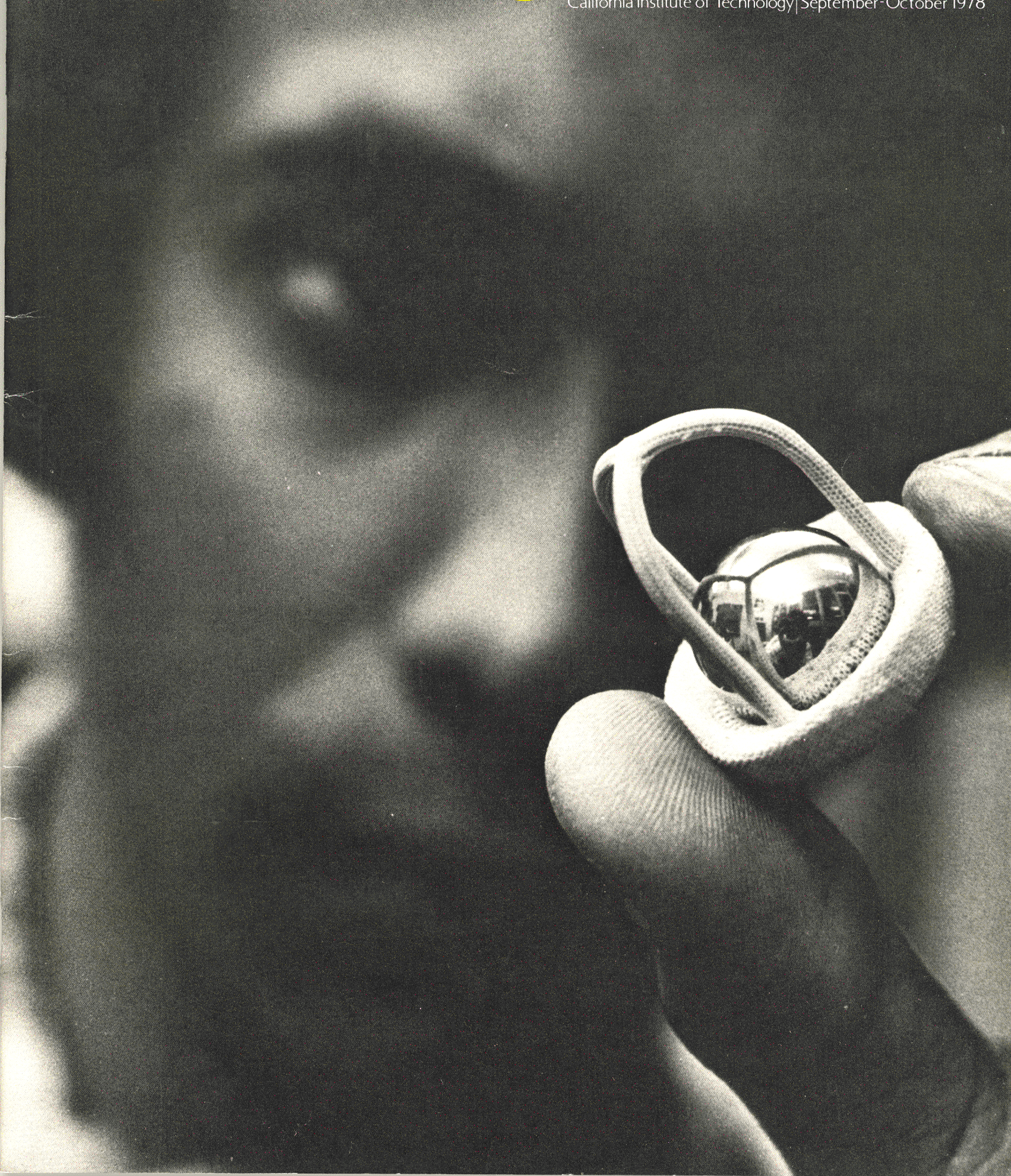
Engineering & Science

California Institute of Technology | September-October 1978



Engineering & Science

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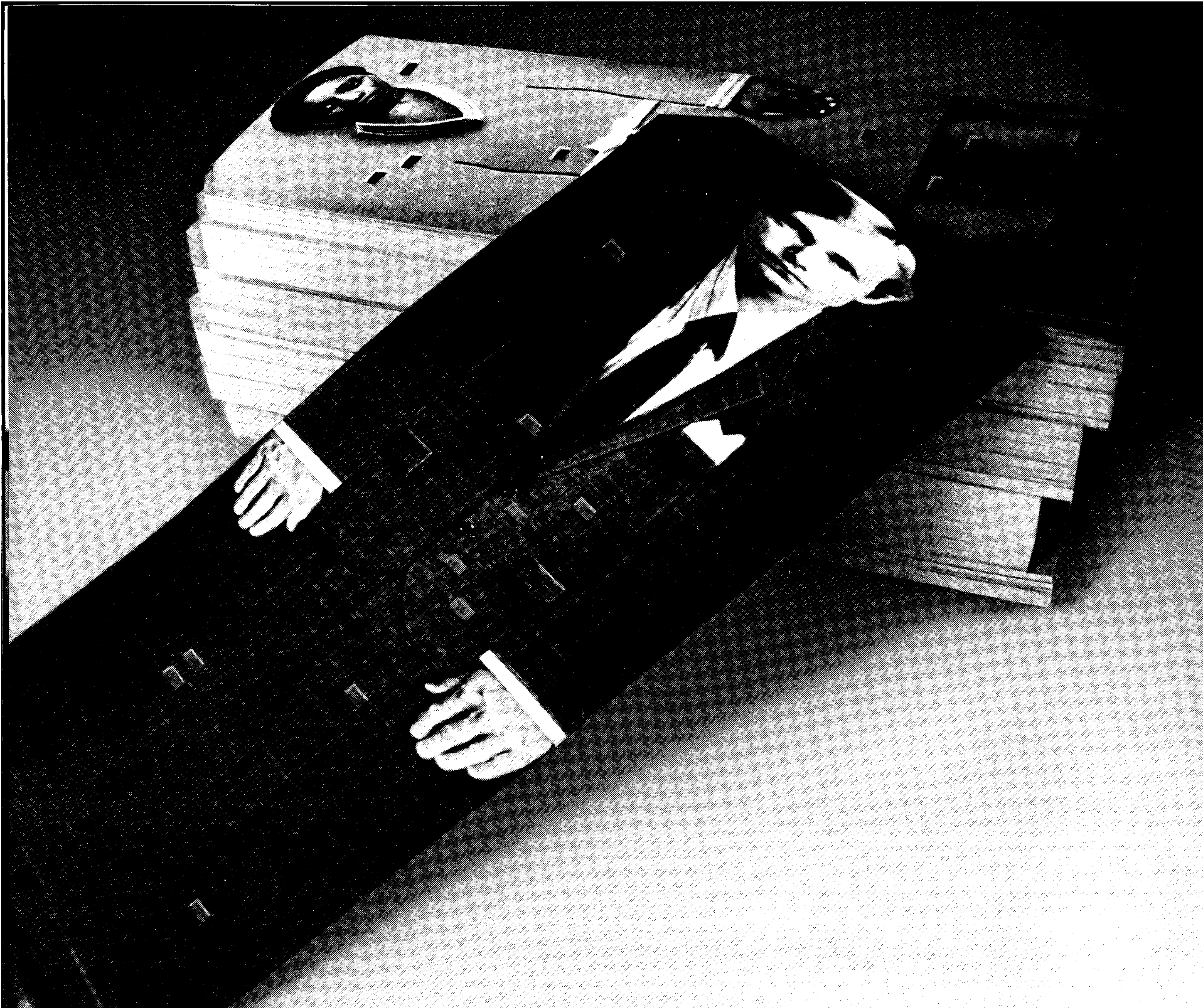

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In This Issue

Heart to Heart

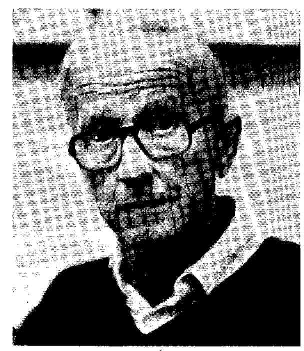
On the cover—Research Fellow Ajit Yoganathan holds an artificial heart valve, which is one component of fluid dynamics research he is doing with Professor W. H. Corcoran. These two chemical engineers hope the end product of their studies will be improvement of such valves, more than 90,000 of which are implanted in damaged human hearts each year. Yoganathan is a native of Sri Lanka with a BS from the University of London and a PhD from Caltech. Corcoran is also a Caltech alumnus and vice president for Institute relations. "Progress in Artificial Heart Valves" on page 20 describes what they do and why.

Yoganathan and Corcoran

Why Are These Trustees Laughing?

Because they are listening to a commencement speech by one of these two men (see page 5).

Woody Allen, comedian.



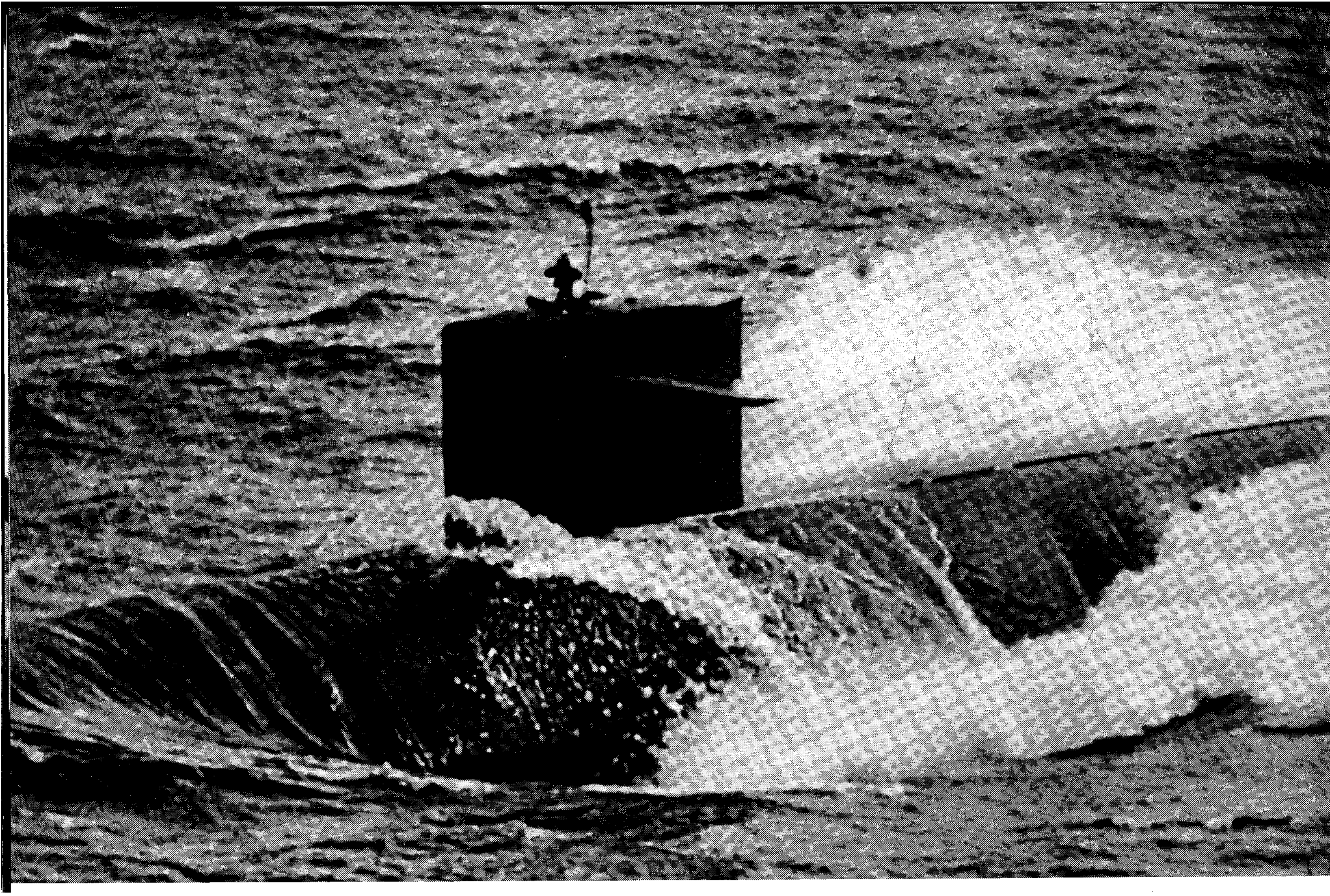
Max Delbrück, comedian—also Board of Trustees Professor of Biology, Emeritus, and Nobel Laureate.

Water Log

James P. Quirk, professor of economics, came to Caltech in 1971 in the vanguard of a group of mathematically oriented economists and political scientists who form the core of the Institute's social science program. That program is an unusual one in its integration of a number of different disciplines for work toward the solution of current socioeconomic problems.

About two years ago Quirk started looking into one of those problems through a research project undertaken by Caltech's Environmental Quality Laboratory. The Lab was interested in the political, social, and economic aspects of the allocation of water, with particular emphasis on the water needs of southern California. Those water needs, strangely enough, are related to problems in connection with smog in the Los Angeles Basin.

Smog is created in part by refineries and power plants, and it is increasingly evident that if the basin is to meet Clean Air Act standards, those plants must be moved out. The logical place to put the power plants is in the desert—if water is available to use for cooling. The only source of surface water is the Colorado River. "The Simple Economics of Water" on page 22 is adapted from Quirk's Alumni Seminar Day talk on May 13 about the history and future of the Colorado.



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Engineering&Science
SEPTEMBER-OCTOBER 1978

The Arrow of Time
— Beginning and End

by *Max Delbrück*

Caltech's 1978 commencement speaker muses on the direction in which the Institute intended—and ought—to continue its greatest thrust

So, here I stand before you, privileged to address this convocation of graduates and their families, of colleagues and friends of the Caltech community. A lively and festive occasion, cameras ready to record this punctuation mark in the lives of you, the graduates. For me, in contrast, it is the final period mark, or, perhaps, the last of my questions: to ask questions—who knows it not?—is the heart of teaching.

And I am supposed to make a speech, say something; something appropriate, not necessarily memorable (who remembers a commencement address?), but something to heighten the mood.

I feel divided between impulses to talk to the few of you graduates I have known and befriended during your sheltered sojourn at CIT and impulses to give my words a broader scope, focusing on my relation to Caltech, four decades of it, on my general sense of what Caltech amounts to or ought to amount to within the framework of our general culture. This is a subject on which I never had occasion to express myself in public, so the temptation is great to take advantage of the fact that somebody made the mistake of inviting me to give this address.

I understand that this graduating class has a certain feeling of uniqueness above other graduating classes of Caltech in having come here four years ago when the relative calm of our social and political life got into some momentary jitters—jitters provoked by the oil crisis, jitters that disrupted normal life to the shocking extent that the candidates for freshman admission were not interviewed personally! I imagine this commotion might have given to some of you a faint inkling that our society is not quite as stable and totally sheltered as it could appear otherwise, from the inside of a student house where you can live embedded in a world of courses and exams, where major decisions revolve around whether or not to cut the morning class, whether to protest the abominable food, or what fun activities to organize or participate in.

With its excellent offerings in the Humanities and Social Sciences, Caltech does try to teach you that, besides the physical universe, there *is* a *human* world outside, three-fourths of which is starving; that there *is* an arms race which may bring the world to ashes; that there *is* a history of civilization ranging over thousands of years; that our institutions indeed have grown out of this history; that science, too, is not merely a matter of the latest results discussed in *Science, Nature,* and *Physical Review Letters,* but that it is an immensely greater effort. It is a cultural effort that has ranged through the centuries and the millennia.

About all this greater human world Caltech's Humanities and Social Sciences gives you offerings that more often than not must seem tantalizing for lack of time to avail yourself, constraining you to be content with a glimmering. Perhaps, for some of you, the concern with man's history and man's destiny, with the powers that shaped man's consciousness of himself, amounted to no more than an amusing diversion, feebly competing for your attention with science fiction and fairy tales. Nothing wrong with that! Thank God the true ivory tower man can still slip by at Caltech. The true egghead is well-rounded—creative, too.

As far as I am concerned, probably you know as little of me as I know of you, and for good reason. We all divide time three ways: real time, the time we have lived through; hearsay time, before we were born; and future time, a matter of fear and hope. I was born and had my childhood in a different country in a different language and at a vastly different historical time, before the First World War, worlds removed from your world. Thus, from your point of view, a specimen like me belongs to hearsay time. I might as well be a relic from the time of the Crusades. Perhaps, though, I can make myself more concrete to you if I mention that Max Planck lived down the street, and that my brother and I picked and ate the cherries from his garden. Concrete or not, the distance is vast. Indeed, it could be argued that we now live too long, compounding too many layers of cultural change. Perhaps modern medicine did the wrong thing, prolonging our lives. Perhaps it should aim to shorten our lives, so as to keep the living better tuned to the fast-changing times. But the compounding has its merits, too, and it is on these merits that I would like to capitalize in reflecting on Caltech.

At this point it may be appropriate to insert an aside on my identity. When President Christy, some months ago, approached me as to whether I would do this job, I asked him, "Why me? Who suggested it?"

"Well," he said, "your name was suggested by a committee and I liked the suggestion. The committee added that the students had once again suggested Woody Allen."

"Well," I said, "that is a splendid idea. He would give a much better speech than any of us—why don't you try him first?"

So he said, "Who is Woody Allen?"

"Oh," I said, "he is a marvelous comedian. He just got a prize for a movie, which he wrote, directed, and played in, about his unsuccessful marriage."

"Well," he said, "I am successfully married, so that's why nobody told me to go, but if you say he is so good, I'll let the students have a try at him, if you don't mind."

"By all means," I said.

So what happened? Well, it's up to you to decide. Is it Max Delbrück, as advertised, talking to you, or is it Woody Allen, impersonating a Senior Academic Citizen, scurrilously named Max Delbrück, or is it Max Delbrück, scurrilously pretending to be Woody Allen impersonating Max Delbrück?

Having been trained in critical thinking for so long at Caltech I am sure you will enjoy pondering these alternatives while I, whoever I may be, go on with my talk.

The motto on the seal of Caltech says, "The truth shall make you free." Like any motto, it lends itself to jokes, crude ones and subtle ones, biting ones and gentle ones. My joke will be to take it straight. The motto and the emblem were chosen by our founding father Millikan in 1925, half a century ago, and in the charge to the artist who designed the seal Millikan put down that the seal should show an older man passing the torch to a younger one, both of them in the clouds. Millikan wanted to symbolize the handing down of truth from one generation to the next. He wanted to symbolize *scientific* truth and the progress toward enlightenment, toward liberation from superstition, toward a better, more rational society.

Many intellectuals of Millikan's generation believed science would outpace and largely displace all other intellectual and spiritual endeavors, as indeed it has done. No question about that. They also believed that science would lead to a better world and most of them believed that it would displace religion by the end of the century. We now know that our age is not a golden age and, indeed, that it is a most unstable age. We also know for a fact that the scientific culture has in no way eliminated the strength and intensity of the religious needs, the religious fervor, the power and appeal of the churches. Indeed, we can take it for granted that science is intrinsically incapable of coping with the recurrent questions of death, love, moral decision, greed, anger, aggression. These are the factors that determine man's values. They constitute the greatest forces that shape man's destiny. You can symbolize all these forces in nice mathematical systems and that may help you in setting up better decision-making institutions, but that is a limited victory. It constitutes medium-hard science but it probes neither the biological nor the cultural origins of these values.

When I first saw the motto, "The truth shall make you free," it thrilled me. It made a strong impact on me. Why the emotional response? Perhaps because in science the name of the whole game is truthfulness. If you cheat in science, you are simply missing the point. You defeat yourself. So, whatever sense of exhilaration and liberation the scientist does derive from the exercise of his profession, it is deeply connected to his commitment not to cheat. This commitment seems to be more religious than rational.

I wondered where the motto came from. Had Millikan coined it? Far from it. A nephew of mine, a student of theology, put me right. It comes from the Fourth Gospel, the Gospel according to St. John, Chapter 8, Verse 32. It occurs as a punch line in one of a series of heated discussions between Jesus and the Pharisees. These discussions, together with the description of the miracles performed by Jesus, form the body of this Gospel, the strangest and the strongest of the four Gospels.

The writer of this Gospel, an impassioned, speculative thinker, a highly poetic symbolizer, uses these heated arguments as a deliberate literary device. The parties (Jesus and the Pharisees) grossly misunderstand each other all of the time. The writer uses these misunderstandings in order, step by step, to unfold and clarify his theological doctrine.

The passage containing our motto is one in which the parties display an extreme degree of frustration; they throw intemperate insults at each other. At one point Jesus, turning aside to his followers, says, "If you continue in my word, then are ye my disciples indeed and ye shall know the truth and the truth shall make you free." The Pharisees promptly misunderstand "free" as "politically free." They think that Jesus wants to propose himself as a political liberator, the Messiah, so they say, "How so? We be Abraham's seed and were never in bondage." And Jesus elaborates that he does not mean political freedom but freedom from sin. Earlier he has made it apparent that by "truth" he means faith in him, Jesus, as the *Son of God.* He does not mean "scientific truth" or "rational truth" in the Greek sense of the word. Not that at all.

Comparing this meaning with that of Millikan's interpretation of the motto, you will note that an extraordinary perversion of the original meaning has taken place. Yet as it stands on the seal the reader is free to interpret the motto as he pleases. Each of us can be his own Supreme Court, responding according to his predisposition. I would not be surprised if the evocation produced in Millikan himself was more of the religious kind than of the rational progress kind. Millikan was artful in choosing this highly ambiguous motto, satisfying both his scientific clients, the faculty, and his other clients, the friends of Caltech, often of a religious bent.

If science, as I said before, is so limited an enterprise, so one-handed a tool to hold the world together, where does that leave Caltech as a whole, and where does Caltech stand in relation to the needs of our times? In which direction might it have to move? Or should it stand pat, on the platform of 50 years ago?

In the late Middle Ages when universities first came into being, they were loosely attached to cathedral schools. They then had the lower curriculum, the trivium (grammar, rhetoric, and logic) and the upper curriculum, the quadrivium (arithmetic, geometry, astronomy, and music). The trivium dealt with the arts of the world, the liberal arts. It uses language in its widest ranges of possibilities, in poetry, myth, divine revelation, down to the crudest brainwashing to which the media subject us. The quadrivium dealt with measurement and calculation, the sciences. The sciences severely limit the use of language, and attempt to eliminate ambiguities, all the way up to the bizarre excesses of the mathematical logician. In the schools of our Western world the quadrivium has taken ascendance over the trivium and you might say that Caltech represents the ultimate faith in the quadrivium. At Caltech we know how to do science, and those who do science here by and large have no qualms whatever about its intrinsic value and are willing to go to bat for it.

This attitude has turned out to be a viable and indeed immensely successful one over the last five decades. How valid will it be in the future? Will its continuation make Caltech and its cohorts of similar schools empty shells, a sounding brass, a tinkling cymbal? Will people of later times look back at Big Science as we look at Stonehenge or the Pyramids—a grandiose creation, but what was the point of it?

When Science was discovered and came into bloom, he was a beautiful youth, like Tithonus of the Homeric myth. The goddess Aurora, the morning dawn, fell in love with Tithonus and requested of Zeus that he be granted immortality. The request was granted by the great Zeus, but an unfortunate situation arose when it was realized that Aurora had failed to include in her request for eternal *life* for her beloved lover also a request for eternal *youth*. Tithonus aged and shriveled and talked incessantly. Since his immortality could not be rescinded (time's arrow does not fly backward), a compromise solution emerged according to which Tithonus was transformed into a cricket, and put away in a box.

Science does chatter and chirp away incessantly. Its chirping, on black holes, on the big bang, on neutrinos, on recombinant DNA's, is sweet music to those few who are tuned in to it, but does it satisfy Aurora's yearnings, Aurora the morning dawn?

The question is not what can science do for us; it can do a lot. The much more important question is what can science *not* do for us. Science orders our external world. It does so in a marvelously coherent way, or almost coherent way. It develops a universe of discourse or, let us say, a few universes of discourse with very large overlaps between them, enough to move back and forth from one to the other without too much jarring.

While primitive man developed theories about the universe which he formulated in terms of myth, science rejects myth. The myth may have talked about the creation of the universe or about the end of the world —indeed, about divine interventions at every thunderclap. In contrast, the aims of science are always, by the nature of its methods, partial aims. Science cannot say anything about the creation of the universe, so it just does not make any statements about the creation of the universe. If science cannot extrapolate the state of the universe backward beyond the big bang, it refuses to extrapolate backward or does so only in the most tentative and conditional way.

Most astonishingly, physics cannot incorporate the *arrow of time* in its basic theories, and it admits that it cannot do so (see Feynman—*Lectures on Physics*). Moreover, science has recognized that in quantum physics the discourse contains a break: The objective world isn't that objective. The observer and the observed cohere in a bizarre way which limits the clean separation between actor and observer. Moreover, biology has taught us that we, the observers, are products of our evolution; our cognition filters reality in a massive way.

Physics copes with the arrow of time in an awkward and contrived fashion. This arrow is much more of the essence of things in biology than in physics. In physics the birth and death of particles are processes which can be looked upon as strict reversals of each other. In biology this is never so. Birth and death are totally different phenomena, future and past are radically different directions, the essence of life of an individual organism is *development*—indeed, development according to a *plan*. This feature of life, *development according to a plan,* which so strongly colored Aristotelian philosophy and through it the whole of Western culture, its science, its art, and its theology—this feature we can now tie up, through our proud new knowledge of molecular biology, with the physical universe. This directionality of time where life is concerned has thus become part of our understanding of the physical universe; it is the hallmark, the specialty of biology.

How do they view time in the humanities? How does the historian view reality? In primitive society he, too, starts out with myth. Faith in miracles, in divine intervention, have colored man's understanding of his own history throughout the ages. Along comes the historian of the 19th century, the positive historian, as proud as any scientist, wishing to describe objective reality. He ascertains the facts and forces, be they military, economic, social, or cultural, and tries to describe history as objectively and even deterministically as any physicist tries to describe the events of nature.

But in our times a critical reappraisal has gained ground, somewhat analogous to that in physics. Can you separate the historian from the history he describes? Is he, the historian, not himself a creature of history and does he not paint a picture that is as much a product of his own historically grown cognitive makeup as it is of the situations he aims to describe? What attitude should the historian take toward the myths of past centuries—myths created by man, believed in by man, and constituting strong forces shaping the decisions of man? Surely no professional historian wants to admit miracles, divine interventions, immediate revelations of God, and the like. But since a belief in these matters constituted the greatest forces of history, he must take full cognizance of them. For him, then, the myths of the past are historical facts. For him, paradoxically, the myths of past generations constitute part of the real historical past time. This past time he tries to order in a deterministic way.

Man, being an actor, an agent, a free though more or less rational agent, must deal with the past, recognizing that the persons in history were agents driven by their form of consciousness. They acted out of some knowledge of the past but most certainly out of ignorance of their future. For the historian, the tip of the arrow of time is even less determinate than that of the meteorologist.

Finally, for man, the individual man, the free agent, the arrow of time takes its deepest meaning from the fact that not even the beginning of the arrow is at hand. We find ourselves in midflight without having asked for it. And to which end does the tip of the arrow point? To some form of eternal life, if he has faith, or into nothingness? This alternative is surely the greatest force shaping man's values, finding its most powerful expressions in the arts, philosophy, and theology of all ages.

Our science, science at Caltech, deals with time as simply a fourth dimension along which you move forward or backward at will. We know that science, this science, is immensely powerful and at the same time most severely and deliberately limited. It copes with the quadrivium, with measure and number, but it ignores the fact that both for mankind and for the individual man the arrow of time has meanings that vastly differ from those of physics or of biology. This realization is one that is powerfully needed, and I think that Caltech is at a turning point where this need could and ought to be given the highest priority. Science is doomed to mistrust by the public and by its best students if it remains self-serving, if it continues in the blind faith that what is good for science is good for mankind.

The essence of Caltech has been to be excellent *and* small—small enough to avoid in large measure the schism into the "two cultures." In fact, the great "Court of Man" in which we hold this solemnity, flanked by the buildings dedicated to Behavioral Biology on one side and to the Humanities and to the humanistic Social Sciences on the other, is a symbol for the direction in which Caltech intended to and ought to continue its greatest thrust. Let us hope that the momentum will not get lost. □

It isn't customary to adorn commencement speeches with references. Nevertheless, for their intrinsic interest, I would like to draw attention to the following two essays from which I borrowed in part: Lynn White, Jr., "Science and the Sense of Self: the Medieval Background of a Modern Confrontation." **Daedalus**, vol. 107, no. 2, pp. 47-59, 1978. Daniel Bell, "The Return of the Sacred: the Argument about the Future of Religion." **Bulletin of the American Academy of Arts and Sciences** 31, no. 6, pp. 29-55, March 1978.

As Max Delbrück concludes his 1978 Caltech commencement address, his colleagues surprise him by displaying a scholarly tribute from the Latin and the heart. In two words—*Maximus est*—he is "the greatest."

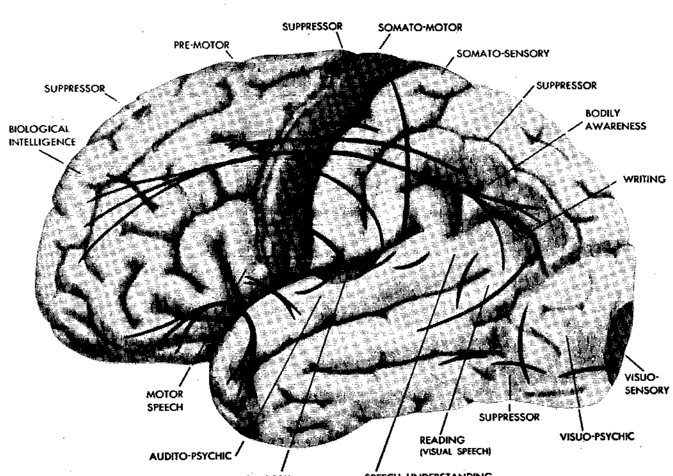
The Elusive Right Hemisphere of the Brain

by Eran Zaidel

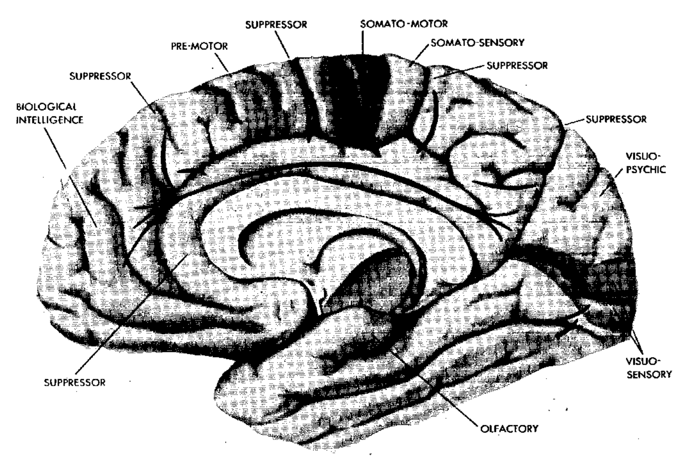
The backbone of our knowledge about hemispheric specialization has been accumulating since the mid-19th century. It consists of clinical observations of patients who have suffered focal damage to one hemisphere (i.e., one-half) of the brain. The damage may consist of a stroke, a tumor, or a gunshot wound. These studies have accelerated after each major war because of the availability of fresh experiments of nature. Given the current state of human nature and of world politics, clinical neuropsychologists are not likely to be out of jobs for some time to come.

Each hemisphere of the brain (below) can be divided somewhat arbitrarily into four parts. The frontal lobe, whose function is still very much a mystery, seems to have a special role in planning and motivation; it also contains the motor areas that control the opposite half of the body. The temporal lobe has auditory, linguistic, and memory functions. The parietal lobe has some of the sensory areas for the opposite half of the body, and association centers for integrating information across sensory modalities and for processing spatial information in particular. Finally, there is the occipital lobe, where the primary visual reception areas are located.

Exposing the medial aspect of the brain reveals the massive fiber system that connects the two cerebral hemispheres: the corpus callosum with some 200 million nerve fibers in it, the anterior commissures, and the hippocampal commissures. This group of connecting cables has been sectioned surgically (that is, cut through) in a special group of neurosurgical patients. They are called split-brain patients, and over the last 17 years they have been the subjects of intensive neuropsychological study.



A view of the outside surface of the left cerebral hemisphere of the human brain.



A medial view shows the fiber system called the corpus callosum, which connects the two hemispheres.

Recent research on the right hemisphere indicates that it has unexpectedly rich linguistic structure—a fact that may help us understand some forms of language disability

The classical neurological model of language representation in the brain is about 100 years old. It says that, at least in most right-handed adults, the left hemisphere is specialized for language and for speech, so that only damage to the left hemisphere can result in a language disorder—so-called aphasia. Today we recognize several distinct forms of aphasia. Though really quite complex, three common syndromes may be oversimplified for purposes of illustration as follows. In Broca's aphasia—named after the French pathologist Paul Broca, who was the first to publish the view that the left hemisphere is specialized for language—we have a predominantly expressive disorder with poor articulation, telegraphic speech consisting mainly of content words, and with impoverished or impaired grammar. If you ask a Broca's aphasic how he has spent the Easter holidays, he may answer something like this: "Uh, uh, uh, Easter . . . ho, ho, ho, holiday . . . I like . . . eat turkey . . . many lights . . . people . . . very good." The speech is very labored and effortful. The patient seems acutely aware of his own deficit, and he may become quite depressed about it. Lesions that produce Broca's aphasia are often in the frontal part of the brain.

A second main syndrome is Wernicke's aphasia, named after the German neurologist Carl Wernicke. Here we have impaired auditory language comprehension with fluently articulated but nonsensical speech. The patient's speech has good melody and uses complex though often incorrect syntax. If you ask a Wernicke's aphasic how he spent the Easter holidays, and if you don't listen too carefully, he may sound quite normal. But some attention reveals semantic jargon. "Oh, yes, we have done it. Could be different but nevertheless done. Go, go, gone. And however successful, it still fails. I wish indeed. Good morning." So here the disorder is predominantly one of meaning rather than of syntax or phonology. The patient is very often quite unaware of his own deficit and will deny it vehemently. Today it is believed that the responsible lesion tends to be more posterior.

A third main syndrome is anomia or amnesic aphasia. Here we have a predominance of word-finding difficulties in both spoken and written language, and in the context of fluent, grammatically well-formed speech and relatively intact auditory language comprehension. It is easier for the patient to evoke over-learned serial speech such as the alphabet or the days of the week. The localization is often temporal parietal. For example, if you point to a fork and ask the patient to name it, he may respond with, "It's a, ah, ah . . . (eating motions). It's a spoon. No. No. I mean it's a . . . You eat with it, a, ah, I can say it." You ask him then, "Is it a knife?" And he will say immediately, "No. No." And if you cue him by starting, "Use your knife and ————" he will often be able to complete it, "fork." Here the disorder is one of reference—i.e., of the relation between words and the things in the world that they stand for.

These three aphasic syndromes—considerably simplified—are all attributable to left hemisphere lesions. The right hemisphere has generally been believed to have no role in language whatsoever. Rather, since the 1940's it has become increasingly associated with visual-spatial information processing. For example, it is now believed to be specialized for the recognition of faces, for three-dimensional constructions in space, and for topographical orientation. But as far back as the 19th century the British neurologist Hughlings Jackson believed that the right hemisphere does have some role in language, especially in serial, automatized, and emotional speech. By now it is clear

Self-portrait by the German painter Anton Raderscheidt, done five months after he suffered a cerebral stroke, shows a severe neglect of the left side.

Courtesy of Prof. R. Jung

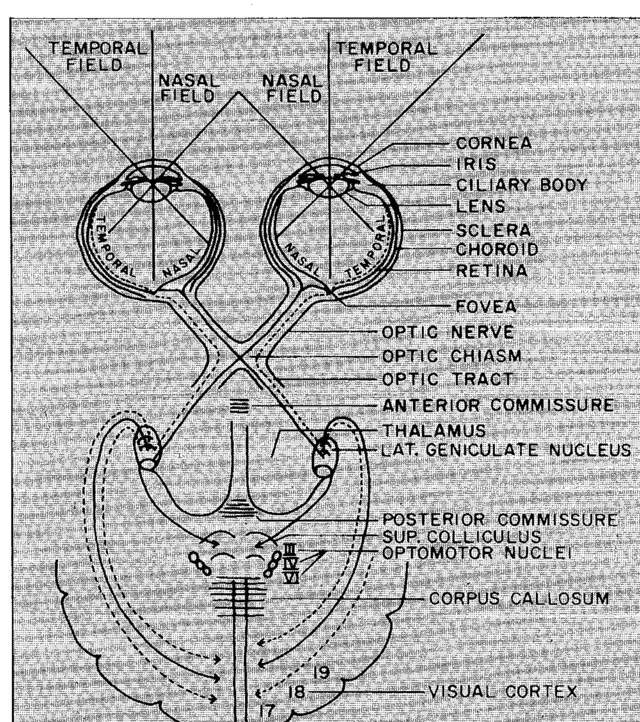
that the standard neurological view needs to be qualified. In fact, we have found that the right hemisphere has an unexpected and unusual form of natural language.

But first let me illustrate a characteristic non-verbal right hemispheric deficit as it has expressed itself in the drawings of the German painter Anton Raderscheidt. He was born in 1892 and died in 1970. In September of 1967, at the age of 75, Raderscheidt suffered a cerebral stroke to the right hemisphere, due to thrombosis of the posterior branches of the middle cerebral artery of the right hemisphere. Since then he had suffered from left homonymous hemianopia, a blind left-half visual field in both eyes. He also had a severe neglect of the left half of space, which subsided gradually. The parietal lesion had characteristically made him unable to recognize faces. At first this was so extreme that he confused even his closest relatives, but this condition also cleared up spontaneously. A self-portrait by Raderscheidt (above), done five months after the stroke, shows a severe neglect on the left side. This neglect could not be explained simply in terms of the blind half-field, because the patient could move his eyes and see the missing part.

This kind of neglect typically happens with lesions to the right hemisphere, but almost never in a severe form with lesions to the left hemisphere. Sometimes this can be very dramatic. For example, the patient may ignore completely the left half of his own body. He may get dressed using only one sleeve but ignoring the other side of a jacket. He may comb his hair on the right half of his head but ignore the left half.

There are several quite serious methodological problems with trying to find out the functions of each hemisphere by looking at patients who suffered damage to one or the other side of the brain. For one thing, it is very difficult still to assess the location, size, and severity of the lesion in the brain. It is even harder to match two patients with exactly the same lesion on the left and on the right side. In any case, it's a bit suspect to infer functions from deficit. One solution seems to be to compare the positive competence of one half of the brain with the competence of the other half in the same patient, so that the two halves are automatically matched for age, sex, education, and so on. This is exactly what a split-brain preparation allows us to do. In addition, since the 1960's we have increasingly become able to look at hemispheric specialization effects in normal subjects. One of the most common techniques used involves an elementary understanding of the visual system.

In the normal visual system (below) the left and the right eye look at the same point. The left halves of the visual field of each eye project to the right halves of the corresponding retinas. The information then goes through the optic tract and on to the occipital lobe in the



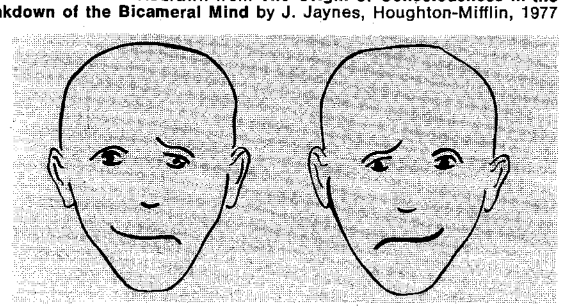
A schematic diagram of the visual pathways from eye to brain.

back of the right hemisphere. The two right halves of the visual field project to the left halves of the retinas and then to the left hemisphere. In a normal subject all you have to do to get information to one hemisphere first is to tell the subject to fixate on a central dot. Then you flash a picture very quickly either to the left or to the right of that fixation point. You have to do it fast enough (for not more than 100 to 150 milliseconds) so that he has no chance to move his eyes. It takes about 200 ms to initiate a saccadic eye movement. If you flash the picture to the left half of the field, it goes to the person's right hemisphere. If you flash it to the right of the fixation point, it goes to his left hemisphere. Of course, the information will also travel between the two hemispheres through the corpus callosum. But the response to information that reaches the processing and responding hemisphere directly will be faster and more accurate than the response to information that comes through the corpus callosum. We use this technique to establish laterality effects—hemispheric specialization effects—*in normal subjects.*

Incidentally, you don't have to flash pictures to see some of these effects. Look at the two pictures below. Which one looks happier? Almost everyone will say that the left picture is happier because the left side of the mouth turns up. The point is that these two pictures are essentially mirror images of each other. So why do we associate the expression with the left half of the picture? Presumably because this is the part that goes to our right hemisphere, which specializes in analyzing faces.

Let me move on now to the kind of experiment we have done with split-brain patients in Professor Roger Sperry's lab here at Caltech. These patients of Dr. Joseph E. Bogen have literally had their brains split surgically. The operation is called complete cerebral

Redrawn from **The Origin of Consciousness in the Breakdown of the Bicameral Mind** by J. Jaynes, Houghton-Mifflin, 1977



Which one looks happier?

commissurotomy, and it is done as a last resort to alleviate intractable epilepsy. In these epileptic patients the number and severity of seizures got higher and higher and could not be controlled by medication. There was reason to believe that by interrupting the mutually reinforcing symmetric epileptic foci in the two hemispheres this situation would be alleviated. Indeed, in general it was; in some of these patients the epilepsy has disappeared completely, and in most it is now controlled by medication.

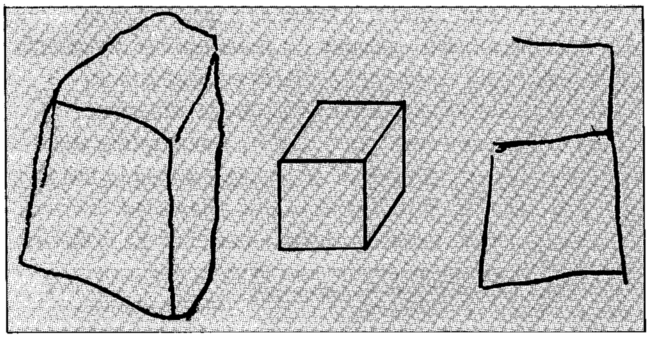
In this surgery the neurosurgeons, Phillip J. Vogel and J. E. Bogen, usually retract the right hemisphere, and in one stage they section all the cables connecting the two hemispheres. What does a person behave like after he has had split-brain surgery? Well, if you met such a person, you wouldn't be able to tell him from your next-door neighbor. And he is quite aware of his condition. One patient, when asked how he was doing on the day after the surgery, said, "Oh fine, except for a splitting headache." Another patient, when she is asked "How are you doing today?" frequently says, "Which half of me?" So there is at least a superficial awareness of the condition. However, it takes subtle psychological testing to find the massive deficits that occur in these patients in terms of crossing of information from one hemisphere to the other.

For example, if you close the eyes of a split-brain patient and put an object in his left hand and ask him what it is, he will not be able to tell you. This is because the right hemisphere controls the left hand and feels the object. The left hemisphere, the one that has speech, cannot tell you what it is because it has no information about it. But if you then take the object away and mix it with other objects and ask the patient to retrieve it, still without seeing it, he will be able to do so with absolute certainty. In other words, the right hemisphere can recognize the object; it just can't tell you about it. During a fairly short-term period after the surgery, when you ask the patient to copy a spatial design or three-dimensional figure, he will often do a better job with the left hand than with the right.

On the next page is a drawing made by a patient three years after split-brain surgery. The model was the figure in the middle. The drawing on the left was done with the left hand; the drawing on the right, with the right hand. Now, remember, the left hand is controlled by the right hemisphere, the one presumably specialized for visual-spatial abilities. And it is definitely superior.

We do also occasionally have the dramatic

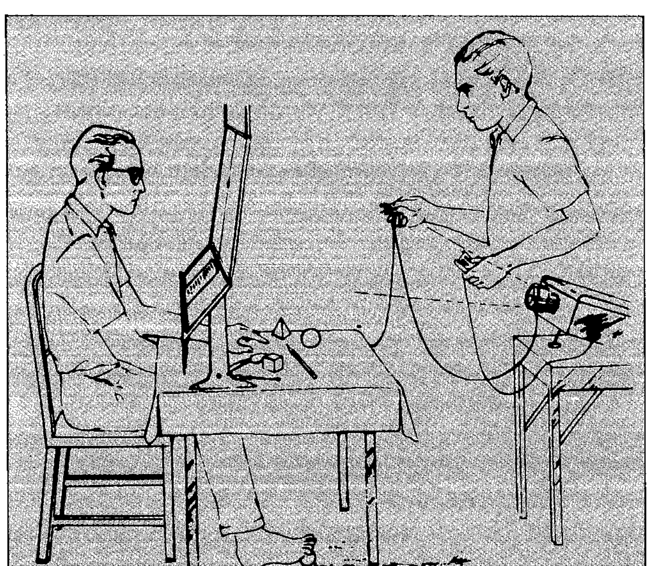
The Elusive Right Hemisphere



A drawing made by a commissurotomy patient three years after brain surgery. The model was the figure in the middle. Drawing on left was done with the left hand, that on right with the right hand.

phenomenon of some antagonistic behavior between the two halves of the body of the same patient, so that some patients complain that they find themselves buttoning their shirt up with one hand and unbuttoning it with the other. But this is not frequent.

The main technique for studying these patients, developed and used by Dr. Sperry and his associates for some 18 years now, uses the tachistoscope (below). The word, from the Greek, means "quickest view," and the instrument has been used in various forms for about 100 years. The patient sits in front of a screen with his hand under the screen, out of view. The examiner then flashes a picture of, say, a cube, to the left half of the visual field, using an electronic shutter that opens up for



The time-tested technique for studying split-brain patients uses an instrument known as a tachistoscope.

100 milliseconds. When you ask the patient what it was, he will deny that he has seen anything. That is the left hemisphere talking. But if you ask him to retrieve with the left hand (or foot) the object whose picture was flashed, he will do so very readily.

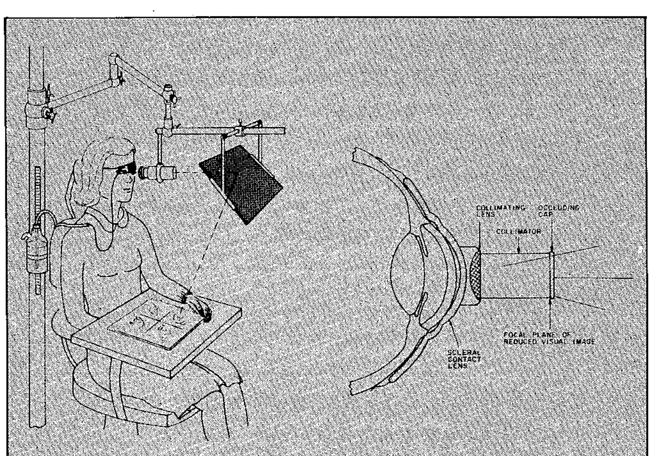
About three generations of graduate students have been working with these patients. From 1961 to 1969 the pioneering generation of Mike Gazzaniga and Joe Bogen, working with Roger Sperry, showed the dramatic splitting into two spheres of cognitive operation in the left and right hemispheres, each one having its own perception, memory, and consciousness. From 1969 to 1972 there was a new crop of graduate students —Jerre Levy, Bob Nebes, and Harold Gordon— topping each other in finding new tasks for which the right hemisphere is superior. And they found quite a few such tasks.

In summarizing the results of the first two generations, we may say that they found the left hemisphere to be linguistic, analytic, logical, sequential, and constructive. The right hemisphere was believed to be visual-spatial, gestalt, synthetic, and perceptual. And what was known about right hemisphere language? Of course, the clinical dogma was that there is no language in the right hemisphere of normal right-handed adults, but from the beginning of the split-brain research there was some evidence that the right hemisphere does have some language after all. To be sure, the left hemisphere is dominant, especially for speech, but there was also some auditory language comprehension in the right hemisphere. Nouns were believed to be comprehended better than verbs in the right hemisphere, and it was believed that the right hemisphere had no grammar at all. There was apparently some selective reading and writing, but nobody knew exactly how much. In particular, there was virtually no data on sentences or longer phrases, because there was no easy way to get all the information to one half of the brain at a time.

This is why in the summer of 1970 I developed the contact lens technique that enables us to get complex and prolonged information to one hemisphere at a time. As shown at the right, the patient sits in a dental chair. A picture, in her lap, is reflected by a mirror, reduced by a photographic lens and projected as an aerial image very close to her eye. On her right eye there is a very stable triple-curvature contact lens of the kind Derek Fender uses for research in visual perception at Caltech. The contact lens is scleral and covers about a third of the eyeball. Attached to this contact lens is a little aluminum tube called a collimator, about half an inch in length. At its base there is a very powerful lens, whose focal length is 1 cm. So here is what happens. The picture that the patient is looking at is reduced and projected at the end point—i.e., the focal plane—of the collimator. But when the patient looks through this whole system the collimator blows up the picture again, and its virtual image appears to him to be of normal size and at normal distance. The catch is that right near the end point of the aluminum tube there is also a little half-circular screen that occludes precisely one-half of the visual field, so that the patient can actually scan the picture quite freely with the contact lens, but at each point the half-circular screen follows the eye movements faithfully and thus permits visual information to enter only one hemisphere. The patient can even monitor his own manual performance on the board by visual guidance.

The reason I came to work on the problem of language in the right hemisphere was probably philosophic. There is a perennial problem in philosophy concerning the relationship of language to thought, and it occurred to me that a right hemisphere makes an unusually interesting model for studying this relationship, because in the right hemisphere you have thought without language.

The first task was to find out how much language there is in the right hemisphere. It turned out to be a substantial amount, and of a very special kind. Thus it is interesting to study right-hemisphere language as a clue to normal, natural language precisely because it is



This contact lens technique enables researchers to get complex visual information to one hemisphere at a time, allowing it to scan the information freely.

organized in a very unusual way.It is, so to speak, in a process of partial structuration, just like a child's language or language after brain damage to the left hemisphere. There you can sometimes study how the components of the cognitive system are put together much more easily than in the fully mature and complex brain of the normal adult. Also, data about right-hemisphere language may have implications for the question of how hemispheric specialization develops in normal children. It may also have important consequences for the potential of the right hemisphere to recover or compensate for language loss after damage to the left half of the brain.

Let me describe a series of experiments on the right hemisphere's ability to do linguistic analysis by describing the scores of the right hemisphere of three patients—LB, NG, and RS—on a battery of tests.

LB is a split-brain patient who was 21 when I tested him. He was 13 when he was operated on, and about 3 when the epileptic seizures first started.

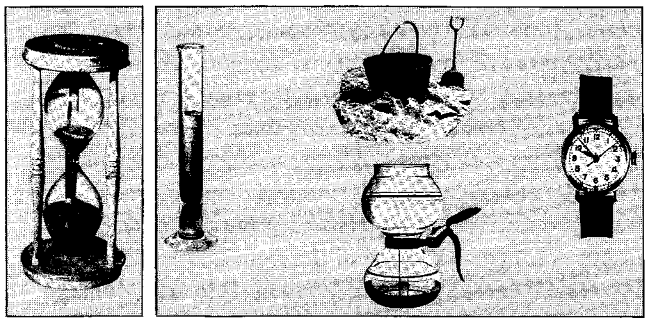
NG was a 40-year-old woman when I tested her; she was 30 when she was operated on, and she was about 18 when the seizures started.

RS is a different sort of a patient; she had her whole left hemisphere removed at the age of 10 in order to prevent a tumor from spreading to the other side. The symptoms first occurred at age 8, and I tested her throughout a long period, but for these particular tests at the age of 14. She was severely aphasic—able to use or understand spoken language only with difficulty, and without the ability to read and write. The main tool that she used for language expression and comprehension was meanings, semantics. Her grammar was relatively poor. Her comprehension was much better than her speech, and she had excellent melody, singing, and non-verbal imitation, which she often used to help her communicate with people around her.

A good way to analyze the scores of the right hemisphere of a split-brain patient is to compare them with the scores of the left hemisphere of the same patient. In the case of RS, I compared her with the scores of DW. He is a patient whose right hemisphere was removed surgically. This was done at the age of 8, symptoms occurring at about 6½, and I tested him when he was about 15. So in many respects DW can serve as a matched control for RS.

First of all, can the right hemisphere recognize the meaning of pictures, of simple common scenes or drawings? Here is one way to find out. Look at the

Visual Reception subtest
Reproduced from the Illinois Test of Psycholinguistic Abilities by S. A. Kirk, J. J. McCarthy, and W. D. Kirk, 1968, with the permission of the University of Illinois Press.

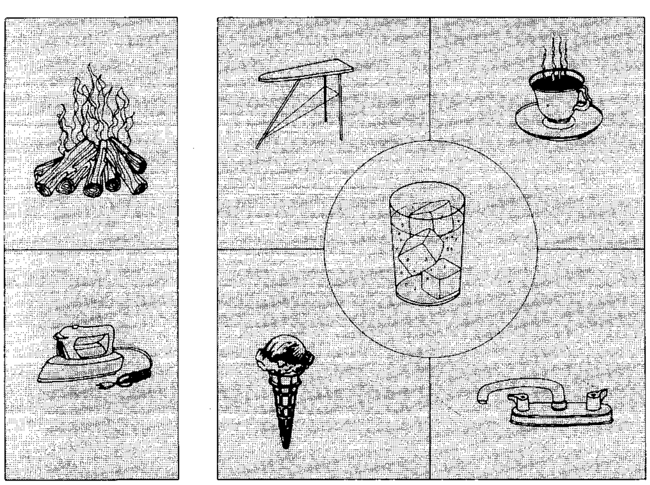


Look at the object on the left, then find one (that performs the same function) among those on the right.

object on the left above. Then match it with one in the group of objects on the right. In the actual test it is made clear that we are asking for functional similarity rather than perceptual similarity. Thus the patient should be aware that we are asking him to match the hourglass with the watch rather than with the coffee pot that looks more like it. The scores of the three right hemispheres in this test are about on the level we would expect from a normal 5-to-6-year-old child. (These are the first scores shown on the graph at the top of page 18—which also gives successive scores for the tests that follow.)

We can make the test a little more complicated by presenting a visual analogies problem. Look at the drawing below. Which of the four items on the right is related to the middle item on the right in the same way that the top item on the left is to the bottom one?

Visual Association subtest
From the Illinois Test of Psycholinguistic Abilities



Which of the four items on the right is related to the middle item on the right in the same way that the top item on the left is to the bottom one?

Whenever I try this test at Caltech, I get many more answers than I care to hear. The semantic relationship I want you to recognize here is that of equal temperature. Both the iron and the burning wood are hot, whereas the ice cream and ice water are cold. Again, the scores are around the normal 5-year-old level.

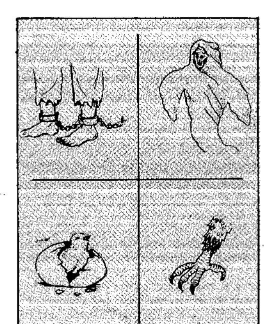
How well can the right hemisphere understand single spoken words? The examiner says a word aloud —for example, "back." Four alternative choices are shown only to the right hemisphere, so although both hemispheres hear the word, only the right hemisphere can see the pictures, and if the right hemisphere then points correctly with the left hand to the correct picture, this means both that it has understood the word and recognized the correct picture. (In this case, the task is a little more difficult because the names of the alternative pictures all rhyme with back—jack, tack, and pack.) The scores of the three right hemispheres range from about 5 to 8 years of age.

We can make the test even more difficult by superimposing a background of conversational noise on the stimulus word. The words are not as clear then; the signal-to-noise ratio is lower. In that case the right hemisphere suffers a certain detriment when compared to a normal child. The left hemisphere, it turns out, actually benefits from this, relative to a normal child. In other words, the right hemisphere makes more additional errors in this noisy version of the test than in the quiet version compared to a normal child who had the same number of errors in the quiet test. The left hemisphere, on the other hand, makes fewer such additional errors than a normal child.

But how well can the right hemisphere understand a single spoken word without any competition or noise? Here is an item from a very commonly used test—the

In this test for children suspected of having language disability, the examiner says the word "emerge," and the patient has to point with the left hand to the correct picture.

Reproduced from the Peabody Picture Vocabulary Test with special permission of the author, Lloyd M. Dunn, American Guidance Service, Inc.



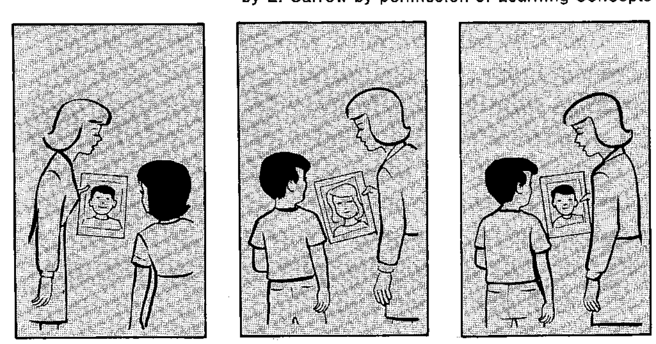
Peabody Picture Vocabulary test. It is used with children who are suspected of having language disability. And it is used because it requires no speech in order to respond. The examiner says a word aloud—for example, "emerge." And the patient has to point with the left hand to the correct picture.

The scores of the same three right hemispheres on this test came as a big surprise. They range all the way from 12 to 17 years of age. That's remarkable for a hemisphere that is not supposed to have any language. It turns out that the right hemisphere can recognize any part of speech equally well, as long as the word frequency is the same. By word frequency I mean the number of occurrences of the word in a typical passage of written or spoken language.

When we plot the performance of the left and the right hemispheres as a function of word frequency, we get parallel curves showing progressively fewer correct responses in both hemispheres as the words get less frequent, i.e., more difficult. But the right hemisphere has a constant decrement of performance relative to its sister left hemisphere. Words that are very frequent occur at the rate of 100 or more per million; infrequent words occur about once per million. An example of a word that is very infrequent is "vitreous." ("Vitreous" is a word I didn't know, but the right hemisphere of one of our patients did. So I remember it very well. It turns out to mean "glassy"—not "liquid," as I thought.)

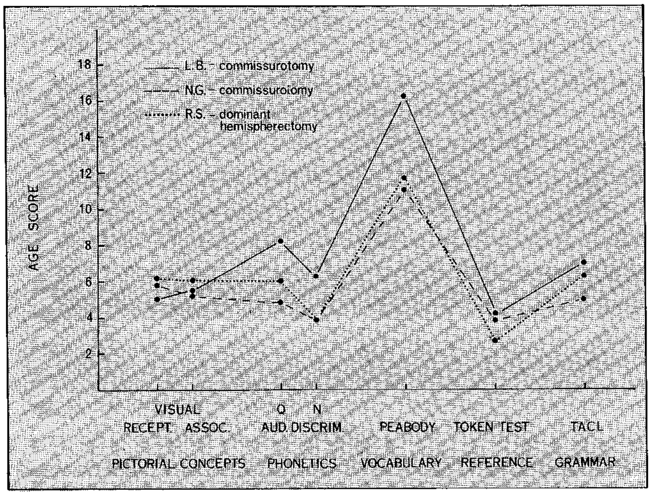
How well can the right hemisphere recognize longer phrases? There is one particularly interesting little test called the Token Test that is very sensitive to the presence of aphasia even when it occurs in a subtle form or when it is already in remission. The test is very simple. There are 10 or 20 chips in front of the patient; they occur in one of two shapes (square and circle), one of two sizes (large and small), and one of five colors (white, red, yellow, green, and blue). The patient has to perform instructions of increasing complexity spoken to him by the examiner. For example, "Point to a large one"; or "Point to a green circle"; or "Point to a large square and a yellow circle"; or "Point to a large green square and a small blue circle." The left hemispheres of these patients perform normally—100 percent on this test. Children who are about 11 also obtain perfect scores. But not the right hemispheres. They perform at about the level of a 4-year-old child. I know this for sure because there are no norms for this test for such young children, so that I had to administer it myself to my son's class in All Saints Day Care Center in Pasadena. These then are the upper (Peabody) and the lower (Token Test) limits of the linguistic ability of the right hemisphere. Why can the right hemisphere not understand the longer phrases? Presumably because this requires a short-term verbal memory, the kind that you use to remember a phone number between the time that you look it up in the phone book and the time you dial it. Short-term verbal memory is a rehearsal buffer that apparently requires phonetic analyzers, precisely what the right hemisphere does not have.

What about the ability of the right hemisphere to understand grammar? This allegedly it cannot do at all. Below is an item from a typical test. In this case the examiner says: "She shows the girl the boy." The correct picture is on the left. This particular sentence measures direct-indirect object relations. How well can the right hemisphere comprehend grammatical constructions? Well, at a respectable level—certainly not what you would expect from a hemisphere that has no grammar at all. Actually, when you compare the performance of the right hemisphere of, say, patient LB to that of a 6-year-old normal child, who has the same total score, you find that the error pattern is quite different. The 6-year-old child will tend to be much more sensitive to the linguistic complexity of the message, the parts of speech, the syntactic complexity. The right hemisphere, on the other hand, seems to be much more sensitive to the perceptual complexity, to the redundancy, and to the memory load of the message. At any rate, if this is how well the right hemisphere can do in a very non-redundant and carefully controlled test situation, imagine how well it can do in a freer, and more redundant normal conversational situation.



Which picture illustrates the phrase "She shows the girl the boy"?

The Elusive Right Hemisphere



The "mental age" profile of three right hemispheres (two of split-brain patients, one of a patient who had dominant hemispherectomy) on a battery of language tests.

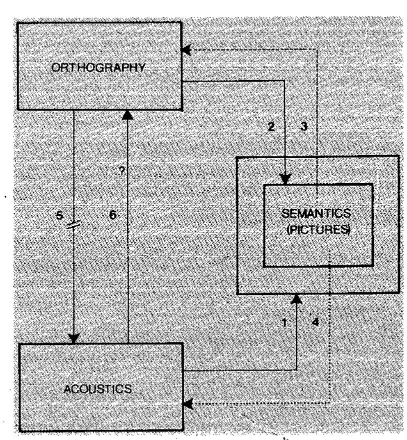
Now, take a look at the graph above that summarizes all these results. What can we say about this mental age profile? It certainly looks very curious. It is not the case that the right hemisphere is uniformly at the same age level for all the language functions sampled. This at once refutes one of the common views on how hemispheric specialization develops in the normal brain. According to that view, both hemispheres develop equipotentially up to a certain age, the age depending on who you read (some people say 5, some say 10, some say 13). At that point the left hemisphere goes on to develop further its language abilities, the right hemisphere goes on to develop visual-spatial abilities. But the prediction, therefore, is that the right hemisphere will remain arrested uniformly at a 5- or 10- or 13-year-old linguistic level. Well, it certainly does not. In some functions it goes on to develop into adulthood; and some functions such as speech it doesn't have at all.

I actually believe what is becoming increasingly accepted today, that hemispheric specialization is specified at birth. We now know that anatomical asymmetries are evident to the same degree in the brains of normal adults and young children, infants, or even fetuses. We also have electro-cortical evidence that these asymmetries occur just as strongly with little children as they occur with adults. What seems to be decreasing with age is the plasticity of the brain, its ability to compensate for damage to any part. So if extensive damage to either hemisphere occurs very early, up to the age of 5, say, then the child will suffer some transient language loss but will almost always recover most of the language. If, however, the damage occurs past the age of 13, some disability will usually be permanent. In right-handed adults deficit occurs only with damage to the left hemisphere.

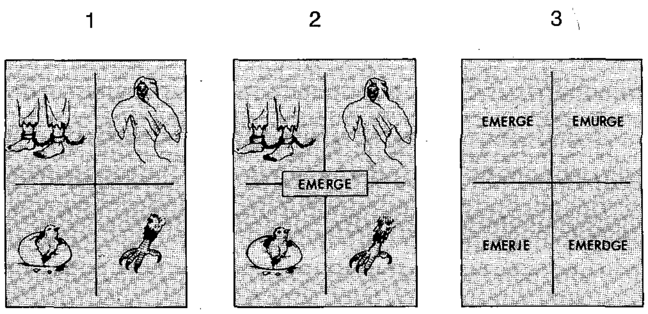
So we now have the following view. Rather than say that language is specialized to the left hemisphere uniformly, we have a continuum of specialization of language functions to the left hemisphere. Speech is indeed highly specialized to the left hemisphere. Even in the split brain it requires unified control so that the disconnected right hemisphere cannot have any speech. Reading is more bilateral, especially for single words, as we will see in a minute. Auditory language comprehension, especially for single words, is heavily bilateralized, and probably involves inter-hemispheric interaction in the normal comprehension process.

There is another way to look at this exotic model of language in the right hemisphere. How can you represent a word or a concept? Well, there are at least three ways. One is with the printed word—that is the orthography, or the spelled word. One way is with the acoustic or auditory form of the spoken word. And one way is with the picture that stands for what the word denotes. All of us, and every normal child past the first grade, can change from any representation to any other easily. We can match a picture with the word that stands for it, and a spoken word with its printed form. But can the right hemisphere do the same? Well, from the Peabody test we already know that the right hemisphere can associate the spoken word with the correct picture. So we have this connection—#1 (below).

A word standing for a thing can be represented by its sound, by its printed form, and by a picture of the thing the word stands for. This diagram shows that the right hemisphere can go from some representations to others but not equally in all directions.



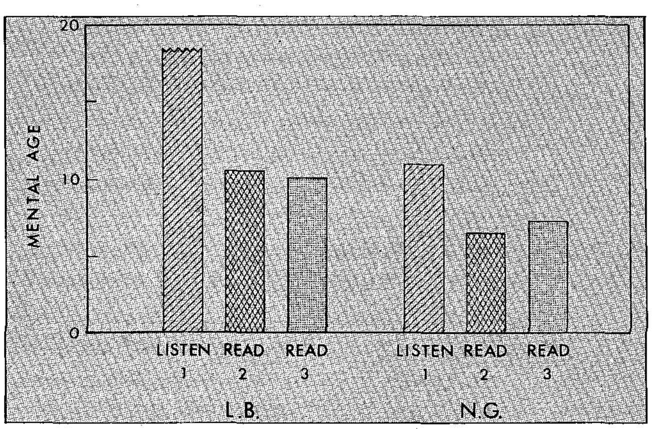
What about the ability of the right hemisphere to read single words? Here are three tests—all of them given to the right hemisphere. The test on the left, shown for comparison, is again the Peabody Picture



Three tests given to the right hemisphere for measuring the comprehension of word meanings—spoken, reading, and spelling.

Vocabulary test, the one we have met before. The examiner says a word aloud, "emerge," and the patient has to point to the correct picture with the left hand. The second test, however, is a reading version of the same test. Exactly the same stimuli are used, but here instead of saying the word aloud, the word is printed in the middle of the page. Finally, we have a spelling test, where the examiner says the word and the patient has to choose the correct spelling from the four provided. The alternatives are actually chosen because they are common spelling errors made by beginning spellers in the first and second grades. Remember that only the right hemisphere can see the visual multiple choice displays during the test.

How well can the right hemispheres do in this test,



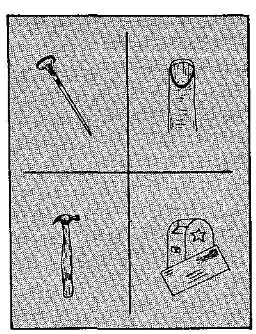
These equivalent ages of two disconnected right hemispheres show that they can comprehend more spoken words than printed words.

in terms of equivalent ages again? As we have seen before, on the standard auditory version of the Peabody test the right hemisphere of patient LB is very good, like that of a normal 17-year-old. For the reading version, he has a definitely lower ability, but still like a respectable 10-year-old, and so it is for the third test. Patient NG has the same pattern in her right hemisphere but lower scores throughout. Her auditory vocabulary is at the level of a 12-year-old; her visual vocabulary is at the level of a 7- to 8-year-old. It is significant that I have never found one case where the right hemisphere of any patient could read a word without being able to understand it when it was spoken. But the reverse is very common.

So we now have connection #2 from the printed form of the word to the meaning, to the picture. And I denote the fact (on page 18) that the visual vocabulary is a proper sub-set of the auditory vocabulary, by showing it as a smaller and dotted square.

What about the ability of the right hemisphere to write, to evoke the printed form from the meaning of the picture? Well, we suspect that there is some of it (connection #3); we know that there is a little bit of it in any case, but not exactly how much. This remains to be found.

Can the right hemisphere associate the sound image of a word with a picture? You may ask, what could I mean by that question? We know that the right hemisphere cannot speak. So how can it evoke the sound image if it cannot speak? Well, it may. Here is one way to find out. This is an item from the homonym test,

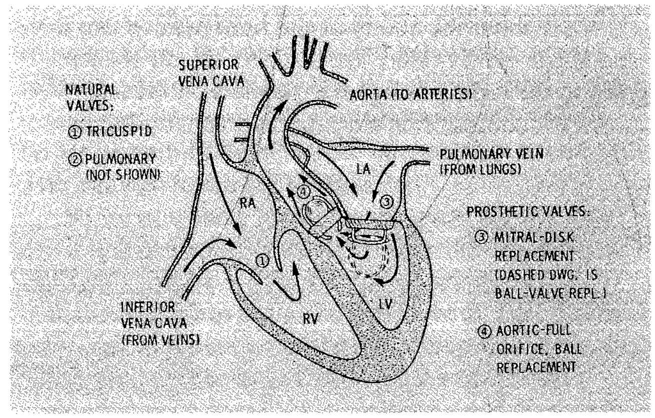


Sample item from the homonym test: "Find two that sound alike but mean different kinds of things."

developed by Ann Peters, from the University of Hawaii, and myself. The task is this: "Find two that sound alike but mean different kinds of things." The answer is a (finger) nail and a (steel) nail. Notice that the two decoys were not chosen randomly; one of them is a

continued on page 29

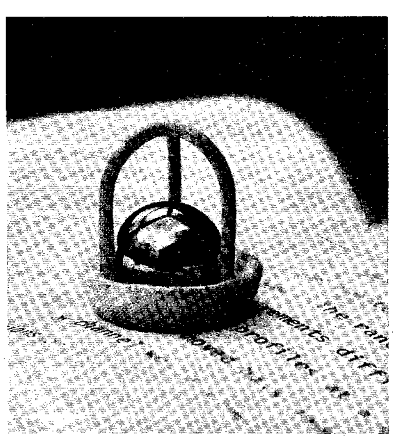
Progress in Artificial Heart Valves



This schematic drawing shows the chambers of the heart and how blood flows through them (except from the right ventricle through the pulmonary artery); it also indicates where prosthetic valves could be implanted.

In the 18 years since the development of the heart-lung machine made open-heart surgery possible, more than 500,000 artificial heart valves have been implanted in people whose own heart valves were defective. For most of those people, the quality of life has been improved and its length extended.

Encouraging as this record is, artificial heart valves are far from problem-free, and a team of southern California cardiologists and chemical engineers is working, first, to understand more about the nature of the cardiovascular system and, second, to apply that understanding to solving some of the problems created by the placing of a prosthesis in the human body. Dr. Earl C. Harrison of the USC-County Medical Center and Dr. Richard Bing of the Huntington Institute of Applied Medical Research are the cardiologists; Caltech's Professor William H. Corcoran and Research Fellow Ajit P. Yoganathan are contributing chemical engineering expertise.



The ball-shaped check element in this artificial heart valve moves up and down inside a Dacron-covered cage.

Heart valves—artificial or natural—operate like check valves in any chemical process system. They automatically limit the flow in a pipe or set of pipes to a single direction. Like natural valves, artificial valves are made in several configurations to accomplish this function. One is a tilting disk that flaps up to allow blood to flow through and down to shut off the flow and prevent regurgitation. Another type of disk valve operates similarly, but the disk moves straight up and down rather than tilting. There are also check elements shaped like balls that move up and down in a metal cage. All of the valve structures incorporate cloth (usually Dacron) sewing rings by which the surgeon sutures the valves into place in the heart. Each valve must, of course, operate dependably, and it must be fabricated of material that will not interact with the body in any harmful way and that will last for the normal life span of the patient.

The pump in the chemical process system of the human is the heart, which in the adult is a muscular organ about 5 inches long, 3 inches wide at the maximum width, and 2½ inches thick. It has four major chambers (two auricles and two ventricles), a number of valves, and associated arteries and veins that act as the pipes, or ducts, of the circulatory system. Briefly, and much simplified, the flow pattern of blood through the heart is as follows.

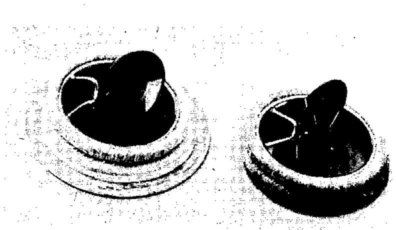
Blood enters the right auricle through the two largest veins in the body—the superior and inferior vena cavas. At this point, the blood is very low in oxygen, and the heart's first task is to help remedy this lack. In its role of circulating venous blood to the lungs, it takes blood from the right auricle in the diastolic beat into the right ventricle through a one-way valve—the tricuspid valve. The right ventricle contracts in the systolic beat to push the blood out. The tricuspid valve keeps the blood from flowing back into the auricle, and so it is forced out through the ventricle's only other opening and then into the pulmonary artery, which carries the blood to the lungs.

In the lungs the blood absorbs oxygen and then returns to the heart, entering the left auricle through the pulmonary vein. The heart in its diastolic beat sucks the oxygenated blood through the mitral valve into the left ventricle.

The left ventricle then contracts in the systolic beat. Again, the blood can flow in only one direction, so it is forced out of the heart, with a maximum flow rate of approximately 420 cc per second, through the aortic valve and into the largest artery of the body, the aorta. At this point the aorta is about one inch in diameter. The blood then makes a round trip through the body, and eventually returns to the heart through the vena cavas but with reduced oxygen content because of the amount left behind for the metabolic processes in the cells of the body.

Blood does not react in the same way with foreign substances like plastic or metal as it does with human tissues. Therefore, artificial heart valves are designed thinking of material requirements as well as those of structure. These valves share many of the design requirements of any flow system, but these must be met using available materials and keeping in mind maximum quality in performance. The research at Caltech focuses on understanding the flow and material characteristics.

In the flow studies, velocities, shear stresses, and pressure losses are investigated. Accurate, detailed observations of all these parameters in the human heart are not yet possible, but chemical engineers can build a model flow system in the laboratory—an artificial aorta, for example—with an artificial heart valve at its entrance, run a simulated blood fluid through it, and then make velocity measurements from point to point.



The tilting disks in these valves flap up to let blood flow through and down to shut it off.

To do this they use a laser-Doppler anemometer.

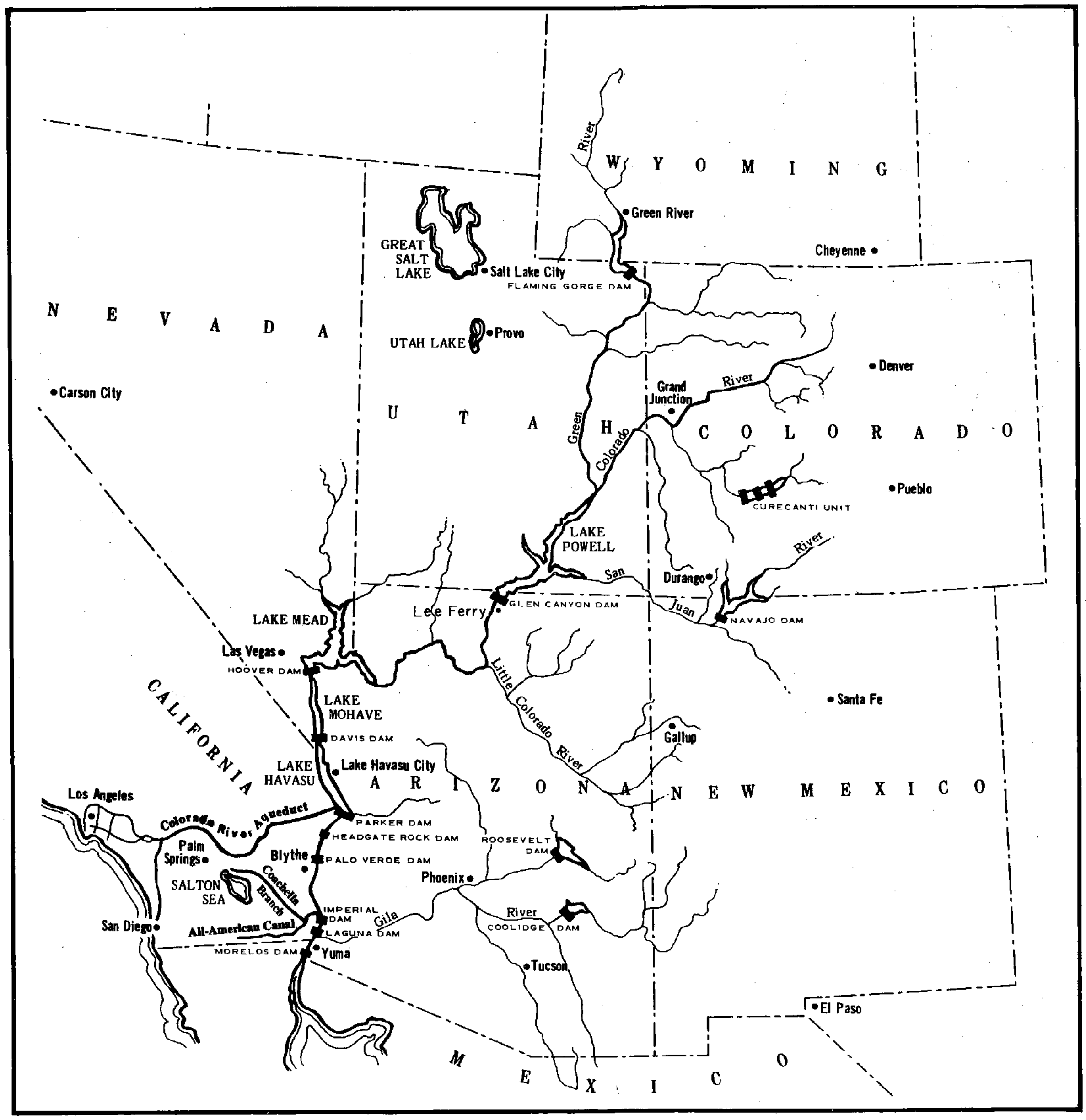
With this type of anemometer, crossed laser beams strike impurities in a stream of fluid flowing through a channel, and the light is scattered from them at a slightly different frequency than from the original source. From this displacement in frequency and the angle at which the laser beams pass through the system, calculations may be made of the exact velocity of the flow at a given point.

An understanding of the velocities is important for several reasons. Jet effects can, for example, damage the walls of the aorta. High shear stresses can damage blood cells, and regions of low flow can lead to clot formation. Under adverse circumstances endothelial cells of the aorta may be sheared off and scar tissue developed. Red cells may be fractured, allowing hemoglobin to leak out into the blood plasma. Platelets in the blood begin to sustain damage at stresses as low as 400 dynes per square centimeter. The result is loss of some of their chemicals, which can initiate clotting. When the velocity of the blood flow is too low, stagnation may take place in such areas as on the minor outflow side of a tilting disk valve, with consequent clotting or buildup of extra endothelial tissue. When the various problems are considered, the value of the research goals of learning more about shear and velocity fields along with pumping pressures becomes more apparent.

What are some of the other desirable features of artificial heart valves? They should be sterile, non-toxic, and surgically convenient to use. They should offer minimum resistance to flow and minimal reverse flow for maximum pumping efficiency. They should be long-lasting (say 25 years), with low mechanical and structural wear during all of that period. They should be reasonably quiet in operation, and it should be possible to manufacture them at a relatively low price.

At present, some 90,000 artificial heart valves are implanted in otherwise handicapped human beings each year, making possible longer and more active lives for the wearers. The failures and malfunctions of those valves—and they are surprisingly infrequent—have led to the cooperative effort to improve valve design and performance. Chemical engineers Corcoran and Yoganathan and doctors Harrison and Bing hope that a combination of meticulous observation of actual patients and careful laboratory research into the nature of the flow system will lead to reduction of the number and severity of the problems and to improvement of the quality and length of life. □

Map courtesy of the 1977 Annual Report of the Colorado River Board.



The Simple Economics of Water

by James P. Quirk

An economist explains the existing water rights to the Colorado River—and how they got that way

The Colorado River, which is the only source of surface water in the southwestern part of the United States, has a fascinating history. I suspect it is the most controlled river in the world, and it's a tiny river at that, with an annual average flow of only about 13.5 million acre-feet (maf). (An acre-foot is roughly the amount of water that it takes to fill an Olympic-size swimming pool—326,000 gallons, or approximately what a family of four uses in a year.) In contrast, the Columbia River, which drains about the same size basin as the Colorado, has an annual flow of 180 maf, so it's almost 14 times as large. What water there is in the Colorado, however, is rigidly controlled and allocated.

The main tributaries of the Colorado are the Green River and the San Juan River that come into it in Utah, the Little Colorado that comes in below the Glen Canyon Dam but above Lake Mead, and the Gila River that enters in Arizona—and hasn't delivered any water to the Colorado for over 50 years. The Phoenix-Tucson area uses up every drop of water in the Gila except for what falls in the form of desert rainstorms at odd times of the year.

There are some flows of water into the Colorado from Wyoming, Colorado, Utah, New Mexico, Arizona, and even Nevada. California doesn't contribute a single drop of water to it. Of the 13.5 maf of water that flow in the Colorado on the average per year, California is currently using 5.0 maf, and its use has gotten up as high as 5.4 maf. So California uses close to 40 percent of the river's water without contributing any part of it. This is cause for some concern among the other states in the Colorado River Basin.

There are a number of dams and reservoirs along the river. The two large ones are the Glen Canyon Dam (located north of Grand Canyon) and Hoover Dam. Lake Powell, the reservoir behind Glen Canyon Dam, has a capacity of about 27 maf. It currently holds about 14 maf, but it reached a peak storage of around 22 maf just two years ago. Lake Mead, which is behind Hoover Dam, is about the same size, 27 maf, and it now stores about 22 maf. The reservoirs located south of Hoover Dam are for holding water to be drawn on for irrigation.

About 85 percent of the Colorado River water is used by irrigation districts. The other large user is the Metropolitan Water District, which brings water through the Colorado River Aqueduct to the Los Angeles Basin, supplying supplementary water to Los Angeles and most of the cities in the basin, including San Diego. It is a major source of water for them.

For purposes of water allocation the river is broken in two, and the split occurs just below Glen Canyon Dam at a town called Lee Ferry. The northern part of the river is called the Upper Basin, the southern part is the Lower Basin. The Lower Basin states are California, Arizona, and Nevada; the Upper Basin states are Wyoming, Colorado, Utah, and New Mexico.

The flow of water in this river has been measured rather precisely since 1896. From 1896 to 1922, the average annual flow of 16.4 maf was relatively high. In fact, scientists making studies of the tree-ring growth over the last 400 years argue that this might have been one of the wettest periods in the history of the Colorado River Basin. Since the early 1920's, the flow has been near the average calculated from these studies —around 13.5 maf. The fact that the flow was heavy between 1896 and 1922 is important because the Colorado River Compact was signed in 1922. That means that the estimates of stream flow available to the people who signed the compact were unrealistically high.

In 1922 there was a meeting in New Mexico among all seven of the states in the Colorado River Basin. The meeting was brought about by the following events: In 1900 the Imperial Valley Irrigation District was opened up. It is the largest irrigation district in the western world, and it uses Colorado River water. At that time the water was delivered to the Imperial Valley through the Alamo Canal. In 1905 a heavy flow in the Colorado caused a break in the banks of the Alamo Canal, which was apparently not the best-constructed canal in the history of engineering, and the entire flow of the river was diverted to the Imperial Valley.

For two years the Colorado River flowed not to the Gulf of California but rather to the Imperial Valley, and in the process the Salton Sea attained its current size. What that indicated to the farmers in the Imperial Valley was that there was need for flood control on the river, and of course they also were interested in evening out the flow of the river for irrigation purposes. So they began to lobby for the building of a large dam on the Colorado River.

Ultimately California was joined by the Upper Basin states as lobbying partners. The community of interest was due in large part to the way in which property rights to water are established in the Western states. And this is where economists get interested in the problem.

In English Common Law, water rights were established under what is called the "riparian" system, where each property owner along a watercourse has the right to the unimpaired use of the water in that watercourse. In principle, then, if I take water out of a river under the riparian system, someone downstream from me can sue me because I have interfered with his right to enjoy that water. Now, a riparian system really makes sense if you're talking about using a river for boating or fishing or swimming or other recreational uses. It does not make sense for irrigation uses, or any uses in which you actually have to consume the water, remove it from the river.

In the western part of the United States, since water is used for irrigation purposes, a different system of property rights developed, called the "appropriative" system. Under the appropriative system a person establishes a property right to water by physically consuming the water. The first person who comes along a river gets seniority over people who come later on; that is, "First in time means first in right."

On the lower Colorado River the first users of water were the Palo Verde Irrigation District (1870), then the Imperial Valley Irrigation District (1900), and later the Coachella Valley Irrigation District. In the Upper Basin the only use of Colorado River water in the early 1900's was in the state of Colorado for small-scale irrigation. But the people in the Upper Basin could see as early as the first decade of the 20th century that California and Arizona were going to be a problem. In these areas, where the land was quite fertile, uses of water for irrigation were going to grow, thereby establishing seniority rights over the Upper Basin users. The Upper Basin states wanted some sort of agreed limitation on the Lower Basin use of Colorado River water. So there was an incentive both for California water users and for the people in the Upper Basin to get together on an agreement to build a dam—the Hoover Dam. Their goal was to satisfy the desires of the irrigators in California and to give some guarantees to the people in the Upper Basin states that their future claims to water wouldn't be washed away. And that's actually what happened.

In the Colorado River Compact, the seven states of the basin got together and divided the river at Lee Ferry, using as the basis for allocating water the "virgin flow" at Lee Ferry, that is, the amount of water that would flow through Lee Ferry if there were no irrigation use or reservoir losses above Lee Ferry. At the time the compact was signed, data on the flows between 1896 and 1922 indicated that the average virgin flow was 16.5 maf in the river, so that when the river was split 50-50, the Upper and Lower Basins were each assigned 7.5 maf of water per year. An extra million acre-feet was also made available to the Lower Basin. This was surplus water above and beyond the 50-50, and the Lower Basin got first crack at it. And there was one further important provision: namely, that the Upper Basin guaranteed to deliver 75 maf each ten-year period to the Lower Basin.

As we have seen, the amount of water in the river was overestimated; and when it turned out to be 13.5 maf instead of 16.5, the Upper Basin bore the whole burden of that loss. What started out as a 50-50 split in the river has become a split of 7.5 maf to the Lower Basin and roughly 6.0 maf to the Upper Basin. This hasn't caused any problems so far because the Upper Basin has been slow in developing its uses of Colorado River water.

Within the next 10 to 15 years, however, the Upper Basin will start running into the limits imposed by the compact. When that happens, there are going to be problems. In the Lower Basin we know fairly well how much water is used each year because it's used by very large irrigation districts, and it's relatively easy to

Colorado River Agreements

1922 — Colorado River Compact
Divided the river at Lee Ferry
Upper Basin to deliver 75 maf to Lower Basin each 10-year period

1928 — Boulder Canyon Project Act
Authorized Hoover Dam
Allocated Lower Basin Water: California 4.4 maf, Arizona 2.8 maf, Nevada 0.3 maf

1944 — Mexican Treaty
Guaranteed Mexico 1.5 maf annually

1948 — Upper Colorado River Basin Compact
Allocated Upper Basin Water: Arizona 50,000 af, Colorado 51.75%, Utah 23%, Wyoming 14%, New Mexico 11.25%

1956 — Upper Colorado River Storage Project Act
Authorized Flaming Gorge, Glen Canyon, Navajo, and Curecanti dams

1963 — Arizona vs. California
Supreme Court ruled that Arizona had the right to 2.8 maf from the mainstream of the Colorado

1968 — Colorado River Basin Project Act
Authorized the Central Arizona Project
Provided an absolute priority of 4.4 maf to California

monitor the water that they divert and return to the river. In the Upper Basin, users are mainly small irrigators, so no one knows how much water is, in fact, being used. Currently, the Bureau of Reclamation estimates how much water it takes to irrigate an acre and how many acres are in use, then multiplies them together to get an estimate of the total use of water in the Upper Basin. But when the Upper Basin runs into the limits imposed by the Colorado River Compact, there are certainly going to be court cases looking into whether the estimates make sense or not. Is the Upper Basin using more or less than it is entitled to?

The Colorado River Compact did nothing at all about dividing water among the states themselves. The division in the compact was only between the two groups of states, the Upper and Lower Basins. It was expected that the states would decide among themselves how to split the water up, but Arizona wanted no part of it, so Arizona didn't sign the compact.

In 1928 Congress, nonetheless, took the six-state compact as the basis for passing the Boulder Canyon Act, which authorized the building of Boulder Dam, or Hoover Dam. The Bureau of Reclamation, which was going to operate the dam, was instructed to sign contracts with the three Lower Basin states—California, Arizona, and Nevada—agreeing to deliver to California 4.4 maf, Arizona 2.8 maf, and Nevada 300,000 af per year. That division was negotiated in Congress, not between the states. It was part of the dickering that took place to get this act passed—which California farmers wanted, and which the Upper Basin people were willing to give them because the Lower Basin had agreed to not take more than 7.5 maf per year from the Colorado.

The dam was built, with Arizona fighting every inch of the way. When Parker Dam was started (the Colorado River Aqueduct draws its water from the Parker Dam reservoir), the governor of Arizona sent National Guard troops to stop the construction. Federal courts acted to force Arizona to send the soldiers home. This was the beginning of a series of six law suits filed by the state of Arizona against the state of California, five of which were thrown out of the Supreme Court. These were all attempts to stop California from using Arizona water and to establish rights to a certain amount of water from the river.

Because the Colorado is not only an interstate river but an international one, one of the provisions of the compact was that the Upper and Lower basins would share responsibility for any deliveries to Mexico to which the federal government might commit the states. In 1944 a treaty was signed with Mexico under which the United States agreed to deliver 1.5 maf per year to Mexico. In principle the Upper Basin is supposed to deliver 750,000 af and the Lower Basin 750,000, but there's a problem of evaporation loss in the river, and so if you start out with 750,000 af someplace up the Colorado, it's not 750,000 by the time it gets to the Mexican border. Who bears the evaporation losses? That hasn't come to litigation yet, but it probably will. The Mexican treaty had no provision in it for the quality of water either, and that turned out to be a problem later on.

In 1948 the four Upper Basin states got together and signed a compact among themselves splitting their part of the river on a percentage basis, plus a token 50,000 af to Arizona. At this time the Upper Basin had no reservoirs, and the federal government wouldn't build dams in the area until the states themselves had agreed on what water they had rights to. So there was pressure on the Upper Basin states to come to an agreement, and once they did, it was possible for them to go to Congress and ask for funds to build reservoirs. In 1956 the Upper Colorado River Storage Project

Act was passed. It provided funds for four dams, Glen Canyon being the most important because it has a reservoir behind it that is roughly the size of Lake Mead, which makes it the major storage reservoir in the Upper Basin.

Glen Canyon was built right above Lee Ferry—for one reason only. According to the Colorado River Compact, the Upper Basin was supposed to deliver an average 7.5 maf per year to the Lower Basin, but the Upper Basin didn't have any way to control that delivery. So Glen Canyon was built at a site where every drop of water that enters the Colorado in the Upper Basin can be caught. No tributary of the Colorado in the Upper Basin comes in below Glen Canyon Dam. It has no use as a dam for irrigation purposes. It provides for recreational uses and electric power generation, but basically it's there to allow the Upper Basin to control releases to meet the terms of the compact.

Since Glen Canyon was opened in 1963, the releases per year have turned out to be very constant at close to 8.25 maf per year—7.5 maf required by the compact, plus 750,000 af to Mexico. Since the Upper Basin uses of water have grown much more slowly than the Lower Basin uses, the water that is not being used gets stored in Lake Powell behind the Glen Canyon Dam.

Between 1963 and 1975 a little over 20 maf was stored in Lake Powell. By 1975 there was a total of 48 maf of water stored on the Colorado—four years' flow. Evaporation losses from the reservoirs had reached 1.5 maf per year, something like 13 percent of the flow of the river. This is a loss that doesn't get back into the system. All this buildup was essentially because the Upper Basin states knew that at some time in the future they were going to run into the limitations of the Colorado River Compact, and so there was an incentive to just simply keep storing water.

The Bureau of Reclamation has been storing water according to rules based on the Arizona vs. California decision and on the 1968 Colorado Basin Act. These rules amount to stating that there would be no further uses of water in the Lower Basin except those that had already been contracted for, and that Lake Mead and Lake Powell should be filled to roughly the same levels. That's the way the Bureau of Reclamation has operated the dams since 1963 when the Glen Canyon Dam was closed.

The background of the 1963 Arizona vs. California case is the following: California has the All-American Canal, opened in 1939 to replace the Alamo Canal. It delivers water to the Imperial Valley Irrigation District and the Coachella Valley Irrigation District. California also has the Colorado River Aqueduct built by the Metropolitan Water District to deliver water to the L.A. Basin and San Diego. The state of California is in a position to use all of the water to which it has rights (and more!). Arizona, on the other hand, which could get 2.8 maf per year from the Colorado (according to the Boulder Canyon Project Act), is not in a position to use that water. About 1.2 maf per year has been used by Arizona in irrigation districts located right next to the Colorado River, but there is no main aqueduct system for carrying water from the Colorado to the places where the Arizona citizens want it—mainly in the Phoenix-Tucson area. What Arizona wanted Congress to do was to finance such an aqueduct.

There's no way that the people of Arizona are *going to pay for such an aqueduct because it's simply* not economical. But under federal government sponsorship, costs to water users are reduced substantially since Bureau of Reclamation projects are paid for on a no-interest-rate basis over long periods of time. The aqueduct that will take water to Phoenix-Tucson will cost between $1.5 billion and $2 billion (maybe more than that now) and will be paid off over a period of about 68 years at a zero interest rate, which means that the payment for it by users will amount to only something like 10 percent of the cost of the project.

Anyway, Arizona wanted such an aqueduct system, and the Arizona senators and representatives kept asking Congress to pass a bill authorizing its building. But California's representatives in Congress opposed it with a real Catch-22 argument that goes as follows: Congress shouldn't appropriate any money for building

Where Is the Water Going?

Claims on the Colorado River	
Upper Basin Use	7.5 maf
Lower Basin Use	7.5 maf
Reservoir Evaporation Losses	1.5 maf
Deliveries to Mexico	1.5 maf
Total	18.0 maf
Water Available	
400-Year Average	13.5 maf
Deficit	4.5 maf

this aqueduct because it might turn out that Arizona doesn't have legal rights to the water it wants to use. It's up to Arizona, in other words, to establish that, sure enough, it does have rights to the water. But under the appropriative system the way you establish your right to water is by using it.

The long-time tradition of the Supreme Court was that it wouldn't get involved in a question of deciding on water rights until there was a dispute about water that was actually in use. So Arizona kept going to the Court (5 times in 30 years) and getting turned down, and going to the Congress and getting turned down. Arizona couldn't establish rights without using water, and it couldn't get the aqueduct to enable them to use it without having the rights.

The sixth time Arizona went into court, the Supreme Court took the case under advisement, and after five years (it was the most expensive case in the history of the U.S. Supreme Court) an almost completely arbitrary decision came down. Going back to the 1928 Boulder Canyon Act, the court said that the contracts signed by the Bureau of Reclamation with California, Arizona, and Nevada under that act constituted the assignment of rights, that in fact California got 4.4 maf, Arizona got 2.8 maf, Nevada got 300,000 af, of the Lower Basin's 7.5 maf allotment.

Those figures in the Boulder Canyon Act were just the result of the lobbying back and forth among congressmen in order to get the act passed. I'm sure that if they had known that this was going to be the basis for the water rights for all eternity, it would have taken a lot longer to have the act passed. At any rate, the main point, so far as Arizona was concerned, was that the 2.8 maf that Arizona had rights to was from the mainstream of the Colorado. California had argued that the million acre-feet that the Gila River could bring to the Colorado if it hadn't been dammed is part of the flow of the Colorado, just as all of the other tributaries are, and so Arizona's 2.8 maf allotted by the Boulder Canyon Act should consist of 1.0 maf from the Gila River and 1.8 maf from the mainstream of the Colorado.

The Supreme Court didn't buy this argument, and so Arizona got to use both the Gila's 1.0 maf (that it had been using for 50 years) plus 2.8 maf from the Colorado mainstream. Once the Arizona vs. California decision came down, Arizona went back to Congress, and in 1968 the act was passed that authorized the Central Arizona Project. This provides for the aqueduct (the Central Arizona Project, or CAP) that is going to carry water from the Colorado to the Phoenix-Tucson area, mainly for irrigation. But there was an extended debate and final compromise in Congress in order to get support from California for CAP. Under the compromise, California was given an "absolute priority" to 4.4 maf of water per year, but just what an "absolute priority" means is a matter for more future lawsuits.

Let me indicate one way of looking at what's been going on in this highly litigated river. Strictly speaking, the Upper Basin is supposed to get 7.5 maf per year, the Lower Basin the same. Reservoir evaporation losses currently are running 1.5 maf per year, and there is the 1.5 maf that has to go to Mexico. This adds up to 18 maf per year for a river with an estimated average annual flow of 13.5 maf. Needless to say, there will be further litigation in the future for the river.

Within the next ten years, the river will be fully used, the Central Arizona Project will be in operation, and some important changes will be in store for present users, especially in the state of California which has been using some 600,000 to 1,000,000 af per year above its rights.

The problem that is going to cause difficulties in California is the seniority of claims within the state. The Palo Verde Irrigation District followed by the Imperial Valley Irrigation District and the Coachella Valley Irrigation District have seniority in claims within California to 3.85 maf of water per year. These are the first three priorities so far as claims to water in the state are concerned. Then comes the Metropolitan Water District with priority number four for 550,000 acre-feet and priority number five for another 550,000 acre-feet. The city of San Diego, which now belongs to the MWD, has also merged its claim to 112,000 acre-feet of water with the MWD.

California has rights to 4.4 maf under the Supreme Court decision and you can see that when you add all these priorities up, you come up with 5.1 or 5.2 maf of water. Since 1964 California has been using anywhere from 0.5 maf to 1.0 maf of water per year more than its rights under the Supreme Court decision. It was able to use that water because Arizona was not in a position to use it. That is what accounts for the excess of use of water over California's rights. But when it comes to the point where California is actually restricted to 4.4 maf per year, the people who will get hurt are the ones at the bottom, the MWD users in the Los Angeles-San Diego area.

The Simple Economics of Water

The MWD, through the Colorado River Aqueduct, has the capacity to deliver 1.2 maf per year to the L.A. Basin. That capacity was not fully utilized in the mid-1970's because the MWD was using water from the State Water Project. In 1977, when the state cut off the delivery of water through the California Aqueduct to the Los Angeles area, the MWD switched back to Colorado River Aqueduct water. So, during the drought, southern California simply shifted from northern California water to Colorado River water.

Arizona is now using much less water than it has rights to, but the magic day is going to come when Arizona claims its full water rights. In about 1985, when the Central Arizona Project comes on line, California is going to be cut back on Colorado River water. When the cutback occurs, it's going to hit the MWD. The MWD will have an aqueduct with a capacity of 1.2 maf per year but with water rights to only about 500,000 af per year. Is there any way to replace the water that the MWD (and especially the city of San Diego) is going to lose because of this cutback? The physical capacity to deliver the water to the L.A. Basin from the Colorado, namely the Colorado River Aqueduct, is sitting there, and it certainly can be used. The answer is that there's water available from the Imperial Valley and the Coachella Valley. At least, in principle there's water available there for the MWD to use.

In the Imperial Valley water is currently selling for about \$4 to \$6 an acre-foot. Basically, the irrigation district is required to just charge enough for water that it will break even. It's a nonprofit organization. The charge for water keeps going down over time because the Imperial Valley is in the process of paying off the bonds on the All-American Canal, a main item of cost for the district. So as time goes on and more bonds are retired, water gets cheaper and cheaper. But water in the L.A. Basin is worth a great deal more than \$4 to \$6 an acre-foot (even net of delivery charges), and the MWD would be quite willing to pay considerably more than that—maybe ten times that amount, say, \$40 to \$50 an acre-foot. People in the Imperial Valley should be quite happy to sell water at those prices.

In any other market goods move to where their prices (after delivery charges) are highest. This is not true in the case of water because of certain existing laws. There is, first of all, a federal law that prohibits any irrigation district from selling water outside the district so long as money is still owed on Bureau of Reclamation projects for the district. So, currently, the Imperial and Coachella Valleys, which still owe money to the federal government for the All-American Canal, can't sell water outside the districts. They can use the water for purposes other than irrigation, but the water has to be used within the geographical limits of the Imperial or Coachella Valleys.

There's a state law that prohibits any irrigation district from selling water outside the district too. So, in order to get water transferred from these districts to where it has a higher value (namely, the L.A. Basin) you'd have to change both federal and state laws. I don't think they're impossible to change, but it's interesting that these laws have been on the books for years and years.

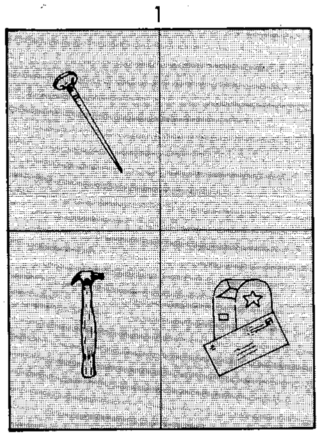
I think it is important to point out that we aren't going to destroy agriculture in the Imperial Valley and Coachella Valley by changing these laws and permitting the districts to sell water to the MWD. We're talking about a relatively small amount of water in any case. If we replace the water that is going to be lost to the MWD when the Central Arizona Project comes on line, we're still talking about less than 15 percent of the water that is currently used in the Imperial-Coachella valleys.

It might even turn out that there is no need to lose any water there at all. There could be water that the MWD can get without any decrease in water available for farmers. The All-American Canal is now an unlined canal. It has dirt sides, and it is estimated that anywhere from 150,000 to 500,000 acre-feet of water per year is lost through seepage in the canal. Currently it doesn't pay to line the canal with cement to stop the seepage because water in the Imperial Valley is only worth \$4 to \$6 an acre-foot. But once water gets up to \$40 an acre-foot, it might very well pay the people of the Imperial Valley to cement the canal; and they might find that they won't have to cut their use of water at all.

Despite a number of apparently adverse factors—that the Colorado River is an intensively used and controlled waterway, that the Lower Basin uses are very close to the 7.5 maf allotment right now, that in the next five to ten years completion of the Central Arizona Project is going to yield an additional 1.3 maf to Arizona, and that there will be a consequent cutback in California withdrawals of water—the truth is that there is no need for panic. We've got lots of water. All we have to do is get it to the right places. □

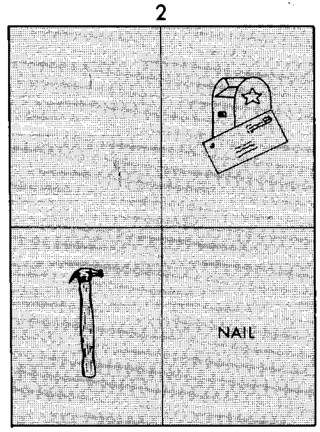
The Elusive Right Hemisphere of the Brain . . . *continued from page 19*

1



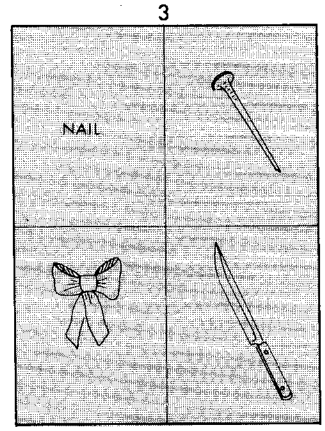
Find two pictures where the names rhyme.

2



Find a picture that rhymes with the printed word.

3



Control test: Which picture illustrates the printed word?

semantic associate of the nail (hammer) and one rhymes with it (mail). The left hemispheres can do this task very well but not the right. One patient, NG, could not do it at all with her right hemisphere. The other patient, LB, could do it above chance but not as well as with his left hemisphere. So we say that connection #4 is possible, but not necessary. This is especially interesting in the case of LB because there the connection occurs without speech. (We know that right hemisphere muteness is not due simply to lack of right hemisphere control over the vocal apparatus.) How can you evoke the sound image of a word without actually being able to say it? We are not sure!

What about the ability of the right hemisphere to go directly from the printed form to the auditory form? This process is very important and is called grapheme-to-phoneme correspondence rules. It is what every beginning reader is supposed to be taught in school—how to associate sound with the printed word. He sounds the word out first and then, since he knows its meaning when it is spoken, he can learn to recognize its meaning when it is printed. Psycholinguists still debate the question whether in fact the mature reader has to go through this stage when he reads efficiently. Do we, in fact, sound out the words when we read silently? Well, we don't sound them out overtly, but maybe we do it sub-vocally or unconsciously. So it's interesting to find a neurological model where this may not happen.

Does it happen in the right hemisphere? Above are three tests again. On the left is a rhyming version of the homonym test. You have seen the homonym test before. But here the task is to find two pictures where the names rhyme with each other. In fact, we used the same stimuli as for the homonym test but the picture of one of the homonyms is removed. There are many stimuli, of course, and this is just one of them—nail and mail. The second test is the crucial one. Here you have to find a picture that rhymes with a printed word. Finally, we have a control test, to see if the right hemisphere can read what "nail" means in the first place. If the right hemisphere cannot read the word, then we have a rather uninteresting reason for its failure to do the rhyming task. To rule that out we require the right hemisphere to match the printed form with the actual picture that goes with it rather than with a rhyme.

The patient who couldn't do the homonym test with her right hemisphere cannot do this either. She can do it only with her left hemisphere. What about the patient LB who could do the homonym test with his right hemisphere? Again, on the rhyming test his left hemisphere is perfect, but his right hemisphere is also very good —just as it was in the homonym test. On the reading version, however, although the left hemisphere is still perfect, the right hemisphere is at chance level. It can't do it, and this is not because the right hemisphere cannot read the word. When you just give the control test of matching the printed word with the picture, the right hemisphere is very good, almost perfect. So we say that the right hemisphere does not have connection #5. It does not do phonetic recoding. This shows that we can read without phonetic recoding; it's neurologically possible to do so, though this is not necessarily the way we actually do it, of course.

Now this is very interesting. Notice what we have here. The same right hemisphere of the same patient can match the printed form with the picture of a word, and, separately, the picture with the sound of the same word, but it cannot spontaneously go directly from the picture to the sound. Formally, this is to say that the lexical transformation

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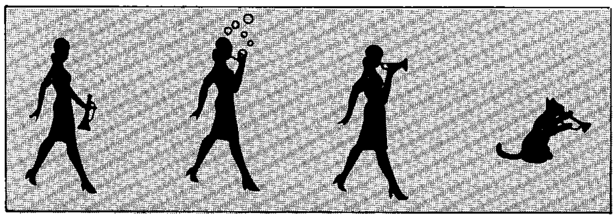


Test sentence: "Lady blowing the horn." Which is the correct picture?

relation is not transitive. By one of the tests I've shown you before where the right hemisphere had to match a spoken word with one of the four spellings of it and from other error patterns in reading, we can show that the right hemisphere does seem to have the ability to go from the auditory to the visual form (connection #6). So we can go in one direction from auditory representation to orthography but not from orthography to sound in the other direction. That means that the lexical transformation relation is not reversible. So Einstein may have been right when he said that God does not play dice with the universe—but He doesn't seem to be playing a simple formal game either. At least not when He made up the right hemisphere.

What about the reading of sentences? Above is a sentence that can be either spoken or printed, and the pictures that go with it. Notice that there are three critical items on this example: lady, blowing, and horn. Unless you get all three, you cannot point to the correct picture reliably. First let's look at the ability of the left and the right hemisphere to perform the auditory version, to listen to the sentence and point to the correct picture. The left hemispheres are normal. They can always decode sentences regardless of how long they are, up to and beyond 4 and 5 elements. The right hemisphere begins to fail if the sentence is longer than 3 items. So for those of you familiar with George Miller's magical No. 7, we may say that the left hemisphere has a short-term verbal memory of 7 plus or minus 2 items. The right hemisphere, on the other hand, may well have a short-term verbal memory of 3 plus or minus 1 items.

What about the reading version of the same test? The left hemisphere can do this still, of course, perfectly well. But the performances of the right hemispheres are definitely lower than they were on the auditory version. This is a bit surprising. I was hoping that because the printed version is always in front of the subject, the right hemisphere will be able to recover here what it had lost in the auditory version; that it can refresh its memory by reference to the print. In the auditory version, once the sentence has been said, it's no longer available, of course. But it turns out that the printed form doesn't help at all. Apparently what you need to decode a longer message is to keep the sentence in some *internal* representation. The printed form out there in the real world helps you not at all.

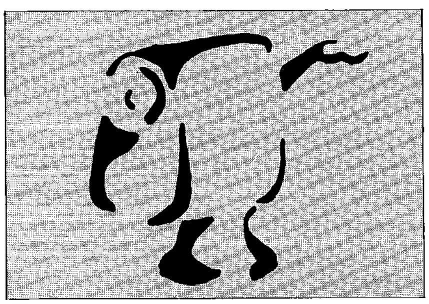
It remains to be answered by further research, what is really the special role of the right hemisphere in reading, if any. Is the right hemisphere especially important in beginning reading—that is, in assigning meaning to new and unfamiliar linguistic symbols? Or, on the contrary, is it especially important for efficient speed reading through the quick recognition of recurring visual patterns, such as the suffix "ing" or common phrases like "in the" and so on?

How does all this fit within a more general theory of human intelligence? We now know that we cannot characterize the differences between the two hemispheres in terms of sensory modality. It is not simply the case that everything visual is done better by the right hemisphere, anything auditory better by the left hemisphere. It's not the material that counts, either. Language in the left, space in the right doesn't work either. What is it then? It's the information-processing style. What are those styles?

One way to try to find out is to look at the psychometricians' concept of human intelligence. You know what the psychometrician, the factorial analyst, does; he makes up many tests. He gives them to many subjects—normal subjects—and using statistical techniques he observes which results cluster together. These he defines as primary and perhaps secondary factors or mental abilities. Most factorial theories of human intelligence, like Spearman's in England, Thurstone's in the United States, and Guilford's, not far from here at USC, recognize many factors and always at least the following three: a spatial factor, a verbal factor, and a numerical factor.

Well, spatial and verbal abilities sound like good candidates for right and left hemisphere factors, respectively, until you look more carefully. It turns out that the verbal factor is indexed, among others, by the size of the vocabulary that a subject has, but this is precisely what does not distinguish well the right hemisphere from the left—the size of the auditory vocabulary of the right hemisphere is very large. What about space? It turns out that the spatial factor is indexed among others by what is called "embedded figure tasks," the ability to extract a figure from the surrounding background. You will see in a minute that that is not a very good right-hemisphere ability. Rather, it is highly specialized in the left hemisphere. There is more promise when we look at what Thurstone called "the two visual closure factors."

The first visual closure factor is defined as the ability to perceive an apparently disorganized or unrelated group of parts as a meaningful whole; that is, the capacity to construct a whole picture from incomplete or limited material. Here is an example from a test developed by Thurstone himself to measure this ability. The question is this: If you fill in the missing parts, what do you see here? (The



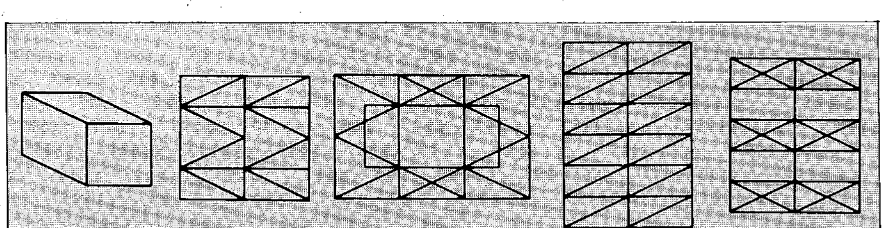
Fill in the missing parts—and what do you see?

answer appears at the end of the article.) If you see a penguin, you're wrong but in good company. Those of you who don't see what this is can argue that their right hemisphere has a lower level of tolerance and has gone to sleep by now. This is presumably a very right-hemisphere type of task, as has been shown both on the split-brain patients, normal subjects, and especially with patients who have had unilateral brain damage. There is often a severe disability on this task after parietal right-hemispheric damage.

The second visual closure factor is the ability to hold a configuration in mind despite distraction; that is, the capacity to see a given configuration that is hidden or embedded in a larger, more complex pattern. Below is an item from a commonly used test for this ability—Thurston's Embedded Figures Test. It turns out that people fall into one of two groups. They are either field-dependent or field-independent, depending on whether they are poor or good on this test, and this goes with a certain personality type as well. The task is simple. Can you trace the design on the left within the more complex pattern on the right, in the same size and orientation? (The answers are shown at the end of the article.) I've given this kind of test to the two hemispheres, and it turns out to be a very heavily left-hemisphere factor. The right hemisphere is very poor in this test—even though to outside appearances it's a spatial task, the kind that the right hemisphere may be good at.

My point is not simply that these two visual closure factors describe the specialization of the two hemispheres in the visual-spatial domain, but rather that they apply equally well to the linguistic domain. The analogy is that the right hemisphere recognizes verbal units—for example, spoken or printed words—as whole patterns, as gestalts, without being able to divide and analyze them into their components. The left hemisphere, on the other hand, decodes words and sentences by feature analysis.

What are some of the prospects of this kind of work? I think that the main advances we will see in the next 10 or 20 years will be technological. We will have techniques to create benign and reversible lesions, so that any one of us could feel what it is like to operate with only part of the brain. One part of the brain could be taken out of commission for a short time by cooling or some other electrical or chemical technique and then restored to its normal operation. Then, for example, we could experience what it means to be a split-brain patient.



Are you field-dependent or field independent? Trace the design on the left within the more complex patterns on the right, in the same size and orientation.

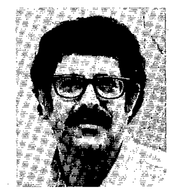
Undoubtedly we will have methods for interhuman communication that involve no language at all. We may have some electrodes implanted in the brain or some other means of sampling cortical neuronal activity, and we will then be able to communicate directly in terms of states of consciousness rather than with words. Here the right hemisphere may become increasingly important for the communication process. But meanwhile, until this happens, the thing I am going to do next is to try to apply the technique of the contact lens to a more general technique that enables us to present information to one half of the visual field of any person without any attachments to the eye, i.e., without the contact lens itself. And this promises to be very exciting because there is even the possibility that we will be able to rehabilitate aphasics using this technique. By getting information only to the good half of the brain, we are perhaps going to remove some pathological inhibitions from the diseased part and encourage the residual structures to take over the language functions. It also promises to be of some value for the diagnosis and remediation of certain forms of specific developmental language disability, where, presumably, hemispheric dominance is never established. Perhaps we can "encourage" and induce dominance by getting information to only one half of the brain.

You may want some more practical implication of this research, and here is my personal advice, not too serious.

If you are worried about incurring some brain damage, and want to minimize its consequences, choose to have it when you are very young. If this is not possible, at least be a female or a left-hander, preferably both. If everything else fails, use the following rule of my friend and colleague Rita Rudel: When you see a bullet coming, turn your right cheek.

Let me conclude with an epilogue. It is a common condemnation these days of our Western educational system that it discriminates against the right hemisphere. There is no doubt that our educational system is half-brained, but is it left-brained? To be sure, there are important differences in the learning styles of the two cerebral hemispheres; the left is constructive, algorithmic, stepwise, and logical. It benefits from narrow examples and from trial and error; it can learn by rule. The right hemisphere, on the other hand, does not seem to learn by exposure to specific rules and examples. Our studies show that it does not benefit from error correction, perhaps because it does not have an internal model of its own solution processes, which it can then interrogate and update. It needs exposure to rich and associative patterns, which it tends to grasp as wholes. Programmed instruction is certainly not for the right hemisphere, but I am not sure what is the proper method of instruction for our silent half. It is part of the elusiveness of the right hemisphere that we find it easier to say what it is not than what it is.

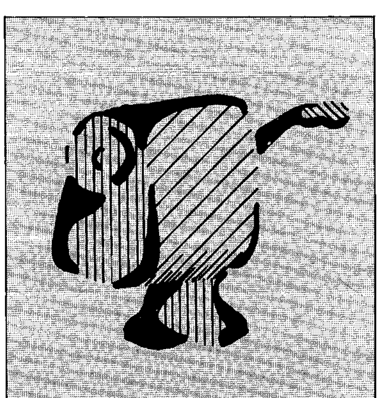
Meanwhile, rather than lament the cultural disadvantages of the right hemisphere, I ask you to take a second look at its moral fiber, lest it lead us all into temptation. I am referring to a news item in one of the issues of *Mind and Brain Bulletin*. It reads as follows: "A team at Rutgers Medical School reported that the brain's right hemisphere has a more pronounced involvement in sexual climax than the left." So I ask you, "Doesn't the right hemisphere have more fun?" □



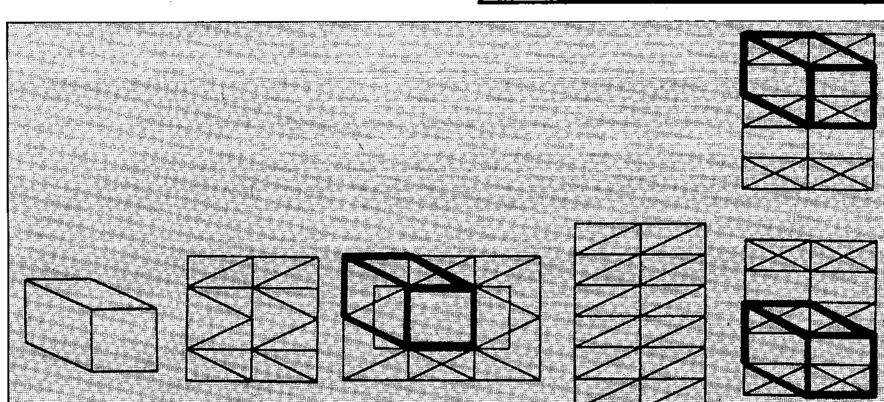
Eran Zaidel received his MS from Caltech in 1968 and his PhD in 1973 in engineering science. He became a research fellow in biology in 1973, and since 1976 he has been a senior research fellow. His article, "The Elusive Right Hemisphere of the Brain," has been adapted from a Watson Lecture given at Caltech on April 12. As a graduate student, according to his colleague Derek Fender (professor of biology and applied science), Zaidel "masqueraded as an expert in mathematical linguistics, working with Fred Thompson (professor of applied philosophy and computer science) on the problems of communication between man and the computer.

"Essentially it was his plan to teach the computer to understand English instead of its normal gobbledygook. But, as he worked on this problem, his interests swung strongly to the human side of the communication link. He transferred his allegiance from Fred Thompson to Roger Sperry (Hixon Professor of Psychobiology) and he began working on the functional capacity of the human brain. Now, his interest is condensed still further—he is only interested in *half* a brain."

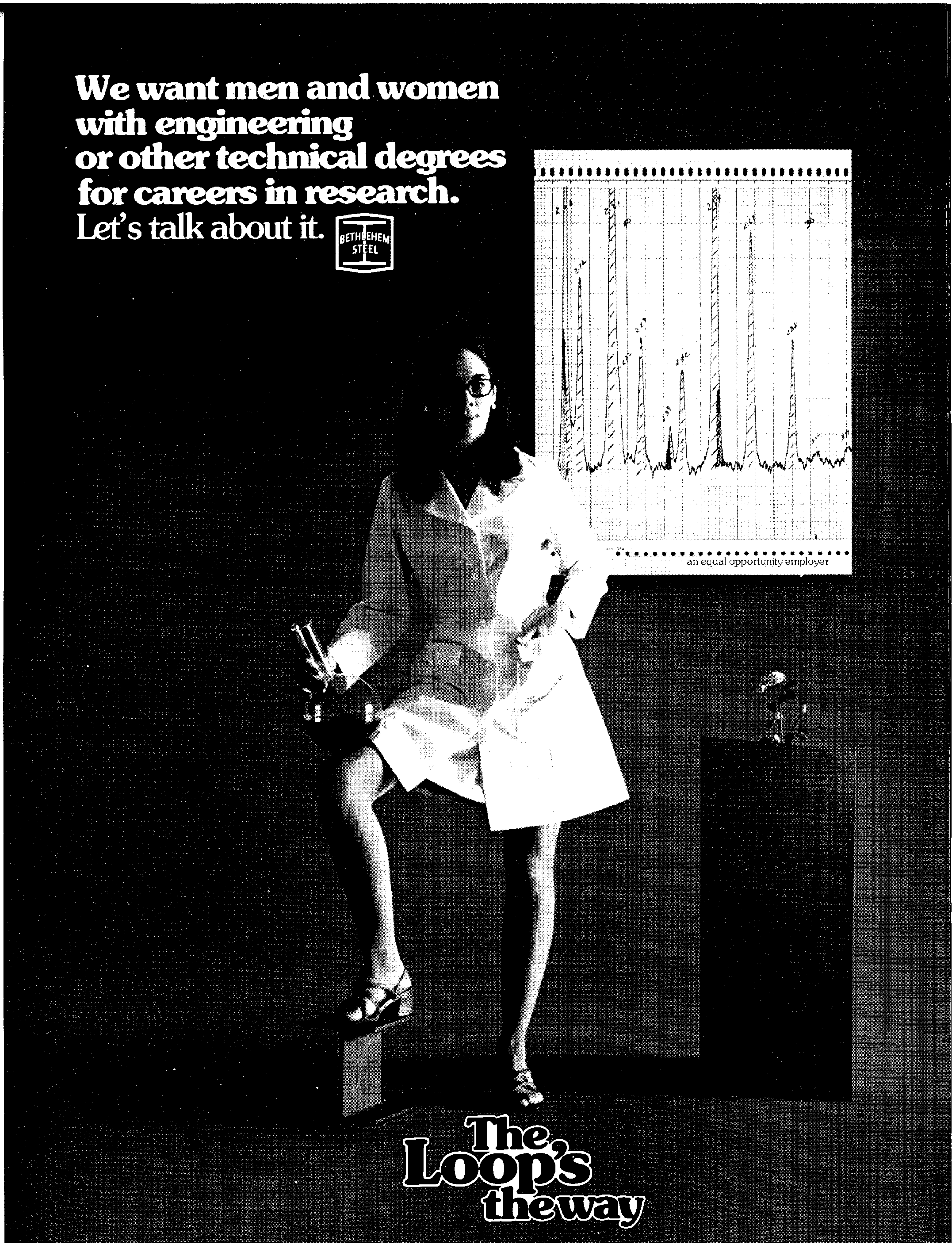
ANSWERS to problems on page 31



Of course—it's a pencil sharpener.



Configuration on left is repeated three times in the larger patterns.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Here's the kind of thing we're talking about; some recent examples of jobs handled by new GE engineers:

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4. *Stephanie B.* Medical systems service engineering. Installation and test of new hospital radiographic and fluoroscopic x-ray system.
5. *Mel D.* Field engineering. Appraisal load testing of low and medium-voltage switchgear and power transformers for utility and industrial applications.

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