THE MIND'S SKY

Human Intelligence in a Cosmic Context

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This Is Not the Universe

The mind does not understand its own reason for being.
—René Magritte

A picture without a frame is not a picture.
—John Archibald Wheeler

Perhaps you’ve seen the painting: A pipe, depicted with photographic realism, floats above a line of careful, schoolboy script that reads Ceci n’est pas une pipe—“This is not a pipe.” René Magritte painted it in the 1920s, and people have been talking ever since about what it means.

Did Magritte intend to remind us that a representation is not the object it depicts—that his painting is “only” a painting and not a pipe? Such an interpretation is widely taught to undergraduates, but if it is true, Magritte went to an awful lot of trouble—carefully selecting a dress-finish pipe of particularly elegant design, making dozens of sketches of it, taking it apart to familiarize himself with its anatomy, then painting its portrait with great care and skill—just to tell us something we already knew. After all, nobody really confuses paintings with reality, and the danger that people will try to smoke paintings of pipes or eat paintings of pears does not rank high among the hazards confronting the working artist.
Perhaps it was with an eye toward discouraging simplistic explanations of his famous pipe that Magritte returned to the same motif toward the end of his career. In *The Air and the Song*, painted in 1964, just three years before Magritte’s death, the pipe is found inside a representation of an elaborate, carved frame, as if to emphasize that it is only a painting—yet smoke from its bowl billows up out of the painted "frame"! In another canvas, *The Two Mysteries*, Magritte is even more insistent: The original pipe painting, complete with caption, is depicted as sitting on an easel that rests on a plank floor; but above it to the left hovers a second pipe, larger (or closer) than the painted canvas and its frame. What we have here is a painting of a paradox. Obviously the smaller pipe is a painting and not a pipe. But what is the second pipe, the one that looms outside the represented canvas? And if that, too, is but a painting, then where does the painting end?

We’ve been set on the road to infinite regress. Suppose, for instance, that Magritte had glued a real pipe to the actual frame of *The Two Mysteries*: Would the genuine pipe qualify as a pipe, or did it become something else once Magritte affixed it to the frame? (The same riddle is posed by Andy Warhol’s Brillo Pad boxes, which are indistinguishable from the Brillo boxes on sale in any supermarket. Had Warhol captioned one with the words, “This is not a Brillo Box,” would the caption be true or false?)

It seems to me that the roots of the paradox reside in the concept of the frame. When we look at a realistic painting—Raphael’s portrait of Pope Leo X and his nephews, say, or Breughel’s *Peasant Wedding*—we accept by convention that it represents real people and actual objects. When that convention is denied, as in Magritte’s pipe paintings or in the many impossible scenes depicted by his fellow surrealists—locomotives emerging from fireplaces, clocks limp as jellyfish—the point is not to remind us that paintings are not real. That much is true, but trivial. The point is to challenge the belief that everything outside the frame is real.

The enemy of surrealists like Magritte, and of artists generally, is naive realism—the dogged assumption that the human sensory apparatus accurately records the one and only real world, of which the human brain can make but one accurate model. To the naive realist, every view that does not fit the official model is dismissed as imaginary (for those who “know” that they err when they entertain contradictory ideas) or insane (for those who don’t). Naive realism is flattering—to set one’s self up as the sole judge of what is actual is to taste the delights of godlike power—but it is also stultifying. Once the realist settles on a single representation of reality, the gate slams shut behind him, and he is doomed to live thereafter in the universe to which he has pledged allegiance. This universe may be elegant and adamantine as the Taj Mahal, but it is a prison nonetheless, and the prisoner’s spirit, if it is still awake, will beat its wings against the bars until it weakens and dies.

The truth, of course, is that nobody can grasp reality whole, that each person’s universe is to some extent unique, and that this circumstance makes it impossible for us to prove that there is but one true reality. Even if we could free ourselves from fantasy and delusion (not that to do so would necessarily be a good idea), we could at most agree upon small swatches of reality. *Everything* thus is framed, cut from its cosmic context by the limitations and peculiarities of our sensory apparatus, the prejudices of our presuppositions, the multiplicity of each individual mind, and the restrictions of our language. We may feel more comfortable with our own frame of reference than with that of others, and assume it to be more valid, but the frames are there nonetheless. There’s no escaping them; the known universe
is and always will be in some sense a creation of our (hopefully creative) minds. Magritte made this point overtly in a 1933 painting. It depicts a canvas on an easel that records every detail of the view outside the window it partially obscures, right down to the drifting cumulus clouds. He titled this work *The Human Condition*.

If modern artists have labored to call attention to the fact that our understanding of reality is limited and variegated, so too have modern scientists. Many people are surprised to hear this. They think of science as a collection of hard facts mined from bedrock reality, through a process as uncreative as coin collecting. The scientists, however, have come to know better. Astronomers understand that each act of observation—photographing of a galaxy, taking an ultraviolet spectrum of an exploding star—extracts but a small piece of the whole, and that a montage of many such images is still only a representation, a painting if you will. The quantum physicists go further: They appreciate that the answers they obtain through experiment depend to a significant degree on the questions they ask, so that an electron, asked if it is a particle or a wave, will answer “Yes” to both questions. (I will say more about this in the final chapter of this book.) Neuroscientists studying the other side of the mind-nature dialogue have learned that the brain is no monolith, either. Each of us harbors many intelligences, and insofar as my various minds take varying views of reality—in terms, say, of spatial relationships versus language, or of sentimental versus rational education—I can no more legitimately impose a single model on myself than I can expect to impose it on others.

This is not to say that every opinion about the universe deserves equal attention—as if schoolteachers, in much the same way as they are being urged by fundamentalists to teach biblical creation myths alongside Darwinism, should also be enjoined to give equal weight to the flat-earth theory, ESP, or the notion that little Sally in the back row was empress dowager of China in a former life. That no one theory of the universe can deservedly gain permanent hegemony does not mean that all theories are equally valid. On the contrary: To understand the limitations of science (and art, and philosophy) can be a source of strength, emboldening us to renew our search for the objectively real even though we understand that the search will never end. I often reflect on a remark made to me one evening over dinner in a Padua restaurant by the English astrophysicist Dennis Sciama, teacher of Roger Penrose and Stephen Hawking. “The world is a fantasy,” Sciama remarked, “so let’s find out about it.” To me, that heroic statement encapsulates the spirit of science: to seek to learn something while accepting that one will never know everything.

Science is young—it has been a going concern for only about three hundred years, and the word *scientist* itself was unknown before about 1825—yet it has already transformed our world view. Thanks to science, educated men and women can contemplate an astonishing array of invigorating facts—that we are kin to the animals, that the tenure of our species has amounted to but a moment compared to the age of the earth, that the sun is one star among many, and that seemingly solid objects are themselves as empty as cosmic space, strewn with atoms lonely as stars.

Owing to its great prestige, however, science often is given credit for understanding more than it really does about what things really are. Actually, science seldom has much to say about what something “is.” Science studies and predicts phenomena, not essences, and to attempt to use it to assert, for instance, that living organisms “are” machines is to choose the wrong tool to do the job. A scientific theory provides a model that enables us to reason about unfamiliar
phenomena by translating them into terms with which we are familiar. It is a kind of language, and as such itself exemplifies the dialogue between mind and nature.

To clarify what I mean, consider that science rests on a tripod whose legs are hypothesis, observation, and faith.

A scientific hypothesis (which aspires to become a theory, which if extraordinarily successful and far-reaching might attain the status of a law) begins as an idea about how something works. A scientist may come up with a hypothesis more or less inductively, by working with raw data for many days or years before it occurs to her. That's the hard way, much esteemed by the work-ethic Victorians: it's more or less how Darwin arrived at his theory of evolution, which is one reason that the Victorians found it impossible to dismiss Darwin even though many were repelled by his idea that we share an ancestor with the apes and chimps. Alternately, a hypothesis may arise suddenly and intuitively. That's more romantic, and we tend to lionize "pure" theorists like Richard Feynman, who got a Nobel Prize for a line of thought that began when he was idly watching a waiter toss a plate in the air in a cafeteria, or Stephen Hawking, a victim of paralysis who thought up his theory of black hole evaporation while his nurse was putting him to bed. But chance, as Pasteur said, favors the prepared mind; the theorist may work with only a pencil and paper, but she is immersed in her field of research, and that field in turn depends on the work of the experimentalists.

Scientific ideas live or die by the verdict of observation. An observation may be overtly intrusive, as when a physicist slams clouds of protons together in a particle accelerator, or relatively passive, as when an astronomer takes the spectrum of a star to learn its chemical composition. In either case the goal is to obtain objectively reliable data. By "objectively reliable" I mean that the result should be replicable: Another experimenter, using another particle accelerator or telescope, should achieve essentially the same result.

Precisely because observation is so important, we need to appreciate its limits.

The most conspicuous of these is observational error. It's easy to make a mistake when measuring, say, the velocity of a faint galaxy near the edge of the observable universe, or differences in the thickness of cortical tissue in laboratory rats that have been raised in enriched and deprived environments. In practice, the observer relies to some extent on the guidance of a promising theory that predicts what he ought to find, even though this may mean disregarding at least some data that contradict a persuasive theory. Albert Einstein ignored the results of an early experiment that seemed to invalidate the special theory of relativity. Einstein happened to be right in this instance (the experimental data were wrong) but there are obvious dangers in leaning too heavily on theory—in discarding, as "noise," those data that deny a theory while retaining, as "signal," those that confirm it. In practice one keeps muddling along, experimenting and observing, hoping that the truth will emerge.

Or hope that part of the truth will emerge, given that the universe is vast and the conclusions of scientific theories and observations almost absurdly narrow. This nasty little fact often gets overlooked in popular accounts that stress the grandeur of the scientific world view. Science does not customarily pose big questions. It poses small questions. As the thermodynamicist Ludwig Boltzmann put it:

The scientist asks not what are the currently most important questions, but "which are at present solvable?" or sometimes merely "in which can we make some small but genuine advance?" As long as the alchemists merely sought the
philosopher's stone and aimed at finding the art of making gold, all their endeavors were fruitless; it was only when people restricted themselves to seemingly less valuable questions that they created chemistry. Thus natural science appears completely to lose from sight the large and general questions. "Progress we have. A little questions!"

Yet it is by such peephole-squinting that science, more than any other discipline, has cast fresh light on the big questions. Research into the family relationships of subatomic particles has produced insights into the early evolution of the entire universe, while studies of the chemistry of radioactive isotopes have made it possible to age-date moon rocks and pre-Columbian Indian campsites. Boltzmann again: "But all the more splendid is the success when, groping in the thicket of special questions, we suddenly find a small opening that allows a hitherto undreamt of outlook on the whole." Never more resoundingly than in modern science have we seen demonstrated the truth of Lao Tzu's and Jesus' dictum that the great and transcendent is to be found in the small and ordinary.

What one gets from science, generally speaking, are relations. Ask a particle physicist what happens when a quark is knocked out of a proton, and she will tell you without hesitation that the result will most likely be the creation of a meson. Ask her what a quark is, however, and the only genuinely honest answer will be no answer at all. (Or, perhaps, a relational answer—"Quarks are the building blocks of hadrons"—which defines these particles in terms of other particles.) Ask an astronomer what a star "is," and the result will be similarly unsatisfying if viewed from the old metaphysical perspective: The astronomer is likely to explain "star" in terms of its relationship to other astronomical bodies, or merely to offer a definition, which by definition will say more about the word than the star. ("A star is a celestial object massive and dense enough for thermonuclear process to have taken place at its core.") Science is silent about the essences of quark-ness or star-ness.

Lost, too, is the comfort of absolute certitude. The philosophers of old could claim with assurance to have discovered exactly how nature works; they did not have to worry about contradictory experimental results, and in any event their formulations typically were too vague to be wrong. Scientists today enjoy no such luxury. They must live with the knowledge that even their most esteemed theories may in the long run turn out to be flawed. The philosopher of science Karl Popper made this point when he argued that no observation can prove a theory true, but can at best permit it to survive until it is tested again.

What science does, then, is to construct mental models of natural processes. These models must make sense; it is the faith of science that nature is rationally intelligible. The models should be efficient; the scientist believes that nature, given the choice, will elect a simple, economical process over a complex and inefficient one. The models should also have predictive power, which is another way of saying that they should remain vulnerable to disproof by observation.

What has all this to do with Magritte's pipe? Just this: that each act of observation, and each scientific model based on observation, puts a frame around a piece of nature. We may then extrapolate, projecting the model onto a larger screen. We are encouraged if it holds up (every star and planet ever observed obeys Newton's and Kepler's laws) but our belief in the model remains forever tentative (Newton's and Kepler's laws fail inside black holes). The model is not reality; it is but a painting, and it has a frame.

The tendency to put imaginary frames around things is not unique to science. We all do it all the time, usually without thinking about it. Here is a little puzzle that
illustrates what I mean. Try to connect all nine dots, using only four straight lines, without retracing or lifting up your pencil.

Most people have trouble with this riddle until they are given a hint—that the straight line may extend beyond the box described by the dots. The problem is that we automatically and often arbitrarily frame the problem. Often that helps, but in this case it makes the puzzle harder to solve.

The way we interpret a physical process can similarly be altered by the size of the frame we put around it. Suppose we view a videotape showing an area one inch square. On the tape we see a wooden hammer striking a wire and producing sound waves in the surrounding air. We would be inclined to describe this process as strictly deterministic: There is a cause, the hammer blow, and an effect, the sound waves. Now pull the camera back, enlarging the reference frame, and we see that the hammer is one of eighty-eight in a piano. Now the process begins to look voluntary; we assume the piano is being played by a pianist, who can choose to play whatever she wants. Pull back farther, though, and we see that it's a player piano: The keys are being struck not by a pianist but by a machine. The system looks deterministic again. Pull back farther still, in time as well as space, and we see a composer writing a piece for the player piano; now the situation looks volitional once more.

Never is the danger of distortion greater than when we extrapolate from a limited reference frame to the infinite universe. Yet all cosmological models do just that, and all, therefore, should be taken with a grain of salt. (Or with a trainload of salt, which is about enough salt grains to equal the number of stars in the Milky Way galaxy.) A cosmologist can describe the shape of the universe in terms of a few numbers—the Friedmann-Robertson-Walker metric, for instance—and if in a rash mood may declare: "There! That is the universe." But it is not. It is at best only one cut through the universe, and a paper-thin cut at that. The real universe glides on about its business, without stopping to read the scientific journals.

Outside our frame of reference forever hovers something else—the larger reality, embracing every bird's egg and mud puddle, every star and planet, every poem and crime in the gigantic and eternally incomprehensible universe. This—this equation, this theory, the finest model concocted by the wisest mind in the universe, or the sum total of all the scientific models, and all the artistic and philosophical ones, too—this is not the universe.

The other night I had a dream about frames. In the dream, a man and his wife, on a stroll near the outskirts of a small town, stop to look into the window of a dusty antiques shop. The man becomes fascinated by an odd object he sees in the window: It is a model of a cottage, fashioned painstakingly if inexpertly with tiny individual slate tiles on the roof, checked curtains at the windows, a painted front door with brass knocker and keyhole. A figurine of a man is kneeling at the stoop, peeking through the keyhole at a couple who are sitting inside by a fire, she knitting, he reading a newspaper.

The man tries to interest his wife in buying this little model. She’s not interested. Over her objections, the husband takes her into the shop and asks the price. He is told the cottage is not for sale. The husband presses the shop
owner to name a price, but the old man won’t budge. The couple leaves. Over lunch they quarrel about his insistence on buying the toy cottage. She goes back to their hotel. He returns to the antique shop and finds it closed.

The early afternoon sun bakes the empty street. Water trickles from a fire hydrant valve that has been left slightly ajar, a wrench still affixed to the bolt on top. The man knocks on the shop door but there is no reply. After pondering the situation for a few moments, he removes the wrench from the fire hydrant and throws it through the shop window. A burglar alarm goes off. The man steps up through the shattered window and reaches for the model of the cottage.

A police patrolman in a blue serge uniform arrives to investigate the alarm. He finds the window intact and unbroken. The wrench is on the fire hydrant; the policeman tightens it to stop the trickle of water, then pockets the wrench. He rattles the doorknob on the front door of the shop and the alarm stops ringing. He looks in the window, and his eyes come to rest on the little cottage. He bends down to look more closely. Inside the cottage, instead of the couple, now sits the figure of a solitary man. Kneeling outside the front door, peering through the keyhole, is a figurine of a policeman in a blue serge uniform.

A psychiatrist might place other interpretations on it, and I wouldn’t argue with them, but to my way of thinking this is a dream about how the mind frames its relationship with the wider universe. We look through a peephole at nature, as Boltzmann said, and interpret the whole in terms of what little we have been able to see. But we, too, are part of the whole—and we, like the universe, are more than the sum of the observations made of us. All swim in an ocean of enigma. "Science cannot solve the ultimate mystery of Nature," wrote Max Planck, the founder of quantum physics. "And it is because in the last analysis we ourselves are part of the mystery we are trying to solve."

The artists have long understood this. "When I look at my work I think I'm in the heart of mystery and there's nothing in the world which can explain it," Magritte said. He added, on another occasion, that "the feeling we experience while we look at a picture is not to be distinguished from the picture or from ourselves. The feeling, the picture, and ourselves are united in our mystery." Magritte's words are echoed by the American physicist and philosopher of science John Archibald Wheeler, who writes, "The vision of the universe that is so vivid in our minds is framed by a few iron posts of true observation—themselves resting on theory for their meaning—but most of the walls and towers in the vision are of papier-mâché, plastered in between those posts by an immense labor of imagination and theory."

We are confronted, then, not with the universe, which remains an eternal riddle, but with whatever model of the universe we can build within the mind. Every thinking creature in the universe shares this predicament; for all, the ultimate subject of inquiry is not the outer universe but the nature of its dance with the mind. In searching for signs of extraterrestrial intelligence, our aim is to better understand the dance by learning how others dance. We hope to widen our perspective, to broaden the base of our perceptions and analysis, to improve the little universes of mind and make them answer more smartly to the vast whole. And what is the emblem of a sound mind, if not conformance between the inner model and the outer reality? What we seek among the stars is sanity.
than a million board-feet of timber. If, instead, they
destroy the rain forests, throwing away terabytes of genetic
data, they will go down in history as wastrels and fools. The
choice is theirs.

Or, more properly, ours, for the more the world shrinks,
the more it becomes a commonweal. We would all do well to
ask ourselves how we are likely to be judged by our
grandchildren. It is one thing to use up oil and precious
metals to fly aircraft and drive cars and trucks, to build an
industrialized world. It is quite another to squander four
billion years' worth of the planet's genetic endowment, to
tear great rents of ignorance in the potential learning of our
descendants, all for the sake of a fleeting profit in rosewood
and ply.

The "developed" world was developed by men and
women who shared a vision of the future and the courage
and determination to make it come true; we live amid their
realized dreams, and enjoy the command over nature that
ranked high among their aspirations. Now we need new
dreams; more of the same won't do. Some can glimpse a
future in which the human mind finds fresh resonances in
the unspoiled wilderness, where everything alive is held
sacred because it all has something to teach us. The Brazil
of that future could be a capital of wealth and learning,
home of the library of the Amazon, a global nerve center
generating new ideas for use in engineering, medicine, and
basic research. If we can dream that dream, we can make it
happen, and we will earn our descendants' esteem. If we
run it into the ground, they will regard us as simpletons,
hayseeds, yokels, bumpkins, and clowns. Either way, we're
going to get what we deserve.
perceive it (yet the book you are holding in your hands is a
definite vacuum, with storms of neutrinos howling through it)
while idealists say that it's all just thought (yet a falling rock
you never saw coming can strike you dead). I'd prefer to set
such dogmatic assertions aside, and concentrate instead on
the act of observation itself. Specifically, I'm going to
outline how a philosophy of science may be constructed
from observational data, rather than on more derivative
concepts such as space, time, matter, and energy. Such a
philosophy would portray the observed universe as made not
of atoms or molecules, quarks or leptons, but of discrete
units ("bits") of information.

I will describe this approach as "information theory." The
term is usually employed more narrowly, to describe a
theory concerned with communications and data processing,
but I'm anticipating its expansion into a wider account
of nature as we behold her.

Given that our observations represent, at best, only a
small and distorted part of the whole, we naturally wonder
to what extent we can ascertain what "really" is out there. To
this vital question physics has proffered two visions of how
mind and nature interact—the classical view, ascendant in
the nineteenth century, and the more recent quantum view.
In practice physics employs both: Classical concepts are
applied to large-scale phenomena (roughly from the level
of molecules on up), while quantum mechanics rules the
small-scale realm of atoms and subatomic particles.

The classical outlook rests upon three commonsensical
assumptions that like many another decree of common
sense are not altogether true. The first is that there is but a
single, objective reality to each event: Some one thing
happens—electricity current flows through a wire, say, de-
fecting a compass needle—and while each observer may
witness only part of the entire phenomenon, all can agree
on exactly what happened. The second classical assumption
is that the act of observation does not in itself influence
what is observed; the classical scientist observes nature as if
from behind a sheet of plate glass, recording phenomena
without necessarily interfering with them. The third assump-
tion is that nature is a continuum, which means that
objects can in principle be scrutinized to any desired degree
of accuracy; observational errors and uncertainties are
ascribed to the limitations of the experimental apparatus.

The classical approach fared well so long as physicists
concerned themselves with big, hefty things like stones,
steam engines, planets, and stars. Such objects can be
observed without obviously being perturbed by the act of
observation. We know today that the influences are there—
when a nature photographer takes a flash photo of a wasp,
for instance, the light from the flashgun buffet the wasp a
bit, and adds fractionally to its mass—but as these intrusions
have no discernible effect on the macroscopic scale, they
usually can be ignored. And ignored they long were; classi-
cal physics can be defined as the physics of objects that
are not noticeably altered by observation.

The classical view started to break down, however, once
physicists began investigating subatomic phenomena like
the behavior of electrons in atoms or the collisions
of protons in particle accelerators. Subatomic systems are
perturbed by every act of observation; to try to count the
number of electrons in a cloud of gas by taking a flash
photograph of them is rather like counting the number of
pupils attending a lecture by blasting them out of the
classroom with a fire hose. We can no more comprehend
the world of the very small without taking the act of
observation into account than we can investigate the de-
struction of a china shop without paying attention to the bull that did the damage.

Thus arose quantum mechanics, in which the information obtained from observations is seen to vary according to the way the observations are conducted, so that the answers we derive from an experiment depend on the questions we choose to ask. In the quantum world, the classical pane of glass is replaced by an elastic membrane that shudders and flexes at the touch of each observation; peering at the dancing lights and shadows of this soap-bubble interface, we cannot always be certain which phenomena are properly to be ascribed to the outer world and which were stirred up by the act of interrogation.

The erosion of the classical outlook dates from the German physicist Werner Heisenberg’s enunciation, in 1927, of the “uncertainty” principle. Heisenberg found that there is an intrinsic limitation to the amount of accurate information one can obtain about any subatomic phenomenon. This limitation arises from the fact that neither we nor anyone else in the universe can observe subatomic particles without interfering with them in some way or another. If we want to determine exactly where a neutron is, we might let it slam into a target (which will stop it in its tracks) or take a photograph of it (which means dawning it with photons that will send it flying away on a new trajectory), or elect to use some other procedure, but in every case we will have destroyed information about what the neutron might have done had we let it alone. And this situation pertains universally in the quantum realm: To learn one thing about a subatomic phenomenon means to be ignorant of something else. The Heisenberg limitation does not depend on conventional experimental error, or the inadequacies of any particular technology; it is fundamental to every act of observation, whether conducted with scaling wax and bailing wire on Earth or by gleaming machines on the most technically advanced planet in the Virgo Supercluster.

The uncertainty principle makes it clear that on the small scale, at least, the only unperturbed phenomena are the ones that go unobserved! The observed universe therefore cannot rightly be regarded as having a wholly independent, verifiable existence, since its apprehension requires the intrusion of an observer, whose actions inevitably influence the data that the observation yields. (As to the unobserved universe we are well advised to heed the counsel of the philosopher Ludwig Wittgenstein, that “whereof one cannot speak, thereof one must be silent.”)

At first blush, the realization that we cannot observe the outer world without influencing it might not seem to threaten the classical assumption that there is an objectively knowable universe out there all the same. Classical physicists could (and did) take refuge in the argument that there can still be but one true reality, even if the observer cannot directly access it, just as there must be but one correct verdict in a murder trial even though the jurors can never know all the facts about the case being tried. But the better one becomes acquainted with quantum physics, the more even the simplest physical events begin to look like Rashomon, the Ryunosuke Akutagawa story about a rape trial in which each witness presents a plausible but incompatible version of the crime. In the quantum domain, every answer is tinted the color of the question that elicited it.

The famous “dual slit” experiment illustrates how quantum physics upsets the classical assumption of objective reality. The question posed by the dual slit experiment is whether subatomic particles like protons, electrons, and photons are particles or waves. All subatomic particles behave like particles under some circumstances and like
waves under others; physicists use mathematically equivalent particle and wave equations in dealing with them, depending on which is more convenient in solving a specific problem. But particles and waves have mutually exclusive properties. Waves spread out as they travel across space, and interfere with one another when they intersect. Particles, in contrast, maintain their discrete, individual identities—individual particles do not spread out—and when clouds of particles intersect they mostly fly right past one another, with few odd collisions. The dual slit experiment forces the question: If classical physics is right there can be but one verdict, either particle or wave.

To familiarize ourselves with the issues involved, let's first set up the experiment using macroscopic (i.e., classical) objects. We erect a wall containing two parallel, vertical slits, place a target behind it, and fire a machine gun at the wall. After a while, the bullets that pass through the slits will have inscribed two vertical stripes on the target. If we close off one slit, we will get one vertical stripe on the target. A physicist, shown only the targets and a diagram of the experimental apparatus, will conclude that what we fired at the target were particles. Now we submerge the wall so that the slits are half under water, send a succession of waves toward the intervening wall, and make a target out of some material that can record wave impacts (beach sand will do). When each wave passes through the slits it generates two new sets of waves on the other side of the wall, one radiating from each slit. Where these new waves strike one another they create an interference pattern—the wave pattern is reinforced wherever wave peaks overlap other wave peaks and troughs overlap troughs, and is canceled out where waves meet troughs. As a result our sandy target will be inscribed with a series of bands. Our referee, shown this interference pattern on the target, will correctly conclude that it was made by waves.

So far so good. But watch what happens when we venture into the quantum realm. We replace the machine gun with a device that emits subatomic particles—electrons, say—and use as our target a phosphorescent screen that glows when struck by electrons. (That's how a TV tube works.) If we leave both slits open and fire a lot of electrons at the obscuring screen, we find that the target displays an interference pattern. Electrons therefore look like waves—so long as we leave both slits open. But if we close one slit, suddenly we get a line on the target; now the electrons are impersonating particles.

This seems strange, but stranger still is what happens if we turn down the emitter power until it fires only a single electron at a time. Now we close one slit, and record but a single impact on the target: Fair enough, the electron is a particle. But if we leave both slits open, and fire but a single electron, we get—an interference pattern!

This is exceedingly weird. If we regard the electron as a particle we must conclude, absurdly, that it somehow manages to split in two and pass through both slits, when and only when both slits are open. If we regard the electron as a wave, then we must imagine that it somehow folds up and imitates a particle, when and only when one of the slits is closed. And the experiment can be made even more mind-boggling: Let's wait until after the electron has been fired, then quickly open or close one of the slits while the electron is on its way. Here we enter the domain of the so-called "delayed choice" experiments, and again the results are the same: The electron behaves like a particle whenever one slit is open, and like a wave whenever both slits are open. So long as we cling to the classical assumption that
electrons are "really" either particles or waves, the dual slit experiment results in paradox. This is what makes the experiment so difficult to grasp; as the Danish physicist and philosopher of science Niels Bohr remarked, when a student complained that quantum mechanics made him feel giddy, "If anybody says he can think about quantum problems without getting giddy, that only shows he has not understood the first thing about them."

Bohr offered a way to escape the paradox, via what today is called the "Copenhagen interpretation" of quantum physics. We concede that the electron is not "really" either a particle or a wave, but assert that it assumes one or the other costume depending upon how it has been interrogated. Quantum physics thus teaches that the identity of (small) objects depends on the act of observation—that our conceptions of the foundations of physical reality result from a dialogue between the observer and the observed, between mind and nature.

True, quantum physics is confined to the realm of the very small; only recently have physicists managed to write a quantum mechanical description of something as large as a single molecule, and molecules are a billion times smaller than human beings. But this does not mean we can ignore the implications of quantum observer-dependency for the macroscopic world. For one thing, the physics of the minuscule has always commanded particular respect in the philosophy of science, inasmuch as big things are made of small things; surely we have learned something important when we discover that apples are made of atoms. For another, quantum effects do influence the macroscopic world; the sun, for instance, wouldn't shine were it not for quantum tunneling and quantum leaps and various other manifestations of quantum uncertainty. Everything is observer-dependent to some degree.

If, then, we accept that the questions the observer asks influence what he has the right to say about what he observes, we are led to consider that we live in a participatory universe, one where the knowable behavior of subatomic systems depends on the methods we employ to study them. Might it be possible to construct our scientific conceptions of the world on the basis of this realization?

I think so. I think, specifically, that both the quantum and the classical approach can be subsumed into the broader paradigm that I am calling information theory—or IT for short. IT accepts that our knowledge of nature always devolves from a partnership between the observer and the observed; it therefore banishes from science all questions about what things "really" are, and focuses instead on the observational data themselves, restricting models of the universe to what is in fact knowable. All else is regarded as beyond the province of science: If I thump my fist on the table and declare that electrons are particles and not waves, I'm talking philosophy, not science.

At this point the philosophically astute reader, suspecting that I am dressing old philosophies in new clothes, may object along something like these lines: "Is not the position you are staking out here simply the logical positivism of the Vienna Circle, those philosophers who dismissed as meaningless all statements that cannot be empirically verified? And are you not perhaps flirting with solipsism, denying the independent existence of the universe and making it all depend on your puny observations?"

Well, maybe so, but for the purposes of this discussion I want to set aside all the "isms," and with them the supposition that we human beings sit on some cosmic court of appeals empowered to decide what does and does not exist. My point is simply that scientific statements about the
universe, to the extent that they depend on observation, cannot be employed to make statements about what nature is like independent of the act of observation. I am not arguing for what has been called "quantum solipsism," the assertion that nothing exists except when it is observed: I assume that there are things out there, but I reject as presumptuous any scientific attempt to declare once and for all what they are. The concept of "things" is itself derived from observational data; therefore data are more fundamental than things. What we call facts about nature are inductions from the data, and it is in this spirit that I invoke Wittgenstein's aphorism that the observable universe is made of facts, not things.

Let me first sketch the background of IT, then describe how it might be expanded into a philosophy of science.

Information theory may be said to date from the year 1929, when the Hungarian-born physicist Leo Szilard wrote a paper identifying entropy as the absence of information. Entropy is a measure of the amount of disorder in a given system. The second law of thermodynamics declares that in any "closed" system—i.e., one to which no energy is being added—entropy will tend to increase with the passage of time. A drink with an ice cube in it is in a low-entropy state. Leave the drink alone, and the entropy increases: The ice cube melts, its water dissipates through the drink, and soon the whole system consists of but one substance, a (watery) drink.

To the thermodynamicists of the nineteenth century, the important thing about low entropy was that it meant you could get work out of a system. An ice cube can do some work. It can cool a drink, for one thing, and it can do other sorts of work as well: If Martians were to dispatch a tiny probe to Earth and land it in the drink, they could, if they were clever about it, use the thermal gradient in the drink to recharge the batteries on their space probe. A drink at room temperature in which the ice has melted, however, can do no such work. We can extract some of it, freeze it, and regain the capacity to do work, but this requires that we put some energy into the system. One always must pay to decrease entropy; that's the second law of thermodynamics.

But to Szilard, the interesting thing was that the drink starts out with more information. It contains, for instance, several distinct realms—one cold (inside the ice cube), another relatively warm (far from the cube), and other, intermediate thermal domains. As the ice cube melts, the amount of information declines, until at maximum entropy the drink has but a single story to tell: "I'm at room temperature." More entropy, Szilard saw, means less information.

Information has a price; there's no such thing as a free lunch, and every time we learn something about a given system we increase its entropy. The price of information, however, is wonderfully small: To extract one bit of data costs only \(10^{-16}\) of a degree of temperature of heat on the Kelvin scale. That's a minuscule number—a penny is more than \(10^{16}\) of the U.S. national debt—and the fact that it is minuscule is the reason we can live in an information society today. Low entropy cost means that phone lines don't need to carry high voltages and that communications satellites can run on modest amounts of solar power. It is because information adds so little entropy to the systems we use to transmit it that we can afford to telesport soccer matches

*The relevant equation is

\[ S = k \log W \]

in which \(S\) denotes the entropy of a given system, \(W\) the number of accessible microstates, and \(k\) Boltzmann's constant, equal to 1.381 \(\times 10^{-16}\) erg/Kelvin. This formula, one of the most wide-reaching in all science, was the work of Ludwig Boltzmann, who decreed that it be inscribed on his tombstone.
around the world, buy books, send electronic mail by computer, and make long-distance phone calls; in each case the cost in entropy per bit of data communicated is low enough to keep the bills manageable.

That is also why we can afford interstellar communication. But before getting into all that, let me outline how information theory works, and offer a few examples of how it can bring fresh perspectives to scientific research.

Information theory originally was applied to practical technological problems, such as designing computers and predicting the signal-to-noise ratio of telephone lines. In a typical IT equation one begins with a data input $A$, traces what happens to the data when they are manipulated or communicated in a given system $B$ (e.g., to what extent data are lost due to noise in a communications channel), and predicts the form in which they will arrive at an output stage $C$. This process has properties that can be quantified mathematically. Claude Shannon of Bell Labs found in the 1940s that the accuracy of any information channel can be improved, without decreasing the data rate, by properly encoding the signal. This discovery, known as Shannon’s second theorem, is today employed in many sorts of communications; the clarity of the photographs that the Voyager spacecraft transmitted back to Earth from the remote planet Neptune owed a lot to Shannon. But the ultimate significance of Shannon’s second theorem resides in its universality: The theorem pertains to every kind of communications channel, embracing not only telephones and computers but brain circuits and perhaps even the mechanism of biological reproduction. Information theory proffers a common ground for understanding every branch of science, insofar as each involves an input stage (data from the outer universe), a communications or data-processing system (the brain), and an output stage (a scientific theory or hypothesis, which then forms a kind of communications loop when projected back onto nature).

If information theory is to unify science, however, there must be a common language, shared by all the various sciences and applicable to every field of scientific investigation. The key to this language, I submit, is digitization, the breaking down of data into bits.

The term bit is short for “binary digit,” the kind of numbers employed by modern digital computers. The binary system expresses all numbers in terms of only two digits, 0 and 1. That makes it much simpler than the base-ten numbering system we learn in school, which requires ten symbols (0, 1, 2, 3, 4, 5, 6, 7, 8, and 9). Here is how the first five digits of the familiar ten-based system translate into binary numbers:

<table>
<thead>
<tr>
<th>Decimal number</th>
<th>Translation</th>
<th>Binary equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0x2^0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1x2^0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>(1x2^1)+(0x2^0)</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>(1x2^1)+(1x2^0)</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>(1x2^2)+(0x2^1)+(0x2^0)</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>(1x2^2)+(0x2^1)+(1x2^0)</td>
<td>101</td>
</tr>
</tbody>
</table>

... and so on. As the numbers grow larger, their binary translations begin to look unwieldy to our eyes—the number 4096, for instance, expressed in binary terms is 1000000000000000—but computers thrive on binary numbers, because they can be expressed by on-off switches, which are among the most exquisitely simple of all mechanical devices. A computer that employed ten-based numbers would have to have ten settings at each of its millions of circuit junctures, plus a storage system with ten possible states at every point, but a binary computer requires only that each
of these millions of switches and encoding points have two states—0 = off and 1 = on. These states may be represented by the presence or absence of punch holes, as was done with the cards and paper tape employed in the 1950s, or of magnetically charged dots on a disc, as in the floppy discs and hard discs of the seventies and eighties, or of dark dots on the optical discs that promise to become the data storage standard of the nineties. Whatever the medium may be, it’s all bits—zeros and ones, off and on states—to a computer.

Anything that can be quantified can be digitized, including sound (a compact disc containing nothing but zeros and ones can reproduce Mozart and Harry Partch), pictures (bits inscribed on laser discs can replicate Hollywood movies or paintings in the Louvre), and abstractions ranging from computer models of rotating galaxies to the EKG patterns of heart attack victims. It is because binary digits act as common currency for every quantifiable phenomenon that an ordinary desktop computer can be applied to an enormous variety of tasks, from calculating bank balances and designing shoes to flying spacecraft and guiding tunnel-digging machines under the English Channel. And that is why scientists, too, whether they are engaged in sequencing frog DNA or imaging distant quasars, increasingly find that their time is spent manipulating bits of data.

Information theory is still in its infancy, and has many shortcomings. One glaring limitation is that IT cannot yet be employed to access the significance of a piece of information. Presented with two telegrams dispatched from Tokyo on September 2, 1945—one reading, “The war is over!” and the other, “The cat is dead!”—IT declares that since the bit count of each telegram is approximately equal, both contain about the same amount of information, even though the first telegram obviously would have meant more to most readers than the second (unless the second message was a code; coding is an important question in information theory, but one that I’ll not go into here). By relating information to thermodynamics, IT postulates that no system can generate more than the total amount of information put into it; there is, in other words, a law of conservation of information, comparable to the conservation of energy. Fair enough, but if we regard the brain as an information-processing system, the conservation law implies that Beethoven’s string quartets, say, contain no more information than the total of everything Beethoven had learned plus the entropy bill paid by the meals he ate and the air he breathed while composing them. This may be true in a way, but it’s not very illuminating. Leon Brillouin, a physicist whose writings did much to call attention to the significance of information theory, tried to quantify the way that human creativity seems to reduce the amount of entropy in the subjects it addresses, but his effort was probably premature and in any event it failed. Information theory is hardly alone in this, however; human thought is a dark continent to every science.

Yet even in its infancy, IT can contribute to explaining the dialogue between mind and nature. Consider what it has to say about questions concerning the brain, biological systems more generally, and quantum physics.

The human nervous system can be analyzed as a data-processing system, with intriguing results. Much of the current excitement about “neural networks”—artificial-intelligence computer systems set up to model the brain—derives from the fact that neurons in the brain, like microswitches in a computer, have but two fundamental states: At any given time each either fires or does not, and so is in a state equivalent to either 1 or 0. This may provide
the *IT* basis for the proof, published by Warren S. McCulloch and Walter Pitts in the 1940s, that the brain is a "Turing machine," meaning that it can do anything a computer can do.

When neurologists inform us that the 125 million photosensitive receptors in the human eye have a total potential data output of over a billion bits per second, and that this exceeds both the carrying capacity of the optic nerve and the data processing rate of the brain's higher cortical centers, we can by using information theory alone hypothesize that the eye must somehow reduce the data it gathers before sending them through the optic nerve to the brain. And, indeed, clinical experiments with human vision indicate that the eye does resort to various data-reduction tricks. To get a sense of just how successful these tactics can be—though this particular deception is relatively trivial—cover your left eye, look at the page number atop the left page of this book, and place a coin near the gutter between the pages. Keeping your right eye fixed on the page number and your left eye covered, move the coin right and left; you will find that there is a spot where the coin *vanishes*. This is the blind spot in the eye. It represents the hole—rather a large hole, actually—where the optic nerve exits through the retina. Note that where the coin disappears you perceive not a black hole but white paper. Yet there is no paper there: The *coin* is there. What the eye is doing, evidently, is filling in the hole with whatever color—in this case, white—surrounds the hole. (Try the experiment on a red sheet of paper, and you will "see" that the blind spot is red.) The fact that the eye must employ some such data-reduction tactics can be predicted by information theory independently of the clinical case studies.

*IT* offers similar insights into memory. The brain's short-term memory can store only about seven digits in the ten-based system; that's why people have trouble remembering telephone numbers more than seven digits long, and resist efforts by the post office to employ postal zip codes longer than seven digits. *IT* postulates that data overload results not in the loss of just a few extra digits, but in a general corruption of the data in memory. And that's what we experience: When we try to remember a long telephone number we don't normally forget just the last few digits, but are apt to scramble much of the number. Teachers, familiar with the danger of memory overload, take care to explain basic concepts before building on them, lest their students become totally confused and "turn off."

Biological reproduction, too, can be likened to a communications channel, one that has evolved through natural selection to maximize its data capacity and minimize error. The DNA molecule, that basis of all terrestrial life, encodes bits of information in triplets of four chemical substances, the nucleotide bases. (The bases are Adenine, Guanine, Cytosine, and Thymine; their triplets correspond to the twenty primary amino acids from which proteins are built.) DNA molecules use this code to synthesize proteins by employing the appropriate sequence of amino acids. It turns out that the error rate in DNA replication approaches the best that information theory permits; biological evolution can be viewed as an ongoing effort to minimize the amount of "noise" in the DNA-RNA communications channel that transmits genetic data down through the generations.

Before information theory can be incorporated into quantum physics, however, we will need to identify a binary code of some sort in the subatomic world—the equivalent, in all matter and energy, of the two-based numbering system employed by digital computers and by the brain.
Quantum theory implies that this may be possible. The word *quantum* (from the Greek for "how much") reflects the fact that matter and energy as we observe them are not continuous, but present themselves in discrete units, the quanta. Quantum mechanics can be construed as meaning that not only matter and energy but knowledge is quantized, in that information about any system can be reduced to a set of fundamental, irreducible units. Quanta alone, however, cannot yet provide us with the two-based numbering system we'd like to have in order to interpret the entire physical world in terms of bits, because quanta as we currently understand them have not two but many different states. An ingredient is missing.

In search of a binary code through which information theory could be universally applied to physics, the physicist John Archibald Wheeler looks to yes-or-no choices made by the observer—like the choice, in the dual slit experiment, of whether we ask the electron to represent itself as a wave or a particle. Wheeler suggests that all the concepts we apply to nature, including the concept of objects, may be built up from on-off decisions made by the scientist in the way he or she chooses to set up each experimental apparatus. He encapsulates this dynamic in the slogan "It from bit":

> Every *it*—every particle, every field of force, even the spacetime continuum itself—derives its function, its meaning, its very existence entirely . . . from the apparatus-elicited answers to yes or no questions, binary choices, *bits*.

Quantum physics deals with the classically-engendered paradox of what things "really are" by declining to assign an identity to any phenomenon until it has been observed. As Wheeler likes to say, paraphrasing Bohr, "No phenomenon is a phenomenon until it is an *observed* phenomenon."

An observation, in turn, is defined as consisting of two operations. First, we "collapse the wave function." This means that energy (and with it some potential information) is collected, as by intercepting light from a star or X-rays from a high-energy particle collision. Second, there must be an irreversible act of amplification that records the observational data, as when the starlight darkens silver grains on a photographic plate or the X-rays trigger an electronic detector. The second part of the definition clearly is necessary; otherwise, all the starlight that has ever washed over the lifeless lava planes of the moon could be said to have been observed, which would be to generalize the concept of observation into meaninglessness. But the idea of amplification is also intriguingly open-ended: It implies that for an observation to qualify as an observation, the data must not only be recorded but also be *communicated* somehow.

Suppose that an automatic telescope, run by a computer at an unmanned mountaintop observatory, records the light of an exploding star—a supernova—in a distant galaxy. The wave function has been collapsed but not fully amplified, for it has not yet been communicated to an intelligent being.* (To argue otherwise we should have to say that any record of a process constitutes an observation, in which case we would be obliged to contend that every time a cosmic ray etches a path in a moon rock it has been observed, and that seems absurd.) The next morning an astronomer visits the observatory and views on a computer screen the dot etched by the exploding star. *Now* we have an act of observation, no?

Maybe not; here things get strange. Let's say that the astronomer goes to the telephone to call a colleague and tell

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*It does not matter who makes and communicates the observational data: any sentient being can qualify, whether he or she or it is a Harvard astrophysicist or a silicon network terminal embedded in an asteroid.
ently leaked into space by terrestrial radio and television transmitters prior to our planet's demise. This scenario parallels that of the unfortunate astrophysicist buried in the avalanche: No act of observation! All human science, then, would in the long run have added up to nothing. Having made no lasting contribution to science on the panstellar scale, we would have bequeathed nothing to the totality of the perceived universe.

How do we avoid the pointlessness of such a dismal denouement? By contributing what we know to other, alien intelligences—either by sending information to them directly or dispatching it to be stored in an interstellar communications network. That act of amplification would ensure that our observations were not hostage to the fate of our one species, but instead had been added to the sum of galactic and intergalactic knowledge, stretching far across space and into the future. As Wheeler writes, "How far foot and ferry have carried meaning-making communication in fifty thousand years gives faint feel for how far interstellar propagation is destined to carry it in fifty billion years."

When speculating about interstellar communication one gets the odd feeling that there is something natural and intuitive about it—that we are meant to do it, as we are meant to write poetry, love our children, fret about the future and cherish the past. Perhaps this inchoate connotation of appropriateness, sustaining as it does so many SETI researchers through their long and daunting quest to make contact with life elsewhere among the stars, derives from this: That by participating in interstellar communication we would not just be exchanging facts and opinions and art and entertainment, but would be adding to the total of cosmic understanding. If we have companions in the universe, then the cosmic tree is not rooted in earthly soil.
alone. Wherever there is life and thought the roots may thrive, until in their grand and growing extent they begin to match the glory of the tree's starry crown.

Why, then, are a lonely few astronomers hunched over the consoles of the radio telescopes, forever listening, seeking, hoping? Perhaps because in some sense we suspect that the known universe is being built out there, in countless minds, and that we can help it flourish. We who came down from out of the forest seek to grow a forest of knowing among the stars.

**Notes**

**PREFACE**

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"All things without . . ." The lines by Sir John Davies come from his poem *Nosce Teipsum;* I have taken the liberty of modernizing his spelling and punctuation.


**THIS IS NOT THE UNIVERSE**

*Page 3*

"The mind does not understand its own reason for being."