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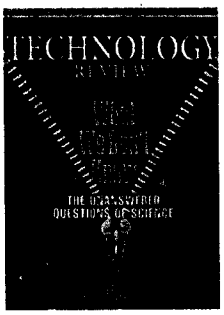
THE GREAT Unknown

ROBERT M. HAZEN

ON HER DEATHBED, ACCORDING TO HER SECRETARY ALICE B. TOKLAS, GERTRUDE STEIN ASKED, "WHAT IS THE ANSWER?" RECEIVING NO REPLY, SHE CONTINUED, "THEN, WHAT IS THE QUESTION?"

Human curiosity, and our insatiable impulse to ask questions, drives scientific research. In the July issue of *Technology Review*, readers had a chance to formulate their own list of the most important unanswered scientific questions. Presented with a list of 14 questions that Carnegie Institution president Maxine Singer and I claimed were among the most important in our book Why Aren't Black Holes Black? The Unanswered Questions at the Frontiers of Science, nearly 200 readers commented on the list by substituting their own favorite questions for ours. ● Most of the respondees agreed with our premise that science, challenged by innumerable fascinating unanswered questions, is far from over. But many readers also identified what



In July, we asked readers to pick today's most profound questions of science. The results, tabulated here, show that while the questions are scientific, the process of identifying them is anything but.

they saw as serious ommisions and a few soundly denounced our list as misguided, elitist, or naive. In short, the survey demonstrated that while scientists are generally convinced that answers are achieved with some degree of objectivity, our choice of questions is highly subjective. Here are what *Technology Review* readers identified as the most compelling questions facing science today.

THE MOST FREQUENTLY ASKED QUESTION

Technology Review readers posed more than 100 different questions, but almost a third of all respondents—by far the largest group—placed questions about the mind, the brain, and the nature of consciousness near the top of their lists. Among the varied questions related to this topic were: How does the mind work? What are emotions? What is love? Can we build a conscious machine? What is the origin of creativity? What do dreams mean? Why do we respond to music?

These questions contrast with our more narrowly focused question: "What are the physical origins of memory?" which one reader described as "almost laughably simple" in comparison with the attempt to understand consciousness. Many of science's deepest thinkers, including Nobel Prize winners Francis Crick and Gerald Edelman, and mathematician Roger Penrose, would agree with *Technology Review* readers that the latter "What is consciousness?" is the most fundamental unanswered question concerning the brain. Crick, who defines consciousness as "attention and short-term memory," has called for an intensified research effort in his book *The Astonishing Hypothesis.*

But the distinction between questions about memory and those about consciousness raises a key point about the nature of science. For a question to be scientific, it must be answerable through a reproducible process of observation, experiment, and theory. Is the study of consciousness, as opposed to the physical brain, scientific? Many researchers, including Stanford computer scientist Terry Winograd and the late physicist Richard Feynman, are not persuaded that it's possible to find a concrete physiological definition of consciousness, much less an unambiguous experimental protocol for its study, any time soon. They contend that since a clear research strategy is lacking, consciousness must for the time being lie outside the domain of science.

Indeed, most unanswered questions about human thought seem to fall somewhere in the nebulous realm between philosophy and science. What is an idea? What is an emotion? What does it mean to be curious or to know something? It's hard to see how these abstract questions can be reduced in any neat way to a collective property of brain tissues, nor is it obvious how to make the giant leap from the concept of thought to a reproducible experiment in the lab.

The problem of consciousness has been pondered by myriad scientists and philosophers, from avowed reductionists who expect that thought and emotion can be explained by neurons alone to skeptics who deny any hope of physical understanding. University of California philosopher David Chalmers adopts a useful intermediate view by dividing the question "What is consciousness?" into what he calls the "easy problem" and the "hard problem."

The AUTHOR'S Questions

In "What We Don't Know" (*see TR July 1997*), Robert Hazen identified 14 questions that he and his colleague Maxine Singer found to be the most important on today's scientific agenda:

1. What is dark matter?
2. What will be the ultimate fate of the universe?
3. Can we devise a theory of everything?
4. How do atoms combine?
5. Will we run out of energy?
6. What's going on inside the earth?
7. How many people can the earth sustain?
8. How did life on earth originate?
9. Can we unravel the genetic code?
10. How did life on earth become so varied?
11. How do we develop from a single cell?
12. What are the physical origins of memory?
13. Is behavior dictated by genes?
14. Are we alone in the universe?

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The easy problem focuses on mechanics of consciousness: How can humans isolate external stimuli and react to them? How does the brain process information to control behavior? How can we articulate information about our internal state? Neurobiologists have long tackled aspects of these questions, which are amenable to systematic study in much the same way that researchers probe the physical mechanisms of memory. Perhaps, with many decades of intense research, such questions can be answered.

The hard problem, on the other hand, relates to the intangible connections between the physical brain and self-awareness, emotion, perception, and reasoning. How can music evoke a sense of longing, or a poem deep sadness? How does reading a book stimulate curiosity or frustration? What are the physical structures and processes that produce love, fear, melancholy, or greed?

Some researchers believe that, in due time, an understanding of consciousness will follow naturally from research on the physical brain. Others argue for a radically new perspective. Chalmers, for example, makes the startling proposition that consciousness must be accepted as a characteristic of the universe completely distinct from previously recognized physical attributes, such as matter, energy, forces, and motions. Perhaps, he says, consciousness is an (as yet unrecognized) intrinsic property of information.

What is consciousness? For the time being, scholars cannot even agree on what exactly the question means, much less imagine the form an answer might take. For as far into the future as anyone cares to foresee, this greatest mystery of the human mind may remain.

Memories are different; they are more tangible and tightly defined. At one level, memories are a kind of information that can be stored, recalled, altered, or deleted—all familiar tasks in the computer age. It's conceivable that each memory is stored in the brain as a molecule or set of molecules that carries a message. Alternatively, memories might be hard-wired into networks of brain cells, or maybe they consist of electrical potentials that pervade the whole brain. Whatever the nature of memories, we can hold out the hope that answers will yield to clever and persistent study.

There's another reason why the quest to understand memory holds a central position in the study of the human brain. Awareness, perception, and thinking depend on receiving information through our senses and analyzing that information in the context of learned patterns of experience—patterns recorded as memories. We cannot be self-aware without a remembered context of existence and personal history. Understanding the physical basis of memories, therefore, is an essential step to knowing what it is to be human—to be conscious of memories.

"Since living things are so beautiful, shouldn't there be an underlying mathematics that describes them?"

Thomas D. Schneider
Molecular Information Theorist
National Cancer Institute

"It seems important to me... to understand the short-term dynamics of solar-type stars. There is considerable evidence that variations in the output of the sun is responsible for wide swings in the earth's climate."

Timothy Fohl
President
Technology Integration Group
Carlisle, Mass.

BOTTOM PHOTO: LINDA ENGLE; ALL OTHER PHOTOS PROVIDED BY READERS QUOTED

"How long will the human race survive? I am most interested in the impact of technology on our survival."
Lauren H. Seiler
Professor of Sociology
The City University of New York

"The most significant science done by humans will, I believe, always be connectable to the human scale, affect human society, in some plausible way. Hazen's questions fail this test."
Rustum Roy
Founding Director
The Materials Research Laboratory
Pennsylvania State University

ONE STEP BEYOND

A number of fascinating questions about the physical design of the universe appeared several times in the survey responses: What is gravity? What is time? What is the connection between the quantum and macroscopic world? What is the relationship between mathematics and the physical world? These are good questions. All are the subject of current research and debate, and any one of them could make a "top 20" list.

But other questions, rather similar in tone and content, are more problematic. Can we develop antigravity? Can we develop time travel? Can matter be transported across space other than physically? Each of these questions postulates technologies that are outside of current physical laws. That's not to say that such technologies are impossible. It's just that science, at present, has no way to address such speculation.

Still other questions approach space and time from a more philosophical perspective: What is the meaning of quantum mechanics? Why is the speed of light what it is, or, why is the speed of light so slow? Why are the fundamental constants what they are? The line between science and philosophy is often fuzzy when we ask why nature behaves the way it does. Scientists can measure the speed of light with exquisite accuracy, but why it has that particular value may defy present theory.

In a similar vein, several readers asked if alternate universes might exist, perhaps with different physical constants. Without specific observations to support or deny these ideas, alternate universes are outside the domain of today's science.

SOCIAL CONCERNS

Quite a few readers condemned us for failing to acknowledge the social sciences. One reader asks, "Where are the big questions with regard to the domain of human [society]?" Another observes, "By focusing on the natural sciences, and completely ignoring the social sciences, both authors neglect to mention the areas of our greatest ignorance: the unanswered questions of sociology, economics, political science, social psychology."

Guilty as charged. Except for our borderline question on behavioral genetics (Is behavior dictated by genes?), we restricted ourselves to the physical and life sciences. A survey similar to ours from the perspective of the social sciences would be fascinating, especially judging from the following questions: Is war inevitable? Can we achieve world peace? How do societies arise? What is the best way to raise a child? What are the relative roles of nature vs. nurture? What is the source of religious impulse? What are the rules of economics? What are the roles of work and leisure time? While

such questions are not on our scientific question list, readers who asked them can take heart that these issues are now in the mainstream of sociological research.

SPECIALIZED KNOWLEDGE

A number of readers' questions seem narrowly focused and specific. For example: What is the nature of turbulence? Why are human females smaller than males? How is the North Pacific High generated? What are the short-term dynamics of solar-type stars? Can we develop synthetic photosynthesis? Can we understand the fundamental principals of catalysts? What causes ice ages? How does a mirror work? What causes ball lightning?

All of these questions are fascinating, but I wouldn't place them anywhere near the top of my own list. Still, determining such rankings is a subjective process that the scientific community faces all the time. Ranking comes most forcefully into play in the day-to-day world in the awarding of prizes and research grants. Academic prizes and the prestige associated with them are usually conferred for work perceived as fundamental and basic. Ernest Rutherford's discovery of the atomic nucleus, Linus Pauling's explanation of the chemical bond, and James Watson and Francis Crick's unraveling of the structure of DNA were all recognized by Nobel Prizes. Prestigious periodicals such as *Science* and *Nature* may only have space for 10 percent of all submissions. Thus, acceptances are based in large measure on the perceived importance of the question being addressed.

Research grants, on the other hand, are usually awarded by government agencies—the Departments of Commerce, Health and Human Services, Defense, and Energy, for example—that have specific pragmatic goals in mind. Many scientists, accordingly, become adept at rationalizing their pursuit of basic research by demonstrating how this research is essential to solving applied problems.

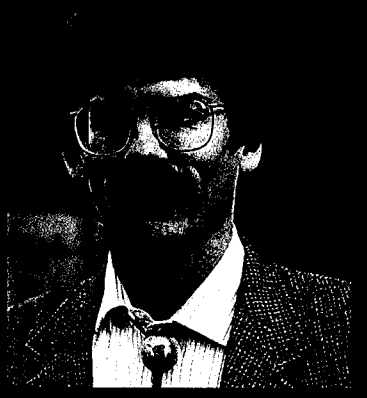
Clearly, the relative importance that we attach to questions is highly subjective. Every culture asks different questions, reflecting their varied beliefs and experiences. All cultures wonder at one time or another about the vast scale of the universe and the ancient origin of life. Not all cultures, however, ask how many stars exist or the exact age of fossil species, much less how these objects evolve. Ultimately, asking the right question at the right time is a key part of the art of doing science.

WAY BEYOND SCIENCE

Perhaps the most fascinating of reader responses were the numerous questions that are, by broad consensus, outside the domain of science. A few examples: Is there a god? What happened before the Big Bang? What

"Can matter be transported across space other than physically? Can matter be transported across time?"
Courtland Lewis
Science and Technology Policy Analyst
Melbourne, Fla.

"By focusing on the natural sciences and completely ignoring the social sciences, [Hazen] neglects to mention the areas of our greatest ignorance: the unanswered questions of sociology, economics, political science, social psychology. What are possible forms that societies can take? Why do collective groups form at all? What are the functions of language?
Keith Sawyer
Professor of Education
Washington University



"Why are the principles of quantum mechanics what they are?. . . Precisely why is it that the position and momentum of a particle seem to represent only different aspects of some underlying single thing, rather than two independent properties, as they [do] in classical physics?"

Michael G. Raymer
Director
Oregon Center for Optics
University of Oregon

"One of the things we need to know is how the leaf of a plant makes starch, carbohydrates, sugar, and protein–the process known as photosynthesis."

John H. Pierce
Environmental Botonist
Ontario, Canada

happens after death? What is the nature of evil? Is the universe infinite? Are there realms of consciousness or reality that we do not normally perceive?

Science addresses only those questions that can be answered by reproducible observations, controlled experiments, and theory guided by mathematical logic. This distinction between scientific and nonscientitfic inquiry, though sometimes blurred, is neither frivolous nor arbitrary.

Science can reveal if a painting is old, but it cannot determine if the painting is beautiful. It may be used to deduce the origins of the physical universe, but it cannot rationalize why we are here to ponder its existence. Many of the most important questions we face—What is the meaning of life? Whom should I marry? Is there a God?—thus lie outside its domain. Such a realization led economist and philosopher Kenneth Boulding to remark, only partly in jest: "Science is the art of substituting unimportant questions that can be answered for important questions that cannot."

A few questions that lie at the boundaries of science are more difficult to classify. Scientists are divided, for example, regarding questions that several readers proposed regarding extrasensory perception, precognition, numerology, and psychokinesis. While many researchers lump these ideas into the broad category of pseudoscience, reproducible experiments can be performed to test individuals who claim to possess such abilities.

HUMAN NEEDS AND NEW TECHNOLOGIES

Several respondees chastised us for neglecting questions that address pressing human needs. "The most significant science done by humans," according to one reader, "will be connectable to the human scale, affect human society in some plausible way. Hazen's questions fail this test."

Among such questions readers asked are: Can we extend the human life span? Is death inevitable? How can we increase food production? What is earth's global water cycle? Is the earth's ecosystem self-correcting? Can we develop synthetic replacements for the body's organs? What causes weather? Can we direct evolution? Can we build in a process of recovery from the next dark age—assuming there is a next dark age?

Others proposed questions related to developing new technologies: Can we develop new energy technologies? (This was also the basis of our fifth question. Can we develop human space travel? What are limits on computer speed? What will become possible through nanotechnologies?

The difficulty of judging the relative importance of applied questions is well illustrated by efforts to find a

cure for AIDS. Basic discoveries related to viruses, DNA, and the immune system, for example, may not directly benefit anyone now infected with HIV, but eventually they will be essential to finding cures for many diseases, perhaps including AIDS. Discovery of a specific AIDS vaccine, by contrast, might not result in any fundamental new understanding of biological systems, but would have an immediate and profound effect on millions of people. It would seem prudent, therefore, for any AIDS research funding strategy to strike a balance between basic and applied efforts.

THIS TOO SHALL CHANGE

According to one observant reader, Hazen and Singer's "questions are an oddly unsorted lot that address different levels in an unsystematic way.... The list is too much a creature of our present preoccupations; it is not built to stand the test of time."

We couldn't agree more. The list will change for three reasons. First, scientific questions are inherently answerable, so the questions may, in fact, be answered. Two centuries ago, one of the greatest questions in science was how to achieve a reliable method to determine longitude. A half century ago, the search for the molecular mechanisms of genetics consumed thousands of biologists. Now, new questions arise to replace the old.

Second, profound questions are not always obvious questions, so new questions may be discovered. While the birth of the universe, the origin of life, and the inevitability of aging and death have invited speculation for thousands of years, other compelling questions, such as the nature of energy, the operation of genes, and the mystery of dark matter, are far more subtle, emerging from the nagging persistence of odd observations and anomalous bits of data. Gradually, over the span of decades or even centuries, we become aware of a fundamental lack in our understanding of the physical world, and a deep mystery—a new question—comes fully to light.

Third, some questions are not now scientific but may be some day. Before Edwin Hubble's discovery of distant galaxies, the question of how the universe began lay outside observational science. Without relevant data, it was a matter of philosophical speculation. But, once astronomers understood what to look for, the origin of the universe entered the mainstream of scientific inquiry. Similarly, "What is time?" and, in my opinion, "What is consciousness?" are today more questions of philosophy than of science, though that situation may change as we learn more about matter, energy, and the brain. And who knows what questions we have not yet thought to ask? But that's the fun part.■

"The great unanswered question in [chemistry] is not the combination of atoms as much as it is the transfer of atoms and molecules that leads to the great chemical processes that constitute both animate and inanimate systems."

Steven J. Lippard
Chair
Department of Chemistry
MIT

"One of the most profoundly hard problems in all of science is that of scene analysis. Imagine creating a computer attached to a camera that could write a description of any scene."

David G. Stork
Chief Scientist
Ricoh Silicon Valley, Inc.
Menlo Park, Calif.