

Industrial Reversals of Fortune: The Meaning of Invention in the Early Airplane Industry

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Abstract

Though the airplane was invented in the United States in 1903, the early commercial industry was dominated by European firms. This “industrial reversal of fortune,” where the eventual industry arises in a different location from the technical invention, is common in business history, but is generally blamed on policy mistakes. In the case of the airplane, explanations have included lawsuits resulting from the wide breadth of the Wright Brothers’ patent, and a lack of government support via military procurement. We propose an alternative, via theory and a novel database of airplane-related microinventions: locations with the resources required to develop an invention may lack the resources to develop that invention to commercial viability, and policies which privilege the technical invention to the commercial development can therefore be counterproductive.

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1 Introduction

On December 17, 1903, the Wright Brothers famously achieved the first controlled, powered, heavier-than-air flight at Kitty Hawk, North Carolina. This technological achievement did not immediately lead to a commercial aviation industry, an outcome which would require a further decade of development across many dimensions of the plane's design. However, despite the Wrights' invention occurring in the United States, the American industry withered. In 1914 there were only 168 aviation workers in the entire U.S., producing 49 planes which were far from the state of the art (Morrow, 1993). Only a single American design would be flown by any country during World War I. This collapse is even more incredible since, by nearly any metric, American designers had technological superiority until 1908, and perhaps until as late as 1910.

These "industrial reversals of fortune," with a commercial industry developing in a completely different geographic location from the industry's keystone invention, are quite common in the historical record. Indeed, American firms have often been the beneficiary, as both film (Bakker, 2005) and steel (Bessen and Nuvolari, 2012) saw critical inventions made in Europe, only to have firms on that continent lose early industry dominance to American producers. Such a loss of technological leadership in a booming industry is important to explain given the continued role of government policy in the development of infant industries, particularly its role funding basic research with the understanding that the fruits of such research might benefit local firms. What explains why some technical achievements lead to industrial clusters in the region of the invention, while others see the industry, its jobs, and its rents shift to distant shores?

The airplane, like many important inventions, involved a series of minor and major technical breakthroughs, rarely arriving in a predestined sequential order, leading eventually to a commercial product. These microinventions encompass ideas that may be obvious and in the air, or alternatively ideas that are the province of a rare genius.² They may involve significant R&D spending to elucidate or may involve simple recombination of existing knowledge. What is critical is that the *economically important* steps in the invention process may be quite distinct from the *technologically important* steps, and that the ex-post assignation of a particular nexus of microinventions to a single designer, or to the creators of a single element in this nexus, is not merely a

¹From the essay "Fate" in *The Conduct of Life*. It is perhaps not well-known that the same Emerson piece is the source of the saying, relevant to the present essay, that "ideas are in the air."

²With a nod toward readability, and with apologies to Joel Mokyr (1990) who coined the term microinventions in a way that specifically excludes scientific discoveries, from now on I will use "microinvention" to mean both individual steps or improvements in a more general product, and individual minor scientific discoveries which, at least potentially, could have aided the development of that product.

sociological quirk, but a tendency that can mislead the historian and feed back through policy in a way that creates real economic harms.³

In particular, consider an invention which involves a series of components - in the case of the airplane, there is the engine, the materials, the control mechanism, and so on. In order to invent the airplane, it is necessary that each of these components is sufficiently advanced to pass the technical milestone of getting the plane into the air briefly in a controlled way. On the other hand, a commercially viable airplane necessitates each of these components to be at a higher level of development, with production cheap and safe, and with the capability of performing auxiliary value-increasing tasks. If a nation is to see a technological breakthrough lead to a commercial industry, it must possess firms with the ability not just to create the original breakthrough but also to create the full nexus of microinventions between that first step and the commercial product, or the potential to import these techniques. A particular technological leap occurring in a particular location tells us very little about whether firms in that location collectively have any advantage in the necessary next steps of the innovation process. In a policy sense, Teece's (1986) complementary assets story applies to the nation as well as the individual firm, with nations possessing deep understanding of the components underlying the initial invention best equipped to expand that invention into a commercial product. Note further than the marginal improvements just necessary to achieve the technical invention may be economically inconsequential: if a powerful engine exists, it is the Wrights' control mechanism that "invents" the airplane, whereas if the control mechanism had been learned earlier, it would have been the inventor of a suitable engine who was given credit for the invention. But the airplane required both components, and hence it is unclear why differential reward should be given depending on which one is invented first and which is invented second.

This frame suggests that explaining the collapse of the U.S. aviation industry requires investigating the components which make up the eventual commercial airplane, and the state of knowledge on those components across nations and time. Further, it requires understanding why, if nobody possesses all of the requisite knowledge, firms from certain areas are able to integrate the outside knowledge, while firms from other areas are unable to do so. I attempt such an explanation using a novel dataset of aviation-related microinventions from 1897 to 1917. My explanation relies entirely on the underlying states of knowledge in different locations, and differs from standard explanations for the poor performance of the early aviation industry, of which there are two.

³The difficulty of defining "the" invention has been considered by sociologists including Augustine Brannigan (1981) in his book about the social construction of ex-post credit, and Simon Schaffer (1996) in his lucid article filled with examples of discoveries that were only seen to be "the" important technological insight after decades had passed, and after certain social conditions made assigning such credit an important goal for particular groups. Even earlier, the sociologist S.C. Gilfillan (1935) masterfully examines what Nathan Rosenberg would later call "low-visibility inventions" in the history of the ship. Indeed, as Rosenberg (1982) has written, "[t]he history of inventions is, most emphatically, not the history of inventors."

First, U.S. industry is said to decline because of a “patent thicket”. An anticommons exists where any improvement involves getting licenses from multiple parties, and various forms of transactional difficulties mean such licenses are not signed (Heller and Eisenberg, 1998). The broad rights granted to the Wrights’ patent, and important patents on improvements held by Curtiss, are said to have caused potential airplane manufacturers to avoid building in the United States (Shulman 2003). The two parties could not agree to licensing terms with each other or to third parties. The development of the airplane patent pool derives from precisely this worry (see, for example, Lampe and Moser (2011)).

A second explanation, made forcefully by historian Tom Crouch (2003a, 2003b), is that the industry failed simply because it receives little government support. The buildup to World War I meant large amounts of investment in all sorts of military technology across Europe, particularly in France. In 1910 and 1911, 208 airplane orders were made by the French government versus 14 by the U.S (Mangolte, 2010). Between 1909 and 1913, Germany spent \$28 million on aircraft, France \$22 million, and Russia \$12 million; the U.S. government spent \$435,000, the 14th highest total internationally and behind even Bulgaria (U.S. House of Representatives, 1913). Given the quick improvement in certain types of aviation technology during the war, it is perhaps not surprising if government-induced innovation in the buildup to World War I, including wars in North Africa and the Balkans preceding 1914, led to different industry outcomes in the United States and Europe.

Surely both factors had some effect, but consider a third explanation derived from splitting the commercial airplane into its nexus of microinventions: the United States “got lucky” by being first to possess the minimal combination of technologies necessary to lift a plane into the air, even though designers in the U.S. lagged in many other areas which would become important to the commercial airplane. Though the U.S. had the Wrights, it did not have any substantial lead in engine technology, and was well behind Europe in material science and in technical scientific research. The Wright patent suits of manufacturers may not have played a large direct role - after all, dominant manufacturers in essentially every new industry try to sue their competitors out of existence - but these patents still indirectly limited the growth of the American industry by decreasing technology transfer from Europe to the United States, thereby limiting the ability of American firms to catch up in lagging technological areas.⁴ Diffusion of technology, particularly in the early 20th century, largely required face-to-face interaction; the information was not entirely codified.⁵ The Wright Brothers, beginning in 1910, found it easiest to enforce their patent by suing

⁴The legal literature puts the “disclosure” role of patents front and center. An oft-cited line from the Supreme Court case *Graham v. John-Deere* (1966): “The inherent problem was to develop some means of weeding out those inventions which would not be disclosed or devised but for the inducement of the patent.” Note that disclose is mentioned before devise.

⁵The importance of face-to-face contact for knowledge diffusion prior to the middle of the 20th century has been investigated by many economic historians. Hornung (2014) describes how the Huguenot expulsion from France improved manufacturing productivity in modern Germany in the 18th century, Epstein (2005) summarizes the literature as showing that “not a single premodern invention was transferred simply through the printed word,”

exhibition organizers rather than plane designers themselves. This caused an exodus of prominent aeronautical shows and contests from the U.S. toward Europe. European firms had possessed a technological advantage in many components important to the commercial airplane as far back as 1900, and the decrease in face-to-face spillovers of that knowledge due to the Wright suits made it even more challenging for American firms to reach the technological frontier.

The remainder of this article is organized as follows. In section 2, I give a brief account of the work of the Wright Brothers, and the rise and fall of the US aircraft industry through 1917. Section 3 contains a stylized model of the incentive to invest in invention and commercial development, showing how differential credit for the technical invention via prizes, pioneer patents, or Mertonian credit can distort research effort toward projects which are unsuited for further local development. This distortion is particularly likely when inventions consist of multiple components, and different locations possess different absolute advantages in developing each of those components. Section 4 describes what was known concerning aerodynamics and airplane design as of 1896. Due to the extensive documentation of work in this area, particularly by the French-American engineer Octave Chanute and the German engineer and experimentalist Otto Lilienthal, inventors working worldwide on the problem of flight entered the late 1890s with a very similar base of knowledge. This base was surprisingly well developed: for example, knowledge of transonic drag created near the speed of sound was known as early as the experiments of Benjamin Robins in the 1740s. Section 5 uses the database of microinventions to locate exactly where certain inventions complementary to the commercial airplane were being developed, showing the early gap between American and European technology. Section 6 concludes. Methodologically, the record developed ex-post by historians of science can be much richer and more complete than modern data sources like patents, and hence the conjunction of theoretical mechanisms with well-developed historical cases can prove a useful counterpart to statistical induction for understanding core issues in entrepreneurship and innovation policy.

2 The Rise and Decline of the U.S. Airplane Industry

The Wright Brothers are universally considered the inventors of the airplane, and were the only people in the world to fly a heavier-than-air, machine-powered, controllable plane before 1906. In order to properly situate the Wrights' achievements and understand what technological advantage they possessed, we must know precisely what they did, and know the contours of technological leadership by American and European designers after the Wright design was made public.⁶

and Rosenberg (1970) notes that, in machine tooling, journals were often effective at generating interest but totally ineffective at teaching new techniques.

⁶The basic historical survey below follows a number of well-written Wright biographies; Howard (1988), Crouch (2003) and Tobin (2003) are particularly insightful examples.

The Wrights, nominally owners of a bicycle store in Dayton, Ohio, spent six years, 1900 to 1905, developing their airplane. They wrote to the Smithsonian for advice in 1899, and by 1900 were familiar with the work of Smithsonian head Samuel Pierpont Langley and German glider experimenter Otto Lilienthal, as well as the earlier pioneers discussed in a book by the engineer Octave Chanute which summarized the state of the art in aviation research. A glider using Chanute's Pratt truss structure was brought in 1900 to Kitty Hawk, North Carolina, where the Wrights hoped to use the steady winds and relatively soft sand to test Wilbur's theory of "wing warping." The brothers hypothesized that birds maintain control by changing the angles of the tips of the wings, and that a similar technique might allow enough lateral stability to control a glider or airplane. Lilienthal had controlled his gliders by swinging his body back and forth to counter unwanted lateral roll, a difficult technique, particularly during wind gusts. The Wright design also contained a "canard", or horizontal elevator in front of the body of the glider, which they hoped would help cushion landings in case of a stall.

Returning to North Carolina the next year, their 1901 glider had larger wings, but the lift generated did not match the tables of lift and drag published by Lilienthal in his book "Birdflight as the Basis of Aviation." Anderson Jr. (2002) argues that the problem was a misinterpretation of Lilienthal's table by the Wrights rather than a mistake on Lilienthal's part. Nevertheless, the problem led the Wrights to construct an elementary wind tunnel where they tested the lift properties of wings with varied aspect ratios and cambers. Though the wind tunnel design gave results which we now know to be fairly inaccurate, it nonetheless was sufficient to learn basic properties concerning optimal wing design (Britcher et al, 2004).

The 1902 glider had wings with much larger aspect ratio and much less camber, plus a small rear rudder to assist in turning. This glider generated more lift and allowed for long duration glides. However, when attempting to turn, the nose of the glider would dip and it would be impossible to stop the turn until the plane hit the ground (so-called "well-digging"). Orville realized a movable rudder and the wing warping mechanisms could be connected, allowing a steady glide to be resumed after coming out of a turn. With this modification, the Wrights were able to glide over 600 feet, a world record had the glides been made public.

After applying for a patent for the glider control mechanism - what would become the famous '393 patent - the Wrights returned to North Carolina in the winter of 1903 to attempt a powered flight. The engine was designed by Charlie Taylor, the mechanic from their Dayton bicycle shop. It was sufficient to do the job, but had a much worse weight-to-horsepower ratio than the Manly-Balzer design being used the same year by Langley in his flight experiments. On December 17, 1903, the plane, named the Wright Flyer, flew in a controlled manner for 59 seconds. Modern tests suggest that the particular 1903 design benefited enormously from the additional lift provided by "ground effect" and probably would not have been able to fly more than a few feet off the ground (Bilcher

et al, 2004). Nonetheless, their 1903 device is generally considered the first airplane.

The Wright Flyer was absolutely not a commercially viable product and bore little resemblance to the passenger and military planes which would appear over a decade later. It was only able to take off facing a strong wind (or, after 1904, with the assist of a catapult derrick). The aircraft was somewhat controllable, but most flights, even the following year, were of very short duration. Indeed, the '393 patent makes clear that the Wrights did not even understand why some of the most basic principles of flight worked. As Chanute (1894, p. 169) noted, gliders can generate lift because pressure is lower above the wing than it is below the wing; planes do not fly because they are somehow lifted by the wind below the airfoils. Nonetheless, the Wright patent claims that their glider is “supported in the air by reason of the contact of the air and the under surface of one or more aeroplanes” (Wright and Wright, 1906).

By 1905, the Wrights had made a number of minor changes to their plane which allowed for longer flights. The rudder and wing warping control were once again disconnected, which meant more difficult flying yet more control once proper technique had been learned. The forward elevator was weighted, assisting with pitch control. An improved engine was installed. The Wrights further learned good piloting techniques through trial and error during their extensive practice time, such as the importance of avoiding stalls caused by low speed turns (McFarland, 1953). Though the 1905 machine was a vast improvement on the 1903 Flyer, with the Wrights able to fly occasional figure-eights and keep the plane aloft for nearly forty minutes, it is also tough to call this device a commercially viable product. It crashed regularly, still had an underpowered engine, and retained a number of design choices which would be repudiated almost immediately by other designers who built on the Wrights' work. The plane was also inherently unstable, a property that the bicycle salesman Wrights may have thought beneficial, but which made for a difficult learning curve. The canard structure could be given some sort of pitch stability by adding ballast to the forward elevator - a point made theoretically in Bryan and Williams (1904) - but there are more elegant solutions with much better airflow properties. The Wrights would sell only about 100 planes, based on the 1905 design, between 1909 and World War I.

Gabriel Voisin, a French flight pioneer, stated what his designs retained from the Wrights' plane: “Ni le pylône de lancement, ni les patins, ni les conditions aéro-dynamiques de centrage supprimant l'empennage, ni les moyens de commande, ni la transmission par chaînes croisées, ni la position du pilote, ni le fameux gauchissement” (Mangolte, 2010). That is, neither the launch tower, the sleds, the system for aerodynamic centering using the empennage, nor the control method, nor control via crossed wires, nor the position of the pilot, nor the famous warping were kept by the frontier French designers.

After testing their 1905 Flyer, the Wrights did no further work on airplane development for three

years, nor did they publicly demonstrate their invention. Rather than establish a factory, the Wrights hoped to sell their technology to various world militaries, beginning with the Americans. Their patent on wing warping, the '393 patent, was granted on May 22, 1906, and a contract to negotiate with European governments was taken out with Flint and Company soon after.⁷ Given that the heavily-funded Smithsonian-Langley experiments in building a heavier-than-air plane had ended in failure, and that the Wrights had made no public flights recorded by the media, there was heavy skepticism about their claims. The Board of Ordnance responded to the Wrights that mere “experimental development of devices for mechanical flight” were not something the Board was interested in pursuing (Tobin, 2003).

By 1908, the Wrights had at last been given contracts to supply an airplane that met certain flight goals - they would eventually be paid \$30,000 by the U.S. government for their military flyer and pilot training. In August of that year, at Le Mans in France, Wilbur Wright flew before a large crowd for the first time. His flight far surpassed anything done in Europe in terms of stability, ease of control, and duration of flight. The New York Times reported “the French press unites in spontaneous and enthusiastic praise” of the performance (New York Times, 1908). “Nous sommes battus” - we are beaten - was the only comment given to the press by the French aviator Leon Delagrange (Tobin, 2003).

2.1 The Aviation Industry, 1909-1917

By the end of 1908, only five men had flown for more than two minutes in a single flight; the Wrights for over two hours, Farman for 44 minutes, Delagrange for 30 and Blériot for 11. Americans at the frontier of some aspects of aviation technology before 1909 were not limited to the Wrights. The American Glenn Curtiss briefly held, in a plane of his own design, the world airspeed record in 1909. The engine used in Langley’s 1903 Aerodrome, devised by Manly and Balzer, had by a large margin the world’s best weight to horsepower ratio. The most efficient propellers in the world were designed by the Wrights (Ash et al, 2000). In 1909, both the Wrights and Curtiss established well-funded airplane companies.

Despite this lead, French designer Louis Blériot was prescient. After the Wrights’ 1908 demonstration, in the same newspaper article where Europeans were effusive in praise about the American lead, Blériot agreed that the Wright machine was superior to anything in Europe. “But wait a little while,” he said, “in a short time, Wright will be equaled, perhaps surpassed, for aviation will make more progress than people imagine” (New York Times, 1908). And indeed this was the case.

⁷The '393 patent was rejected and amended multiple times. The first application was made in March 1903, before a powered flight had taken place, and hence referred only to the warping method as a technique for glider control (Johnson, 2004). Worrel (1979) notes that the original patent application was done without the aid of a lawyer and was rejected partly for its sloppiness.

Table 1 shows airplane production in the United States and France during the following 8 years, with France outpacing the U.S. every year by increasing amounts. Though there is no firm data on U.S. civilian production in 1910 and 1911, it is known that neither the Wrights nor Curtiss, the two most prominent American airplane producers at the time, sold more than a handful of planes during those years. Development of the airplane industry in Europe was not limited to France; Britain was the world's largest aircraft producer by 1918, and prominent designs appeared in Italy, Germany, and the Netherlands, among others (Staniland, 2003).

A similar shift toward Europe, particularly France, can be seen in Table 2, which lists speed, distance and altitude records over this period. Worldwide improvements in airplane technology were phenomenal between 1903 and 1913. The Wrights' best flight in 1903 was 59 seconds, traveling 852 feet, at an altitude of about 10 feet. Ten years later, record planes had flown 126 miles per hour, traveled 634 miles, and reached altitudes of over 20,000 feet (Crouch, 2003b).

Though the FAI rules meant that a number of unofficial records were not recorded, it is nonetheless clear in the historical record that the U.S. was far behind European designers by 1913. Describing a new American altitude record by Lloyd Thompson in 1914, *Popular Mechanics* noted that "European fliers, however, have surpassed Americans in altitude work, several of them having flown much higher" (*Popular Mechanics*, 1914). Crouch (2003b) quotes the President of the Aero Club of America on the lack of an American plane in the 1913 contests at Reims: "We could not send an American biplane or monoplane over because none of our machines are half speedy enough." Such technological backwardness would have been unthinkable only four years earlier, when Curtiss won the Gordon Bennett race at Reims. Broadly, American plans were inferior to European designs, and produced in much lower numbers, from 1910 until well after the end of World War I.

Until well into World War I, the commercial and military applications of the heavier-than-air airplane were far from certain. Germany was still using dirigibles (the "Zeppelin"), even bombing England from the lighter-than-air machines. Airplane safety records were abysmal, and the science to understand why planes sometimes failed was still in its infancy. Vivian and Marsh (1920) wrote that "in no country were the full military potentialities of the aeroplane realised; it was regarded as an accessory to cavalry for scouting more than as an independent arm." The fast and agile Fokker Eindecker was the first non-scout military plane to prove decisively the importance of air power using heavier-than-air planes. Soon after the end of World War I, the success of the Eindecker and its counterparts generated rapid diffusion of both military air fleets and civilian uses including airplane mail delivery, passenger flight, and crop dusting.

2.2 Early Patents and the MAA Patent Pool

In addition to their '393 patent in the U.S., the Wrights took out patent applications in France and Germany, among many other nations. The German patent was eventually accepted, though with only very narrow claims, and the French patent remained tied up in court until it expired (Johnson, 2004).⁸ In the U.S., however, the Wrights were particularly litigious, interpreting the '393 patent broadly enough to cover nearly any airplane without a Wright license.⁹ And given the final U.S. court verdicts in the Wright patent suits, they were right to assume a very broad claim. Judge Hazel, in 1914, found that “employment, in a changed form, of the warping feature or its equivalent by another, even though better effects or results are obtained, does not avoid infringement.” Judge Learned Hand noted in one suit that the Wright patent covered not just their invention, or just a means of turning a rudder and wings, but “an invention of a combination of which this action of the rudder is a part.” Glenn Curtiss was sued in August 1909, soon after selling his first airplane. The Wrights then began to sue airshow producers who did not pay them a license fee to make up for the unlicensed planes at those shows (Johnson, 2004).

At the time, the Wrights were producing only a small number of planes, and were adding improvements only very slowly. For instance, they were one of the last producers to stop using the tail-first “canard” configuration (Roland, 1985). The Wrights were also often unwilling to license improvement patents from firms who they were concurrently suing. For example, Wright engineer Grover Loening claimed plans to build a Wright seaplane were stifled by Orville’s desire not to violate a Curtiss patent. This led to a limited market for improvement patents in the United States (Johnson, 2004).¹⁰ Uncertainty about the final outcome of the Wright suits plus a very high licensing fee meant that by 1916, Burgess was the sole Wright licensee.

The U.S. entry into World War I, and the technical information gathered by the National Advisory Committee for Aeronautics starting in 1915, made the lagging status of U.S. manufacturers particularly acute. A letter in January 1917 from Franklin Delano Roosevelt, then Assistant Secretary of the Navy, reported that only a small fraction of the military’s 1916 order for aircraft was fulfilled due to a fear about patent lawsuits (Szakalski, 2011).¹¹ After implicitly threatening to confiscate

⁸A version of the Wright Model B sold by the Wrights’ French licensee (Compagnie Générale de Locomotion Aérienne) was far behind its European competitors technologically, and CGLA was forced into bankruptcy before they were able to finish pushing patent lawsuits through the French courts (Mangolte, 2010).

⁹An assistant of Curtiss recalled that at Hammondsport, where he performed many early trials, it was said that the Wright Brothers would sue if you even jumped in the air and waved your arms (Shulman, 2002). Attorney Thomas Hill, writing in *Aeronautics* in 1909, noted that nothing in the '393 patent gives evidence that the Wrights conceived of their invention to include supplementary surfaces like ailerons used with rigid wings, rather than wing warping, so it was less than obvious contemporaneously that the Wright legal gambit would be successful (Howard, 1988).

¹⁰Arrow (1962) discusses the important role of patents in creating a market for information, rather than just giving the inventor monopoly rights.

¹¹Only 54 of 366 ordered planes were delivered (Roland, 1985).

outstanding aircraft patents, of which the Wright '393 patent and patents on flying boats and ailerons held by Curtiss were the most important, the Manufacturer's Aircraft Association formed a patent pool, the result of which was significantly lower royalty payments on new planes. For instance, the DH-4 had a unit cost of \$11,250 and the holder of the Wright patents had been demanding a 5% royalty, or \$562.50 (Szakalski, 2011). The MAA patent pool set a fixed royalty per plane of \$200, of which \$132.50 went to the holder of the Wright patent, \$40 to Curtiss, and the rest to the MAA for administrative expenses, with a 2 million dollar cap in lifetime royalties to each of the two principal patentholders. That cap was reached before either the '393 or the Curtiss patents expired. All other patents held by MAA members were cross-licensed to other members with no royalties.¹² The patent pool did not immediately lead to new technological developments in the United States; Curtiss seaplanes were the only American-designed plane to be used in Europe during World War I.

To summarize, American-designed planes were the most frequently produced, the most technologically advanced, the fastest and the furthest flying from the time of the early Wright experiments through the end of the first decade of the twentieth century. Their lead quickly diminished, and by 1914 the American airplane industry was all but dead. Even though the United States produced many planes during World War I, especially for her allies, these planes were almost universally copycats of European designs. Not until the early 1920s would an American-designed plane again hold any aviation record.

2.3 The Airplane and Simultaneous Invention

Before discussing microinventions in the early aviation industry, consider the question of when the airplane would have been invented in the absence of the Wrights. This counterfactual is best expressed in terms of the delay the world would have experienced before learning the techniques developed by the Wrights had they remained mere bicycle repairmen. That is, would commercial aircraft have appeared by World War I had the Wrights never lived? The standard technique used to investigate this question is an examination of simultaneous, independent discovery. Many authors, particularly Merton (1973) and more recently Lemley (2012) and Bikard (2016), have pointed out numerous cases from calculus to the telephone where multiple scientists have appeared to discover the same property or principle independently at almost the same time.¹³ Even within

¹²The nature of the airplane patent pool is discussed in detail by Dykman (1964) and Bittlingmayer (1988). Worries about the use of the patent pool for anticompetitive purposes was widespread during the life of the MAA pool, with the inventor James Martin an early and virulent critic. The welfare effects of patent pools are nonobvious, and are more complicated than just assuming that complementary patents can be pooled without harming welfare. See Lerner and Tirole (2004), Langinier (2011) and Hovenkamp and Hovenkamp (2015) for discussions on this point.

¹³Though note the objection of Schmookler (1966), who carefully documents how few of the supposed examples of multiple discovery actually do represent the simultaneous invention of the "same" object.

early flight, there are examples of multiple discovery: the aileron appears to have been discovered by Boulton in 1868, forgotten, then rediscovered independently by Farman in France and Curtiss in America in the early 20th century.

However, the Wrights appear to provide a nice natural experiment proving that not all important discoveries are simultaneous, as they largely did not make their work public until 1908, and only rarely discussed their work with other experimenters. From their first flight in 1903 to their demonstration at Reims, France in 1908, making only minor adjustments to the plane after 1905, the Wrights maintained technological superiority. This is the case even though their 1901 lectures before the Western Society of Engineers, talks presenting the basic principles of wing warping by Chanute in France in 1903, and their patent application (public as of 1906), were all available as resources for future inventors to draw upon.

That said, the secrecy of the Wrights concerning many aspects of their invention before 1908 also let us see the counterfactual of what was learned in the relative absence of the Wrights' knowledge. Which aspects of the Wright inventions went undiscovered? The Wright engine was underpowered in 1903, so even granting the relative efficiency of their propellers, the thrust generated by propeller/engine combinations invented by others easily exceeded that of the Flyer. Advances related to the automobile also meant that lightweight engine efficiency was rapidly increasing in the first decade of the 1900s, hence every year after 1903 would have allowed less and less efficient planes to take off. The Wrights' experiments on wing design certainly helped choose appropriate airfoil shapes, but problems with their wind tunnel and the fact that their test results were only valid at low speeds (their results all rely on a very low Reynolds number) make it doubtful that inappropriate airfoils were holding back the counterfactual airplane designer; indeed, by 1908, a number of European designers had planes whose airfoils had better lift and drag properties than the Wright flyer.

This leaves the control mechanism, wing warping or some analog, as the bottleneck restricting counterfactual development of a commercial airplane. It seems unlikely that another inventor would come up with wing warping in the precise sense, as a superior method of changing the shape of the wings, the aileron, was used by nearly all designers by World War I. It is impossible to say when the aileron would have been invented in the absence of the Wrights¹⁴, but any discussion of whether the commercial airplane's introduction would have been delayed must hinge on exactly that question. One suggestion that it may not have been delayed comes from a letter to Octave Chanute by Wilbur Wright in 1900. Wright argues that Lilienthal failed to control his glider in part because "in five years' time he spent only about five hours" in the air, and "even Methuselah could never have been an expert stenographer with one hour per year for practice" (Howard, 1998). That is, with stronger engines or wings able to generate lift more effectively, other early aircraft

¹⁴That is, whether the aileron would have been *rediscovered*; recall that it was invented in the 1800s but forgotten.

designers might have gained enough practice in the air to become aware of the problem of lateral roll and to discover that one can control direction by suitably changing the shape of the wing and rudder. Had they done so, all other important aspects of the commercial airplane were developed in Europe during the Wrights' period of secrecy, and hence there would have been no delay in the beginning of commercial aviation.

3 A Theory of Component-Based Invention

Before turning to the empirics of microinvention in the early airplane industry, consider the following stylized model of two-stage innovation production which will guide interpretation of those empirical facts.

Let there be two potential firms, A and B, attempting to invent in two sequential stages, 1 and 2. Firm i can work on invention stage 1 at cost c_{i1} . If firm i invents the first stage invention, it can work on the second stage at cost c_{iw} ; if it did not invent the first stage invention, it can work on the second stage at cost $c_{il} \geq c_{iw}$. The inventor of the first stage earns π_1 and the inventor of the second stage earns π_2 .

Timing of the game is as follows. Firms choose simultaneously whether to work on stage 1. If only one firm chooses to pay the cost c_{i1} and work on the first stage invention, it invents with probability 1 and earns payoff π_1 . If both firms choose to work, then firm A invents with probability p_{A1} and firm B with probability $(1 - p_{A1})$.¹⁵ After the inventor of stage 1 received its payoff, firms simultaneously choose whether to work on stage 2. Again, if only one firm pays the second stage cost, it invents with probability 1 and earns payoff π_2 , while if both firms work on the second stage invention, firm A invents with probability p_{A2} and firm B with probability $(1 - p_{A2})$. Assume parameters such that in every stage, every firm is willing to work if the rival does not work in that stage.

The parameters of this model can be interpreted as follows. Stage 1 involves a technological invention which is not inherently valuable in the absence of a strong pioneer patent, a governmental prize, or the subjective value of getting credit for the invention. That is, π_1 is to a large extent a parameter chosen by policymakers. Stage 2 involves a commercially viable extension of stage 1. For a multicomponent invention, it may be the case that one firm possesses an advantage in the first stage ($p_{A1} > .5$) but not the second stage ($p_{A2} < .5$). Costs c_{in} can be seen as the opportunity cost of using inventive talent developing the particular inventions 1 or 2.

¹⁵This can be derived as the reduced form of the Loury-style continuous time patent race in Bryan and Lemus (2016).

Taking parameters as exogenous, who does research in each stage? Solving backward, and restricting to pure strategies:

Lemma 1. *If firm A invented in the first stage, then firm A works in the second stage if either $p_{A2}\pi_2 \geq c_{Aw}$ or $(1 - p_{A2})\pi_2 < c_{Bl}$ and firm B works in the second stage if either $p_{A2}\pi_2 < c_{Aw}$ or $(1 - p_{A2})\pi_2 \geq c_{Bl}$.*

If firm B invented in the first stage, then firm A works in the second stage if either $p_{A2}\pi_2 \geq c_{Al}$ or $(1 - p_{A2})\pi_2 < c_{Bw}$ and firm B works in the second stage if either $p_{A2}\pi_2 < c_{Al}$ or $(1 - p_{A2})\pi_2 \geq c_{Bw}$

Working backward from the second stage equilibrium, and again restricting to pure strategies, firm in the first stage work as follows:

Lemma 2. *Let $1_{(Aw,Bl)}$ denote the indicator for the second stage equilibrium involving both firms working conditional on A inventing in the first stage and B not inventing, and $1_{(Aw,-Bl)}$ denote the indicator for the second stage equilibrium involving only firm A working conditional on A inventing and B not inventing.*

Firm A works in the first stage conditional on firm B working in the first stage if and only if

$$p_{A1}[\pi_1 + (\pi_2 - c_{Aw})1_{(Aw,-Bl)} + p_{A2}(\pi_2 - c_{Aw})1_{(Aw,Bl)}] + (1 - p_{A1})[(\pi_2 - c_{Al})1_{(Al,-Bw)} + p_{A2}(\pi_2 - c_{Al})1_{(Al,Bw)}] \geq c_{A1}$$

Firm B works in the first stage conditional on firm A working in the first stage if and only if

$$(1 - p_{A1})[\pi_1 + (\pi_2 - c_{Bw})1_{(-Al,Bw)} + (1 - p_{A2})(\pi_2 - c_{Bw})1_{(Al,Bw)}] + p_{A1}[(\pi_2 - c_{Bl})1_{(-Aw,Bl)} + (1 - p_{A2})(\pi_2 - c_{Bl})1_{(Aw,Bl)}] \geq c_{B1}$$

Consider now a local planner in the region of firm A who lexicographically wants to increase the probability the commercial product in stage 2 is invented by firm A, but does not want to induce local work in stage 1 unless stage 1 effort increases the probability of local stage 2 invention. That is, the local planner wants to encourage invention if it leads to a commercial industry, but does not want to distort effort away from alternative opportunities otherwise. The planner is able to choose π_1 , the first stage payoff which represents prizes, scientific credit, pioneer patents, or otherwise, to achieve this goal.

From Lemmas 1 and 2, it is straightforward to show that:

Lemma 3. *Increasing π_1 to π'_1 increases the probability firm A invents the second stage invention if and only if (1) firm A does not work in the first stage under π_1 but does under π'_1 , and (2) $p_{A2}\pi_2 \geq c_{Aw}$ but $p_{A2}\pi_2 < c_{Al}$. A corollary is that if $c_{iw} = c_{il}$, then π_1 does not affect the probability firm A invents the second stage invention.*

Lemma 3 suggests when differentially incentivizing first stage invention does not increase the probability the local firm invents the commercially viable second-stage invention. If firm A is

already, in the absence of an increase in first stage payoff π_1 , willing to working on the first stage invention, then the probability it invents the second stage invention is unchanged by the increase in the first stage subsidy. However, if the increased payoff induces work in the first stage, it only induces second stage effort if the decrease in cost of developing the second-stage invention conditional on successful first stage invention is sufficiently large.

Consider a multi-component good, where the commercial product involves development of many unrelated components, while the initial invention requires only a marginal improvement along one of these stages. In this case, the cost of second stage development does not depend greatly on whether successful progress is made on the initial invention, since the initial inventor’s capability to improve the other components has not changed. Therefore, since c_{iw} and c_{il} are similar, additional reward to first-stage inventors (such as a pioneer patent, or an “X-Prize” style contest for a technological achievement) will only induce entry in the first stage but not increase the probability a firm switches from being unwilling to develop the second stage to being willing to do so.

4 Knowledge as of 1896

The basic principles of heavier-than-air flight were not novel at the turn of the century. The legal scholar Carl Zollmann, writing in 1926, points out that “planes supported in their flight by the reaction of the air against an inclined surface which presses against the air as the plane advances, thereby inclining the plane to rise while the natural resistance to forward motion is overcome by steam machinery, were patented in Great Britain as early as 1842” (Zollmann 1926). By the early 1800s, the English engineer George Cayley had drawn a relatively modern looking airplane: a cambered wing with dihedral, vertical tail and horizontal tail in the back to stabilize pitch and yaw, and a choice of airfoil based on aerodynamic properties learned through precise experimentation.

Table 3 lists many of the most prominent inventions and discoveries related to heavier-than-air flight from before 1896. There is a mixture of pure theory (the Euler and Navier-Stokes equations, the separation of lift and thrust), tools for investigating principles of flight (the whirling arm, the wind tunnel), auxiliary technical achievements (kite structures, the internal combustion engine), and demonstrations of propulsion, oftentimes controlled propulsion, by models (those of Cayley, du Temple, Penaud and Lilienthal, in particular).

Meyer (2012b) contains a list of early publications related to aeronautics, of which there are an enormous number. Most of these publications discuss experimental failures, but economic theories of invention have shown, perhaps not surprisingly from a Bayesian perspective, that knowledge of experimental failures plays an important role in scientific progress (see Keller and Rady (2010) and the references therein). Early aeronautics research tended to be done publicly, with results

freely shared via personal correspondence, lectures or journal articles. It was exceedingly rare for experimentalists or theorists before 1896 to patent and sue those who tried to follow up on their work. Meyer (2012a) has counted German and American patents related to aeronautics in this era, and found that inventors with the most patents tend to be a completely different set of people from those considered most important in contemporary discussions or in modern history texts.

Given the limited communications technologies of the day, it is not surprising that many important discoveries were forgotten and rediscovered. As was mentioned, Boulton's 1868 discovery of a primitive aileron, the wing flap used by most modern planes for roll control, was long forgotten in the early 1900s when it was discovered anew. Much of Cayley's research was unknown when Otto Lilienthal was performing his glider experiments in Germany, experiments which directly inspired the Wright Brothers' interest in aeronautics. Rediscovery was also common since practical airplane design used "virtually nothing from theoretical aerodynamics" was used by Lilienthal and Samuel Langley, the Smithsonian director who came very close to completing a working plane before the Wrights (Anderson Jr., 1998). The problem was partially that the academics with good understandings of these formulae were not interested in applied flight - Langley, though an academic, was well known for his dislike of theory vis-a-vis experimentation - but also that the approximation methods necessary to solve Navier-Stokes equations and other important theoretical concepts in fluid dynamics were only just being developed. This is not to say that experimenters were pure amateurs in this era. Lilienthal, Langley and the Wrights all understood basic principles of lift and thrust, ran experiments whose results could only be interpreted through the lens of theoretical constructs like Smeaton's drag coefficient, and constructed devices, like the Wrights' famous wind tunnel, which showed at least elementary theoretical knowledge. Further, there was at least some knowledge transfer between experimentalists and theorists; Zhukovsky's modern lift theory, for example, came about after he bought a glider from Lilienthal (Ackroyd et al, 2001).

However, by the 1890s at the very latest, a classic "invisible college" for aeronautics researchers had developed. Learned societies like the Aeronautical Society of Great Britain (1866) and SAMF in France (1852) had been founded. Knowledge was systematically recorded and published in books and society journals, and this knowledge was generally diffused worldwide. Octave Chanute, a French-American elder statesman in the engineering community, published a collection of his reports in the 1894 book *Progress in Flying Machines*. These reports referred to experimental and theoretical results from all over the world, from Cayley's work in the early 19th century to the kite experiments of Hargrave far off in Australia. Samuel Langley is known to have followed and written commentary on a number of foreign aeronautics publications, such as a Lilienthal article in *Zeitschrift fur Luftschiffahrt*, to which he subscribed (Anderson Jr., 1998). The Wrights were referred to a number of these commentaries and compilations when they wrote to the Smithsonian concerning their early interest in the problems of flight (Tobin, 2003).

By 1896, it was still not clear which aspect of airplane design would be the most difficult: generating enough lift, generating enough thrust, or maintaining control. Most designers at that time were still attempting to build a machine that was “automatically stable”. The problem of generating enough thrust to get into the air was thought to be of particular difficulty. Taylor (1971) notes the difficulty an earlier airplane experimenter might have had in getting a lightweight yet powerful engine: “Although successful automobiles were in operation both in Europe and in the United States, most of them were equipped with engines far too heavy and too low in power for airplane use. Accessory equipment such as spark plugs, carburetors, and magnetos were not available on the open market and had to be obtained from reluctant automobile builders or else built by hand.” These hand-built engines, naturally, tended to be far from the world technological frontier.

Many potential innovators were therefore, after 1896 at the latest, working on the problem of flight from a very similar knowledge base, and were concerned with the development of multiple components including the engine, materials, and control mechanism. The Wrights, as well as nearly any other interested party, would have access to gliders in the basic shape of the 1903 Wright Flyer, to internal combustion and steam engine technology which could be converted with little difficulty to work on an airplane at the efficiency of the Wright engine, to experimental technology like the wind tunnel, and to an exhaustive collection of stable models. 1896 is a fitting end to the prehistory of aviation for two reasons beyond this unified knowledge base. On August 10, 1896, glider pioneer Otto Lilienthal died following a stall in one of his gliders. Lilienthal held a number of patents related to engines and was known to have been preparing an engine for his working glider when he died (Anderson Jr. 1998). Second, the head of America’s Smithsonian, Samuel Pierpont Langley, tested his first working aerodrome model on May 6, 1896, flying a powered, controlled, heavier-than-air model airplane for over a kilometer along the Potomac River; convinced that the design was stable when winds were low, he set about building a larger scale model with an engine powerful enough to lift a man.

After 1896, inventors from France, America, Germany, Russia, Austria-Hungary, the UK, and Australia, among others, would achieve important technological steps which eventually led to a commercial airplane. As noted, wing warping, a control method sufficient for a powered aircraft, was developed in the United States. The next section considers the timing and location of other microinventions important to the commercial airplane, and particularly the role played by American inventors.

5 Airplane Microinventions, 1897-1917

Appendix A contains a novel database of 91 airplane microinventions from 1897 until 1917. A discussion of the dataset’s construction can also be found in the appendix. Examination is halted in 1917 for a number of reasons. In the United States, the Manufacturer’s Aircraft Association patent pool began in July 1917 (Dykman 1964). In Europe, the principal innovations related to World War I airplanes had been invented following the success of the Fokker Eindecker fighters first introduced in 1915. International commercial passenger service would begin by the end of the 1910’s - “Pappy” Chalk’s flights from Florida to the Bahamas were followed by intercontinental airlines by the 1920s. In the U.S., airmail testing began in 1918 (Amick 1998). The first known cropdusting by heavier-than-air planes took place in 1921 in Ohio as an experiment by the U.S. government (NAAA, 2012). In the late 1920s, theoretical work by Frank Whittle and A.A. Griffith laid the groundwork for the jet engine. That is, after 1917, heavier-than-air aircraft were without question a commercially viable innovation.

The following stylized facts are evident from the microinvention database.

First, important inventions in the development of the airplane occur throughout the 20 year period. Even in the prewar years 1911-1913, which are sometimes considered a quiet interlude between the explosive change after the 1908 demonstrations at Le Mans and the rapid technological improvement during World War I, there are a number of important innovations. The flying boat, which will dominate passenger air travel in the period between the two world wars, is invented. The first modern mathematical description of airplane flight with six degrees of freedom is laid out. The monocoque structure (essentially a modern fuselage) with a propeller spinner on the Deperdussin Racer provided a model for airplanes away from biplane construction. The most important engine of the War, the Gnome Monosoupape, is developed.

Second, American innovation collapses well before the Wright patent suits or World War I spending begin. Between 1904 and 1909, there are no significant American inventions. The Wrights spent 1905 to 1908 attempting to sell their 1905 machine. Wilbur Wright had not even flown between 1905 and his preparations for the European demonstrations of 1908 (Tobin, 2003). Langley’s experiments were over as of 1903. Glenn Curtiss and the AEA were far behind the frontier until 1909. John Moisant, a promising American designer and aviator who died tragically in 1910, would not head to Europe to begin his experimentation until 1909. The glider experimenter John Montgomery died in a 1905 test. Therefore, though the Wrights had a clear technological lead when they demonstrated at Reims in 1908, there were only a handful of potential American designers who could have built on that lead. On the other hand, there were dozens of designers in France who immediately set out to incorporate what they learned from the Wrights into their own designs, which were by that time more advanced in terms of engine design, more streamlined, and more

stable. Voisin, Levavasseur and the Breguet brothers, among others, understood enough about aeronautics in 1908 that they could immediately incorporate Wright-inspired lateral control into their existing designs after seeing an in-person demonstration.

Third, the European lead in engine design and in theoretical knowledge was insurmountable as early as 1909. Alessandro Anzani, Darracq, and the Seguin brothers, among others, were producing innovative aircraft engines far superior to the Wright designs. In addition to superior engines, better streamlining of bodies, and propellers that had finally caught up to the Wright standard, meant that European companies would seize control of flight records for speed, distance and duration within a year of the Le Mans demonstration. This development is simply too fast for a group of potential inventors starting from a base of zero knowledge; rather, it reflects the continuation of design choices that were already being used in Europe before the first public Wright flight, such as the less turbulent tractor configuration instead of the Wrights' canard configuration. Theoretical knowledge was similarly advanced in Europe compared to the United States. Prandtl and Blasius in Germany were developing techniques that would at last allow the theoretical equations of the mid-19th century to be applied in practice. The Frenchmen Jules-Marey's smoke photography allowed a more precise examination of airflow over a surface than the Wrights could have learned using their primitive wind tunnel. Bryan, Williams, Kutta and Zhukovsky provided detailed descriptions of lift on various types of airfoils. Indeed, the relative backwater status of American theoretical aeronautics continued until well after World War I; Mowery cites a survey suggesting the late development of jet aircraft in the U.S. may have resulted simply from "ignorance of aeronautical design theory" (Mowery 1985).

The fact that the Europeans had a technological advantage over American manufacturers is not a sufficient explanation for American decline, however. In nearly every late 19th and early 20th century industry, particularly in areas of high technology, the Europeans held the initial technological lead. Indeed, Mowery and Rosenberg (1998) claim that *American* usurpation of an industry despite an early *European* technological lead is a defining characteristic of this era. For instance, the "American System of Manufacture" had an ability, analogous to Japanese manufacturers in the 1970s, to take repetitive industrial processes developed overseas and improve them so rapidly that the American firms quickly established industry dominance. In the automobile industry, whose principal inventions almost all came out of Europe, U.S. manufacturers would have over half the world market share by 1914 due to "Fordist" assembly line techniques and an American comparative advantage in repetitive manufacturing as opposed to the "artisanal" style of autobodying which predominated overseas (Mowery and Rosenberg 1998). Aluminum was first isolated in Germany and produced in small quantities by the Frenchman Sainte-Claude Deville in 1854; yet by 1896, the Pittsburgh firm which would become Alcoa produced more aluminum than the rest of the world combined, taking advantage of cheap energy and the Hall-Héroult process for smelting first developed by a domestic engineer (Graham and Pruitt 1990).

From the perspective of theory, the airplane appears to be a multicomponent invention where the American knowledge base as of 1903 may have made unprofitable the full development of a commercially viable airplane in the absence of artificial rewards for early technological development. The scientific credit and fame granted to the inventor of the airplane, and the legally broad pioneer patent given to technological inventors, induced the entry of American tinkerers even when they, like the Wrights, did not have the knowledge to develop the airplane from a novelty into a commercial product. This does not mean that basic research should be discouraged, of course - for inventions with a more straightforward path from early invention to commercial viability, where that path relies on similar complementary assets at each stage, differential rewards to early inventors can be important for generating effort in the early stages where market rewards are limited. For instance, the basic research on insulin by Banting and Best was performed in a Toronto lab in 1921, tested on humans in that city in 1922, and produced commercially on the basis of collaboration between the Toronto lab and Eli Lilly shortly thereafter. The scanning electron microscope was developed in its basic form by Ernst Ruska, a PhD student in Berlin, in 1933; he was soon after hired by Siemens and developed the commercial SEM by 1939. In cases like these, where development following invention requires similar skills, industrial reversals of fortune are unlikely.

5.1 Why European Knowledge Did Not Flow Back to the U.S.

What made the airplane different? In many very high tech industries, the binding constraint for American firms hoping to incorporate overseas technology is simply that not all knowledge is codified. During World War I, the United States spent over 70 million dollars attempting to replicate the Haber-Bosch process for ammonia production without success. When the British gave the United States coded documents during World War II describing how to build a jet engine, it took ten months of work before a suitable engine was built by an American manufacturer (Mowery and Rosenberg 1998). Moser and Voena (2012) discuss in great detail the difficulty American firms had in replicating German chemical technology when the U.S. freed German patents during the First World War; this was true even though the firms had access to patents which supposedly gave full and detailed descriptions of how to construct the relevant inventions.

The airplane industry had rapidly improving non-codified knowledge. A graph of early frontier airplane designers with links denoting personal, frequent contact would be densely connected. Voisin partnered with Blériot in 1904, then was hired by Archdeacon to design a plane inspired by Chanute's 1903 presentation of the Wright Brothers' discoveries. Farman bought a practice plane from Voisin, and practiced flying in 1907 in a field with Delagrange. The British designer Claude Grahame-White attended Blériot's flying school, and learned to fly on a Farman plane.

Such frequent contact, including simple friendly meetings at events where planes were shown off, appears to have been critical for generating knowledge spillovers.¹⁶

In general, American firms had a great ability to take a settled European process, improve it, and massively increase the scale of production. Simply by virtue of distance, however, American firms were going to be at a disadvantage in quick-developing, high technology industries. The broad patent granted to the Wright Brothers made this disadvantage even worse by giving the Wrights an incentive to take actions which limited the already small trickle of technology transfer coming from Europe to America, a process which could be called “anti-disclosure”.¹⁷

Consider anti-disclosure from the perspective of the theory developed previously. The local planner only wanted to increase the reward to first-stage inventors π_1 if, conditional on first stage invention, the local cost of producing the commercial product fell. In a multicomponent setting like the airplane, the Wright Brothers’ wing warping mechanism only slightly reduced the cost of developing a commercial airplane domestically, since it did not change the cost of developing more powerful engines, or more aerodynamic fuselages, or more efficient wings. Worse, if the Wright pioneer patent was best exploited by taking actions which decreased spillovers of foreign knowledge to other American producers, the overall cost to all American producers of further developing the airplane may have risen enough to counteract even the modest knowledge benefit from wing warping.

What did this anti-disclosure look like empirically? In the era before airplanes were commercially viable, fliers and designers generally made money by participating in exhibitions or air races (Villard 1968). Frontier designers were associated with demonstration flyers who traveled to “meets”. At the major air meets, such as the British Aero Show in March 1909, the Dominguez Hills Los Angeles meet in January 1910 - the “first big successful exhibition held in America” (Aeronautics 1910) - or the Harvard-Boston Aero Meet in September 1910, there were competitions to see whose plane could fly the highest, longest and fastest, as well as the ability to examine the state of the art from other designers and discuss with their representatives why certain engineering choices were made. In countries lagging the frontier, domestic producers regularly made their first planes by copying the most successful designs from overseas; for instance, at a show in Britain in 1910, “nearly all of the [domestic] monoplanes were shameless copies of the [French] Blériot” (Brett 1933).

After being given permission by the courts to seek injunctions against manufacturers or exhibitors

¹⁶Rosenberg (1970) cites a 1916 machine tooling guide whose genealogy of knowledge transfer is likewise dependent on a very small number of “hub” innovators who traveled with their knowledge in tow.

¹⁷Beyond the inefficiency discussed in the present paper, overly broad patents for technological leaders can cause many other inefficiencies. Maskin and Bessen (2009) use a similar model with cost uncertainty to show how broad patents can lead to inefficiencies in sequential innovation. Bryan and Lemus (2016) show that broad patents can cause races to be the first to perform a technological breakthrough even if the breakthrough is achieved in a manner useless for producing the commercial product. Libecap and Wiggins (1984) and Merges (1999) discuss inefficiencies resulting from the difficulty of negotiating ex-post even when a broad patent has been granted.

who violated the '393 patent, the Wright Brothers began suing meet participants who did not purchase a license, price set in advance. An injunction was filed against the Frenchman Louis Paulhan when he arrived in New York with four state-of-the-art French planes in January 1910. Before the trial date, Paulhan flew one of these planes in Los Angeles, setting a world record for altitude. The Wright suits would make Los Angeles, in many ways, the last meet with top international participants in America. U.S. Marshals caught Paulhan midway through his American tour, and he was forced to cancel the rest of his shows. Fred Howard (1998) claims that “this action elicited a strong response abroad, especially from French aviators who had been invited to compete in the international air races to be held in New York in October” of 1910. English aviator Claude Grahame-White would also be sued, in 1911, for flying exhibition planes that had not paid for a Wright patent license; the judgment of \$1,700 against Grahame-White served as further inducement against foreign participation in American shows (Crouch, 2004). The journal *Aeronautics* declared that “exhibition flying is dead” in 1912, and the preeminent events shifted to Europe (Jones, 1912).¹⁸

It is by no means obvious that the American industry could have caught up to Europe even with frequent technology transfer from these visiting flyers; such a counterfactual is beyond the ability of history to answer. However, since we have seen that potential American designers lagged European, and particularly French, builders in a number of technologies important to the commercial airplane, the fact that lawsuits resulting from the breadth of the '393 patent limited spillovers for both the Wrights and other potential American designers only made things worse. Further, since by the middle of World War I both the British and the Germans, and to a large extent the Italians, had in fact caught up with the French, it is not unreasonable to assume that even a small lag in the rate of technology transfer due to the Wright lawsuit threat could have been enough to doom the hypothetical American industry.

5.2 Alternative Explanations for the Decline of U.S. Aviation

Consider again the traditional stories for the decline of the early American aviation industry. First, a number of commentators have suggested that “hold up” from the Wright and Curtiss patents caused the American aviation industry to stagnate. There were only two major American patentholders in the late aughts and early 1910s: the Wrights and Herring-Curtiss. Standard analyses of patent thickets and anticommons require either so many potential patents causing infringement that it is too costly to negotiate with each patentholder, or else an inability to

¹⁸The events at the Berlin Flugwoche, the Olympia Aero Meets in London, the Paris Aero Salons, and the Gordon Bennett races appear prominently in contemporary journals. It is difficult to give a completely objective accounting of which meets and races were the most important, since audience attendance or similar quantitative statistics tell us little about how important the meet was considered for frontier engineers and designers.

“sell the firm” to the important patentholders. The first certainly doesn’t hold in this case: any controllable aircraft would need a Wright license, and some more advanced planes would need a Curtiss license, but many improvements to airplane parts or engine design, for instance, could be developed without needing any license at all. In any case, two firms is not much of a thicket. The second condition also does not seem to hold: if the Wright patent was so problematic, why didn’t some parvenu simply buy them out? The Aero Club, a hobbyist group, actually considered doing exactly this in 1908 (Johnson, 2004). And if buying out the patent proved impossible for some reason, what made it impossible to sell any improvements on to the Wrights or to Curtiss?

Further, as of 1909, when U.S. dominance is already fading, the Wright patent cases were still winding their way through courts in both the United States and Europe. It was not clear at that time that the courts would grant the Wrights particularly strong protection in the U.S. and relatively weak protection in most of Europe; indeed, the German assignee of the Wright patents was backed by the Kaiser and a number of prominent industrial concerns (Villard 1968). That is, Europe had more firms that could potentially be involved in a patent thicket, and equal uncertainty about a potentially very broad Wright patent; why, then, should the patent thicket harm American firms more than European firms?

Even if a patent thicket made it difficult to sell domestically produced planes in America, prizes remained an important inducement to innovate after 1908. For instance, the Daily Mail promised 1000 pounds to the first who crossed the English Channel, and many air races were held, particularly in Europe.¹⁹ If the U.S. legal environment made innovation impossible, you might expect American designers with ideas at the frontier to try their fortune in Europe instead; migratory labor of this type was fairly common in this era, with French-born engineer Octave Chanute coming to Chicago, and American-born machine-gun inventor (and early airplane experimenter) Hiram Maxim moving to Britain. I am unaware of any important invention or discovery in aviation made by an American in Europe in the twenty year period studied (perhaps Moisant came closest); this suggests at least anecdotally that the problem with American innovators has more to do with a lack of adequate human capital than with onerous domestic legal restrictions.

Explanations relying on World War I spending also cannot explain the entire pattern of microinventions. In particular, it is problematic to assume that domestic demand must be identical to domestic supply. Countries in this era frequently bought imported planes, especially when the dominant technology was located overseas. 9500 British-designed de Havilland DH-4’s were ordered by the Triple Entente from the United States (Jane’s, 1990). The preeminent designer of German aircraft, Anthony Fokker, was Dutch. In 1911, the German government bought 35 planes, of which

¹⁹The debate about whether prizes can induce innovation was alive and well even at the turn of the 20th century. Punch magazine, satirizing prizes, offered 10000 pounds to the first aeronaut who traveled to Mars and back within a week, “deeply impressed as always with the conviction that the progress of invention has been delayed by the lack of encouragement” (Scott, 1995).

22 were Farman-type, the brothers Farman being Frenchmen. In 1912, the Germans bought 20 British planes from Bristol (Jane's, 1913). The British fleet included planes from French designers Blériot, Deperdussin, and Nieuport. Austria-Hungary bought German planes. Russians bought French planes. The Turks, by the end of World War I, had an air force made up of captured planes from nearly every European airplane-producing country (Villard 1968).

The Second World War provides even better evidence on this point. Simonson (1960) quotes an aviation executive about the boom in U.S. production during the mid 1930s: "Where there were revolutions, wars, or threats of war, there were our aircraft customers." If a nation's industry is the technological leader in a military device, and a war is on the horizon, there is good reason to believe this will increase demand, and increase the incentive to innovate, rather than decrease the two (Pattillo 2001). This isn't to say that differential military spending was totally unimportant. Partially driven by potential wartime applications, aeronautical research facilities appeared in Europe earlier than in the U.S. (Crouch, 2003b). Politics may have biased spending toward domestic firms, all things equal. Nevertheless, both World War I and World War II saw extensive innovation in weaponry, including aircraft, by nations other than the eventual buyer. Had the United States possessed a strong aviation industry in the run-up to World War I, it seems reasonable to believe that the industry could have experienced a war-driven boom like it did twenty years later.²⁰

The timing of American rise and decline fits explanations based on preexisting scientific and engineering knowledge better. Consider the base of technical knowledge as represented by industry journals and academic research on aviation. Jane's 1913 guide lists aviation journals by country in 1912. France published fourteen. Germany published eleven, one of which was issued multiple times each week. The U.S. had but four (Aeronautics, Aircraft, Fly and Aero). Supplier networks in France developed with much more specialization than in the United States: Gnome and Renault and Clement-Bayard enter principally as engine designers. Wright and Curtiss tended to handle design of all of the airplane components in-house, and one reason may have been the limited potential suppliers in the United States given preexisting mechanical engineering knowledge. Academia was little help here. Prandtl's Modellversuchsanstalt der Motorluftschiff-Studiengesellschaft, an institute at Göttingen for theoretical airship and airplane research, was established in 1907. The French had an entire university devoted to aeronautics in 1909 (ESACM), as well as chairs at the Sorbonne and Saint-Cyr the same year. The U.S., on the other hand, would not have a single professor of aeronautics until M.I.T. appointed one in 1913 (Mangolte, 2010).

The list of microinventions and microdiscoveries in Appendix A makes clear that this European advantage in technical capability exists even before the Wrights invent their flyer in 1903 and, as

²⁰It ought not be forgotten that the era right before World War I was the high water mark for international trade. Despite Britain's massive domestic demand for dyestuffs, German chemical firms held 85 to 90 percent market share even within Britain (Murmah 2003). Such a situation was not unusual in many industries during this period.

noted, continues through the rest of the first decade of the twentieth century. The Wrights and the Langley/Manly project at the Smithsonian are the only two American teams producing any advance at the frontier of technical knowledge until 1909. Langley, by 1903 already elderly, gave up his project in that year after running out of money. The Wrights kept their invention, to a large extent, secret, and did not perform innovative work at all between 1905 and 1909. America was a technical laggard in 1903, and was a major technical laggard by 1908; once the Wright technique for wing warping was demonstrated publicly in 1908, the Europeans were quick to add techniques for lateral stability based on the Wrights' wing-warping to all of their other improvements in fuselage, materials and engine design. Distance and the Wright suits combined to make it difficult for American firms to integrate European technology in the same manner.

6 Concluding Remarks

It is left to a sociologist of science to discuss exactly why individual inventors, or individual steps in a nexus of inventions, are canonized as representing the invention as a whole.²¹ The Wrights have slowly usurped that distinction from other pretenders to the throne such as Farman, Langley or Santos-Dumont. No matter the reason why such special significance is awarded, it is important for economists and policymakers to be aware that credit, pioneer patents, or other distortions generated on this basis not only decouple the link between initial invention and commercial development, but can generate a strictly harmful waste of resources.

The inventions of the Wright Brothers are historically important and are rightfully canonized in the annals of science. But they were also only a part of a sequence of inventions occurring over decades and across continents which led from basic understanding of the principals of flight to airplanes of significant commercial and military value. The lateral control affected by wing warping is complementary to these other microinventions, but not uniquely so. The link between the inventions of the Wrights and other aviation innovations goes beyond the discovery of one step of a sequence; rather, they discovered one element of a set, a set whose order in time is not clear in advance. Consider a counterfactual world where the Wrights discover wing warping before the internal combustion engine is discovered. Steam-driven planes would likely have seen little success in getting off the ground due to their weight. The “technological achievement” and special patent protection would likely have been granted to an engineer who suitably adapted his

²¹Such delineations are by no means a new problem. In a letter to Dr. Benjamin Waterhouse on March 3, 1818, while discussing the question of who was most responsible for the American Revolution, Thomas Jefferson writes: “Who invented the Lavoisierian chemistry? The English say Dr. Black, by the preparatory discovery of latent heat. Who invented the steamboat? Was it Gerbert, the Marquis of Worcester, Newcomen, Savary, Papin, Fitch, Fulton? The fact is, that one new idea leads to another, that to a third, and so on through a course of time until some one, with whom no one of these ideas was original, combines all together, and produces what is justly called a new invention” (Jefferson, 1818).

lightweight engine while borrowing the Wrights' control method. But no matter which comes first - the engine or the control - the nexus of microinventions, and hence the economic situation, is identical. Technological achievement is often wholly unrelated to economic importance.

The difference between technological achievements and economically important development is why industrial reversals of fortune can occur even when there has been no policy mistake or erroneous firm strategy. Why some countries succeed in turning a piece of basic research or an early invention into a valuable industry depends critically on the ability of firms in the inventing country to perform the necessary development work. This is perhaps an obvious point, but it is one sorely lacking in descriptions of the rises and falls of many industries.²² From a policy perspective, if a region incentivizes, via a prize, a strong patent, or some other mechanism, an important multi-component invention but does not have the proper complementary capabilities to develop the commercially relevant extension of that invention, policymakers have two options. Either they can additionally offer policies which induce transfer from abroad of the necessary complementary skills, or they can drop the expectation that the technological breakthrough will generate a strong local industry building on that invention.

²²And though the analysis in this paper extends only through World War I, relative national advantages in development potential may explain many subsequent episodes. The famed Douglas DC-3 in the 1930s relied critically on Alcoa's duralumin alloy, wing design research done by NACA, and fuel improvements such as the addition of tetraethyl lead into aviation gasoline. On the other hand, the failure of American firms to develop early jets may have resulted, as noted, from the limited American knowledge about its theoretical underpinnings (Mowery and Rosenberg, 1982).

7 Appendix A: Microinventions 1897-1917

Table 4 presents a database of microinventions from the death of Lilienthal until the end of 1917. The table was constructed by analyzing both histories of technology and early airplane makers, as well as contemporaneous documents including periodicals like *L'Aerophile* and *Aeronautics*. During this period, there are literally thousands of airplane-related patents as well as an enormous number of important scientific discoveries, seemingly minor changes in design, and insights into potential uses of heavier-than-air flight. The 91 microinventions listed in Table 4, then, are only a subset. The difficulty of delineating “airplane-related” inventions from other technological improvements is, of course, a real problem. Consider the following, from Vivian and Marsh (1920): “An important development in connection with the inspection and testing of aircraft parts, particularly in the case of metal, was the experimental application of X-ray photography, which showed up latent defects, both in the material and in manufacture, which would otherwise have passed unnoticed.” And indeed, such inspection was important, but I do not include X-ray related developments in the table below, nor other tangentially related technologies. There are also a number of advances which were incredibly incremental, and thus difficult to assign to any particular inventor. For example, design choices related to welding, cellulose acetate “doping”, or minimal changes in strut position or wing aspect ratio, though important in aggregate, tended to be too incremental to identify individual advances *ex-post*. Many of these incremental advances tend to fit Robert Allen’s model of “collective invention” (Allen, 1983).

A vast majority of patents and unpatented ideas from this period ended up having no impact whatsoever on the later development of the airplane industry. The principle used to choose among inventions is to restrict the table only to breakthroughs which were mentioned in multiple texts as being both influential and at the worldwide technological frontier. For example, this means I include engines which are seen as being technologically beyond other available engines, but I do not include engines simply because they were popular in one region of the world or another: the Gnome Monosoupape is included, and the Curtiss OX-5 is not.

I have made an attempt to search the literature for inventions in plane structure, military technique, engine design, oils/fabrics/metals/coatings and theoretical developments. As with any list of inventions, there can be quibbling about who ought have priority for a given idea; where possible, I follow the priority assigned most commonly by our sources.

The table draws on the following: Abzug and Larrabee (2002), Ackroyd, Axell and Ruban (2001), Anderson Jr. (1998), Anderson Jr. (2002), Andrews (1977), Ash, Miley and Landman (2000), Colby (1944), Crouch (2003a), Crouch (2003b), Garber (2005), Gibbs-Smith (1970), Jakab (1997), Magoun and Hodges (1931), Matthews (2001), Munson (1969), Pattillo (2001), Scott (1995), Short (2012), Stamper (1995), Taylor (1971), Tobin (2003), Vivian and Marsh (1920) and Wright (1988), as well as numerous issues of airplane-related periodicals from the 1900s and 1910s like *L'Auto*, *L'Aerophile* and *Aeronautics*.

References

- [1] Malcolm J. Abzug and E. Eugene Larrabee. *Airplane Stability and Control: Second Edition*. Cambridge University Press, 2002.
- [2] J.A.D. Ackroyd, B.P. Axcell, and A.I. Ruban. *Early Developments of Modern Aeronautics*. AIAA, 2001.
- [3] Aeronautics. Los Angeles Meet. March:104, 1910.
- [4] Robert C. Allen. Collective Invention. *Journal of Economic Behavior and Organization*, 4, 1983.
- [5] George Amick. How the Airmail Got Off the Ground. *American History*, 33.3, 1998.
- [6] John D. Anderson Jr. *A History of Aerodynamics*. Cambridge University Press, 1998.
- [7] John D. Anderson Jr. *The Airplane: A History of its Technology*. AIAA, 2002.
- [8] Allen Andrews. *The Flying Machine: Its Evolution Through the Ages*. G. P. Putnam's Sons, 1977.
- [9] Kenneth J. Arrow. Economic Welfare and the Allocation of Resources for Invention. *in The Rate and Direction of Inventive Activity (NBER)*, 1962.
- [10] Robert L. Ash, Stanley J. Miley, Kenneth W. Hyde, and Drew Landman. Evolution of Wright Flyer Propellers Between 1903 and 1912. *Old Dominion Aerospace Engineering Department Working Paper*, 2000.
- [11] Gerben Bakker. The Decline and Fall of the European Film Industry: Sunk Costs, Market Size, and Market Structure, 1890-1927. *Economic History Review*, LVIII.2, 2005.
- [12] James Bessen and Eric Maskin. Sequential Innovation, Patents, and Imitation. *RAND Journal of Economics*, 40.4, 2009.
- [13] James Bessen and Alessandro Nuvolari. *Knowledge Sharing Among Inventors: Some Historical Perspectives*. MIT Press, 2012.
- [14] Michael Bikard. Simltaneous discovery as a research tool: Method and promise. *Mimeo*, 2016.
- [15] George Bittlingmayer. Property Rights, Progress and the Aircraft Patent Agreement. *Journal of Law & Economics*, 31, 1988.
- [16] Augustine Brannigan. *The Social Basis of Scientific Discoveries*. Cambridge University Press, 1981.
- [17] R. Dallas Brett. *History of British Aviation, Vol I and II*. Air Research Publications, 1933.
- [18] Colin P. Britcher, Drew Landman, Robert Ash, Kevin Kochersberger, and Ken Hyde. Predicted Flight Performance of the Wright 'Flyer' Based on Full-Scale Tunnel Data. *AIAA Paper 2004-0104*, 2004.

- [19] G. Bryan and W. Williams. The Longitudinal Stability of Aerial Gliders. *Proceedings of the Royal Society of London*, 73, 1904.
- [20] Kevin A. Bryan and Jorge Lemus. The Direction of Innovation. *Mimeo*, 2016.
- [21] CAA. *CAA Statistical Handbook of Civil Aviation 1958*. US Department of Commerce, 1958.
- [22] Emmanuel Chadeau. *De Blriot Dassault: Histoire de l'industrie aeronautique en France*. Fayard, 1987.
- [23] Octave Chanute. *Progress in Flying Machines*. The American Engineer and Railroad Journal, 1894.
- [24] C.B. Colby. Can We Land Our Planes Safely? *Popular Science*, May 1944.
- [25] Tom D. Crouch. Blaming Orville and Wilbur: The Wright Patent Suits and the Growth of American Aviation. *Jalonick Memorial Lecture at the University of Texas at Dallas*, 2003.
- [26] Tom D. Crouch. *The Bishop's Boys: A Life of Wilbur and Orville Wright*. W.W. Norton, 2003.
- [27] Tom D. Crouch. Wright Brothers: Pattern for American Air and Space Power—Innovation and Legacy of Ingenuity of the Winged Crusade. *U.S. Air Force Academy Harmon Lecture*, 2003.
- [28] Tom D. Crouch. *Wings: A History of Aviation from Kites to the Space Age*. W.W. Norton, 2004.
- [29] F.E.C. Culick. The Wright Brothers: First Aeronautical Engineers and Test Pilots. *AIAA Journal*, 41.6, 2003.
- [30] Vincenzo Denicolo and Piercarlo Zanchettin. How Should Forward Protection Be Provided? *International Journal of Industrial Organization*, 20, 2002.
- [31] Harry T. Dykman. Patent Licensing within the Manufacturer's Aircraft Association (MAA). *Journal of the Patent Office Society*, 646, 1964.
- [32] Stephan R. Epstein. Property Rights to Technical Knowledge in Premodern Europe, 1300-1800. *American Economic Review Papers & Proceedings*, 94.2:382–387, 2004.
- [33] Flight. 18 Years of World Records. February 7, 1924.
- [34] Lester W. Garber. *The Wright Brothers and the Birth of Aviation*. Crowood Press, 2005.
- [35] Charles Gibbs-Smith. *Aviation: A Historical Survey from its Origins to World War II*. Her Majesty's Stationary Office, 1970.
- [36] S. Colum Gilfillan. *Inventing the Ship*. Follett Publishing Co., 1935.
- [37] Margaret B.W. Graham and Bettye H. Pruitt. *R&D for Industry: A Century of Technical Innovation at Alcoa*. Cambridge University Press, 1990.
- [38] *Graham v. John-Deere*, 383 US 1,11. 1966.

- [39] Michael A. Heller and Rebecca S. Eisenberg. Can Patents Deter Innovation: The Anticommons in Biomedical Research. *Science*, 280, 1998.
- [40] Erik Hornung. Immigration and the Diffusion of Technology: The Huguenot Diaspora in Prussia. *American Economic Review*, 104.1:84–122, 2014.
- [41] Erik Hovenkamp and Herbert J. Hovenkamp. Patent pools and related technology sharing. *Mimeo*, 2015.
- [42] Fred Howard. *Wilbur and Orville: A Biography of the Wright Brothers*. Courier Dover, 1998.
- [43] Peter Jakab. *Visions of a Flying Machine*. Smithsonian Books, 1997.
- [44] Jane’s. *All the World’s Aircraft*. Sampson Low Marston, 1913.
- [45] Jane’s. *Fighting Aircraft of World War I*. Military Press, 1990.
- [46] Thomas Jefferson. Letter to Dr. Benjamin Waterhouse, March 3, 1818.
- [47] Herbert A. Johnson. The Wright Patent Wars and Early American Aviation. *Journal of Air Law & Commerce*, 69, 2004.
- [48] Ernest L. Jones. A Review of 1911. *Aeronautics*, Jan. 1912.
- [49] Godfrey Keller and Sven Rady. Strategic Experimentation with Poisson Bandits. *Theoretical Economics*, 5, 2010.
- [50] Ryan Lampe and Petra Moser. Do Patent Pools Encourage Innovation: Evidence from 20 Industries in the 1930s. *Working Paper*, 2011.
- [51] Corinne Langinier. Patent Pool Formation and the Scope of Patents. *Economic Inquiry*, 49.4, 2011.
- [52] Mark A. Lemley. The Myth of the Sole Inventor. *Michigan Law Review*, 110.5, 2012.
- [53] Josh Lerner and Jean Tirole. Efficient Patent Pools. *American Economic Review*, 94, 2004.
- [54] Gary D. Libecap and Steven N. Wiggins. Contractual Responses to the Common Pool: Prorating of Crude Oil Production. *American Economic Review*, 74.1, 1984.
- [55] Alexander F. Magoun and Eric Hodgins. *A History of Aircraft*. McGraw Hill, 1931.
- [56] Pierre-Andre Mangolte. Patents Wars: Deuxieme partie, les consequences: la paralysie de l’industrie, le freinage de l’innovation. *Working Paper*, 2010.
- [57] Birch Matthews. *Race with the Wind: How Air Racing Advanced Aviation*. Helix, 2001.
- [58] Marvin Wilks McFarland. *The Papers of Wilbur and Orville Wright, Vol. 1 and 2*. McGraw Hill, 1953.
- [59] Robert P. Merges. Institutions for Intellectual Property Transactions: The Case of Patent Pools. *University of California Berkeley Working Paper*, 1999.
- [60] Robert K. Merton. *The Sociology of Science*. University of Chicago Press, 1973.

- [61] Peter B. Meyer. Combined Patents List. *Personal Correspondence*, 2012.
- [62] Peter B. Meyer. Open Sources of the Invention of the Airplane. *Revue Economique*, Forthcoming, 2012.
- [63] Rudolf Modley. *Aerospace Facts and Figures 1962*. American Aviation Publications, 1962.
- [64] Joel Mokyr. *The Lever of Riches: Technological Creativity and Economic Progress*. Oxford University Press, 1990.
- [65] John M. Morrow. *The Great War in the Air*. Smithsonian Institution Press, 1993.
- [66] Petra Moser and Alessandra Voena. Compulsory Licensing: Evidence from the Trading with the Enemy Act. *American*, 102.1, 2012.
- [67] David C. Mowery. *Papers Commissioned for a Workshop on the Federal Role in Research and Development*, chapter Federal Funding and Research and Development in Transportation: The Case of Aviation. 1985.
- [68] David C. Mowery and Nathan Rosenberg. *Government and Technical Progress*, chapter The Commercial Aircraft Industry. Pergamon Press, 1982.
- [69] David C. Mowery and Nathan Rosenberg. *Paths of Innovation: Technological Change in 20th Century America*. Cambridge University Press, 1998.
- [70] Kenneth Munson. *Pioneer Aircraft: 1903-14*. Blandford Press, 1969.
- [71] Peter Johann Murmann. *Knowledge and Competitive Advantage: The Coevolution of Firms, Technology and National Institutions*. Cambridge University Press, 2003.
- [72] NAAA. *History of Agricultural Aviation*. <http://www.agaviation.org/content/history-agricultural-aviation>, 2012.
- [73] New York Times. French Praise Wrights. August 9, 1908.
- [74] Simon Newcomb. Is the Airship Coming? *McClure's*, 17, September 1901.
- [75] Ted O'Donoghue, Suzanne Scotchmer, and Jacques-Francois Thisse. Patent Breadth, Patent Life, and the Pace of Technological Progress. *Journal of Economics & Management Strategy*, 1998, 7.1.
- [76] Donald M. Pattillo. *Pushing the Envelope: The American Aircraft Industry*. University of Michigan Press, 2001.
- [77] Popular Mechanics. American Altitude Record Broken by Army Airman. *Popular Mechanics*, December 1914.
- [78] Alex Roland. *Model Research*. NASA, 1985.
- [79] Nathan Rosenberg. Economic Development and the Transfer of Technology: Some Historical Perspective. *Technology and Culture*, 11.4:550–575, 1970.

- [80] Nathan Rosenberg. *Inside the Black Box: Technology and Economics*. Cambridge University Press, 1982.
- [81] Simon Schaffer. Making Up Discovery. *Dimensions of Creativity* (Ed. M. Boren), MIT Press, 1996.
- [82] Jacob Schmookler. *Invention and Economic Growth*. Harvard University Press, 1966.
- [83] Phil Scott. *The Shoulders of Giants: A History of Human Flight to 1919*. Helix, 1995.
- [84] Simine Short. United States Aviation Patent Database, 2012.
- [85] Seth Shulman. *Unlocking the Sky: Glenn Hammond Curtiss and the Race to Invent the Airplane*. Harper Collins, 2002.
- [86] G.R. Simonson. The Demand for Aircraft and the Aircraft Industry. *Journal of Economic History*, 20.3, 1960.
- [87] George Stamper. The Sikorsky S-16 and Russian Aviation During the Great War (M.A. Thesis). Master's thesis, University of Georgia, 1995.
- [88] Martin Staniland. *Government Birds: Air Transport and the State in Western Europe*. Rowman & Littlefield, 2003.
- [89] Dustin R. Szakalski. Progress in the Aircraft Industry and the Role of Patent Pools and Cross-Licensing Agreements. *UCLA Journal of Law & Technology*, 15.1, 2011.
- [90] C. Fayette Taylor. *Aircraft Propulsion: A Review of the Evolution of Aircraft Piston Engines*. Smithsonian Institution Press, 1971.
- [91] David J. Teece. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research policy*, 15(6):285–305, 1986.
- [92] James Tobin. *To Conquer the Air*. Free Press, 2003.
- [93] U.S. House of Representatives. Report 5304: Aeronautics in the Army. *Committee on Military Affairs*, 1913.
- [94] Henry Serrano Villard. *Contact! The Story of the Early Birds*. Thomas Y. Crowell, 1968.
- [95] E. Charles Vivian and Lt. Col. W. Lockwood Marsh. *A History of Aeronautics*. 1920.
- [96] Rodney K. Worrel. The Wright Brothers' Pioneer Patent. *ABA Journal*, December 1979.
- [97] Orville Wright. *How We Invented the Airplane: Illustrated Edition*. Dover, 2003.
- [98] Orville Wright and Wilbur Wright. *Flying-Machine*, 1906.
- [99] Carl Zollmann. Patent Rights in Aircraft. *Marquette Law Review*, 216, 1926.

Table 1: US and French Airplane Production

Year	French production	U.S. military production	U.S. civil and exports
1910	57	0	N/A
1911	92	11	N/A
1912	147	16	29
1913	316	14	29
1914	411	15	34
1915	796	26	152
1916	5111	142	269
1917	7793	2013	135

French production from Chadeau (1987). U.S. production from CAA (1958) and Modley (1962). Of the French production, roughly a quarter is exported each year before WW1. U.S. data on number of planes exported is unavailable during this period. Data are for commercially sold production - there are many "homebrew" planes during this period, the vast majority of which cannot fly; for instance, Jane's (1913) lists "nearer 1000" as French production in 1912, while Jones (1912) lists U.S. 1911 production as 174. Official U.S. statistics likely understate production for touring exhibition teams, but by any measure, French commercial production far exceeds U.S. production by 1913.

Table 2: World Altitude and Speed Records

Year	Altitude Record Location	Altitude Record Country of Development	Speed Record Location	Speed Record Country of Development
1903	USA	USA	USA	USA (Wright)
1904	USA	USA	USA	USA (Wright)
1905	USA	USA	USA	USA (Wright)
1906	USA	USA	USA	USA (Wright)
1907	USA	USA	USA	USA (Wright)
1908	France	USA	USA	USA (Wright)*
1909	France	France	France	France (Blériot)**
1910	France	France***	USA	France (Blériot)
1911	France	France	France	France (Nieuport)
1912	France	France	France	France (Deperdus.)
1913	France	France	France	France (Deperdus.)
1914	France****	France	France	France (Deperdus.)

Speed records from Cooper (1951). Altitude records from Flight (1924). All records are “official” FAI records as of December 31, unless otherwise noted.

* As the Wrights did not demonstrate their plane until 1908, previous records are unofficial, though the Wrights’ own notes show that they had many flights which would have held the world record during this period.

** Glenn Curtiss briefly held the record in July 1909 with his No. 2 at Reims. No American designs except those by the Wrights and Curtiss were potential recordholders in this period.

*** Hoxsey in a plane by Wright set an unofficial record at Los Angeles but the barometer was destroyed in a crash which took his life shortly thereafter.

**** No official records were set during World War I, but had there been FAI-approved trials, the Italian Ansaldo, the British Sopwith F1 and SE5, the German Fokker D.7 and the French SPAD S.13 were all faster than the pre-war Deperdussin and contenders for the title of world’s fastest.

Table 3: Selected Important Discoveries in Aviation Before 1896

Invention	Year	Inventor	Notes
Importance of Streamlining	1400s	da Vinci	
Whirling Arm	1740s	Robins	Precursor to the wind tunnel
Euler Equations	1750s	Euler	PDE for inviscous fluid dynamics
Fixed Wings rather than Ornithopter	1804	Cayley	Da Vinci also considered this
Principles concerning Lift and Thrust	1804	Cayley	Noted that problem of generating thrust and problem of generating lift are quite different
Importance of Wings at Dihedral Angle	1810	Cayley	Providing automatic stability
Importance of Cambered Wings	1810	Cayley	Also noted more extensively by Lilienthal
Navier-Stokes Equations	1840	Navier/Stokes	Fluid dynamics with friction
Successful Heavier-than-air Flight	1848	Stringfellow	Flew steam-powered model across a room, with only limited control; takeoff is controversial, but du Temple is known to have flown a powered model with certainty in the late 1850s
Powered lighter-than-air Flight	1852	Giffard	Flew 27km in a steam-powered airship
Internal Combustion Engine	1860	LeNoir	Many precursors going as far back at Huygens in the 1600s
Wind Tunnels	1871	Wenham	With improvements by Horatio Phillips in the 1880s
Longitudinal and Lateral Stability	1871	Pénaud	Rubber-band powered models with dihedral wings and tilted rudder fly with stability
Transition from Laminar to Turbulent Flow	1883	Reynolds	Region where fluid flow transitions to turbulence depends on “Reynolds Number”
Lift and Drag Tables	1889	Lilienthal	In “Birdflight as the basis for aviation”
Drag Polar Diagram	1889	Lilienthal	Modern diagram of lift and drag of airfoil
Powered Uncontrolled Manned Flight	1890	Ader	50 meter uncontrolled flight driven by steam engine; also powered hops off on inclines earlier by du Temple and Mozhaysky
Skids for Takeoff/Landing	1890	Ader	Later used by the Wrights
Correct Calculation of Smeaton Coefficient	1891	Langley	Corrects commonly used (metric) coefficient of .13 to .08 in “Experiments in Aerodynamics”
High Aspect-Ratio Wings Provide More Lift	1891	Langley	Experimental verification of a property suggested by Wenham
Box Kite Structure	1893	Hargrave	Later used on Santos’ bis-14
Pratt Truss Biplane Structure	1896	Chanute	On Chanute’s Indiana glider, also later used by the Wrights

Table 4: Microinventions and Microdiscoveries 1897-1917

Invention	Inventor	Country	Year	Notes
Smoke tunnel photography of vortices	Etienne Jules-Marey	France	1899	Allowed photographs of surface discontinuity
Diesel engine	Rudolf Diesel	Germany	1900	Used infrequently in planes because of weight, though appeared in Packard planes in the 1920s
Wing warping	Wright Brothers	USA	1900	In No. 1 glider
First gasoline powered model flight	Langley/Manly	USA	1901	
Balzer-Manly model engine	Manly/Balzer	USA	1901	Incredibly lightweight 7lb, 3.2hp engine
Controlled wing warping during flight using hip cradle	Wright Brothers	USA	1901	In No. 2 glider
Helicopter model with internal combustion engine	Jan Bahyl	Slovakia	1901	
Zhukovsky-Kutta Theorem about lift of aerofoils	Martin Kutta	Germany	1902	Independently expanded by Nikolay Zhukovsky in Russia in 1906
V8 engine	Leon Levavasseur	France	1902	The original Antoinette
Fixed link between wing warping and rudder	Wright Brothers	USA	1902	
Early gas turbine producing net power	Jens W.A. Elling	Norway	1903	Precursor to Whittle's jet engine in the 1930s
Balzer-Manly engine	Manly/Balzer	USA	1903	Very efficient 135lb, 52hp non-rotating radial engine using in Langley's Aerodrome A; record low weight-hp ratio until 1918
Wright-Taylor engine	Wrights/Taylor	USA	1903	179lb, 12hp engine much less efficient than Manly's, but still quite light for its time
Longitudinal equations for airplane motion	Bryan/Williams	UK	1903	
Efficient propeller design using airfoil principles	Wright Brothers	USA	1903	Much more efficient than contemporaneous propellers; designed using "blade element theory" where propeller is seen simply as a vertical airfoil
Duralumin	Alfred Wilm	Germany	1903	By 1920s, material used for lightweight metal plane fuselage
Calculation of fluid flow using boundary layer	Ludwig Prandtl	Germany	1904	Presented August 12 at International Conference of Mathematicians in Heidelberg
Catapult derrick to assist takeoff	Wright Brothers	USA	1904	
Turbocharger	Alfred Buchi	Switzerland	1905	Installed on a La Pere Liberty by GE in 1918, allowing new altitude records to be set
Water-cooled V-type engine	Leon Levavasseur	France	1905	
Tractor propeller	Trajan Vuia	France	1906	Replaces pusher configuration nearly entirely by World War I; first full scale tractor biplane due to Alfred de Pischhoff in 1907
Pneumatically tired airplane wheels	Trajan Vuia	France	1906	
Powered monoplane	Trajan Vuia	France	1906	Blériot followed up with far more successful monoplane designs
Spring shock struts on landing wheels	Gabriel Voisin	France	1907	In Voisin-Farman plane

Unstable manned helicopter flight	Breguet brothers and Charles Richet	France	1907	The "Gyroplane No. 1"
Knowledge of Wingtip Vortices	Frederick W. Lanchester	UK	1907	In the book Aerodynamics
Control stick-Rudder bar control aka "cloche system"	Louis Blériot	France	1907	Similar less-developed idea by Esnault-Pelterie the year before
Manned helicopter flight	Paul Cornu	France	1907	
Swept wings	John William Dunne	UK	1907	Dunne D.1 Glider
Lightweight airplane	Alberto Santos-Dumont	France	1908	The bamboo "Demoiselle"
Blasius equation for PDEs	Heinrich Blasius	Germany	1908	Allows solution of PDEs involving shear stress
Enclosed wheels	Jacob Ellenhammer	Denmark	1908	
Production rotary airplane engine	Seguin brothers	France	1908	Gnome 50hp air-cooled rotary engine
Hydraulic wheel brakes	Robert Esnault-Pelterie	France	1908	On the REP No. 2
Aileron	Henri Farman	France	1908	In a limited way, invented in a "forgotten" patent in 1868 by Boulton, and on the Santos-Dumont bis-14 of 1906; Curtiss patented another independent aileron design soon after
Modern aircraft tail	Leon Levavasseur	France	1908	Fixed vertical and horizontal tail with movable rudder and elevator in the Antoinette IV
Venetian blind deck of wings	Horatio Phillips	UK	1908	Suggested by Wenham in the 1860s
Propeller not mounted directly on crankshaft	Renault	France	1908	Propeller connected to Renault V-8 mounted on extension running at half crankshaft speed, a precursor to propeller reduction gears
Tricycle landing gear	Edward Mines	UK	1909	
Streamlined body	Edouard Nieuport	France	1909	The Nieuport IV
Chauviere propeller	Lucien Chauviere	France	1909	Efficient curved propeller blade
Between-wing ailerons	AEA	USA	1909	
Airplane engineering university	Unknown	France	1909	École supérieure d'aéronautique et de constructions mécaniques
Anzani fan-type engine	Alessandro Anzani	France/Italy	1909	
Darracq 2-cylinder opposed engine	Darracq	France	1909	First airplane engine with mechanically operated inlet valves
Two-cycle gasoline engine	New Engine Company	UK	1909	Mechanically simple
Flight Simulator	Antoinette Company	France	1909	The "Antoinette Training Barrel" for large wheel of Antoinette VII
Fabre Hydravion floatplane	Henri Fabre	France	1910	First seaplane - seaplanes have fuselage above water, while flying boats use fuselage for buoyancy
Ducted fan propeller	Henri Coanda	Romania	1910	This plane likely never flew
Automatically stable tailless aircraft	John Dunne	UK	1910	
"Horn" balances	Louis Blériot	France	1910	On the Blériot XI, later used to lessen pilot effort and particularly visible on Fokker D7 wing design
Spats to enclose wheels	Leon Levavasseur	France	1911	
Flying boat	Glenn Curtiss	USA	1911	The "Model E"
Tailhook for aircraft carrier landings	Hugh Robinson	USA	1911	
Bombsight	Lt. Riley Scott	USA	1911	

Successful airplane parachute jump	Grant Morton	USA	1911	
Modern control wheel	Louis Bechereau	France	1911	In the Deperdussin B
Standard “six degrees of freedom” mathematical model of the airplane	G.H. Bryan	UK	1911	Particularly concerns questions of stability
Monocoque structure	Emile Ruchonnet	France	1911	Developed into the Deperdussin Monocoque the following year
Enclosed cockpit	A.V. Roe	UK	1912	
All-metal aircraft	Hans Reissner	Germany	1912	The American John Moisant had a prototype in 1909, as did Frenchmen Ponche-Primaud in 1912; the Romanian Vlaicu has one soon after Reissner
Improved inherent stability	Geoffrey de Havilland and E.T. Busk	UK	1912	The RAF B.E.2
Propeller spinners	Deperdussin	France	1912	Reduced drag on the Deperdussin Racer
Gyroscopic autopilot	Sperry Corporation	USA	1912	
Aircraft radio	Charles Maddox	USA	1912	
Helicopter with cyclic control	Jacob Ellenhammer	Denmark	1912	
Ramjet	Rene Lorin	France	1913	Principle known and patented, but practical ramjet not built until much later
Four-engine aircraft	Igor Sikorsky	Russia	1913	In Le Grand, which inspired the more famous Ilya Muromets
High-speed biplane	Sopwith	UK	1913	The “Tabloid”
Gnome Monosoupape engine	Seguin brothers	France	1913	Replaces many moving parts, cowling with central air intake, oil and exhaust discharge underneath the engine
Purpose-designed bomber	Gianni Caproni	Italy	1913	Model for the Ca.3 bomber
Amphibious airplane	Sopwith/Saunders	UK	1913	Airplane that can land on both water and land
Deflector wedges	Eugene Gilbert	France	1914	Allows safer gun firing through propeller blades
Passenger saloon	Igor Sikorsky	Russia	1914	
Aluminum en-bloc cylinder engine construction	Mark Birkigt	Spain	1914	The “Hispano-Suiza” engine used in SPAD fighters, cast rather than forged
Automatic lubrication of valves by engine oil	Mark Birkigt	Spain	1914	The “Hispano-Suiza” engine
Thick cantilevered wings	Hugo Junkers	Germany	1915	In the J1
Flaps/Air brakes	Royal Aircraft Factory	UK	1915	On the RAF F.E.2a, used for help on landing despite low speed
Interrupter gear	Anthony Fokker	Germany	1915	Synchronizes machine gun firing with propeller rotation
Mercedes 6-cylinder engine	Mercedes	Germany	1915	First engine with welded-steel cylinder construction
Rationalized airplane design textbook	Barnwell/Sayers	UK	1915	“Airplane Design” and “A Simple Explanation of Inherent Stability”
Retractable landing gear	James V. Martin	USA	1916	Incorporated landing gear into Martin K-III Scout
Semimonocoque fuselage	Albatros	Germany	1916	
Spreader bar on landing gear	Reinhold Platz	Germany	1916	In the Fokker V1 and D7, adding lift and keeping wheels stable

Drift Sight	Harry Wimperis	UK	1916	Allowed accurate bombdropping accounting for winds
Split-Axle landing gear	James V. Martin	USA	1917	Allows spreader bar to be done away with
Turbocharger fitted to airplane engine	Auguste Rateau	France	1917	Replaces crankshaft-driven compressor for mechanical supercharging at high altitude
Liberty 400hp V12	J. Vincent and E.J. Hall	USA	1917	Powerful engine designed for easy mass production
Valve cooling with mercury coating	Midgley/Kettering	USA	1917	
Discovery of petroleum oil rather than castor oil for engine lubrication	US Navy Aero-Engine Lab	USA	1917	
Major improvement in flying boat hull design, including "Felixstone notch"	John Cyril Porte	UK	1917	Modifies Curtiss flying boat into Felixstone F.2A