# Following Schrödinger's Code: A Personal Journey*

**Michael S. Gazzaniga**

## Abstract

■ On a wintery afternoon over 60 years ago, I was browsing the Baker Library stacks at Dartmouth College and stumbled across a small book with an arresting title: *What Is Life?* [Schrödinger, E. *What is Life? The physical aspect of the living cell and mind.* Cambridge: Cambridge University Press, 1944]. This small volume contained numerous concepts that would transform the future of the biological sciences, giving rise to new fields, dogmas, approaches, and debates. Here, I present the core concepts of Schrödinger's book, the influence they have had on biology, and the influence they may continue to have on the cognitive neurosciences. ■



## INTRODUCTION

> *When a problem persists, unresolved, for centuries in spite of enormous increases in our knowledge, it is a good bet that the problem entails the nature of knowledge itself. The nature of life is one of these problems. Life depends on matter, but life is not an inherent property of matter.*
>
> *Howard H. Pattee*

On a wintery afternoon over 60 years ago, I was browsing the Baker Library stacks at Dartmouth College and stumbled across a small book with an arresting title: *What Is Life?* (Schrödinger, 1944) The title was a shock. I sat down amidst the long rows of books and read it right then and there.

I had been aimlessly looking for inspiration. Little did I know how much inspiration was packed into Erwin Schrödinger's small volume. As an undergrad, I had no real idea how monumentally important the book was and would become. We all have had the experience, though—the vague sneaking suspicion—that something we stumbled upon might be precious and game-changing, even though we cannot articulate why in the moment. It has taken me six decades to articulate the importance of the ideas in that book.

## THE FIRST CODEBREAKERS

A few years after my first Schrödinger run-in, I started my graduate work at Caltech, an institution that shimmered with scientific talent. Down one hall was Linus Pauling, the brilliant and relentless chemist who had recently lost the fierce race to figure out the structure of DNA. Two floors below was the legendary physicist Max Delbrück, who was the intellectual leader of a newly minted field: "molecular biology" (Delbrück, 1949). Around the corner, the equally legendary A. H. Sturdevant was working out the rules of genetic mapping. At night, I slept across from Matt Meselson's old bedroom, wondering if he had dreamt the mechanisms of DNA replication. During the day, Richard Feynman would pop into the lab with questions that we graduate students struggled to answer. Having won a Nobel for theoretical physics, Feynman was spending his sabbatical learning about biology in Delbrück's lab. At the year's end, he announced biology was too difficult for him and he was returning to physics!

Why all the excitement about biology? Why would respectable, card-carrying, award-winning physicists all suddenly want to study *life*?

A scientific bomb went off in 1953. Every beginning biology student knows that Watson and Crick used Franklin's photos to work out the structure of DNA. However, they did not simply decipher the structure of DNA. They established a structure for the field of biology.

Franklin, Pauling, Crick, Watson, and others had waded into the swampy mechanisms of cellular life and its hereditary foundations. They emerged with an answer: a "molecule." Atoms built molecules, which built cells, which built organisms. "Life" was now squarely in the realm of physics.

Since then, flat-footed physicalism has reigned supreme. All upper level phenomena could and, in fact, *must* be explained only by the physical/chemical nature of molecules. The great biologist Erwin Chargaff summarily dismissed any and all explanations not firmly rooted in this belief as fantasy stories. Physics was plenty good enough to describe the logic of living things.

Yet, from the beginning, there have been pockets of resistance. At the head of the resistance? Schrödinger.

University of California, Santa Barbara

*Aspects of this article were first presented at a conference: Schrödinger at 75: The Future of Biology, Trinity College, Dublin, Ireland.



*Journal of Cognitive Neuroscience 31:12, pp. 1777–1781*
*https://doi.org/10.1162/jocn_e_01463*

Schrödinger believed a "new physics" was needed to explain biology. The old physics couldn't now and wouldn't ever get the job done. Living things were not just assemblies of particles that behaved according to certain equations. Living things were governed by "codes."

At Caltech, I was surrounded by the code breakers of mid-20th-century biology, an enterprise full of swagger and swing. The geneticists were looking for the immutable patterns of inheritance. The molecular biologists were, for the first time, extracting the information encrypted within DNA. Four letters had been worked out—A, C, G, and T. Now, it was time to figure out the rest.

## THE BRAIN CODE

Thinking about codes in biology swirled through Caltech. The physicist Seymour Benzer had had his own run-in with Schrödinger's book of essays and had converted to biology. Benzer joined the lab of Roger Sperry on a sabbatical, and suddenly, there was vague talk of figuring out the "brain code."

We worked, slept, ate, and drank amidst these notions. We partied amidst them, too. Perhaps as a consequence of the partying, the idea of codes did not really crystallize in my mind. Honestly, codes did not seem entirely relevant to me. My own thinking at the time was focused on the physical brain.

I had also joined the lab of Roger Sperry, who had formulated a groundbreaking idea—the chemoaffinity hypothesis (Sperry, 1963). Sperry had framed brain development in terms of chemical gradients: Molecular distributions crisscrossed the brain guiding budding young neurons into their proper place as they explored wildly. The chemoaffinity hypothesis is no longer a hypothesis. Every introductory development textbook will tell you that chemical gradients guide brain development.

The message Sperry was introducing, however, was not about chemicals at all. Sperry was suggesting that some kind of "code" managed growth dynamics and development. The chemicals were of secondary importance. What mattered were the codes, the underlying rules, of how chemicals behaved in space and time.

Although he did not formally articulate it, Sperry was suggesting that there were *three* layers of brain coding. The first was the genetic code. The second was a series of chemical codes (under tight genetic control) that dictated the wiring of the developing brain. The third code, he believed, shuffled messages—actions, plans, ideas—around the largely predetermined brain structure. That third code proceeded to carry out the major role of the brain: generate adaptive behavior in a highly dynamic environment.

None of the rest of us quite knew what a "brain code" really meant, let alone three brain codes, but we assumed it must be something akin to the Morse code. Schrödinger himself had suggested such a thing 20 years earlier. So, when I left to do my postdoctoral studies with two young neurophysiologists in Pisa, Italy, Giovanni Berlucchi and Giacomo Rizzolatti, we thought we better get to work cracking the code.

As ambitious, though naïve, young scientists, we thought we had everything we needed to decipher the brain code. We knew the left brain communicated with the right brain, and we knew the communications ran through the corpus callosum. The callosum was the wire that transmitted signals from one hemisphere to the other. So all we had to do was stick an electrode in the callosum and the code would reveal itself. Why not? How hard could it be to eavesdrop on the brain's communications?

Fifty years later, the answer is: "unbelievably hard." There is no one code, or at least no one code we have cracked. The diversity of codes is not necessarily a failure of neuroscience. Instead, the diversity of brain codes may reflect the diversity of things brains code "for." As recently captured by Christof Koch and Gary Marcus:

> Sounds, for example, are inherently one-dimensional and vary rapidly across time, while the images that stream from the retina are two-dimensional and tend to change at a more deliberate pace. Olfaction, which depends on concentrations of hundreds of airborne odorants, relies on another system altogether. (Koch & Marcus, 2014)

General principles do reign over neural codes, though. Neurons fire action potentials, and we believe these action potentials are important. Now we are trying to figure out how different neurons use the same signal to accomplish multiple tasks. Sometimes the patterns are obvious. The machine gun-like bursts of the auditory system easily contrast with the single-shot lone hunter approach of the visual system. Sometimes the patterns are subtle. Four spikes from one cell type may mean something quite different than four spikes from another cell type, just as "coin" in English means something quite different to "coin" in French.

The hunt is on by the best and brightest. Yet, something from my Caltech days makes me wonder. By merely focusing on the brain's equivalent of the Morse code have we incorrectly framed the problem? By working within one level of explanation, have we fallen into the trap of simplistic physicalism? Was there something more that Schrödinger was trying to tell us?

## DECODING CODE BIOLOGY

In the 1950s and 1960s, reductionism had captured the biological world. Information technologies, artificial intelligence, and computer science were being imported and used to study psychology, anthropology, and linguistics. Suddenly, the cognitive sciences were not looking for minds or for molecules; they were looking for machinery.

But disquiet emanated from the University of Chicago. The "Chicago School," of which Sperry was a product, had already realized that the machine analogy for life was backward. Brains are not like machines; machines are like brains but with something missing. Whatever that something was, it answered the question, "What is life?"

I first encountered this idea as a graduate student from the chemist/economist/philosopher and polymath Michael Polyani. Polanyi took a stand against pure reductionism: Knowing the parts of something does not always tell you what the whole might be (Polanyi, 1958). He was joined by University of Chicago professor Nicolas Rashevsky, the father of mathematical biophysics and theoretical biology, who had also asked himself "What is life?" After 20 years of feverish work from a purely deterministic stance, he had become uneasy. As described by his graduate student, theoretical biologist Robert Rosen, Rashevsky came to the realization that "no collection of separate descriptions (i.e., models) of organisms, however comprehensive, could be pasted together to capture the organism itself" (Rosen, 1991). Knowing everything that can be known about the structure tells you nothing about the function. One mode of description was not enough.

The emerging field of code biology formalized this resistance to hardcore reductionism. The driving force behind it is Marcello Barbieri. He thinks the biologists of the early 1960s missed the truly revolutionary aspect of the discovery of DNA. "The genetic code has been universally accepted into Modern Biology, but let us not be naive about this: what has been accepted is the name of the genetic code, not its ontological reality" (Barbieri, 2018).

The heart of the code issue is that there is no deterministic link between a symbol and its meaning. A real code is a set of rules or conventions (i.e., not physical laws) that establish a correspondence or mapping between the objects of two independent worlds. A code faithfully links a sign (aka a symbol) with its meaning, even where there is no obligatory link. This allows arbitrariness into the physical world, a nonstarter for a flat-footed determinist.

Instead of being accepted as a real code, says Barbieri, "the genetic code has been accepted under the assumption that its rules were determined by chemistry and do not have the arbitrariness that is essential in any real code" (Barbieri, 2018). Various theories have argued that the genetic code is chemically determined and therefore not arbitrary. Eventually, however, studies have shown that there is no deterministic link between DNA's codons and amino acids they code for. Cephalopods can recode their transfer RNA—the bridge between DNA and the amino acid for which it codes. New proteins can be constructed while the DNA sequence of symbols stays the same (Liscovitch-Brauer et al., 2017). This is not a violation of physics. It is simply a change in convention.

Caltech was the epicenter of biological code breaking during my formative years. What I had not appreciated until recently was what a code implied. I was surrounded with people who rejected flat-footed physicalism, even if they did not admit it. They were not taking the old physics and applying it to biology at all. Everyone was looking for the key, the look-up table, and the Rosetta Stone that would suddenly turn the seemingly nonsensical writings of biology into a beautiful clear language. The code is what would bridge the gap.

## MIND THE GAP

Like me, the Stanford-educated physicist who waded into theoretical biology during his stunning career at The State University of New York at Binghampton, Harold Pattee concerns himself with the gap between the objective material brain and the subjective experience of the mind. Unlike me, the mind–body problem reminds him of physics. "For physics the relation of subject to object has always been the fundamental problem" (Pattee, 2015). What may superficially sound like a linguistic concept is hardly that. It shook the foundations of physics when it was first formally articulated (vaguely) by Niels Bohr.

Empirical science is a business of measurements. By virtue of doing an experiment, one injects an element of subjectivity. Measurement requires an observer, a subject, or an agent separate from the object being measured. Measurement has arbitrary aspects: The observer determines when, where, and what to measure (and implicitly what to ignore) and what (arbitrary) symbols will be used to express the measurement. Finally, the measurement process is irreversible—once it has been made, it has interfered with the system forever. Meanwhile, all microscopic events are assumed to follow reversible dynamic quantum laws (Schrödinger's equation).

The complementarity principle formally accepts both objective causal laws and subjective measurement rules as fundamental to the explanation of the phenomena. Bohr emphasized that, although two modes of description were necessary, this did not correspond to a duality of the system under observation. Quantum objects have complementary (paired) properties; only one of which can be exhibited and measured and, thus, known, at a given point in time. However, both exist always—the system itself is unified, two sides of one coin.

Physicists of the time did not take the idea of complementarity lying down. Einstein simply hated it. Ultimately, Bohr prevailed: complementarity as an empirical necessity. Physicists now refer to the inescapable separation of the measurer and measured as *die Schnitt.* There is a chasm across which a symbol is related to its referent, a subject to its object. Although neuroscience calls it the "mind/brain gap," Pattee calls this separation the "epistemic cut" (Pattee & Rączaszek-Leonardi, 2012).

He is interested in *where* this cut lies: Where is the fundamental gap in biological knowledge? Many of the early quantum theorists placed the cut at the level of human consciousness, as do many of today's neuroscientists. Pattee believes the gap arose way before any brain was on the scene.

He proposes that to bridge the gap between the mind and brain, we must go much farther back in evolutionary time. We must first explain how certain conglomerations of matter produce a lifeless material object and how other conglomerations of the same matter produce a living thing. He believes that the gap between quantum and classical behavior is inherent in the distinction between inanimate and living matter and was there at the origin of life.

## THE NEW PHYSICS OF SYMBOLS

Pattee argues that complementarity is an epistemic necessity that originated with life. Life must be seen as a layered system in which each layer has, and indeed requires, different models, its own vocabulary. On one side of the *Schnitt*, there is some physical thing (a molecule, the firing of neurons). On the other side, there is the symbolic representation of that thing.

It was John von Neumann who inspired Pattee to think more deeply about symbols and what they implied. Von Neumann tackled "What is life?" a few years after Schrödinger's lecture. He reckoned that living things not only reproduce, but they do one better, they evolve, that is, they increase in complexity. To accomplish this required two things: (1) information in the form of nondynamic symbolic constraints, which would be sharply distinguished from (2) the construction dynamics they control (von Neumann, 1966).

At this point, von Neumann was off to other endeavors. He did not work out the physical requirements for implementing his logic—what Pattee calls the "physics of symbols." Pattee expanded von Neumann's logic.

Pattee recognized that the formation of any replicating biological thing comes face-to-face with the "measurement problem" of quantum mechanics.

Biological symbols making up the hereditary record must be stored not as an abstract entity but as physical material (DNA's nucleotides). This material constrains the phenotypic construction process in a way that follows Newton's physical laws. However, there is no obligatory link between a symbol and its meaning; the correspondence is not the physical outcome of universal laws. Instead, the link is a rule-governed selection process focused on function: Select the one that does the best job.

In our case, the hereditary record is made of DNA. The nucleotides that are DNA's symbols are physically stable and have been conserved. However, neither the nucleotides nor the rules that relate DNA to protein sprang forth fully formed at the origin of life. The nucleotides evolved; the rules evolved, though a rule can adapt much faster than the physical materials it links.

Symbols thus lead a double life. When functioning as constraints, the physical structure of symbols follows Newton's unchangeable universal laws. However, in their informational role as hereditary records, the symbols are governed by rules, which are local and can change. Symbols have two complementary modes of description, and one cannot be derived from the other. Both are needed.

Pattee laments that this double life of symbols is largely ignored in biology. Researchers focusing on information processing ignore their material side, the physical manifestation of the symbol. Molecular biologists focus only on the material side and ignore the arbitrariness of their informational side. Both miss their complementary character and, in so doing, miss the importance of the link between the two: the code. According to Pattee, "It is precisely this natural symbol-matter articulation that makes life distinct from non-living physical systems" (Pattee & Rączaszek-Leonardi, 2012).

There are at least two people who might be pleased with this conclusion. Schrödinger's question had previously been asked by Karl Pearson in *The Grammar of Science,* first published in 1892: "How, therefore, we must ask, is it possible for us to distinguish the living from the lifeless if we can describe both conceptually by the motion of inorganic corpuscles?" (Pearson, 1892). Over a century later, Rodney Brooks had penned a similar lament: "Despite the fact that living systems are composed only of non-living atoms there seems to be limits in the current levels of understanding within these disciplines in what is necessary to bridge the gap between non-living and living matter" (Brooks, 2001).

Pattee believes this gap can be closed by determining how physical systems transcend their immediate physical properties, that is, how a molecule becomes a message. We must ultimately understand (a) how physical systems become symbols, (b) that symbols have no dynamics and are not governed by physical laws, and (c) how these symbols can be used to build a logic across scales. To close the gap requires breaking the code.

"What is life?" has yet to be answered. But at least now, there is a plan.

## CLOSING THE GAP

I read Pattee's answer, and it puts me right back there in the Dartmouth library 60 years ago. The genotype and the phenotype abide by radically different physics. The physics on one side can never account for the physics on the other. Barbieri links the two with a third party: "The genotype is the seat of heredity, the phenotype is the seat of metabolism, and the ribotype is the codemaker of the cell, the seat of the genetic code" (Barbieri, 2008).

My mind drifts back to Caltech, and I imagine Delbrück trying to invent Schrödinger's "new physics" to describe biological systems. Delbrück, the student of Bohr, had already whole-heartedly embraced complementarity. And suddenly, I get it. I see the other side of the *Schnitt*. It was right there from the beginning.

DNA was the molecule that gave rise to modern biology. DNA is a material—an "aperiodic crystal"—with characteristic, predictable, stable physical properties. It twists with certain frequencies and folds in certain ways and melts at certain temperatures. This molecule can be stored away and then recalled on demand. However, it has a second, hidden life. Within the physical properties of these molecules is information in symbolic form, decoded by RNA, which is needed to build a new unit of life. The properties of the molecules symbolically direct and physically constrain the building process. DNA therefore has two realities, just like light is a wave and a particle at the same time: information and construction, structure and function—irreducible properties of the same physical object that exist in different layers with different protocols.

Pattee has given us a schema and a way to think about how life comes out of nonliving stuff. Life replicates itself but also increases in complexity. Understanding life requires that we achieve two levels of understanding of any of its components. We must accept the material properties of a physical thing on one level. However, we must allow that thing to have a symbolic life on another level. If we can extend this generosity of spirit to living systems, then one day we can close the gap.

## THE JOURNEY CONTINUES

If Pattee is correct, the cognitive neurosciences must fully embrace the legendary, unwanted gift of modern physics: the principle of complementarity. We should not approach conscious cognition as either the physical reality of neural dynamics or the symbolic reality of information processing. Consciousness is not reducible to one or the other, by definition. Both should be kept on the table because they are complementary properties of the same system. It is our job to crack the code that relates one to the other, the physical to the symbolic (Gazzaniga, 2018).

So again, I return to Schrödinger, to what he first tried to tell me in the library all those years ago. Schrödinger's little book planted a seed in my mind. I was lucky this seed germinated and was nourished by 60 years of excitement and discovery and friendship. This past year, I was lucky enough to help celebrate him at Trinity College, on the 75th anniversary of his now historic series of lectures.

Schrödinger famously asked, "What is life?" To me, life has been asking the most difficult questions one can imagine and then searching for answers. It is a life I highly recommend.


### Acknowledgments

I would like to thank many colleagues who have helped me on this effort, including Steven Hillyard, Marcus Raichle, Michael Posner, Steven Pinker, Bridget Queenan, Robert T. Knight, Leo Chalupa, Barry Stein, Craig Montell, Tomás Ryan, Joseph LeDoux, Leah Krubitzer, Walter Sinnott-Armstrong, and of course my sister Rebecca Gazzaniga.


## REFERENCES


Barbieri, M. (2008). Biosemiotics: A new understanding of life. *Naturwissenschaften*, *95*, 577–599.

Barbieri, M. (2018). What is code biology? *Biosystems*, *164*, 1–10.

Brooks, R. (2001). The relationship between matter and life. *Nature*, *409*(6818), 409–411.

Delbrück, M. (1949). A physicist looks at biology. *Transactions of the Connecticut Academy of Arts and Sciences*, *33*, 173–190.

Gazzaniga, M. S. (2018). *The consciousness instinct: Unraveling the mystery of how the brain makes the mind*. New York: Farrar, Straus and Giroux.

Koch, C., & Marcus, G. (2014). Cracking the brain's codes. *Technology Review*, *117*, 42–46.

Liscovitch-Brauer, N., Alon, S., Porath, H. T., Elstein, B., Unger, R., Ziv, T., et al. (2017). Trade-off between transcriptome plasticity and genome evolution in cephalopods. *Cell*, *169*, 191–202.

Pattee, H. (2015). The physics of symbols evolved before consciousness. *Cosmos and History: The Journal of Natural and Social Philosophy*, *11*, 269–277.

Pattee, H., & Rączaszek-Leonardi, J. (2012). *Laws, language and life: Howard Pattee's classic papers on the physics of symbols with contemporary commentary*. New York: Springer.

Pearson, K. (1892/2007). *The grammar of science*. New York: Cosmino.

Polanyi, M. (1958). *Personal knowledge*. London: Rutledge.

Rosen, R. (1991). *Life itself: A comprehensive inquiry into the nature, origin, and fabrication of life*. New York: Columbia University Press.

Schrödinger, E. (1944). *What is life? The physical aspect of the living cell and mind*. Cambridge: Cambridge University Press.

Sperry, R. W. (1963). Chemoaffinity in the orderly growth of nerve fiber patterns and connections. *Proceedings of the National Academy of Sciences, U.S.A.*, *50*, 703–710.

von Neumann, J. (1966). *Theory of self-reproducing automata*. Urbana: University of Illinois Press.