

Quantum Biological Phenomena The European robin is a familiar and curious songbird. Attendant to tilling gardeners uncovering the insects or seeds on which it feeds, it perches on its twig-like legs with inquisitive attention. It has a distinctive red breast and face under a hooded cloak of brown and grey feathers and a lighter belly, with a small, rounded head and body and dark brown eyes. (The eyes of the robin, as we will see, hold surprises.)

The robin's range is vast, spilling over all of Europe into North Africa, Western Siberia, and West Asia north of the Arabian Peninsula. Not every robin migrates: many are resident year-round in the west and south. But those that do migrate fly vast distances over the width of their east-west or north-south range, including over large seas: the Black, Caspian, and even the Mediterranean. Although robins are primarily diurnal, many of them migrate at night. How do they manage this spectacular feat?

It appears that robins use a variety of abilities to migrate successfully, some innate and some learned, such as the memory of geography. The former include the compass-like ability to reckon by the position of the sun at sunset, the orientation of the stars, and—surprisingly—the Earth's magnetic field. (Patterns of these orientations in migration are part of what is committed to memory.) There are a variety of experiments testing this; describing one will suffice to indicate the kind of evidence collected for this extraordinary ability [1].

In this experiment, robins are captured temporarily during their migration season.i During this time, they have a “migratory restlessness”—an instinctive urge to migrate. Each such robin is placed in a large, enclosed space, like a barn, that shields it from the other cues, visual or otherwise, besides magnetic fields that might mediate their behavior, on average. Inside this barn, the robin is placed in a specialized cage called an Emlen funnel [2]. The funnel is shaped like a blunted, inverted cone, with the bird initially on the blunted end of the cone on the ground. As the bird hops or jumps in a direction to fly, its direction is noted.ii The distribution of marks—towards a cardinal direction, or more evenly distributed—indicates the mean of the bird's migratory tendencies.

This general setup allows experimenters to manipulate external conditions that might affect the bird's migratory navigation. In the case in hand, the Emlen funnel is placed inside different magnetic environments—either at different locations on Earth with this property, or by generating an external magnetic to override the natural one from the Earth. The mean directional tendency of a migratory bird is at a certain angle to the inclination of the magnetic field to the horizon. This tendency does not depend on the direction of the field lines—whether they are going into the Earth's surface or out of it. Moreover, if the magnetic field lines are roughly parallel to the horizon—as happens at the Earth's magnetic equator—or eliminated altogether, the birds show no tendency to orient in any cardinal direction.

This *avian magnetoreception* is surprising in at least two ways. The first surprise is that, unlike the positions of the sun and stars, the magnetic field of the Earth is not a prototypically visual stimulus. Eyes and photoreceptors more generally do not seem to be designed to have sensitivity to magnetic variation. Thus, unlike (say) vision, this magnetoreception is a seemingly unusual and atypical perceptual sensitivity. The second surprise is that the magnetic field of the Earth is very weak (about 0.5 Gauss), less than 1% of that of a typical refrigerator magnetic. The inorganic effects of magnetism—magnetic forces—seem to require stronger fields to make a difference to the motion of a bird, even one as light as a robin (weighing less than an ounce).

Thus, the answer to the original question—How do robins migrate successfully?—has begotten further questions: How do they sense magnetic fields? And how do they sense such weak ones? Importantly, these questions arise not as generalizations of or from issues tangential to the original question. It's not the case that the original question has been completely satisfactorily answered, and these questions arise through merely related issues. Rather, the answer to the original question does not sufficiently mitigate the surprise or unexpectedness of the phenomenon—migration—to be explained. The answer—avian magnetoreception—is not much less surprising or unexpected than the phenomenon itself. So even if this answer is correct, it is not yet itself satisfactory as an explanation. A satisfactory explanation along these lines would require answering the above further questions so that the phenomena to be explained is substantially more expected.

The first further question—How do robins sense magnetic fields?—may be divided into two: (i) What physical mechanism within robins is sensitive to magnetic fields?; and (ii) How does that sensitivity transmit to a

robin’s central nervous system? Quantum theory enters into an answer to (i) via the *radical pair mechanism* [3]. In chemistry, a “radical” is an atom, molecule, or ion with at least one unpaired valence electron; hence radicals tends to be chemically reactive. Radicals are often generated through absorption of light. A “radical pair” is a typically short-lived reaction intermediate consisting of two such radicals, with the *spins* of at least one unpaired valence electron from each *entangled*. To explain: According to quantum mechanics, electrons have an intrinsic, discrete angular momentum called “spin”, which relative to any direction can be in one of two basic states: up and down. (Think of these like the two directions of rotation of a top: counterclockwise and clockwise.) These basic states can be combined (put into *superposition*), like musical tones, and correlated (entangled). For two electrons, one of their correlated (entangled) basic states is called the singlet state: it has a lower total angular momentum than the other three basic states, called triplet states. Quantum mechanics predicts that these states change over time, in a phenomenon called spin precession: singlet states can transform into triplet states, and back. The rate at which this oscillatory process occurs is sensitive—sometimes highly—to the magnitude and orientation of an external magnetic field to the spin direction (axis), even for fields as weak as that of the Earth.iii

Although there are many candidate molecules for radical pair mechanisms in birds, not any will do: the mechanism must be sensitive to the magnitude of the Earth’s magnetic fields, the kind of light in the bird’s environment, and be in a place receptive to that light. The best candidate for this is cryptochrome-4a (Cry4a), a flavoprotein located in the rod cells of the bird’s retina. Cry4a contains flavin adenine dinucleotide (FAD) and tryptophan amino acid (Trp), and upon absorbing a photon of blue light, FAD becomes a radical pair with Trp, the latter donating an electron to the former. Cry4a tends to be oriented in a certain direction with respect to the expected horizon in the rod cells of the retina, so on average its radical pair’s oscillation between singlet and triplet states will depend on the orientation of the Earth’s magnetic field relative to the bird’s retina. The next key observation is that Cry4a containing a radical pair may undergo a transition to what is understood as a signaling state, with the electron donated to FAD returning to Trp, and then back to its initial non-radical-pair and un-signaling state. The probability of this transition is higher for the triplet state than the singlet state, so if the ambient magnetic field orientation of the Earth affects the proportion of time spent in a triplet state over biochemically relevant timescales, as it seems it does, then the rate of signaling is affected by this magnetic field.iv Because spin and entanglement are characteristically quantum mechanical properties, so too is this explanation to (i).

The answer to (ii), though not fully understood, is likely less unusual: because of Cry4a’s concentration in the rod cells, the signaling state likely affects the intensity of the visual signal that they transmit through the retinal nerve to the bird’s brain. Because the rod cells are sensitive to overall light intensity and play a role in night vision, rather than color contrast, the bird may literally “see” varying intensities of ambient light depending on its head orientation with respect to the magnetic poles.

Some Extant Accounts Avian magnetoreception is perhaps *the* prototypical topic of quantum biology. So, correctly answering “what is quantum biology?” is substantively descriptive: all else being equal, an answer to it is good to the extent that it captures phenomena that biologists (and physicists) take to fall within the remit of quantum biology, such as avian magnetoreception. But it has a normative component as well. Whether some phenomenon should fall within quantum biology bears on the size and scope of this research area, impacting its perceived legitimacy and its prospects for receiving funding [4]. Quantum biology proponents might tend to expand the field’s remit, while skeptics, to shrink it. But without a common understanding or framework within which to evaluate a phenomenon’s place within or without quantum biology, proponents and skeptics are liable to unproductive misunderstandings.

Classical Inadequacy

Some researchers define the phenomena of quantum biology comparatively, in reference to the relative success of the application of pre-quantum and quantum physics. For instance, according to Marais et al [5], “Quantum biology is the application of quantum theory to aspects of biology for which classical physics fails to give an accurate description [and explanation].” The implicit assumption is that the quantum description is adequately accurate. So, quantum biology includes just those biological phenomena for which quantum physics provides a more accurate description and better explanation than classical physics.

There is some initial plausibility to this view in the case of avian magnetoreception, if it is framed in terms of, say, the apparent inadequacy of explanations in terms of ferromagnetic materials. The latter attempt to describe magnetoreception in terms of some model with a classical magnetic compass, but apparently do not accurately fit the experimental evidence.

However, a bit more scrutiny reveals that the definition is too narrow. The main issue is the requirement that there be some attempt to apply classical physics at all to explain a biological phenomenon, much less explore or exhaust possible classical explanations. The status of the radical pair mechanism as a (possible) quantum biological explanation of avian magnetoreception, for instance, is not contingent on the elaboration and demonstrated failure of all or even some explanations in terms of ferromagnetic materials. To be sure, that elaboration and failure may give added confidence to the radical pair explanation; but it is not necessary for the radical pair proposal to fall within the remit of quantum biology.

Part of my diagnosis of the inadequacy of this kind of account of quantum biology is that it arises from a too physics-oriented perspective on this interdisciplinary field. Within physics, it is natural to read “quantum X”, where X is some physical subject matter (e.g., mechanics or electrodynamics), as the quantum version of a pre-quantum (classical) theory of X. The need for such a theory usually arises because of the descriptive or explanatory inadequacy of the classical theory in certain cases. But there is no classical physical theory of biology, simply because physics and biology have distinct explanatory and descriptive concerns. Quantum biology rather involves the synthesis of physical and biological concepts and theories, not the replacement of a “classical” biological theory with a quantum one.

Non-trivial Quantum Effects

In grappling with the purview of quantum biology, Al-Khalili and McFadden [6] asked: “isn’t everything, including us and other living creatures, just physics when you really get down to the fundamentals? This is indeed the argument of many scientists who accept that quantum mechanics must, at a deep level, be involved in biology; but they insist that its role is trivial.” Here, “trivial” describes the kinds of application of quantum theory that should be excluded from the remit of quantum biology. They thereby allude to one of the more influential descriptions of quantum biology, which attempts to shrink its domain to the non-trivial quantum effects. The challenge is providing an adequate characterization of this distinction.

Actually, calling it an influential *description* is a bit misleading: one articulation of it was in fact part of a prompt for a debate held on May 28th, 2004, at the Second International Symposium on Fluctuations and Noise: “Quantum effects in biology: trivial or not?” The moderator, physicist Julio Gea-Banacloche, explained [7]: “The other thing—that I am probably responsible for—is the final wording of the question: putting the word ‘trivial’ in there. What I am personally expecting to get from this [is for] the No Team to try to provide some surprising facts, things that we would not have expected.” I shall return to this characterization, in terms of surprise, in the next section. It suffices to say here that the debaters did not explicitly take up this definition, and indeed, the characterization of “non-trivial” remained an occasionally recurring issue in the debate.

An alternative, albeit implicit conception of non-trivial quantum phenomena in the debate defines it in terms of the presence of certain characteristically quantum phenomena. We find an explicit list of such candidate phenomena in Davies [8], who was one of the debaters:

- superpositions and various aspects of quantum phases, such as resonances;
- entanglement;
- tunneling;
- aspects of environmental interactions, such as the watchdog and inverse watchdog effects;
- abstract quantum properties such as supersymmetry.

Unlike the “Classical Inadequacy” account, this conception doesn’t describe quantum biology negatively, in terms of the deficiency of classical physics to describe and explain the phenomena with which it is concerned. Rather, it describes it positively in terms of a distinguished list of quantum phenomena that must be involved.

The distinguished list of quantum phenomena is both a strength and a weakness of this conception. It is a strength in that the mere application of quantum theory that just reproduces the predictions of classical

physics or standard chemistry won't count as quantum biology when applied to some biological system. It is a weakness in that it raises the question of to what extent which phenomena appear on the list is conventional, arbitrary, or contrived. Authors have not completely agreed on which phenomenon should appear on the list. What should appear implicates the subtle and difficult question of what "truly" quantum phenomena consist in.

But let's suppose, for the sake of argument, that this problem is resolved: agreement is formed on the correct list, which includes at least the most common item on such lists: quantum entanglement. There is still another problem. Even this conception of quantum biology is too broad. Consider the problem of the stability of matter, of chemical species: if their constituents are substantially charged particles—proton in the nucleus and electrons orbiting them—then why don't they collapse into neutral dense particles? Why don't cats, birds, and bacteria immediately dissolve in a poof, composed as they are of this matter? It takes quantum theory, including the theory of spin and entanglement, to tell the story of how electrons, otherwise undisturbed, remain peacefully in the ground state of an atomic or molecular system, including an organic one [9]. But no one considers the stability of (organic) matter to be a phenomenon of quantum biology. Indeed, as McFadden and Al-Khalili [10] write in their review of the history of quantum biology, "the term 'quantum' in quantum biology does not simply mean quantization: the discretization of electron energies to account for chemical stability, reactivity, bonding and structure within living cells." Crucially, it is not just the discreteness that accounts for all these things, but the quantum statistics of electron states, including their spin and entanglement properties.

The problem with this final account, as I see it, is that non-trivial quantum phenomena, so defined, are ubiquitous across the biological and non-biological realms—so ubiquitous that there is no special explanatory problem of the stability of organic systems over inorganic ones. Because there is nothing exceptional to organic stability over stability in general, nothing more surprising about it than one would expect, it is not a phenomenon that belongs to quantum biology. A descriptively accurate account of quantum biology thus must concern itself not just with the content of its explanations, but how those explanations compare with similar phenomena. In a word, it must incorporate the understanding of a non-trivial quantum effect that Gea-Banacloche suggested above in the debate in the Canary Islands: it must also be surprising, given its subject matter.

My Account To set the context for my account, it will help to review some key features of avian magnetoreception. Behavioral studies establish strong evidence that robins sense magnetic field lines, an unusual or atypical phenomenon. Magnetoreception itself deserves explanation: what is the origin of this exceptional ability? If, by contrast, the robin's migration navigation depended purely on vision, there would be no further question to answer for migration, even if the full explanation of the workings of vision itself requires quantum theory.

In sum, there is a phenomenon described at a certain level, that has some atypical, hence unexplained, features when compared to other members of that level. By connecting the level with another (typically lower), we can provide further explanations using the resources at the other level. This is common enough that it is not too surprising. But sometimes the connection runs across multiple levels, which is more surprising and characteristic of the center of quantum biology.

It seems therefore that behind the significance of quantum biology is a leveled picture of reality. Within biology, we have concepts such as migration. Within (classical) chemistry, at a level lower, we have magnetic effects. Within quantum mechanics, we have the phenomena of coherence, entanglement, and tunneling. What is surprising, therefore, about the explanatory relevance of quantum mechanics to biology is an assumption of the leveled picture, a kind of screening off between levels. Once we condition on the details at a certain level below the level of the phenomena with which we are primarily interested, we don't expect any further explanatory gain by considering even lower-level details. Chemistry may inform us about biological phenomena regularly, in other words, but physics doesn't explain anything further. The explanations in quantum biology challenge this explanatory screening-off assumption in the leveled conception of reality.

Thus, I describe quantum biology as an interdisciplinary research field characterized by:

- phenomena at a high level (i.e., biology),

- explanation of which is improved by answering further questions at a lower level (i.e., quantum physics), because
- explanation only at a higher level does not render the phenomena unsurprising (or is otherwise unsatisfactory).

An advantage of this account is that it has the means to place phenomena more towards the center or the periphery of quantum biology, depending on the degree of improvement of the explanation and the reduced surprise that the explanation renders.

An objection to involving the notion of surprise entering my account is that it is subjective or opaque. As Howard Wiseman lamented to Gea-Banacloche in the debate in the Canary Islands: “that what physicists like Julio and many of us here are surprised or interested by here are notoriously obscure”. I admit that surprise is cognitively variable, but here I think it is a proxy for informativeness. In other words, it’s not so much the affect of surprise which must be invoked here as the unexpectedness that it attends. That expectation is conditioned by a scientific community’s agreement on the current state of evidence and theory. That agreement is not perfect, and so the informativeness of surprise will not be perfectly uniform; but the extent to which a community does agree, it will determine the surprisingness, in this sense, of the phenomena in question: what count as non-trivial quantum effects for biological phenomena.

Conclusions I take my account of what quantum biology is to have several advantages. It is descriptively accurate, accommodating avian magnetoreception while excluding the generic stability of matter. Moreover, it articulates a sense in which some phenomena are more central to quantum biology than others, in that they are connected more surprisingly by deeper explanatory connections across levels. In doing so, it has a normative edge that one can apply to categorize potential phenomena as being towards the core, periphery, or outside quantum biology. And it reveals the underlying commitment to a leveled reality on which all these distinctions rest.

In discarding the explanatory screening-off assumption in the leveled conception of reality, quantum biology implicitly challenges certain forms of the epistemological unity of science, while supporting others [11]. Roughly, the former assumes that science, despite being divided into levels, is unified by reductive relationships between the levels: a good theory of a given level is reducible to a good theory of the level immediately below, encompassing and explaining all its successful features. (Indeed, this view of the unity of science may be for many the basis of the screening-off assumption.) That an explanation at a certain level can be improved by including theory from an even more basic level shows that the level immediately below the certain level cannot with complete success reduce the level above it.

However, quantum biology supports other conceptions of the unity of science that emphasize instead unity as theoretical dependence and connection [12], albeit ones that preserve the hierarchical, leveled structure by allowing these connections to be asymmetric. By contrast, many views on the unity of science that emphasize dependence and connection in fact stress *interdependence* and *interconnection* [13]—i.e., symmetric connection only. In a rush to disavow a too simplistic, austere picture of the relations between levels, these views of interconnection may themselves lose sight of ways in which dependence and connection can sometimes be in one direction only, as they are in the eyes of the robin.