belt attached to their shop's steam engine. They found it hard to get a smooth flow of air. Instead there were turbulent eddies, which meant results were not well measured and not perfectly reproducible. They studied this problem at length, and found a way to arrange slats to make the air flow straight and smooth.

Inside the wind tunnel, they clamped tiny wings, carved usually of wood, to a carefully tested "balance" device which measured the lift force induced by various wing shapes. The wind tunnel and balance combination were apparently much better for testing wings than anything that had been used before. The brothers tested more than a hundred wing shapes, and arrived at an efficient lift-generating design.

Many of the experimental wings were symmetrical from front to back, looking in cross section like a thin slice off of a circle. The Wrights found they could get more lift if the highest part of the wing was near the leading edge. By one estimate, their final wing was within 2% of the "optimal" shape later computed in aeronautical simulations, given the kind of craft they had and its expected speed. (Crouch, 1989).

It took skill and effort from the Wrights, but fewer than six months. It is not clear why somebody had not done this before, but such surprises are intrinsic to new, immature technologies. Different innovators have different resources, knowledge, and interests, and an approach that seems straightforward to one person may not yet have been tried.[11]

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[11] This is a widely recognized advantage of open processes in software development. In the language of open source programmer Eric Raymond, "Given enough eyeballs, all bugs are shallow."

Airplanes need speed for their wings to produce lift. Internal combustion engines were an area of active technological development for automobiles, unrelated to aircraft. It had become clear that lightweight internal combustion engines produced more power than lightweight steam engines could, and Langley and colleagues made special effort to make lightweight engines that still had a lot of power for aircraft. The Wrights never specialized in this area. They built internal combustion engines with local mechanic Charlie Taylor, but never approached the lightest most powerful engines of the time.

Propulsion came from a pair of propellers which spun in opposite directions so as to avoid causing the aircraft itself to spin. On watercraft, propellers pushed water backwards, and thus pushed the craft forward. Aircraft makers usually assumed that propellers in the air should have the same basic function, and therefore be shaped like propellers in water. Having just conducted their wing experiments to optimize the lift generated by various shapes, the Wrights tried a different design. By giving their propeller blades a cross-section like that of a wing, they designed them to generate lift, like a wing would, but in the forward direction. This simple idea, carefully implemented, gave the Wrights propellers that delivered 50% more forward acceleration for a given level of engine power, than propellers of their contemporaries.[12] They recognized this quickly, and celebrated their find. This design idea lasted. Here, the Wrights permanently advanced the field of aeronautical engineering.

In December, 1903, they flew their powered glider in a self-sustaining flight, were able to control it, land safely, and fly again for longer and longer distances. Though this aircraft was a great invention, many aspects of their design were abandoned soon afterward. One example was the control mechanism of warping the wings to control the craft in a turn, or to return it to a straight line if it rotated. Their pilot lay down on the lower wing of their first powered gliders, but this design was abandoned and after 1908 the pilots would sit up in Wright or other airplanes. Thus the Wrights were not simply "better than" other aeronautical experimenters. Rather, they accomplished qualitatively different things which were uniquely valuable at the time. They were not permanently technological leaders of flight.

Exiting from the "open source" dynamics

Langley felt under pressure not to conduct his experiments too publicly because the Smithsonian Institution should not be associated with exotic experimental failures. It was hard to keep them entirely secret since they involved a huge houseboat with a hangar, and experiments were conducted on the Potomac river near Washington, D.C. He tried to keep technical details secret after 1901.

As he developed his final aerodrome, Langley shared his wing design with Chanute, asking Chanute to keep the details secret. Langley believed this was a good wing design. Entirely against Langley's permission, Chanute – a believer in keeping information open – forwarded the wing design to the Wrights, who by then were experts on wing shape.

[12] Anderson (2004, pp. 140-142), and Jakab (1990, pp. 194-5),

The Wrights thought the wings were not well shaped. Partly because of the new secrecy at both ends, however, Langley did not learn this.

Starting in late 1902, the Wrights also clamped down and became more secretive. Crouch (p. 296) infers that this was because they foresaw their great 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 the demonstration of . . . success on the dunes in 1902 had changed their attitude.

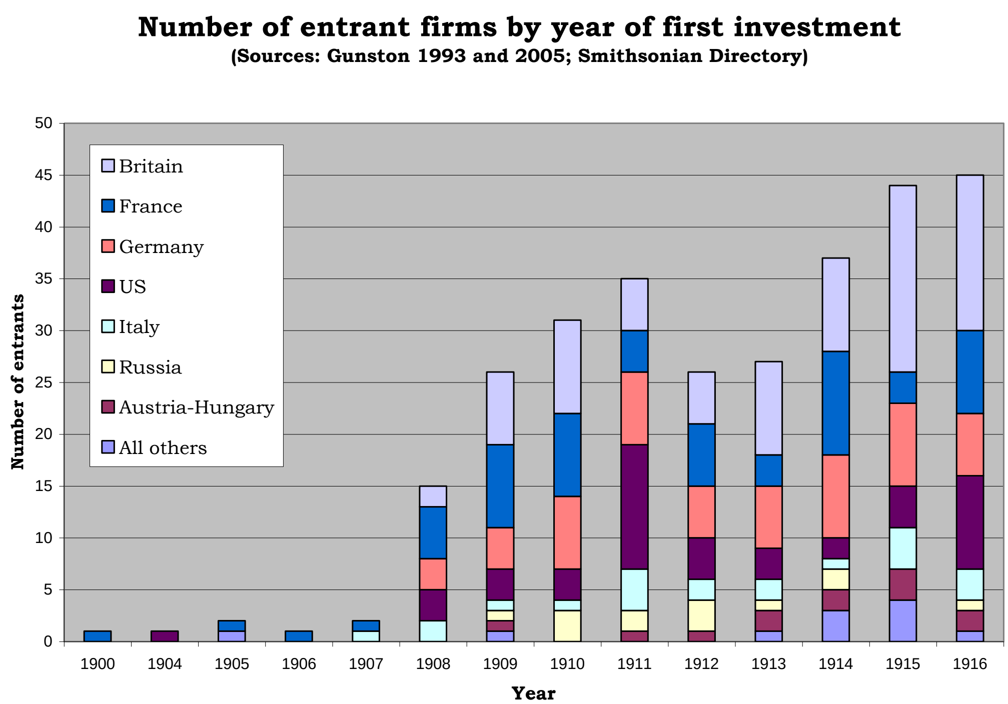
In becoming more secretive, the Wrights created a disagreement with Chanute. His point of view remained that aircraft design information should be made public. Indeed they eventually had a lifelong split from him, although he had been an important supporter. They applied for a patent in March 1903, received it in 1906, and started an aircraft business. Chanute had criticized others who kept secrets before, and he began to have conflicts with the Wrights. These conflicts grew severe and in the end, Chanute and the brothers were no longer on speaking terms. Similar 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.

The Wrights then contacted the military in various countries to make long term large contracts, and founded a company to manufacture airplanes. Bt 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 and the rise of a new industry

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 is perceived suddenly as legitimate. In data not shown here, it appears starting in 1907 there was a sharp rise in the flow of patents on aircraft.

In 1908, a burst of airplane-making firms appear across the industrial countries, immediately dwarfing the number that had ever existed before. More than 25 firms worldwide per year enter the incipient industry for each of the next several years. Differences across countries seem relatively small; the initial burst and subsequent flow looks similar in Britain, France, Germany, the U.S., and elsewhere. The next chart summarizes the flow of new firms by country based on preliminary data on airplane makers. The year of the entrant firm is measured by the first identifiable date in which its founders make a profit-oriented investment into a firm, not the later date of a product launch (in the rare cases that these can be distinguished).



These data on the new firms are under development; for early versions of a data working paper see Meyer (2010). There were a spectrum of privately provided services to add to the data in time: exhibition companies; flying schools; makers of engines, propellers, other parts, and models; consultants; and service firms offering maintenance and repair.

In preliminary research so far it seems that few of the founders of these new firms were experimenters in the period before 1900. We can identify hundreds of experimenters, authors, theorists, and patentees in the 1800s. These lists overlap little with the list of founders, designers, and funders of the new companies in the period starting in 1908. Surprisingly it seems that none of the major contributors to the information stream in the 1890s a central figure in the infant industry of 1910.

Such rapid change or obsolescence is unusual in histories of technological development. This unusually 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. I am endeavoring to quantify the degree of transition and to identify individuals who participated in both phases.

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., Klepper (2009) defines a *spinoff* 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. With these definitions, Klepper shows that Detroit's centrality in the automobile business, and Silicon Valley's centrality in the semiconductor business, arise not because these industries started in those locations, but because firms there generated many successful spinoff companies. The aircraft field was never so localized, but it may be able to measure its rate of spinoffs in a comparable way and this may have contributed to its rapid success. (Note that the field was already large before heavy use of aircraft in World War I.) Using definitions like Klepper's, I hope to quantify, or at least find upper and lower bounds on, the numbers of the new firms which are spinoffs and diversifiers.

Chadeau (1987, p. 435) estimates the numbers of airplanes and aircraft motors made in France starting in 1909. Rapid growth follows.

	Airplanes ("Avions")		Motors for airplanes ("Moteurs")	
	Produced	Exported	Produced	Exported
1909	57	20	95	50
1910	92	22	270	100
1911	147	33	540	300
1912	316	91	1050	600
1913	411	125	1580	1000
1914	796	85	2355	1100
1915	5111	635	8090	1000
1916	7793	241	17683	800

Industry growth in the U.S. probably started a bit more slowly but was otherwise analogous. The Wrights had a contract with the U.S. military 1909. Head (2008) reports that the first private sale of an airplane in the U.S. was in 1909. Most of the demand in both countries came from the military. Other forms of demand came from private buyers and from exhibitions which sold tickets. Passenger service and mail and freight delivery did not bring in significant revenue in the earliest years.

Modeling the open source period and the new industry

How can we model the earlier period of tinkerers and its transition into a new industry? Are there models and laws that help us understand and predict how open-source phenomena can turn into an industry? I have argued that the invention of the first airplanes was based on open-source information and networks which were like those in open source software development, and unlike formal research and development in which technical advances are kept secret or are owned and valued as intellectual property. There were a variety of patented, proprietary, and secret technology efforts, but these mechanisms either did not help, or contributed mainly through the degree to which they made a technology public, not through the price and ownership mechanisms. For example, patented work was almost never licensed, but experimenters did learn from the information published in patents.

This process matches a model of open-source technology development in which the participants care greatly about the advance of the technology itself or some other ideal, and are not mainly competing. It is helpful to assume also that the technology is not yet understood well enough for it to be clear how to generate profits from it. This assumption (a strong version of "technological uncertainty"[13]) is necessary to explain why existing firms do not directly seize the opportunity with their own research and development. If no market is established and the technical problems are too hard or unclear, existing profit-oriented firms would shy away from them. Under such conditions scientists or hobbyists will rationally share information and engage in specialization, 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 (2007b).[14]

A private company might share private knowledge without payment, for several reasons discussed in the collective invention literature.[15] However, that literature does not describe the behavior of networks of individuals operating outside organizations.

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

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[13] 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.

[14] That paper formally models tinkerers who would choose to form such networks. These tinkerers would be willing to make tradeoffs of their time and investments to achieve engineering standardization and modularization and specialization to ease working together and lower 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").

[15] 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 find it worthwhile to spend the costs or effort necessary to keep its privately developed information secret (which is hard if, for example, there is 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. See Meyer (2003). (6) The firms follow 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 (2006).

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, but only other tinkerers, then any restriction 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.

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 from others, and start directed research and development to make a product. In the model, the network may continue on if others wish to 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 and future research

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, this mode of technological advance 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.
- The experimenters share much 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 (like Hargrave, and also Santos-Dumont) deliberately avoid intellectual property institutions because they would delay progress.
- The Wrights used publicly known knowledge and technology. Intellectual property was not relevant to advances in the field until 1903.

Perhaps "open science" or "user innovation" (von Hippel, 2006) characterizes the phenomenon better. We see such open processes supporting later industry in the case of the invention of the personal computer, and in steam engine makers of the early 1800s Nuvolari (2004). We also know that in the industrial revolution period in Britain, science and technology were supported by a relatively free press and a flowering of many scientific and technical societies with hundreds of thousands of members. This description and argument is made by Inkster (1991, pp 71-79), and Mokyr (1990 and 1993, p.34). We see it also in the cases of shared content, such as the Wikipedia. The Internet, Web, and distinctive software help support easy collaboration in this case.

Setting theory aside there are prospects for a substantial database of a bibliography of aeronautical publications before 1909, and a database of the new aircraft firms and entrepreneurs in 1909-1916, and we can expect to compare those lists in the future.

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