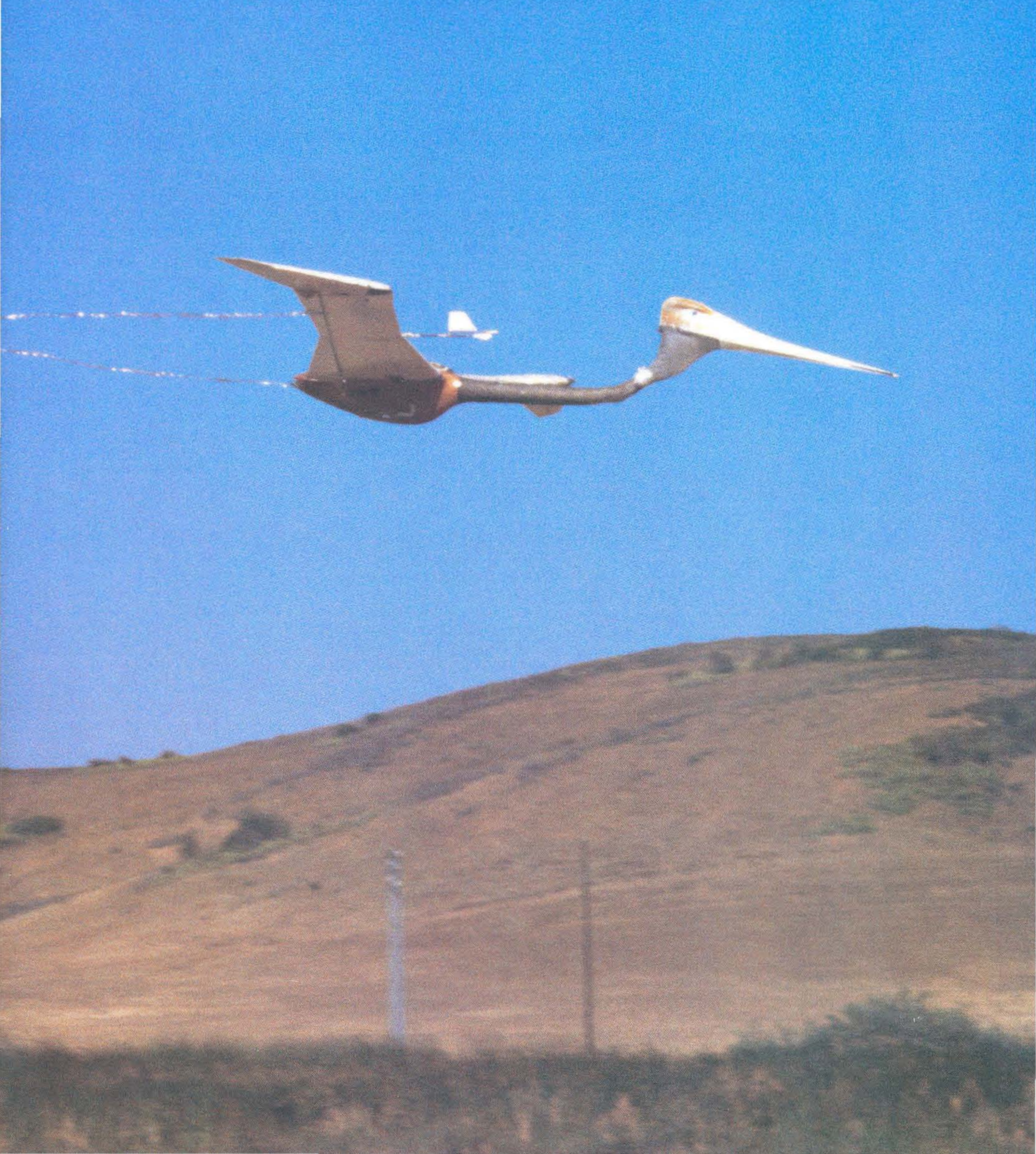
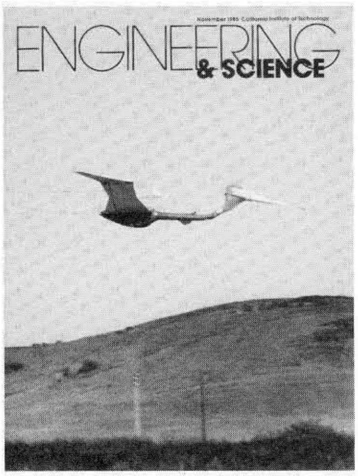
November 1985 California Institute of Technology

ENGINEERING & SCIENCE



In This Issue



Look, up in the air — it's a . . .
On the cover — a half-scale prototype (18-foot wingspan) replica of the giant pterodactyl, *Quetzalcoatlus northropi*, glides above Simi Valley in a radio-controlled test flight last August. This model was used to develop the lateral-control autopilot. The streamers trailing behind serve to indicate air flow to observers on the ground.

The working model of the prehistoric flying reptile is the creation of Paul MacCready. Known for his *Gossamer Condor*, which made the first sustained, controlled, human-powered flight in 1977, MacCready has also created the *Gossamer Albatross*, the first and only aircraft to be pedaled across the English Channel (as well as the *Gossamer Penguin, Solar Challenger,* and *Bionic Bat*).

Caltech gave MacCready its Distinguished Alumni Award in

1978; he earned his MS in physics here in 1948 and PhD in aeronautics in 1952 (his BS is from Yale). His firm, AeroVironment, Inc., based in Monrovia, California, provides services and products in the fields of alternative energy, the environment, and aviation, in addition to building pterodactyls. The pterodactyl project has a remarkable density of Caltech alumni, including Peter Lissaman (MS 1955, PhD 1966), who co-founded the company, Alec Brooks (PhD 1981), Henry Jex (MS 1953), and Alan Cocconi (BS 1980).

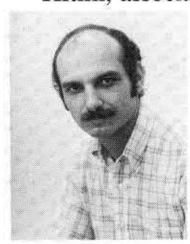
MacCready's article "The Great Pterodactyl Project," begins on page 18. Portions of the article appear in the National Air and Space Museum Research Report 1985 as "QN — The Time Traveler™." Other parts were adapted from his talk to the Southern California Skeptics at Caltech in October.

Delbrück vs. Descartes
In his acceptance speech on receiving the Nobel Prize for Physiology or Medicine in 1969, Max Delbrück previewed many of the epistomological topics that he would later discuss more fully in his series of Caltech lectures given first in 1974 and again in 1976. He described these lectures, entitled "Mind From Matter?," as an " investigation into human cognitive capabilities as expressed in various sciences," and his motivation for presenting them was "to summarize his lifelong exploration of the implications of [Niels] Bohr's philosophy for the possible sources of human knowledge."

Delbrück died in 1981 without having published these lectures as he had intended. They have, however, been issued as a book this fall by Blackwell Scientific Publications, Inc., edited by Delbrück's friend and former colleague, Gunther Stent. "The Cartesian Cut," one of the later chapters of the book, begins on page 6.

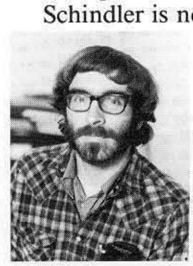
ZZZZZZZZ
David Hitlin and Rafe Schindler, co-authors of the article "Catching Some Zs," beginning on page 13, haven't really been dozing much lately. They've been designing and building a detector to capture in greater numbers the elusive Z^0 particle — first theorized in the unification of the electromagnetic and weak forces and observed experimentally only two years ago. The complex project, under Hitlin's direction, has been undertaken by groups from Caltech, the Stanford Linear Accelerator Center, Columbia University, University of Washington, and the TRIUMF Laboratory in Vancouver.

Hitlin, associate professor of



physics, earned his BA (1963), MA (1965) and PhD (1968) from Columbia. Before coming to Caltech in 1979, he was assistant professor at Stanford.

Schindler is now assistant



professor at SLAC, but began this article as a senior research fellow at Caltech, a position he had held since 1982. He holds a BA from University of Rochester (1974) and an MA (1975) and PhD (1979) from Stanford.

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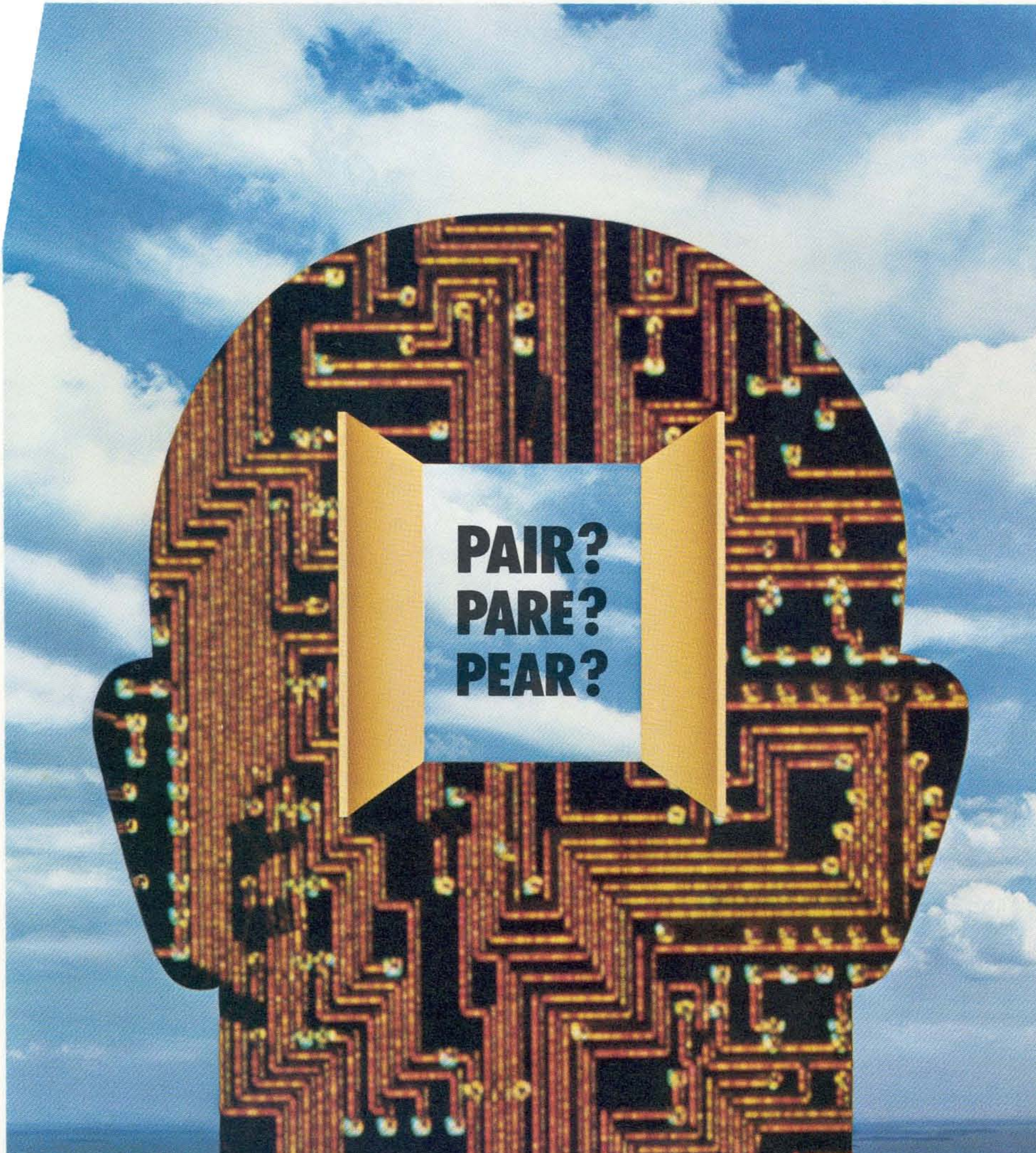
Departments


PAIR?
PARE?
PEAR?

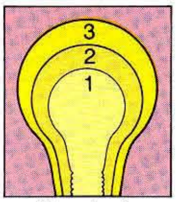
Would you like to know how computers can tell the difference between a pair in a poker game and a pear on a plate?

How they can understand a variety of speakers with a diverse variety of accents—and reply in pear-shaped tones, using normally connected speech?

Then read on to learn more about computers that recognize words, comprehend meaning from context, even synthesize human speech from a mere shadow of itself.

It's All In The Algorithms

Utilizing three levels of speech-processing algorithms, AT&T is giving the computer a more 'robust' understanding—the capacity to comprehend connected speech from different speakers.



Three levels to understanding

Acoustic pattern matching (1) identifies the spoken words.

Grammatical processing (2) figures out how the words are put together.

And semantic processing (3) extracts meaning from the context. With each successive step, the computer moves closer to accurate understanding.

Acoustic pattern matching determines how much latitude the waveform (pronunciation) of a word can have before it becomes unintelligible to the computer.

By isolating the specific characteristics the waveform of a word contains—independent of the accent of a speaker—we increase the probability that it will be correctly matched to a pattern stored in a computer's memory. But, correct recognition of words is only the beginning of computer understanding.

Computer Grammar 101

Grammatical processing further increases the probability of recognizing words. It analyzes them within the constraints imposed by language—the allowable sequences of syllables in a word or words in a sentence.

For a specific vocabulary and situation, it is possible to define every sequence the computer can recognize. Based on probabilities assigned to each word it recognizes—and where that word falls—the computer determines which of its possible sequences is the most likely. This process gains two advantages: It allows words that might not otherwise be recognized to be correctly accepted; and it speeds up processing time by using sequence position to limit the number of words it looks at for a pattern match.

A Meaningful Relationship

Semantic processing is the point where the computer crosses the line between recognition and understanding—the point where words are given meaning within a specific context. This endows a system with one of its most human qualities: knowing when a request isn't understood, and asking for appropriate clarification.

Talk Isn't Cheap

Making a computer listen intelligently is one thing; making it respond intelligibly, however, is another.

Enabling a computer to talk, reproducing the subtleties of human speech, has required large amounts of memory—a high cost item. Therefore, an 85 percent reduction in the amount of information needed to store and generate high-quality speech can mean significant cost reductions.

That's just what a new AT&T speech synthesis technique, called multi-pulse linear predictive coding (MP-LPC), provides. It reduces the 64 thousand bits per second previously needed to 96 hundred.

Speech signals mimic the human vocal tract—they have redundancies built in. MP-LPC codes speech to remove these redundancies, then tells the computer how to reconstitute the original speech from the mini-version in its memory. This coding eliminates unnecessary bits from being stored and transmitted.

Getting Down To Business

At AT&T, our goal is to make computers listen and understand as fast as people speak—and speak to and understand as many people as possible. Speech-processing algorithms, developed by AT&T Bell Laboratories, have moved us several steps closer to that ideal.

For example, most speech recognition systems make the speaker pause between words. But AT&T, using advanced recognition algorithms, has developed a Stock Quotation System, now in field trial, that allows callers to enter and retrieve current market information in natural, normally-connected speech. Users simply speak the number codes for any of over 6,000 stocks, and the service provides current quotes—delivered in computer-generated speech.

Numbers are nice, but make for limited conversation. Closer to our goal of a conversational computer is the Flight Information System. It uses the Official Airline Guide as its data base. In its limited environment, this laboratory system converses with the user in natural speech in response to normal flight information queries.

One Of Our First Callings

AT&T has been deeply involved in speech technology since the genesis of the telephone. From the beginning, our goal was to make mechanical communications fast, foolproof and economical.

Today, with the advent of the computer, we're moving toward the ultimate ideal: creating machines that serve our needs and save our energy in the most natural manner—by voice command.

AT&T

The right choice.

The Boundary Dynamic

The performance of a polymeric adhesive depends on the properties and composition of its surface. Now a scientist at the General Motors Research Laboratories has developed and validated a theory that describes the coupled effects of diffusion and chemical reaction on the changing surfaces not only of adhesives, but of chemically reacting surfactant systems in general.

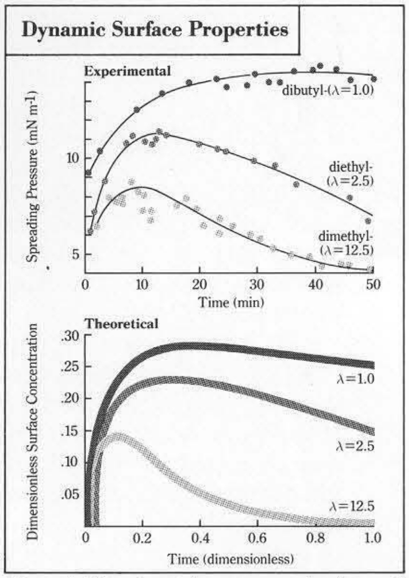
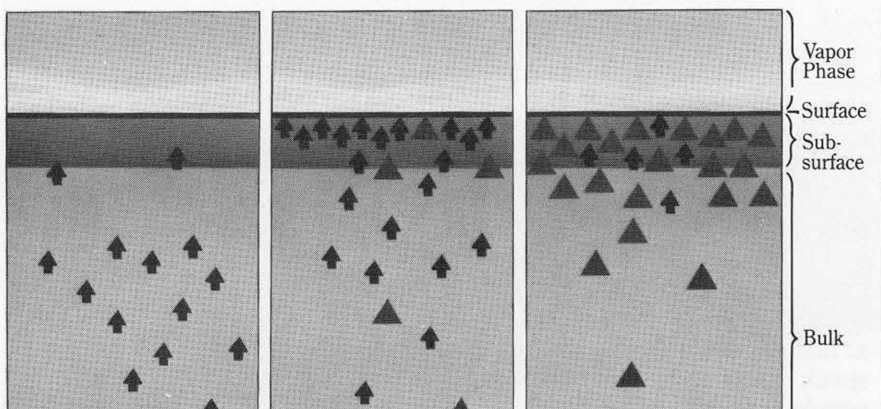


Figure 1: Experimental measurements of spreading pressure v. time for dialkylaminopropylamines with various Damköhler numbers (λ), and corresponding theoretical calculations of surface concentrations.

Figure 2: Evolution of an adhesive surface: Surface-active Solute 1 reacts with host resin to form surface active Solute 2.



THE USE OF adhesives in the production of an automobile promises to make both the product and the process more efficient. Both weight and operations can be reduced. In practice, however, steel and other metallic surfaces are often contaminated by process lubricants. A durable bond depends on the ability of an adhesive to displace contaminants and to wet the substrate.

Assuring intimate contact between adhesive and substrate requires detailed knowledge of adhesive surface tension, since it is this property that controls displacement of contaminants and wetting. Up to now the surface tension of an adhesive has typically been assumed constant. In reality, though, surface-active components in the adhesive collect preferentially at the interface and also react, so that the surface composition varies with time, giving rise to dynamic surface tension. Variations can be large enough to significantly affect adhesive performance.

The understanding of time-dependent surface tension has been advanced by the work of Dr. Robert Foister, a scientist at the General Motors Research Laboratories. Investigation of dynamic surface properties of thermosetting adhesives led him to develop a general theory of adsorption kinetics in binary, chemically reacting surfactant systems. The significance of this theory is that it includes the coupled effects of surfactant diffusion and chemical reaction, making it possible for the first time to describe quantitatively the changing surfaces of such systems.

In a typical adhesive that polymerizes, or "cures," by chemical reaction (Figure 2), a surface-active curing agent (Solute 1) reacts with the host resin to form a second surface-active species (Solute 2) that is also reactive. Both solutes migrate to the surface, lowering the surface tension. Diffusion to the surface is driven by a potential energy gradient between the surface and the bulk, with the solute molecules experiencing a lower energy at the surface.

Dr. Foister derived appropriate transport equations to describe diffusion and chemical reaction in the bulk, in a subsurface region, and at the surface itself. The transport equations can be solved analytically if the chemical rate equations are assumed to be first order in the concentrations of reacting species, and if the subsurface and surface concentrations can be related to one another by a linear adsorption isotherm. For more complicated isotherms, a set of coupled, non-linear integral equations is generated.

These must be solved numerically.

Analytical solution for the special case of the linear isotherm indicated that the change with time in surface concentration (and consequently in surface tension) is composed of two terms: first the diffusive flux of Solute 1 into the subsurface from the bulk, and second the depletion of this solute due to chemical reaction. Hence, the surface concentration of Solute 1 exhibits a maximum with time (Figure 2). This maximum in surface concentration corresponds to a minimum in surface tension.

MODIFYING the transport equations to include binary adsorption isotherms allowed for consideration of competitive adsorption of the two reacting and diffusing solutes. By solving these equations numerically and conducting dimensional analysis, Dr. Foister identified various dimensionless parameters as predictors of system behavior. The most important of these parameters was a dimensionless number (λ), of the Damköhler type, involving terms representative of reaction, diffusion, and adsorption.

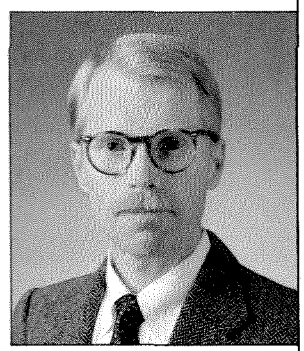
$$\lambda = \frac{k\,(\Gamma_m\,a)^2}{4D}$$

Here k is the reaction rate constant of Solute 1, D its diffusivity, Γ_m its "surface capacity" (the maximum number of molecules absorbed per unit surface area), and a its "surface affinity" (a measure of its energy of adsorption). For an adhesive, lowering λ by reducing k (the reactivity of the curing agent), for example, would prolong the time to maximum, and would increase the value of the surface concentration at the maximum (see Figure 1, Theoretical). As a practical consequence, this would improve wetting by minimizing the surface tension.

In experiments using a series of dialkylaminopropylamine curing agents (dimethyl-, diethyl-, and dibutyl-) in a host epoxy resin matrix, good agreement has been demonstrated between theoretical predictions for surface concentration and the measured dynamic spreading pressure, which is the change in adhesive system surface tension due to the curing agent (Figure 1, Experimental).

"I expect," says Dr. Foister, "that the physical insights gained from this analysis can be applied to other reactive surfactant systems by using specifically tailored isotherms and chemical reaction schemes. Predicting surface behavior can certainly help us design better adhesives for specific applications, but it is also pertinent to the performance of anti-oxidants and anti-ozonants in synthetic rubber, for example. And applied to interfaces in biological systems, a suitably modified theory may prove valuable in understanding the phenomenon of enzyme activity."

THE MAN BEHIND THE WORK

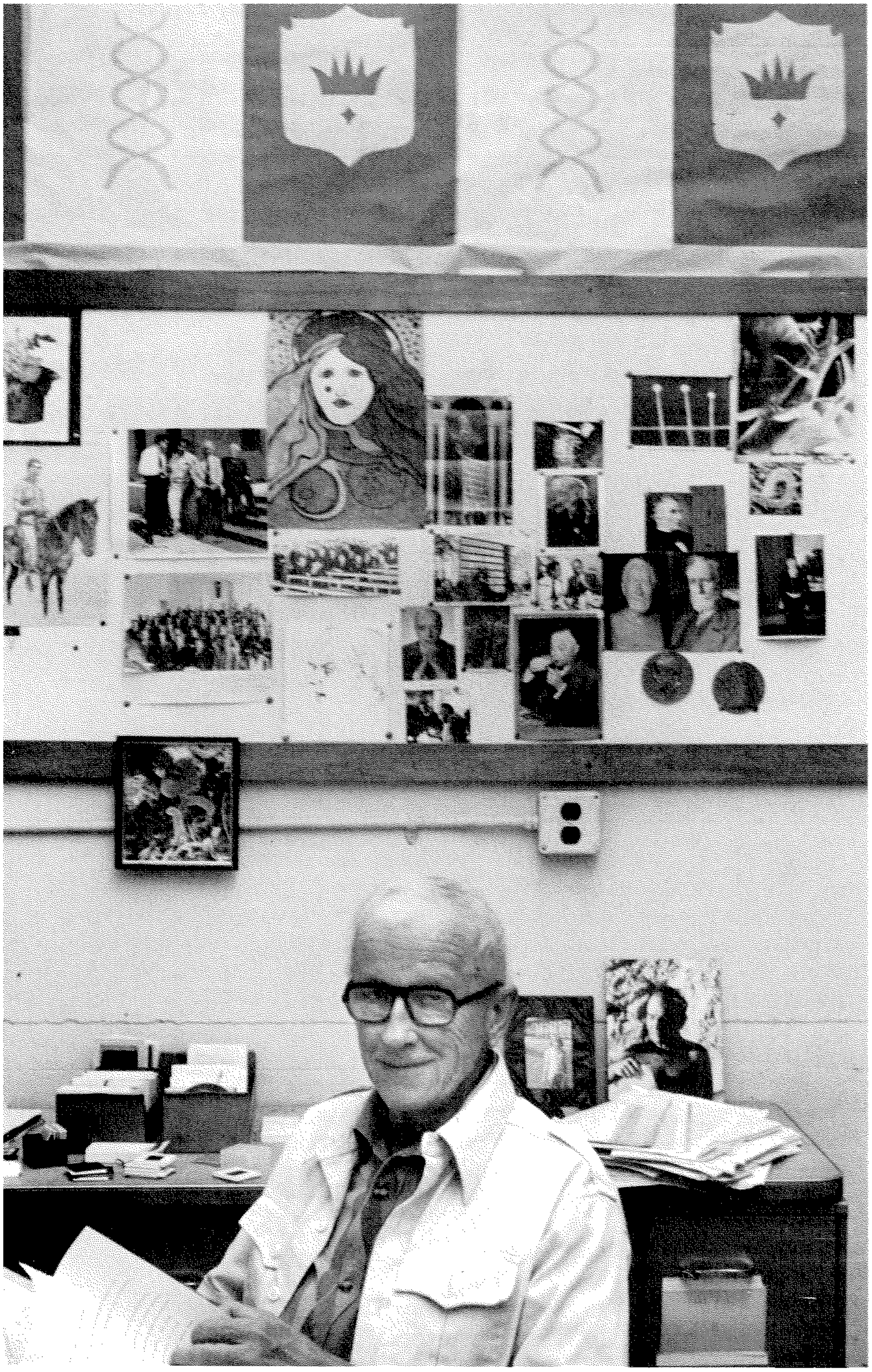


Dr. Foister is a Staff Research Scientist in the Polymers Department at the General Motors Research Laboratories.

Dr. Foister received his undergraduate degree from Guilford College, and holds a Ph.D. in Physical Chemistry from the University of North Carolina at Chapel Hill. His thesis dealt with the role of liquid inertia in the intrinsic viscosities of rod-like polymers.

He did post-doctoral work in Canada as a Fellow at McGill University in Montreal, and in the Applied Chemistry Division of the Pulp and Paper Research Institute of Canada, working on the microrheology of colloidal dispersions.

Dr. Foister joined General Motors in 1980. He is the leader of the Structural Adhesives Group in the GMR Polymers Department. His current research interests center on surface chemistry and adhesion.



Max Delbrück poses in his Caltech office about the time of the "Mind From Matter?" lectures. These lectures were published in November by Blackwell Scientific Publications, Inc.; this chapter appears in the book.

The Cartesian

by Max Delbrück

IN 1932, WHEN NIELS BOHR conjectured that there might exist a mutual exclusion between experiments that would provide a description of an organism in terms of atomic physics and experiments that would provide a description in terms of genetics, physiology, and embryology, these three biological disciplines were already well developed. The phenomena they addressed seemed to be unique to living matter, transcending what physical chemists were able to account for in terms of the kinetics and thermodynamics of chemical reactions. At least it appeared so at that time, when there were many biologists who embraced the view of "vitalism." According to that view, living matter owes its characteristic properties to a "vital force" not present in nonliving matter.

Vitalist biologists insisted that the features of living systems that seem to defy the laws of physics and chemistry are attributable to special drives and forces. For example, the evolutionary increase in organismic complexity, which appears to run counter to the second law of thermodynamics (whose basic prediction of a loss of capacity of a system to do future work is equivalent to predicting a decrease of order or an increase in entropy in the system over time) was explained by an "anti-entropic principle." Other biologists, especially those approaching living systems from the biochemical or physiological point of view, were strongly opposed to such vitalist notions. They insisted that it is quite unacceptable to have a picture of the world in which matter is viewed as subject to addi-

Cut

tional, "unphysical" forces as soon as it forms part of a living organism. They held that the comportment of living matter is also governed wholly by the laws of physics and chemistry.

Bohr's contribution to this controversy was to point out that the invocation of special laws that transcend the laws of physics to account for the comportment of living matter is not necessarily in irreconcilable conflict with the notion that there is no essential difference between the atoms of which living and nonliving matter are composed. In line with his general complementarity argument, Bohr suggested that, just as quantum physics managed to construct a rational theory of matter in which its wave and particle aspects coexist harmoniously, so might biology manage to provide a rational account of living matter by accepting the coexistence of seemingly conflicting notions about the laws that govern its behavior. Bohr thought that the two types of mutually exclusive observations arise from the fact that it is necessary to kill an organism if one wants to examine it closely enough to locate its atoms, a situation equivalent to the necessity of changing the state of an atom in order to locate its electrons.

The fate of Bohr's proposal regarding the role of complementarity in biology was different from that which it had been accorded in atomic physics. It was not necessary to invoke any mutual exclusion of observational arrangements in biology to account for living matter. Instead, the development of systems theory, especially of cybernetics, has shown that many of the life processes that seemed miraculous 50 years ago can, in fact, be simulated by machines. In 1948 John von Neumann showed that a self-reproducing machine, or automaton, is feasible in principle. In the following excerpt from a lecture by von Neumann (published posthumously in 1966), the designations now used by molecular biologists for the parts of the cellular apparatus of self-reproduction are indicated in brackets for the components of the automaton listed by von Neumann.

> . . . a self-reproducing automaton must have four separate components with the following functions: Component A is an automatic factory, an automaton which collects raw materials and processes them into an output, specified by a written instruction, which must be supplied from the outside. [Component A corresponds to the enzymatic apparatus of the cell that catalyzes the synthesis of building blocks of macromolecules, such as amino acids (for proteins) and nucleotides (for nucleic acids) from foodstuff, as well as the ribosomes and other accessories of protein synthesis, such as tRNA and tRNA-aminoacyl synthetases. The "written instruction" corresponds primarily to the nucleotide sequence embodied in the DNA, and secondarily to its mRNA transcript.] Component B is a duplicator, an automaton which takes the written instruction and copies it. [Component B corresponds to DNA polymerase and other enzymes directly associated with the process of DNA replication.] Component C is a controller, an automaton hooked up to both A and B. When C is given an instruction, it first passes the instruction to B for duplication, then passes it to A for action, and finally supplies the copied

instruction to the output of A while keeping the original itself. [Component C corresponds to (1) the apparatus that governs the initiation of DNA replication, (2) RNA-polymerase and other enzymes responsible for DNA transcription and synthesis of mRNA, and (3) the mitotic spindle (or its equivalent in prokaryotes), which assures that each of the two sister cells resulting from the activity of component A receives one of the DNA replicas generated by component B.] Component D is a written instruction containing the complete specifications which cause A to manufacture the combined system, "A plus B plus C." [Component D corresponds to the genome or the entire DNA complement, which encodes the set of mRNA's that specify the set of enzyme molecules that catalyze the synthesis of the cellular components.]

Von Neumann's automaton was conceived to be a minimal one. It describes a self-reproducing system different from that represented by living cells in not interposing an intermediate messenger (mRNA) between the master tape (DNA) and its realization (protein); rather it envisages a direct translation of the DNA nucleotide sequence into the protein amino acid sequence. However, some viruses that contain RNA rather than DNA as their genetic material do resemble von Neumann's minimal scheme: for instance, the genetic material of the poliovirus serves as its own mRNA in directing the synthesis of poliovirus proteins, as well as replicating directly. Viruses, however, are simpler than von Neumann's system, in that they relegate function A of his automaton, the production of the output, to the apparatus for synthesis of building blocks and proteins of the host cell.

The existence proof of self-reproducing automatons is not the only, or even the most significant, accomplishment of cybernetic systems theory, especially since no such automaton has actually been built. The most significant accomplishment of cybernetics is probably its demolition of the old prejudices that machines cannot adapt to novel situations, cannot learn from experience, and cannot interact with human beings in any meaningful way. For it turned out to be possible to design and construct machines that refute these claims. Some of these machines will be discussed in these final chapters.

Let us now recapitulate our assessment of how the progress of science has managed to denature the old concepts of object, number, time, topological space, projective space, metric space, and causality. What has happened to all those concepts that constituted our naive view of external reality? What has happened to this evolutionary acquisition, of immense adaptive value, that enables us to cope with the world? It is ironic that science has pulled the rug out from under this conceptual structure. The special relativity theory has replaced the concrete space-time frame with an abstract one, in which one twin may go on a trip and return a younger person than the stay-at-home twin — a claim that is irreconcilable with our concrete mental operations regarding space and time. The general relativity theory tells us of "singularities in space," black holes with an "event horizon" from which no signals can emerge, and finite but not bounded space — concepts that we can learn to manipulate in a formal way but cannot visualize. Quantum theory, the worst offender, does away with object identity and trajectory of objects (electrons do not revolve in orbits). It proclaims a conspiracy of nature that forces us to choose, to make either/or decisions between various aspects of reality that in any observational act are mutually exclusive. Is this a Kierkegaardian notion, with every observation becoming an existential act? Have physicists become religious thinkers? Einstein was unwilling to accept this conspiracy. His attitude is reflected in such remarks as "The Good Lord may be cunning, but malicious He is not" and "God does not play dice with the universe." Whether God is malicious or not, no satisfactory assimilative alternative to accommodate (in Piaget's sense) to this conspiracy has been found, and as Bohr's analysis made clear, none is likely to be found.

No, physicists have not become religious thinkers, since the either/or choice they are forced to make is not an ethical one, not even the choice of an individual observer, but one that concerns collective observations on, say, light quanta: pass them through an analyzer that permits statements about their circular polarization (clockwise or counterclockwise) or through an analyzer that permits statements about their plane polarization (vertical or horizontal). We make this choice, and our choices materially exclude each other, because any one quantum, once it is observed — that is, recorded by a counter — is irreversibly gone. Such is the individuality, the quantum nature, of any atomic interaction involved in constructing an object world. It always leaves this object world with a residue of uncertainty and limits us to statistical predictions.

This bizarre dialectical situation goes to the heart of the concept of the reality of the physical world, so basic to the evolution of the human mind. For a million years or so we have been animals that know the dichotomies: actor-observer, I and the world, mind versus reality, a confrontation between an inner world of thoughts, volitions, and emotions and an outer world of objects. The poet Rainer Maria Rilke commented on the regrettable loss of existential wholeness brought about by this turn of our evolutionary history, which less evolved creatures have been spared.

O Seligkeit der *kleinen* Kreatur,
die immer *bleibt* im Schosse der sie austrug;
O Glück der Mücke die noch *innen* hüpft,
selbst wenn sie Hochzeit hat: . . .
. . . .
Wer hat uns also umgedreht, dass wir,
was wir auch tun, in jener Haltung sind
von einem welcher fortgeht? . . .

Oh bliss of *tiny* creatures that *remain*
forever in the womb that brought them forth!
Joy of the gnat that still can leap *within*,
even on its wedding day: . . .
. . . .
Who's turned us round like this, so that we always,
do what we may, retain the attitude
of someone who's departing? . . .

From Rilke, "The eighth elegy," in Duino Elegies, *trans. J. B. Leishmann and S. Spender (New York: Norton & Co. 1939).*

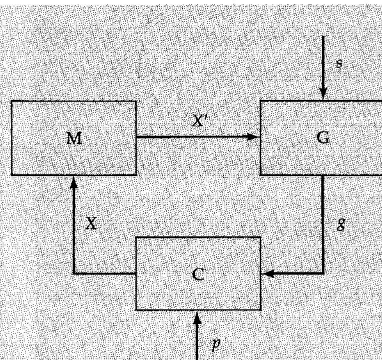
From these dichotomies springs the Cartesian cut — the separation of the world into two distinct substances — *res cogitans* (mind) and *res extensa* (matter) — which has been the stance of science for 300 years, ever since its eponymous champion René Descartes clearly formulated it in his *Passions of the Soul.* The Cartesian cut has been the bane of psychologists, whose job it is to cope with both aspects of existence and to tie both substances together in some fashion. Is the tree I see in front of me the same as the object that is out there, or are the two things distinct? On the one hand, when we consider that the retinal image of the tree is processed not only in the neural network of the retina itself, but also in the lateral geniculate nucleus, in the visual cortex, and in yet other cortical areas, we realize that what consciousness sees, that is, the tree in here as a percept, is literally worlds apart from the tree out there as an object. On the other hand, does it make sense to take the object and its percept apart in this way? Is there not but one reality: the act of seeing what our language makes us call an "object"? These are the opposing positions of the dualist and the monist. Battalions of philosophers have manned the barricades in defense of either position.

We form the notion of the objective reality of the external world, independent of the observer, in earliest infancy, and we form it with the aid of mental equipment evolved over millions of years of adaptive evolution. It is a notion that has been necessary for survival, not only in the cave, but also up in the trees before moving into the cave. It is also the notion that has been most solidified, hardened, and codified, by the development of the classical physical sciences, into the "physical laws." It has been claimed, indeed it is commonly believed, that physical laws describe the external world in an objective way and that they reduce this description to numerical relations. Let us look at this claim more closely, and dissect it in the manner proposed by the psychologist Norbert Bischof. He invites us to examine the relation $S = gt^2/2$. It is indeed a relation between numbers. However, to make it a law of physics we need to know that S is a distance, t a duration, and g an acceleration. The numerical relation as such does not express a physical law. A law is expressed only if we understand that the numbers are measures of a quality of the thing measured: a spatial length represents something completely different in quality from a duration or an acceleration. In addition to the qualities of the quantities measured, we need to know where and what to measure. We need to know the class of actual situations to which the law refers. In fact, a physical law, far from existing totally detached from the observed object, refers explicitly to situations actually or potentially experienced by an observer and to nothing else. This is true, let us add parenthetically, even if we make statements about the big bang origin of the universe — even though there could not have been an observer present to observe it. It would be an illusion to think that physical laws describe an external world independent of the observer.

In what sense, then, are the findings of the physical sciences objective? We say they are objective in being "reproducible" for each observer, and "the same" for different observers. These two criteria are the pride of the physical sciences, and they are indeed met. Information stored in enormous handbooks of physics and chemistry and the solid core of theories presented in the textbooks of these disciplines give vivid testimony to their objectivity. One might characterize the physical sciences as domains of knowledge for which explicit connection to actual experience constitutes an annoying constraint from which they are ever more trying to liberate themselves.

Physical law is supposed to refer to larger and larger classes of experiences. The infant's first construction of space-time frames and notions of persistent objects and of causal connections between events constitute giant steps in this direction. Nevertheless, the fact remains that the physical sciences represent the actual or potential experiences and observations of individuals, in however abstract a form, and as such are as psychic as any emotion or sensation. Both the blue of a summer sky and the 4,400-angstrom wavelength of its light refer to experiential acts, differing principally in the affective components accompanying these acts and in their expressions. The statement is often made that "blue" is a private sensation that cannot be identified with another person's sensation because it is subjective. But the same is true for the size of a table. How do I know how large you see it? Indeed, your impression must be different from mine, if you are farther away from it.

A cybernetic circuit uses feedback from the external environment to help maintain a desired internal state. Here such a circuit is applied to the control of torpedo depth and to the production of handwriting.



Torpedo		**Writing**
Depth of torpedo below surface	X = Controlled variable	Actual script
Water pressure gauge	M = Monitor of X	Seeing of writing
Pressure gauge dial position	X' = M's measure of X	Seen script
Control element	G = Governor	Mental comparison
Setting of G	s = Setting of governor	Guiding mental picture
Rudder position	g = Governor output	Command to hand
Water waves, etc.	p = Perturbing input	Rough paper, worn pen
Depth control	C = Control point	Hand motion

p & s Free inputs
X→X' Rigidly coupled
X'→X Feedback loop

So we measure it with a ruler. But measurements of length — noting coincidences of marks on the ruler with edges of the table — are private acts too, being intersubjective, and hence comparable only to the extent that we have linguistic expressions for them.

It is the parsimony of the number of elements singled out for attention that makes the notion of duality of observer and observed so successful and gives the illusion in physics that the object is totally distinct from the observer. This distinctness is true in the sense that we do not mention the observer when we say, for instance, that the present temperature of the blackbody radiation left over from the big bang is 3 K, or that a supernova exploded 10^9 years ago. However, any such statement is linguistic in the first place and, as such, is meaningful only within the framework of the total scientific discourse, which reflects individual and collective experiences and acts.

Norbert Bischof pointed out that modern cybernetic machines, which are able to "observe," or take note of external reality, and "interpret," or adjust their internal reality adaptively, can be called on to demystify the relation between the Cartesian *res cogitans* and *res extensa*. Bischof asks us to consider a cybernetic circuit designed to maintain a present constant internal state in the face of a fluctuating external environment as shown in the figure at left. In this circuit a quantity x is measured by a monitor M. The monitor provides its measurement of x as signal x' to the governor G, which is set to maintain a level s. G compares x' with s, and gives an output g, either as an off-on or a graded signal. That signal acts at control point C to control the value of x which must be controlled because the system is subject to an external source of perturbation p. This circuit can be applied to a variety of situations, and Bischof considers the example of a torpedo that is to travel to its target beneath the surface of water at a preset depth. Let x be the actual depth of the torpedo, M the water pressure gauge, x' the reading from the gauge, s the setting of the depth control governor G, g the angle made by the rudder with the horizontal plane, C the control point for the depth control, and p the water waves. The perturbation p and the setting of the governor s are independent inputs into the circuit, while x and x' are physically coupled. The important point made by Bischof in presenting this example is not so much that the torpedo can be said to have a mind but that the same cybernetic circuit can also be used to control processes obviously involving "real" mental activity, for instance handwriting. When the circuit is applied to handwriting, x is the actual script and x' the seen script. Here there is a mental image of what is to be written, which the governor G compares with the seen script. The perturbation arises from rough paper and a worn pen. The lesson of this comparison is that in the case of the torpedo, we deal exclusively with physical quantities, while in the case of the writing, mental elements come into play, namely the perceived output of the pen doing the writing and the internal image with which the script is compared. Another application of such a cybernetic circuit to mental activity would be a tennis player's hand-eye coordination when trying to hit the ball. The eye sees the ball coming, the brain commands the arms and legs to make appropriate motions, the eye and proprioceptive apparatus contain the monitor M and correct this output by comparing it with an internal image in the governor G of what should happen — a feedback loop containing a conscious visual image as part of an interactive network.

Are we comparing processes that are not, in principle, comparable? I think not, because the difference between the mental and the physical is not at all a radical one, but one merely of degree. The depth of the torpedo, the reading from the water pressure gauge, the angle of the rudder, and so on refer to our spatial perceptions and as such include object and observer in their definitions. It is true that meter readings and settings lend themselves to quantification more easily than the mental images of an intended piece of writing or of hitting the tennis ball, and for that reason are more conveniently communicated either in ordinary or in mathematical language. In principle, however, all three are mental and all three are physical phenomena. The links in the cybernetic circuit are equally applicable to them, although when the circuit elements are not easily quantified they are less easily modeled. But modeling must be performed if we are to discover how valid an understanding of a situation is provided by a particular cybernetic circuit.

The distinction between external and internal reality — between subject and object — seems especially confusing when we consider phenomena in which the object is the

Delbrück uses his own cybernetic circuit to hit a tennis ball.

consciousness of ourselves or that of another person. Say you are thirsty. In what sense does your conscious sensation of thirst correspond to a physical quantity? In the sense that whatever thirst may be, it is something of which you can have more or less. In principle, therefore, thirst is measurable, either by behavioral tests or by physiological correlates. Admittedly, it may be useful to make a practical distinction between conscious and nonconscious phenomena. But as Bischof has pointed out, in the *res cogitans*, just as in the *res extensa*, some quantity a acts on another quantity b in a manner that augments, diminishes, or otherwise alters the influence of a third quantity c, which normally has this or that mental effect. We can take this for granted, even if we are unable to specify any procedure for measuring the quantities a, b, and c: they are defined simply by the cause-effect relation that links them to each other and to further, directly observable quantities. That is to say, they are defined by their position within the cybernetic circuit.

The resistance to considering consciousness on a par with physical phenomena seems to arise from our fear of the encroachment of science on the human person, an encroachment that would stifle and depersonalize us and thus open the way to our being used in inhuman ways. This resistance is a defensive stance often encountered in the humanities, where those who oppose the development of a science of man are afraid that the mind might be shown to be no more than a machine. Yet as we have seen, the antithesis of external and internal reality is merely an illusion: there is only one reality. Quantum mechanics has simply reminded us of this fact, which seems to have gotten lost in the abstractions of the physical sciences.

Do I deny, then, that there is any difference between knowing something — about animals in particular and humans most particularly — by extrospection from the outside and by introspection (direct in myself, or by empathy in others) from the inside? There certainly is a difference, but the gulf between the machinery of the brain, target of observations from the outside, and the mind, target of introspection from the inside, is not unbridgeable. If brain surgery is performed under local anesthesia, it is possible to converse with the patient while carrying out experimental procedures on the patient's brain. Wilder Penfield conducted many such experiments, in which he stimulated specific areas of the patient's brain by focal passage of electrical currents. In one case, a single stimulation of a particular area, and only that area, of the patient's cerebral cortex evoked the conscious recall of a particular memory, all the while the patient was consciously aware of being in the operating room. In another case, passage of current through one of the cortical areas dedicated to the production of speech made the patient unable to recall the names of certain familiar objects; when passage of the current ceased, the patient immediately regained the capacity to recall those names. These results show that the content of the conscious mind can be altered in a predictable way by direct manipulation of the brain from the outside. Moreover, quite unexpectedly they also show that such a crude interference with brain function as passage of electrical current through an area of cerebral cortex containing thousands of nerve cells can evoke enormously complex and highly organized mental events, rather than simply causing chaos as an analogous manipulation would do in a computer.

To summarize, the Cartesian cut between observer and observed, between inner and external reality, between mind and body, is based on the illusion that the physical world has no subjective component. This illusion arises from the high degree of quantitative reliability of scientific statements about the outer, physical world. Their quantitative reliability makes us forget that these statements are as related to subjective experiences as statements about the inner, mental world. In experiencing the physical world, we limit our attention to a narrowly circumscribed set of perceptions, such as those resulting from the reading of dials of instruments that measure such quantities as time, distance, or force. But in experiencing the mental world we include a wider repertoire of perceptions, not only primitive perceptions such as color, sound, and smell, but also higher level, complex perceptions of visual space in general and of gestures made by other human beings — their smiles, vocal or facial expressions of threat or fear or affection — in particular. While these higher level perceptions about mental states are less easily quantified than perceptions about physical states, they nevertheless fit into the same kind of cybernetic network of interactions. □

Catching Some Zs

by David Hitlin and Rafe Schindler

Ever since Empedocles in the 5th century BC classified the interactions between bodies, which he thought propagated by means of different effluences emanating from them, physicists have dealt with the fundamental phenomena of nature as if they were distinct. Modern physics has narrowed these phenomena down to four forces of varying strength and dependence on distance: electromagnetism, the strong and weak nuclear forces, and gravity. With the advent in the past decade of so-called Grand Unified Theories (GUTs), it has now become possible to contemplate a common origin for the first three of these forces. More speculative supergravity theories have also recently been advanced (*E&S* September 1985), which may lead to the eventual unification of all four types of interactions.

The search for experimental support for GUTs is one of the most exciting topics in elementary particle physics. As yet there is no direct experimental evidence to support the idea, but the attractiveness of the goal is seductive, and the search continues. A step below the GUTs is the theory based on the Lie groups SU(2) × U(1), which unifies the electromagnetic and weak interactions. This theory has already produced two Nobel Prizes — to Glashow, Salam, and Weinberg in 1979 for the theoretical work and to Rubbia and van der Meer in 1984 for the experimental demonstration of the existence of the fundamental gauge bosons of the theory — the charged W bosons and the neutral Z boson. Together with the photon, these particles are the carriers of the unified weak and electromagnetic force.

Even before observation of the W and Z particles, experimental support for this theory was impressive. Many phenomena, from parity violation in atomic systems to the scattering of high energy polarized electrons and neutrinos, are elegantly and consistently explained in this picture. Nonetheless, the actual production of the gauge bosons in high energy proton-antiproton collisions at the CERN laboratory in Geneva, Switzerland, in 1983 was greeted with enormous interest throughout the high energy physics community. Only a handful of Ws and Zs have so far been produced in this way, but this explicit demonstration of their existence has substantially bolstered confidence in the validity of the concept of a unified weak and electromagnetic force.

There is another way to produce W and Z particles, one that promises to yield vastly larger samples for study. This method is called electron (e^-)-positron (e^+) annihilation. The e^+e^- technique has produced a number of dramatic discoveries in the past, notably that of the psi meson and its relatives, which were found at the small SPEAR storage ring at the Stanford Linear Accelerator Center in 1974. The SPEAR machine is still generating exciting results; the current Mark III experiment, with which we are both associated, has been in the forefront of searches for exotic new elementary particles and in the study of the decay properties of charmed mesons.

The technique used in electron-positron storage rings is conceptually simple, but difficult to execute. A ring of magnets guides bunches of electrons and positrons (the antiparticle relative of electrons) in a circular orbit. Since the electrons and positrons have opposite electric charge, the same magnetic field can serve to guide them in circular orbits in opposite directions. At two or more points, called interaction regions, the electrons and positrons are brought into collision (hence the name "colliding beam accelerator"). In the collision the electrons and positrons may annihilate, forming a short-lived state with an energy that is the sum of energies of the electron and positron. This short-lived state then decays into a variety of elementary particles.

A typical experiment occupying one of the interaction regions of the storage ring consists of an apparatus that has the capability of identifying the types of particles produced in

Leptons — a family of elementary particles having no known substructure and participating in electromagnetic, weak (and gravitational) interactions.

Hadrons — the largest family of elementary particles (several hundred are known). Hadrons are composed of a quark-antiquark pair (mesons) or three quarks (baryons); they participate in all known interactions.

Quarks — the elementary constituents of hadrons. Five "flavors" (up, down, strange, charmed, and bottom) have been experimentally confirmed. A sixth, the top quark, is thought to exist, but experimental evidence for it is controversial.

Gauge bosons — the carriers of the forces between elementary particles. The unified electroweak force is carried by the massless photon, two heavy charged bosons (W^+ and W^-) and the heavy neutral Z^0. The strong force is carried by gluons.

Positron — the antiparticle of the electron. It is identical to the electron except for the sign of its electric charge and its lepton quantum number.

Muon — another lepton, 207 times the mass of the electron. It is unstable, decaying with a mean lifetime of 2.2 microseconds.

Neutrino — a neutral, very light (or massless) lepton that interacts only through the weak force. The neutrino interacts so weakly that its typical mean free path is 100 light years of water.

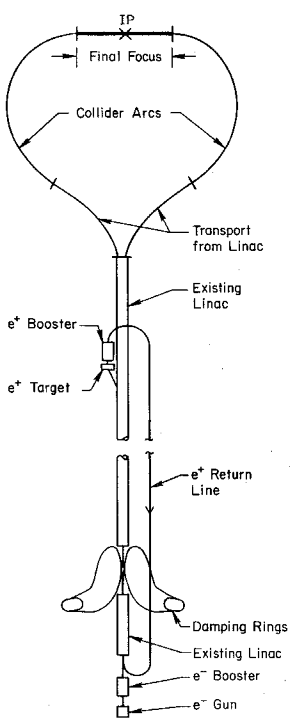
Pi meson — the lightest meson composed of one quark and one antiquark of the two lightest quark species, usually called up and down. It is the most commonly produced secondary particle in elementary particle interactions.

K meson — the lightest meson that contains a "strange" quark; it has 3.5 times the mass of the pi meson.

Psi meson — a bound atomic system composed of a charmed quark and an anti-charmed quark. It is most easily seen in electron-positron annihilation at a mass of 3.1 GeV as a spectacularly prominent narrow enhancement in the annihilation cross-section.

Upsilon meson — a bound atomic system of the next heaviest quark and antiquark, the bottom quark.

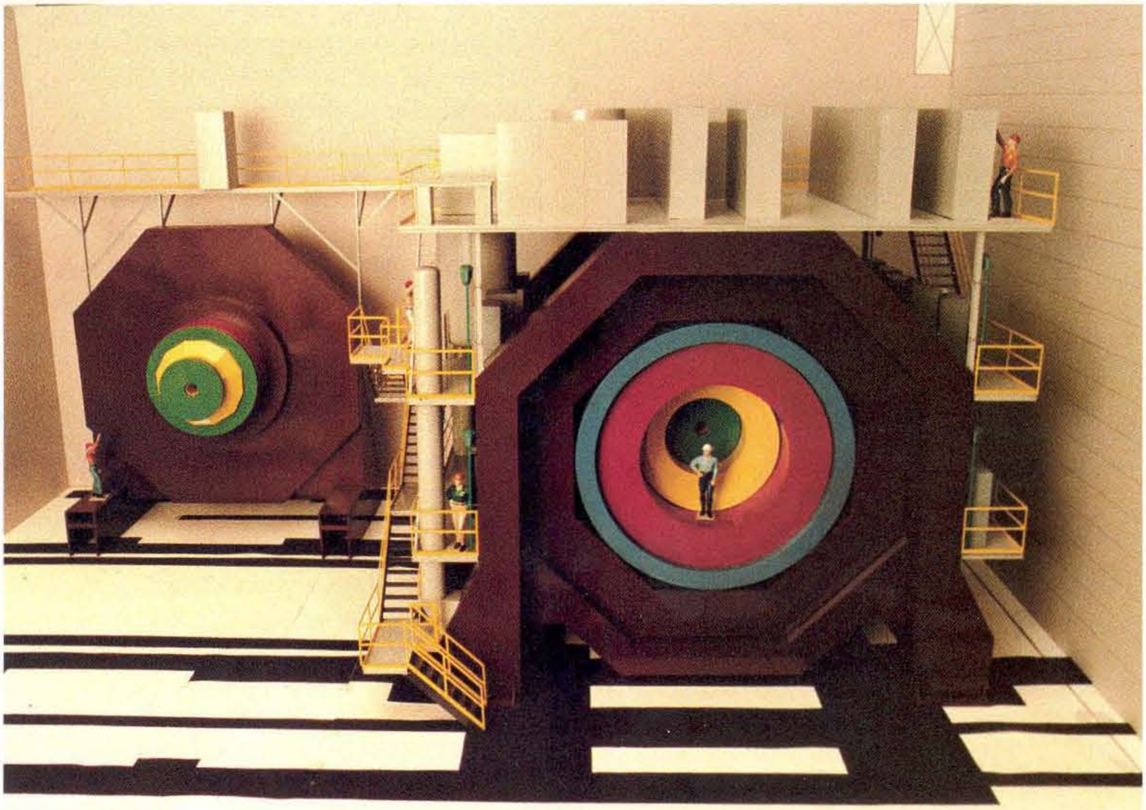
Supersymmetric particles — a class of new particles related to known particles in supersymmetric theories, a type of GUT. Each known particle has a supersymmetric partner in this scheme. Thus the photino is the partner of the photon, the gluino is the partner of the gluon, etc. Many of these supersymmetric particles interact weakly and so must be searched for by "missing energy" signatures.



The layout of the SLC is shown above. The e^+e^- beams from the existing two-mile linear accelerator (Linac) are introduced into the collider arcs and brought into collision at the interaction point (IP).

the annihilation and of measuring their directions and energies. The final states so produced are examined for evidence of new states of matter or are used as a particularly clean source to study the detailed properties of already known particles. One of the most interesting phenomena seen in the final states produced in e^+e^- annihilation are resonances. When the available energy (that is, the sum of the electron and positron energies) corresponds to the mass of certain new particles, there is a spectacular increase in the reaction rate. The psi meson was discovered in just this way. As the beam energies were tuned in very small steps, an unexpected increase of the number of interactions by a factor of a thousand occurred within a small energy region. The psi turned out to be a bound state of a new quark and antiquark, in this case the charmed quark. A few years later another resonance of this kind, called the upsilon (a bound state of the next heavier quark, the bottom quark) was found in a fixed-target experiment at Fermilab in Illinois and subsequently produced via e^+e^- annihilation.

Physicists expect that the most spectacular resonance of all — an increase of several thousand in the reaction rate — awaits them if they can build electron-positron colliders that can produce the mass of the Z^0 particle. The Z^0 is, however, 30 times more massive than the psi and 10 times more massive than the upsilon and will require large new accelerators to produce this much energy in electron-positron collisions. The obvious approach to the problem is to build a storage ring, such as the LEP machine under construction at CERN, of sufficient energy to reach the Z^0 regime. But this technique faces a problem intrinsic to the nature of electrons and positrons themselves. When light charged particles are accelerated (circular motion is continuous acceleration), they radiate electromagnetic energy, typically in the form of x-rays. This synchrotron radiation is an enormous technical problem; the radiated energy heats the vacuum pipe in which the electrons and positrons are circulating, necessitating elaborate cooling systems to remove the heat. Furthermore, the energy lost to radiation must be continuously restored to the beam. Since the synchrotron radiation loss increases rapidly with acceleration, gentle bends are required, and very large machines are the result. CERN's LEP storage ring, 27 kilometers in circumference, is generally felt to have reached the practical limit of this approach. Since electron-positron annihilation has been extraordinarily successful in exploring new physics at high energy, the abandonment of the technique due to the



In this scale model of the SLD detector the main body of the detector stands at right, and one of the two doors that close off the ends is on the left. The red cylinder is the barrel of the liquid argon calorimeter; the red of this calorimeter can also be seen in the end cap at left. The blue cylinder is the solenoidal coil that provides the magnetic field. Green represents the drift chambers that serve to track particles, while the yellow sections are the Cerenkov Ring Imaging Devices for particle identification. The large brown structure is the iron flux return for the magnet.

limitations of storage ring economics is not a happy prospect.

But there is a possible solution to the problem. Since the continuous repetitive acceleration due to circular motion is the source of the difficulty, it is tempting to think of an accelerator design that avoids this motion and the inevitable synchrotron radiation. Conventional electron accelerators, those whose beam is eventually delivered to a stationary laboratory target, have long been built as one-pass, straight-line devices — linear accelerators.

The two-mile linear accelerator at the Stanford Linear Accelerator Center (SLAC) is the largest machine of this type. Now nearly two decades old, it has had an illustrious history, serving both as a conventional accelerator and as a means of injecting electrons and positrons into the two SLAC e^+e^- storage rings, SPEAR and PEP. The two-mile accelerator is currently being converted into a new type of colliding beam machine called a linear collider (the SLC), in which electrons and positrons are produced, accelerated to high energy, and then introduced into circular arcs through which they travel only once, colliding at the interaction region. The repetition rate of the SLAC accelerator is 180 hertz, so there are only 180 opportunities per second for the electrons and positrons to interact, compared to the 45,000 opportunities per second at the LEP accelerator.

The measure of the brightness of the source in colliding beam accelerators is called luminosity. Since the luminosity clearly depends on the number of electron-positron crossings per unit time, the SLC is at a competitive disadvantage. The luminosity also depends on the current density in each beam, however, and it turns out to be possible to increase the current density in a linear collider over that in a storage ring by a large enough factor to achieve comparable luminosity. In the SLC this is done by having a large number of particles — as many as 10 billion electrons or positrons — in each accelerated bunch, and by making the transverse size of the beam bunches very small — a few microns in diameter. Techniques for achieving these very high currents and very small beam sizes have already been successfully demonstrated.

It thus appears possible to convert the existing accelerator into a linear collider with performance in the center of the mass energy regime of the Z^0, which is competitive with that of the LEP storage ring. This is an exciting prospect for several reasons: first, it can be done quickly, so that Z^0 studies at SLAC can begin several years before LEP is completed in 1989 or 1990; and second, the SLC can be viewed as a prototype of much larger linear colliders, which can extend the electron-positron annihilation technique to even higher energies where storage rings are economically impractical.

When the SLC begins to deliver beams for physics experiments in 1987, only one detecting device will be able to use the beam at any given time. The first such detector will be the Mark II, a device originally commissioned at SPEAR in 1978 and then moved to PEP. The Mark II is currently undergoing extensive revisions to enable it to cope with the more difficult experimental demands of the Z^0 energy region. Caltech is participating in this upgrade of the Mark II and will engage in the initial experimental phase of the SLC.

At the same time construction of a new detector, the SLD, which is specifically designed for Z^0 detection, has begun as a collaboration among several universities, including our Caltech group. The SLD is a much larger and more ambitious device, comparable to detectors planned for LEP. It will share beam time with the Mark II beginning in 1988 or 1989, ultimately supplanting it. The greater experimental capabilities of the SLD will be crucial in many of the most exciting experiments to be performed on the Z^0.

The Z^0 exists for only 10^{-24} seconds before it decays; we can investigate it only through the products of its decay. Since the decay of the Z^0 results in final states with many more particles having higher energies than previously produced in electron-positron collisions, this new generation of detectors will confront an unprecedentedly difficult experimental situation. The SLD detector is designed to cope with Z^0 decays through a variety of sophisticated subsystems. Measurement of charged particle momenta is accomplished by recording the radius of curvature of the particles in a 0.6 tesla solenoidal magnetic field by means of a large drift chamber, which measures position along particle tracks to an accuracy of better than 100 microns. Charged particle identification, that is, the classification of final state tracks as pi mesons, K mesons, protons, and so on, will be done with a Cerenkov Ring Imaging Device (CRID), which detects the angle at which Cerenkov light (a shock wave analogous to a sonic boom) is emitted when the particles pass through layers of carefully chosen gas and liquid. The largest detecting element of the SLD will be its calorimeter, which consists of two parts: a liquid argon calorimeter and an iron calorimeter which is integrated with the magnet flux return. Management of the design and construction of the liquid argon calorimeter, perhaps the most important single component and a $13 million undertaking, is centered at Caltech.

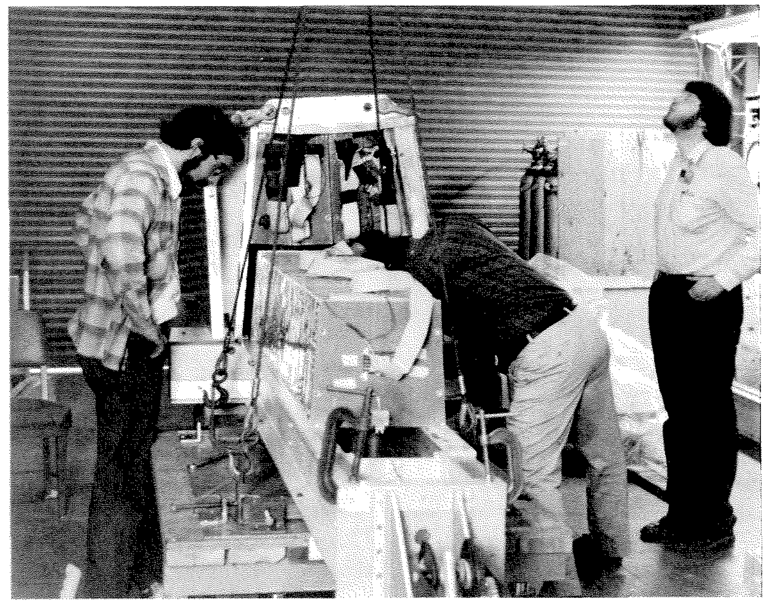
By measuring the total energy of all decay products of the Z^0, the calorimeter "takes the temperature" of each event, hence its name. This method of total energy measurement has several advantages. First, the technique is independent of the detailed structure of any particular event. It does not depend on the number or type of particles into which the Z^0 has decayed. Since events are very complex, the ability of the calorimeter to make this measurement independent of event type is particularly valuable. At high energies many detected events consist of jets — tightly grouped bunches of particles. Reconstructing the parameters of a jet by measuring the individual constituents can be difficult. A calorimetric measurement generally provides the most precise information on jet properties, because it does not require measurement of the parameters of the individual particles in the jet.

The primary function of the calorimeter, however, is the detection of "missing" energy. This somewhat paradoxical goal is the key to many of the more interesting experiments that can be carried out at the Z^0 resonance. Many of the new phenomena sought by high energy physicists as evidence for the validity of GUTs and related theories have a common signature. The new particles produced (in our case through the decay of the Z^0) are predicted to decay further in a characteristic fashion. A significant fraction of *their* decay products are particles such as neutrinos (or even other hypothetical objects such as photinos, gluinos, and Goldstinos), which interact very weakly with matter. The energy carried off by these particles will thus not be registered in the calorimeter. Comparison of the well-known initial-state energy (the mass of the Z^0, that is, the sum of the energies of the incoming electron and positron beams) with the total final-state energy detected by the calorimeter will show a discrepancy. This missing energy is the most powerful signature we have for the production of new particles required by unified theories. The discovery of the W boson at CERN was in fact made possible only by the use of an analogous calorimetric technique, which took advantage of the fact that the W boson decays into an electron or muon accompanied by a neutrino, whose energy is not registered in the detector.

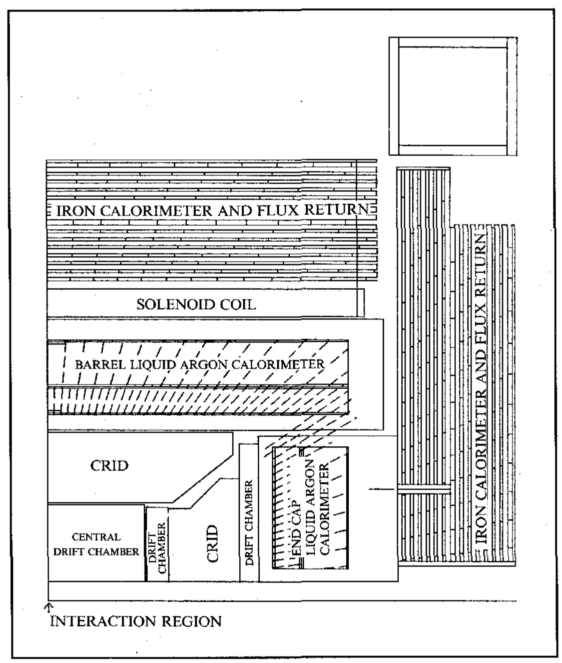
Construction of a calorimeter capable of identifying events with missing energy is no small undertaking. It is vital that the calorimeter be hermetic, that is, that it allow no detectable energy to escape. The calorimeter must therefore completely surround the interaction region and have no substantial leakage paths through the support structure or out the ends. The SLD calorimeter surrounds the interaction region with a large cylindrical annulus, called the barrel, 12 feet in internal diameter, 20 feet long and more than 3 feet thick. The ends of the cylinder are plugged by two end caps, also 3 feet thick. The complex internal structure of the calorimeter consists of more than a million individual elements. It has more than 50 layers of lead absorber and weighs more than a million pounds. Particles produced in Z^0 decay enter the calorimeter, interact with the lead, and produce showers of secondary particles. The energy of these showers is then detected by a sensitive medium consisting of very pure liquid argon at a temperature of 86 K. When the secondary shower particles pass through the liquid argon, they ionize it, producing an electric charge, which is then drifted in an electric field to collecting plates, amplified, and measured. The charge collected is proportional to the detectable energy produced in the Z^0 decay.

We want to measure more than just the temperature of the event; we must also find the direction and shape of the energy flow. The barrel and end caps are divided into segments, forming a projective structure much like the lenses of a fly's eye, which converge to a point. The 35,000 projective segments are formed by tiles of lead that are incorporated into alternate layers of the radiator structure and wired together into towers pointing in toward the interaction region. This allows us to measure both the direction and energy of all the particles in a collision. The complete calorimeter "sees" more than 99 percent of the neutral particles (photons) and about 97 percent of all the other types of particles that emerge from collisions.

Before deciding on the final design, we have had to perform an elaborate series of prototype studies to optimize the calorimeter's performance and to choose between alternative engineering approaches. Such a prototype program has been under way for the last two years. Last spring at Caltech we completed the construction of an eight-ton prototype of one section (about 1 percent of the total), which embodies most of the final design choices for the barrel calorimeter. We successfully tested this prototype in a beam of pions at SLAC in May and we are now working out the final design in detail. Actual construction will begin early in 1986 and will take three years. When completed, the SLD detector promises to yield new insights into the structure of the currently accepted theories of elementary particle physics and to provide one of our best opportunities to see beyond current ideas to the next level in our attempt to unify the forces of nature. □

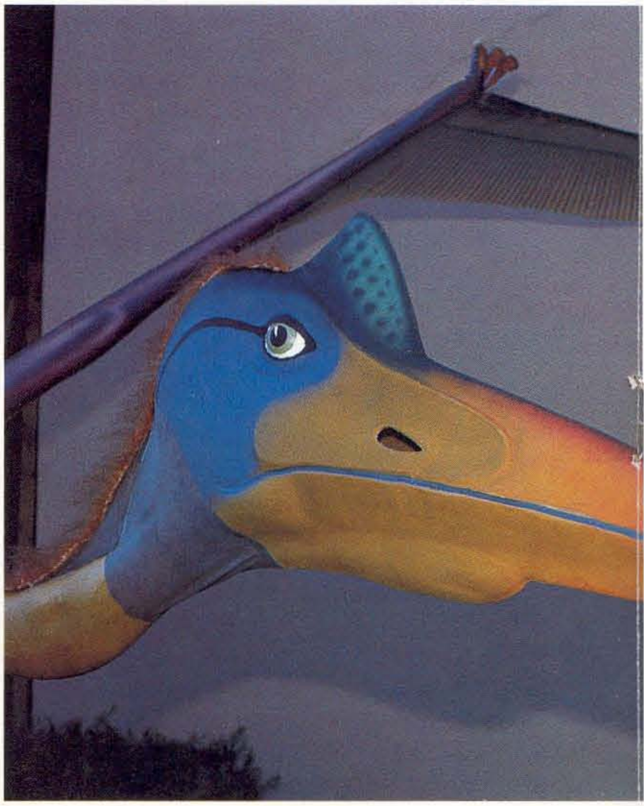


Dave Hitlin (center) peers into the prototype section of the liquid argon calorimeter for a final inspection before it is tested at SLAC. Rafe Schindler (left) and research fellow Gerald Eigen look on.



The diagram at left shows a vertical section in the plane (including e^+e^- beams) of one quadrant of the detector.

Alan Cocconi (left, BS 1980) and project manager Alec Brooks (PhD 1981) calibrate the angle-of-attack vane on the swing-wing development model of the pterodactyl.



Below — the half-size, lateral-control development model is pulled into the air by ground-based winch. The auxiliary tail is dropped away after release from the tow line. The small bump on the creature's back houses an emergency parachute — just in case.

by Paul MacCready

SOME 65 MILLION YEARS AGO, a gigantic pterodactyl — a flying reptile — lived in the region now called Big Bend National Park in west Texas. By remarkable good fortune, a few of its fossilized bones, which provide clues to its size and appearance, have survived and been found. These clues suggest that the creature, designated *Quetzalcoatlus northropi*, had a wingspan of 11 meters (36 feet) — the size of a four-person airplane. It is the largest natural flier known.

In late 1983 I realized that there had been recent advances in the aerodynamic theory of oscillating airfoils, in the theory and practice of stability and control, in robotics, mechanisms, sensors and servos, and in composite structural materials and techniques — advances that meant that perhaps now a flying replica of *Quetzalcoatlus northropi* would be feasible. So we decided to try it. A primary reason for mounting the project was to give people the chance to experience the awesome grandeur of this natural creation in a manner that could never be matched by looking at a static display or even an animated film. A zoo or nature park lets one

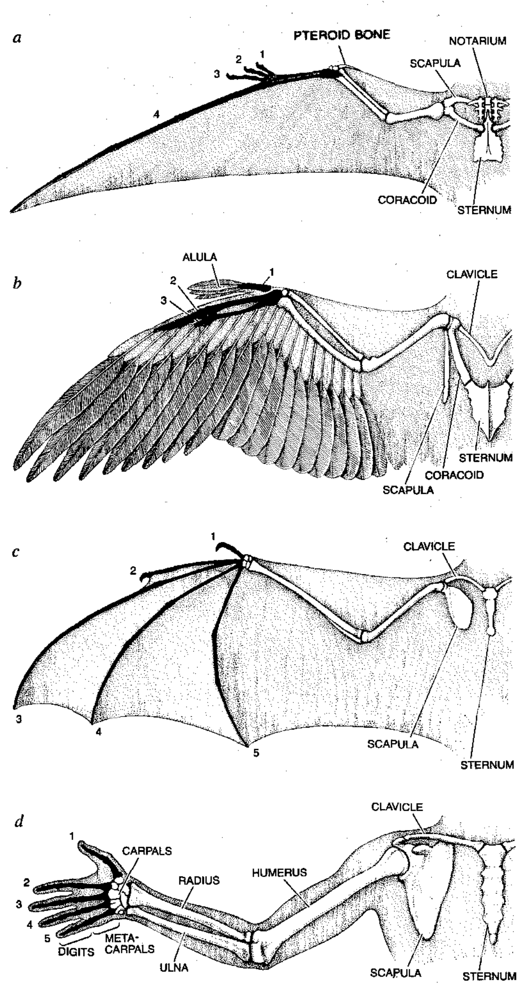
The Great Pterodactyl Project

observe modern living creatures; a natural history museum displays inanimate items from prior times. The flight of the pterodactyl replica would combine the "aliveness" of the zoo with the time grasp of the museum.

In April 1984 the Smithsonian Institution's National Air and Space Musuem initiated the project to build and fly the replica (called QN™), and subsequently the Johnson Wax company agreed to provide the major funding. The project team is based at AeroVironment, Inc., with outside consultants helping in specialty areas. One goal of the project is to fly the QN replica on the Mall in Washington, D.C., in June 1986 in conjunction with the opening of the National Air and Space Museum's IMAX film, "On the Wing," also funded by Johnson Wax. The QN replica will play a significant role in the film, which explores the connections between nature's fliers and aircraft.

The fossil remains of *Quetzalcoatlus northropi* had been found in 1972 in west Texas by Douglas Lawson, working with Professor Wann Langston, Jr., at the University of Texas at Austin. Two groups of fossils were found. The first group contained only fragments of half of the bones of one wing and one neck vertebra. The other group, 50 kilometers away in distance and an unknown difference in time, contained fossil remains of at least a dozen smaller creatures. The common fossils from both groups were nearly identical in shape, differing only in size. Both groups were given the genus name *Quetzalcoatlus* after the Aztec feathered serpent god, Quetzalcoatl. The species of the larger animal was named *northropi* after the Northrop Corporation, which had built several giant flying wings. The smaller animals have not yet been assigned a species name and are referred to simply as *Quetzalcoatlus* sp.

On the basis of rather complete sets of bones and from extrapolations from *Pteranodon*, a somewhat differently shaped pterodactyl, the wingspan of *Quetzalcoatlus* sp. was estimated to reach 5.5 meters. Early estimates of the span of *Quetzalcoatlus northropi* wings ranged from 11 to 21 meters, but as we kept reviewing the subject, with inputs about the engineering limits of muscles, tendons,



The wings of a pterosaur (a), a bird (b), a bat (c) and the arm of a man (d) indicate evolutionary variations on a theme. Adaptation to successful flight took several different routes.

and delicate hollow bones, the estimates edged toward the lower end of the range.

Roughly 85 known species made up the order *Pterosaurus* of flying reptiles. A suborder, *Rhamphorhynchoidea*, appeared 200 million years ago. They were rather small, some the size of sparrows, and featured short heads and necks and long tails. The other suborder, the *Pterodactyloidea*, emerged 50 million years later. These had long heads and necks, were almost tailless — and large. The *Quetzalcoatlus* species were pterodactyls, as was *Pteranodon*, whose wingspan reached seven meters. Many pterosaurs had crests on their skulls; in *Pteranodon* the crest reached an extreme size, doubling the length of the skull in some cases. In other fossils the crest was apparently lacking. If the lack arose from the animal not having a crest, rather than from the imperfect preservation of fossils, this casts doubt on the use of the crest for some operational function — such as to balance the head, to reduce loads on the neck, or to add to yawing forces or drag during maneuvering. The large pterodactyls had, relative to size, bigger brains than did the smaller, more primitive pterosaurs and reptiles; nature apparently found it an efficient tradeoff to increase brain size at the expense of eliminating the tail.

Similarities between the wings of a pterosaur, a bird, and a bat, and the arm of a human bespeak their common ancestry. The adaptation of biological flight, wherein the laws of aerodynamics and muscle strength and the structural realities of tendons and bones must prevail, designs the configuration. From different starting points there are a variety of routes leading to successful flight.

The pterodactyls were apparently dying out toward the end of the Cretaceous period, the last portion of the Mesozoic. This was a time of substantial changes in climate and habitat. *Quetzalcoatlus northropi* may have been the last to depart. The timing of the final disappearance of the pterosaurs may well have coincided with the great extinction about 64 million years ago. Whether or not this event was attributable to a large meteorite striking the earth, the catastrophic consequence of *some* special event is unquestioned; half the species of flora and fauna disappeared, including all land and flight animals larger than about 23 kilograms. Some birds and pterosaurs occupied equivalent ecological niches a hundred million years ago. The pterosaurs died out after evolving some extremely large forms. The birds proved to be more adaptable to the changing world, and they survived. Much later a huge bird emerged — the Giant Teratorn. This vulture-like bird, with a wingspan over seven meters and probably weighing well over 80 kilograms, was found as a six-million-year-old fossil and may represent the heaviest creature to have flown. Some extinct flightless birds were much heavier still.

The physical laws of aerodynamics determine the minimum power required for a flying device, animal or man-made, as a function of its shape, size, and weight. In comparing many large birds, we find that the muscle power available per kilogram for propulsion actually decreases with increasing weight. However, the power *required* per kilogram increases slowly with increasing weight. This is a consequence of the fact that for flight vehicles of the same shape and density, the larger ones fly faster because they have to carry more weight per square meter of wing area. If you double the dimensions of such a vehicle, the wing area goes up by a factor of 4, weight by a factor of 8, and the speed and the power required per unit of weight both increase 1.4 times.

Birds that are primarily soarers do not have much margin of power beyond that needed for takeoff and brief climbing and cruising to locate upcurrents in which to soar. Power required and power available are closely matched. Therefore a bird that grows much larger will end up with inadequate power unless there are some refinements not yet considered. There are three refinements available: (1) as size and/or speed increases, an aerodynamic scale effect comes into play and yields slightly more efficient wings; (2) the creature can alter its configuration to be more efficient, becoming, say, more like a sleek sailplane; and (3) the weight can be kept below that which would be expected if the density stayed constant as the bird grew in all three dimensions. We suspect that *Quetzalcoatlus northropi* needed all three approaches, with the lighter weight effect being especially important. The thin walls of the wing bones indicate a very light structure. They are delicate tubes, and other parts of the creature were fashioned with comparable delicacy. Thus, in spite of its large size, its wing loading and power required per kilogram might have been about the same as for some modern vultures.

There has been speculation that *Quetzalcoatlus northropi* was a poor flier and could take off only by launching from cliffs or trees and fly by gliding. Paleontologist Kevin Padian of UC Berkeley, who has studied pterosaurs extensively, suggests that the legs of pterosaurs were more like those of birds and dinosaurs than was previously assumed. For *Quetzalcoatlus northropi* the takeoff and flight characteristics and behavior are envisioned as those that might appear if one combined various features of a frigate bird, an albatross, a pelican, and a stork or crane, and then increased the size about sixfold, decreased the density somewhat, and cut the wing flapping rate down to one cycle every two seconds. The original was deemed to be able to walk and take off from flat ground without wind, climb weakly, and stay aloft for long times and distances by soaring on upcurrents. It did not land and take off from water, although it may have been able to snatch fish from near the surface while it remained flying. In spite of its gargantuan size, its wing loading and hence flight speed were comparable to those of existing large soaring birds. It did not have teeth, although many of the smaller pterosaurs did. Perhaps it hunted small aquatic creatures as it wandered the shallows. Its full diet and many other aspects of its life style are unknown. We look forward to the discovery of further fossil evidence, which can augment our present knowledge and support or correct our conjectures.

Before the giant pterosaur's discovery, the size limits for biological flight were assumed to be much lower than an 11-meter-span flier. But nature is no respecter of performance limits assumed by man for biological creatures. To arrive at a consensus about the size, shape, and operating features of *Quetzalcoatlus northropi*, as well as to assess the overall feasibility of building and flying the QN replica, we convened a workshop at Caltech in July 1984. The workshop brought together experts in paleontology/paleobiology, ornithology, aerodynamics, vehicles/mechanisms, and other disciplines. We arrived at a design consensus amicably but without great confidence because the fossil record was so sparse. The consensus configuration that emerged had the following physical specifications:

Span	11 m (36 ft)
Wing loading	8 kg/m^2 (1.6 lb/ft^2)
Area	8 m^2 (86 ft^2)
Weight	64 kg (140 lbs)

The version we will actually be building will weigh 15 to 20 percent less, and hence have a 15 to 20 percent lower wing loading. This gives it a 7 to 10 percent lower flight speed and helps to provide for gentler landings and easier flight testing, while still being in a possible range for the specific original creature.

There was general agreement at the workshop that, among the many technical challenges, two in particular stood out: (1) obtaining stability/control around all three axes for a gliding QN replica, and (2) adding propulsion via wing flapping, sufficient for a gentle climb, to the gliding version.

The stability/control challenge arises for several reasons. First, *Quetzalcoatlus northropi* had no horizontal tail to help with stability and control in pitch. Also its wing appears to be unstable in pitch, inasmuch as it has undercamber and little sweep; so the wing can be considered more a part of the problem than part of the solution. Second, there is no vertical fin or rudder to help with yaw trim, and it has a long neck and large head (large when viewed from the side, especially if a crest is assumed), which are destabilizing. Roll control via wing twist does not pose a basic problem.

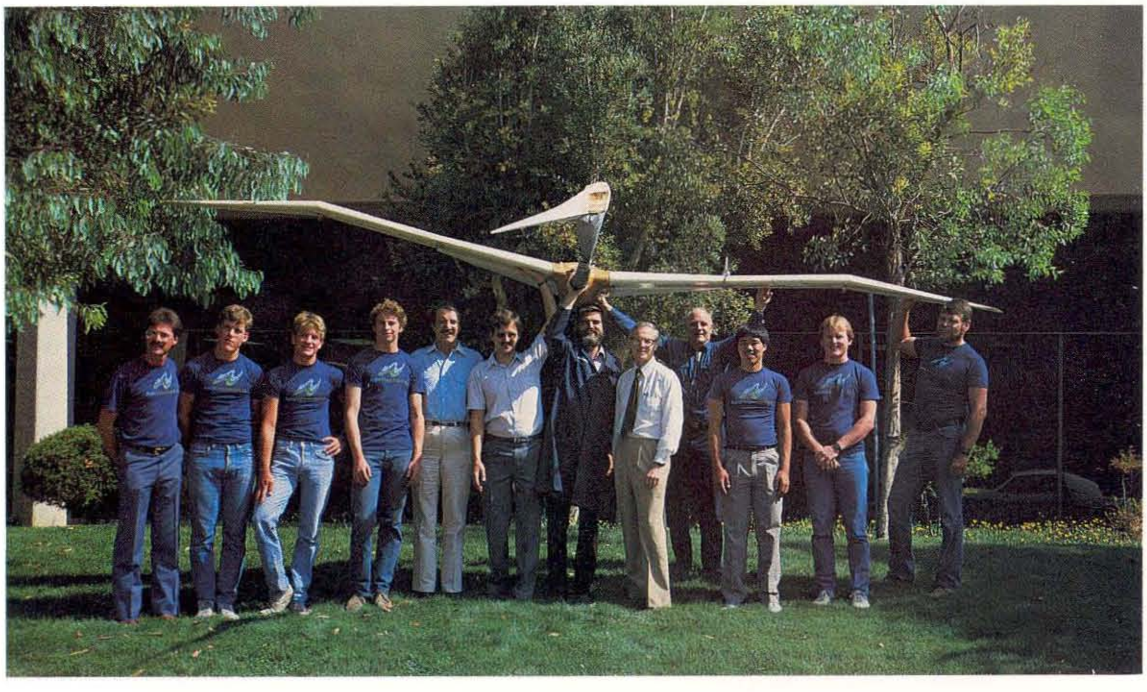
Adding propulsion via wing flapping presents many mechanical and structural challenges. However, the details of wing flapping, with the associated twist magnitudes and phasing, are not considered critical. If the flapping is done inelegantly, propulsion efficiency will be low, but this can be compensated for by installing more power. The bigger question involves the interaction between wing flapping and pitch stability and controllability. Will the flapping upset the vehicle in pitch? Perhaps, but there are various approaches to solutions. We have confidence in our ability to achieve a final satisfactory result because nature provides so many successful role models. The albatross, with essentially no tail, is certainly stable in pitch during its efficient cruising flight. It is reported that some moulting birds can fly and maneuver without a tail by moving the wings forward and back. Active control presumably permits stable flight; small fore-and-aft movements of the wing continually adjust the position of the center of lift relative to the center of gravity, just as a person on a bicycle is unstable and remains upright only because of continual steering corrections, which quickly become automatic.

Questions remain about the airfoil shape and the aeroelasticity of the wing of the replica. The airfoil behind the spar may be primarily a membrane, as with a bat, hang glider, or sailboat. Aerodynamically, a reflexed trailing edge (upward camber) could be best for helping pitch stability, but this would require ribs or battens or even a more solid structure. There are some rare clues about the flesh and membrane portions of pterosaurs for small specimens, suggesting that the membrane does have some rigidity, opening up the possibility of an airfoil with "nice" characteristics, but the extrapolation of such structures of giant pterosaurs is subject to question.

Recreating *Quetzalcoatlus northropi* involves designing, building, and testing a number of flight models of increasing size, complexity, and accuracy of reproduction of pterodactyl features. We are also continuing to search the literature and to talk with people who have built wing-flapping models and gliding pterosaur replicas. The relative lack of literature on birds' pitch stability and control forced us to mount some actual bird flight investigations with still and video cameras.

This latter research has gotten us more acquainted with the evolution of the structure and control of biological flying devices and given us a healthy respect for the elegant way nature has solved all the operational problems. Nature has been designing birds and other flying creatures for at least 150 million years. The task has obviously been well done. Design features meet a survival purpose, some by way of aerodynamic efficiency,

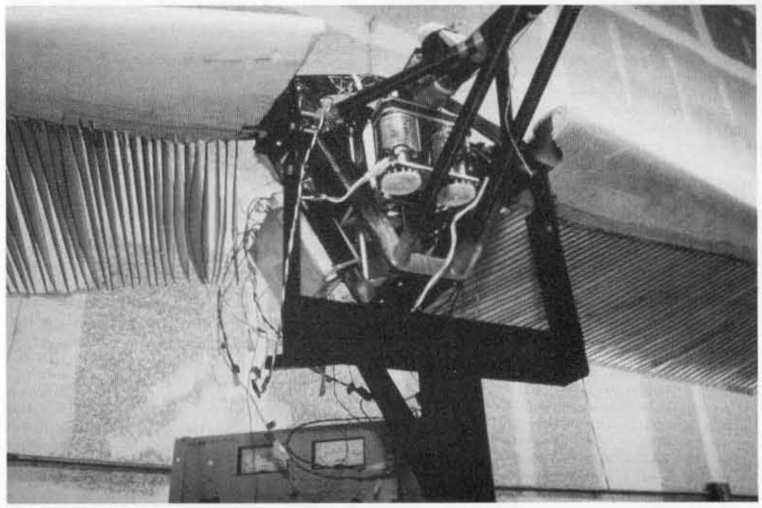
The project team includes (from left) Martyn Cowley, Adam Curtin, Mark Hawker, Tyler MacCready, Peter Lissaman, Alec Brooks, Ray Morgan, Paul MacCready, Henry Jex, Lance Inoue, Bob Curtin, and Les King. Not pictured are Dave Busch, Parker MacCready, and Alan Cocconi.

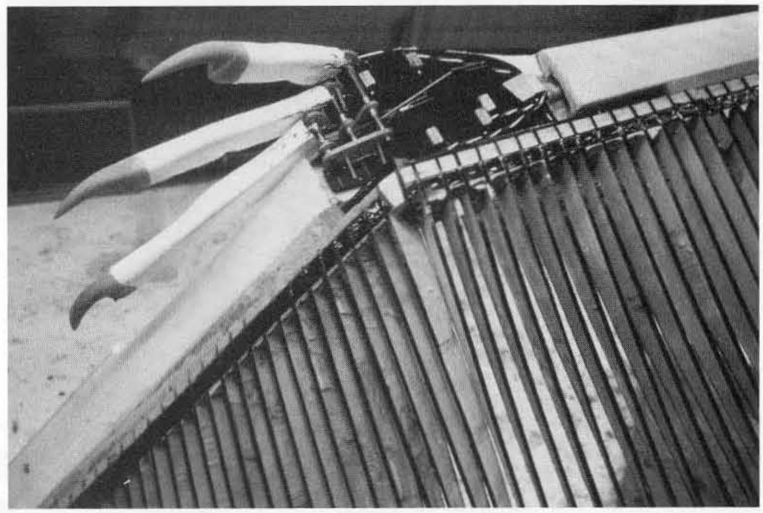


others by way of biological adaptability or sexual selection. Thus a bird has elegantly handled the aerodynamic problems such as boundary layer control, stability, and sensors. Basic study of bird aerodynamic features may be expected to yield valuable dividends to both research aerodynamicists and engineers.

After the workshop a series of small (two-meter-span and less) gliders were tested that had configurations analogous to *Quetzalcoatlus northropi*. These gave initial clues as to reasonable sweep, twist, and airfoil compromises. Some 1-meter and 2-meter-span wing-flapping models were also flown. Next a 3.7-meter-span model was constructed. It was made flexible and extremely strong so that it could survive the expected (and achieved) rough landings and crashes inherent in a development program. It was finally equipped with radio control and launched by tow line. The conclusion drawn from its testing was that, with a bit of sweep forward to the wings, with some trailing edge reflex, and with appropriate twist, static pitch stability could just barely be achieved with a configuration having poor but perhaps adequate efficiency. But the pitch control operated with too little authority to be practical. The inescapable conclusion was that pitch control had to come from wing sweep movement. The head and neck are too slender in planform to permit their use as a forward control surface the way a canard stabilizer (forward horizontal surface) operates on some aircraft.

We then built a 2.5-meter-span, radio-controlled glider. It had a standard configuration but incorporated a mechanism for sweeping the wings, in flight, forward and backward from the root. During initial flights this provided the sole pitch control, while a normal horizontal stabilizer at the rear was in place to help with stability and damping. Then the stabilizer was replaced with smaller and smaller ones, and the glide tests continued to the "almost-no-tail" configuration. During these flights the "brain" on the vehicle was an autopilot incorporating a pitch-rate gyro and an angle-of-attack vane as sensors. The autopilot characteristics were developed by Henry R. Jex (MS 1953) of Systems Technology, Inc., using advanced aircraft computer analyses utilizing the dynamics of the flight vehicle, the sensors, and the servos. All in all, theory agreed with experiment and set the stage for the next vehicle — the half-size (perhaps youthful) version of *Quetzalcoatlus* with a 5.5-meter wingspan.





Top — the wing-flapping mechanism consists of two one-horsepower samarium-cobalt DC motors (the round objects in foreground), which drive the flapping through a gear box and ball screw drive. The mechanism is normally powered by six lbs. of nickel-cadmium batteries, but for testing here a 50-amp power supply is used.

Bottom — The finger motions of the hand halfway out the wing act as spoilers and drag breaks and operate on only one wing at a time to provide yawing moments. Each finger is driven by a small model-airplane servo.

The first version with a pterosaur configuration had a semi-rigid wing (for gliding only) and was aimed at demonstrating lateral control. A sensor detects vehicle yaw, the head is turned to produce a correcting yaw force, and a hand (spoiler) half way out on the leading wing can create drag and reduce lift. It has ailerons on the trailing edge of the wing. Launched by electric winch, this rudimentary pterodactyl was flown successfully in August.

The final wing-flapping version, the same size as the lateral-control development model and weighing more than 15 kilograms, was recently completed and is currently being flight tested. The flapping mechanism requires three independent motion controls: besides flapping, wing twist is to be used for achieving the appropriate flapping lift distributions as well as for controlling roll; wing sweep is to be used for controlling pitch. The replica has an actuator system powered by nickel-cadmium batteries, but will still be launched by electric winch. For landing, it glides gently down to land on a skid on its stomach. The head is tilted upward just before touchdown, so if the pterodactyl pitches forward on contacting the ground, the rounded, rugged front of the neck coasts along the ground, protecting the vulnerable head and its actuating mechanism.

This version also looks like a realistic *Quetzalcoatlus northropi* (at least as far as anyone knows). The wing structure uses carbon fiber and foam with latex covering. This structure is strong and flexible and, when painted, looks very "biological." The 5.5-meter replica was chosen as a stepping stone toward the final replica because it's small enough to keep construction costs low, large enough to model the dynamics, structure, and autopilot of its larger relative, and actually could represent a younger version of *Quetzalcoatlus northropi.* The final goal is to produce the QN replica with its 11-meter wingspan. We do not expect the doubling in size and six-times increase in weight to affect its efficiency and controllability significantly.

Will the recreation of the flight of *Quetzalcoatlus northropi* be accurate? The paleontological evidence will always be too sparse to give us all the answers we want about configuration, flight mode, and appearance. However, the requirement that the replica fly like the original introduces aerodynamic and structural constraints that should tend to move the reconstruction toward reality.

We will be satisfied if the replica, viewed from 50 to 100 meters away, can be mistaken for the real thing as it flies. We don't intend to have it take off unassisted. The complexity of developing a leg mechanism for stable running is far beyond the scope of this project. The battery and motor systems for controls and wing flapping will be capable of permitting climb and level flight for five minutes, and of course for longer flights if soaring is used.

Everyone has daydreamed about being a time traveler, able to observe at first hand events of long ago. We cannot physically go back in time, but we can create mental images of the past and make the images stronger through books and art and moving reconstructions with film or replicas. In making its journey over tens of millions of years, a time period we can quantify but scarcely comprehend, QN — The Time Traveler,™ will allow us to look more openly and appreciatively on nature's engineering of flora, fauna, and the earth and cosmos. □

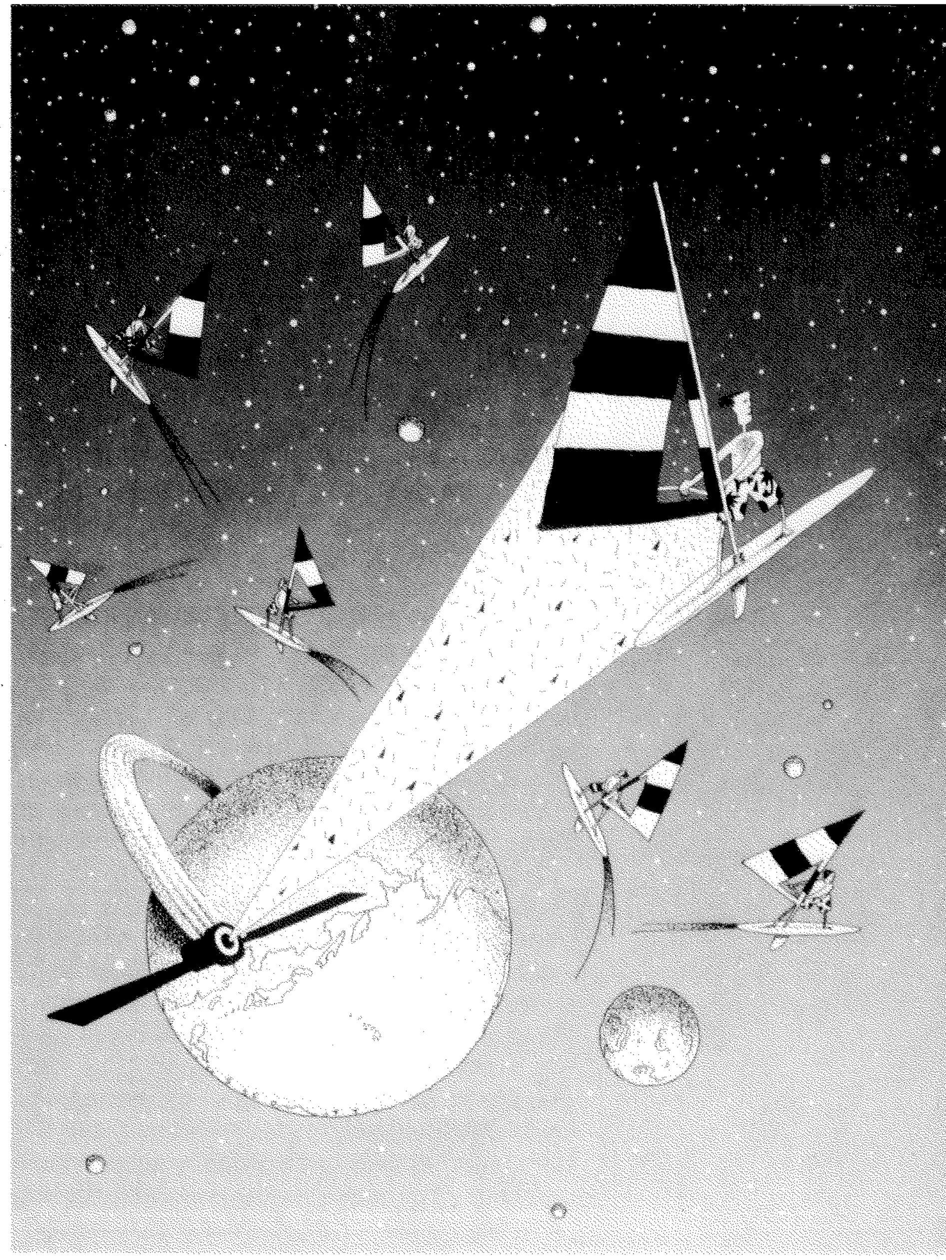


Illustration by Julie Scott

Interstellar SURFing

We may soon be traveling to the stars, at least by proxy, thanks to a group of seven Caltech undergraduates. Participants in the Summer Undergraduate Research Fellowship (SURF) program, the students investigated the possibility of sending an unmanned probe to a nearby solar system. They considered methods of propulsion, the types of instruments the probe should carry, and the best means of communicating the probe's data back to Earth. They wanted to design a spacecraft that could feasibly be launched in 50 years or so, one that would reach the nearest stars in a reasonable amount of time. This requires a final velocity of at least one-tenth the speed of light for a 50-year mission.

The design work on the probe is far from complete — there remain fundamental disagreements within the group on which propulsion system is best, for example — but a look at how these students spent their summer vacation affords an interesting glimpse at the earliest stages of one of humankind's greatest adventures. The sponsors for the project are Joel G. Smith, JPL's manager of telecommunications and data acquisition technology development, and Edward C. Posner, a member of the JPL staff and visiting professor of electrical engineering. There was also a JPL advisory board consisting of specialists in propulsion and engineering. The SURFers themselves are Allen Gee, Ara Kassabian, Charles Neugebauer, Stephan Pietrusiak, Dana Pillsbury, Gino Thomas, and Stephen Winters.

Of the three main aspects of the problem — propulsion, payload, and data communications — the first is certainly the most critical. The choice of propulsion system determines whether the probe will reach its destination in 10 years or 200 years and whether the probe will be able to carry 1 kilogram or 10,000 kg worth of scientific instruments.

An antimatter annihilation drive presents by far the most attractive possibility, at least on paper. In such a system, fully 61 percent of the fuel mass is converted directly to energy. (This compares with 0.4 percent for fusion and 0.07 percent for fission.) Ara Kassabian evaluated both electron-positron and proton-antiproton propulsion systems and discovered that, while both work in theory, electron-positron propulsion is probably unworkable in practice. The problem is that the products of electron-positron annihilation are two gamma rays. The only way of expelling these uncharged particles out the back of the spacecraft to produce propulsion would be to use some sort of mirror. But the gamma rays would be certain to burn up any physical mirror. Says Kassabian, "You'd have to have a really fancy kind of electron cloud mirror. There are a few that have been proposed, but they don't seem to work that well."

Proton-antiproton annihilation, on the other hand, produces pions and kaons. Two-thirds of these particles carry a charge, and can therefore be reflected with magnetic fields. Just 331 kg of antiprotons could accelerate a 10,000 kg spacecraft to a tenth of the speed of light (0.1c). And the quantity of antiprotons could be reduced significantly if the annihilation energy were used to heat a propellant, which in turn would be expelled out the back of the spacecraft. In such a scheme, the same 10,000 kg ship would require only 39.75 kg of antiprotons to reach 0.1c, but it would have to carry about 40,000 kg of propellant.

Unfortunately, 39.75 kg of antiprotons is a bit hard to come by, for antimatter is one of the most costly commodities in the world and one of the rarest in the universe. Present-day antimatter production is extremely inefficient and highly energy intensive. Even if present efficiencies were to be upgraded by three orders of magnitude, as is expected in the not-too-distant future, antiprotons would still cost about a million dollars a milligram. The spacecraft's fuel alone would thus cost an astronomical $40 trillion. This cost would have to come down by at least a factor of a thousand to make antimatter propulsion even remotely conceivable.

One of the great attractions of an antimatter-propelled ship is its extremely low mass ratio — the ratio of the mass of the fully fueled ship to the mass of the ship after its fuel has all been expended. The lower the mass ratio, the less energy is wasted in accelerating the fuel itself. Several propulsion systems that make use of nuclear fission or fusion also have acceptably low mass ratios, but they have their own problems.

Fusion engines, for example, could produce a large amount of energy from a small amount of fuel, but fusion is still in an early stage of technical development. And it requires drastic conditions to get a fusion reaction going: a small bit of deuterium has to be either compressed by a huge magnetic field or subjected to inertial confinement and bombarded on all sides with extremely powerful laser beams produced by extremely bulky lasers. So even though a fusion-powered vehicle would use a relatively small amount of fuel, the engine would be so large that much of its energy would be wasted in accelerating its own enormous mass.

Several schemes employing nuclear fission seem to hold more promise. One idea, worked out by Kassabian, is based on the Orion Project developed by Freeman Dyson and Theodore Brewster Taylor. The Orion Project involves an immense manned interstellar spacecraft, propelled by atomic bombs that explode, one after the other, at the ship's back end. (Gino Thomas appreciates the economy of such a scheme. "You kill two birds with one stone. You go to the stars, and you also get rid of a lot of nuclear bombs.") Dyson and Taylor designed a scaled-down prototype of Orion, designated "Putt-Putt," and Kassabian's idea for an unmanned ship is scaled down further from this; he calls it the Tuff-Tuff engine.

The Tuff-Tuff engine uses fission microexplosions to propel the vehicle. The fission fragments from these explosions compress a magnetic field produced by a superconducting coil, and the compressed magnetic field pushes the vehicle forward. The microexplosions would be produced in small pellets of uranium 235, each with a mass of only 0.02 grams. Since the critical mass of ^{235}U is 20 to 40 kg, the pellets need an external source of neutrons to get the chain reaction going. This would be provided by a jacket of californium 252, which in turn would be surrounded by beryllium 9, a neutron reflector. The californium is one of the weak links in this scheme. It costs $100 million per gram.

But the most serious problem with the Tuff-Tuff engine is that when the microexplosion starts, the pellet will rapidly expand, the neutron density will rapidly decrease, and the fission reaction will quit after only a small fraction of the uranium is consumed. Even present-day atomic bombs have an efficiency of only about 0.8 percent, and the efficiency of the micropellets is likely to be worse, although Kassabian has found this difficult to determine since much of the relevant data is classified.

Another scheme, called the Vulpetti engine, could overcome the low efficiency problem. In this design, jets of ^{235}U are exposed to a neutron source. The reaction fragments are redirected by a magnetic field, and the unburned uranium is recycled. The problem with the Vulpetti engine is that it's extremely complex, even in theoretical form. Says Kassabian, "When you draw up plans for a rocket it may look simple on paper, but when you give it to the engineers, they give you a blueprint that's miles long. So if the plans are complicated to start with, it's probably going to be unworkable."

Some of the students considered the possibilities of nuclear electric propulsion (NEP), a type of ion drive. In an NEP thruster the fuel — mercury is one possibility — is first ionized and then accelerated through grid electrodes and out the back of the ship. The fuel itself contributes no energy. The energy is supplied by a fission or fusion power plant aboard the ship whose function is to hold the grid electrodes at a very high electrical potential. In order for this design to be workable, however, present-day ion thrusters would have to have their power supply mass ratios improved more than three orders of magnitude: from 0.05 to 100 kilowatts per kilogram. And even then, the spacecraft would take 225 years to reach Proxima Centauri, the nearest star.

Several of the SURFers favor spacecraft powered by external laser or particle beams. The main advantage of such schemes is that the spacecraft would carry no fuel whatever. The beam would use between 10^{11} and 10^{15} watts of power for several minutes to several months — total world power output is currently about 10^{12} watts — and would be placed in Earth or moon orbit. Although laser or particle beams of this strength do not yet exist, the Strategic Defense Initiative (also called Star Wars) may soon make them available. The spacecraft itself would have a sail-like structure against which the photons or charged particles would push, accelerating it to high speeds. Since most of the expense in a beam-rider spacecraft would be in the power source, it's possible that many such spacecraft could be sent out sequentially, all in different directions.

If a laser were chosen as the power source, it would have to be focused onto the spacecraft's light sail by an immense lens system 100 kilometers in diameter. The sail would be about 40 meters in diameter and the photons would accelerate the 100 kg ship at 80*g* for two months. The ship would reach Proxima Centauri (4.2 light years away) in just 17.5 years. The laser beam's high temperature presents some problems, though. It could melt its own optical system, and even if a way were found around this, the beam would heat the spacecraft itself, possibly causing damage to delicate components.

Heating would not be a problem with particle beam acceleration, since the particles never make physical contact with the sail, which in this case would be a charged plate of some sort. But particle beams have their own problems. If a beam of positively charged protons were sent out, for example, electrical repulsion would quickly cause the beam to spread out, dissipating its energy. To get around this, Allen Gee conceived a scheme in which electrons could be added to the protons, so the beam would essentially be sending out a stream of hydrogen atoms. The spacecraft would then have to strip the electrons, and the remaining protons would push against a positively charged plate. But even then such a beam would diverge quickly due to random collisions, unless its temperature were kept very low — on the order of 10^{-5} K. To avoid the problems of beam divergence, the ship would have to be accelerated very rapidly. In one scheme a 10^{15}-watt beam would accelerate a 100 kg ship at $10^4 g$ for just five minutes to reach a speed of 0.1c. Of course, all the spacecraft's components would have to be built to withstand such high accelerations.

Although getting the spacecraft to another solar system is the biggest problem, the SURFers also investigated what it would do once it got there. Virtually none of the scenarios assume a rendezvous mission (the NEP drive scenario is an exception) so the spacecraft will zip through the other solar system in at most a few weeks. And the instruments will have to be very compact and lightweight; in many of the scenarios the spacecraft will only be able to carry 10 kg worth of instruments. This may not be a problem, according to Dr. Posner. "Ten kilograms these days is a lot. At less than half a kilogram, for example, you can get a portable cellular telephone with a battery, an antenna, a 99-digit memory for telephone numbers, the entire FM transmitter and receiver, and an error correcting code, and it all fits in a space smaller than two cigarette packs. And

that's today, not 50 years from now. It isn't clear that the spacecraft is going to have to be much more complicated."

Since the spacecraft's main objective will be to characterize the star and any orbiting planets, it will have to carry an imager of some sort. Using the Sun-Jupiter system as a model, Gino Thomas tried to determine the best way to pick out a planet like Jupiter at a reasonable distance. The Sun, of course, is much brighter than Jupiter at all wavelengths of light, but Jupiter shines brightest relative to the Sun at a wavelength of 21 micrometers in the infrared. At this wavelength the Sun is only 1,000 times as bright as Jupiter. Given this wavelength, and data on the mean separation between the Sun and Jupiter, Thomas calculated that the spacecraft would have to carry a 1.3 meter telescope with a rather large aperture. But a better plan, according to Thomas, would be to use a one-meter interferometer with somewhat smaller apertures. Such an instrument would be able to resolve a Jupiter-like planet at a distance of two light years, far enough away to make the minor course changes that would allow the spacecraft to come close to the planet.

The interferometer would not be trained only on its destination. In combination with Earth-based telescopes, it would also make parallax measurements of other stars. Such long-baseline parallax measurements would lead to a considerable refinement of our distance scale of the universe. On its way out, the spacecraft would also be in an ideal position to make measurements of the interstellar medium. For this it would probably carry a fly-paper-type contraption: sticky strips of metal that would capture and analyze interstellar dust.

Communicating the data back to Earth does present some problems. At a distance of four or five light years, both radio frequency beams (30 cm wavelengths and longer) and microwave beams (1 to 30 cm) would diverge too much. Stephan Pietrusiak investigated this problem and determined that wavelengths of light on the order of one micrometer, just beyond the visible region, would be best. This light would be produced by a relatively modest 1,000-watt laser carried on board the spacecraft. In this scheme precise pointing would not be necessary, since at the receiving end the beam would still be larger than the orbit of the Earth. A spaceborne photon bucket could capture the signal and relay it to ground stations no matter where the Earth was in its orbit.

The communications system will be able to transmit an amazing 10 bits of data per photon. This seemingly paradoxical result would be achieved with a JPL system called Pulse-Position Modulation (PPM). In this PPM system there would be 1,024 (2^{10}) possible time slots in which a signal could arrive, so the actual time of arrival would stand for 10 bits of information. A PPM system that communicates 2.5 bits per photon has already been demonstrated, and a 10-bit-per-photon system could be developed. Such a system would only be able to communicate between 10 and 100 bits per second, so the large amount of data the ship collects during its breakneck race through the other solar system may have to be parceled out and sent to Earth slowly, over a period of months to years.

The SURFers considered propulsion, payload, and communications, but there remain several important aspects of the mission that they were unable to study this summer. The spacecraft, for example, will need to be largely autonomous, since closed-loop control is not possible at a distance of several light years. And all the spacecraft's components will have to be extremely long-lived; however, given the excellent record of Voyagers I and II as well as other spacecraft, this is not expected to present much of a problem. Many of these design considerations may be worked out soon, since a number of JPL scientists are interested in launching a precursor mission, called TAU, that will travel a Thousand Astronomical Units from the Sun. (An astronomical unit is the distance from the Earth to the Sun. Pluto orbits the Sun at 39.5 a.u.)

Once a commitment is made to embark on an interstellar mission, the launch date would be at least 50 years away. Travel time will take another 20 to 200 years, and the data won't all be returned for another decade beyond that. This may seem a long time to wait but, as Dr. Posner says, "The mission does not require science-fiction type breakthroughs or unknown physical laws or unknown economic will on the part of the Earth. It may require vision to have a hundred-year mission. I personally believe that humans are capable of that. After all, some of the cathedrals of Europe took over a hundred years to build, and it may take longer than that to get the Long Beach Freeway through South Pasadena." □ — *RF*

Research in Progress

A New Infectious Agent

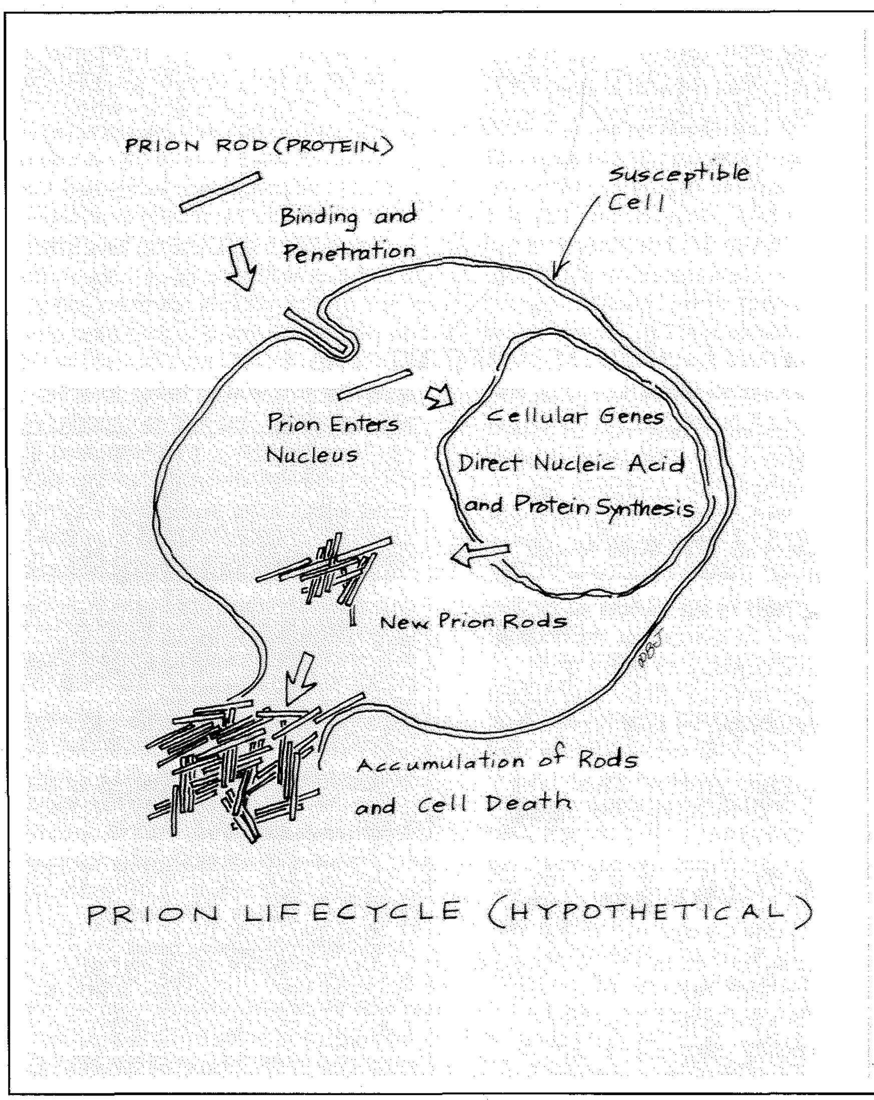
Caltech scientists are studying something new under the sun — an infectious agent that appears to violate the central dogma of biology. This agent, called the prion (pronounced PREE-on), seems to be a self-replicating protein, and as such it either bypasses totally or adds a new wrinkle to the normal sequence of information flow in the cell: DNA→RNA→protein. Named by Stanley Prusiner of UCSF, the prion is known to cause scrapie, a brain disease of sheep and goats.

Scrapie is one of a group of so-called slow virus diseases, a group that includes Creutzfeldt-Jakob Disease and kuru, two devastating neurological diseases of humans. The hallmark of a slow virus disease is its extremely long incubation period, which can extend for months or years. And these diseases share another common feature — the brains of those afflicted contain numerous amyloid plaques: large, regular arrays containing a rod-shaped protein. Amyloid plaques are also seen in Alzheimer's disease.

Despite the name, though, slow virus diseases seem not to be caused by conventional viruses. Viruses consist of molecules of nucleic acid — DNA or RNA — surrounded by a protein coat. When a virus invades a cell, it uses its nucleic acid to subvert the cell's genetic machinery, reproducing many copies of itself and often killing the cell in the process. But as far as anyone can tell, prions consist entirely of protein and contain no nucleic acid. In a lengthy series of experiments, Prusiner has isolated scrapie prions and has shown that they maintain their infectivity when subjected to treatments that should destroy nucleic acid, while they lose their infectivity when treated with protein-destroying agents.

Caltech researchers have obtained additional detailed information on the scrapie prion by using the powerful resources of the Division of Biology's Program in Advanced Biological Instrumentation, which has developed state-of-the-art instruments that make detailed analysis and high-yield synthesis of proteins and nucleic acids possible. The researchers determined that the scrapie prion is a glycoprotein with a molecular weight of between 27,000 and 30,000 and they've named it PrP 27-30. They analyzed its amino acid composition and determined the sequence of a 15-amino-acid segment of the protein. With this sequence in hand, they synthesized a corresponding oligonucleotide probe that enabled a group of Swiss researchers, led by Charles Weissmann, to isolate a gene coding for PrP 27-30 from scrapie-infected hamster brains. (The Caltech group includes Leroy Hood, the Ethel Wilson Bowles and Robert Bowles Professor of Biology; Stephen Kent, senior research associate; David Teplow, research biologist; Ruedi Aebersold and Paul Tempst, both research fellows; and Eric Heer, now a Stanford undergraduate.)

The Swiss researchers determined that even normal, uninfected mammalian cells contain a very similar gene. This gene produces PrP 33-35, a protein somewhat larger than, but closely related to, PrP 27-30. PrP 33-35 is not infectious and is easily bro-



ken down by enzyme treatment. The infectious PrP 27-30, on the other hand, is strongly resistant to degradation, which may explain why it accumulates in cells, kills them, and forms large amyloid plaques. In another series of experiments, the researchers are using synthetic fragments of the prion to raise antibodies. They hope these antibodies will cross-react with both proteins and will be useful in immunocytochemical studies. These studies may help in determining the function of the normal prion protein and in following the course of the infection.

The lifecycle of the infectious prion is still the subject of conjecture. According to one hypothesis, a point mutation occurs in the gene coding for the normal PrP 33-35. This mutation would render the protein infectious and immune to degradation. According to another hypothesis, illustrated here, alterations in the cell's genetic material would be unnecessary. The infectious prion protein could exert a regulatory effect leading to increased synthesis of the normal prion protein. In yet another hypothesis, the infectious protein increases the half-life of messenger RNA, thereby causing overproduction of the protein. There are other hypotheses as well, all of which are currently under evaluation.

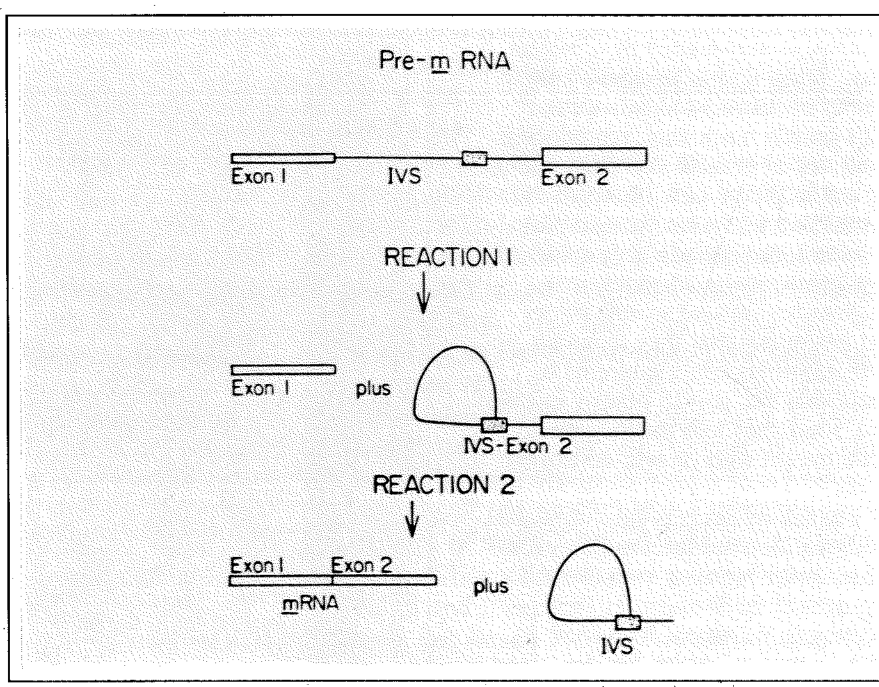
But according to many researchers, the most important unanswered question is whether the prion is truly an infectious protein containing no nucleic acid. Although all results to date point to this conclusion, it's so counter-intuitive that many researchers insist that there must be some nucleic acid somewhere, possibly buried so deeply in the protein molecule that the methods used so far can neither detect nor destroy it. Says Stephen Kent, "We just plain don't know. Speculation is always fruitful and one should indulge in it, but in this case we just don't have enough reference points to guide useful speculation. That's what makes the thing so interesting. If I were a guessing man, which I am, I would guess that it's a DNA virus. But it really doesn't matter whether it turns out to be a virus or an infectious protein. Whatever it is, it's really, really different from known infectious agents."

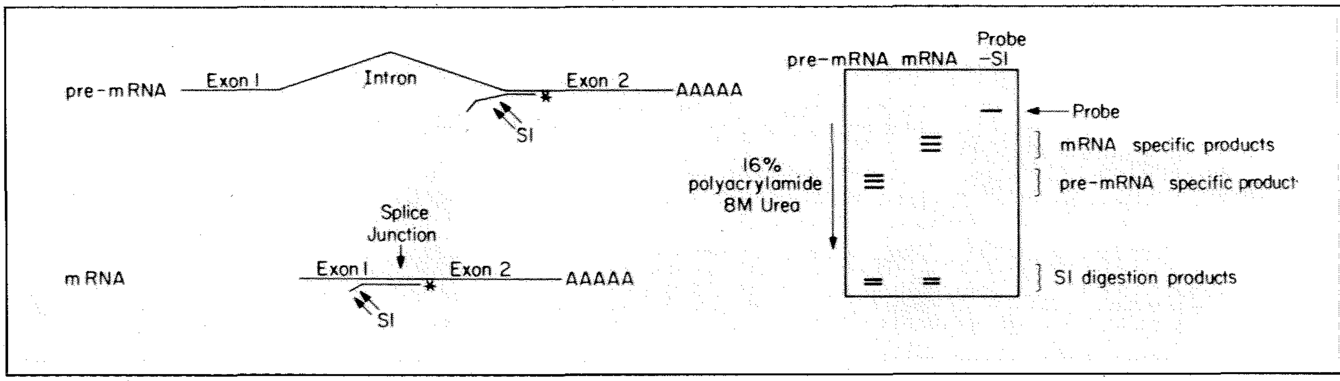
One ambitious series of experiments, currently under way, could provide an answer. The Caltech researchers are trying to confirm the amino acid sequence of PrP 27-30 deduced by the Swiss group from the gene they found. Once this is done, copies of this protein can be synthesized chemically. If the synthetic protein proved infectious, then need for nucleic acids could definitely be ruled out. But if the synthetic protein were not infectious, this would not prove that nucleic acids were necessary. It could be that the difficult-to-analyze carbohydrate portion of the glycoprotein is needed for infectivity.

Meanwhile, the Caltech researchers are working on detailing the differences between PrP 27-30 and PrP 33-35. And they're excited about the possibilities. Says David Teplow, "This thing is as controversial as the germ theory of disease was in the 19th century. It's very unusual and could really upset the whole foundation of scientific thinking." □ — *RF*

A New Cellular Organelle

BIOLOGISTS HAVE LONG tried to determine how cells process messenger RNA (mRNA) for translation into protein. This question took on a special urgency in 1977 when several laboratories reported one of the most startling facts in the history of molecular biology. It seems that the coding regions of virtually all genes from eukaryotic cells are interrupted, sometimes repeatedly, by long non-coding regions — regions that are never translated into protein. These long sections of DNA came to be called intervening sequences, or "introns," while the sections of the gene that are translated came to be called "exons." Scientists quickly discovered that the entire gene, introns as well as exons, is transcribed into mRNA. But these pre-mRNA molecules have their introns neatly snipped away before they're translated into proteins.





In the splicing assay, first an oligonucleotide probe is synthesized. The probe is designed so that part of it will bind or "hybridize" to one exon of the mRNA, part will hybridize to the other exon, and part will not hybridize at all. After hybridization, everything is digested with an enzyme called S1. The products of this digestion are separated with gel electrophoresis and will depend on whether or not the intron has been excised and splicing has taken place.

The mechanism the cell uses to cut away the introns and splice the exons together must be extraordinarily precise. If the splicing mechanism makes its cut a single nucleotide too soon or a single nucleotide too late, the entire reading frame of the mRNA will be thrown off and the cell will construct a nonsense protein. The search for the splicing mechanism has presented enormous technical and methodological difficulties, but these difficulties have recently been overcome by John Abelson, professor of biology, and his co-workers: Edward Brody, visiting associate in biology (now back at the Institut de Biologie Physico-chimique in Paris); Andrew Newman, former senior research fellow in biology; postdocs Soo-Chen Cheng, Ren-Jang Lin, and Gloria McFarland; and graduate student Usha Vijayraghavan.

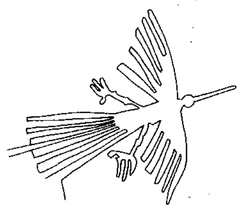
Working with yeast, they have discovered that mRNA splicing takes place on a previously unknown organelle that they have dubbed the "spliceosome." Splicing proceeds in two stages. In the first stage, the exon separates from the 5′ end of the intron, which loops around to form a "lariat." [In nucleic acids, the 5′ hydroxyl group of one nucleotide normally connects to the 3′ hydroxyl group of the next one in the chain, so nucleic acids or sections of nucleic acids are said to have a 3′ end and a 5′ end.] In the second stage, the 3′ end of the looped intron separates from the second exon and the two exons join together.

These details on the splicing mechanism emerged only after seven years of labor. One major advance came with the development by Abelson's group of an ingenious assay capable of detecting mRNA splicing *in vitro*. To do this they first synthesize a radioactively tagged oligonucleotide probe. Part of this probe matches the nucleotide sequence of one exon and another part matches the sequence of the exon on the other side of the intron. When mixed with unspliced pre-mRNA, only one end of the probe will bond. Digesting the probe with S1, an enzyme that specifically degrades single-stranded nucleic acids, will then yield a characteristic set of radioactive products that can be separated and detected on a polyacrylamide gel. If, on the other hand, splicing has occurred and the intron has been removed, a larger proportion of the probe will bond to the mRNA and a different set of radioactive products will appear on the gel. The inclusion on the probe of a small section that does not match any part of the mRNA allows a distinction to be made between probe molecules that had been protected by bonding and residual probe molecules that had simply remained undigested after S1 treatment.

With the splicing assay in hand, Abelson's group then began looking for the site at which splicing takes place. They incubated radioactively tagged pre-mRNA with a yeast-cell extract and immediately centrifuged the mixture in a glycerol gradient. This procedure demonstrated that much of the radioactive pre-mRNA was associated with a 40S particle. (The Svedberg unit — S — is a measure of the speed at which a particle sediments in a centrifuge. The ribosome, for comparison, sediments at 80S.) But when a mutation was introduced into the pre-mRNA, a mutation that prevented the formation of the lariat and thus prevented splicing, there was no radioactivity detected at 40S. Abelson inferred from this that the 40S particle was the site of splicing — the spliceosome.

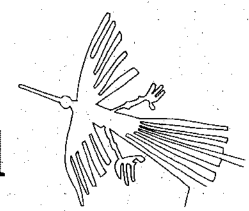
Work on spliceosomes is proceeding on several fronts in Abelson's lab. Says Abelson, "We'd like to know what's in the spliceosome. We're fractionating the extract and trying to reassemble spliceosomes from the fractionated components. And we're trying to understand the role of ATP [adenosine triphosphate — the cell's energy currency] in the formation of spliceosomes. ATP is required in the reaction and we don't know what its role is." ATP could be the energy source for the cutting and splicing reactions, but these are phosphotransfer reactions, which generally do not require an outside source of energy. Alternatively, ATP could provide the energy necessary for the correct folding of the pre-mRNA molecule.

In another set of experiments, Abelson is trying to find spliceosomes with the electron microscope. "We haven't seen anything distinctive yet. It's a very tricky experiment because we're putting a crude extract together with the pre-mRNA and sedimenting it. Anything will sediment. You're bound to see some particles and it's easy to ascribe any particle you see to the spliceosome. So we're being very cautious, but we're looking. My guess is that once we know what it looks like someone will say, 'Oh yeah, I saw that 15 years ago.' There must be a lot of them in the cell." □ — *RF*



The Travel Program Of

Alumni Flights Abroad



This is a private travel program especially planned for the alumni of Harvard, Yale, Princeton and certain other distinguished universities. Designed for the educated and intelligent traveler, it is specifically planned for the person who might normally prefer to travel independently, visiting distant lands and regions where it is advantageous to travel as a group. The itineraries follow a carefully planned pace which offers a more comprehensive and rewarding manner of travel, and the programs include great civilizations, beautiful scenery and important sights in diverse and interesting portions of the world:

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THE ORIENT: The serene beauty of ancient and modern Japan explored in depth, together with the classic sights and civilizations of southeast Asia (30 days). *BEYOND THE JAVA SEA:* A different perspective of Asia, from headhunter villages in the jungle of Borneo and Batak tribal villages in Sumatra to the ancient civilizations of Ceylon and the thousand-year-old temples of central Java (34 days).

EAST AFRICA AND THE SEYCHELLES: A superb program of safaris in the great wilderness areas of Kenya and Tanzania and with the beautiful scenery and unusual birds and vegetation of the islands of the Seychelles (14 to 32 days).

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In addition to these far-reaching surveys, there is a special program entitled *"EUROPE REVISITED,"* which is designed to offer a new perspective for those who have already visited Europe in the past and who are already familiar with the major cities such as London, Paris and Rome. Included are medieval and Roman sites and the civilizations, cuisine and vineyards of *BURGUNDY AND PROVENCE*; medieval towns and cities, ancient abbeys in the Pyrenees and the astonishing prehistoric cave art of *SOUTHWEST FRANCE;* the heritage of *NORTHERN ITALY,* with Milan, Lake Como, Verona, Mantua, Vicenza, the villas of Palladio, Padua, Bologna, Ravenna and Venice; a survey of the works of Rembrandt, Rubens, Van Dyck, Vermeer, Brueghel and other old masters, together with historic towns and cities in *HOLLAND AND FLANDERS:* and a series of unusual journeys to the heritage of *WALES, SCOTLAND AND ENGLAND.*

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Random Walk

Richter Dies

CHARLES F. RICHTER, professor emeritus of seismology, died of coronary artery disease on September 30. He was 85.

Richter was born on a farm outside of Hamilton, Ohio. His family moved to Los Angeles in 1909 where he went to elementary and preparatory school. He earned his AB degree at Stanford University in 1920.

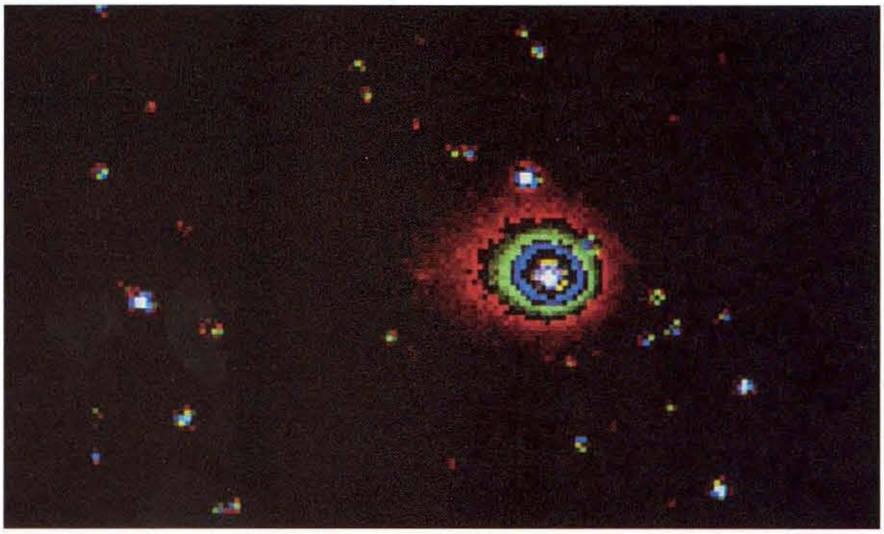
He entered Caltech that year to work on a PhD in theoretical physics (his special field was atomic theory). But a year before he was to get his degree, Robert A. Millikan, then head of Caltech, asked Richter if he would be interested in an opening for a physicist at the newly established Seismological Laboratory.

Richter accepted the job, and soon became fascinated with seismology. His work in co-creating the original instrumental scale for determining the amount of energy released by an earthquake (done in collaboration with Beno Gutenberg) eventually made his name a household word.

Richter may have been the only person to keep a seismograph in his living room. He maintained that his wife, Lillian, whom he married in 1928, considered the device a good conversation piece, and that she wouldn't remove it if she could.

Richter was well known for his book *Elementary Seismology*, used as a text in many countries. He also wrote, with Gutenberg, *The Seismicity of the Earth.*

Richter remained with Caltech until his retirement in 1970. He was a research assistant with the Seismological Laboratory from 1927 to 1936, and thereafter a faculty member. He was named professor of seismology in 1952. After retirement he remained active with his consulting firm, Lindvall, Richter, and Associates.



This false-color photograph shows Halley's comet as it appeared on September 25. JPL's James Gibson used the 60-inch telescope at Palomar Observatory in making this computer-enhanced image. A red filter revealed primarily the comet's dust coma. The concentric rings of color indicate the increasing brightness of the image toward the comet's nucleus. The bright spot above the nucleus is a background star. Halley's tail, which was just beginning to form, is at left in the photo. The comet is now located in the constellation Orion and can still be observed only with large telescopes.

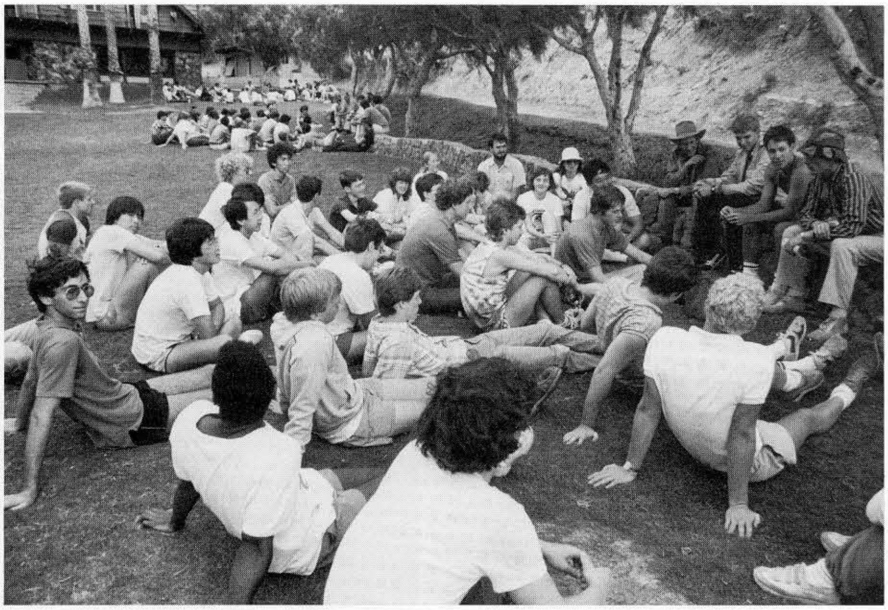
Breaking ground at the site of the Keck Telescope are (left to right) Albert Simone, president of the University of Hawaii; George Ariyoshi, governor of Hawaii; Howard B. Keck, president of the W.M. Keck Foundation; Caltech President Marvin Goldberger; David Gardner, president of the University of California; and William Frazer, chairman of the California Association for Research in Astronomy (CARA) and vice-president for academic affairs at the University of California. The site is at the 13,600 foot level on Hawaii's Mauna Kea. With its ten meter diameter mirror, the telescope will be the largest in the world when it is completed in 1991. It will be operated jointly by Caltech and the University of California. The grant of $70 million from the W.M. Keck Foundation for the telescope's construction is the largest private donation ever for a scientific enterprise.

The Associates Hold Annual Dinner

A CAPACITY CROWD of The Associates of Caltech and their guests gathered October 15 at the Athenaeum for the annual dinner. Richard L. Hayman, president of The Associates, welcomed the group to the festive, black-tie evening, which also included a reception for the President's Circle, dancing to the music of the Caltech Jazz Band, and an address by Roger B. Smith, chief executive officer and chairman of the board of General Motors Corporation.

Caltech President Marvin L. Goldberger introduced Smith, who became a Caltech Trustee last year. Smith, who spoke on "The Future of the Automobile Industry," expressed optimism about the evolution that innovations in technology and management will bring.

Freshman Camp



Once again Caltech's new freshman class (plus 22 transfer students) convened on Catalina Island before the fall term for three days of fun, fellowship, and finding out what's ahead of them. Here a group listens to Chris Brennen (right), master of student houses, explain the house system; other small group sessions dealt with health and counseling services, career planning, financial aid, etc. The class also was introduced to quarks, acid fog, marine biology, Catalina's geology — and Catalina's rain. Numbering 200 men and 31 women, the class is the largest in the past decade.

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Right: *Quetzalcoatlus northropi* as he may have looked 65 million years ago. Drawing by Gregory Paul and copyright by AeroVironment, Inc.
Below: The final wing-flapping version of the half-scale, 18-foot-wingspan pterodactyl waits for testing.
Below right: Paul MacCready poses with the glider model used for developing lateral control, which appears flying on the front cover.