Coherence: Purple Bacteria, Quantum Physics at Room Temperature, and Scientific Atomism

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> [W]e must be careful to avoid the aura of mystery which can so easily be produced by reference to "quantum-mechanical effects."
>
> *H.C. Longuet-Higgins*[1]
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> The beauty of how the purple bacteria have evolved a solution to the problem of efficiently harvesting light energy comes, as we show below, from how *they have, by trial and error, been able to elegantly exploit quantum mechanics.* We find that this is a truly remarkable outcome.
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> *Richard J. Cogdell*[2]
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> Imagine photosynthetic quantum computers!
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> *MIT Technology Review*[3]

Introduction: What took you so long?

You are purple bacteria. You live in a sewage sludge digester in Göttingen, Germany, or in a "waste lagoon of a vegetable canning plant in Minnesota."[4] There's no air where you are (you're anaerobic) and little light: you likely live underneath layers of floating plants, some algae, and perhaps cyanobacteria.[5] This is a problem, because you create energy from sunlight through photosynthesis. And it doesn't help that the lilies above you are filtering out most of the blue and red light.[6] Is this a poor choice of an energy source for an organism that doesn't live in direct sunlight? Possibly. But consider this: the structures you use to process sunlight may be as old as photosynthesis itself; furthermore, scientists have measured the efficiency with which you turn photons from the sun into ATP, and you're a whiz.[7] Between your light-harvesting antennae and the nearly circular ring structures through which you transfer electrons to your reaction core, your energy efficiency can be almost one-and-a-half times the efficiency of terrestrial plants growing in direct sunlight.[8] In particular, there's

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[1] H. C. Longuet-Higgins, "Quantum mechanics and biology." *Biophysical Journal* 2 (1962): 215.

[2] Richard J. Cogdell et al., "The architecture and function of the light-harvesting apparatus of purple bacteria: from single molecules to in vivo membranes." *Quarterly reviews of biophysics* 39 (2006): 229. Italics added.

[3] "First Evidence of Entanglement in Photosynthesis." MIT Technology Review, May 28, 2009. https://www.technologyreview.com/s/413634/first-evidence-of-entanglement-in-photosynthesis/.

[4] Michael T. Madigan and Deborah O. Jung, "An overview of purple bacteria: systematics, physiology, and habitats," in *The purple phototrophic bacteria,* ed. C. Neil Hunter, Fevzi Daldal, Marion C. Thurnauer, and J. Thomas Beatty (Dordrecht, Netherlands: Springer Netherlands, 2009): 9.

[5] Cogdell et al., "The architecture and function," 230.

[6] Cogdell et al., "The architecture and function," 229.

[7] John M. Olson, and Beverly K. Pierson, "Photosynthesis 3.5 thousand million years ago." *Photosynthesis Research* 9 (1986): 253.

[8] David Chandler, "Secret of Efficient Photosynthesis Is

one part of your mechanism whose efficiency is, to use a technical phrase, “astonishingly high.”[9]

On the way to the reaction core, your electrons—they used to be photons, before your antennae persuaded them to change their minds—need to pass through several rings, like a roller coaster with multiple loop-de-loops. Here’s what is so astonishing: your electrons make it from ring B800 to ring B850 with nearly 100% efficiency in less than one trillionth of a second.[10] It’s almost as if your electrons appear in the B850 ring *before they’ve left the B800 ring*.[11] As if, for a split second, they’re in two places at once.

This phenomenon is called quantum coherence: the theory that two electrons may share such a similar state that you can gain information about one by observing the other. It derives from quantum mechanics. In a very basic way, quantum coherence describes energy transfer much more accurately than classical physics could—and it explains why purple bacteria pass their electrons around with such efficiency and speed.[12]

Two statements are important at this point. First, since the 1930s theoretical physicists have repeatedly suggested that quantum effects undergird all vital phenomena; second, only within the past ten years have molecular biologists accepted quantum-mechanical explanations of certain vital phenomena. Why did it take seventy years for molecular biologists to accept quantum mechanical explanations of vital activity? A possible explanation for this is technological: it took some time before biologists had the optical microscopes to confirm such quantum effects, or the ability to observe certain energy transfer mechanisms in isolation from their native organisms. But the original discussion over quantum effects in biology was pre-technological: the computations for energy transfer were theoretical, as were the musings of physicists on quantum effects in organisms. As we will see, even when biologists and biochemists admitted the influence of quantum mechanics in their fields, they thought of the field as providing them with problems to investigate (such as the nature of electron transfer) and equations to undergird better technology (such as for microscopes) rather than precisely describing vital activity.

In her book *The Restless Clock*, Jessica Riskin describes the 300-year history of the conflict between mechanist and vitalist explanations of vital phenomena. She writes that biology has been, and remains, under the influence of “a dialectical tradition at the heart of scientific explanations of life and mind,” the conflict between naturalizing and eradicating agency in explanations of vital phenomena.[13] Riskin tracks not only the influence of these two competing ideologies, but

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Decoded,” *MIT News*, May 13, 2013. https://news.mit.edu/2013/secret-of-efficient-photosynthesis-decoded-0514.

Studies have put the overall efficiency of C3 plants (rice, barley, woody trees) at 4.6% and C4 plants (sugarcane, grasses) at 6%. See Xin-Guang Zhu et al., “What is the maximum efficiency with which photosynthesis can convert solar energy into biomass?”, *Current opinion in biotechnology* 19 (2008): 155.

A foundational study measured hydrogen production efficiency for certain species of purple bacteria to be 7.9% in extremely low sunlight. See J. Miyake and S. Kawamura, “Efficiency of light energy conversion to hydrogen by the photosynthetic bacterium Rhodobacter sphaeroides,” *International Journal of Hydrogen Energy* 12 (1987): 147.

[9] Y. C. Cheng and R. J. Silbey, “Coherence in the B800 ring of purple bacteria LH2,” *Physical review letters* 96, no. 2 (2006): 1.

[10] Cheng and Silbey, “Coherence in the B800 ring,” 1.

[11] This is a feature of quantum coherence.

[12] Gregory D. Scholes, “Quantum-coherent electronic energy transfer: Did nature think of it first?.” *The Journal of Physical Chemistry Letters* 1 (2010): 2.

[13] Jessica Riskin, *The Restless Clock* (Chicago: University of Chicago Press, 2016): 374.

also how these ideologies borrow from one another and, at times, become a single conception of life: the eponymous "restless clock." Yet Riskin's main source materials are the popular writings of biologists, both molecular (as the field came to consider itself) and evolutionary. She limits her central critique to the sciences of life and mind, and ends her book at the outset of molecular biology—before biology became even more atomized and researchers began to spend entire careers working on a single molecule in a single structure of a particular bacteria's photosynthetic cycle. Riskin fails to ask, however, whether one can hope to impose a critique of "dialecticism" on a field of science that lives and dies by the infinitesimal details of its experiments.

The story of quantum coherence in electron transfer can be read as a test case of Riskin's hypothesis. Did the "dialectical" conflict over agency keep molecular biologists tongue-tied on the question of quantum effects in living things? Or was it simply a matter of course—that is, was the eventual "discovery" of quantum effects simply the result of a plodding progression of empirical study?

This complicated story borrows histories from two extremely sophisticated scientific disciplines. And it is this progression of sophistication that ultimately concerns me: to what extent can historians of science project social tensions onto the most advanced scientific studies? When, so to speak, is a quantum explanation of vital activity just a quantum explanation of vital activity?

This essay aims to answer this question by telling the history of quantum theory in biology; its initial mixed—but not entirely disapproving!—reception among biologists; the emergence of evidence for quantum effects in organisms; and the ongoing period of acceptance of quantum effects in biology. My goal is to see just how likely it was for biologists to accept the reality of quantum effects in vital phenomena in the 1990s and early 2000s. I will attempt to do so through my readings of a few influential papers on the subject. Though green-sulfur bacteria and European robins play a role in the last part of the story, I focus on purple bacteria, as they appear to have the longest publication history for speculation over quantum effects by biologists.

As you may have inferred from the second epigraph to this essay and its cheeky intro, I agree with Riskin that biologists cannot pretend to have effectively eradicated the notion of 'agency' from the study of vital activity; at the very least, their writings suggest otherwise. Whether theoretical physicists would agree or not, biologists seem to have perceived something disquieting about the randomness—the apparent vitalism—of quantum mechanics. Can the emerging field of quantum biology overcome biology's resistance to vitalism? Or will quantum effects be subsumed into the vital machine? Can science, to challenge Riskin, ever be "made anew"?[14]

A note on terms

Throughout this essay I differentiate between the activity of living organisms and "life" writ large—with its philosophical implications—by referring to the former with the adjective "vital." (For example, photosynthesis is a vital phenomenon.) This may be somewhat confusing, as my essay references the back-and-forth (or "dialectic," as Riskin calls it) in biology between vitalism and brute mechanism. *Vitalism*, briefly, is the idea that the existence of vital phenomena is not due to the interaction of physicochemical forces, but rather to something deeper: a self-determining principle, a kind of physical teleology. (Henri Bergson called it "élan vital," or vital force.) *Mechanism*, the intellectual op-

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[14] Riskin, *The Restless Clock,* 373.

ponent of vitalism, is the notion that physicochemical interaction is all there is to it.

Ghost in the cell: The view from quantum physics

In 1944 Erwin Schrödinger published *What Is Life?,* a book based on a series of lectures he gave in Dublin, to significant interest. The treatise found favor with big names such as J. B. S. Haldane, Michael Polanyi, and Max Delbrück, and made a wide impression on the field of biology.[15] (It caused quite the ruckus in Dublin's religious community.) The book is famous for having "predicted" the discovery of DNA: Schrödinger supposed that if there were a gene-molecule responsible for heritability, it would likely be "aperiodic," in the sense that even single atoms might have a role to play in constituting and reconstituting such a molecule.[16] Such was DNA: an "aperiodic crystal."

Schrödinger's interest in the importance of lone atoms in biology was unusual—that was considered the domain of physics. As an earlier commentator has noted, when Schrödinger published his book, biologists weren't concerned about the complexity of vital phenomena on such a small scale: from Schrödinger's book they "merely appropriated the idea of studying the molecular structure of the gene."[17] But as a physicist, Schrödinger saw a strong connection between the behavior of individual atoms and vital activity, drawing a foundational connection between quantum mechanics and biology.

He wrote that the "jump-like" changes observed by Hugo de Vries in thoroughbred horses "[remind] a physicist of quantum theory—no intermediate energies occurring between two neighboring energy levels. He would be inclined to call de Vries's mutation theory, figuratively, a quantum theory of biology."[18] Schrödinger went on to walk a fine line, in which he posited this atomic understanding of the "gene," without directly tying the *forces* of atomic physics to vital activity. "We must be prepared to find," he wrote, that vital activity works in a way "that cannot be reduced to the ordinary laws of physics."[19] This wasn't to say that "any 'new force'" held sway over "the behaviour of single atoms within a living organism."[20] The ultimate question, he concluded, was a structural one. In words that anticipate François Jacob's theory of the "integron," Schrödinger wrote that natural phenomena "are visibly based to a large extent on the 'order-from-order' principle"—life produces orderliness.[21] He then tied this to a recent paper from the physicist Max Planck that suggested that large-scale physical phenomena are tied to the behavior of "small-scale events, the interaction of the single atoms and molecules."[22] Schrödinger was trying to create a bridge between the "dynamical"—or mechanical—processes of planets and the same of cellular activity—structure from structure, a system of systems—even though he knew that such "dynamical" processes were only known to happen at temperatures close to absolute

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[15] Edward J Yoxen, "Where does Schroedinger's *What is life?* belong in the history of molecular biology?" *History of science* 17 (1979): 18.

[16] Riskin, *Restless Clock,* 371.

[17] Yoxen, "Where does Schroedinger's *What is life?* belong," 36.

[18] Erwin Schrödinger, *What Is Life?: The Physical Aspect of the Living Cell*, Cambridge: University Press, 1955: 34.

[19] Schrödinger, 76.

[20] Schrödinger, 76.

[21] Schrödinger, 80. Jacob's "integron" was any organic structure that is made up of a class of smaller structures and in turn makes up a larger structure, e.g., a kidney, or a lipid. See François Jacob, *The Logic of Life: A History of Heredity* (New York: Pantheon Books, 1973): 302.

[22] Schrödinger, *What is Life?*, 82.

zero (such as the temperature of outer space).[23]

As Riskin has pointed out, Schrödinger seemed to have been trying to "rebuild" science by merging vitalism and brute mechanism.[24] This claim holds up for Schrödinger's statements on the unity of structure and behavior. But there is a greater ambivalence to his book. At the same time that Schrödinger suggested that all things in the universe may have the same mechanical underpinnings, he seemed not to want to extend the boundaries of that structure to the atomic level. He used a telling metaphor: imagine a steam engineer inspecting an electric motor. Such an engineer would intuit, from the motor's construction, "an entirely different way of functioning," not that the electric motor was "driven by a ghost."[25] This is a decidedly mechanist way of viewing the physical underpinnings of biology, but, crucially, understood in a way that maintains a separation between physics and biology: quantum mechanics—or atomic-scale phenomena—become a kind of tool or machine used by a biological system. This is what I call the *utilitarian* understanding of quantum mechanics in vital activity. It continues to hold sway in current literature. Quantum physics was (and is) considered a mechanism-in-itself.

Other physicists and influential scientists in Schrödinger's world had taken up the question of how quantum mechanics might be important to the biologist. Niels Bohr, Pascual Jordan, Henry Marganau, and Pierre Teilhard de Chardin all attempted to create theories of matter that linked quantum mechanics with a decidedly classical understanding of vital activity.

Bohr, in the early 1930s, was taken with the possibility that his recent theory of complementarity—that complete knowledge of an atom requires information on its wave and particle functions—might be relevant to the life sciences.[26] In 1933 he published a two-part essay in *Nature*, in which he suggested that life is reducible to phenomena that are studied by the atomic physicist. In photosynthesis in particular, he wrote, "the individuality of photo-chemical processes must undoubtedly be taken into consideration."[27] Scientists should expect that analysis of "the mechanism of living organisms" on the atomic scale would find similar features to the "properties of inorganic matter."[28] Bohr was convinced that "no well-defined limit can be drawn for the applicability of physical ideas to the phenomena of life."[29]

Bohr's ravings and writings were hugely influential on Max Delbrück, a biophysicist, who hosted a regular, informal meeting of theoretical physicists at his home to discuss the potential for physical theories of vital activity. Their discussions centered, for the most part, around photosynthesis, as they considered it the most fruitful ground for biology and theoretical physics to meet.[30] Delbrück would go on to publish a foundational paper for the field of molecular biology, "On the Nature of Gene Mutation and Gene Structure."

The question of quantum physics in vital activity was a kind of proving ground for these physicists'

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[23] Schrödinger, 84.

[24] Riskin, *Restless Clock,* 373.

[25] Schrödinger, *What is Life?,* 76.

[26] Kärin Nickelsen, *Explaining Photosynthesis: Models of Biochemical Mechanisms, 1840-1960*. Vol. 8. Springer, 2015: 284. She refers to Bohr's 1928 complementarity theory as a "quantum mechanical dialectic."

[27] Niels Bohr, "Light and life," *Nature* 131 (1933): 457.

[28] Bohr, "Light and life," 458.

[29] Bohr, "Light and life," 458.

[30] Nickelsen, 123-4.

larger epistemological and ideological theories.[31] While Schrödinger spoke of quantum physics from what I have termed the utilitarian stance, Pascual Jordan saw "quantum biology," as he termed it, as a way to link modern science to Nazi ideology by identifying quantum physics with the vitalism that was so important to Nazi theories of life.[32] Henry Marganau and Pierre Teilhard de Chardin—two very spiritually-minded scientists—incorporated different versions of Bohr's "limitlessness" hypothesis into their grand theories of everything, Margenau with an eye towards describing consciousness as a fundamental feature of matter and Teilhard seeing eventual divine unification of matter in quantum mechanical theory.[33]

Throughout the rest of the 20th century, many physicists published speculative works about the possibilities for understanding vital activity by recourse to quantum mechanics. Some of these papers were based off experiments conducted by the physicists, while some were state-of-the-field articles meant to build support for quantum theories of life. Herbert Fröhlich, a British physicist, noticed in 1968 that certain biological systems show a kind of coherence found in super-chilled Bose gas. "Stimulated by a different attitude" from those who would discount low-temperature phenomena in vital activity, he found that processes in the cell membrane, among other things, might be expected to exhibit long-range electron coherence.[34] He suggested that this quantum mechanical effect might be important to cell division.[35] And, in language echoing Schrödinger's "order-from-order" principle, he suggested that biologists interested in understanding life structurally might find that life's co-operative features are mirrored by material physical theories.[36] Though he referred to his subsequent suggestions for biological research as "speculative," he ended his paper by noting that one of his findings "may be relevant to photosynthesis."[37]

Andrew Cochran, a professor of physics at the University of Missouri, published many papers in the late 1960s and 1970s on the possible inter-relatedness of quantum physics and biology—though in a much more polemical style. In a 1971 article he wrote:

> The known facts of modern quantum physics and biology strongly suggest the following related hypotheses: atoms and fundamental particles have a rudimentary degree of consciousness, volition, or self-activity; the basic features of quantum mechanics are a result of this fact; the quantum mechanical wave properties of matter are actually the conscious properties of matter; and living organisms are a direct result of these properties of matter.[38]

This is unabashed vitalism. Cochran blamed classical physics for characterizing atoms as lifeless, lamenting that this definition maintained its dominance despite

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[31] For more on Bohr, Pascual Jordan, and Delbrück, see Leyla Joaquim et al., "Quantum Explorers: Bohr, Jordan, and Delbrück Venturing into Biology," *Physics in Perspective* 17 (2015): 236-250.

[32] Jordan: "The extension of quantum ideas would stand in an extension of the power of the German imperium." Quoted in Richard H. Beyler, "Targeting the organism: The scientific and cultural context of Pascual Jordan's quantum biology, 1932-1947," *Isis* 87 (1996): 250.

[33] See particularly Henry Margenau, "Reality in quantum mechanics." *Philosophy of Science* 16 (1949): 287-302., and Teilhard's *The Human Phenomenon.*

[34] Herbert Fröhlich, "Long-range coherence and energy storage in biological systems," *International Journal of Quantum Chemistry* 2 (1968): 643.

[35] Fröhlich, 648.

[36] Fröhlich, 642.

[37] Fröhlich, 649.

[38] Andrew A. Cochran, "Relationships between quantum physics and biology." *Foundations of Physics* 1 (1971): 236.

the quantum revolution in physics and its theoretical antecedents. Thus, despite Schrödinger's preference for a mechanistic universe, there was clearly a strain of vitalism in quantum physics. We might call this the *emergent* theory of quantum mechanics in vital activity, as opposed to the earlier described *utilitarian* theory. (And it echoes, to some degree, Jordan's Nazi quantum biology.) Here, we might locate a preliminary reason why biologists may have remained averse to quantum explanations of vital activity: that they perceived it not as fascist, but as vitalist. The irony is that, in many cases, physicists saw quantum effects as simply the next system down from cell organelles, much in the way that Jacob described the hierarchy of "integrons" that make up organisms.[39]

How did biologists receive this quantum speculation? There is a particular document that current biologists are pointing to in their articles on the origins of 21st century quantum biology. In a 1962 lecture, H. C. Longuet-Higgins, a biochemist, touted his conservatism on "the usefulness of quantum mechanics to biologists."[40] He argued that the job of the biochemist and biologist is to study whole-cell processes, following the structural argument of biologists at the time. He found value, however, in quantum mechanics as a descriptor of the underlying reality of all things, in the sense that "all physico-chemical phenomena are quantum-mechanical in nature."[41] Longuet-Higgins maintained that though "it is always unwise to underestimate the ingenuity of the living cell," biological systems could be understood without recourse to quantum mechanics. That is, he understood quantum mechanics as a tool (albeit an inadequate one) that biologists could use to describe vital activity by analogy—and as an *unlikely* tool of living cells.[42]

Longuet-Higgins' ambivalence was the defining feature of this speech: he discussed quantum mechanics as a useful tool not of organisms, but of biologists, at the same time that he explicitly made the case against over-complicating explanations of vital activity. Quantum physics, he admitted, had posed research questions for molecular biologists to consider, and provided them with better imaging technology with which to conduct their research. But when it came down to it, quantum mechanics had an "aura of mystery" that was not necessary for the biologist, especially when vital phenomena could be likened to watches, locks, and keys.[43] To his credit, he did allow that "the photo-synthetic act is that biological problem to which quantum mechanics has made, and is likely to make, the most useful contribution."[44] Yet the questions of exciton energy transfer would more likely "yield to attack" by experimental, and not theoretical, investigations.[45]

Though Longuet-Higgins described his view as "conservative," there is little evidence that suggests biologists and biochemists felt otherwise—either more or less interested in quantum effects. Perhaps the most significant piece of evidence is that biologists published little on the subject in the intervening years between Longuet-Higgins' speech and the seminal experiments on purple bacteria.[46] In certain cases, other biologists

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[39] Jacob, "The Integron," in *The Logic of Life: A History of Heredity* (New York: Pantheon Books, 1973).

[40] H. C. Longuet-Higgins, "Quantum mechanics and biology," *Biophysical Journal* 2 (1962): 207-215.

[41] Longuet-Higgins, 208.

[42] Longuet-Higgins, 211.

[43] Longuet-Higgins, 215.

[44] Longuet-Higgins, 212.

[45] Longuet-Higgins, 213.

[46] There are many speculative articles about quantum

seemed to agree with Longuet-Higgins that quantum mechanics was too mysterious. Gunther Stent, a prominent biologist at Berkeley, published an article in 1968 picking up on an idea advanced by Niels Bohr: that, like particles, organisms remained fundamentally obscure to scientists because one would have to kill the organism to study it on an atomic scale. "On this view," he wrote, "the existence of life must be considered as an elementary fact that cannot be explained, but must be taken as a starting point in biology."[47] Stent would have us consciously appoint mechanism as the first principle of biology. Stent even concluded by speculating that Bohr's conundrum might mean that humans could never achieve an understanding of life as such.[48] Like Longuet-Higgins, and seemingly in opposition to the prevailing biological concepts of structural hierarchy, Stent proposed that there was a bottom to biological investigation: floorboards underneath which a biologist need not—indeed, could not—look.

Life isn't too warm and wet after all: quantum physics in organisms

In his PhD dissertation in 1952, Louis Duysens, a Dutch biophysicist, made several important findings. One of these was that in purple bacteria's light harvesting process, energy transfer between photosynthetic structures was nearly 100% efficient.[49] In an earlier paper he had also identified the three proteins involved in purple bacteria's photosynthetic process: B800, B850, and B890, so named for the wavelengths of light (measured in nanometers) they grabbed energy from.[50] He calculated the energy transfer efficiencies using a particular theorem, Förster resonance energy transfer. "Estimations" of transfer efficiency, he wrote, "based on Förster's considerations, are in accordance with, or at least do not contradict, the results recorded above."[51]

For over sixty years molecular biologists approached the study of electron transfer under the influence of a single theory, published in 1946 by Theodor Förster, a German scientist (and a member of the Nazi party).[52] His theory, known as Forster resonance energy transfer (FRET), described the way that energy transfers between two chromophores, which are the regions of organic structures and organisms (such as the retina, plant cells, certain bacteria, and the emerald green sea slug) that absorb and emit certain wavelengths of light. In photosynthetic organisms, the chromophore absorbs light by "exciting" an electron, sending it into a chain of reactions that ultimately turn the electron into energy (in the form of ATP) for that organism. The process is thus called " excitation energy transfer," or EET. Forster knew that his theory could be derived either through classical or quantum physical calculations, though it described a theoretical version of electron transfer that approximated the outcome of EET: the baking-soda-volcano equivalent of *in vivo* (occurring within the organism) electron transfer mechanisms.[53] In his model, energy transfer efficiency was highly sensitive to changes in distance, which eventually made it a

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mechanics and psychology. For example, see Ivan D. London, "Quantum biology and psychology," *The Journal of General Psychology* 46 (1952): 123-149.

[47] Gunther S. Stent, "That was the molecular biology that was," *Science* 160 (1968): 392.

[48] Stent, "That was the molecular biology that was," 395.

[49] Nickelsen, *Explaining Photosynthesis,* 193.

[50] L. N. M. Duysens, "Transfer of light energy within the pigment systems present in photosynthesizing cells," *Nature* 168 (1951): 548.

[51] Duysens, quoted in Nickelsen, *Explaining Photosynthesis,* 286.

[52] Theodor Förster, "Energiewanderung und fluoreszenz," *Naturwissenschaften* 33 (1946): 166-175.

useful tool for molecular biologists measuring distances between intracellular structures.

Yet earlier research had essentially derived Forster's same formula: research conducted on—you guessed it!—the speed of EET in photosynthetic structures in bacteria. In 1941, a short abstract appeared in the back of *Physical Review*. It described how energy transfer in photosynthesis was analogous to a similar process—having to do with radiation and decay—in gamma rays.[54] The abstract had been presented at a meeting of the American Physical Society in Pasadena in June 1941. Its presenter was one J. R. Oppenheimer.[55] Though he would later get sidetracked by a larger, more pressing project, in 1950 Oppenheimer and his research partner on this question, William Arnold, published a more in-depth treatment of EET and its similarities with quantum mechanical processes. "One is tempted to speculate," Arnold wrote, "on the possibility that we have here a method for the transfer of energy through the chloroplast."[56]

At this point it is important to note that FRET—either Forster's theory or Arnold and Oppenheimer's—is *not* quantum mechanics. It has to do with light quanta, but it describes a form of energy transfer that is *not* coherent. In FRET, energy is shared between proteins through overlap of light spectra (i.e., 800nm, 850nm, and 890nm). In quantum coherence, two molecules "couple" in such a way that they share certain characteristics and are considered a single "superposition." FRET can occur over much wider distances than quantum coherence, but only when the light spectra of the proteins overlap. Thus when Duysens wrote that FRET "[did] not contradict" his data, what may be inferred is that FRET, as a model, accounted for a significant portion of purple bacteria's photosynthetic efficiency—but quantum coherence explained what was really happening, and the energy transfer's near-perfection.

Many other researchers built upon Duysens' most celebrated findings: not only the three proteins that processed light in purple bacteria, but also his discovery that most plants contained two photosystems. In the late 1990s, however, the particular question of how energy transferred between B800 and B850 became interesting again. Renewed interest in this process was due, as papers at the time said, to advances in 3D imaging of light-harvesting structures in purple bacteria.[57] Still, a group of researchers had recently performed some tests and found that FRET didn't explain completely the speed of energy transfer.[58]

Researchers presenting findings in the *Journal of Physical Chemistry B* offered possible new ways of understanding EET in purple bacteria that didn't rely solely on FRET. Hu et al. offered a quantum mechanical model that better predicted the EET efficiency in 1997; Mukai et al., in 1999, didn't buy fully into the Hu team's findings, though they did allow that coherence was at play in EET between B800 and B850.[59] Further

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[54] Nickelsen, *Explaining Photosynthesis,* 284.

[55] Yes, *that* J. R. Oppenheimer. See J. R. Oppenheimer, "Internal conversion in photosynthesis," *Phys. Rev* 60 (1941): 158.

[56] William Arnold and J. R. Oppenheimer, "Internal conversion in the photosynthetic mechanism of blue-green algae," *The Journal of general physiology* 33 (1950): 434-435.

[57] Xiche Hu et al., "Pigment organization and transfer of electronic excitation in the photosynthetic unit of purple bacteria," *The Journal of Physical Chemistry B* 101 (1997): 3854.

[58] S. Hess et al., "Enhanced rates of subpicosecond energy transfer in blue-shifted light-harvesting LH2 mutants of Rhodobacter sphaeroides," *Biochemistry* 33 (1994): 8300.

[59] Koichiro Mukai et al., "Theory of rapid excitation-energy transfer from B800 to optically-forbidden exciton states of B850 in the antenna system LH2 of photosynthetic purple bacteria," *The Journal of Physical Chemistry B* 103 (1999): 6096.

papers in the early 2000s cemented the experimental and theoretical validity of quantum coherence in purple bacteria.[60] The researchers noted, in particular, that modeling the reaction with quantum mechanics helped explain certain phenomena (the timescale being hundreds of femtoseconds) and created a more intricate picture of the reaction itself. It also provided, perhaps most astonishingly, that quantum coherence was possible at room temperature, when physicists had long assumed quantum mechanical effects could not happen anywhere other than near zero degrees Kelvin, and certainly nowhere warm and wet like a cell.

In the late 2000s and early 2010s, papers pointing toward quantum effects in other biological phenomena emerged, at the same time that early review articles on the subject began to get published. In 2007, Engel et al. observed quantum effects in the FMO complex—another photosynthetic structure—in green-sulphur bacteria.[61] In 2011 Gauger et al. published a paper pointing to the role of quantum coherence in the European robin's avian "compass"—the means by which birds are able to navigate the globe. The researchers concluded that their findings were "starkly at variance with the view that life is too 'warm and wet' for such quantum phenomena to endure."[62]

The review articles that connected the findings across bacteria and birds used language that harkened back to the utilitarian understanding of quantum mechanical effects. Gregory Scholes, writing in 2010, said that the recent studies on bacteria suggested that "rather than being constrained by classical probability laws, some antenna proteins are able to employ interference of quantum amplitudes to steer energy transfer."[63] Scholes also recognized that finding quantum effects in "warm" environments sustained for periods of hundreds of femtoseconds would galvanize quantum-computing researchers, and provide a springboard for theories of "quantum photosynthetic computers," as one *MIT Technology Review* article had raved a year earlier.[64] In 2011 Lambert et al., who gave an overview of the new reports on purple bacteria, the FMO complex, and birds, also conformed to the utilitarian view of quantum effects, noting, "[P]reliminary evidence suggests that nature may also leverage quantum effects to enhance the efficiency, or functionality, of some of these amazing feats."[65] The follow-up questions, the authors speculated, would be around technological applications and the extent of quantum effects in other organisms.

Lambert et al. also re-inaugurated the discipline of "quantum biology," a term that had largely been on hiatus in the more prestigious journals and among prominent scientists since Pascual Jordan's era, the 1930s and 1940s. Since the Lambert article, biologists and physicists have taken to the new term. But in both Lambert and articles that have followed it, a strict demarcation remains between biological systems that use quantum effects and those that are simply classical. Quantum

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[60] See Scholes and Fleming 2000; Jang et al 2004; and Cheng and Silbey 2006.

[61] This is the lone non-review paper published on the subject of quantum effects in organisms that shows an awareness of the long back-story of speculation into quantum possibilities in vital activity. Gregory S. Engel et al., "Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems," *Nature* 446 (2007): 782-786.

[62] Erik M. Gauger et al., "Sustained quantum coherence and entanglement in the avian compass," *Physical Review Letters* 106 (2011): 1.

[63] Gregory D. Scholes, "Quantum-coherent electronic energy transfer: Did nature think of it first?," *The Journal of Physical Chemistry Letters* 1 (2010): 2.

[64] "First Evidence of Entanglement in Photosynthesis," *MIT Technology Review*, May 28, 2009.

[65] Neill Lambert et al., "Quantum biology," *Nature Physics* 9 (2013): 16.

mechanics is like the new kid in town—who's been there all along.

Conclusion: A part that is not part of the whole

Scholes' 2010 article ends on a telling note: "The benefits" of creating a discussion on quantum effects amongst physicists, chemists, and biologists, he writes, "will be the elucidation of insights into the light-initiated dynamics of very complex systems that were, until recently, unforeseen."[66]

"Ignored" might fit better in that conclusion. Despite—or perhaps because of—robust support from the founding fathers of atomic physics, biologists and biochemists did not pursue, and hardly even considered the possibility of, quantum effects in vital activity. Even as physicists continued to speculate on the importance of quantum physics in biology—whether it was from the point of view of positing an origin for consciousness or hoping to answer specific structural questions—biologists, for the most part, didn't respond.

Biologists and biochemists also spoke—and continue to speak—of quantum effects in a way that demarcated their discipline. Quantum effects have consistently been referred to as a "tool" of biological systems, not inherent to them. This may turn out to have some experimental validity, as some biologists have speculated that quantum effects may have, in some cases, evolutionary advantages over processes that appear to be strictly classical (such as providing purple bacteria with the energy transfer efficiency necessary to survive in low-light conditions). But even then, biologists probably wouldn't speak of an opposable thumb as a tool we humans use to grip beer bottles or hitchhike. There is a biological theory of "self," perhaps, yet to be articulated—an attempt to locate the root of "being" in an organism. Is there a difference between the "being" and what organic "tools" the being uses?

A central irony of this story is that though molecular biology's founding documents were written by physicists, the discipline in many ways resisted identification with modern physics, which was quantum physics. This paper tries to sketch a possible outline for why non-physicists like Longuet-Higgens found "an aura of mystery" in quantum physics, but it's hard to be sure. The fixation on inherent consciousness held by more than a few quantum physicists certainly did not help.

Why biologists seemed to define their field in part in opposition to quantum mechanics remains to be seen. Despite the prevailing "integron" theory of biology, quantum physics has remained an alien presence in biology, a monster under the floorboards. It is used by life but is not life: a part that is not part of the whole. At many times in this story the tension of the possibility—and then the experimentally validated proof—of quantum effects in organisms has seemed to take on aspects of Jessica Riskin's vitalist/brute mechanist dialectic. Yet the whole discussion takes on an intensely complicated (and somewhat mystical) cast when you consider that some quantum physicists genuinely think the big takeaway from quantum mechanics is that matter *is* consciousness.

In the introduction I speculated that with a field like molecular biology it becomes difficult to find exactly where and how baked-in ideological stances affect research programs and results. The story given here is not a complete enough picture of the course of molecular biology, or of purple bacteria research in particular, to satisfy our curiosity on a study-by-study scale. But from a bird's-eye view, there is sufficient evidence to claim, at the very least, that discipline-level stances—like the false dilemma of mechanism outlined by Riskin—are identifiable even in the hardest of sciences. The hyper-specialization of disciplines in the sciences may well be

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[66] Scholes, "Quantum-coherent electronic energy transfer," 6.

to blame for this. It's possible that molecular biology going forward—perhaps with quantum biology as the first bridge—will begin to look more like applied quantum physics and less like atomized biology.

In a work published in translation in 1945, the influential geochemist Vladimir Vernadsky proclaimed, "The twentieth century is the century of scientific atomism."[67] One could say, after examining the history of quantum biology, that the self-isolation of the various disciplines left significant research gaps, quantum effects in vital activity being a central one. What exactly contributed to that atomism, and how it was characterized and defended by successive generations of biologists, was only loosely sketched here. The 21st century, so far, seems to be a period of scientific holism, with a resurgence of interest in the cross-pollinatory possibilities of physics and biology, biology and geology, and so on. It is possible that the resurgence of quantum hypotheses in biology in the late 1990s had something to do with the growing industrial imperatives and enthusiasms of scientific collaboration and holism, as with the *MIT Technology Review*'s "quantum photosynthetic computers." When I consider such an explanation, however, I become deeply skeptical of scientific holism—perhaps it is just as disagreeable in the 21st century as atomism was in the 20th. It remains to be seen whether the biases and "dialectics" of biology will be subsumed under or negated by a quantum biology; or, alternatively, that scientists determine that biology is best left in its "classical" state. Future developments rest at least in part on a dimension that has emerged subtly through my own historical analysis: what are the political stakes of disciplinary holism in the modern study of organisms?

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67 W. I. Vernadsky, "The biosphere and the noösphere," *American Scientist* 33 (1945): 6.