Aeronautics, 1898–1909: The French-American Connection

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In August 1908, Wilbur Wright gave the first public demonstration of the Wright airplane, at Le Mans, France. Two weeks later Orville was the first to fly publicly a powered man-carrying aircraft in the United States, at Fort Myer, Virginia. Those astonishing flights were the beginnings of the Wrights' programs to fulfill the requirements of contracts the Brothers had made with the French and U.S. goverments. At the time nobody else had a practical aircraft fully controllable and capable of being maneuvered at the pilot's command.

Yet within a year, France was clearly the leader in aviation. Blériot flew the English Channel in July 1909. For that dazzling accomplishment he gained Lord Northfiled's *Daily Mail* prize in a highly publicized competition. Due to the press of other business Wilbur chose not to enter, even though he likely could have won easily.

The first international flying meeting, sponsored by the champagne industry and hence called "La Grande Semaine d'Aviation de la Champagne", was held in August 1909 near Reims, France. Again the Wrights elected to be absent, although three of their aircraft were entered, all flown by Frenchmen. Of the remaining 35 aircraft, one was designed and flown by the American Glen Curtiss and the rest were all French designs.(1) Twenty-two aviators competed for eight days before two million people. French pilots flying French aircraft won all but three of the fourteen prizes; the three were won by Curtiss.

By the end of 1909, just six years after the Wrights historic 1903 flights, Frenchmen held most of the world's flying records for speed, altitude and distance. The French dominance in aviation did not diminish. During World War I, France produced more airplanes (67,987) and lost more (58,144) than any other country. The United States had

55 front line aircraft in 1914 and 740 in 1918, almost all French designs.(2)

Those events in the two years 1908–1909 raise questions which, if they have been asked, merit further attention. Why did the Wrights have a contract with the French, leading Wilbur to fly first publicly there while Orville showed their airplane in the U.S.? How did it happen that the French then not only became proficient in flying, but in fact quickly had their own superior designs? If, as apparently was the case, French aviation pioneers were prepared to exploit the new invention in ways which other countries were not, why was the U.S. and not France the birthplace of the powered man-carrying airplane?

The answers to those three questions are interrelated and follow as much from the styles of the inventors working in the two countries as on the state of aeronautics at the end of the nineteenth century. Because it moves in three dimensions, the airplane presents scientific and technological problems not previously encountered with vehicles moving on the earth's surface. Traditional methods of investigation successfully followed by inventors in the nineteenth century served poorly as the basis for solving the problem of mechanical flight. Major advances were necessary, both in understanding basic principles and in aeronautical technology. The Wrights' approach leading to the first practical airplane appears to us now as a fine — indeed, arguably the first — example of a modern program of research and development.

In contrast, the contemporary French aviation pioneers worked more in the fashion of trial and error with markedly less emphasis on determining the basic principles. Despite the obvious differences between the methods used and results obtained in the two countries, there was in fact a strong connection between the Wrights' work and the efforts of the aeronautical community in France. That connection did not give the French sufficient help for them to be first with a practical airplane, but it was a direct cause for Wilbur's appearance at Le Mans in 1908.

While the Wrights worked alone, the apparently rapid use of aeronautics in France after 1908 was actually the product of many years of work by a small enthusiastic community of inventors and experimenters. They were sustained in part by a few wealthy supporters and by their intense drive to make France the country that would give birth to the airplane. An influential member of that community, Ferdinand Ferber, established the first connections between American and French aeronautics, and played a central role in the beginnings of powered flight in France.

Independently of the Wrights, Ferber had begun his own project to build gliders. At first alone, he soon persuaded others to join him. As a visionary, popularizer, and constructor of experimental aircraft, he initiated the re-birth of aviation in Europe. Although he is not distinguished by any famous flights or aircraft designs, Ferber was an important figure in early French aeronautics.

Ferdinand Ferber was born in Lyons, France, in 1862, five years before Wilbur Wright's birth. Having shown some aptitude for the sciences, he was encouraged to attend university.(3) His family finances could not bear the expense, so he entered l'Ecole Polytechnique in Lyons and after graduation joined the French artillery.

As a young officer, Ferber still found time to pursue his own researches in mathematics and physics. Some results he obtained while working on ballistics, and a degree in the sciences, led to his appointment as a teacher at l'Ecole d'Application de Fontainebleau. There, while browsing in the library in the spring of 1898, he discovered an article describing Otto Lilienthal's experiments in manned flights with gliders, the type now called hang gliders.

Except briefly in his youth, Ferber had not been especially attracted to aviation. He was not acquainted with French journals on the subject, and he could not have anticipated the amazing story of Lilienthal's pioneering successes. According to notes he wrote later, he was instantly struck by the truth of Lilienthal's approach to the problem of flight, namely that construction of a successful airplane required also learning how to fly. He soon began to build and test gliders, and thus began a career that placed him at the center of French aeronautics.

A few years earlier, Wilbur Wright had also started to think about the problem of flight when he had read of Lilienthal's death in 1896. He began his experiments in August 1899, with a small kite confirming his idea of wing warping for roll control. With Orville, he conducted glider tests in 1900, 1901 and 1902 at Kitty Hawk, preparing them for their powered flights in 1903. Following Lilienthal's principle, learning to fly was an essential part of their program.

Ferber learned of the Wrights' work in 1901 and began a correspondence with Wilbur. What he learned led him to become the first European to build gliders according to the Wrights' design. That relationship was an important influence in the events that brought Wilbur to France in 1908.

Thus the aeronautical careers of both Ferber and the Wright Brothers are rooted in the remarkable work of Otto Lilienthal. They began their flying experiments almost simultaneously, with nearly the same basis and motivation, but they produced drastically different results. Even as Ferber was later joined by other French inventors intent on making the airplane a French invention, the Wrights were several years ahead. By August 1908, French successes were growing, but Wrights still held a fundamental advantage.

To understand the significant differences between the Wrights' and the French accomplishments up to August 1908, it is helpful first to review briefly aeronautical developments in the nineteenth century. Only those developments germane to subsequent discussion will be mentioned. That will serve as background for examining some of the technical problems of mechanical flight which the Wrights succeeded in solving, but which the French barely recognized until the Wrights flew publicly.

AERONAUTICS IN THE NINETEENTH CENTURY

The invention of the airplane was the result of international efforts spread over a century.(4) In 1799, the Englishman Sir George Cayley (1783–1857) opened the modern era of aeronautics with engravings on a silver disc showing the basis for a fixed-wing aircraft.(5) He realized that, in contrast to birds who use their wings both for propulsion and for lifting against gravity, the means for producing lift should be separated from the source of thrust required to overcome air resistance. On one side of the disc he drew a diagram of forces illustrating the idea. On the reverse side he sketched a fixed-wing aircraft. Five years later he constructed a model glider clearly recognizable as a device likely to fly stably. The tips of the wings were raised above the root, giving the dihedral angle that provides stability in rolling motions. It had an aft horizontal tail for pitching stability; and a vertical tail providing both directional stability and, according to Cayley's conception, steering. In addition to flying model gliders, Cayley is reported to have successfully tested a full scale version carrying his coachman.

Cayley worked on the problem of flight throughout his distinguished engineering career. His contemporaries and followers in Great Britain adopted his ideas with only modest results and no fundamental advances in the technology. Without an adequate engine they could not succeed with powered flight and none tried gliding. Their efforts did, however, popularize the possibility of flying machines and contained some ideas that were later realized in practice.

Following Cayley, the next great advances were made in France by the aeronautical genius Alphonse Pénaud (1850–1880). He carried out fundamental researches on the forces experienced by bodies in motion and developed a thorough understanding of the problems which had still to be solved in order to achieve manned flight.

For all his fundamental work in aeronautics, Pénaud is probably best known as the first person to use twisted rubber bands to power models. He constructed and flew model helicopters sustained by rotating wings; ornithopters which flew with flappings wings; and most significantly, in 1871, a fixed-wing model airplane with thrust provided by a propeller. The fixed-wing model was the first flying demonstration of an airplane having the modern configuration. Apparently Pénaud was at first unaware of Cayley's work and so re-invented the horizontal tail as a device for longitudinal stability. In a classic paper(6) published in 1872, he analyzed its operation, the first correct discussion of stability for an aircraft. As a result, the tail became known as the "Pénaud tail." His success with the stable powered model subsequently caused almost all aviation enthusiasts, especially the French, to seek an inherently stable aircraft for manned flight. His ideas were influential long after his suicide at age thirty.

Pénaud's accomplishments were not surpassed until Otto Lilienthal (1848–1896) became the first man to fly repeatedly as master of his machine. Educated as a mechanical engineer in Germany, Lilienthal followed a long methodical program to solve the problem of mechanical flight. While a schoolboy, he and his brother Gustav had been inspired by birdflight to attempt flying themselves by flapping mechanical wings.

The Lilienthal Brothers worked together on manned ornithopters for many years.

Their failures finally led Otto to seek more basic understanding. He built a whirling arm apparatus for measuring aerodynamic forces and resolved to determine the airfoil shape having best ratio of lift to drag. Quite naturally he tested shapes resembling the cross-sections of birds' wings, thereby excluding airfoils which were discovered later to be superior for fixed wing aircraft. That prejudice for thin highly cambered airfoil sections was copied by others almost universally until World War I. Aerodynamical theory and extensive laboratory tests then formed the basis for selecting more efficient airfoils. His book(7) *Birdflight as the Basis of Aviation*, thoroughly documents Lilienthal's research and flight test program.

Lilienthal's monumental achievements are twofold: he gathered the first quantitative data for the lift and drag forces on useful airfoils; and he designed, constructed and flew the first truly successful gliders, carrying him more than 300 yards in his best flights. His experimental data were subsequently used by the Wright Brothers in their initial designs, and independently motivated the first theory of airfoils invented by Kutta in 1902. His widely publicized gliding flights inspired first Octave Chanute and later the Wrights in the United States; Percy Pilcher in England; and Ferber in France. Lilienthal has justifiably been lauded by the French aviation historian Dollfus as "the father of modern aviation."

There can be no doubt that Lilienthal's greatest contribution to aviation was his public demonstration that manned flight was possible. He understood that learning the skill of flying was inseparable from the development of a successful airplane. In contrast, many of his predecessors and contemporaries took Pénaud's success to its extreme. They believed that an airplane could be built to fly so stably as to require the pilot merely to steer. Learning the skill of flying was not understood to be part of the problem. Lilienthal instinctively knew better. He constructed and tested more than fifteen different glider designs. Near Berlin he built a dirt hill as a test site for launching his gliders in the direction dictated by the prevailing wind. The new technology of commerical photography dramatized the reports of his wonderful gliding flights. Pictures appeared in illustrated journals throughout Europe and the United States for several years in the mid-1890's. His death in 1896 from an injury suffered in a crash made international news.

The first in Europe to be inspired to his own flying experiments by the reports of

Lilienthal's gliding tests was Percy Pilcher (1867–1899). After his discharge from the Royal Navy at aged 20, Pilcher served as an engineering apprentice in several shipyards and in 1893 accepted a position as an assistant in naval architecture at the University of Glasgow.(8) Two years later, having read of Lilienthal's work, he began his own flying program.

Although he had seen photographs of Lilienthal's gliders, all of which had horizontal tails, Pilcher determined to make his own design without a tail. He had no success. In the spring of 1895 he visited Lilienthal who convinced him that a horizontal tail was essential for stability. During the next four years Pilcher constructed and flew a succession of four gliders, the *Bat*, *Beetle*, *Gull*, and *Hawk*.

Pilcher made only modest progress in his work, but his best glides did exceed 250 yards. His other business activities prevented him from spending much time on his flying experiments. He had plans to build a powered aircraft, but his death in a crash of the *Hawk* in 1899 ended his program. Pilcher's work was not fundamentally different from Lilienthal's and he discovered no important new ideas.

Octave Chanute (1832–1910) was Lilienthal's second disciple. Born in France and raised in the United States, Chanute was a prominant civil engineer particularly well-known for his work on projects related to the development of railways in the midwest. He pursued a serious interest in aviation by travelling in Europe and the U.S., wherever necessary to speak with anybody actively trying to build airplanes, and writing articles. In 1894, the articles were combined and published(9) as *Progress in Flying Machines.* In that classic book, Chanute gave a thorough survey of aeronautics in the 19th century, including discussions of the scientific and technological foundations of aeronautics, at the time very crude and poorly understood. Thus the book offers a particularly good basis for appreciating the inadequate knowledge of aeronautics available to inventors at the end of the 19th century.

In 1895, imitating Lilienthal, Chanute began his own program of hang-gliding, with assistants doing the flying. He made no fundamental advances beyond Lilienthal and Pilcher, although he spent much effort unsuccessfully trying to devise an "automatically stable" glider that would carry a person in complete safety without the need for control by the pilot. Chanute's chief technical contribution to aeronautics was his adaptation of a bridge design, the Pratt truss, as the basis for his biplane configuration. The Wrights learned this structure from Chanute and adopted it for their aircraft. It became the standard structural design for all biplanes until cantilevered wings were used.

When Wilbur Wright (1867–1912) read of Lilienthal's death, his boyhood interest in flight was renewed. Joined by his brother Orville (1871–1948), in 1899 he began his work to build a flying machine. Their approach to the problem of flight was initially guided by Lilienthal's example, but from the beginning they added their own fundamental ideas and worked in their own style. For five years the Wrights pursued a systematic program of research, design, construction, and testing. Two years after they flew their first powered aircraft in December 1903, they had a practical airplane capable of flights as long as thirty-eight minutes (limited by the fuel supply) and under complete control at all times. It is a measure of the Wright's remarkable achievement that not until 1907 was anyone else (Farman, in France) able even to exceed the duration of the Wrights' longest powerered flight of 59 seconds in 1903 — and the airplane used was not fully controllable.

The competition to invent a practical airplane was nowhere more intense than in France. A Frenchman had first risen into the atmosphere when the Montgolfier Brothers invented the hot air balloon and flew in 1783. Throughout the 19th century from Giffard to Renard to the Lebaudy Brothers and Santos-Dumont, the French led the world in historic advances of powered ballooning. By the end of the century, the dirigible — the name itself is French — seemed clearly to offer the best prospects for controlled flight. The French Artillery looked to the airship for scouting and reconnaissance. Societies meeting in France, as elsewhere to discuss aviation, were chiefly concerned with "aerial navigation," flight with lighter-than-air craft.

Early experiments with heavier-than-air craft in France came to an end with Ader's disappointing results :(10) he had been able to achieve only a "tentative hop" with a crudely designed aircraft alternatives to balloon in 1890. Nevertheless, the first European flying had happened in France and some members of the aeronautical societies still discussed helicopters, ornithopters and fixed-wing aircraft. Pénaud had been a proponent of the last, but even in France his influence did not make the airplane the obvious choice for solving the problem of mechanical flight. For some unknown reasons, Lilienthal's gliding tests made essentially no contemporary impression in France. When Ferber entered aeronautics, the mainsteam of interest, particularly in the army, lay with airships.

PROPULSION, GEOMETRY, EQUILIBRIUM AND STABILITY

Despite considerable discussion of the "problem of mechanical flight" during the years ending the nineteenth century, the "problem" was in fact not at all well-defined. Lilienthal, professionally a mechanical engineer, carried out a large number of tests to determine the lift and drag of airfoils having the profiles similar to the cross-sections of birds' wings. He then built his gliders using his best airfoil shape (i.e. that one having the highest lift/drag ratio). That was a sensible beginning, but the most difficult problems were associated with the configuration of the aircraft. Lilienthal adopted the geometry invented by Cayley. It was a good choice, and he made essentially no improvements. His chief contributions were the idea of control by shifting the pilot's weight; and, far more influential, the principle that to construct a successful airplane, the inventor must also learn how to fly. Although he must have given some thought to the matter, Lilienthal never offered an analysis of the mechanics of flight. He apparently never tried to attack the problems of lateral control and turning.

With his book *Progress in Flying Machines*, Chanute intended to provide a technical basis for constructing a man-carrying aircraft. Yet the best parts of his writings are descriptive, summarizing the history of the subject. Even with his background in engineering, Chanute did not even pose the basic problems which had to be solved. One reason is that as a 19th century civil engineer, Chanute had not been well-educated in physics and mathematics.

Samuel P. Langley (1834–1906) tried to follow a more fundamental strategy. Beginning in the 1880's while he was Director of the Allegheny Observatory, he set out to discover the "principles of flight" by conducting a series of tests to measure aerodynamic characteristics.(11) Unfortunately, he resolved to learn all he could about the performance of one airfoil section, and he chose the worst possible case to study: a flat plate. For all his effort and expense, Langley obtained only one useful correct result, the drag of a plate oriented normal to the stream. His experiments contributed nothing to aeronautics, including his own program.

For ten years while he was Secretary of the Smithsonian Institution, Langley spent $50,000 given to him by the U.S. Army, and at least $20,000 of his own discretionary funds, on his aeronautical work. He tested powered models, commissioned the design and construction of a light internal combustion engine, and finally attempted twice to fly a full-scale aircraft carrying a man.(12) Both trials were highly publicized failures in the fall of 1903. Langley's results convinced government officals everywhere that public funds must not be wasted on schemes to invent airplanes.

Langley's plans may seem to have been systematic, but there were serious gaps. The major reason that he did not succeed with his full-sized airplane was his failure to apply Lilienthal's principle. His assistant and intended pilot, Charles Manly, had no opportunity to learn how to fly in gliders before testing the powered airplane. Langley the physicist didn't appreciate the difference between experimenting to solve a well-defined but narrow problem, and the extended research and development program required to produce a practical engineering system. Somewhat surprisingly, he also did not try to analyze the mechanics of flight except for superficial consideration of equilibrium. He did not progress beyond the results of Cayley and Pénaud. Like Lilienthal, he never considered lateral control and evidently thought his airplane could be turned by manipulating the vertical tail.

Prior to the twentieth century, only the Englishman Frederick Lanchester (1878–1946) studied flight mechanics. Motivated by his observations of model airplane tests, Lanchester worked out many fundamental results, including the essential basis for early wing theory. His work was unknown until his two books(12) appeared in 1907 and 1908 and so had no impact on the invention of the airplane. Even had he published his results, they would have had limited value for someone concerned with the practical problems of building the first flying machine. During his early work, Lanchester too was concerned only with pitching motions.

Thus at the turn of the century, there was almost no theoretical basis for designing an airplane. The issue was not merely that known problems were unsolved; rather, the greatest difficulty was that several crucial problems had not even been posed: the right questions had not been asked. In that respect, the successful Wrights' program and the halting efforts of the French in the period 1898–1908 present startling contrasts. Particularly the disappointing experiences of Ferber and others in France emphasize the obstacles to solving the problem of mechanical flight.

A hundred years earlier, Cayley had divided the problem into two parts: propulsion and aerodynamics. During the last quarter of the nineteenth century, the invention of the four-stroke cycle internal combustion engine finally gave a superb powerplant. The weight to power ratio was reduced from 4000 pounds per horsepower for the steam engine in 1875, to 4 for the best internal combustion engine available in the early 1900's. Improvements in propellers completed the system required to propel an aircraft.

But before the inventors could take advantage of the new engines they had to discover what shape the aircraft should have. Details of the structure posed no serious difficulties: techniques adapted from ship-building, bridge-making and kite construction served perfectly well for early aircraft. The essential problem was the geometry of the airplane.

Not only did Cayley recognize that the problem of propulsion must be considered separately from the matter of producing lift. He also knew the geometry of the fixed wing aircraft in essentially the form now familiar: for that discovery he has been properly called "the inventor of the airplane." Why then did a hundred years pass before a successful man-carrying airplane was flown? Why was the complete solution to the problem of mechanical flight so difficult to find? The answers require some understanding of basic aerodynamics and dynamics of flight.

An airplane is really a collection of surfaces so arranged that in forward motion sufficient lift is generated to support the weight of the structure and useful load. An engine is required as the source of thrust to overcome the drag forces opposing the motion. For a glider following a downward inclined flight path, like a ball rolling down a hill, gravity provides the thrust required. We can therefore examine the aerodynamics of the airplane or glider without concern for the means of propulsion. In other words, we can suppose that the drag is exactly compensated and simply consider an aircraft in steady flight supported by the lift force.

Most of the lift comes from the wing and effectively acts vertically at some point called the center of pressure or center of lift. If the craft is not to pitch up or down, the center of lift must coincide with the center of gravity. Otherwise, the lift force acts with a lever arm about the center of gravity and exerts a torque or moment tending to rotate the aircraft. That fundamental condition for a state of equilibrium was understood by Cayley and all who followed him. Most airplanes are symmetric about a central vertical plane: the left side is the mirror image of the right side. The center of gravity and the center of lift both lie in the plane of symmetry. Thus if perfect symmetry is maintained, there will be no tendency in steady flight for the aircraft to roll about its longitudinal axis and the wings will remain level.

If the structure does not change shape in flight, and there is no movement of any of its parts, the center of gravity remains in a fixed position. Hence, a condition of steady flight in equilibrium is conceivable if the wing and other surfaces are so placed as to cause the net lift force to act precisely at the center of gravity. That is a delicate state due to the behavior of the force acting on a surface in motion.

Cayley already knew most of the fundamental results for the forces exerted on a moving object, partly from earlier experiments by others and partly from his own work. The force exerted on a plate in a fluid stream is proportional to the density of the fluid; it increases with the square of the velocity (twice the speed produces four times the force); it increases as the angle between the plate and the stream (the angle of attack) increases; and it is proportional to the area of the plate. Moreover, Cayley was the first to learn experimentally that a curved plate is more efficient than a flat plate — it will generate more lift with less drag under wide conditions useful for flight.

The variation of the lift force with angle of attack is qualitatively independent of the airfoil shape. From zero, it increases almost linearly until it reaches a maximum at some angle typically in the range $15 - 25^\circ$. This phenomenon, called stalling, occurs because the flow does not adhere smoothly to the airfoil. That a surface stalls was a known phenomenon, but was not well-understood by Lilienthal and his immediate followers.

More complicated, and not understood by Cayley, is the behavior of the center of lift. The center of lift is difficult to measure and, unfortunately for anyone trying to build an aircraft, moves fore-and-aft as the angle of attack of the surface changes. This occurs because, except for quite special shapes, an airfoil immersed in a stream generates not only a lift force but also an aerodynamic moment: even if the angle of attack assumes the value for which the lift vanishes, the moment is non-zero and tends to rotate the nose of the airfoil downward. This means that when the lift is nearly zero, the center of lift must be effectively far downsteam of the airfoil, so the small force acting upward with a long moment arm will produce the necessary finite moment. When the angle of attack, and therefore the lift, is increased, the center of lift moves forward. This forward movement continues as the angle of attack is increased until the stalled condition is reached. The center of lift reaches a maximum foward position and then moves aft as the angle of attack is increased further. That peculiar and unexpected behavior was discovered first by the Wrights during their gliding tests of 1901.

The early aircraft designers were aware that the center of lift may shift during flight, but they understood neither the details, nor the important fact that the behavior is sensitive to the shape of the airfoil. Obviously, if equilibrium requires that the center of lift and center of gravity must coincide, then some means of control must be found to maintain equilibrium in the face of changing flight conditions. There are two choices: either adjust the center of gravity, or incorporate an aerodynamic method for forcing the center of lift to remain at a fixed location. Lilienthal chose the former: he suspended himself from the structure and was able to move his body relative to his glider, so he could actively shift the center of gravity of the combined pilot/airplane during flight. The Wrights took the revolutionary step of installing a surface that the pilot could move at will, thereby controlling the movement of the center of lift of the aircraft.

Throughout early aeronautics there was confusion between the ideas of equilibrium and stability. Both Lilienthal and the Wrights were trying to maintain equilibrium during flight by providing the pilot with a means of control; stability was a secondary issue, particularly for the Wrights. But Cayley had long before shown that a glider could be constructed to fly by itself, and Pénaud had successfully flown a powered model for flights of many seconds. Those devices were surely subject to disturbances during their flights and hence must somehow have been able to compensate automatically in such a fashion as to assure coincidence of the center of lift and the center of gravity.

To understand the idea of stability and how equilibrium is maintained, suppose first that a small wing is launched on an intended glide: it tumbles and falls spinning about its long axis. That distressing result is due to the fact mentioned earlier that the surface developes not only lift but also a pitching moment. It is impossible to make a wing alone glide smoothly unless the moment is zero. Flying wings do exist, but the airfoil must be shaped with a reflexed trailing edge, a property discovered in 1906 by a Canadian physicist, W. R. Turnbull.(14) However, Cayley, Pénaud, Lilienthal and all others trying to build early aircraft used airfoils formed roughly as they interpreted birds' wings. A horizontal tail is then essential. If the tail is set at the proper angle, the center of lift of the combined wing and tail will coincide with the center of gravity. There is therefore no resultant aerodynamic moment, and the configuration may glide in equilibrium.

But what happens if there is a disturbance? For example, if the glider encounters an upward gust of wind, the wing suddenly experiences an increase in angle of attack, its lift increases and worse, its center of lift moves forward. To restore equilibrium, the lift on the tail and its center of lift must respond in just the right way to cancel the incremental change of moment due to the wing. It was the remarkable perception of both Cayley and Pénaud that a horizontal tail will do just that. Automatic restoration of equilibrium is called stability. Pénaud gave a partial explanation of this mechanism and published his results in 1872.(6) His conclusions were well-known in the aeronautical communities in all countries.

Thus a Pénaud tail can provide both equilibrium and stability. Lilienthal built his gliders with aft tails and they were probably capable of stable flight without a pilot. However, he introduced the further notion of control by the pilot swinging his body, so the combination of glider and pilot was stable even under circumstances when the glider alone might be unstable. His means of control was so limited that his machines had to be stable, or very nearly so. Shifting his weight was chiefly a means of combating disturbances in unsteady winds.

The Wrights' system of using a moveable control surface allowed their aircraft to be unstable alone. Indeed, all their early aircraft were seriously unstable and could be operated only by skilled pilots. Mainly because of their experience with bicycles, the Wrights were comfortable with a machine which was always unstable — so long as they had enough control. Consequently they were also not driven to use the aft tail just because it was accepted practice. They put the tail in front — the canard — because their two immediate predecessors, Lilienthal and Pilcher, had both been killed flying gliders with aft tails. They believed that they could have more effective control with their canard, and besides they could see what the surface was doing in flight. That their aircraft were unstable was not a necessary consequence of their geometrical configurations. Neither they nor any of their contemporaries truly understood the notion of stability. An aircraft with a canard can be made stable if the center of gravity is properly positioned; the Wrights were unaware of that property.

Just as for pitching motions, we must distinguish equilibrium, stability, and control of lateral motions. The term lateral motions refers both to rolling — the wing rotates about the direction of forward motion — and to yawing, in which the nose swings right and left. Stability of yawing motions, or directional stability, is provided by a vertical aft tail. The idea is simple: the vertical tail on an airplane acts in exactly the same way as the feathers on an arrow cause its flight to be straight. If the arrow should swing to the right or left, the feathers are then oriented at an angle to the direction of motion. Thus a small force is generated in just the right direction to rotate the arrow so it points in the intended direction. On an airplane, a portion of the vertical tail is made moveable so the pilot can have control over yawing motions. It is important to realize that the vertical tail is not properly used to *steer* an airplane. To turn an airplane, the pilot first causes it to *roll*, so one wing tip is lower than the other, a maneuver which the Wrights discovered. That was crucial to their invention.

Turning an airplane is analogous to swinging an object in a circular path at the end of a string. A force exerted inward by the string is required to prevent the object from flying off in a direction tangential to the intended path. Similarly, an aerodynamic force must act on an aircraft to maintain a turn. The necessary force is quite large and is best obtained by tilting the vertical lift force so that a portion acts in the direction of the desired turn. Because the lift is perpendicular to the wing, the wing itself must be tilted, or banked. To initiate a turn, the pilot therefore operates the ailerons, or wing warp, so as to roll the airplane into the suitable bank angle. It is true that with the addition of special control surfaces, sufficient side force can be generated to turn an aircraft without rolling. A disadvantage is that this kind of maneuver is also accompanied by a sideways acceleration, very uncomfortable for occupants of the vehicle, so almost all airplanes are turned by banking.

Equilibrium and stability are as important for rolling as for pitching but easier to achieve. During steady flight with wings level, an aircraft having a plane of symmetry is in a condition of equilibrium in roll. That stability in roll is so simply accomplished is likely a major reason that the need for control of rolling motions was overlooked by all aviation pioneers prior to the Wrights. Cayley discovered that if the wing is made with a slight dihedral angle, so its tips are higher than the center section, small disturbances will be compensated automatically and the surface will be stable. One way to see this is to form a shallow cone out of paper. Dropped with the point down, the cone falls smoothly. But if the cone is dropped with the point up, it will quickly tumble and assume the stable orientation. With care, one may draw the same conclusion from tests with a strip of paper folded in the center to form a dihedral angle: if it is released with the point of the vee downward, it tends to fall more smoothly than in the inverted position.

The preceding remarks explain why uncontrolled model airplanes — which must have automatic stability — have their familiar geometry. A horizontal tail is located some distance forward or aft of the wing, for pitch equilibrium and stability. The vertical aft tail provides directional stability; and the dihedral angle of the wing gives stability in roll. Satisfactory glides can be obtained with a device having this geometry, providing the center of gravity is correctly placed. Tests with a glider usually show that best performance is obtained if a bit of weight is added to the nose of the glider. The reason is that stability is improved when the center of gravity is moved forward. That property of all aircraft is more difficult to understand and was a continual source of problems with early aircraft which were commonly unstable, even to the point of being dangerous.

By trial and error the Wrights found that their aircraft became less unstable if the center of gravity was shifted forward, but they did not know the theoretical reason. Coincidentally, a few months before the Wrights' flights in 1903, the first complete analysis of pitch stability was published(15) by G. W. Bryan, a Professor of Mathematics at the University College of North Wales, and his student W. E. Williams. He showed how gliders with either aft tails or canards could be made stable. Bryan's work was unknown to the Wrights and to all other constructors of aircraft for several years, and only gradually influenced aircraft design. In 1911 Bryan produced a small volume(16) *Stability in Aviation* that founded the theory of aircraft stability in essentially its present form.

Cayley had found the correct geometry of an aircraft, but he did not thoroughly understand the physical basis. Among his small number of followers, only Pénaud made significant progress; even he did not appreciate the further advances required to build a successful man-carrying airplane. Not until the early years of the 20th century were the missing ideas supplied, primarily by the Wrights. The chief reason that the solution to the problem of mechanical flight was so difficult to find is that an aircraft moves in three dimensions. Its motions involve not only translations horizontally, vertically and sideways, but also rotations about the three axes of pitch, roll, and yaw. With only aerodynamic forces available to compensate the pull of gravity, the problems of equilibrium, stability and control are vastly more complicated for aircraft than for vehicles moving on the earth's surface.

Today we have a complete theory of aircraft flight. In the 19th century, not only was information about aerodynamics sparse, but there was no theoretical framework for understanding the mechanics and dynamics of aircraft. The fundamental physical theory — Newtonian mechanics — of course existed, but until Bryan began his work, no one had made even the most elementary attempt to analyze the motions of an aircraft in pitch. Pénaud's explanation of the aft horizontal tail was correct but qualitative and did not suggest the general nature of stability.

Consequently, the aircraft inventors, who generally lacked backgrounds in physics and mathematics, progressed by trial and error. Success then depended entirely on their own tests, observations, reasoning and insight. It's a tedious procedure. Ferber and the French aviators discovered that failure is the more likely result.