THE TURN

by WILLIAM LANGEWIESCHE

At the very heart of winged flight lies the banked turn, a procedure that by now seems so routine and familiar that airline passengers appreciate neither its elegance and mystery nor its dangerously delusive character. The author, a pilot, takes us up into the subject

PEOPLE who distrust the sensations of flight, who balk when an airplane banks and turns, are on to something big. I was reminded of this recently while riding in the back of a United Boeing 737 that was departing from San Francisco. Directly over the Golden Gate we rolled suddenly into a steep turn, dropping the left wing so far below the horizon that it appeared to pivot around the bridge's nearest tower. For a moment we exceeded the airline maximum of a thirty-degree bank, which is aerodynamically unimportant but is imposed for passengers' peace of mind. Sightseeing seemed more important now. Our pilots may have thought we would enjoy a dramatic view of the famous bridge and the city beyond. But as the airplane turned, startled passengers looked away from the windows. A collective gasp rippled through the cabin.

The reaction did not surprise me: as an instructor of beginning pilots, I've heard gasps and worse from my students. Pilots are merely trained passengers. They have to be told not to flinch, whimper, or make audible appeals to the Savior. They have to be encouraged to ride the airplane willingly, as they

Illustrations by Guy Billout

would a horse, to think as it thinks. And they have to be persuaded of the strange logic of the turn. At its core lies the relationship between banking and the resulting flight path, and the fact, difficult at first to accept, that neither can be felt.

Most people—certainly the ones who were sitting next to me over San Francisco—would insist that they can indeed feel the bank. We have all had the experience while reading or dozing on an airliner of feeling a lurch and looking up to see, as expected, that the airplane is tilted. The lurch comes when the airplane dips or raises a wing, starting into a turn or starting out of one. Sometimes we can even give a direction to the bank. But if we then close our eyes, we have no way of telling that we are sitting at an angle. I know from experience how difficult it is to convince people of this. When the bank is visible—for instance, on a clear day—the tilted horizon looks so unusual that the view overpowers other perceptions. But during flight on black nights, or in clouds, the bank is imperceptible, and passengers are heedless. They may feel the odd lurch, but they have no way of guessing the airplane's degree of bank. The inner ear, and with it the sense of balance, is neutralized by the motion of flight. The airplane could be momentarily upside down and passengers would not know.

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Of course, none of this matters unless you are the pilot. But historically pilots have made the same mistakes as passengers. Having been given the airplane, they had to learn to use it. Generations were required. Eventually they admitted that instinct was unreliable in clouds, and that they needed special instruments to tell them what was happening to the plane. Without the instruments they went into mysterious banks and dived out of control. Thus was born the most basic distinction in flying, between conditions in which the turn is visible and conditions in which it must be measured. The ability to fly through weather and in darkness is more important than speed in the conquest of distance. The mastery of the turn is the story of how aviation became practical as a means of transportation. It is the story of how the world became small.

SOME definitions are in order. The bank is a condition of tilted wings, and the turn is the change in direction that results. The connection between the two is inexorable: the airplane must bank to turn, and when it is banked, it must turn. The reason is simple. In flight with level wings the lifting force of the wings is directed straight up, and the airplane does not turn; in a bank the lifting force is tilted to the side, and the airplane therefore must move to that side. It cannot slide sideways through the air, because it has a vertical fin on the tail, which forces the turn by keeping the tail in line behind the nose. The result is an elegantly curved flight path, created as the airplane lifts itself through the changes in direction.

The turn, however, comes at a price. As the bank steepens, the airplane has greater difficulty holding its altitude. Flown at bank angles approaching ninety degrees—in which the wings point straight up and down—a normal airplane cannot keep from descending. In such "knife-edge" flight the force that once lifted the wings in a direction perpendicular to the earth's surface is now directed parallel to it, and gravity pulls the airplane down. However, if the pilot controls the airplane carefully and allows it to keep turning, it will happily roll past the vertical, onto its back, and finally right side up again. During such a maneuver San Francisco Bay would momentarily appear above you, and the Golden Gate Bridge would seem to hang from the water. This is fine if you are prepared for it. Full rolls are the purest expression of flight. They are normally flown only in fighters and other acrobatic airplanes, but if you ignore convention, you can fly them in any airplane, including a Boeing 737.

None of this would have comforted the man sitting next to me during that steep turn over the Golden Gate. He was large, sharp-eyed, and alert. When the wing dropped, he said, "Hey!" and grabbed the armrests. Now he rode "above" me in the bank, leaning into the aisle as if he feared toppling into my lap. He need not have worried. If he had dropped his pen, it would have fallen not "down" in the conventional sense—toward me and the earth—but rather toward the tilted carpet at his feet. If he had dangled the pen from a string, it would have hung at a ninety-degree angle with respect to the tilted floor.

A dangled pen is a primitive inclinometer, like a plumb bob or the heel indicator on a sailboat. On land or at sea it will hang toward the center of the planet. But in flight it will hang toward the floor, no matter how steeply the airplane is banked. A carpenter's level would be equally fooled. This peculiar phenomenon is a manifestation of the turn's inherent balance. The earth's gravity acts on an airplane, and of course on objects in an airplane, but so do the forces of inertia, the desire of any mass to keep doing what it has been doing. The neatness of this Newtonian package is beautiful to behold. Bob Hoover, a stunt pilot, mounted a video camera in his cockpit, set an empty glass on the instrument panel, and poured himself a soft drink while flying full rolls. Our United pilots seemed inclined to fly the same way. If they had done so, as we passed inverted above the Golden Gate Bridge and saw it hanging from the water, my sharp-eyed neighbor could have watched his pen dangling toward the sky. During the roll the flight attendants could have walked upside down. And some passengers, too busy to look outside, wouldn't even have noticed.

The human body is another inclinometer. Undisturbed by the view, it sits quietly, dangling toward the tilted floor, churning out memos for the home office. The man next to me was not about to fall into my lap. He could have relaxed, lowered the tray in front of him, and called for a coffee. Unlike a table on a sailboat, an airplane tray requires no gimbals. Flight attendants do not develop sea legs. They brew coffee on a fixed counter, deliver it without worrying about the bank angle, and fill cups to their brims. Full cups make people behave during turns: if they try to hold them level with the earth, the coffee pours out and scalds their thighs. If this is hard to believe, imagine the alternative—an airplane in which "down" was always toward the ground. Bedlam would break loose in the cabin during turns.

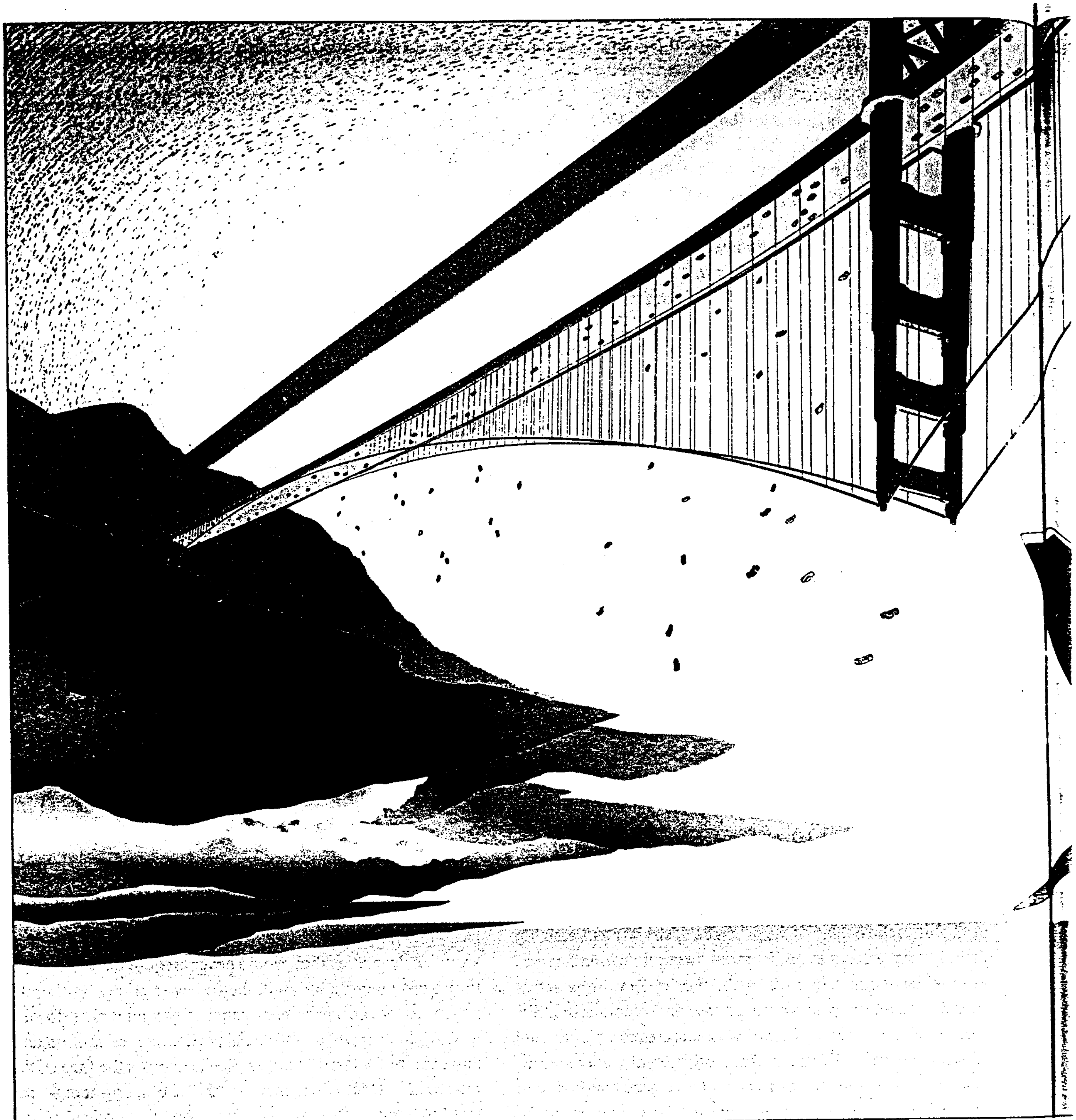
As long as its wings are level, an airplane is well mannered and slow to anger. If you pull its nose up and then release the controls, it puts its nose back down; if you push it down, it answers by rearing up. Like horseback riding, flying consists mostly of leaving the beast alone. The problem is that this particular beast does not stay on the trail unguided, and once it strays, it develops a strong impulse to self-destruct.

Unguided, any airplane will eventually begin to bank. That by itself would be fine if you didn't mind the resulting turn. But as the bank tilts the lift force of the wings, reducing their vertical effectiveness, it erodes the equilibrium that previously countered the pull of the earth. The airplane responds to the loss by lowering its nose and accelerating. Sitting in the cockpit with folded arms and watching it proceed is like letting a temperamental horse gallop down a steepening slope: it requires steady nerves and a morbid curiosity. In flight the slope steepens because the acceleration tightens the airplane's turn, which increases its bank angle, which causes further acceleration. Sooner or later a sort of aerodynamic lock-in occurs. The airplane banks to vertical or beyond, and points its nose straight down.

That's the spiral dive. In its most lethal forms it is called the graveyard spiral. The airplane flies in ever-steeper circles and either disintegrates from excessive speed or hits the ground in a screaming descent. Most flights would suffer this end if the pilot (or autopilot) did not intervene. In good weather the intervention is easy. When you see that the airplane has banked, you unbank it. During turns you hold the controls more firmly, and keep the nose from dropping.

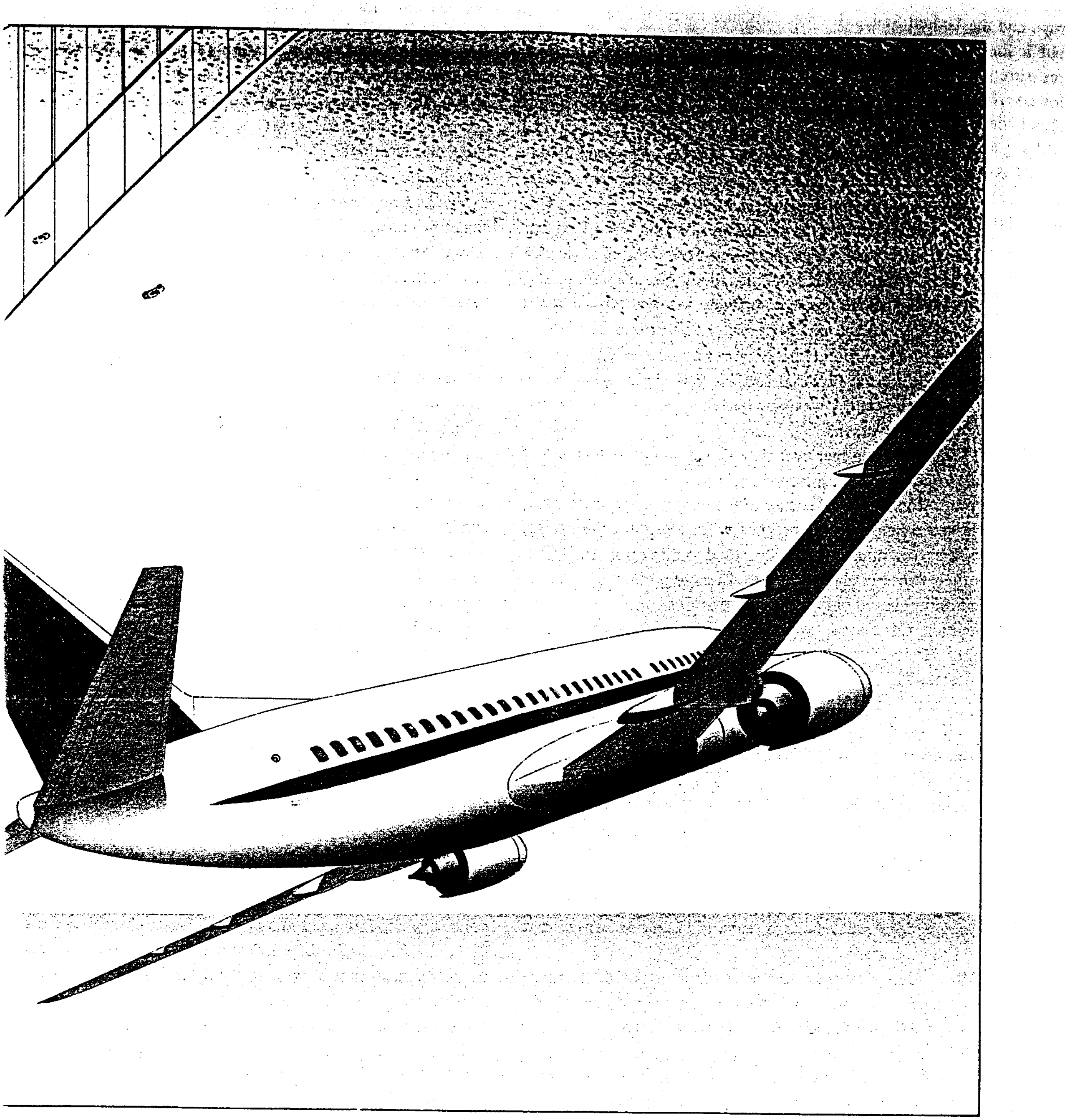
The increased loading caused by inertia during a well-flown turn is felt within the cabin as a peculiar heaviness. Pilots measure it in "Gs," as a multiple of gravity's normal pull. An airplane that banks to thirty degrees creates a loading of 1.15 Gs: the airplane, and everything in it, temporarily weighs 15 percent more than normal. Fifteen percent is hardly noticeable. But when the bank grows only a bit steeper, to forty-five degrees, the load increases to 1.4 Gs: people feel pressed into their seats, and they might notice that the wings have flexed upward. Technically it is not important. Airplanes are strong. Pilots shrug off two Gs, and may feel comfortable at twice as much. But passengers are unaccustomed to the sensation. As we pivoted over the Golden Gate, I estimated that my neighbor had gained about eighty pounds. Had he dangled his pen toward the tilted floor, it would have pulled on the string with surprising force. This might not have reassured him. But the extra heaviness is a measure of the pilot's success in resisting the spiral dive. If we had felt "normal" during the turn, it could only have meant that the nose was dropping fast toward the water.

No pilot would make such a mistake on a clear day. The view from the cockpit is dominated by the horizon, the constantly renewing division between the sky and the earth. It forms a line across the windshield, and makes immediate sense of the airplane's movements. In clouds or on black nights, when they cannot see outside, pilots keep their wings level by watching an artificial horizon on the instrument panel. The artificial horizon is a gyroscopically steadied line, which stays level with the earth's surface. The airplane pitches and banks in relation to this steady line, which in spatial terms never moves. Of course, in *airplane* terms it does move—which presents a problem, because pilots are part of the airplane: they fly it from within, strapped to their seats. In clear skies they would never misjudge a bank as the tilting of the earth, but with their view restricted to the abstractions of the instrument panel they sometimes do just that: when the airplane banks, they perceive the motion as a movement of the artificial horizon line across the face of the instrument. This causes them to "fly" the wrong thing—the moving horizon line, rather than the fixed symbolic airplane. For example, as turbulence tilts the airplane to the left, the pilots, tilting with it, notice the artificial horizon line dropping to the right. Reacting instinctively to the indication of motion, they sometimes try to raise the line as if it were a wing. The result of such a reversal in such cases is murderous. Pilots steer to the left just when they should steer to the right, and then in confusion they steer harder. While cruising calmly inside clouds, I have had student pilots suddenly try to flip the airplane upside down. These were perfectly rational people, confronted by the turn.



AIRPLANES did not shrink the world overnight. The Wrights flew straight and level at Kitty Hawk in December of 1903, and nobody paid much attention. They went home to Dayton, rented a cow pasture, and spent the following year stretching their flights and learning to turn. The first detailed account of their flights appeared in *Gleanings in Bee Culture*, a journal for beekeepers published in nearby Medina. The editor, A. I. Root, traveled to the pasture and on September 20, 1904, saw Wilbur fly the first full circle. Bees, of course, are the great specialists in full-circle flying; they spend their days on round-trip missions, and construct whole worlds out of their ability to turn. I do not know if Root was influenced by these thoughts, but he understood the significance of the Wrights' achievement. The U.S. Army was slower to catch on. Five years later, after much persuading by the Wrights, it reluctantly took delivery of its first airplane. In 1909 horses still seemed more glorious.

The war in Europe changed that. Unsullied by the carnage



in the trenches, pilots chased across the sky, turning hard on each other's tails. The war taught them to fly with confidence, and encouraged the myth of instinct. Those who survived made the dangerous discovery that they could feel at home in the sky. They learned to accept the strangeness of a steep bank—the G load and the tilted horizon—and the magic of a full roll. Nonetheless, they still believed in instinctive balance: when they ducked through small clouds and emerged with their wings slightly tilted, they did not appreciate the significance of this small clue—did not suspect the importance of the unfelt bank. Although scientific thinkers on both sides of the Atlantic had, by the end of the war, come to understand the intricacies of the banked turn, pilots, trapped by vanity, paid little heed. And because pilots at the time rarely flew in bad weather or on black nights, they did not expose themselves to the conditions that would have fostered deeper insight.

At the end of the war regular airmail service started in Europe and the United States. It made airplanes useful to the public for the first time, gave birth to the airlines, and placed pressure on the pilots to operate on schedules. They followed rivers and railroads in open-cockpit biplanes, flying under the weather, sometimes at extremely low altitude, dodging steeples and oil derricks. Many pilots were killed.

In December of 1925 a young Army pilot named Carl Crane got caught in the clouds at 8,000 feet directly over Detroit while trying to fly a congressman's son to Washington, D.C., in a biplane. Crane later became a famous master of the turn. Recalling this particular flight, he said, "In a short time I was losing altitude, completely out of control. I could not fly the airplane at all—it had gotten into a spiral dive. Halfway down I looked around at my boy in the back, and he was enjoying the flight no end. He was shaking his hands and grinning, and I was slowly dying because I knew we were going to crash."

The boy in the rear cockpit was just unaware. Crane had an altimeter and an airspeed indicator. He thought he was dying "slowly" only because of the way experience is compressed when an airplane goes wild. People's minds can work extraordinarily fast. Pilots tend to think not about God or their lives but about solutions. Crane searched his training and remembered only vague admonitions to stay out of bad weather. Of course, he was in it now, and couldn't see a thing. He knew he was turning but could make no sense of the compass. It is a notorious problem: because the earth's magnetic field does not lie parallel to the globe's surface but dips down toward the magnetic poles, the compass responds to banks by spinning erratically, jamming, and sometimes showing turns in reverse. Crane did not know which wing was down, let alone by how much. If he tried to level the wings, he was just as likely to roll upside down as right side up. If he tried to raise the nose, the effect would be exactly the opposite: the turn would quicken, steepening the descent. For a pilot these are the central issues of the spiral dive. Crane understood none of it at the time, but he sensed that his situation was hopeless.

In modern times air-traffic control recorded the radio transmissions of an unskilled pilot who, with his family on board, tried to descend through overcast. After he lost control, he began to sob into the microphone, begging the radar controllers to tell him which side was up. But radar shows air traffic as wingless blips on a map, and is incapable of distinguishing banks. Controllers are in the business of keeping airplanes from colliding. Pilots are in the business of flight control. This one had instruments on board by which he could have kept his wings level, but in the milkiness of the clouds he became confused. The controllers listened helplessly to his panic and, in the background, to the screams of his children. The transmissions ended when the airplane broke apart.

Crane's biplane was stronger. "Finally it got down to under a thousand feet, and I said, 'Well, here we go. I'm going to look at my boy once more.' And as I turned around to look at him, a sign went by my wing. It said 'Statler Hotel.' I had just missed the top of the Statler Hotel. In all the mist and rain, I could see the buildings and the streets. I flew down the street and got over the Detroit River, and flew about ten feet high all the way to Toledo, shaking all the way."

Shocked by the way intuition had abandoned him, Crane began to ask questions. For years he got no intelligent answers. Veterans of the military and the airmail service still insisted they could fly "by the seat of the pants," and they thought less of those who could not. Their self-deception now seems all the more profound because the solution to the problem of flying in clouds and darkness—a gyroscope adapted to flying—was already widely available.

THE gyroscope is a spinning wheel, like a child's top, mounted in gimbals that allow it freedom of movement. It has two important traits: left alone, it maintains a fixed orientation in space (in relation to the stars); and when tilted, it reacts in an odd but predictable way. Elmer Sperry, the great American inventor, started playing with these traits in the early 1900s. As a curiosity, he designed a gyrostabilized "trained wheelbarrow," and he tried, without success, to interest a circus in it. Undiscouraged, Sperry turned to the U.S. Navy instead, and interested it in gyro-compasses and ship stabilizers. Competitors in Europe developed similar devices, and during the buildup to war interested their countries' navies, too.

Airplanes were an intriguing sideline. Sperry built a gyroscopic autopilot in 1910, not to enable blind flight but to stabilize the otherwise unruly early flying machines. In 1915 he began to ponder instrumentation, and with prescient insight into the problems of flight was able after three years to produce the first gyroscopic turn indicator, an instrument still in use today. Its face consisted of a vertical pointer, which indicated turns to the left or right. (Necessarily, it also included a ball like the one in a carpenter's level, an inclinometer that showed not bank but "skid" or "slip"—conditions of imbalance.) Sperry called the instrument a "crutch for the compass." In his patent application he described it as an instrument that would allow pilots to fly indefinitely through clouds, implying that without it they could not.

One of the earliest cloud flights with a turn indicator was made by William Ocker, an Army pilot, in 1918. Though he, too, spiraled out of overcast, he concluded correctly that his mistake had been to favor sensation over the instrument's indications. During the 1920s a few Post Office pilots began to fly by instruments. When Charles Lindbergh crossed the Atlantic, in 1927, a turn indicator kept him from spiraling into the sea when he met fog. Two years later Jimmy Doolittle made a "blind" landing, after flying a complete circuit around an airport in a special biplane modified with a domed cockpit from which he could not see outside. The landing itself was a technical dead end. Once Doolittle was over the field, he reduced the power and waited until the biplane plunked into the grass—a technique that would not be practical for the airlines. More significant were the special devices that made the precisely flown circuit possible. The airplane was equipped with navigational radios, an airspeed indicator, an improved altimeter, a turn indicator, and two new gyroscopic instruments from Elmer Sperry—a gyroscopic compass and an artificial horizon. This combination was so effective that it still forms the core of instrument panels today. Doolittle compared the artificial horizon to cutting a porthole through the fog to look at the real horizon. Devising technology was the easy part. The more stubborn problem of belief remained. As late as 1930 one of the airlines wrote to Sperry complaining about a mysterious problem: the instruments worked fine in clear air, but as soon as they were taken into clouds, they began to indicate turns.

Still worried about his near collision with the Statler Hotel, Carl Crane read with fascination the descriptions of Doolittle's flight. He was now, in 1929, an Army instructor at a training base in Texas. Though his superior officers disapproved of instrument flying, Crane was convinced of the need for gyroscopes. He finally got permission to cover over a cockpit and turn one of the biplanes into an instrument trainer. While he was at work on this, William Ocker wandered into the hangar. Ocker didn't look like much of a pilot, with his bifocals and his mournful, puritan face, but he had a powerful mind and the restless soul of a missionary. The truth about instrument flying had come to him in 1926, during a routine medical examination in San Francisco. To demonstrate that the senses could be fooled, a doctor had asked Ocker to close his eyes while being spun in a chair. Ocker felt the chair begin to turn, and guessed the direction correctly—but when the chair slowed, he felt it had stopped, and when the chair stopped, he felt it was now turning in the opposite direction. For the doctor, it was a trick on the inner ear, an amusing exercise in vertigo. For Ocker, it was a stunning revelation: the sense of accelerating into a turn is the same as that of decelerating from the opposite turn. The chair induced the same false sensations that led pilots to mistrust their turn indicators. Even those who accepted their inability to feel the bank were losing control. Ocker now knew why. He had found here in the spinning chair the proof that instinct is *worse* than useless in the clouds.

Ocker became so obsessed with the spinning chair that he was hospitalized twice for sanity tests and later banished by the Army to Texas. His preaching had become tiresome. Nonetheless, he had discovered the most disturbing limitation of human flight—the feelings that cause people to sway dizzily from wings-level flight into spiral dives. Having gyroscopes is not enough. Pilots must learn to believe them, even though their bodies may have invented phantom turns. And fiction can be compelling. I have seen students break into a sweat in the effort not to submit.

Ocker and Crane began a systematic exploration of flying inside clouds. In 1932 they published *Blind Flight in Theory and Practice*, the first clear analysis of instrument flying. The book had an enormous influence. The authors tried to lay to rest the old faith in flying by instinct. They described the physics of the turn and the confusion experienced by the inner ear, but their most dramatic argument grew out of an experiment with pigeons. From everything pilots had learned, it seemed evident that birds, too, must be unable to fly without a visible horizon. Ocker and Crane blindfolded pigeons, took them up in biplanes, and threw them out. Sure enough, the birds dropped into fluttering emergency descents—they panicked and went down like feathered parachutes. It is possible, of course, that they did not like the blindfolds, which were made of Bull Durham tobacco pouches. But anyway, the experiment was the kind pilots understood. If God had meant birds to fly in the clouds, He would have given them gyroscopes.

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BIRDS are not the perfect flyers that you might expect. They cannot fly through heavy rain. They get sucked up by thunderstorms, frozen by altitude, and burned by lightning. They crash into obstacles, wander offshore, run out of fuel, and die by the millions. They would rather not migrate in bad weather, and usually don't. Nonetheless, it now appears that Ocker and Crane may have been wrong: there is evidence that some birds do occasionally fly inside clouds. This is big news. Word of it appeared in 1972, in the proceedings of a NASA symposium on animal navigation. Hidden among reports like "When the Beachhopper Looks at the Moon" and "Anemomenotactic Orientation in Beetles and Scorpions" (that is, "When a Bug Feels the Wind") was a paper titled "Nocturnal Bird Migration in Opaque Clouds." It was written by Donald Griffin, the Harvard zoologist who discovered the use of sonar by bats. Griffin reported that he had bought a military-surplus radar and on overcast nights in New York had tracked birds that seemed to be flying inside clouds. There were only a few, and Griffin was able to track them only for a couple of miles, but they appeared to be flying straight. Griffin's biggest problem was uncertainty over the flight conditions at the birds' altitude. Were the clouds really as thick as they looked from below? Were the birds really flying blind? Griffin had good reason to believe so, but as a scientist he had to be cautious. His final report, in 1973, reinforced the earlier findings but was more cautiously titled "Oriented Bird Migration in or Between Opaque Cloud Layers." Ornithologists still cite it from memory. To those interested in bird navigation, the difference between "in" and "between" is just a detail; the point is, the birds seemed to know their way without reference to the stars or to the ground. But to birds, whose first job is keeping their wings level and controlling their turns, the distinction might be crucial. Griffin, a former pilot, understands its importance. I recently mentioned to him my impression that some ornithologists seem stuck on the ground, and he laughed. "I keep telling them, 'Gee, birds fly!'"

Assuming they fly in the clouds, the question is how? Ornithologists have no answer, and they shy away from speculation. It is known that birds navigate by watching the ground and the positions of the sun, the moon, and the stars—none of which would help them in clouds. But they may also use a host of nonvisual clues, and may use mental "maps" based on sound, smell, air currents, variations in gravitational pull, and other factors. Experiments have shown that some species are extremely sensitive to magnetic forces. In their heads they have magnetite crystals surrounded by nerves, which may give them intuitive knowledge of their direction (and location) in the earth's magnetic field.

Another possibility is that birds have internal gyroscopes of a primitive sort. This is less farfetched than it seems: the rhythmic flapping of wings could have the effect of Foucault's pendulum, allowing a bird to sense turns without any external cue. A pendulum is more than a hanging weight—it is a hanging weight that has been pushed and is swinging freely. Swinging gives a pendulum its special ability to maintain spatial orientation. Leon Foucault was the French physicist who first used one, in 1851, to demonstrate the rotation of the earth: though the pendulum appeared to change direction as it swung, in fact the plane of its swing remained constant, and the apparent change was caused by the turning of the earth underneath it. If birds rely on the pendulum effect, they are not alone. Flies and mosquitos (along with more than 85,000 other species of Diptera) use specially adapted vibrating rods to maintain spatial orientation in flight. Not only can they turn sharply, roll upside down, and land on the underside of leaves, but they can do it in fog.

Pilots, too, have relied on pendulums. It is said that an airliner inbound to New York in the 1950s lost all its gyroscopes in heavy weather over Block Island. The captain was a wise old man who had risen with the airlines from the earliest airmail days and was approaching retirement. A lesser pilot might have fallen for the trap of intuition. But the captain simply took out his pocket watch, dangled it from its chain, and began to swing it toward the instrument panel. Flying by the pendulum and the compass, he proceeded the length of Long Island in the clouds. After breaking into the clear near the airport, he landed and wished his passengers a good day.

The story is not impossible. I had it in mind one night when I flew out over the Pacific Ocean in a small airplane. High clouds darkened the sky. The light of a fishing boat drifted close by the coast. Flying a mile above the water, I headed beyond it, into complete blackness.

Nowhere can a person find greater solitude than alone in flight. At night in clouds and over water, the cockpit becomes a world of its own, and the instrument panel another world within it. The instruments glow in a warm light, telling the strange story of the airplane's motion. Enjoying this isolation, I flew on until, behind me, the fishing boat was a distant glimmer. The gyroscopes functioned perfectly. The radios were blissfully silent. I hooked a metal pen to a fishing line and dangled it from a knob on the ceiling. Flying by the artificial horizon, I made a steep turn and watched the pen dangle toward the tilted floor. Then I straightened out, pushed the pen toward the instrument panel, and released it. It swung for almost a minute before requiring another push. Each renewal would, of course, erase the pendulum's spatial memory. Nonetheless, I thought the device might work. After turning parallel to the coast, I covered the gyroscopes with slips of paper.

The night air was smooth. The pen swung rhythmically toward the panel and back. When eventually the airplane banked and therefore turned, the swinging pen, though it continued to swing through a point perpendicular to the floor, maintained a memory of the airplane's original heading, and seemed to have redirected itself to the left. This could only mean that the airplane had banked to the right. I steered left gingerly, hoping to raise the right wing just enough to return to straight flight. The pen seemed to stabilize in its new direction. I renewed the swing, shoving the pen again directly toward the panel. It soon confirmed that the airplane had indeed leveled its wings. After the compass settled, it showed that I had turned twenty degrees to the right. Lowering the left wing cautiously, watching the pen swing to the right, I crept back to my original heading. Later, when I tried to make a large turn, I spiraled and had to peek at the gyroscopes. But with the wings level again I flew on for miles, learning to work with the swinging pen. Trust comes slowly in the indication of turns. It is a peculiar faith that makes the world so small.