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

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Abstract

The early airplane industry was dominated by European firms. These "industrial reversals of fortune," where early industries arise far from the location of the technical invention, are common. We show that, for 21 canonical inventions, the early industry grows far from the invention location at least 16 times. We argue theoretically that this split is most likely for multi-component inventions that are artificially induced by patents, prizes, or Mertonian credit. In the context of the airplane, a novel dataset of microinventions shows that even before 1903 America lagged in most of the complementary technology necessary for a commercial airplane.

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Tis frivolous to fix pedantically the date of particular inventions. - Emerson[1]

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 breakthrough 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. 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; for example, 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. Indeed, we will show that *most* canonical inventions see their early commercial leaders arise in locations far from the site of the invention. 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 spill over locally.

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 answer concerns the distinction between technical invention and innovation. The airplane, like many important inventions, involved a series of minor and major technical breakthroughs, rarely arriving in

[1] From 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 in two senses to the present essay, that "ideas are in the air."

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 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 region 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, the Teece [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

[2]With a nod toward readability, and with apologies to Mokyr [1990] who coined the term microinventions in a way that specifically excludes scientific discoveries, from now on we 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.

[3]The difficulty of defining "the" invention has been considered by sociologists including Brannigan [1981] in his book about the social construction of ex-post credit, and 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 masterfully examines what Nathan Rosenberg would later call "low-visibility inventions" in the history of the ship (Gilfillan [1935]). Indeed, as Rosenberg has written, "[t]he history of inventions is, most emphatically, not the history of inventors" (Rosenberg [1982]).

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 from an *economic* standpoint why differential reward should be given depending on which one is invented first and which is invented second. Even worse, giving *extra* reward on the basis on economically inconsequential technical achievements biases inventors away from research more likely to develop into a strong local industry with spillovers to other firms and workers.

This frame suggests that explaining the poor early development 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 missing outside knowledge, while firms from other areas are unable to do so. We attempt such an explanation using a novel dataset of aviation-related microinventions from 1897 to 1917. Our 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.

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 [2002]). 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 (Crouch [2003a]), 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]

What was this indirect harm of patents? 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 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

[4]The legal literature puts the "disclosure" role of patents front and center. An oft-cited line from the Supreme Court case Graham v. John-Deere, 383 US 1,11 [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 (on this point, see Ouellette [2012]).

[5]The 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 [2004] summarizes the literature as showing that "not a single premodern invention was transferred simply through the printed word," and Rosenberg [1970] notes that, in machine tooling, journals were often effective at generating interest but totally ineffective at teaching new techniques.

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. Section 2, we investigate the growth of the early industry of 21 canonical inventions from the classic book "Sources of Invention" by Jewkes et al. [1962]. 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. In section 4, we describe the global state of knowledge on airplanes at the end of the 19th century, the developments of the Wright Brothers, and the rise and fall of the US aircraft industry through 1917. 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.

2 The Airplane and 21 More: A Stylized Fact

Before investigating why industrial reversals of fortune happen, through theory and a case study of the early airplane industry, we ought first clarify how common these reversals have been historically. That is, of a given set of important technological breakthroughs, what fraction saw their early commercial industry arise with some geographical proximity to the site of the invention? There does not exist a canonical database of inventions and their resulting industry - indeed, the link is often difficult to establish. Therefore, we select 21 inventions of the late 19th and early 20th century from the classic Jewkes et al. [1962] book "The Sources of Invention", and detail the early industry that follows each of those inventions using historical texts and contemporaneous sources.[6] In particular, we investigate the early history of: the automobile, synthetic plastic, the ballpoint pen, catalytic petroleum cracking, the cotton picker, the refrigerator, the helicopter, the jet engine, magnetic recording, short pulse radar, radio, rockets, disposable blade razors, silicones, stainless

[6]The book describes just over 50 inventions. We drop some where the "industry" ought be more broadly defined, such as when we combine bakelite, neoprene, polystyrene and nylon into "synthetic plastics", or expand automatic transmission into "automobiles".

steel, synthetic detergents, television, leaded gasoline, the transistor, xerography, and the zipper.

These selected inventions span both high- and low-tech industries, and were invented on both sides of the Atlantic. Table 1 lists these 21 inventions, with their most commonly credited inventor(s), date(s) of invention, and place(s) of invention.[7] The table further lists the location of the early commercial leaders in that industry.

The striking stylized fact is that at minimum 16 of those 21 inventions saw their early related industry develop far from the geographical location of the initial invention. The only possible exceptions are radar (for which private government development during World War II makes assigning a specific industry location impossible), synthetic plastic, the refrigerator, the safety razor with disposable blades, and stainless steel.

Omitting radar due to its development largely in wartime government labs, what do the four inventions which stayed local have in common? Three of them - plastics, the refrigerator, and stainless steel - were invented in a location with an existing globally dominant industry in a related field. New Jersey was a center of American chemistry research when Baekeland invented Bakelite in nearby New York, Frigidaire was the dominant refrigeration company when its employee Thomas Midgely worked out the nature of freon refrigeration, and Sheffield in the United Kingdom was the "Steel City" when Brearley famously dropped his stainless steel in the wastebasket. The one exception, the safety razor, required a strong patent, worldwide marketing, and rapid speed to become the world industry leader.

That is, of the 21 canonical inventions in Table 1, only one plausibly created an industry leader where one did not previously exist. Note that the safety razor is unusual in that the invention and the commercial product are essentially identical, a topic we return to in the theory of the following section.

What happened with the 16 inventions whose early industry appeared elsewhere? In a number of cases, the inventor themselves physically moved. Houdry took his French lab developing catalytic cracking of petroleum to New Jersey. Marconi and the radio moved to London for financing reasons. Judson brought his zipper manufacturer from Chicago to Pennsylvania where his employee Gideon

[7] Data sources and further details on sample construction are in Appendix A.

Sundback perfected the zipper improvement which at last induced sales.

In other cases, the technology is licensed to manufacturers far away. Xerography is licensed to Haloid in Rochester. The ballpoint pen is licensed by the Hungarian-Argentine inventors to producers with better mass-market sales experience in France and Chicago. The Bell Consent Decree leads to expanded licensing of transistor technology, and an exodus of engineers in this area to Texas, Massachusetts, and California.

In a final set of cases, the gap between the initial invention and the commercial product is long. Synthetic detergents, first produced commercially in Germany during World War I, require decades of further development at Proctor & Gamble before Tide is released. Kipping's research on silicones in the United Kingdom is far from the inexpensive production of silicones pioneered at Dow Corning in Michigan. Goddard's rocket experiments in Massachusetts in no way immediately imply the military uses of the V-2 developed at Peenemünde in Germany. Poulsen's work on magnetic recorders in Denmark sees little commercial success, until refinements at AEG and in the United States create marketable products using the technology. Benz' automobile would not create a world leader without the ability to produce in volume at low cost - as the French and Americans figured out how to do.

It is important to note a factor which does not appear critical in explaining why industries and their core invention appear in different places: policy mistakes. Industries move when IP protection is strong, and when it is weak. They move to major cities, as in the case of the ballpoint point, and away from them, as in the case of the zipper. They move with the inventor, and when the inventor stays home and tries to develop an industry there. They move to countries with strong high technology support, and away from them.

The technologies selected are "macroinventions," and the data in Table 1 in no way contradicts the large empirical literature (e.g., Jaffe et al. [1993] and Thompson and Fox-Kean [2005]) on the extent of local knowledge spillovers. Research activity may in general spill over to local firms, but research performed in an area with existing advantages in bringing that research to market will benefit more. Looking at universities who suffered a large shock to their endowment, Kantor and Whalley [2014] finds that universities in areas where local firms commercialize technology similar to what the university produces see the largest spillovers. With big macroinventions like radio, plastics, or the airplane, the relevant local complementary firms are those who can take an unrefined invention and develop it into a commercially viable product. When those firms don't exist, it appears, in the broad cross-section, that the region does not directly benefit from the invention.[8]

3 A Theory of Component-Based Invention

To move from this cross-sectional evidence to a more precise elucidation of the mechanism hypothesized above, let us add precision with a light theoretical model and a deeper investigation of the history of one particular technology, the airplane. The model will suggest the conditions under which government encouragement of invention ought lead to a local leader in the industry which follows that invention. We will then look at the history of the airplane, with particular attention to the geographic distribution of absolute advantage in aviation technologies important to commercial viability.

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 $c_{il} \geq c_{iw}$ (where l and w denote the loser and winner of the first stage race to invent). 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. Firm 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 $1 - p_{A1}$.[9] 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, each firm is willing to work if the rival does not.

[8]Of course, inventions also matter on the demand side, and regions may want to encourage invention for this reason alone.

[9]This can be derived as the reduced form of the Loury-style continuous time patent race in Bryan and Lemus [2017].

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.

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* $\mathbb{I}(Aw, Bl)$ *denote the indicator for the second stage equilibrium involving both firms working conditional on A inventing in the first stage, and* $\mathbb{I}(Aw, -Bl)$ *denote the indicator for the second stage equilibrium involving only firm A working after A completes the first stage invention.*

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

$$\begin{aligned} p_{A1}[\pi_1 + (\pi_2 - c_{Aw})\mathbb{I}(Aw, -Bl) + p_{A2}(\pi_2 - c_{Aw})\mathbb{I}(Aw, Bl)] + \\ (1-p_{A1})[(\pi_2 - c_{Al})\mathbb{I}(Al, -Bw) + p_{A2}(\pi_2 - c_{Al})\mathbb{I}(Al, Bw)] \quad &\geq c_{A1} \end{aligned}$$

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

$$\begin{aligned} (1-p_{A1})[\pi_1 + (\pi_2 - c_{Bw})\mathbb{I}(-Al, Bw) + (1-p_{A2})(\pi_2 - c_{Bw})\mathbb{I}(Al, Bw)] + \\ p_{A1}[(\pi_2 - c_{Bl})\mathbb{I}(-Aw, Bl) + (1-p_{A2})(\pi_2 - c_{Bl})\mathbb{I}(Aw, Bl)] \quad &\geq c_{B1} \end{aligned}$$

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 $\bar{\pi}_1$ 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 $\bar{\pi}_1$, 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.

What does Lemma 3 tell us about how innovation policy can be used to both incentivize "great" technological inventions and grow a local industry afterward? 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. In this case, π_1, the incentive for the technological breakthrough, is at best merely a transfer to the inventor, and at worse has the usual distortionary properties of patents or tax-financed prizes. However, even if the increased payoff induces the local inventor to work on the first stage technological breakthrough, it only induces second stage effort - the development of the local industry - if the decrease in cost of developing the second-stage invention conditional on successful first stage invention (that is, $c_{il} - c_{iw}$) is sufficiently large.

Those conditions imply that regional innovation policy will work best when the pure market return from a commercial invention is insufficient to induce R&D by local firms, *and* when the developer of a technological breakthrough gains a large cost advantage in moving from the invention to commercial viability. For example, when Midgely developed freon as a refrigerant in Dayton, Ohio, a strong patent plus relatively straightforward development of that invention into commercial Frigidaire refrigerators by Midgely's employer GM and its partner DuPont meant that the early refrigerator industry developed in Ohio.

On the other hand, consider a multi-component good, where the commercial product involves having each of these components developed to a sufficiently high level, while the initial invention requires only getting each component to a lower level. In this case, the cost of second stage development does not depend greatly on whether successful progress is made on the initial invention; the inventor's contribution may have simply been to push one component above the threshold of technological viability, while still lagging in knowledge of other components that will prove critical to commercial viability. 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. Indeed, this incentive for technological invention may be outright harmful if it diverts inventor effort away from other inventions where regional knowledge and capabilities are better able to expand the invention into a commercial product.

In the case of the airplane, which we now turn to, commercial viability required further advances in light engines, material design, airflow engineering, and auxiliary military inventions. Simply inventing the technological airplane in North Carolina/Ohio did not imply much of a cost advantage in developing those components, particularly when inventors in those states already lagged far behind the frontier. To dig more deeply into this mechanism, we will now describe the basic rise and decline of the early airplane industry, the state of knowledge in each component of the airplane in various countries over time, and the mapping of these facts to the theory above.

4 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.[10] We begin by describing the shared "invisible college" knowledge held by prospective inventors as of 1896, then discuss the Wrights' invention, the European response, and the collapse of America's position at the technological frontier by 1910.

4.1 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 2 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]

[10] The basic historical survey below follows a number of well-written Wright biographies; Howard [1998], Crouch [2004] and Tobin [2003] are particularly insightful examples.

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 "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 für 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. The problem of generating enough thrust to get into the air was thought to be particularly hard. 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 eventual 1903 Wright Flyer, to internal combustion and steam engine technology which could be converted with some 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.

4.2 Developments by the Wright Brothers

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 (Britcher 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] 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 salesmen 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 croisèes, 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.[11] 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 [August 9, 1908]). "Nous sommes battus" - we are beaten - was the only comment given to the press by the French aviator Leon Delagrange (Tobin [2003]).

4.3 The Aviaton 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 demonstra-

[11] The '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 [December 1979] notes that the original patent application was done without the aid of a lawyer and was rejected partly for its sloppiness.

tion, 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 [August 9, 1908]). And indeed this was the case.

Table 3 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 4, 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 Americans were far behind the European frontier 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 [December 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.

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.

4.4 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]).[12] 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.[13] 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]).

[12] A version of the Wright Model B sold by the Wrights' French licensee (Compagnie Gènèrale de Locomotion Aèrienne) 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]).

[13] An 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 [1998]).

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]).[14] 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]).[15] After implicitly threatening to confiscate 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.[16] 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.

[14] Arrow [1962] discusses the important role of patents in creating a market for information, rather than just giving the inventor monopoly rights.

[15] Only 54 of 366 ordered planes were delivered (Roland [1985]).

[16] The 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 that just assuming that complementary patents can be pooled without harming welfare. See Lerner and Tirole [2004], Langinier [2011] and Hovenkamp and Hovenkamp [2017] for discussions on this point.

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.

4.5 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 [2018], 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.[17] Even within 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

[17] Though 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.

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 have 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 Wrights[18], 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 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.

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

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. The idea that a lack of simultaneous invention necessarily means the sole inventor was *economically* important is not, in general, true. To show that, a historian must prove that the commercial industry, not merely the invention, would have been delayed.

5 Airplane Microinventions, 1897-1917

Let us now turn to the development of various components of the airplane, in line with the theory in Section 3. Appendix A contains a novel database of 91 airplane microinventions from 1897 until 1917.[19] 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

[19] A discussion of the dataset's construction can also be found in the appendix.

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 [1985] cites a survey suggesting the late development of jet aircraft in the U.S. may have resulted simply from "ignorance of aeronautical design theory".

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, a pattern we saw in Section 2. 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 autobuilding 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 made the full development of a commercially viable airplane unprofitable. 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.[20] Though Americans were skilled at scaling repetitive production, they were going to be at a disadvantage in quick-developing, high technology industries, simply by virtue of distance. 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".[21]

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

[20] Rosenberg [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. Seamans et al. [2018] show how airmail routes passing through certain small towns induced future airplane inventors in those towns.

[21] Beyond the inefficiency discussed in the present paper, overly broad patents for technological leaders can cause many other inefficiencies. Bessen and Maskin [2009] use a similar model with cost uncertainty to show how broad patents can lead to inefficiencies in sequential innovation. Bryan and Lemus [2017] 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.

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 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. 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 [Jan. 1912]).[22]

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

[22]The 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.

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 "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 advances 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.[23] 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. No important invention or discovery in aviation was 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 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 Eu-

[23] The 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]).

rope 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 experience a war-driven boom like it did twenty years later.[24]

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 that 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 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. Considering the state of development across all components necessary for a commerically viable airplane, rather than

[24] It 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 (Murmann [2003]). Such a situation was not unusual in many industries during this period.

simply the performance of built mchines, 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.[25] 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

[25]Such 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 Lavoiserian 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]).

due to their weight. The "technological achievement" and special patent protection would likely have been granted to an engineer who suitably adapted his 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.[26] 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.

[26]And 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]).

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Appendix A: Data on Inventions and Early Industries, and on Airplane Microinventions 1897-1917

Table 1 presents the location of invention and early industry for 21 canonical inventions described in Jewkes et al. [1962]. In many cases, an invention has multiple plausible inventors, and data on the early industry for more abstract inventions like "radar" or "synthetic plastics" is difficult to come by. For this reason, we have been conservative in that we occasionally credit multiple independent inventors and multiple locations as the home of early industry leaders. These 21 inventions were selected to cover a broad selection of canonical inventions of the late 19th and early-to-mid 20th centuries, both in North America and Europe.

The data in Table 1 comes from the inventor descriptions in Jewkes et al. [1962], and the industry histories in Bardou [1982], Freeman [1974], Enos [1962], Holley [2000], Peterson and Kislev [1986], Leslie [1980], Shiel [1984], Leonard and Pilarski [2018], Clark [1993], Blumtritt et al. [1994], Maclaurin [1950], Tellis and Golder [1996], Tweedale [1983], ACS [2006], Watzinger et al. [2017], Langlois and Steinmueller [1999], Freeman [1958], and Smith and Alexander [1999].

Table 5 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 et al. [2001], Anderson Jr. [1998], Anderson Jr. [2002], Andrews [1977], Ash et al. [2000], Colby [May 1944], Crouch [2003a], Crouch [2003b], Garber [2005], Gibbs-Smith [1970], Jakab [1997], Magoun and Hodgins [1931], Matthews [2001], Munson [1969], Pattillo [2001], Scott [1995], Short [2012], Stamper [1995], Taylor [1971], Tobin [2003], Vivian and Marsh [1920], Wright [2003], as well as numerous issues of airplane-related periodicals from the 1900s and 1910s like L'Auto, L'Aerophile and Aeronautics.

Table 1: Invention and Early Industry Location for 21 Canonical Inventions

Invention	Inventor	Year	Invention Location	Industry Location	Note on Invention	Note on Early Industry
Automobile	Karl Benz	1885	Mannheim, Germany	Detroit, MI; France	Credit goes to Karl Benz in 1885 and near-simultaneous inventions of Daimler and Maybach, also in Germany	By 1900, Germany producing only 800 cars per year (600 by Benz & Cie, the world's largest car company), while France does 4,800 and the U.S. 4000. By 1907, 44,000 are produced in the US, 25000 in France, 12000 in Britain and only 5100 in Germany total.
Synthetic Plastic	Leo Hendrik Baekeland	1907	New York	New Jersey	Leo Baekeland in New York invented Bakelite, first fully synthetic plastic (some earlier variants like parkesine or Hyatt's celluloid, but not fully synthetic because they included things like cellulose). Invention kept secret while patent was processing, then announced publicly at ACS meeting in 1909.	Alternative thermoplastics to Bakelite not invented until 1930s and not popular until later. Industry shifts to Dupont and German firms like IG Farben after WW2, though even Dupont is not far from Baekeland's original location in the NYC metro area. Statistics very poor, but appears to be US predominance through 1960 at least.
Ballpoint Pen	Ladislao J. Biro	1938	Hungary, Argentina	Chicago, IL; Clichy, France	Biro brothers do initial research in 1930s in Hungary, but flee Nazism by moving to Argentina. They begin producing patented pen in small numbers there.	Milton Reynolds had seen Biro pens in 1945 and developed a hugely successful pen that would not infringe the Biro patents. Biro sold his patent to Baron Marcel Bich of France. In 1950 Bich (Bic), launched his own cheap, disposable, mass-produced ballpoint pen.
Catalytic Cracking of Petroleum	Eugene Houdry	1927	France	New Jersey	Houdry worked on developing a catalytic process to convert lignite coal to gasoline throughout the 1920s, building a demonstration plant with French government money in 1929. It proved economically unviable. Vacuum Oil Company invited him to move his lab to New Jersey in 1930. By 1937, joint with Sun Oil, a demonstration plant and full scale installation of catalytic cracking unit in PA, and by 1940, units being licensed widely.	On seeing the invention in 1938, Standard Oil formed a research consortium Catalytic Research Assocaites in 1938. With help from MIT, they invented fluid catalytic cracking methods which didn't infringe on the Houdry patent, and begin installing in the 1940s.
Cotton Picker	Rust Brothers	1935	Memphis, TN	Chicago, IL	Rust Brothers produce first practical spindle cotton picker in 1930s.	By 1963, International Harvester had 29.7% of all picker sales, and John Deere was the second largest firm. Rust Brothers went out of business in the early 1940s, though they did license their technology to Pearson and Allis-Chalmers, with modest success. Note IHC had been working on developing a picker since at least the 1920s, and Chicago was the center of the farm machine industry during this period.
Refrigerator	Thomas Midgley, Jr	1930	Dayton, OH	Ohio	Charles Kettereing asked Midgley, at GM's Dayton Research Lab, to look for a non-toxic, non-flammable compound that would boil below the freezing-point of water. After discovery of freon, joint venture of GM and DuPont formed as Kinetic Chemicals.	Frigidaire, the GM appliance division, is largest producer in the world up to World War II at the very least.

Helicopter	Paul Cornu	1907	France	Buffalo, NY	Cornu built first experimental helicopter in France in November 1907. This was unstable, and practical helicopter would wait for Sikorsky.	SNCASE in France sees success with Alouette II and III in the late 1950s and 1960s, using a turbine design. Post world war II, but Bell and Sikorsky designs dominated until this point, and even by 1970 US manufacturers had a 65% market share. Sikorsky R-4, also American, is first mass-produced helicopter.
Jet Engine	A.A. Griffith and Frank Whittle	1937	Rugby, UK	Everett, MA; East Hartford, CT	Griffith writes fundamental scientific piece on compressors, and Whittle builds first working model at Power Jets in 1937.	Boeing 707 becomes most popular early jet, using Pratt & Whitney engines (twice as many sales as the Sud Caravelle, Avro Arrow, deHavilland Comet, and Tupolev TU-124 combined). Military sales using GE engines very important as well during late 1940s and early 1950s.
Magnetic Recording	Valdemar Poulsen	1898	Denmark	Berlin, Germany; USA	Poulsen set up production facilities in Denmark and the US, but they sold fewer than 1,000 machines before going defunct. No telegraphones at all sold in US or Europe after 1913. Little research in US in 1920s, but some commercial success for early magnetic tape in Germany in 1930s (principally at AEG).	Magnetic Recording equipment had not been made in USA until 1937. For several years after the war, high-quality recorders were manufactured mainly by small companies all located in USA. Bell had a world-leading "answering machine" in the mid-1930s, but suppressed its use due to worries that its existence would lessen demand for telephone service, since callers would worry they were being recorded
Radar (modern short pulse)	At least 8 independent inventors	1930s	Global	Global	Credit for this work goes to scientists working in government research establishments, radio companies and universities.	First viable use is in World War II, where radar in various forms is used by nearly all large powers.
Radio	Guglielmo Marconi	1894	Bologna, Italy	USA, UK	Marconi generally credited for first long-range broadcast, though Fessenden and others made important follow-up breakthroughs.	There were developments of the radio after 1918 in the UK, USA, and Germany. Armstrong produced frequency modulation, an important followup invention, in 1924. Until RCA founded in 1919, though, Marconi companies dominate US and UK business, and RCA has Marconi as a founding firm (along with GE and Westinghouse). Marconi was connected at high levels with finance sources and government in the UK, via his mother, hence his move there.
Rockets	Robert Goddard	1928	Auburn, MA	Peenemünde, Germany	First liquid-fueled rocket	Launch of the V-2 in Russia, team from Peenemünde leads rocket development post-war in both USSR and USA.
Safety Razor with Disposable Blade	King Gillette	1895	Boston, MA	Boston, MA	Gillette invented safety razor with disposable blade, allowing users to avoid stropping and honing their own blades.	Gillette retains market share >70% through to the 1960s.
Silicones	F. S. Kipping	1904	Nottingham, UK	Midland, MI	Kipping (Nottingham University) works out basic ideas of silicon-carbon polymers in a series of papers	Staudinger's work on polymers and Muller-Rochow Synthesis in 1940 permit early work on commercialization. Dow Corning joint venture introduces first commercial silicones and is early market leader.

Stainless Steels	Harry Brearley	1913	Sheffield, UK	Pittsburgh, Germany, Sheffield, UK	Brearley (England) usually given credit, though idea of iron-chromium alloys was known and exploited previously.	By invention in 1912, Germany and US already pulled ahead of UK in overall steel; Brearley himself goes to Pittsburgh to form American Stainless Steel Company; Krupp in Germany produces precise blend used on Empire State buliding. Firth-Sterling, part of ASSC, was founded in Pittsburgh by Firth's, a Sheffield UK firm. That said, there remained extensive steel production, especially cutlery, in Sheffield.
Synthetic Detergents	Krafft, Twitchell, Reychler	1896	UK, Belgium, Germany	Cincinnati, OH	Krafft published the first observations of the soap-like properties of non-soapy substances. Twitchell prepared other synthetic catalysts. Reychler found long-chain alkane sulphonates were good detergents and were more stable than soaps to acid conditions. WWI was first attempt to market synthetic detergent in Germany.	IG Farben shut down sythetic detergent research not long after WW1 due to cost of production and inability to clearn heavy-duty stains. P&G research extending this idea working well in early 1930s, so they take out licensing agreements with Deutscher Hydrierwerke which was making synthetic alykl sulfate for the textile trade. They launched first mass-market synthetic detergent Dreft in 1933, and pursued further research until inventing a heavy-duty cleaning solution Tide, introduced just after WW2 and quickly taking large share of the market.
Television	John L. Baird and Philo Farnsworth	1927	United Kingdom, San Francisco, CA	Camden, NJ	Philo Farnsworth invented electrical television; Baird first demonstrated a working TV with low mechanical image quality	RCA dominates early TV industry worldwide, following famous patent battle with Farnsworth. Farnsworth himself operates small TV factory in Fort Wayne, IN.
Leaded Gasoline	Charles Kettering and Thomas Midgley	1921	Dayton, OH; New Jersey	New York City, NY	Research started in 1912 by Kettering but was stopped by WWI. Resumed in 1919 when GM purchased Kettering's interests and him and Midgley worked in the research labs of GM.	In 1924 Ethyl Gasoline Corporation formed by ESSO and GM (holder of chemical patent and use patent, respectively). Patent strongly controls industry.
Transistor	John Bardeen, Walter H Brattain and William Shockley	1948	Murray Hill, NJ	Massachusetts, California, Texas	Invention grew out of a study for semiconductors (including germanium and silicon). Work was announced in June 1948 by Bell Telephone Laboratories.	Bell license on favorable terms in 1951, and forced to do so broadly by the 1956 Consent Degree. Spinouts do not stay near Bell Labs (Shockley Semiconductor in Silicon Valley, Gordon Teal to Dallas to join Texas Instruments). In 1955, Hughes, Transitron and Philco are largest producers of transistors, and Raytheon dominates the hearing aid market (an important beachhead). TI main supplier to IBM in 1960s, and to military in Minuteman II. Japan doesn't make major inroads until the late 1970s, and even as late as 1978, US market share in 59%.
Xerography	Chester Carlson	1937	New York City, NY	Rochester, NY	Carlson worked at Bell Telephone Laboratories first as a researcher then in the patents department, and developed the basic concept of Xerography in 1937. Attempting to license it failed until after World War II when Haloid began to develop the "Xerox".	In 1972, Xerox controlled 95% of the copies made in the world (according to its own analysis) and accounted for 73% of the copies in 1977. Outside sources put Xerox's portion at about 65%. Xerox 914 in 1959 was a major early success.
Zipper	Whitcomb L. Judson	1893	Chicago, IL	Meadville, PA	1895 patent by Judson; Judson's Universal Fastener has trouble with sales and moved to New Jersey and then Pennsylvania.	In 1913, researcher Gideon Sundback at same company invented a fastener which is essentially the modern zipper. "Hookless Fastener" later named Talon would be the world leader into the 1970s with Meadville the center of the world industry.

Table 2: 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 3: 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 [Jan. 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 4: 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 [February 7, 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 5: 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 Prandt	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 Pischoff 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