The Puzzle of Flutter and Tumble

Physicists reconsider the fall of leaves

By PETER WEISS

"Glancing up through oaks
dry leaves still hanging on,
some tilt
and airy wobble down, dry settles"
—Gary Snyder, *Axe Handles*
(1983, North Point Press).

The graceful dance of a leaf's fall has long inspired physicists as well as poets.

As early as 1854, a pioneering theorist on electromagnetic radiation, James Clerk Maxwell, studied the motion of paper strips in air. Since then, scientists have sporadically tried to explain the gyrating, tumbling flights of such thin, flat objects.

There was a burst of interest in the 1950s and 1960s when the U.S. military funded some studies. After that, little happened until recently. "There has been a flurry of activity in the literature," says Lakshminarayanan Mahadevan at the Massachusetts Institute of Technology.

It's a tough problem. Falling bodies and the liquids or gases through which they fall, known as fluids, refuse to interact in a simple manner. The objects move irregularly, perhaps even randomly. The equations that have been developed to describe motions of fluids prove too complex to be solved in the case of falling leaves or even the simpler, surrogate materials used in experiments.

Despite the challenges, the puzzle has a perennial draw. "It seems like such a standard, elementary problem in physics" that physicists feel as if they should have solved it already, says Franco Nori, a theorist at the University of Michigan in Ann Arbor.

There are practical reasons to study leaves or paper falling. The aerodynamics of their drifting may hold lessons for other forms of flight, whether the maneuvers of fighter-bombers or bees. Such knowledge may also apply to sedimentation of silt and shells, the dispersal of seeds, and the separation of materials in chemical engineering.

This time around, physicists are optimistic that they are finally getting a handle on the problem's complexity.

The recent resurgence of interest has been inspired by chaos theory. The scientific concept of chaos dates from the 1960s, when scientists discovered it as a new way to understand apparently random processes. In the early 1990s, researchers interested in chaos focused on the falling-object puzzle. This triggered interest by fluid-mechanics researchers, who are revealing underlying regularity in the motion.

"We are revisiting a problem as old as the falling leaves with new eyes," Nori says.

Field/Colorado State University

A quarter launches into an unpredictable tumbling motion as it drops through a tank of water.

Chaos theory governs events that appear to be random but are nevertheless governed by strict rules. The apparent randomness arises because a slight change in the starting point can lead to a radically different outcome, making a chaotic system unpredictable in practical terms (SN: 4/29/95, p. 264).

So sensitive are most chaotic processes to those initial changes that they typically carry on in a never-repeating pattern.

Scientists have long noted an element of randomness in the fall of objects in a fluid. In his *Principia*, published in 1687, Isaac Newton mentions experiments by a Dr. Desaguliers, who formed hogs' bladders into "spherical orbs" and dropped them from the cupola of St. Paul's Cathedral in London. "The bladders did not always fall straight down, but fluttered a little in the air, and waved to and fro as they were descending," Newton reported.

Scientists came to regard the unpredictability of falling objects' paths as a consequence of the complex interplay between the object and the disorderly, often turbulent motions of the fluid. By the late 1980s, theorists in the then–Soviet Union began to suggest that chaos might play a role.

To test that notion, Hassan Aref and Scott W. Jones of the University of Illinois at Urbana-Champaign conducted a theoretical study, published in the December 1993 Physics of Fluids A. Their evidence indicated, for the first time, that a body moving through a fluid could have chaotic motion. The researchers used computers to solve the equations of motion of an egg-shaped body navigating through a hypothetical ideal fluid that couldn't cling to the egg or force it to rotate. Aref says the research relates also to objects such as leaves or paper, which can be considered extreme examples of flattened ellipsoids. "So, it's not that far away," he says.

Aref takes special interest in the possibility of making aircraft or submersibles that could purposely go into chaotic motion to become more maneuverable. The jerky motions of chaos could allow extraordinarily sharp turns if they could be controlled. Studies of chaotic flights of simpler, leaflike shapes might give designers useful clues, he says.

To test whether the vehicles could also regain control, his group is developing a "smart" coin that they could command, while in the air, to come down as heads or tails. It will contain tiny actuators that, in flight, would redistribute its mass internally to control the fall, Aref says.

Perhaps some creatures in nature already exploit chaos, he speculates. "Maybe butterflies know about this and use it to swerve to one side to escape from a predator. Who knows?"

Unaware of the studies by Aref or the Soviet researchers, Kunihiko Kaneko and Yoshihiro Tanabe at the University of Tokyo in the early 1990s launched an independent test of whether there is chaos in the fall of a piece of paper.

Kaneko's inspiration came from leaves. "It is often said that the motion of falling leaves is unpredictable, in contrast with planetary motion. While I was walking around the street and saw leaves falling, I recalled this," he remembers.

He and Tanabe created a simple computer model depicting the paper as a rigid line, as if seen edge on, that falls in a vertical plane. They subjected it to simulated forces of gravity, aerodynamic lift, and friction.

The simulated paper fell in five different ways as the friction was varied, two of which are chaotic, they reported in the Sept. 5, 1994 PHYSICAL REVIEW LETTERS. The five types of fall included only three basic motions: dropping straight down, swaying from side to side, and tumbling (SN: 9/17/94, p. 183).

The research drew some harsh criticism, particularly from Mahadevan, Aref, and Jones. In the Aug. 14, 1995 PHYSICAL REVIEW LETTERS, they challenged Tanabe and Kaneko for, among other reasons, leaving out of their calculations the way fluid pushes back on a body moving through it. Other scientists have also reported flaws in the Japanese team's approach but have found it useful as a guide and stepping stone.

"They got some of the right answers, but for the wrong reasons," grumbles Aref.

An unpublished study from the College of William & Mary in Williamsburg, Va., that recently reproduced Tanabe and Kaneko's computer simulations raises the additional question of whether their work, and other research on falling leaves and paper, really got relevant answers.

Maura Williams, an undergraduate who worked with chaos physicist Reggie Brown at William & Mary on the analysis, notes that Tanabe and Kaneko, for instance, had used 0.1 as the relative density of air to their simulated paper, whereas the typical density ratio is actually closer to 0.002. Williams is now a graduate student in physics at the University of Maryland in College Park.

Rerunning the simulation with the smaller ratio and some other numbers that she and Brown consider more realistic, she found only two of the five falling patterns, neither of them chaotic.

The last time the falling-leaves problem received such close scientific scrutiny was shortly after World War II. The U.S. military was unhappy with its limited ability to land large drums of high explosives, known as depth charges, on enemy submarines and to drop packages to ground forces without losing them or having them swirl crazily and crash back into the delivery plane. So, it funded scientists to pursue basic research on the falling behavior of nonstreamlined, or "bluff," bodies, the simplest of which is a coin.

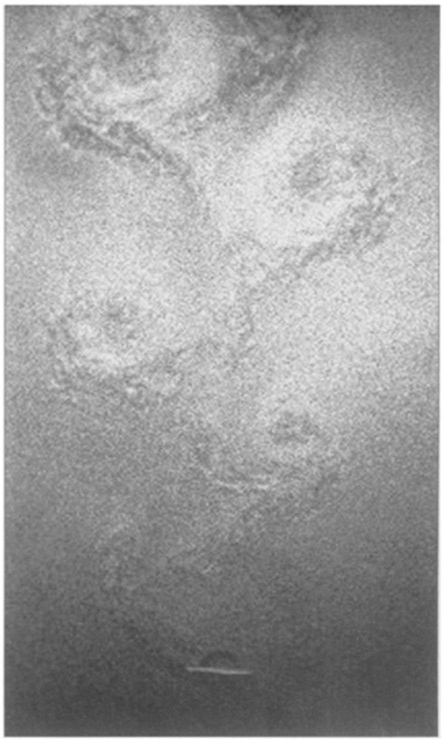
The scientists compiled data on the motions of metal and plastic disks falling through air and various liquids. After discovering that researchers in 1928 had done similar experiments, they included those findings.

In essence, the military was funding chaos research. It just didn't know it, says Nori. He likens dropping depth charges and packages to tossing coins into a bowl of water at a carnival booth where the object is to win prizes by landing the coins in cups submerged inside the bowl. Because the coins' motions are chaotic, the carnies almost always win.

The military's postwar headaches turned out to be a gold mine for a group of scientists who recently decided to put the theories of Aref and Kaneko to the test.

By videotaping the trajectories of hundreds of steel and lead disks dropped in both water and more viscous water–corn syrup mixtures, Nori's team and Stuart B. Field at Colorado State University in Ft. Collins filled in the blanks in a chart of disk trajectories started more than 30 years ago. They also dropped a few paper disks in air as part of their experiment.

In the July 17, 1997 NATURE, the scientists presented the first experimental evidence, including data from military-funded studies published in the 1960s, of chaos in the motion of falling bodies (SN: 7/19/97, p. 37).



Moses

Swirls of water, or vortices, spin off the edges of a falling strip each time it reverses direction in its fluttering descent. Aluminum particles in the water make the whorls visible.

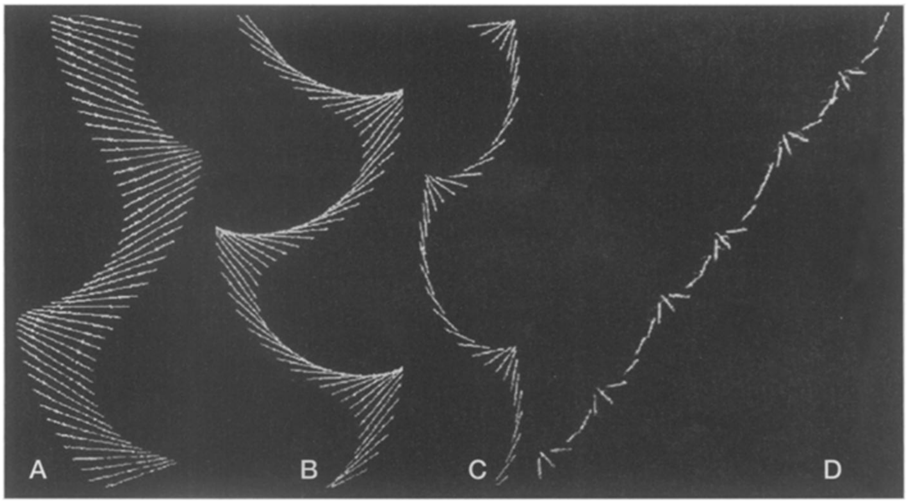
They found four modes of motion, three of which are regular and similar to the straight fall, side-to-side sway, and tumbling previously described by theorists. They also discovered a chaotic mode in which the disk sways back and forth, gradually swinging higher and higher. After an unpredictable period, it tips to such a steep angle that it overturns into a tumble. Then, after some time, also unpredictable, it recovers the oscillating mode.

William W. Willmarth, an emeritus professor of engineering at the University of Michigan in Ann Arbor, was one of the researchers whose 1964 data Nori and Field used. He doubts that calling certain trajectories chaotic is saying anything new.

"We just called it unpredictable," he says. "Chaos seems to me to be a name for something you don't understand."

Nori and Field, however, insist that chaos theory deepens understanding of the motion. Moreover, they say, the new findings have expanded the frontiers of chaos theory by demonstrating a path of sudden transitions in and out of chaotic behavior, known as intermittency, that had been predicted but never before seen experimentally.

Andrew Belmonte had a "breathtaking experience" the first time he watched a metal strip flutter through a special experimental tank at



Moses/Weizmann Institute

Rigid strips dropped in a narrow water tank flutter (A-C) or tumble (D), depending on their length and mass. For each of these four video montages, experimenters used narrow rectangles of plastic or metal confined by hoops. They recorded each strip's descent every 20 milliseconds.

Elisha Moses' lab at the Weizmann Institute of Science in Rehovot, Israel. "It was such a beautiful motion," he recalls.

More recent experiments using that tank showed no clear signs of chaos, report Belmonte (who is now at Pennsylvania State University in State College), Moses, and Hagai Eisenberg, also at Weizmann, in the July 13 PHYSICAL REVIEW LETTERS.

The researchers videotaped and analyzed the falling behavior of rigid strips of plastic or metal in water and other, more viscous fluids. By confining a strip between hoops that hug the walls of the narrow tank, they restricted the strip's movement as it descends. The only motions observed were nonchaotic side-to-side fluttering and tumbling.

The absence of chaos doesn't trouble them, Belmonte and Moses say. Nor does it disprove prior claims. Perhaps the restrictions squelched the behavior, they speculate.

Rather, they draw attention to their ability to calculate accurately, given a few properties such as the strip's shape and the fluid's density, which of the two motions a particular strip will take. Moreover, by modifying Tanabe and Kaneko's theory, the researchers also achieved agreement between experiment and theory in defining these trajectories.

"One of the interesting things about our experiment is that it shows regularities in the fall" of the strips, Belmonte says.

As they did with the Tanabe and Kaneko study, Williams and Brown question the relevance of this experiment and Nori's to actual falling paper or leaves. In both cases, the researchers primarily dropped objects whose relative density to the fluids is, by Williams' calculations, much greater than the relative densities of paper or leaves to air.

"They may have a point," Belmonte says.

In an experiment to be described in an upcoming issue of PHYSICS OF FLUIDS, Mahadevan and Harvard University students William S. Ryu and Aravinthan D.T. Samuel have also found a regularity. By dropping hundreds of long, rigid plastic strips in air under controlled conditions and measuring their tumbling frequency, they found that they could calculate the tumbling rate from just the width and thickness of the strip.

The simplicity of the relationship surprised them, given that the strip is sloughing off complex swirls of fluid with each spin, Mahadevan says. "The solid is somehow in resonance with the fluid so that it slides and rotates in a regular way," he says.

A leaf also sheds vortices of air each time it flutters back and forth. To refine their theories further, researchers must find out more about the interaction between those vortices and the edges where they form, Mahadevan says. "That's the big puzzle that needs to be solved."

Falling leaves seem to hold a researcher's attention for only so long. Belmonte says that he is starting experiments to better understand vortices but with a focus on a different sort of fluttering—insect flight.

Nori has set the falling-leaf problem aside for now, too, but he may take it up again. In a few years, the growing power of supercomputers may allow a full-blown simulation of the currently unsolvable equations for descending objects, he says.

Where the current round of research will lead seems as unpredictable as the flight of an autumn leaf. □

Biomedicine

A sugar averts some ear infections

How sweet it is! A natural sweetener called birch sugar helps to prevent some ear infections when given to young children, Finnish researchers report in the October PEDIATRICS. In the United States, gum made with birch sugar, also called Xylitol, is mainly sold in health food stores. It is more widely available in Europe.

Preschoolers receiving 8 to 10 grams of birch sugar five times each day—in either lozenges or pieces of gum—came down with fewer middle ear infections over 3 months than playmates who daily received gum sweetened with sucrose and containing only a trace of birch sugar, says study coauthor Matti K. Uhari, a pediatrician at the University of Oulu in Finland.

Among 178 preschoolers given the sucrose-based chewing gum, 49 children were diagnosed with a total of 72 ear infections. Among 179 getting birch sugar gum, 29 children had 44 ear infections. Of 176 children receiving birch sugar lozenges, 39 came down with 52 infections.

Five-a-day doses of birch sugar given as a syrup proved less effective in preventing ear infections, but a distinction still emerged between birch sugar syrup and sucrose syrup. Of 165 children who received a sucrose syrup, 68 contracted 114 infections, whereas 46 of 159 children getting birch sugar syrup came down with 69 infections.

Even though it is a sweetener, birch sugar was shown to prevent tooth decay in earlier tests. So the researchers included 0.5 gram of birch sugar per day in the doses of sucrose syrup or gum to offset any tooth decay the sucrose might cause.

Laboratory experiments have shown that birch sugar inhibits growth of *Streptococcus mutans*, a bacterium that causes dental caries. Based on this, Uhari and his colleagues earlier had tested birch sugar against *Streptococcus pneumoniae*, a common cause of ear infections. They reported in 1995 that the sweetener inhibited this bacterium's growth in laboratory tests. The new work is the first large study to gauge birch sugar's effectiveness against the microbe in children.

S. pneumoniae latches onto cells in mucus, apparently riding this fluid up from the mouth and throat via the eustachian tubes to the ears, where it can cause an infection, Uhari says. Birch sugar seems to prevent this attachment some of the time, limiting the disease, he says.

If indeed that is the bacterium's mechanism, Uhari says, the microbe would "have no reason to develop resistance" to birch sugar, since the sweetener isn't killing it. Uhari and study coauthor Tero Kontiokari hold a U.S. patent on the use of Xylitol as a treatment for respiratory infections. —*N.S.*

Survival improving in organ recipients

The success rate of organ transplants has improved in the 1990s. A survey of all 97,587 transplants performed in the United States between 1988 and 1994 shows markedly higher patient survival rates for liver, lung, and heart-lung transplants and slight gains in every other organ transplant category.

Researchers at the United Network for Organ Sharing (UNOS) in Richmond, Va., compared organ transplant operations performed from January 1988 through April 1992 with those done from May 1992 through April 1994. The 1-year survival rate improved between these two eras only slightly for recipients of a kidney, heart, or pancreas. Substantial gains, however, showed up in people receiving a liver (77 percent survival rose to 82 percent), lung (68 percent to 75 percent), or heart and lung (59 percent to 70 percent), the researchers report in the Oct. 7 JOURNAL OF THE AMERICAN MEDICAL ASSOCIATION.

Transplantation "is not an experimental procedure anymore," says study coauthor O. Patrick Daily of UNOS. "Survival rates and the outlook for all organ transplants are quite good and remarkably consistent from center to center."—*N.S.*