CHAPTER 1, INTRODUCTION

DAREDEVILS TO SYSOPS: HOW THE ART OF FLYING BECAME (MOSTLY) A SCIENCE

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Chapter I Introduction: How Technologies Evolve

The search for patterns of technological change has occupied scholars in many disciplines for more than 50 years. Such regularities can provide predictive and normative insights for public policies and for a variety of private activities. This book emphasizes one major pattern in technological change, the tendency for technologies and work to become more scientific, as they become more and more powerful. By "scientific," I refer not to the increasing use of laboratory-derived scientific knowledge in industries such as chemicals and health care, although that is certainly important, but to shifts in how each technology is carried out. New technologies are first practiced as crafts, done directly by individuals using their own judgment and eye-hand skill. In order for a technology to become economically important, it must progress beyond craft. Some industries eventually move to highly scientific operation, including standardized methods, predictable and consistent results, formal systems for training workers, sophisticated tools, rapid and accurate measurements, and explicit knowledge about causes and effects.

How do industries become more scientific? Is being "scientific" always desirable? Does an industry's growth make it more scientific, or does causality run in the other direction? Can and should a technology remain a mixture of scientific and craft methods? The answers are important for a variety of issues, including the future of work, technology transfers between countries, and the future competitiveness of highly developed economies.

The main industry analyzed in this book is commercial aviation, primarily long distance passenger transport. The specific technology is that of flying (or aviating) – the tasks of controlling an aircraft in flight. Flying has clear metrics for problems and success, such as accident rates. Accident rates have improved by four to six orders of magnitude, depending on how they are measured, since regularly scheduled air transportation began around 1930. Early airmail pilots had a life expectancy of a few years. Now, commercial aviation is safe, predictable, routine, and mostly efficient. Per passenger mile, the accident rate for flying in the US is about 200 times lower than for driving, so that if I fly 1000 miles but drive 25 miles to and from the airports, I am 10 times more likely to be fatally injured during the ground portion of the trip than in the air.[1]

Such safety is the result of a century of progress since the Wright brothers' first flight in 1903. For its first decades, flying was a dangerous craft, conducted by experts who had little more than their own senses and athletic abilities to guide them. Every flight was an adventure, with the possibility of a forced landing or crash. The only way to learn how to fly was by doing it, and since beginning flyers are necessarily poor pilots, luck played a large role in separating the quick from the dead. When the US Army Air Corps briefly took over flying the airmail in 1934, in 78 days of operation it had 66 accidents and 12 fatalities.

Comparing a 1934 DC-2 aircraft with a modern A380 Airbus, performance has increased in range (8x), capacity (55x), effective speed (6x), productivity (250x), and accident rates (200x).[2] What explains these large improvements? There were several key factors, one of which was a shift from craft to science in the way aircraft are flown. By comparison, American infant mortality rates improved less than 10-fold over the same period.

A. Craft and Science in Technology

Early pilots used their senses and muscles to control an airplane very directly. Open cockpits allowed them to directly feel, hear, and smell the engine, aircraft, and wind. Pilots had to keep their hands on the controls, and muscular strength was essential. Wires directly connected cockpit controls, such as foot pedals, to control surfaces in the airstream, such as the rudder. Instruments were basic, initially little more than engine tachometer and temperature gauge. Pilots judged airspeed by sound and feel of the wind. Navigation was based on visual landmarks such as following roads and railroads, and navigating above clouds used an estimating method called dead reckoning. The main weather forecasts were from talking to a pilot who had just flown the same route, and decisions about whether to take off in bad weather were based purely on judgment. Each pilot flew idiosyncratically, according to whatever personal methods and style they developed over many years. When heavy clouds stranded aircraft out of sight of the ground, the approved solution was to fly in circles until out of fuel, then descend by parachute.

Today, flying is almost entirely applied engineering science, and highly standardized. The role of pilots is radically different, with their raw senses replaced by digital readouts, and their muscles replaced by computer-controlled motors. Computers do the actual flying, while the pilots monitor and direct the computers. Pilots have discretion to take control back from computers, but usually they direct the aircraft by typing instructions into the various computers.

Other technologies and industries have undergone similar transformations. In 1800, metal parts were shaped by skilled craftsmen using tools to manually remove metal. Today, they are made by computer-controlled machines which are much faster and more accurate than an expert. In 1920, the blood glucose levels of diabetics was measured by boiling their urine for 30 minutes and judging the resulting color. Now, a machine smaller than a cell phone accepts a drop of blood and returns a digital reading in ten seconds.

Many other technologies are still mixtures of art and science. Despite a huge base of formal knowledge, most surgeons still use their eyes and hands for essential activities. In accounting, banking, and many other information-processing technologies, many activities have been reduced to computer programs, but others still rely on human judgments. In many such fields, the proper balance between craft and science is debated. In an article in *Harvard Business Review*, "When Should a Process Be Art?," authors Joseph M. Hall and M. Eric Johnson argue that in many situations customers prefer variation in the products they receive, and often this is best achieved by an "artistic" production method.[3] "Process standardization has been pushed too far, with little regard for where it does and does not make sense. We aim to rescue artistic processes from the tide of scientific standardization ….. We argue that artistic and scientific approaches need not be at odds but must be carefully harmonized." Their examples include making concert pianos, writing custom software, industrial design, and hedge fund management.

Entertainment industries have long relied on art to both make and evaluate their products. The "mercurial movie director" is beyond cliché. Stephen Spielberg's movie, "Raiders of the Lost Ark," was offered to every studio in Hollywood, and every one of them turned it down except Paramount.[4] It ultimately won five Academy Awards and was one of the highest grossing movies in history. Today mathematical models are used to predict movie success, and even suggest edits to increase popularity. Echoing the concerns of Hall and Johnson, movie critics argue that this leads to too many soulless sequels, and little new art. And the movie making is still far from reliable; many movies flop.

In American health care, various organizations are compiling "best practice" guidelines for treatment of various conditions, and measuring compliance rates for different hospitals. Since hospital reimbursement sometimes depends on compliance scores, they have considerable weight behind them. Doctors J.S. Bujak and E. Lister wrote an article titled *Is the Science of Medicine Trumping the Art of Medicine?* which complains that guidelines are being used without discretion, leading to inappropriate treatments. On the other hand, a widely cited article in *Annals of Internal Medicine* says that doctors must "transition from the mindset of craftsmen." It explicitly compares medical and aviation practice:[5]

> We believe that to achieve the next increase in safety levels, health care professionals must face a very difficult transition: abandoning their status and self-image as craftsmen and instead adopting a position that values equivalence among their ranks. For example, a commercial airline passenger usually neither knows nor cares who the pilot or the copilot flying their plane is; a last-minute change of captain is not a concern to passengers, as people have grown accustomed to the notion that *all pilots are, to an excellent approximation, equivalent to one another in their skills.* Patients have a similar attitude toward anesthesiologists when they face surgery. In both cases, *the practice is highly standardized, and the professionals involved have, in essence, renounced their individuality in the service of a reliable standard of excellent care.* They sell a service instead of an individual identity. As a consequence, the risk for catastrophic death in healthy patients (American Society of Anesthesiologists risk category 1 or 2) undergoing anesthesia is very low—close to 1×10^{-6} per anesthetic episode. [emphasis added]
>
> Conversely, most patients specifically request and can recall the name of their surgeon. Often, the patient has chosen the surgeon and believes that the result of surgery could vary according to that choice. This view is typical of a craftsman market. Safety outcomes for surgeons are much worse than for anesthesiologists, nearer to 1×10^{-4} than to 1×10^{-6}.

These are excellent discussions, but not very precise. One possibility is that the need for personal expertise is fixed and inherent in a technology. I will demonstrate that instead the use of science is limited by the *current* level of technological knowledge. Technologies that are very scientific today were not always that way, and there is every reason to expect continued progress toward greater science in most technologies. Yet simply adopting a "scientific management" approach, without sufficient knowledge, can make the results worse than a craft approach.

Flying is a good setting for analyzing evolution of a technology that mixes craft and science. We know a lot about what flying was like in the past, because it was recorded by photographers, popular writing, and various technical sources. There are a multitude of stories, often written by protagonists, to illustrate different stages of flying's evolution. Flying is also a familiar and interesting technology for many. We all sit on airplanes as passengers, and some of us have taken rides in small planes, which are much closer to the roots of piloting. Stories about failures (crashes) continue to make headlines.

For generations, the heroes of aviation stories have been daredevils who broke the rules but ultimately triumphed over his or her more law-abiding comrades.[6] Early pilots were celebrated loners, who really did make their own rules and were masters of their own fates. Charles Lindbergh and Amelia Earhart are still remembered today, but there were many others. Henry "Dick" Merrill was a famous pilot who, among many other exploits, used ping-pong balls for emergency flotation when he made the first flights in both directions across the Atlantic, piloted Dwight Eisenhower during his presidential campaign, married a movie star half his age (twice, the first time by eloping to Tijuana and the second to satisfy his mother-in-law), and may have flown more than anyone before or since (45,000 hours and 8 million miles). A reporter once photographed him preparing for a mail flight wearing little more than a bathing suit and parachute (Figure 1-1 left). General Eisenhower chose him as pilot because although he "wasn't the best pilot in the country, he was the luckiest." Barnstormer and speed-racer Roscoe Turner was a showman who flew with a lion cub. When animal rights groups complained, he provided the cub with its own parachute. (Figure 1-1 right)

*Figure 1-1 Airmail Pilot Henry "Dick" Merrill, 1920s (left);
Roscoe Turner and lion (right)*

Within the fraternity of early 1950s test pilots, Chuck Yeager was famed for his flying skill, his laconic manner in deadly situations, and his escapades. It was Yeager who first broke the sound barrier, in the X-1 rocket plane. But Yeager's behavior was nothing like that of modern test pilots. As Tom Wolfe recounts in his book about the first astronauts, *The Right Stuff,* two days before Yeager's record-breaking flight, he and his wife went drinking at the local bar. The bar itself was an aviation legend, nicknamed the "Happy Bottom Riding Club" by Medal of Honor winning pilot Jimmy Doolittle, and owned by Florence "Pancho" Barnes, herself a flying legend. Barnes was raised in a wealthy and respectable family that married her off to a minister at age 18 in an attempt to keep her out of trouble.[7] Once she inherited from her parents, she abandoned her husband and child, disguised herself as a man, and wandered around Mexico during its Revolution. Returning to California, she took up flying, where she ran her own barnstorming group, set numerous speed records, and was the first female stunt pilot in Hollywood. When her husband refused to divorce her, she buzzed his Sunday sermons.

On this particular night at Pancho's bar, Yeager decided to indulge in a pilots' tradition that Wolfe calls "Flying & Drinking and Drinking & Driving"-- with a twist. Instead of driving a car, Yeager took his wife on a horseback ride, or rather "a proficiency run at full gallop through the desert in the moonlight." They borrowed horses from Pancho and headed out. But in the moonlight Yeager ran his horse full speed into a closed corral gate. (Wolfe, 1979, p. 41)

The next day Yeager was in massive pain and his right arm was almost useless. Reporting his condition to any authority meant that his flight would be canceled, so Yeager went to see a private doctor, who treated him for two broken ribs and instructed him to "avoid exertion for a few weeks!" Yeager confided the situation to a friend, the project's flight engineer. The two of them walked Yeager through his flight plan, and found that he could do everything with one arm, except closing the door of the X-1 after climbing into it from the B-29 mother ship at 29,000 feet. Their solution was a sawed-off broom handle. Using this primitive device he closed the door with his left arm instead of his right, and made his flight into the record books.

According to Tom Wolfe, Chuck Yeager became the role model for generations of jet pilots, some of whom became the Mercury astronauts. In reality, Yeager was obsolete for most test piloting by 1960 and could never have qualified as an astronaut – he had no college education, and little interest in analyzing the results of his tests.[8] Test flying by the 1960s had moved decisively away from individualism. Much of the behavior lauded in the early chapters of *The Right Stuff* would get modern airline pilots fired, and military pilots disciplined. Most commercial flying today consists of putting new instructions into computers, which actually fly the airplane.

These shifts and the reasons behind them are the subject of this book. What are the differences between the extremes of pure craft and pure science in technology? How did flying evolve from one to the other? What are the advantages and difficulties of each stage? What is required to go from one stage to the next? Is more scientific flying always better?

It is useful to define some key terms.

- *Craft*: An occupation or trade requiring special skill, especially manual dexterity. (Multiple sources) The term “art” is sometimes used with the same meaning, as in “the art of sailboat design.”
- *Pure Craft:* An extreme craft, where practitioners rely entirely on their own senses to control an activity. Although they may use power tools, all process feedback and control is through their own eyes and hands. Few examples still exist, except in non-commercial activities.
- *Skill*: The ability to do something that is gained from training, experience, or practice. (Merriam-Webster)
- *Operational science*: An organized, systematic, method of carrying out activities, which uses consistent methods to produce consistent outcomes, even when conditions vary.
- *Perfect operational science:* A level of procedural science that uses feedforward and feedback control to anticipate, and head off, all problems, creating results which exactly meet their specifications at all times. An unattainable ideal.

The terms art and craft are sometimes used interchangeably, but “art” is usually tied to creativity and aesthetic judgment, so I will generally use “craft.” Unfortunately, there is no term in English that corresponds to what I am calling “operating science.” I will often abbreviate “operational science” to “science,” with the understanding that I am not referring to the systematic study of nature (natural science), but to practical methods for achieving desired operational results.

Pure craft and perfect operational science are the opposite ends of a spectrum. Movement “from craft toward (or to) science” refers to technology changes that reduce the role of craft, and increase the role of operational science.

B. Changes in Aviation: Aircraft and Performance

Accident rates for aviation in the US fell each decade. Figure 1-2 shows total accidents per million miles of travel for scheduled air carriers. The average for the five most recent years is .0033 accidents per million miles. This compares with 4 per million miles from 1927 to 1931: a 1000-fold reduction over 80 years. Fatal accident rates have improved even more. There were no fatalities in 1980, 2002, 2007, 2008, 2010, or 2011.

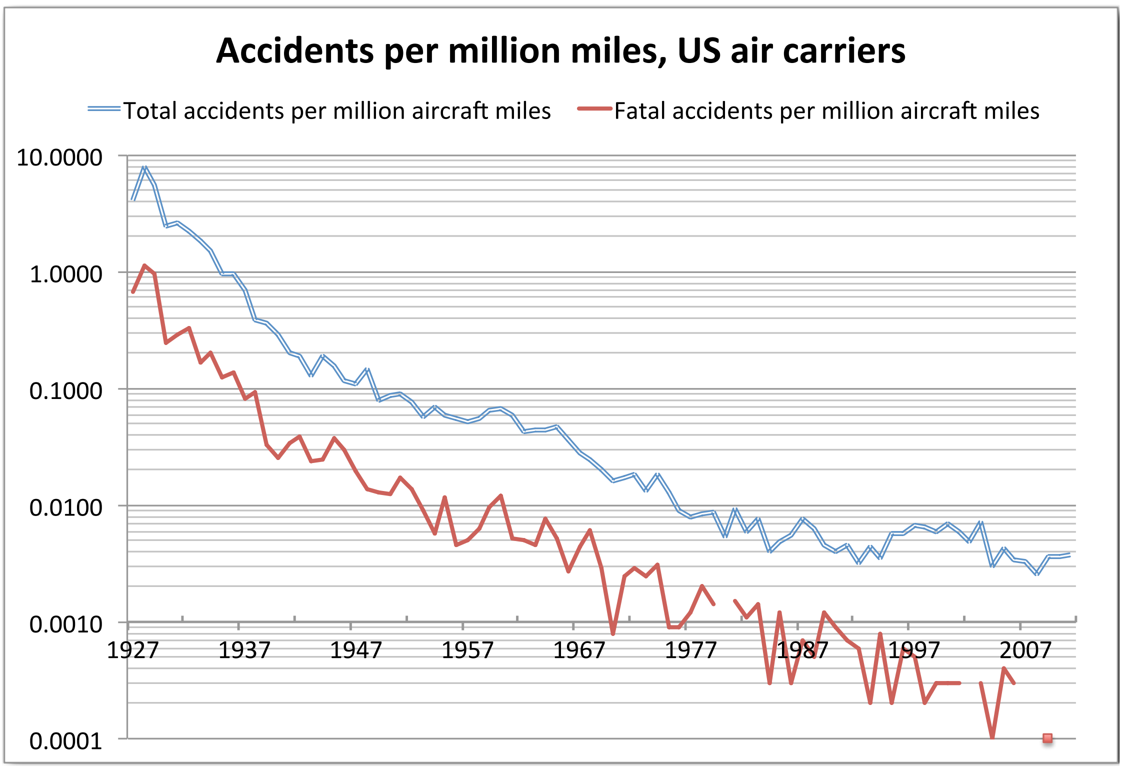


Figure 1-2 Accident rates per aircraft-mile fell ten-fold from 1927 to 1937, and an additional 100 fold to 2010[9]

These statistics are per aircraft-mile, while accidents per passenger-mile are more relevant to travelers. That data is not directly available, but the number of fatalities per passenger mile has probably improved by an additional factor of 10, a factor of 10^4 overall.

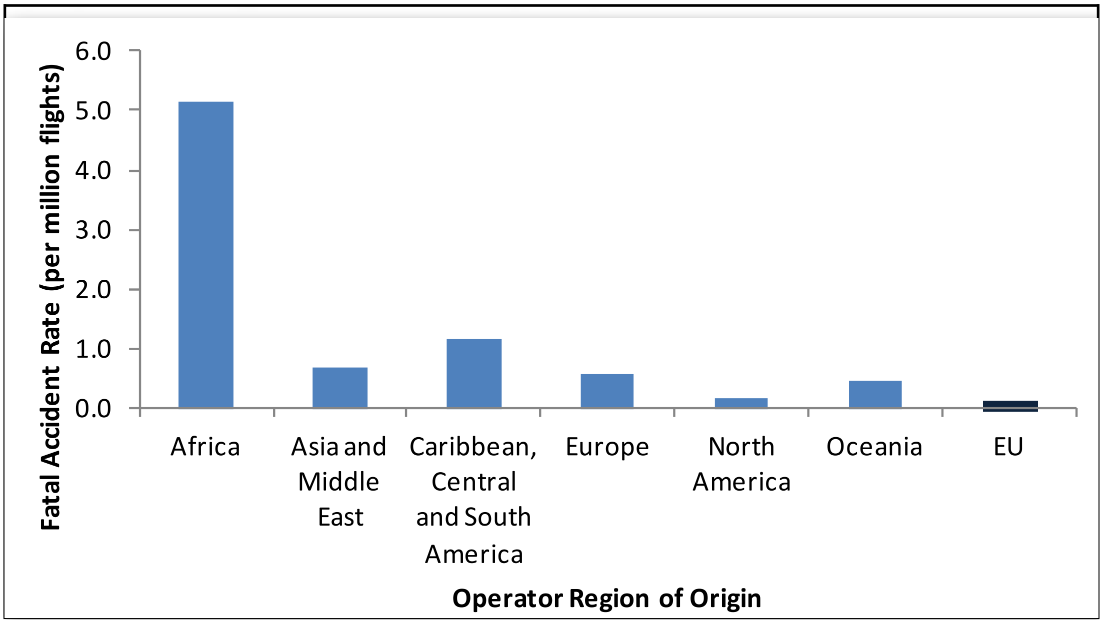


Figure 1-3 Average fatal accident rate 2002-2011, by region of operator

Source: UK Civil Aviation Authority. EU is a subset of Europe.

This excellent safety record was not universal. The numbers in Figure 1-2 cover only scheduled airlines based in the United States. Accident rates of many non-US airlines are considerably worse. Figure 1-3 compares accident rates of operators from different continents over the 10 years from 2002 to 2011.[10] Depending on which measure of accident rates is used, the rate for the worst group, African carriers, was 20 to 100 times worse than the best group, North American carriers. For African airlines over the 10 years, there were 63 fatal accidents with 1,826 fatalities, and 149 fatalities per million flights. For North America, the comparable numbers were 18 accidents with 158 fatalities, and only 1.3 fatalities per million flights. Thus, the technology leading to improved safety is unevenly distributed around the world.

Complexity

Early aircraft had only a few controls and a few inaccurate instruments. Henry Ford's 1925 Tri-motor, one of the first purpose-built passenger transports, had a spartan instrument panel (Figure 1-4) with only six flight instruments, none very accurate: altimeter, magnetic compass, air speed (with a fundamental design flaw), rate of climb, turn-and-bank indicator, and clock[11]. Instruments for two of the three engines were on the engines themselves, below the wings; pilots read them by looking out the windows. There was no radio, no trim tabs to adjust the controls (Chapter 3). It did have landing lights, (inaccurate) gas gauges, and hydraulic brakes that allowed steering on the ground.

Figure 1-4 Ford Tri-Motor instruments, 1929

Increasing performance requires higher complexity. Higher performance requires dealing with more and more phenomena, each of which has its own sub-phenomena, and so on. Once pilots learned how to fly in clouds, ice became a risk, so anti-icing systems were needed. After WW2, still higher altitudes required cabin pressurization, and superchargers to increase the pressure of air going to the engines. So increased performance required multiple new systems, not just better performance from old systems.

The new systems had to be controlled, so while airliners of the mid 1930s had a pilot and copilot, twenty years later they had a flight crew of up to five: pilot, copilot, navigator, flight engineer, and radio operator. Increasing complexity also increased the number of potential mechanical failures. While trading safety for higher performance seems eminently logical to economists, and in the 1920s was acceptable to some daredevil pilots, it was not acceptable to regulators or travelers, and therefore not to airlines or aircraft manufacturers. Therefore, many of the new performance systems added still more complexity for safety.

Table 1-1 gives a few statistics on the complexity of a modern jet aircraft, the Boeing 777-200, as it is experienced by its pilots. Among the main documentation for pilots is a two-volume *Flight Crew Operating Manual*. Volume 1 includes about 100 procedures, and 40 voluminous tables of data for different decisions. For example, one table specifies maximum allowed takeoff weight, which depends on runway length, weather conditions, altitude, air temperature, brake type, and the settings of various discretionary controls such as wing anti-ice protection. The list of abbreviations near the front has 400 entries: ABV, AC, ACARS, ACP, ACT, ADF, ADI, ….

Volume 2 discusses aircraft systems, divided into 15 categories such as fuel, flight controls, fire protection, air, and navigation. Drilling down into protection against icing, there are six different types of subsystems, most of which are replicated on left and right sides. For example, a subsystem prevents icing on each wing. Wing ice alters the airfoil (shape) of the wing in unpredictable ways, and used to be responsible for many crashes. Large jets now cruise above icing weather, but on ascent and descent they must still pass through regions where icing is possible. The anti-icing system includes plumbing, controls, and fault detectors. (Figure 1-5) If one engine is inoperative, both wings still need heated air, so the plumbing has crossover valves. Every valve in the plumbing has its own actuator, and for safety a sensor to measure the valve's actual position. The system even has detectors for air leaks.

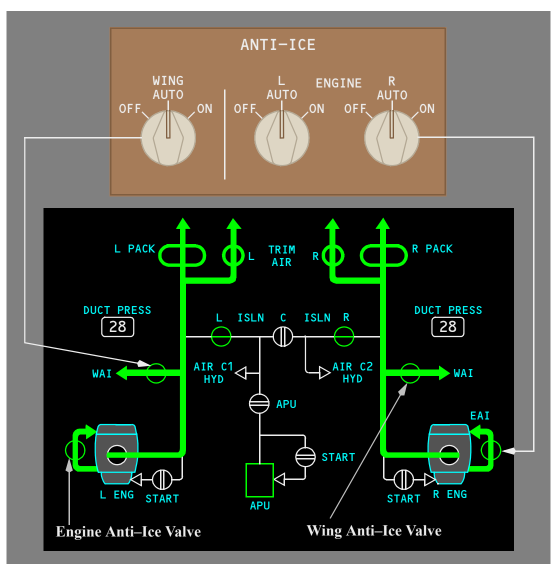


Figure 1-5 Controls and real-time display for wing and engine anti-ice systems, 777-200.

	Number of items	Example	Sample value
Flight Crew Manual volume 1: Procedures			*Length 450 pages*
General limits	~20	Max cabin pressure differential	9.1 psi
Takeoff limit tables	~7	Max takeoff weight, dry runway	259.2 tonnes
Enroute limit tables	8	Critical fuel reserve	10.6 tonnes
Landing limit tables	4	Go-around climb gradient, one engine	6.54%
Normal procedures	23	Go–Around and missed approach procedure	`After flap retraction to the planned flap setting,` select `FLCH or VNAV.`
Supplementary procedures	75	Engine cross-bleed start	Increase thrust until 5% N2 above idle.
Quick Reference Handbook			*Length: 564 small-format pages*
Warning message procedures	250	BRAKE TEMP	`One or more brake temperatures are high.`
Other emergency procedures	20	Fuel Leak	`Do not accomplish the following checklist: FUEL DISAGREE`
Flight Crew Manual vol 2: Systems			*Length 1260 pages*
Fire protection (chapter 8)	10 subsystems, such as Main Wheel Well Fire Protection, Cargo compartment, Fire detection system fault test.		
Fuel system (chapter 12)	9 subsystems, such as Fuel temperature, Fuel cross-feed, Fuel quantity, Fuel imbalance.		
Anti- ice, rain (ch 3)	Window heat, wipers, probe heat.		

Table 1-1 Examples of aircraft complexity as revealed by pilots' manuals: Boeing 777 aircraft. From documentation carried during every flight. [12]

A third manual for the 777, called the *Quick Response Handbook,* is designed for use in emergencies. It has hundreds of procedures and checklists for detecting, diagnosing, and responding to problems. It also has dozens of tables showing optimal control settings and performance in various contingencies, such as one engine not operating.

Complexity grows much faster than any high-level summary suggests. Aircraft can be approximately modeled as a hierarchy of systems, subsystems, and components. Each level in the hierarchy expands by a multiplier. If the number of systems doubles, each system has (at least) twice as many subsystems, each of which has at least twice as many components, each of which has … more subcomponents. The subcomponents themselves become more complex -- microprocessors now have hundreds of millions of transistors each. How much is the final complexity multiplier? That's a research question, and it may not even have a well-defined answer. The underlying issue is that *physical reality itself is fractal*. Throughout the book we will look at how achieving each increment of performance requires "increasing the microscope's power" to understand, and control, deeper and deeper levels.

The other reason complexity expands rapidly is *interactions.* For example, wing de-icing looks like an independent subsystem, designed to accomplish one function without affecting anything else. But it uses pressurized air from the engines, which reduces their thrust. The calculations for taking off therefore depend on whether anti-icing is on or off. Even the amount of fuel an aircraft needs for long over-water flights can be affected by planning for icing conditions. And the anti-icing control system includes conditional logic for different situations. Pilots have a three-position switch for control: On, Off, Automatic (Figure 1-5). But no matter how the pilot sets the switch, on warm days anti-ice will not come on for the first few minutes after takeoff.[13] As this illustrates, a modern aircraft is filled with complex interactions.[14]

C. Five Paradigms of Control

Until the 1930s, flying was almost entirely craft. Only experts could do it well, and the only way to become an expert was by doing it. Formal teaching was not possible because even the vocabulary to describe key actions did not exist. Not surprisingly, learning to fly was very dangerous. Now, flying is based on procedural science. Almost anyone can fly an aircraft if they study and practice diligently. Over time, “how to fly” was specified in more and more detail, for a growing list of subsystems, and for increasingly rare or extreme situations. Knowledge became increasingly detailed, codified, and distributed, and training changed to methods better suited to the new forms of knowledge.

This evolution occurred in a series of distinct stages. Each was based on a conceptual leap and accompanying inventions. Each constituted a new paradigm for the “right way to fly.” Many aspects of flying had to change with each paradigm, usually including pilots’ responsibilities, use of instruments, training, and how decisions were made. Often the new approach was resisted by many experienced practitioners.

There were five paradigms, each of which dominated flying for a decade or longer. There are no standard names for them, so I have adapted names from elsewhere. The paradigms, and associated stages, were:

1. Heroic Craft Flying
2. Rules + Instruments Flying
3. Standard Procedure Flying
4. Automated Flying
5. Computer Integrated Flying

The role of pilots evolved from constant second-by-second control in Heroic Craft Flying, to high-level planning and oversight of computers in Computer Integrated Flying. Table 1-2 gives some characteristics of the five paradigms.

Paradigm for Control	Per-iod of domin ance	Basis of flight control	Example of solved problem	Sample of key knowledge needed
1. Heroic Craft Flying	1910-1929	Personal skill	Avoiding/Escaping stalls and spins	Stick + pedals arrangement of cockpit controls
2. Rules + Instruments Flying	1930s	Instru-ments	Flying in clouds	Quantitative instruments that are better than human senses
3. Standard Procedure Flying	1940s-50s (in US)	Written proced-ures	Complexity; human "carelessness"	Detailed field data on aircraft performance, from test pilots
4. Automated Flying	1950s-1970s	Mechanical /Electronic feedback	Fast reactions needed for jets; pilots' limited attention spans.	Mathematical models of aircraft dynamics & control; feedback systems
5. Computer Integrated Flying	1980s to today	Small digital computers	Controlled Flight Into Terrain (CFIT)	Software models of aircraft subsystems & interactions

Table 1-2 Highlights of five paradigms of flying control

What were the effects of these changes? Each new paradigm gave results that were more consistent, more robust against external variations like weather, and usually more efficient. These changes improved safety -- avoiding crashes. They also improved flight reliability, meaning the ability to get to the destination on time despite adversity. Night, clouds, and eventually storms were no longer obstacles to routine flight. Flights had to be cancelled or diverted less often. Finally, they improved flying performance, according to whatever criteria were important at the time, such as range, speed, and cost.

Figure 1-6 Crashes were a normal part of craft flying.

Slow speeds meant that many were not fatal.

Stage 1, Heroic Craft Flying

(Chapter 3): From its invention in 1903 by the Wright brothers until about 1930, flying was done by hand. Pilots controlled airplanes by laboriously developed personal skill, emphasizing intuitive judgment and eye-hand athletic ability. Learning to fly was very dangerous, and pilots often crashed several times during training. This was “learning by doing, or dying,” as opposed to the more normal “learning by doing” used in other industries. The French Air Force in WW1 kept instructors on the ground when teaching new pilots to fly. Fortunately, aircraft flew slow and low, so crashes were not necessarily fatal. (Figure 1-6)

Even expert knowledge of what worked was shallow and entirely empirical, developed by trial and error. Instruments were minimal, so pilots used their raw senses instead of measurements, and flew in open cockpits to get more sensory detail. An example of their methods was “dead reckoning” navigation, meaning flying above the clouds and guessing when the destination was underneath.

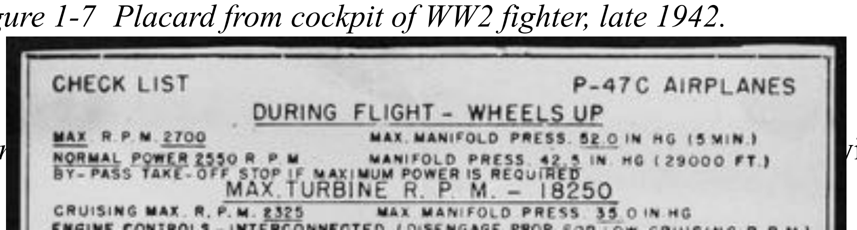
Even though the basic paradigm stayed the same, flying improved considerably during this period. The phenomena of *stalls* and *spins* were identified, and countermeasures eventually found. Numerous hardware inventions made it easier to fly, such as seat belts, flaps, and trim tabs. Aircraft engines improved in power and reliability, and speed, range, and altitude increased as a result. But it was still easy for pilots to inadvertently fly into situations they could not escape from. For example, pilots who attempted to fly through clouds for more than a few minutes usually lost their sense of orientation.

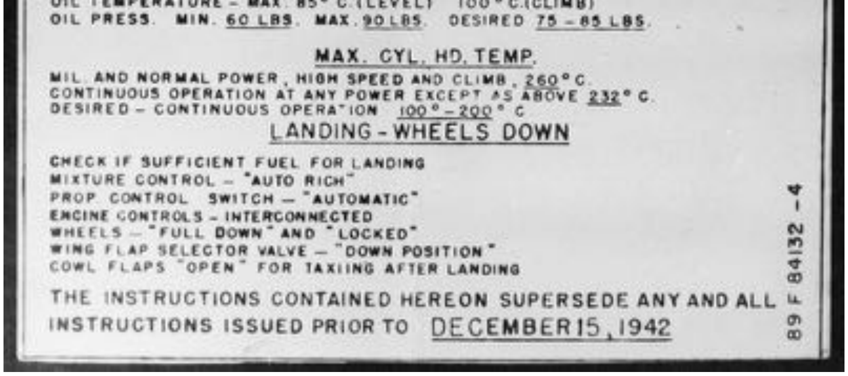
Stage 2, Rules + Instruments Flying (Chapter 4): In the early 1930s, commercial pilots relied on instruments and rules to fly. Pilots learned a variety of rules about how to fly in different situations, although choosing how and when to apply the rules was still up to the individual. New precision instruments gave better information than human senses. The new *artificial horizon* instrument, which used a gyroscope to maintain its orientation as the aircraft rotated around it, allowed pilots to fly inside clouds safely. Using the new instruments properly required many hours of training. Some experienced pilots were unable to make the transition, and were either killed or forced out of their jobs.

With more understanding of what worked, pilot training shifted to classroom lessons, followed by apprenticeships as co-pilot in a two-pilot aircraft. Increasing aircraft range and altitude made navigation more difficult, so aerial charts and simple radio navigation were developed. Pilot licensing began, with both a written test and a practical exam required.

Stage 3, Standard Procedure Flying (SPF, Chapter 5): In the 1930s a number of subsystems were added to aircraft to improve performance. Using these systems properly was problematic, especially for pilots who had not flown that type before. The aviation industry moved to standardized methods, 30 years after they were invented for manufacturing. *Procedures* are explicit sequences of activities, executed under a specific set of conditions, such as during final approach to an airport. These procedures were standardized, published in manuals, and taught to pilots, so that every pilot would, in theory, do the same thing in a given situation. Initially, only a few standard procedures were provided, such as for starting engines, taking off, and landing, but procedures were gradually developed for emergencies. Tables of quantitative settings for controls were another type of standardization, also borrowed from manufacturing. A third key innovation was checklists, which are summaries of procedures, used to ensure that critical steps have been performed. Checklists and critical numbers were always carried in the aircraft, sometimes even visible on the instrument panel, and pilots were taught to use them each time they flew. (Figure 1-7)

Figure 1-7 Placard from cockpit of WW2 fighter, late 1942.





Standard Procedure Flying was invented by the American military, which needed it in the early 1940s to train thousands of aviators each month during World War 2. But many pilots felt that its approach was too constraining. After the war, different air forces adopted it at different times. Some groups of pilots delayed adoption for decades.

Stage 4, Automated Flying (Chapter 6): In automated processes, an artificial system controls portions of the aircraft, using real-time feedback without direct input from a human pilot. The earliest practical flight automation was simple mechanical autopilots in the 1940s that could maintain an approximate course for large aircraft. In the 1950s, automation became more than a convenience; some automation was necessary to cope with the much higher speeds of jet aircraft. Once feedback could be instantiated into electronics automation grew rapidly, and the field called Avionics (Aviation Electronics) was born.

Automation created another conceptual shift in the nature of flying. Pilots moved toward managing machines, rather than using personal sensorimotor skills. They decided when to activate the automation, and monitored that it was performing correctly, but they no longer did the second-by-second control. Automation could also tirelessly monitor the aircraft's status, and alert pilots to problems via lights, and auditory cues. It reduced accidents that were previously due in part to fatigue or divided attention. A variety of aircraft functions were automated over time, such as following radio beams and warning if an aircraft got too low. Pilots still did all the system integration, juggling the different automated systems and warnings and making all longer horizon (minute by minute) decisions.

Stage 5. Computer-Integrated Flying (CIF, Chapter 7): This was "super-automation," and it required small digital computers and ultimately microprocessors. Aircraft were run by networks of redundant digital computers with different responsibilities. Control systems became smart enough to control multiple variables in a coordinated way, with varying behavior over time, and complex conditional procedures. Computer Integrated Flying today includes optimization: goal-seeking behavior by the automated system. For example, if a flight plan calls for reaching a particular position and altitude at a specified time, the system can adjust the engines and controls to hit a "window" of latitude/longitude/altitude/time with minimum fuel consumption.

In this paradigm, most of the detailed knowledge about how to control the aircraft is instantiated into software, written by engineers, and executed by computers. Pilots still give instructions to the computers about where to go, but using high-level commands such as the name of an airport and runway. They also monitor and back up the computerized flight system, and can take manual control using Automated Flying (paradigm 4) or even Standard Procedure Flying (paradigm 3). Most airlines discourage pilots from taking over except under narrow circumstances. At least in principle, such flexible authority lets each form of "intelligence" handle what it is best at: computers for well-understood, highly scientific, processes, and humans for flexibility, including emergencies.

Cracks in Computer Integrated Flying have become visible recently, as pilots who learned to fly using CIF have become common. Although all pilots are trained to fly without CIF support, and receive mandatory refresher training, if the CIF systems shut down these pilots sometimes have difficulty reverting to earlier paradigms. This was a major factor in the loss of Air France 447, whose pilots were unable to regain control of a completely functional aircraft after its computers briefly turned control over to them due to a brief failure of an airspeed sensor. Over the next 3 minutes, the Airbus A330 with 228 people on board fell from 35,000 feet down to sea level. For most of that time, the pilots could have regained control by following standard procedures for "stall recovery."

When each new paradigm was invented, it did not magically come into use everywhere. Only after some years was it accepted by other countries and organizations (such as civilian versus military aviation). Aircraft had to be retrofit with new instruments, and often had to be designed with the new technology in mind, which limited adoption to the rate of turnover of an aircraft fleet.

Most flying activities evolved through all five stages during the 20th century, and are now at the Computer Integrated Flying stage. But different flying activities used different paradigms at the same time. For example, it proved much easier to automate attitude

> Terminology note: The most important characteristics of an aircraft in flight are its speed and its attitude. Attitude is the orientation of the aircraft relative to the ground and to its flight path, and is discussed in Chapter 3.B, "Why is flying hard?" The word "aTTitude" is easy to confuse with "aLTitude," but it means something completely different. Both words are used many times in this book. I will distinguish them by writing attitude or altitude, as appropriate.

(directional) control than engine control. So in the 1950s, a plane "on autopilot" could hold its altitude and course automatically in good weather, but the pilot was still responsible for setting the throttle. Conditions also matter: flying in bad weather is harder, so it was done at a lower stage of control than flying in ideal conditions. Even today, if conditions are too extreme, pilots can find themselves in situations where the knowledge incorporated into their computers is inadequate, and they must take manual control.

A famous example of extreme conditions forcing pilots back to earlier flying methods is the 2009 ditching of US Air Flight 1539 in the Hudson River. After both its engines were disabled by bird strikes, the pilots immediately turned on the Auxiliary Power Unit, a step that was not in the standard procedure but that turned out to be important. (Stage 2: Rules + Instruments) They started to go through the "two engines out" checklist (Stage 3: Standard Procedure) but found it useless.[15] Their key decision was to attempt to land in the river, which was a rule-based (stage 2) decision. Their actual landing was heavily assisted by the Fly-by-Wire system in their Airbus 320 aircraft, a form of Computer Integrated Flying.

Flying versus Aviation

Aviation is a huge sector, and many authors have written about its overall progress as a technology and an industry.[16] This book has the limited goal of understanding how flying methods changed. I look only at aviation activities that take place on aircraft flight decks (cockpits). I refer to this as "*flying;*" the terms *piloting* and *aviating* are sometimes also used. Flying is only a fraction of the aviation industry and aviation technology.Today only one seventh of the employees of United Air Lines are pilots.

The book is about evolution and change in flying technology, but other parts of aviation have been just as important to its overall progress. Four areas have made fundamental contributions to aircraft performance and safety:

- Flying methods (this book)
- Aircraft structures and especially wings, which depend on the fields of materials,

aerodynamics, and manufacturing

- Propulsion
- Manufacturing and Maintenance

All four of these evolved from craft to science. For example, periodic maintenance sometimes caused accidents when a mechanic forgot to remove his tools or left a fastener undone. An early antidote was “standard procedure maintenance.” Today we have computerized maintenance, with autonomous self-monitoring systems that automatically detect problems, diagnose them, and radio the information ahead to the destination.

A variety of other specialized functions also emerged and played their own vital roles, such as air traffic control, scheduling, regulation, and airport construction/management. Supporting each of these were a number of other technologies that developed in parallel with the needs of aviation, such as mathematical methods, simulation, and crash investigation.

Aircraft design is itself a very interesting technology, and the subject of multiple books. In my terms, the work of designing an aircraft evolved from an almost pure craft (build and try), to much more of a science. Initially there was very little theory, so progress was made through empirical research. The Wright brothers used wind tunnels to test airfoil designs, for example. But even after an aircraft was built and test-flown it was hard to know why it performed as it did. As Walter Vincenti documents in *What do engineers know and How Do They Know It?* key theories developed only over time (Vincenti, 1993). On the other hand, aviation historian James L. Hansen emphasizes the evolution of aerodynamics theory as essential to aircraft design.[17]

This book concentrates on the United States. Although the Wright brothers developed the first successful aircraft, between 1910 and approximately 1940 European countries were the world leaders in aviation, especially France. By 1929 the French company Compagnie générale aéropostale carried air mail down the coast of Africa, across the Atlantic Ocean to Brazil, over the Andes, and down to Tierra del Fuego. Chapter 3 discusses some of the adventures of its most famous employee, the author Antoine de Saint-Exupéry. American flying methods reached parity with by World War 2 (WW2), and American aviation post-war led in flying methods and almost all other aspects of aviation.

Other Industries

The issues of craft and science in technology extend far beyond flying. Decision making in most industries uses a mixture of methods that fall between pure craft and pure operational science. But flying has some distinctive characteristics. All decisions are provisional in the face of changing circumstances. Sometimes rapid decisions are required, with only limited information. Second, in addition to minute-by-minute and hourly planning processes, pilots provide "hands-on" control in real time. They use their own senses, augmented by instruments, to estimate what was happening to the aircraft and its environment. Then they adjust controls to make the aircraft execute their decisions. Third, controlling an aircraft uses a variety of interlocking feedback loops, on time scales from sub-second to hours. Other technologies with these characteristics include surgery, anesthesiology, professional sports, and certain kinds of teaching.[18] In these jobs, practitioners can plan, but once the scalpel begins cutting or the center snaps the football, there is no pause button.

On the five-stage spectrum between craft and full operational science, several of these occupations currently use approaches similar to stage 2, Rules + Instruments. Health care is an example. One difference between flying and the fields like surgery is that most involve people, with our variety and unpredictability. It may appear that interacting with people cannot become fully scientific. However, flying used to be considerably less predictable than surgery is now. On afternoon flights through Allegheny Mountains, thunderstorms were a gamble. The weather today is no better than it was in the 1930s, but flying is nonetheless much more scientific and predictable.

Most industries operate primarily at Stage 3, Standard Procedures, or higher. Precision metal manufacturing is an example.[19] Today it is at the equivalent of Computer Integrated Flying (Stage 5). Machines do the work, i.e. shaping the parts; people control, repair, and enhance the machines. To get there, manufacturing went through the same five stages as flying, in the same sequence, plus two additional intermediate stages that flying skipped. (Table 1-3) Since the nature of work and technology in manufacturing and flying are quite different, this suggests that many other technologies may also pass through discrete stages and corresponding paradigms on the way from craft to science.

Manufacturing Epoch	**Approx beginning**	**Flying Equivalent**	**Approx beginning**
0) The **Craft System**	1500	1. **Heroic Craft** Flying	1910
1) The invention of machine tools and the **English System** of Manufacture	1800	2. **Rules + Instruments** Flying	1930
2) Special purpose machine tools and interchangeability of components in the **American System** of Manufacture	1830	No equivalent	
3) Scientific Management and the engineering of work in the **Taylor System**	1900	3. **Standard Procedure** Flying	1940
4) **Statistical process control** (SPC) in an increasingly dynamic manufacturing environment	1950	No equivalent (SPC is now used for maintenance)	
5) Information processing and the era of **Numerical Control** (NC)	1965	4. **Numerically Controlled** Flying	1955
6) Flexible manufacturing and **Computer-Integrated Manufacturing** (CIM/FMS)	1985	5. **Computer Integrated** Flying	1980

Table 1-3 Comparing the evolution of firearms manufacturing and flying

Knowledge and Training

Technological progress rests on growing knowledge. Flying knowledge is now heavily documented, making the knowledge explicit. But in Heroic Craft Flying, knowledge was almost entirely tacit – it could not be written down, and had to be learned by direct experience. Communication in open-cockpit aircraft was almost impossible until a one-way speaking tube was invented in 1917. And on the ground, vocabulary of aviation was minimal, since many important concepts had not yet been discovered.

In the second stage, Rules + Instruments Flying provided a way to embody new knowledge. Some knowledge was built into precision mechanical instruments, and some into verbal rules. Interpreting the rules, and deciding when to apply them, was still mostly learned by observation. Apprenticeship therefore became critical. It was cheaper and less risky than direct experience or dedicated instruction, since the apprentice served as an assistant to the experienced pilot. Passenger aircraft now included an enclosed cockpit, with two pilots sitting side by side and able to talk. Of course direct personal experience was still needed to learn many flying skills.

The third stage, Standard Flying Procedures, can be viewed as an attempt to write down all of the necessary knowledge. Once it was written down, students could learn it from manuals and textbooks. The more complex and less commonly used knowledge was accessible inside the aircraft, in written manuals, handbooks, diagrams, tables, charts (maps), and procedures.

When Automated Flying arrived as the fourth stage, human pilots shared flying responsibility with machinery, and the machinery had knowledge embedded into it when it was designed. Pilots did not need to fully understand the embedded knowledge themselves, and could treat the automated systems as “black boxes.”[20] However, aircraft complexity increased faster than aircraft automation, so pilots had to know more and more. Most of the new knowledge was explicit and formal, so pilots learned it on the ground. In addition, knowledge about the equations governing flight and flight control advanced enough to allow flight simulation of routine flying activities, with moderate fidelity. This added a new training mechanism, including training for some craft skills.

In the fifth stage of Computer Integrated Flying, aviation knowledge continued to grow exponentially. On the aircraft flight deck, the knowledge was partitioned among the human crew and multiple computers and databases. For example, ground-collision warning systems now carry a 3-dimensional map of much of the Earth, which in conjunction with satellite-based GPS navigation provides a "virtual radar" picture to show pilots nearby terrain. The new systems include elaborate self-diagnostics and automated failure recovery, so that pilots get considerable assistance when something malfunctions.

The knowledge now embedded on the flight deck is beyond what any single organization, even a giant company like Boeing with 170,000 employees, can encompass. Avionics companies play a key role in providing specialized knowledge embedded into their equipment. Knowledge is valid only within limited domains, and unexpected problems can always occur. In the last decade, several classes of problems attracted industry-wide attention. One is pilot fatigue, which is not a new problem but in the past was small compared with other problems. Second is the interactions between human pilots and computers, and general "human factors design." Again this is not a new problem, but it has become much more important under Computer Integrated Flying. Third is that skills at hand flying are apparently lower among young pilots, as discussed.

D. Plan of the Book

Chapter 1, this chapter, introduces the themes of the book and summarizes a century of flying technology. Chapter 2 discusses the evolution of other technologies from craft to science. Technology consists of specific knowledge, so shifts in technology correspond to specific patterns of growth in knowledge. This relates to longstanding research about tacit knowledge and to what extent knowledge can, and should, be codified. I discuss different classification systems for knowledge including tacit/codified and know-how/know-why.

Chapter 2 also discuss parallels between flying and other technologies, especially manufacturing and medicine. The central problem in all three is how to consistently achieve the desired outcomes, in the face of inescapable variability in inputs, workers, and the situation. Manufacturing also evolved from craft to (procedural) science, and went through a parallel series of distinct stages, each with its own paradigm. As for flying, each manufacturing paradigm brought revolutionary changes on a number of dimensions. I surmise that medicine will go through a similar sequence of stages, and quite possibly with similar effects at each stage. Currently much of medicine is at the Rules + Instruments Stage, and debating whether to move to Standard Procedures.

Chapters 3, 4, and 5 look at the first three flying paradigms in turn. For each, I show how the new paradigm was able to solve problems that were previously insoluble. In Chapter 3 (Stage 1: Heroic Craft Flying), I discuss why controlling an aircraft is inherently difficult. Rules+Instruments Flying (Stage 2, in Chapter 4) solved the previously fatal "blind flying" problem. Heroic Craft Flying is obsolete in commercial aviation, but Rules+ Instruments Flying is still used today under certain conditions. Chapter 4 also includes a discussion of learning by apprenticeship. Apprenticeship was a fundamental teaching method, and is used to a limited extent even today.

Chapter 5 discusses the invention of Standard Procedure Flying (Stage 3) in the late 1930s. It was partly a response to the growing complexity of aircraft, as more subsystems were added. Each subsystem required pilot actions, and if done wrong the effect could be disastrous. A notorious although rare example was forgetting to lower retractable landing gear before landing. Standard Procedure Flying made technological knowledge much more explicit than before, and Chapter 5 analyzes how it was expressed. The paradigm is still important, and I examine some of its weaknesses.

Chapter 6 examines Automated Flying, which supplemented pilots' eye-hand coordination with artificial feedback loops. Undesirable aircraft behavior that was hard for humans to deal with could now be tamed by artificial circuits, which made more sophisticated aerodynamic designs possible. Automation damped aircraft motion, making flights more comfortable for the expanding number of travelers on the new jet aircraft. It reduced crew size by taking over many control tasks almost entirely. For example, large and expensive inertial navigation systems removed the need for celestial navigation on over-water flights.

Automation brought automated warnings, which made flying safer by channeling pilots' attention. A notable example was the problem of "Controlled Flight Into Terrain," referred to as CFIT. As the overall accident rate fell over time, in large part due to new applications of the Standard Procedure Flying paradigm (such as to maintenance), some problems that had been minor in relative terms loomed larger. By the late 1960s, CFIT accidents, in which pilots did not realize they were at too low an altitude, were a major cause of fatalities. New automation was adopted, first voluntarily and later by regulation, which warned of impending ground collisions by using a simple radar.

The last historical chapter is Chapter 7, which looks at the Computer Integrated Flying stage. This uses networked digital computers as "multiple specialist crew members." One capability is fuel management, which fuses data from 100 or more sensors to provide a very accurate real-time assessment of the fuel situation. This paradigm again changes the nature and management of knowledge. Very complex procedures and calculations are written in software, which, after extensive testing, can be quickly downloaded into hundreds of aircraft, rather than needing to be taught to thousands of pilots. In addition, detailed information about terrain, airports, radio frequencies, and the like can be stored in unified databases that cover most of the world. Almost identical software and data can also be used for simulator-based training of pilots.

Chapter 8 discusses the current status of several issues that began at earlier stages. Pilots have been trained in simulators since the Link simulator in World War 2, but simulation today has gotten to the level where it is arguably better than actual flying for some kinds of training. A second issue is conflicts among objectives, which goes all the way back to the origins of commercial aviation. Safety is a key objective, but cost reduction and schedule reliability are also important. How do flying methods balance these?

Finally, Chapter 9 looks at overall patterns. Table 1-4 summarizes changing answers to some of the fundamental issues of flight. Each stage solved at least one class of important problems that could not be solved using the old methods. A variety of other changes also occurred with each stage. For example, most required new training methods.

Paradigm of Control	**Heroic Craft Ch. 3**	**Rules + Instruments Ch. 4**	**Standard Procedures Ch. 5**	**Automation Ch. 7**	**Computer Integrated Flight Ch. 8**
First wide use	1910	1930	1940	1960	1985
Distinguish-ing character-istics	Personal skill paramount	Altimeter + Artificial horizon; instruments over human senses	Procedures for routine + emergency operation; formulas	Electronic feedback control and monitoring	Federated computers for each aspect of flight. Forecasting + real-time optimization.

Key resolved problem	Stable flight	Maintaining orientation in clouds	Complexity of controls	Stratospheric, high speed flight	Reliability; sensor fusion
Key goal	Survival	+Reach destination	+Keep on schedule	+Passenger comfort	+Economy/speed tradeoffs
Location of knowledge	Nervous systems	Pilots' memories	Procedure manuals	Electronic circuits	Software programs and databases
Knowledge transfer	By observation	Verbal, and guided practice	Reading manuals	Circuit design	By software download
Instruments	Human senses e.g. wind + sound in cockpit	Fewer than 10; Mechanical	Dozens of electrical instruments	Electronic signals, analog displays	Hundreds of networked digital sensors, "glass cockpit" displays
Second by second control	Pilots' hand skills and muscles	Pilots' hand skills + rules about what to do	Hand skills + Hydraulic power	Analog electronic autopilot	Digital autopilots; Fly-by-wire
Minute by minute decisions	Pilot craft knowledge	Craft knowledge + rules about what to do	Standard procedures	Little change from previous period	Flight Management Systems
Navigation	Eye and memory	Aerial charts; simple radio	Radio airways VOR	2-D position finding eg LORAN	Inertial/GPS and integrated 4-D navigation
Method to avoid ground collision (CFIT)	Visual track of obstacles	Copilot + charts + altimeter	Stipulated minimum altitudes by location	Radio altimeter / simple warning	3-D digital map of earth's surface compared to position
Ground control	None	By radio, based on pilots' own reports	Local Radar near airports	Central tracking with manual update	Digital tracking in 3-D; automated collision alerts
Learning to fly	Self-taught by trial & error	Apprentice-ship	Memorizing procedures; systematic training	Same, plus detailed flight simulators	High-fidelity simulators with airport-specific training.
Mathematics used in the cockpit	Purely qualitative	Time/distance calculations	Multiple formulas on slide rules	Differential equations using analog electronics	Computer programs; multi-variate optimization

Table 1-4 Five Paradigms for Controlling Aircraft – some of the major differences

E. Themes

Several themes come up again and again in the evolution of flying, and are discussed in multiple chapters.

- Flying is about *controlling* an airplane. The study of flying technology is the study of control.
- The nature of pilots' *work* changes each time the flying paradigm changes. The attributes of ideal pilots also change, although more slowly.
- The core of all technology is *knowledge*, of several kinds and in various forms. It is intimately related to, but distinct from, flying methods. The structure and evolution of flying knowledge is a theme throughout the book.
- Technological knowledge advances mainly through deliberate *innovation*.

Control

The job of the pilot is to control the aircraft, in the face of a variety of disturbances. Control equals making the aircraft do what the pilot wants.[21] Better flying means controlling an aircraft better: more precisely, more robustly, more effectively, under worse conditions, meeting additional goals, and for larger/faster/more capable aircraft. A novice pilot with only 10 hours of instruction could in 1920, and can today, fly a small airplane safely, as long as it is in daylight, with clear visibility and perfect weather, within a few miles of the airport where she took off, the aircraft does not develop any mechanical problems, no other aircraft are around, and she does only simple maneuvers. In contrast, today crews routinely fly 100 ton aircraft, in the stratosphere, near the speed of sound, across trackless oceans, through night, storms, and fog, while staying within one hundred feet of the assigned altitude and within a few miles of the intended position, using only a tightly controlled amount of fuel, and arriving within minutes of the intended time.

The evolution of flying can therefore be viewed as the evolution of *control* of aircraft.

Among the control problems that have been solved were:

- Maintaining aircraft stability under all conditions
- Control the position of more than 20 control surfaces (flaps, elevator, spoilers, etc.) on a time scale of less than a second and an accuracy of a few degrees of motion
- Flying at night and in clouds
- Flying in storms, or avoiding them
- Dealing with contingencies such as loss of an engine, failure of an instrument, failure of a subsystem
- Keeping passengers and crew comfortable, and engines operating at full power, at altitude 35,000 feet, where air pressure is one quarter of sea level, and the temperature is -50 degrees F
- Measuring and managing fuel consumption
- Handling high complexity: thousands of sensors and actuators
- Navigation - knowing the present location, and how to get to the intended destination
- Transitioning from high altitude and high speed, to approach configuration, where the aircraft has different aerodynamic behavior.
- Dealing with numerous regulatory constraints, such as noise emissions near an airport, air traffic control, and limits on crew work hours.
- Optimizing speed and altitude along the entire flight path, as a function of aircraft weight, weather, and economics.
- Avoiding mountains and other terrain (“controlled flight into terrain,” CFIT)

All of these control problems, except the last three, were reasonably well solved by Automated Flying (Stage 4) in the 1960s. Since then, the accuracy of all controls has improved, optimization reduced fuel consumption and improved on-time performance, and aircraft have become larger and faster (and therefore more difficult to control). Most important, all of the controls have become more *robust*, meaning that they perform acceptably under a wider range of conditions, and more *reliable*, meaning that they fail less often.

Chapter 3 discusses the fundamental control problems that make flying difficult. The most basic is that aircraft attitude must be kept within narrow limits, to avoid fatal "loss of control accidents." This control loop has a time scale of seconds, so pilots must operate without conscious decision making.

Control depends crucially on measurement and feedback, and Chapter 4 describes the inadequacies of critical human senses, and how instruments supplemented raw senses in the Rules + Instruments paradigm (Stage 2). Most control problems other than aircraft attitude, such as navigation, take place on a time scale of minutes. On this scale, higher order thinking was useful, and the new paradigm provided a framework for it.

Chapter 5 describes the new control problems brought by complex multi-engine aircraft, with dozens of knobs, levers, switches, and dials. Operating them incorrectly could set off a sequence of events leading to an accident. In addition, the number of possible situations any pilot *might* encounter was far larger than what he would actually experience in his first few years of flying. Therefore, experience alone was not adequate for learning. The solution was Standard Procedure Flying (Stage 3).

Chapter 6 describes how pilots' control was supplemented by machines. Automation was especially important for jets, which required faster control loops. Automation also helped with fatigue and inattention. It was also used for monitoring, in addition to control.

Chapter 7 describes how Computer Integrated Flight (Stage 5) provided new layers of control that integrated many subsystems, and further supplanted the need for human decisions. Many of the new capabilities applied to the minute-by-minute scale decisions, such as complex navigation.

People and Work

The questions that started this research were about the nature of work in technology-intensive industries, and specifically how work evolves. In the early stages, the pilot himself or herself was a crucial piece of the technology.

What traits and behavior described good pilots? Early pilots were athletes, with well developed sensorimotor skills. The earliest pilots were willing to take extreme risks. These and many other traits have changed. (Chapter 3) Flying instructors since WW2 have told trainees: "There are old pilots, and bold pilots, but there are no old bold pilots."[22] Pilots have always had their own cultures, which reinforce certain behavior. Chapter 3 discusses the early pilots, while chapter 5 briefly contrasts diverse pilot personalities and cultures among WW2 combat aviators. Different nationalities, and pilots flying different kinds of aircraft (fighters versus bombers) approached flying very differently.

Until the 1950s, the biggest challenges for pilots were often physical, such as vertigo, cold, and lack of oxygen at high altitude. In crises, pilots had to keep working despite smoke, confusion, and fear. These problems are discussed in Chapters 3 and 4. With automation and pressurized cabins, physical constraints became less of an issue, but new challenges revolved around *managing attention*, including managing human errors, discussed in Chapter 5 and 6. Today, a big challenge is managing the relationship between pilots and automated control systems, discussed in Chapter 7.

Each paradigm brought a new concept of how to fly, and correspondingly it emphasized different pilot abilities. Heroic Craft Flying rewarded athletic ability. Rules +

Instruments Flying (Stage 2) required concentration for many hours. Intellectual skills began to matter in Standard Procedure Flying (Stage 3), and grew increasingly important thereafter. Jet aircraft, which arrived in the late 1950s, required faster reactions as speed and performance increased. Pilots had to monitor increasingly complex instruments as well. Not coincidentally, Automated Flying arrived to reduce both burdens. Yet even today there are situations where automation is insufficiently powerful, and pilots must take manual control. In some situations, human pilots can still fly better than computers. [23]

How do novices reach the level where they can fly for many hours without crashing? How does a decent flyer turn into an expert? How do knowledge and ability get communicated from the aviation community at large, into the heads and bodies of the crew? Each chapter discuss how training during the corresponding period. Early training was almost entirely by physical practice. Some of the training techniques were crude: one senior pilot thrust burning matches into his co-pilot's face. Years later the novice, by then an aircraft commander, discovered that the earlier brutality had shown him how to concentrate on flying even while his aircraft was on fire. (Chapter 4)

From Stage 3 onward, students could learn useful information from books, and from simulations of specific flying tasks. Figure 1-8 shows the the famous Link Trainer, which sealed the trainee in a small box with information coming only from instruments and headphones. As aircraft became more complex and aeronautical knowledge grew, pilots had to assimilate and apply more and more formal knowledge, which was contained in increasingly extensive written textbooks and manuals.

The attributes for good pilots shifted in concert with the flying paradigm. In WW2, American bomber pilots over Germany had to fly according to rigid formulas and procedures, even while being shot at. Spontaneity was bad for the mission and generally dangerous for the aircraft. Good fighter pilots were very different; among other things they needed a willingness to take risks and even to break rules. Commercial pilots post-war were like bomber pilots, and the need to follow complex instructions carefully has only increased since then. On the other hand, raw athletic skills like strength and fast reflexes are no longer important.

Technological Knowledge

The differences between aviation in 1910 and today are entirely due to better knowledge, embodied into aircraft, people, and the surrounding infrastructure. Technological knowledge is about manipulating artificial objects. Without the right knowledge, no technology will work. One theme of the book is the nature and evolution of knowledge.

Figure 1-8 Link Trainer, 1940

Previous researchers have developed a number of ways of describing and contrasting different knowledge, which I discuss in Chapter 2. Flying knowledge became both more explicit and more quantitative over time. The earliest pilots had to train themselves, because common concepts and vocabulary did not exist. As late as 1917, the French Air Force trained pilots by having them fly solo, with their instructor watching from the ground. Knowledge was inarticulate, encoded in the pilot's nervous system. Early pilots learned to estimate airspeed by the sound of wind in the wires of their biplanes.

Gradually, direct sensory measurements were replaced by instruments. By the 1930s, some knowledge could be stated verbally, using a standard vocabulary that could be taught to novices. In the 1940s, some knowledge was quantitative, and written down as tables and graphs. Today, most flying knowledge is expressed as software algorithms and databases.

We can visualize technological knowledge as a directed graph (network). The nodes are variables, while the arcs are causal relations among them.[24] The graph shows the relationships between causes and effects. New knowledge fills in the graph with more variables, and more arcs that show previously unrecognized interactions between variables.

When new variables are recognized, they tend to progress through a stylized sequence of "stages of knowledge." (Chapter 2) They evolve from qualitative to quantitative, and then from measurable but "random," to controllable. More and more variables must be brought into the equations to improve accuracy. Determining whether an aircraft could reach its destination without running out of fuel is an example. Under Heroic Craft Flying, aircraft range was expressed in hours with a simple rule of thumb:

```
Flying time = Capacity of gas tank / Fuel consumption rate
Range = Flying time x Cruising speed
```

The values of the variables were simple estimates based on past experience. Chapter 3 describes how a famous pilot got lost, and then calculated when he would run out of fuel using incorrect information about his aircraft. As passenger service grew in the 1930s, accurate estimates became more important. Headwinds could be predicted from weather report, and distances between locations were known, so the emphasis shifted to estimating fuel requirements.

```
Fuel required = Flying time * Fuel consumption rate
Flying time = Distance to destination/ Ground speed
Ground speed = Air speed + Wind speed * cosine(wind direction)
```

Actual wind speeds and direction, however, were still mainly guesswork.

Standard Procedure Flying (Stage 3) incorporated a number of new variables into more accurate formulas, such as distinguishing several kinds of air speed: true air speed, indicated air speed, and calibrated air speed. (Chapter 5)

Today, forecasting the fuel requirements for a long flight, and then tracking actual consumption and fuel remaining during the flight, involves roughly 100 different variables, depending on the aircraft and the route. For example, the energy per kilogram of fuel varies by exact fuel type, and the specific gravity of fuel depends on the temperature in each fuel tank. Wind speed is forecast for each altitude and each possible course, and air speed becomes a variable to be optimized for each leg of the flight, rather than a single choice of the pilot. (Chapter 7)

As this example shows, the sophistication and importance of mathematics grew with each paradigm. Under Standard Procedure Flying, pilots carried analog computers and were good at mental math. Today, specialized onboard computers solve large systems of equations every minute. Some automatic procedures are timed to tenths of a second, and navigational instruments such as GPS use microseconds.

Innovation

The evolution of flying methods relied on directed innovation. Most of the innovation was incremental: small changes in local portions of the technological knowledge graph, and corresponding small improvements in performance. The four paradigm shifts, in contrast, set off widespread changes in both knowledge and practice, and created major new sections of the knowledge graphs, as well as rendering some of the old sections obsolete. I will define such situations as *technically radical innovation*, which is not the same as the usual definition of radical innovation in business terms.

The most important force driving innovation was competition: business competition in commercial aviation, and of course military competition in military aviation. Airlines that figured out how to get better performance from their crews and their aircraft reduced costs and attracted passengers. Aircraft manufacturers (and their suppliers) strove to produce better aircraft along a multitude of economically relevant performance dimensions, including speed, comfort, reliability, operating costs, and maintainability.

Innovation was also motivated by airplane crashes, which dramatically suggested flaws in existing flying methods. Crashes and general safety had influence through at least three channels: publicity, economics, and government regulation. Airplane crashes have always attracted disproportionate press coverage compared with other accidents, and in the US, Congress pushed regulators to pressure airlines for better safety. Fear of crashes also deterred potential passengers, making crashes directly important to airline economics. The extreme example of this is probably terrorists' use of commercial airliners on September 11, 2001. The result was a 30% drop in US passenger traffic, which was not made up until 2004.[25] Crashes also motivate change because they have direct out-of-pocket costs for airlines, and affect insurance rates.

Driven by competition and regulation, the performance standards for flying increased over time. For passengers, the goals went from arriving at the correct destination safely, to arriving on schedule, to keeping passengers comfortable. Passengers no longer need vomit bags, and today's pilots even try to use gentle bank angles to reduce passenger anxiety. Gradually, external goals were added by regulators, such as noise limits and environmental restrictions.

Intermediate requirements, those important to pilots but less visible to passengers, also increased steadily. Higher/farther/faster were always sought. Landing in bad conditions affects schedule reliability. Sufficiently bad weather has always shut down airports, but less often with each decade. Properly-equipped aircraft and trained pilots can now land in fog so severe that, once on the ground, they cannot taxi to the terminal because they cannot see the runway. Still other changes have been driven by costs, as the airlines became substantially more competitive in the decades after deregulation of routes and prices. Fuel conservation has become more important because fuel is now a major cost, and Computer Integrated Flying (Stage 5) gives many tools for reducing fuel consumption.

Multiple objectives always have the potential to conflict, such as safety and schedule reliability in bad weather. Once the causal relationships governing outcomes were understood well enough, the "requirements" became less absolute, and pilots and airlines began to trade off conflicting objectives more systematically.

Innovations generally take decades to become widely used. The process of an innovation that starts in one location or organization and gradually becomes widely used is referred to as technology *diffusion*. Despite high stakes, most flying innovations took years to diffuse. Most of the new flying paradigms required new hardware in aircraft, such as instruments. Sometimes new hardware could be retrofit into the cockpits of existing aircraft, but often it had to be designed into each aircraft model. Designing an aircraft takes several years, and purchases of a new aircraft proceeded gradually, so hardware-based innovations took years to become widely available. Even innovations that did not require new hardware still took time to diffuse. Pilots had to be trained to use them. Chapter 3 describes the diffusion of stall and spin recovery. Because Rules + Instruments flying (Stage 2) was counter-intuitive, pilots needed special training for it. (Chapter 4) Chapter 6 describes the diffusion of Standard Procedure Flying (Stage 3) across different air forces during and after WW2. Adoption was heavily driven by organizational cultures and politics.

One important obstacle to improvement was the concept of "pilot error." During the

Heroic Craft Flying period (Stage 1), when pilots flew into clouds and ended up in deadly spins, it was viewed as evidence of their poor skill. Pilot error has been used to explain getting lost, forgetting to lower the landing gear, or shutting down the wrong engine in a fire. But none of these problems could be solved by yelling at the surviving pilots. On the contrary, as long as crashes were blamed on individual pilots, there was little incentive to investigate further and no incentive to make systemic changes. But in the long run improvements came from looking for deeper root causes: *why* were pilots making these mistakes, and what would reduce their frequency?

On the positive side, safety innovation in the last few decades has been helped by a collaborative culture among competitors. Rival airlines and manufacturers, and the regulators who are in some way their natural enemies, cooperate on crash investigations. Many accidents involve players from multiple countries, and most of the time accident investigations avoid national rivalries.[26] Crash investigations will be discussed briefly in Chapter 8.

One reason that commercial aviation is so safe is that the industry is quite systematic about learning from accidents. Knowledge gaps lead to accidents, accident investigations discover that such a gap caused the accident, research fills in the missing knowledge, and the resulting new knowledge is eventually retrofit into old aircraft and taught to pilots. Rigorous certification requirements require extensive testing of new devices and aircraft for issues that, in the past, have been problem-prone. On the other hand, these certification systems also inhibit innovation and create barriers to entry.

Path Dependence

Many specific aviation problems could have been solved in multiple ways, and the ultimate solution arose as much through chance as by deliberate choices. Generally some events lead to one particular solution taking an early lead, and this makes it easier or less risky for subsequent developers to work on, instead of developing one of the alternatives.[27] The 1920s transition from wood and fabric aircraft to all-metal construction could have been postponed for at least 15 years.[28] But in 1931 a small plane carrying a famous football coach crashed. The crash was ascribed, perhaps incorrectly, to deterioration of glue holding together its wooden wing joints. The industry could have developed better glues, but instead it moved away from wooden parts and switched entirely to all-metal aircraft. Yet a decade later, a British company developed the all-wood Mosquito fighter/bomber, which was roughly as effective as the American B-17 bomber despite having one fifth the crew and a fraction of its cost.

Bad-weather landing systems are another example. When the problem of flying *through* clouds was solved around 1930 (Chapter 4), it created the problem of *landing in* clouds or ground fog, i.e. when the runway is not visible. Eric Conway documents the twists and turns of solving this problem in *Blind Landings: Low-visibility operations in American aviation, 1918-1958.* Very different approaches were technically feasible, and several were developed by competing groups. The eventual choice was heavily affected by network externalities. Both aircraft and airports needed to support the same method. Such network effects are common with aviation technologies, because of the close linkage between infrastructure (airports, navigation systems, even regulations), aircraft, and flying methods. Adopting a common system nationwide, and eventually worldwide, reduces costs for everyone.

Although the *solutions* to technical problems were often path dependent, I will show that the flying problems themselves were often inevitable given the business objectives. Both customers and balance sheets wanted faster trips, which required faster aircraft, which eventually required jet propulsion. Jet engines are more efficient at higher altitudes and with swept-back wings. High altitude, high speed, and swept wings all created new control problems, both individually and through interactions with each other. The modern stratospheric jetliner is a case of form, following function, following technical goals, following business goals.

On the other hand, business goals, including customer desires, might have developed very differently in some alternate world. Fuel prices and recessions, both exogenous to the aviation industry, sometimes re-sorted technical goals. Even the relative emphases placed on safety versus speed versus cost in commercial air travel is partly historical accident. For example if the attacks of September 11, 2001 had occurred in another country instead of the US, air travel in the US today would probably be more pleasant and less expensive.[29]

Is Science Inevitable?

If pure craft and pure operational science are at opposite ends of a spectrum, does progress always move from the former toward the latter? Fully answering this requires the entire book. But a short answer is that movement toward science always occurs when two factors coincide: pressure on organizations to perform better, and appropriate kinds of new knowledge, either developed internally or from outside. Once there is pressure to improve, one of the key routes to large-scale performance improvement is developing better (operating) science. On the other hand, an alternate strategy is to teach "better craft," such as via longer apprenticeships (Chapter 4). But in the long run, the strategy of "develop and apply knowledge at higher stages of operational science where feasible" dominates the strategy of "better craft." At least for large-scale application, good science beats good craft.

It is certainly possible to go too far toward applying science. This is especially frequent in extreme situations that are outside the capability of the current designs and methods. In such situations, high-science control will malfunction. This has happened throughout the history of flying. The right approach is to fly with methods that are closer to craft. For example, autopilots are designed so that when their sensors fail, they relax their control, and the pilots revert to an earlier paradigm. Analogous approaches are used in law firms and many other professional services.

Unfortunately, organizations may not always recognize that their stage of operational science is too high for their current knowledge. At one time the American automobile industry thought that automating its assembly plants was the best way to compete with rising Japanese companies like Toyota. General Motors invested approximately $40 billion in automating assembly plants in the 1980s, but discovered that robots were not able to fit parts together as well as experienced workers could.[30] Standard procedure manufacturing (Analogous to Stage 3 of Flying) worked better than automated manufacturing (analogous to Stage 4).

A corollary is that although progress from craft toward science is a general trend in successful industries, steps back toward craft are sometimes necessary. Sometimes external changes shift a technology into situations where less is known and therefore the current paradigm is too advanced. In aviation, when certain altitude or speed level were reached for the first time, previously unknown phenomena became important. For example, human physiology causes difficulties at high altitudes. Pioneers in these situations had to use techniques that were closer to craft. Around World War II testing methods were formalized, including the role of test pilot, to run experiments in novel situations.

The following chapter puts aviation technology in a broader context. Patterns of evolution have been investigated for many other industries and technologies. These provide a rich set of insights and hypotheses that subsequent chapters apply to flying.

Endnotes

[1] Calculations are as follows. From 2005 to 2009, air carriers in the US flew 39 billion miles with 6 fatal accidents and 118 fatalities. This is .3 fatalities per 100 million vehicle miles, and approximately .003 per 100 million *passenger* miles. Source: ("NTSB - Aviation Accident Statistics," n.d.) http://www.ntsb.gov/aviation/Table6.htm. The comparable numbers for automobiles from 2004 to 2008 are 15 trillion vehicle miles and 155,000 fatalities, or 1.0 fatalities per 100 million vehicle miles and about .7 per 100 million passenger miles. ("FARS Encyclopedia," n.d.) Many statistics on auto accidents include non-occupants, which I exclude from these calculations.

[2] In 1934, a DC-2 flew from London to Melbourne in 90 hours. It had a capacity of 14 passengers. The A380 has a capacity of 550 to 800+ passengers, depending on configuration, an unrefueled range of 9,800 statute miles, and cruise speed of 560 mph. Accident rate comparison is not aircraft-specific; data later in chapter.

[3] Joseph M. Hall and M. Eric Johnson "When Should a Process Be Art?" *Harvard Business Review,* March 2009, pp. 58-65.

[4] This paragraph is heavily based on "The Formula" by Malcolm Gladwell, *The New Yorker* 82.33 (Oct 16, 2006): p138.

[5] Amalberti, R., Auroy, Y., Berwick, D., & Barach, P. (2005). Five System Barriers to Achieving Ultrasafe Health Care. *Annals of Internal Medicine*, *142*(9), 756 -764.

[6] I will generally use the masculine pronoun when discussing pilots of the past, and feminine when referring to present-day pilots.

[7] *Florence Lowe "Pancho" Barnes,* U.S. Centennial of Flight Commission, http://www.centennialofflight.gov/essay/Explorers_Record_Setters_and_Daredevils/Barnes/EX17.htm, nd; Lauren Kessler, *The Happy Bottom Riding Club: the life and times of Pancho Barnes,* Random House, 2000.

[8] David A. Mindell, *Chauffeurs and Airmen in the Age of Systems*, ch. 2 in *Digital Apollo*, MIT Press 2008.

[9] Sources: 1927-37: AA Statistical Handbook (December 1945). 1938–71: CAB Handbook of Airline Statistics (1973), Part VIII, Items 19c,d, pp. 595-596; NTSB Safety Studies Division. 1972–82: FAA Statistical Handbook (1972-82), Table 9.3, p. 161, citing NTSB for totals; 1983–present: NTSB Aviation Accident Statistics, Table 6, National Transportation Safety Board, *Accidents, Fatalities, and Rates, 1992 through 2011, for U.S. Air Carriers Operating Under 14 CFR 121, Scheduled Service (Airlines)*. Fatalities for 2001 and 1994 exclude effects of sabotage. Data until 1992 compiled by Air Transport Association. Calculation of accidents per million miles is by the author.

[10] Exhibit and data from UK Civil Aviation Authority, *Global Fatal Accident Review, 2002 to 2011*, Report CAP1036, 2012. In contrast to the previous graph, this data covers all cargo and passenger flights by turboprop and jet aircraft.

[11] William T. Larking, *The Ford Tri-Motor 1926-1992*, Schiffer Publishing Ltd., 1992. Also Anonymous, *Instruction Manual for Ford Trimotor*, 1929.

[12] Sources: The Boeing Company, *777-200/-200LR/-300/-300ER/ F Flight Crew Operations Manual,* Document Number D632W001-TBC, April 01, 1994, Revision 49 December 12, 2011. Boeing,

[13] "If the total air temperature (TAT) is above 10°C, both manual and automatic wing anti-ice operation is inhibited for five minutes after takeoff." Continental 777 Flight Manual, page 6.3.3, Revised 05/01/02 #8.

[14] Modern aircraft are diverse, and often accomplish the same goal, such as wing de-icing, in a variety of ways. Therefore, blanket statements about aircraft design have an implicit qualification, "generally" or "in most cases." For example, bleed air is used for wing deicing on most Boeing jets, but the most recent, the 787, uses electric heaters.

[15] William Langewiesche, *Fly by Wire: The Geese, the Glide, the Miracle on the Hudson*, Penguin, 2009.

[16] Such as Tom D. Crouch *Wings: A History of Aviation from Kites to the Space Age,* Smithsonian Institution, 2003; Robin Higham, *100 Years of Air Power and Aviation*, Texas A&M University Press, 2003.

[17] Aviation historian James L. Hanson points to aerodynamics as the most essential technology behind improvements in aircraft performance. His list of other important technologies includes stability and control, propulsion systems, structures, materials, internal systems, and manufacturing. James L Hansen, *The Bird Is on the Wing: Aerodynamics and the Progress of the American Airplane*, 2004,. Of Hanson's list, only stability and control is covered in this book.

[18] My wife spent many years as a Montessori pre-school teacher (ages 2.5 to 6). Every day, every student had a unique set of activities. Every student had their own personality, was at a different stage of learning each subject, and had unique strengths and weaknesses. Her job was to plan, and then orchestrate, the apparent chaos. Lecturing to 200 students in a physics class is very different.

[19] The analysis of manufacturing is specifically for the Beretta firearms company, and is from Ramchandran Jaikumar, "From Filing and Fitting to Flexible Manufacturing: A Study in the Evolution of Process Control," *Foundations and Trends in Technology, Information and Operations Management* Vol 1, No 1, 2005. Also available as Part 1 of Roger Bohn and Ramchandran Jaikumar, *From Filing and Fitting to Flexible Manufacturing,* Now Publishers, 2005.

[20] The term "black box" is believed to have originated in British aviation during or shortly after WW2. It means a system whose inner workings are invisible.

[21] Chapter 2 of David A Mindell, Digital Apollo: human and machine in spaceflight. MIT Press 2011.

[22] First known attribution is to Harry Copland, 1934. "N. E. Aviation Notes," *Boston (MA) Herald*, 10 June 1934, pg. 6, col. 2. Cited in blog entry http://www.barrypopik.com/index.php/new_york_city/entry/there_are_old_pilots_and_bold_pilots_but_there_are_no_old_bold_pilots, March 4, 2013. The newspaper article says about Copland :"incredible as it may sound he has been flying since 1911. If my arithmetic is correct that is 23 years." Early aviation author and commercial pilot Ernest K. Gann, speaking about commercial flying in the late 1930s, said that good pilots had to take some risks, but choose them carefully. See Chapter 4 for a discussion of Gann.

[23] Such as landing with high side winds. A contributing factor the 1995 crash of American Airlines flight 1572 was that the autopilot was unable to stay on course due to high cross-winds. The pilot therefore shifted to a more manual mode, which increased his workload. See Chapter 6.

[24] Bohn and Jaikumar, 2003. Stylized versions of network causal models are discussed in Judah Pearl, *Causality* (Cambridge University Press, 2009, second edition. However, Pearl's graphs are acyclic, while in technology feedback is very important, so the graphs are cyclic.

[25] "Airline Travel Since 9/11," *BUREAU OF TRANSPORTATION STATISTICS Issue Brief* Number 13, December 2005.

[26] One of the few exceptions has been investigations of pilot suicides. Such cases are very rare. "Difficult Diagnosis," *Aerosafety World*, May 2012, p. 30 lists only three in the last 30 years.

[27] The general phenomenon is known as *path dependence*. Leonhard Dobusch and Elke Schüßler "Theorizing path dependence: a review of positive feedback mechanisms in technology markets, regional clusters, and organizations," *Industrial and Corporate Change*, Volume 22, Number 3, pp. 617–647. doi:10.1093/icc/dts029

[28] Eric Schatzberg, "Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920-1945", *Technology and Culture* vol. 35 no. 1, 1994, pp. 34-69.

[29] The budget of the US Transportation Security Administration, whose job is to protect airports against hijackers, is about the same size as the budget of the Federal Aviation Administration, which is responsible for all other aspects of aviation regulation and safety.

[30] Keller, Maryann. 1989. *Rude Awakening: The Rise, Fall, and Struggle for Recovery of General Motors*, New York: Harper Perennial. Amal Nag, "Tricky Auto Makers Discover 'Factory of the Future' Is Headache Just Now --- Robots Misfire and Scanners Misread at a GM Plant; Ford Has to Alter a Van --- But Firms Are Still Believers"

Wall Street Journal 13 May 1986, p 1.