The airplane as a collective invention

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Abstract. This study draws lessons from the network of developers and inventors who contributed information to the development of the first airplanes. Much of the information about aircraft available to the Wright brothers was in the public domain. Experimenters and researchers repeatedly contributed to this quasi-public pool of knowledge. There is an analogy to other collective invention processes such as those for open source software. This study attempts to draw stylized facts from the invention and communication process for purpose of supporting a formal model of individuals engaged in collective innovation processes, and how the transition occurs from a network of experimenters into a competitive industry. An underlying mechanism seems to be that when the technology is primitive, many players share their findings, but when the technology is advanced enough, a number of them no longer contribute to the public pool of information.

Introduction

Sometimes individuals develop important technology without an obvious revenue opportunity. For example, there were hundreds of experimenters and researchers trying to advance the technology of aircraft long before there was an industry. The same kind of forces seem to be in play among the early personal computer developers (discussed in Meyer 2003), and open source software projects such as those of Linux, email transmission tools, browsers, Web software, and many others (for many descriptions, see the social science papers at opensource.mit.edu).

This collective invention among individuals is a source of productive technological development, but there does not seem to be a model of this activity – that is, a labeling of where it comes from and any formal (that is, algebraic) mechanism for why individuals decisions generates the technological information flow, and what happens to it once there is an industry generating a real product such as airplanes or personal computers.

We do have such models for expenditures by companies, which may foresee demand for their products that would result from the research and development expenses. And in models of governments as necessary and efficient suppliers of public goods, can explain or justify research and development to achieve them. In an economic model, an expected net present value calculation can underly this decisions by organizations. For companies, the presence of competition may induce another incentive to conduct R&D to outdo the competitor. Setting privately financed R&D aside, there is a collective invention story[1] (not a formal model) in which companies would share their technology with one another in a kind of exchange, and this produces technological advance. Here no distinctive funding is required, but the account or model explains why a private company would share its private knowledge without direct revenues to repay the costs of development. There are a number of justifications in the collective invention literature.[2] All of these kinds of models characterize incentives of firms, but do not fit individuals well.

The agenda in this paper is, first, to describe the kind of information flow that was available to developers of a certain kind of aircraft as it became increasingly feasible around 1900 to develop what we now think of as an airplane. There is remarkably detailed and clear documentation and historical research on the Wright brothers and the world around them. We can trace some of the knowledge they had, where it came from, and the networks of innovators who produced it.[3] We can use this kind of evidence to arrive at some conclusions about the utility functions and social or economic environments of the people who created that knowledge, which later had a great social payoff. This summary, and the characterization of particular inventions is based on secondary sources only. Second, the agenda is to explore whether we can explain or describe in a generic way the motivations and incentives that create this the information flow. Some of this is predicted by the environment, rather than the exceptional individuals in it. By understanding how, we can discuss how far off airplanes were if there were no Wright brothers.

The Wright brothers

Having said this, it is easier to describe the network of information from the point of view of the Wright brothers, and what they saw, than to describe it abstractly. They had always been interested in mechanical things, but did not go to college, and apparently did

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[1] Defined and discussed by Allen (1983), Nuvolari (2002), and Meyer (2003).

[2] Among these: (1) Better public technology may raise the value of assets owned by the innovator. (2) The innovating firm garner publicity by making successes known; (3) An organization may not intend for its privately developed information to be released, but does not find it worthwhile to spend the costs or effort necessary to keep it secret, which is nearly impossible if for example there is substantial movement of employees between firms. (4) Publications in an open environment give employers a way to judge the contributions, skills, or certifications of a research employee which may be hard to judge directly. (5) To establish desirable engineering standards in order to achieve market power or to make a particular feature universal even if it requires upgrading a competitor's technology. Network effects of features can justify this.

[3] The Wright brothers are a very useful example to focus on, but the purpose of this is not to claim that they were first at any particular thing or that their inventions were uniquely more important than anyone else's. If the Wrights had not in fact flown, the information flow around them would still exemplify the hoped-for model.

not have any interest in establishing themselves as engineering professionals or academics. They started a bicycle shop, a relatively high tech activity at the time, in Dayton, Ohio, in 1893.

In 1899, Wilbur Wright took a specific interest in making aircraft, and wrote to the Smithsonian Institution to ask what previous research there was on aircraft. In this letter, he wrote: "I am an enthusiast, but not a crank in the sense that I have some pet theories 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." (Anderson, 2004, p. 89) The Smithsonian responded with substantial information, and the Wright brothers then searched the literature on the topic.

A key book surveying and unifying the previous research had been published by Octave Chanute (1894), a Chicago engineer who was independently wealth from his previous railroad work and took a determined interest in the aircraft problem. The Wrights wrote to him for more information, then continued a long correspondence with him for years afterward. These letters have helped historians describe what happened technologically. Jakab (1990) investigates their strengths and methods in detail, and some of this is summarized here.

Among aircraft experiments, the Wrights seem to have been more mechanically proficient toolsmiths than others. They were able to measure precisely what they meant to measure, in case after case, better than other experimenters did. The Wrights had their own active bicycle workshop with steam engine power, and yet had some freedom to leave others in charge of the bicycle shop when they wanted to take a long trip to North Carolina to fly their gliders.

Because they ran a bicycle shop, they thought constantly about vehicles, balancing a vehicle, and about riders and what they do. As we will see later this gave them an unusual and valuable perspective on what it means to be a pilot of an aircraft. They seem to have been able to think clearly both abstractly visualizing objects in three dimensions, and concretely, imagine how to machine parts and assemble them to create an object they had imagined. Although they were aware that they lived in an age of mass manufacturing, they rarely used any manufactured parts. They crafted each piece.

Jakab (1990) finds that the Wrights were effectively focused on the “design features required to make an airplane fly” – the shapes of wings, propellers, and control mechanisms. They were less drawn to scientific questions, and were not attempting to establish themselves as academics.

It helped that here were two of them, in the sense that two minds are better than one – and they did debate different approaches, and collaborated intensely. Furthermore, they gave one another support when it looked like the project was hopeless.

They followed an iterative process, spending years building aircraft for years which could fly as kites, then as gliders with pilots. They did not add an engine until late in their project, at a time when they were sure it would work. They thus benefited from the advances in internal combustion engines that were taking place parallel to their own work. In December, 1903, they flew their powered glider in a self-sustaining flight, were able to control it, land safely, and fly it 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 would rotate. Another was their arrangement of the pilot, who lay down in their first powered gliders, but in planes made after 1908 the pilots would sit up. The significance of these points is that the Wrights were not simply and totally "better than" other aeronautical experimenters, but rather to establish that they were unique, and benefited from the uniqueness of others through a social network of experimenters – and not long before, and not long after, their critical flights, others were technological leaders of this activity.

What were aeronautical experimenters developing?

Each one knows well what their resources are and what they want to do, and figures out a next step. But, as is characteristic of radical technological development, they do not know for sure what they are collectively developing. They have different ideas about what success would mean. But there were a set of metaphors and technologies guiding the imagination of various aeronautical experimenters of the 1800s as they imagined a flying craft: balloons, birds, helicopters, rockets, and kites. These seem to be different enough ideas that the networks of information about them do not exchange much information with one another.

The balloon idea suggests a light object which can ascend into the air without power. Hot-air and hydrogen balloons and dirigibles existed and were experimented on, especially in France. Small balloons were used in meteorological research, and there were services to fly tourists in big ones. But it seems that there was not much communication between balloon experimenters and the network the Wrights drew from.

In a bird model, the aircraft's lift would come from flapping wings. Chanute (1894) documents dozens of designs in which human muscles would power the wings, but these have not worked. His analysis is that birds are light and have big wings, and that humans are so heavy that they would need wings so huge that human muscles would not be strong enough to flap them. This idea seems to have been pretty much replaced by 1870 with designs in which steam engines would flap wings. Clement Ader's 1890 aircraft was a relatively successful example, designed to have wings like a bat. Apparently, it flew 165 feet. This is the last design with flapping wings that I know of. It is not clear why the idea of flapping wings goes away at that point, but perhaps it is because propellers could be driven by such powerful engines after that point that the wings-flapping idea is outcompeted. The topic does not seem to be actively explored by the time of the Wrights.

A helicopter does not have fixed, aerodynamic wings, and it needs a powerful engine to take off directly from a stationary position. An operator might have precise control of such a craft. The idea was discussed, and experiments were ongoing, but it appears that the helicopter idea was not relevant to the people with whom the Wrights actively interacted. Primitive working helicopters appeared only a few years later, as shown in the appendix.

The main line of discussion and development relevant to the Wrights had to do with kites and gliders. These are aircraft which are light, and which have aerodynamic fixed wings designed to generate lift, and which would be able to move slowly at first, then launch into the air using the lift forces. An operator might have only partial control of such a craft. They need not carry people or engines, and hobbyists would experiment both ways. There was an active international network of researchers and hobbyists experimenting with this line of devices. The experimenters communicated through books, journals, and correspondence, and the Wrights were well acquainted with the knowledge in those lines of communication.

One can imagine another network, oriented around the idea of an aircraft which was something like a rocket, an aircraft that was only somewhat aerodynamic but which had great power, especially at the moment when it was launched, and over which the operator had little control. I do not know of rocketry researchers at the time, but in the research of Samuel Langley was drawn in this direction, toward powerful engines and a rigid aircraft. Modern passenger jets are somewhere between kites and rockets, in this way of thinking. The relevance of this kind of research to the Wrights was indirect, only insofar as steam engines and internal combustion engines were advancing, and this turned out to be important to them.

Motivation of the experimenters

In a society where much technological development is conducted by large organizations and justified by future revenue streams, why would individuals develop technology on their own, at their own expense? There are a variety of answers to this which can be summarized in two lists. Here is one set of possible justifications:

- To start a company, and make money selling products like airplanes, or the entertainment service of watching an aeronautical performance
- To get revenues from patented technology
- To establish oneself professionally, and get hired as an engineer
- To earn research funding

Certainly these were relevant to some airplane experimenters. Otto Lilienthal invented the modern hang glider, and sold a few in kits. Samuel Langley had research funding from the Smithsonian and from the War department which was interested in using aircraft to spy. Many experimenters including the Wrights patented their inventions, though until after the Wrights there were not (as I understand it) any substantial revenues from any aircraft patents.

Lerner and Tirole (2002, and subsequently in various publications) have taken the view that the contributions of open source developers can also be explained in these terms. This is an extreme view, quite contrary to the self-descriptions of many open source software developers and many social scientific findings about them, collected in papers at http://opensource.mit.edu. We can think of airplane experimenters as an analogous population. In both cases, some experimenters say they are interested in other goals, not closely tied to revenues, such as these:

- The prestige of contributing to an eventual accomplishment
- To win a competition by accomplishing something
- To grapple with interesting opportunities and problems
- To attain some special experience, such as the experience of flying, for themselves
- To get the problem solved, so that others can fly. That is, they might want to change the technology available, not their own prestige, rank, or wealth in a static environment. They might want to change the world, period.

These are clearly motivators of aeronautical experimenters, and early personal computer developers, and open source developers too. Part of the reason such motivations are not much discussed in the economic literature on technological development is that there is no formal algebraic model of this activity. Indirectly this research can contribute to such a model.

Consider the Wrights in particular. In his 1899 letter to the Smithsonian, Wilbur wrote that he intended to “add my mite to help on the future worker who will attain final success.” And, in a later text, the brothers together (or Orville alone; it is not clear from the context), wrote: “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 . . .” (Wright et al, 1953, p. 87). Thus both before and after their critical inventive activities, the Wrights said they were motivated by elements of the second list, more than by anticipated successes or revenues. We cannot actually know if it was true, but they did say that.

Furthermore, there is a kind of consistent rationality about that motive and their early behavior. Many aeronautical experimenters seemed to have similar motivations, and few if any had gotten rich this way. The behavior of experimenters who devoting their time to the problem was thus rational in an economic sense if their own account of their motivations is true – that they are interested in the problem, or they love the idea of flying, or they want to help the world be a better place. If instead we think of them as being motivated by the long shot possibility of getting rich, their behavior is then poorly informed, or dubiously rational, because their behavior was so extremely unlikely to pay off financially well enough to repay even their immediate expenses.

Therefore in a formal model of this activity I propose to assume that the early experimenters are somehow distinctively interested in the particular project their network has attacked. In economic language, their utility functions justify their early interest. This then explains within a model why there are relatively few of them – that in a world of millions, only a few hundred are trying to make an airplane. Something is unusual about them or their circumstances. If we make this assumption, it helps rationalize, or clarify, why they would share their innovations with others in their own small network – they have an interest in the end goal itself, whether they personally do or do not reach it.

Octave Chanute and the open information network

For a hundred years, various engineers and tinkerers tried to figure out how to make powered vehicles carry passengers safely through the air. Many hobbyists, engineers, and other specialists devoted energy to aeronautics although there were many people who thought it was unrealistic.

A worldwide network of flight experimenters and researchers built up in the last half of the 1800s. Octave Chanute corresponded with many of them and can be thought of as an important node of the information network. His 1894 book *Progress in Flying Machines* summarized and evaluated much previous research and expressed optimism about the future of flying machines. There were aeronautics associations and journals on the subject in Britain, France, Germany, and the U.S. Chanute served as a kind of technology information moderator, for many of his correspondents since he 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]

When the Wrights entered the picture, this network made available to them much of the information that seems to have existed on the topic.[5] The Wright brothers took an interest in the aeronautical problems partly because of the success of the network in

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[4] Similar technology moderators, with similar ideologies, appear in other cases of collective invention, summarized in Meyer (2003). 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. Many other open source projects also have charismatic founders who encouraged openness and do not seize on their main chance to keep the technology secret and extract maximum profit.

[5] There is a selectivity problem in making such assertions because discoveries and innovations that did not lead into them have a tendency to be forgotten. So, in principle it could be that many important novel discoveries and inventions were not available to the Wrights. Historical research naturally has a tendency to start from the success and work backwards and might not uncover them. But the historians who have done primary research do seem to be unified on this point, and the publications in the various countries were not secret documents.

establishing so much about what a passenger aircraft would be, and in gathering together the necessary information together, and defining, dramatizing, and publicizing the technical problems. The appendix table lists many events, discoveries, and inventions that occurred before 1903, and the Wright brothers knew, or could have known, perhaps 90% of them.

The Wrights were not particularly secretive during most of their investigations, and contributed back to this network. They wrote the Smithsonian Institution for information about previous written work, and the Weather Bureau to locate a windy location for flight tests, and to Chanute for further information. They corresponded frequently with Chanute, who identified them early 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. They 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. Wilbur Wright also published two papers in 1901. In a British journal he published a clearheaded paper stating an important relation between the angle of an airfoil with respect to the flow of air and the area, weight, and speed of the airfoil. Anderson (2004, pp. 110-111) argues this was an important contribution to the field of aeronautics. Wilbur Wright also published another paper that year in a German journal, recommending that aircraft pilots lay flat rather than sit up.

Such interactions were also personal. In the fall of 1901, Wilbur helped George Spratt set up a wind tunnel to test airfoils (Crouch, p. 249). In a visit, Spratt helped the Wrights identify a particular problem that was causing their gliders to stall and be hard to control. The problem was that if the center of the lifting forces on the aircraft was in front of its center of gravity, the aircraft would tend to point upward, lose its aerodynamic profile, and stall. The Wrights knew such a problem existed in theory but did not realize they faced it themselves. Part of the reason that airplanes have tails is to control this kind of imbalance.

This evidence supports the conclusion of Crouch (p. 296), that with respect to the other aeronautical pioneers: "The brothers had been among the most open members of the community . . . . 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 whom they had every reason to believe were their closes rivals in the search for a flying machine." But by the end of 1902 the Wrights had become more careful and secretive. Before detailing this, let us look at some practical choices of aeronautical technologies.

Langley's technology choices

As a professor at the University of Pittsburgh, Samuel Langley in 1896 had a notable experimental success with his powered gliders that traveled over half a mile. He then became director of the Smithsonian Institution in Washington, DC, whose trustees allowed him to continue some experiments there, sometimes assigned to Smithsonian employees. He also apparently received some resources from the War department, which had the idea of spying from airplanes. So unlike most aeronautical experimenters, Langley's research program had considerable financial resources.

After several experiments, Langley believed he was on the cusp of sustained powered flight, and made a number of investments in making a large aircraft. He called it an aerodrome. Langley made a couple of key decisions to keep its pilot safe. He decided, like most hobbyists, that his pilot would sit up rather than lay down. More crucially, he decided that the aircraft would be stable in the sense that it would glide smoothly ahead if the pilot exercised no control, not change direction in response to tiny wind gusts.

These two basic design choices had a strong effect on the path of his research. A sitting pilot imposes more drag than a pilot laying down, so, holding all else constant, the sitting pilot required more lift, and larger wings. An intrinsically stable craft would have to be stronger and more rigid than a glider. To make it strong, Langley innovated by making the frame of the aircraft out of steel tubes, instead of wood as most glider hobbyists did. The sitting pilot and larger wings required a much stronger engine. Yet the engine could not be too heavy.

This drove Langley to draw in a top expert on internal combustion engines, Stephen Balzer, to make a light yet powerful engine. Previous internal combustion engines did not have to be particularly light because they were not meant to provide the power to lift themselves off the ground. Balzer made progress had trouble with this work. Eventually Langley was able to bring Charles Manly onto the project. Manly had recently earned a PhD in mechanical engineering from Cornell and was highly recommended. He was able to complete Balzer's engine. It delivered 52 horsepower and weighed 124 pounds.[6] Manly served as the aerodrome's pilot.

The aerodrome was designed to fly as a powered glider only. It could not fly without its one-of-a-kind engine. It was designed to be stable, and did not have much in the way of control mechanisms. It had no way to land on a hard surface without damage; a landing gear for a heavy craft would itself be a further heavy load. Langley's experiments always took place over water – the Potomac river, near Washington, DC. He had a giant houseboat-hangar built so that the aircraft could take off over water too. Because the launching mechanism fit on the houseboat, the craft had to accelerate quickly, so that within 70 feet of starting it would be airborne. (Crouch, p. 288) For all these reasons, it was not easy to experiment with the craft, and any flight would have to be a major one-time effort.

In many of these decisions Langley was making the choices that the designer of a modern passenger jet would make – strong steel materials, large wings, and a powerful

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[6] Jakab, p. 193. The Wright brothers engine in their 1903 glider weighed between 140 and 179 pounds, and delivered only 12 horsepower.

engines. But in the context of the novel technology, he was also not able to tinker and iterate designs very much. His pilot, by definition, had almost no experience. His airframe and engine were expensive. The houseboat was expensive. The aircraft was 58 feet long and weighed 830 pounds.[7] Any test flight was a big production, and put valuable equipment at risk.

In a demonstration in October, 1903, the aircraft crashed immediately after takeoff. But after further work, Langley believed that the aircraft was good enough. He invited reporters and other spectators onto the houseboat to a major demonstration in December, 1903. The wind was gusty, not good for an experimental flight, but he and pilot Charles Manly to try anyway. As the aircraft launched, something appeared to went wrong with its tail very early – it went sideways at a moment it should not have – and again the aircraft was out of control during takeoff and crashed immediately.

It has been disputed, subsequently, whether the aircraft was basically good enough for sustained flight under favorable conditions but the choppy conditions had prevented success (Shulman, 2004). It is possible that Langley felt pressured by the spectators, and decided to take an unnecessary risk to launch that particular day. His need to justify his investments may have made it necessary to invite the visitors, and the visitors made it necessary to make an attempt.

There is a sense in which Langley's approach painted him into a particular kind of corner, with a heavy, expensive, irreplaceable aircraft which could not be iteratively tinkered with, and could not easily be flown twice. In a sense, these were design mistakes. But Langley was trying to do something truly difficult, a thing that had never been done before. He had a long track record of experimenting with aircraft, and his aerodrome had the best aeronautical engine ever made.

However, after the December 1903 crash, his efforts were perceived by some as a waste of public money. Langley was attacked in a New York Times editorial (Shulman) called "Langley's Folly" which described the problem of sustained flight as essentially impossible. 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).

The Wright glider's control mechanism

The Wright aircraft evolved iteratively, from kites to gliders. They first studied and designed kites, then larger but similar gliders which could also hold a pilot on board. As their gliders became larger, they designed one that could also carry an engine.

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[7] The Wrights' 1903 glider weighed a little over 700 pounds. (Jakab, p. 204)

All of their aircraft up to 1903 were light and relatively inexpensive, and were made of carefully chosen wood and canvas. Their wings were not solid, but were made of stretched canvas over a frame. The Wrights decided to have the pilot lay flat, because this would produce less drag than a sitting pilot.

They thought in detail about the control problems as they experienced them – what to do if the aircraft were to slide toward one side, 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, because of their prior experience. They were intimately familiar with bicycles. Bicycles are intrinsically unstable – if there were no rider, a bicycle falls down immediately. It is the combination of the bicycle and a rider which is stable, because the rider is tacitly trained to respond instantly to instability. The Wrights came up with an invention that made it possible to apply the same kind of control to gliders. They attached wires from the wing tips to the pilot's hips so that by swiveling his hips, the pilot could quickly adjust the wing tips to turn the craft a little to 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 very different technological trajectory than Langley. Their control mechanism was light and precise, as long as the pilot knew how to react. They became trained as pilots of by flying their gliders hundreds of time, off of hills near Kitty Hawk, into the wind. They became trained, not only cognitively but also tacitly, to respond quickly to gusts of wind or other problems that affected the glider. They jointly invented the aircraft *and 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 the wing warping technique was no longer in use, shortly after that. 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, and even without leaving the ground. That meant the pilot could have real experience, in a sense that Langley's pilots could not.

The Wrights' wings

It was known that kites, gliders, or wings would generate more lift, meaning upward force, if they had a particular kind of shape. The leading edge should be above the trailing edge so that the flow of air would hit the underside. And further, Horatio Phillips, Otto Lilienthal, and other researchers had shown that a curved shape of a certain kind would produce more lift. The highest point of the airfoil (that is, the airplane, wing or other object in the air flow) should be above the leading edge and below the trailing edge. Airfoils with this curvature are said to be "cambered".

Many of the experimental wings were symmetrical from front to back however, looking in cross section like a thin slice off of a circle. Only a few used wing shapes in which the highest part of the wing was near the leading edge, which does generate more lift. Surprised that there was not more scientific evidence on the matter, the Wrights conducted detailed, systematic investigations into the best wing shapes in late 1901.

The Wrights designed and built a small wind tunnel. Its airflow came from a fan powered by a moving belt attached to their shop's steam engine. Like previous wind tunnel experimenters going back to 1870, when it was invented, they found it hard to get a smooth flow of air through it. Instead there would be 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 would measure the lift force induced by various wing shapes. The wind tunnel and balance combination was apparently the best of its kind by a wide margin for testing wings. The brothers tested more than a hundred wing shapes, and arrived at a design that was highly efficient at generating lift. It was within 2% of the "optimal" shape later computed in aeronautical simulations.

It is not clear why somebody had not done this before. It took skill and efforts from the Wrights, but fewer than six months. Their direct effort and success may be intrinsic to radically new technologies – effective approaches that seem straightforward to some investigator do not seem straightforward to others, or the technology is so immature and uncertain that no one had quite made the effort yet. Different innovators are operating from different axioms, have different resources. In a model of innovations, one might think of such insights as the result of a random draw which is the result of idiosyncratic histories and resources that do not need to be modeled.

The Wrights' propellers

Airplanes need speed for their wings to produce lift. Internal combustion engines were an area of active technological development apart from the airplanes – that is, apart from the network under study. It had become clear that lightweight internal combustion engines produced more power than lightweight steam engines could. Propulsion came from propellers. In many cases a pair of propellers were designed to spin in opposite directions so as to avoid causing the aircraft itself to spin.

Propellers were standard on watercraft, where their main function was to push the water backwards, and thus push the craft forward. It was apparently assumed by aircraft makers that propellers in the air should have the same basic function, design, and shape, along the lines of the shape of a screw which would be driven into wood.

Having just conducted their wing experiments to optimize the lift generated by various shapes, it occurred to the Wrights tried out a different idea. 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 power coming from the engine, than the propellers of their contemporaries.[8] They recognized this quickly, and celebrated their find. This design idea lasted. Here, the Wrights permanently advanced the field of aeronautical engineering.

Secrecy: a later phase

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 his experiments were conducted on the Potomac river near Washington, D.C. He did try to keep the 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. 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 could see how successful they had been, and infer they were close to inventing the airplane. In becoming more secretive, the Wrights had a disagreement with Chanute about this; his point of view remained that technological information should be made public. Indeed they eventually had a lifelong split from him, although he had been a meaningful backer along the way. In some tellings, Orville's later years (after Wilbur died young) were unhappy, bitter ones, engaged in patent struggles that he could have avoided, and which hindered the development of aircraft to human benefit. (Shulman, 2003).

In a similar way, members of the Homebrew Computer Club dropped out once they started startup companies such as Apple Computer (Levy, 1984). The phenomenon seems different in the open source context, where some of the source code remains permanently in the public domain, but startup companies develop other add-on code and services. The problem of secrecy or dropping out has a different appearance, there; the secret technologies can be permanently distinct from the network's technologies.

Stylized abstractions for a model

It seems difficult to model the space of possible technologies and to use identifying information about the experiments to model the kinds of progress that are possible and that occurred. To do that seems to requires ex post information about what was possible and what path-dependent experiments would get them there. Consider the propeller case.

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

The Wrights prepared themselves perfectly to confront the propeller problem and to have an apparently unique insight. This was a path-dependent result of their previous experiments and unusual experiences – it is not plain that their study of wings was intended to prepare them to confront the propeller problem. It is possible to imagine a problem space designed by a historical investigator in which the wing problem was similar to the propeller problem; that is, that the ways of addressing them were correlated although this was not widely recognized in advance.   But this is hard to do, and harder still to generalize to other cases like the development of the early personal computers.

Instead, suppose a model ignored all the details of a technological problem except the cost to produce some experimental output and the perceived quality of the output, and that a random flow of "discoveries" and "inventions" occurred to the experimenters which would improve this perceived quality. In real life, the flow of ideas and innovations depends on the experimenter's own history, as we have seen, but this would be harder to model. Someone in the population may be well positioned to make a particular necessary innovation, and then share it. If not, time passes.

Then in each round, an experimenter's technology can be represented on the horizontal axis of graph. With time, the experimenter may make inventions and his technology position would then move to the right. At each turn an innovator decides whether to make only one unit of the product, for himself, or to make more and sell them. An example of a "product" is a glider, and the experimenter has an incentive to make only one because its market value is less than its cost except for the one he makes for himself because he is interested in the problem.

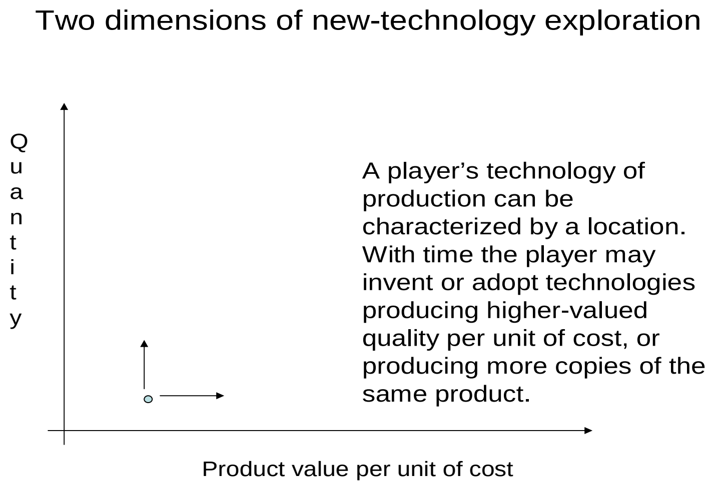

Figure 1.   In this stylized description, a player's technology is represented on the horizontal axis. The player may have opportunities to invent or adopt improvements to it, and the player's technology could then advance in rightward towards lower cost per quality-adjusted unit.

Suppose further that a sharing institution exists already, and that the hobbyist is a member of a network of people working on the same kind of product. In the real world this means that some institution, or some person like Octave Chanute is already in correspondence with knowledgeable and interested people, and that this is not a function of innovators like the Wrights themselves. That is, let us assume this process depends on the prior existence of someone like Octave Chanute, and do not try to explain his behavior in this model.

After making an invention, improving the quality of the product, suppose the innovator chooses whether to share it with others, or keep it secret. If the network is made up of people who have a special utility function and who wish to improve the product, they may endogenously find it preferable to share their technologies with others, and to receive technological information, at the beginning. The players may receive some benefit such as prestige, or a psychic joy of sharing or the satisfaction of a desire for technological progress.

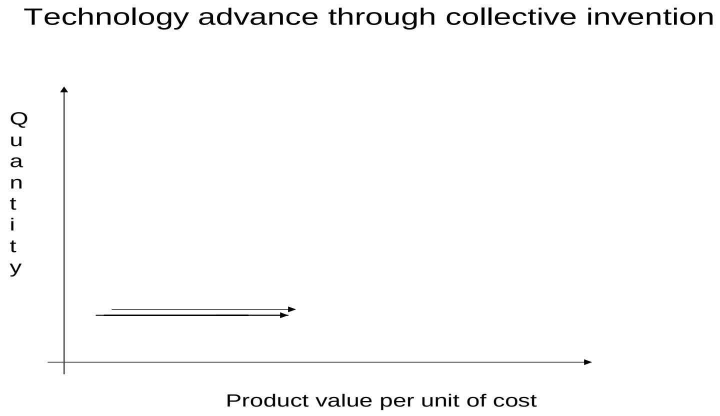

Figure 2. Players with sufficiently unprofitable technologies may advance together, sharing information, each one gaining value from information received, but losing no value from giving information away.

As long as that process continues, the public pool of information is growing and productive in the sense that it increases the value of output without raising costs.

But suppose too that there is an exogenous demand function for products of the kind they are making. As the device or product approaches some threshold of quality, a profit motive would appear. The players evaluate scenarios in which they start to sell the product in a market. If both hobbyists start businesses and sell the product, they have become competitors. Then their incentive could be to stop sharing technology. Their decision about sharing would be a function of whether they could sell the product at a profit. Within a model they might stop sharing information before beginning quantity production, because they foresee the beginning of a product market. Once quantity production begins, there is an industry.

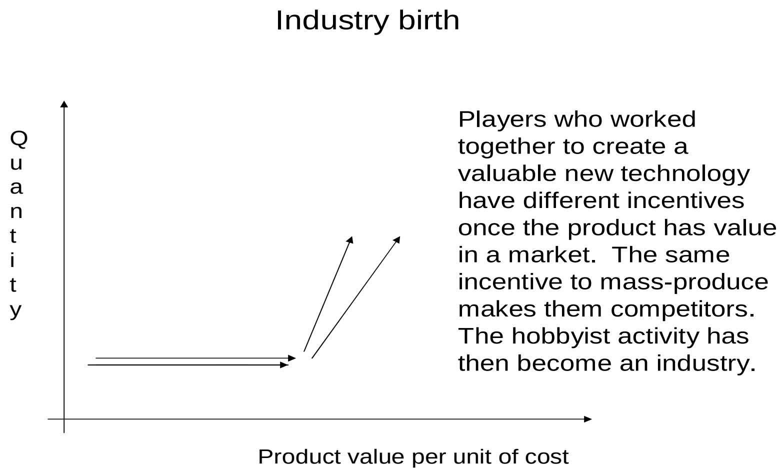

Figure 3.   After the technology advances to some threshold, a competitive regime begins.

Once the activity becomes a competitive industry, the entire network loses importance and may shrink or break up. If the sharing of inventions is a core endogenous variable, then an endogenous outcome in a successful model would be that the network self-destructs if there is enough success with the technology. Then the players are in a profit-seeking industry with private intellectual capital and may not share any R&D.

To summarize, a model would successfully reproduce the information-sharing and industrial stylized facts if it has three phases: In the first, pre-competitive phase, the players have distinctive technologies, each producing one unit of the good for use and experimentation. It costs money but each player's utility from spending the money is higher than if he did not spend it. They choose to share technological innovations and discoveries. As the shared technology approaches some threshold of technological or market success, each player wishes to be first to reach the threshold, and he drops out of the network, or at least stops sharing innovations with it.   The players are then in a kind of "race", like patent races which have been modeled in economics.   This is a second phase. If the threshold of market acceptability is reached, they pursue profit through production and sale. This is a third phase, the "industrial" stage. The transitions in the model would have analogues to transitions observed in the histories of innovation of aircraft, personal computers, and open source software.

If a model could achieve these things, it provides a framework to at least primitively demonstrate and test certain hypotheses about environmental conditions:

- Cheap and easy information sharing technologies such as journal printing, transportation to clubs, and the Web, should assist the process. If publication were expensive there the model should predict less sharing.
- When there are experimenters willing to subsidize the process, they can move the process forward much more quickly than it otherwise would go. The alternative to progress through collective invention may be no progress at all.
- If freedom of assembly or freedom of the press were not allowed, making it harder to find others with the same interests and harder to share at will, the collective invention process among individuals should slow, in the model, as one would expect in the real world, and therefore the technology should advance more slowly.
- If a society is rich, relative to the costs of innovation, there would be more collective innovation because it would be easier for the players to subsidize experimentation.
- If there is a common language (e.g. English) collective invention is easier; if not, it is slower.
- If the subject draws interest and fascination and experimenters *believe* it will work, there will be more collective invention than if they are interested but they believe it will not, in the end, work.

Conclusion

At the end of 1903, the Wrights had the best shaped wings, and by far the best propellers, of aeronautical experimenters in their network. They were also experienced at piloting gliders, using gliders very much like their powered glider, using an elegant, precise, and light control system. Their pilot lay flat, which reduced air friction. This choice was good enough to get them into the air, but unsustainable – by 1908 they and all other airplane makers had the pilot sitting up. The Wrights' engine was well-suited to their early craft but not near the best of its kind.

They had followed a technological path that got them quickly to the frontier, and past it. But they were not using the best practice in all areas, and their early craft was quirky and distinctive from the ones that came later. This seems to be characteristic of innovators who break through important barriers – they are using a technology which is standard within some social network with some unique improvements and some differences which are just unique, not improvements. Therefore terms like radical collective, or collective invention among individuals, describe their mode of technological advance.

The phenomenon of collective invention by individuals, as described here, has a number of attributes which could be modeled together. In such a model, the individuals can be motivated by utility functions that can represent a variety of real-world interests. They join together for reasons that might or not be explained in the model. Their discoveries are random. A key choice they make is whether to share their findings or not. It seems that to match the history, their choice is to share unless their discovery is large, or near to the threshold or marketability. After profits are possible, individuals have an incentive not to share.

In an extreme historicized version of this account, we might say that Octave Chanute and Samuel Langley were co-inventors of the Wright airplane since they supplied crucial information, motivation, resources, and so forth. Indeed there were hundreds of contributors to this information flow who may have been essential, at least to making the particular flight that occurred on December 17, 1903. It is not necessary to do any violence to the story as historians tell it to say it this way.

If a model would have an information flow in which innovators decided to share or not, and their choices generated a product market with a time path of events like the one shown in figure 3, it would match a couple of the stylized facts in this stylized history of the airplane's invention. Such a model could allow a variety of experiments to see the degree to which it captured other cases of collective invention.

The value of modeling the process is not to tell the history differently, or not much differently. Rather, a model gives us ways to label and discuss the economics of questions like these: How much of invention X is due to its inventor, and how much to the network from which the inventor draws information? If the famous inventor of invention X had not existed, how long would it have been before some similar invention appeared? What kinds of technological development depend on a free flow of information, free association, and free speech, rather than the well-discussed incentives built into private ownership and capitalism? And, if the open-source structure is increasingly common in software development and potentially in other areas, what does this imply for future technological improvement?

Appendix table

Informational events in the development of airplanes

When	Who	Informational event	Historical source(s)	Accessed by Wrights?
before 1600	Many	jumping with wings by many; designs and visions of da Vinci	many	generally no
1742	B Robins	whirling arm (pp16-17) and aspect ratio findings (apparently unknown to the wrights)	Anderson, pp 16-17	
1753	Benoulli and Euler	Bernoulli's eqn relating pressure to velocity of airflow	Anderson, p 42	
1759	Rouse and Smeaton	table and equation. table of force measurements on objects in air flow.	Anderson, p. 20	yes
1783	Montgolfiers	hot air and hydrogen balloons	Anderson, p.21	
1784	Launoy and Bienvenu	toy helicopter	http://www.4to40.com/earth/science/index.asp?article=earth_science_helicopter	
1799	George Cayley	Documented the idea of a fixed-wing aircraft, with a separate propulsion system. Like a kite, its wings would received the force of lift. This was unlike the long lasting vision of an aircraft with wings flapping like a bird's. Cayley experimented with whirling arms to test airfoils (shapes which in airflow generate lift). Much of this was forgotten in later years and re-discovered.	(JD Anderson, ~p26)	
1804	George Cayley	hand-launched fixed-wing gliders, with "cruciform tail" combining rudder and elevator; formulated "fundamental problem of aeronautics" which is: how to apply resistance of air	Crouch, p. 28, and Jakab	
1823	A.A. Mason	failed (but inspirational) Aerial Steamboat		
1842	W.S. Henson, Stringfellow, Chapman	Patented and publicized Aerial Steam carriage design with fixed wings, fuselage, tail, and engine+propeller for thrust.	p. 29	
1843	Cayley	first biplane; had dihedral wings (sloping up toward the tail)	P. 32	
1845	Navier and stokes	Navier-Stokes equations governing fluid flow (1822 work was little-known)	Anderson, p 43	
1849	Cayley	"Boy Carrier"	Jakab?	
1852		Paris Societe	Anderson, p.44	
1858-9	F.H.Wenham	glider with curved ("cambered") wings		
1866	British engineers	founded Aeronautical Society of Great Britain	Crouch, p. 30; Anderson p. 4	

1866	Wenham	finds superiority of long narrow wings over short wide ones in generating lift (though this is sometimes forgotten, later)	Anderson, p. 45	
1868	Britain	beginning of publication of Annual Reports of Aeronautical Society	Crouch, p. 31	
1868	Moy	identifies scale effects in aerodynamics / airfoils	Anderson, p. 46	
1869	Paris	beginning of publication of L'Aeronaut	Crouch, p. 31	
1870-71	F.H.Wenham and John Browning	developed wind tunnel	Crouch, p. 31	
1871	Wenham	found that the center of pressure (center of lift) tended to be near the leading edge of a wing -- a fact sometimes forgotten, later	Anderson, p. ??	probably
1871	Alphonse Penaud	upward sloping tail, for stability; center of pressure . . . .; understood it; had theory, created standard.	Anderson, pp. 35-37	
1871	du Temple	powered hop in France	Anderson,p.41	
1875	Octave Chanute	discovers, on trip to Europe, that European engineers treat airplane as possible	Crouch, p. 26	
1876	Penaud	cambered wing. dihedral angle 2 degrees. Was on track to further success, but committed suicide	Anderson, p. 37	
1876	Enrico Forlanini	fitted a gas-driven engine to a helicopter machine which rose to a height of 13m after a vertical take-off from the park of Milan.	http://www.4to40.com/earth/science/index.asp?article=earth_science_helicopter	
1877	Mozhaiski	Horse-drawn glider, in Russia	Anderson,p.41	
1883	Osborne Reynolds	analysis of "laminar" (smooth) versus turbulent air flows	Anderson, p. 44	
1884	Mozhaiski	powered hop	Anderson, pp. 41-42	
1888	France	beginning of publication of the Revue de l'Aeronautique	Crouch, p. 31	
1889	Lilienthal	published Birdflight as the Basis of Aviation and data on lift coefficients	All	yes
1890	Clement Ader	Piloted, steam-engine-powered airplane, the Eole; no controls; wings moved like a bat's	Anderson, p. 51	
189x?	Hargrave	box kite	Jakab, p. 55	
1891-96	Lilienthal	hang gliders	many	yes
1894 Jan	Chanute	Publication of Progress in Flying Machines	Stoff, p. iv	yes
1894	Hiram Maxim	Flying machine	Anderson, p. 4	
1896	Chanute and Herring	adapted Pratt truss to gliders	Stoff, p. iv	yes
1896	Chanute/Herring	two-surface, double decker wings	Jakab,47;54-58	yes
1896	Samuel Langley	steam-powered unpiloted one minute flight over Potomac	Anderson, p.5	yes
1897	Arnot and Herring	Indiana gliders	Crouch, p. 210	

1898	Langley and others	internal combustion gasoline engine found better than steam engine for lightweight power	Anderson, p. 143	yes
1899	Wright brothers	wing warping for control of rolling motion; contacts Smithsonian	Jakab, p. 54	Yes
1900 Mar	Wrights	Wilbur Wright contacts Chanute	Stoff, p. vi	Yes
1901	Dumont-Santos	Flight of dirigible in Paris		
1901 Jul	Wilbur Wright	Publishes on “angle of incidence” in *The Aeronautical Journal*.	Anderson, p. 109	Yes
1901 Oct	Wrights	calculation of Smeaton coefficient; wind tunnel and wing tests; and Lilienthal re-calculation	Jakab, circa p. 130	yes
1901	Balzer & Manly	high powered light engine, best ever at the time	Anderson, p 144	no
1903 May	Wrights	Wrights blade-element propeller, 50% more efficient than contemporaries; apparently highest recorded to that time, because of the wing-shaped curvature of its cross section	Anderson, p. 141	yes
1903 Dec	Langley and Manly	public demonstration of aerodrome; crashes before sustained flight; *New York Times* editorial, "Langley's folly" says success could take a million years	many	yes
1903 Dec	Wrights	self-powered sustainted flight, with takeoff and landing at same level	many	
1904	Wrights	tested new versions at Huffman Prarie	many	
1904	Robert Esnault-Pelterie	Experimented with wing flaps called ailerons for control of aircraft	Shulman, p. 34	
1906	Wrights	receive patent on wing warping	Shulman	
1907	Louis Breguet, Jacques Breguet, Charles Richet	"built a helicopter . . . which [reached] 2m above the ground, but it was very unstable."	Judy Rumerman, at http://inventors.about.com/library/inventors/blhelicoptor.htm	
1907	Paul Cornu	First piloted helicopter, uncontrolled	Judy Rumerman, at http://inventors.about.com/library/inventors/blhelicoptor.htm	
1911	Italy	First use of airplane in war by Italy against the Turks in Tripoli		
1913	Pegoud	upside-down flight; "loop"	Shulman	
1914	Curtiss & Zahm	attempts to reconstruct Langley's aerodrome	Shulman	

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