In Context

A Publication of **The Nature Institute**

#51

Spring 2024

Dear Readers,

At The Nature Institute we have always had two complementary and often intertwined ways of working. One can be seen in our deep commitment to giving concerted attention to natural phenomena. Through phenomenological studies we hope to articulate and bring awareness to the living qualities we can discover everywhere around us. This practice is a central feature of our courses and workshops, and it drives many research projects. During a fellowship at the institute last spring, Ceinwen Smith carried out a careful and engaging study of the coming-to-color and form in some of our native trees. Her article in this issue (p. 5) lets you participate in her process and insights.

Complementing this engagement with the living world is our way of examining contemporary research in biology. Here we are not directly observing the natural world. Rather, we are studying researchers' findings and their conceptual frameworks. We want to take seriously and see what the wealth of often highly technical research into the minutiae of living organisms can show us. This frequently involves the not-so-easy task of distinguishing between the findings and the assumptions or interpretations of the researchers. We often find ourselves holding at bay the conceptual biases in order to let the findings speak in more living ways. This has long been the focus of Stephen Talbott's work. In his feature article in this issue (p.17), he describes two areas of research in molecular biology that show the remarkable — and hardly fathomable — flexibility and coordination of micro-activities that facilitate the healthy and responsive existence of an organism as a whole. His central question is: How can we adequately conceive of the wisdom-at-work in living beings, a wisdom that reaches into the depth of its physiological processes?

In this spirit, Ryan Shea reviews a book in this issue, *Properties of Life: Toward a Theory of Organismic Biology* (2023) by Bernd Rosslenbroich (p.3), that wants to show how the findings of modern biology can lead to a more holistic and organismic view of life that transcends prevailing mechanistic frameworks.

Our current research project concerned with the question of "Intelligence in Nature" weaves together direct observation of natural phenomena with critical consideration of the anthropomorphic conceptions that often frame the discussion of plant intelligence in current scientific literature. The feature article by Jon McAlice and myself (p.11) introduces the topic and how we are approaching it. In this project we spend many hours both observing plants and discussing articles on plant intelligence in our weekly research meetings. We have become increasingly aware of how important it is to be conscious of one's own perspectives and to realize what a given perspective can illuminate and what its limitations are. This helps us to heighten conscious flexibility in thought so that we are more able to practice what Goethe called "delicate empiricism." Greater mobility of mind can allow the qualities of plants or other beings to reveal themselves in ways that we might otherwise overlook.

Craig Holdrege

Craig Holdrege

The Nature Institute

In Context

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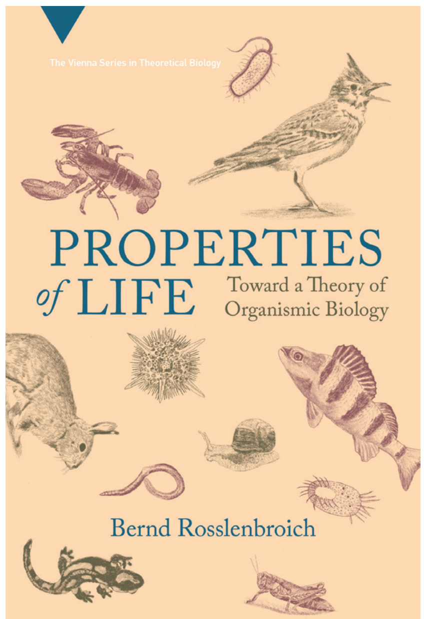
Notes and Reviews

Organisms and the Phenomena of Life

Ryan Shea

A Review of Properties of Life: Toward a Theory of Organismic Biology (2023), *by Bernd Rosslenbroich; MIT Press Vienna Series in Theoretical Biology, $60 paperback; free PDF on MIT Direct)*



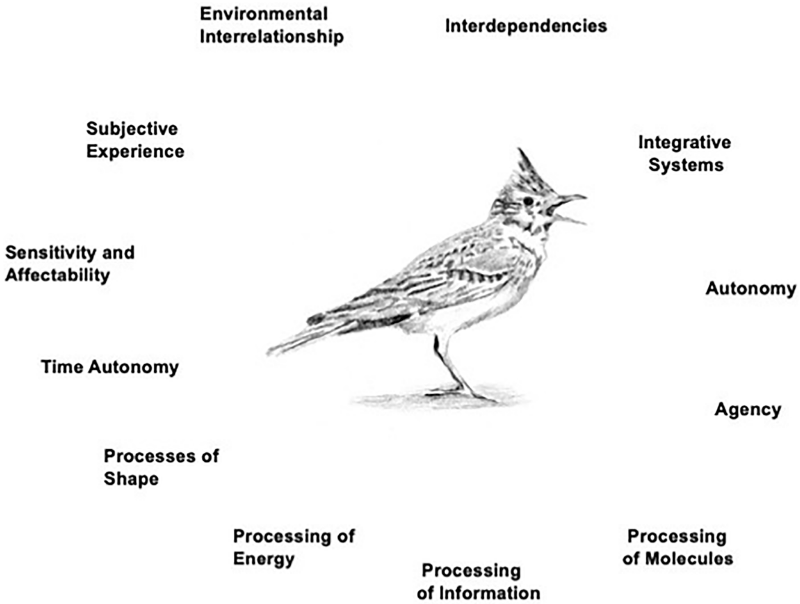
While walking down a crowded city street, most of us would intuitively recognize that the blue jay squawking, the linden tree rustling, the mosquito buzzing, the grass growing, and the humans bustling are all alive, whereas the cars, the gravel stones in driveways, the buildings, and the clouds overhead are not. Distinguishing between living and non-living is for us easy, direct, and all but completely automatic. When, however, we turn away from our intuitive recognition of life towards a reflective attempt to define life, we then run into seemingly insuperable problems. In order to define life, we need to create a chasm that would separate the organic from the inorganic by isolating the essence of life, or at least by providing a list of characteristics that everything with life has and which are all absent from every non-living being.

After a couple thousand years, and hundreds of proposed definitions and lists, there is not yet any consensus. If we cannot define life, then how could we possibly study it? How could we have a *logos* (account/understanding) of bio*logy* if we cannot agree on what life *(bios)* is? Perhaps the problem is even deeper. Many scientists and philosophers would argue that the reason for our failure to define life is, to be blunt, because there is no such thing. For these thinkers, there are only physical and chemical substances, processes, and causes. At the end of the day, there really is no distinction between blue jays and cars, linden trees and gravel stones.

Bernd Rosslenbroich, in his new book *Properties of Life: Toward a Theory of Organismic Biology*, proposes a different and more fruitful approach. Instead of worrying over pinning down the essence of life, or boxing it up with a definition, why not simply make a list of those striking and mysterious phenomena that all biologists encounter in their work? Rosslenbroich acknowledges that many, if not most, contemporary biologists would advocate some form of mechanistic reductionism. Yet, he shows that in their actual empirical research, they keep coming back over and over again to characteristics of life that seem widespread and are not able to be reduced down to exclusively physico-chemical causes. Rosslenbroich's overall method in the book is thus quite similar to much of Stephen Talbott's writing. Both go into great depth and detail to show that the empirical findings of modern biology are almost always more qualitative, holistic, and organism-centered than the theoretical assumptions of modern biology allow.

The longest and best part of the text is "Chapter 4: Properties of Life," where he spends a great deal of time describing fifteen characteristics — for example, autonomy, agency, morphodynamics, subjective experience, evolvability, and reproduction — that are admitted by all modern biologists, yet which resist standard explanations.

Let us take, for example, the first property he considers, which he calls "Interdependencies." He reminds us of something we probably recall from high school biology, yet most likely did not give a second thought. A good deal of the processes that modern biologists have discovered, and now take for granted, are actually cycles, e.g., the citric acid cycle (the Krebs cycle). Here we have quite a profound mystery. For a cycle cannot be understood by linear causality, like a series of dominoes. The end result and final effect is also



Some features of an adult bird that can be studied. *Source:* Drawing courtesy of Angela Rosslenbroich

the first cause of the next cycle, which means we must start thinking in circles and "circular causality" rather than straight lines. Indeed, we need a whole new and ever-expanding taxonomy to chart the different forms of interdependencies. Rosslenbroich lays out a few to start us off: linear causation, multiple effects, multiple causality, circular causation, networks, trigger causality, constraints, and regulatory/cybernetic systems. But the citric acid cycle is just a drop in the ocean of all the indefinitely complex interweaving and interdependent processes involved in almost any biological activity such as, for example, eating and digesting your lunch. The book spends twenty pages going through all these minutiae of "Interdependencies." All of that for just the first of the fifteen characteristics he investigates.

Rosslenbroich emphasizes that his book is meant only as a beginning (the subtitle is *Toward a Theory of Organismic Biology*) and by no means pretends to offer a final theory of life. The fifteen properties themselves are just suggestions and meant to initiate interest in other researchers to develop a new organismic way of approaching biology. In 2016, he published a paper that is an early summary version of the book wherein he lists only ten characteristics. Ten, fifteen, twelve, or twenty does not matter — Rosslenbroich wants us to leave aside bickering about lists and definitions. Instead, start by making your own list of vital phenomena and then get to work trying to gain a more living understanding of them.

The author stresses throughout that when we take an unbiased phenomenological approach to these characteristics, we find ourselves required to develop better ideas and more holistic ways of speaking. He develops, for example, a notion of "concurrency" in an attempt to forge a new organismic vocabulary that moves away from reductive notions of causality and simplistic notions of complexity. I found this notion of concurrency to be powerful and highly suggestive.

The book is primarily addressed to those who work in modern academia and mainstream science. Its style of writing and method of argument reflect its intended audience, for its goal is to show that the empirical findings of modern biology themselves demand that we rethink its conceptual foundations. Those who are not working in academia or mainstream science may find a good deal of the book to be hard going. Rosslenbroich also makes clear in the final chapter that the book, as a whole, is but a first foray into an organismal biology that he hopes will become more prominent in the future. His book ends where Craig Holdrege's whole organism studies begin.

T.S. Eliot once asked, "Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?" Contemporary biology is inundated with beautiful and wonderful experimental findings. Often, it is drowning in a deluge of information. What is needed, perhaps now more than ever, is what Rosslenbroich, following Conrad Hal Waddington, calls "biological wisdom" (p. 276). Only through returning to such wisdom might we have any hope for a future biology that is vitalized by living thinking and a future bio-technology that does not merely manipulate life, but seeks regeneration and increased fecundity. For those hoping to contribute to this work by participating in mainstream academic biology, Rosslenbroich's book will prove a valuable reference manual and a portal through which they might make some first steps.

Springing into Color

Ceinwen Smith

Ceinwen Smith is a biologist from South Africa who completed our Foundation Course in Goethean Science in July 2022. She returned to The Nature Institute in 2023 for a research project and this essay describes some of her experience.

The invitation to pay attention to color opens a window, brings a particular lens into focus and shapes the way an object, a process, or a landscape is experienced and thus how it is perceived.

I have often wondered what it would be like to experience the world without color. What details would be seen and what would remain unseen? Observing the transition into spring and early summer may give some insight into the experience of how color has this ability to reveal, and to conceal, aspects of what is being observed. Here I share an account of my observations and explorations of the emergence of spring colors in maple and oak trees, which formed part of a recent three-month research fellowship at The Nature Institute.

In early spring, I arrived in a landscape I thought I knew and yet felt I was seeing it for the first time. Stripped of color and lacking contrast in the overcast light, the wooded hillsides held a quiet permeability, allowing my gaze an unobstructed view through clusters of gray trunks and interwoven branches that extended deep into the forest. My experience of distance across the landscape, between objects within the landscape and my proximity to them felt stretched and distorted in this canvas of gray and muted tones. I felt unsettled and restless, my eyes hungrily scanning for signs of color. While shape, form, and subtle movement were more visible, more striking in this muted forest landscape, individual trees appeared indistinguishable from each other.

My other senses, searching for familiar stimuli in the quiet and cold, felt deafened by the crunch of dry leaves underfoot, and burned by the crisp air in my nostrils. Not much moved in the cold, though the few birds I noticed appeared to share my sensory unease — noisily flitting about, appearing restless and hesitant to linger.

Light, Color, and Change

While the physical effect of a leafless landscape gives one greater viewing access to the forest, there is a distinct quality of light at this time of year which both enhances and subdues aspects of this stark, gray-toned canvas.

Light is a curious phenomenon, ungraspable, ever changing, color-creating, and essential for our experience of perception. Perhaps we may grasp something of the nature of light through studying the behavior and expression of colors. But it is not merely this outward expression that we must see and pay attention to. Our inner light, the very activity of our thinking, is necessary for, and actively shapes, our perception.

The diffuse light of a cloudy day flattens the definition of a landscape, which appears shadowless and monotone. In the early morning and at dusk when the sun's golden light radiates out beneath the thick blanket of cloud, for a fleeting moment the landscape is illuminated and our experience of it transformed. One evening in early spring while walking up to The Nature Institute, I lifted my gaze from the rutted track and was struck by the most vibrant hues of magenta buds glowing like scattered embers emerging from the ashen forest across the hillside. My searching eyes (my spotlight) so expectant for the green of spring, had previously missed this explosion of warmth! Over the following days, I began to notice many more trees flushing with varying shades of scarlet, amber and coral, the subtle differences appearing stronger in bright illumination than in muted light. This first flush of color is the work of the red maple. With its winter store of sugary sap rising to the crown, the red maple brings forth not leaves but a burst of flowering warmth to meet the growing light and warmer temperatures of spring.

With the days gradually getting longer and continuing to warm, new colors emerged in the landscape. The red maple flowers on different trees became more distinct, introducing peach, orange, and yellow hues to the canvas, as the flowers opened and revealed their difference in floral parts. The red maple has flowers that are either seed-bearing or pollen-bearing, and these usually appear separately on individual trees, but not always. The seed-bearing flowers tend to keep their deep scarlet and amber hues as their stalks extend, hung with dangling winged fruits. In contrast, the pollen-bearing flowers quickly distinguish themselves, their mass of stamens bringing forth a wealth of yellow pollen. These pollen-bearing flowers are short-lived and begin to wither and fall from the branches while the seed-bearing flowers continue to fruit.

Red maple flowers: seed-bearing (left) and pollen-bearing

While the red maple's fiery flower show unfolds, the oaks start to awaken. Tiny gray-brown buds begin swelling, lengthening and their protective sheath of scales slowly loosen for the first wrinkled leaves to appear with curling pale-green tips and a blanket of magenta-pink filaments. Under a microscope, these appear as clusters of fine hair-like structures called trichomes that contain red pigment and are evenly spaced across the pale green leaf blades.

A closed red oak bud; first leaves; and a closeup of trichomes

The oaks bring some of the early signs of green to the forest, tinged with subtle peach hues next to the fiery red maple flowers, which soon are accompanied by the slow emergence of pale-green maple leaves. Within days the forest canopy is dusted with a soft ethereal veil of vibrant and pastel colors. Out of the uniformity of gray trunks and entangled branches the unique expression of a single tree becomes visible — individual trees are now easily identified and different species distinguished from each other. This display of color highlights the beauty and diversity of the outer landscape and, through the act of perceiving, an inner light of joy can be illuminated too.

Form, Color, and Substance

Within a month of my arrival at the institute, the forest's greening is in full force as more trees bring forth leaves and continue to grow into the space around them. Hues become stronger and the spaces between individual trees in the forest gradually fill with color and substance. At this point there is a transition in the translucent ethereal quality of the canopy of new leaves, which appear to be more color than substance. The growing leaves expand outward as the branch tips extend outward and upward; leaf forms change shape, increase in size, thickness, and density.

Images of the forest edge on April 13 (top) and May 6

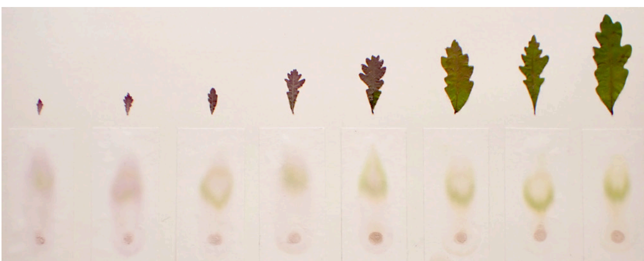
This three-fold process of form, color, and substance transformation changes our experience of the individual tree and its expression in the landscape. As the substance of the leaf grows and becomes denser, less light penetrates through the canopy and shadows form on the forest floor. The forest not only becomes darker but comes closer to any footpath as young branches, heavy with leaf growth, bow down across the path and invite us to do the same. Trees begin to lose their individuality and distinct identity. We no longer observe a tree 'treeing' but rather 'foresting.' Through this foresting, trees begin to express different qualities which emphasize the collective interaction between the forest and the elements. As a forest forms a single porous canopy, the wind moves through it as a wave in the ocean.

Throughout these processes of 'leafing,' 'treeing,' and 'foresting,' the qualities of form, color, and substance — from the leaf to the landscape — are transformed. Observing and attempting to document, to capture, this process was often overwhelming as I struggled to pay attention to the myriad changes unfolding all at once.

To add further to this colorful story, I regularly left the forest outside to delve into the very substance of the leaf through laboratory techniques, exploring the presence of pigments inside the leaf.

Color and Chromatography

The technique of paper chromatography (see 'Revealing Pigments') provided further insight into the phenomenon of color development in leaves by capturing snapshots of the pigments present within the leaf substance. I collected leaf samples from selected trees and processed them at regular intervals, providing sequences of chromatographs or 'color images' that captured the qualitative change in pigments over time.



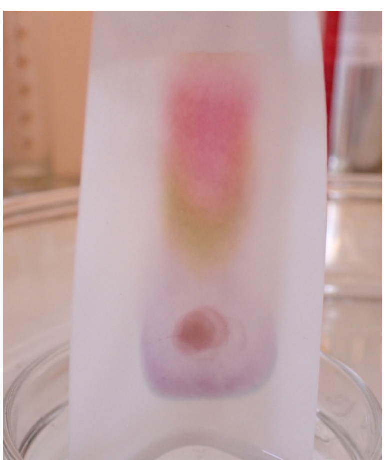
Pigment sequence over time

What became visible in these sequences further supports my external observations: the new budding leaves are dominated by red pigments (anthocyanin), while green (chlorophyll) and yellow (xanthophyll) pigments appear more subtle. As the leaves grow, the green pigments become more abundant, and the red pigments decrease (relative to the green) until they are no longer visible — which for most trees observed was roughly six weeks after the first leaves emerged.

These pigment changes within the leaf have implications for both the structural formation and the photosynthetic capacity of the leaf as it develops. Further investigations into these internal processes of emerging leaves — particularly in relation to the development of form, substance, and color expression — may provide yet another lens through which to view the phenomenon of color emergence in spring.

Continuing the Story

So where does this all lead us? In the life of a tree, this investigation attempted to explore a tiny snapshot of the phenomenon of color change in maples and oaks. As with many research endeavors, this exploration has revealed several riddles to be investigated further. These may lead to further research into the dynamics of leaf form; color and substance in the fall; red maples and their different expression of flower forms; and trichomes as an external pigment structure in oaks. And perhaps this account of color exploration will also inspire you to step out into the spring landscape and go in search of your own colorful journey.



Chromatography of leaf material

Revealing Pigments

Paper chromatography is a technique used to capture the variation and composition of pigments within organic material. Samples (of individual leaves in this case) are collected, pulverized in methanol, and five drops of the leaf mixture are then placed (allowing drying time between each drop) onto a marked point (the 'loading spot') on a 5-inch strip of chromatography paper about one inch from the bottom. The paper is then placed upright into a shallow petri-dish of solvent (a combination of petroleum ether, ethanol, and acetone), with the level of solvent just below the loading spot. A glass jar is placed over this set-up to reduce evaporation and inhalation of fumes. As the solvent moves up the paper and through the leaf material on the loading spot, it picks up the pigments. Pigments have different molecular properties and thus have different relationships with both the paper fibers and the solvent. As a result, they are carried up through the paper at different rates. In this way the method creates discrete 'color images' by drawing up and separating out the different pigments within each leaf sample. These can be placed together in a sequence to show the changes in pigmentation within the leaves of a tree over time.

News from the Institute

Events

▪ During his fellowship at the institute in late 2023, Stefan Ambrose studied the geology of our region, focusing on **clay soils in the Hudson River Valley**. Collecting samples from a variety of local eco-systems, Stefan processed each one to explore its constituent silt, sand, stone and especially its clay. He then shaped test bars with the purified clay that will next be fired at 14 temperatures ranging from 1607 °F to 2350 °F. His work seeks to reveal the unique and varying characteristics of local clay embedded in the landscape.

▪ At the end of 2023, Jon McAlice and Henrike Holdrege hosted a series of four interactive online demonstrations for the Anthroposophical Society of America. Each 75-minute live session used phenomena to address the topic of **"Engaging in Goethean Practice: From Transformation to Metamorphosis."**

▪ Henrike and Craig Holdrege taught a three-day workshop in December near São Paolo for students enrolled in **Escola Schumacher Brasil**, introducing them to Goethean practice.

▪ In February, Craig Holdrege facilitated an online colloquium for the **World Goetheanum Association**, whose aim is to provide an overview of current Goethean research and its approaches. The association also supports interdisciplinary exchange and promotes meaningful collaborations. Its current focus explores how Goetheanism can transform the challenge of our ecological crisis.

▪ We held our second **Climate Change Colloquium** at the institute on February 23-25, bringing together educators and others to explore how climate change can best be taught in school curricula for grades 7-12. The group conducted various experiments related to topics central to understanding climate and life processes.

▪ By request, this past winter Craig Holdrege gave an online presentation, "An Introduction to Goethean Phenomenology," for health professionals enrolled in a program called Whole Health at **Osvaldo Cruz German Hospital** in São Paolo.

▪ Australian poet, author, and philosopher Luke Fischer gave a public talk on February 28 at the institute, sharing **"A Poetic Vision of Nature."** His work explores how poetry and Goethean science can transform our experience and understanding of the natural world.

▪ In early March, The Nature Institute held a colloquium on the **Forms of Meaning in Living Beings,** exploring ways of connecting Goethean practices in observation and exact imagination with the insights of an alternative holistic approach called biosemiotics (bio= life, semiotics = meaning). Our staff was joined by Australian poet and philosopher Luke Fischer and English paleontologist Judyth Sassoon.

▪ Henrike Holdrege gave a slide presentation in March at the **Bombay Beach Biennale 2024** in California. Her topic, "To the Infinite and Back Again: What Can Projective Geometry Teach Us (even if we're not mathematically inclined)?", highlighted the value of projective geometry in contemporary thought and life.

▪ A cohort of 22 participants from around the world began our 15-month **Foundation Course in Goethean Science** this spring with assigned readings and online meetings.

▪ Henrike Holdrege and Marisha Plotnik recently led our 2024 **Math Alive!** professional development workshop for middle school teachers and homeschool educators. They addressed topics such as the Pentagon, Pentagram, and the Golden Mean, and created a forum for collegial exchange.

▪ Our series of **“Drawing into Nature”** workshops with artist-educator Ella Lapointe resumes this spring with six outdoor afternoon sessions from May through June. The course is designed for individuals who want to develop a regular drawing practice while appreciating the beauty, rhythms, and changes of spring and early summer.

▪ Jon McAlice has been involved with schools in America and Europe developing phenomenological approaches to collaborative leadership and curriculum development. In April, he hosted a workshop on Goethean practice at the **International Teacher Education Conference** at the Goetheanum.

▪ On April 22, Craig Holdrege gave a public talk at the institute on the wisdom of plants in honor of **Earth Day.** A recording of this talk will be shared this summer through our podcast, *In Dialogue With Nature.*

▪ At the end of May, institute educator Ryan Shea will travel to the Netherlands to present at the **Coworkers Gathering,** a week-long initiative of the Youth Section of the Goetheanum that aims to help young adults connect their university studies with anthroposophy and explore various vocations that can be fully engaging.

▪ John Gouldthorpe will offer an online exploration this spring of Thomas Fuchs’ essay, **“The Brain — A Mediating Organ,”** for those who have completed our Foundation Course.

▪ Those who have completed our Foundation Course have been invited to participate in four days of collaborative advanced study on **“Plant Observation and the Living World”** this summer. This offering is in response to requests we’ve received to further develop the practices we have introduced in our other education programs.

Recent Podcast Episodes

You can find our podcast on the institute’s website (natureinstitute.org/podcast/*in-dialogue-with-nature*) or wherever you access podcasts.

▪ Last November, Ryan Shea gave a talk at the institute on **“Living in the Present: Practices for Being In and With Nature,”** that is now available at our podcast. By working through several concrete practices, Ryan explores ways in which nature might help us develop the capacity to be fully present. His focus gives attention to the difference in lessons from plant and animal teachers.

▪ In a rare interview with Henrike and Craig Holdrege, filmed in Brazil in 2019, they speak of their transformative work and the Goethean perspective that has long inspired it. A video of the interview, **“On Goethe and His Science,”** can be found at our YouTube channel *https://youtu.be/DJFHiitAUxI* or you can listen to an audio recording of the interview at our podcast.

Staff Changes

▪ After five years of ably managing our office affairs, **Kristy King** left her position in March to work closer to home. We thank her and wish her well! Taking up responsibilities in the office, **Jill Jakimetz** joined our staff in April. She brings a background in environmental studies and experience in biodynamic farming.

From Our Mailbox

Dear Craig,

I’ve never written a message to a stranger before but after reading your “Story of an Organism: Common Milkweed” I really needed to tell you what an exceptional job I thought you did in explaining the biology of this plant. The science was complete without being overwhelming and I was so grateful for the accompanying photos. I could clearly understand what you were saying by seeing the actual plant and it’s relevant parts. I found your article while searching for an aerodynamic explanation of how milkweed seeds float and disperse. Although I wasn’t able to find anything on milkweed specifically, I did find a fascinating explanation of dandelion seed vortexes. I’m grateful to have found The Nature Institute on this trip down the “Google hole” and have added my name to your mailing list. Thank you for your thoughtful work.

— Franki Brinkman

Thank You!

We are privileged to thank all who have made donations or contributed goods or services to The Nature Institute between October 2, 2023, and March 30, 2024.

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A longtime friend of the institute, Susan Starr, passed away last year. She thoughtfully left us a bequest in her will. We are very grateful to Susan.

Are Plants Intelligent?

An Initial Exploration

Craig Holdrege and Jon McAlice

This is the first article to arise out of our research into the broader topic of "intelligence in nature." More will come in the future.

Initially, we might view plants as we see many other things in the world: as objects — each complete unto itself and separate from the things around it. When, however, we attend more closely to plants, we find an intricate array of relations in which they play an active role. Roots growing down through the soil not only take up water and minerals, but also secrete substances into the soil and change it. Plant leaves unfold into the air and grow with the help of the light. They form expansive surfaces that create shade for some of their own lower leaves, the ground, and perhaps other plants. Leaves take up carbon dioxide, give off moisture to the atmosphere and, importantly, emit the oxygen that we and animals breathe. Mycorrhizal fungal networks connect physically and physiologically different plant species with each other via their roots.

These examples point to the countless ways in which plants and what we call environment interpenetrate and mutually influence one another. The life of the plant is one of dynamic interactions. There is in this sense no separateness. Can we say where a plant ends and its environment begins?

In its life history — from seed through germination, vegetative growth, flowering, fruiting, and new seed formation — a flowering plant is in ongoing transformation. Its development is integrally woven into a specific environmental context that is also changing. This dynamic relation comes to expression in all aspects of a plant's form and physiology. A wild radish seed that comes to rest in relatively barren, compacted ground or another one at the edge of a meadow only 30 feet away find very different conditions for their development. It could be that neither germinate, but if they do and thrive, they develop in strikingly divergent ways (see image). The plant in the compacted ground grows immediately and continuously in relation to those specific conditions. It develops a few very small leaves, a short main stem, with a couple of flowers, and finally a few fruits and seeds. In contrast, the plant at the edge of the meadow displays effusive growth of branching stems, leaves, flowers, fruits, and seeds. If it weren't for the distinctness of the flower, you might not notice that the two plants belong to the same species.

An example of plant plasticity in silhouettes of six pressed specimens of the annual plant species, wild radish *(Raphanus raphinistrum)*. They grew in close proximity to each other but in different microenviroments. All were flowering at the same time. See text for further description.

The compact-ground plant goes through its whole life cycle in a way that intimately corresponds with the relations it takes up in that place. It doesn't start out with a fixed body plan that prescribes leaves or stems of this or that size or number. No, its becoming is wholly embedded and flexibly active in a specific context. Had the same seed dropped at the edge of the meadow, it would have developed in a radically different way. This is one example of the plasticity that plants reveal in all aspects of their development. The same species of plant has the possibility to be itself differently in different contexts, to subtly respond in its growth and physiology to changing conditions. Clearly, plants have remarkable capacities.

Are Plants Intelligent?

Within mainstream biology, the question of plant intelligence has become a hot — and controversial — topic during the past two decades.[1] It is, however, not a new question. In his 1908 address as President of the British Association for the Advancement of Science, Francis Darwin, Charles Darwin's son, made the statement: "We must believe that in plants there exists a faint copy of what we call consciousness in ourselves" (Darwin, F. 1908). The notice of his address that appeared on the front page of the New York Times (Sept. 3, 1908) bore the title "Plants as Animals" and stated: "Few more imaginative and more original speeches have been delivered from the Presidential chair than his, though the scientific audience shook their heads." Francis Darwin's thoughts sparked a controversy that spanned the Atlantic and led to a flurry of articles. The notion that plants could express anything resembling even the most primal aspects of human consciousness or animal nature was inconceivable for those who worked closely with plants. On September 4, 1908, the day after the initial notice of Darwin's address, an article appeared on page 6 of the Times with the headline "Scoffs at Theory that Plants Think." The article quotes at length Dr. W. Alphonso Murrill, assistant director at the New York Botanical Gardens. He says: "When a true plant performs actions that might seem to imply intelligence and a nervous system, I am inclined to suppose that they have developed powers peculiar to plants and quite distinct from the faculties of animals, even though their results appear similar."

Murrill and his colleagues at the time were convinced that assigning animal or human capacities to plants was "unscientific." Plant physiology and morphology is fundamentally different from that of animals. In phenomenological terms, we could say that plants are in the world differently than animals. Defining plant existence in terms of animal behavior or human consciousness was, from their scientific perspective, untenable.

Francis Darwin was drawing from the extensive experimental work he carried out as a young man with his father, which culminated in the 1880 book by Charles Darwin, *The Power of Movement in Plants*. Without using the term "intelligence," Darwin ends the book with an enthusiastic and vivid tribute to the remarkable capacities of the tip of the primary root ("radicle") in plants and ends by analogizing the root tip with the brain of a "lower animal" (see box with his description).

Through much of the 20th century, the topic of plant intelligence lay dormant. It became, in a sense, forbidden territory as mechanistic explanations for all biological phenomena became ever more dominant. In recent years, a number of researchers have returned to the question "Are plants intelligent?", answering it in the affirmative. They often cite the authority of Charles Darwin, referring back to his work with plant movement. And like the Darwins, they claim to have identified aspects of plant existence that resemble human intelligence. When you read the books and articles that argue for acknowledging plant intelligence, you see that one major motivator is the desire to raise the status of plants in the eyes of fellow biologists and the general public. They feel that the remarkable capacities of plants have been overlooked or not valued enough. We entirely agree.

Plants, Human Intelligence, and Survival Value

Current plant intelligence researchers lean toward using the way humans experience their own intelligence as the touchstone for their conclusions. This leads them to hypothesize plant modes of perception and representation and conclude that plants "make decisions," "remember," "learn," and "communicate." They are "able to receive signals from their environment, process the information, and devise solutions adaptive to their own survival" (Mancuso and Viola 2015, p. 5). A recent article provides a good sense of how plant intelligence is viewed:

> Plants have developed complex molecular networks that allow them to remember, choose, and make decisions depending on the stress stimulus, although they lack a nervous system. Being sessile, plants can exploit these networks to optimize their resources cost-effectively and maximize their fitness in response to multiple environmental stresses…. In this opinion article, we present concepts and perspectives regarding the capabilities of plants to sense, perceive, remember, re-elaborate, respond, and to some extent transmit to their progeny information to adapt more efficiently to climate change. (Gallusci et al. 2023)

Anthony Trewavas, one of the leading advocates for plant intelligence, writes of seed germination: "The skill in environmental interpretation, that is learning, determines which seeds will most accurately assess the time of germination and environmental conditions for the young plant. These are clearly the most intelligent" (Trewavas 2017).

Trewavas' approach here is to start from our own self-conscious human intelligence. We can think through

1. See references for a small selection of publications from the scientific literature, both pro and contra. There are also many popular articles and books that have brought topic into broader societal awareness, among them Peter Wohlleben's *The Hidden Life of Trees* (2017), and Suzanne Simard's *Finding the Mother Tree* (2021), both international bestsellers.

what he is proposing in his kind of terms — vividly and literally. Seeds fall onto the earth. Wind and rain, passing animals, or falling leaves cover the seeds and they sink into the soil. They lie there waiting, collecting information and interpreting it in order to determine when they should break dormancy. Each seed is doing this on its own, informed by the strategy that the right decision will bring forth a plant that will survive. Imagine it even more concretely. One calendula plant can produce hundreds of seeds by the end of the growing season. These fall to the soil beneath the plant. They will be rained on, dry out, be subjected to freezing temperatures, be covered with snow, and exposed once more to the sun and the rain. Some will have been eaten by birds or rodents; some may have been penetrated by worms; some rot. In the spring, a small percentage of those that remain will germinate. They have laid there analyzing data and, secretly competing with one another, they wait for the perfect moment to begin to sprout. According to Trewavas, some of the seeds are more intelligent than others. The more intelligent seeds will have interpreted the data more accurately, made better decisions, and are thereby more likely to survive.

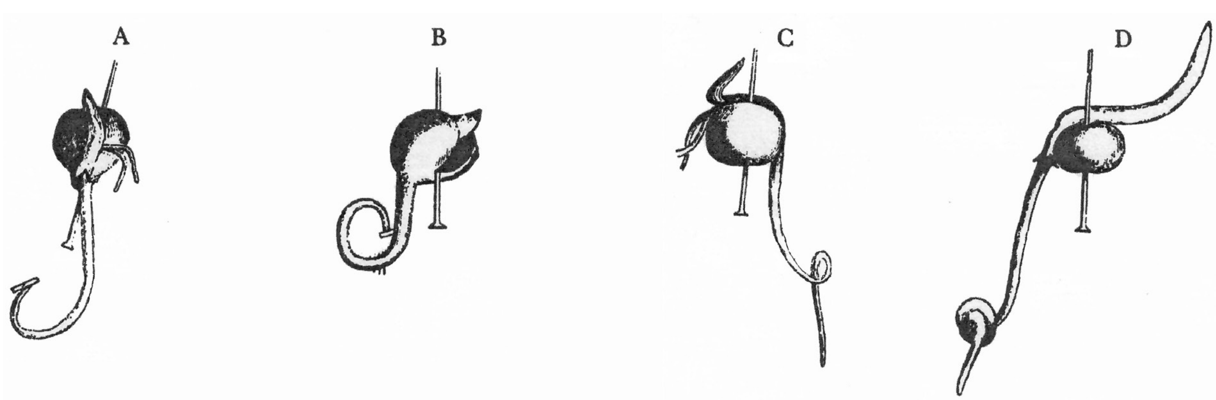
For both mainstream science and contemporary plant intelligence researchers, the ultimate ground for intelligence is survival. Here is a formulation in an article in the journal *Annals of Botany*:

> The inbuilt driving forces of individual survival and thence to reproduction are fundamental to life of all kinds. In these unpredictable and varying circumstances the aim of intelligence in all individuals is to modify behaviour to improve the probability of survival. (Calvo et al. 2019)

The emphasis on individual survival in biology goes back

Charles Darwin on the capacities of the root tip:

We believe that there is no structure in plants more wonderful, as far as its functions are concerned, than the tip of the radicle [primary root]. If the tip be lightly pressed or burnt or cut, it transmits an influence to the upper adjoining part, causing it to bend away from the affected side; and, what is more surprising, the tip can distinguish between a slightly harder and softer object, by which it is simultaneously pressed on opposite sides. If, however, the radicle is pressed by a similar object a little above the tip, the pressed part does not transmit any influence to the more distant parts, but bends abruptly towards the object. If the tip perceives the air to be moister on one side than on the other, it likewise transmits an influence to the upper adjoining part, which bends towards the source of moisture. When the tip is excited by light (though in the case of radicles this was ascertained in only a single instance) the adjoining part bends from the light; but when excited by gravitation the same part bends towards the centre of gravity… The course pursued by the radicle in penetrating the ground must be determined by the tip; hence it has acquired such diverse kinds of sensitiveness. It is hardly an exaggeration to say that the tip of the radicle thus endowed, and having the power of directing the movements of the adjoining parts, acts like the brain of one of the lower animals; the brain being seated within the anterior end of the body, receiving impressions from the sense-organs, and directing the several movements. (Darwin 1880)

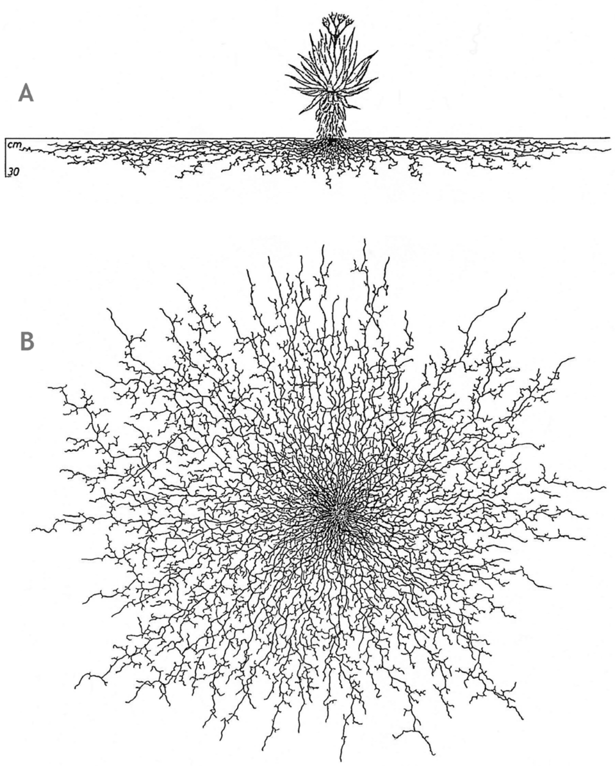


This figure from *The Power of Movement in Plants* by Darwin illustrates how roots curve away from an impediment. In this case the impediment is a little card attached to the side of root tips of corn *(Zea mays)*. Darwin carried out many experiments of this kind.

to Charles Darwin, whose highly influential theory of evolution has as its central notion the idea that individual variants of a species compete with each other in the context of a hostile environment. This struggle for existence leads to "survival of the fittest" (a phrase coined in 1864 by Herbert Spencer). What's puzzling about Darwin is that, in one way, he is clearly aware that when he uses phrases such as struggle or competition he is speaking metaphorically or perhaps even improperly:

> A plant on the edge of a desert is said to struggle for life against the drought, though more properly it should be said to be dependent upon the moisture. (Darwin 1859/1979, p. 116)

He was conscious of the different connotations of these two ways of phrasing the same phenomenon. When you say "the plant is dependent upon moisture," you disclose a vital relationship between plants and their environment. Struggling for life, by contrast, implies an agent who stands over and against the world and is confronting something that is for it a problem. Drought is a problem for a plant. Yet although Darwin admits that the notion of struggle in this context is less adequate, less "proper," his thinking was dominated by the notion of "us against them" — the struggle of entities against each other. This way of conceptualizing and expressing relations was widespread in the social and economic thinking of Darwin's time. Darwin found in the ideas of competition, struggle, and the survival of the "most favored" the theoretical framework that enabled him to bring his observations of nature into an intelligible whole, even though — as the previous quotation and others in his 1859 tome, *The Origin of Species,* indicate — part of him evidently felt that there was something not fully appropriate about this way of articulating the relation between organisms and their environment.



Windhoek aloe (*Aloe litoralis*) growing in the desert near Windhoek, Namibia. Researchers carefully dug down and around the roots to make the whole root system visible and then drew the roots. A: View of the plant with its roots from the side. B: View of the roots from above. The roots grow out many feet in all directions horizontally in the dry soil and penetrate only about a foot (30 cm) into the soil. (From Kutschera et al. 1997)

Darwin's words point to the importance of considering how the language you choose affects the way you see and conceptualize the world. In one case, you posit an initial separateness, place the plant in an antagonist relation to, say, the lack of moisture, and imbue the plant with a centered agency through which it struggles against drought. You frame its existence in a way that resembles a human being struggling against something adversarial. In the other case, you view the plant in one of its connections with the world that supports its existence; you don't start with separation. You express the dependency of the plant on moisture and don't go further; you leave open what still can be discovered about the nature of this relation.

Language really matters. It is the reflection of our way of understanding the world. It shapes how we understand and even how we experience the world. In science, phenomena are always portrayed through a certain perspective and the language used embodies and enables that perspective. It is important to give due attention to this framing. The phenomena may show quite different features when viewed from another perspective. For that reason, we should appreciate what truths can be revealed by various perspectives. But we also need to be careful to never limit our approach to only one way of looking — which we implicitly or explicitly believe to be *the* way to consider things — that can hide more than it illuminates.

The language used in contemporary plant intelligence studies generally portrays plants as having human-like intelligence. We know very well from our own experience about remembering, choosing, making decisions, re-elaborating, or responding. Evidently, the proponents of plant intelligence believe there are phenomena within plants that justify such expressions. They look at plants through the lens of what they know about intelligent human behavior from self-conscious reflection and speculate on plant specific mechanisms that underlie the appearance of similar behaviors. Certain features of reflective human intelligence become the standard for how to understand plants.

Expanding the Idea of Intelligence?

Some years ago, there was an article in *Frontiers in Artificial Intelligence and Applications* that listed about 70 different definitions and brief descriptions of intelligence collected from books and articles (Legg and Hunter 2007). Most of the definitions clearly relate to rational human intelligence. For example:

> Intelligence is a very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience.

Other definitions are more general and broad. A definition such as, "the ability to learn or to profit by experience," can easily be applied to animals. And plants can surely be said to possess "adaptively variable behaviour within the lifetime of the individual" (in Trewavas 2017).

The broadest criterion for calling something intelligent seems to be: "the ability to adapt to the environment" (Legg & Hunter 2007; reference 13). From this perspective, virtually everything in the world is intelligent: A stone that warms up in the sun is intelligent, because it adapts to the sun's radiating heat. Similarly, water that flows downhill or remains still in a basin would be intelligent, since its momentary state is adapting to the conditions in which it finds itself. If, following the same definition, we move into the realm of the living, then a plant that grows effusively in a nutrient-rich soil is intelligent. A deer that flees when it sees a coyote on the field is intelligent. And a person who lies down in bed and falls asleep is also intelligently adapting to the environment.

Nothing exists in isolation. Nothing exists without a larger world to which it belongs.

One way to react to such a list of divergent ways of being "intelligent" is to say: When a definition is so broad, it ends up denoting virtually nothing specific. The concept of intelligence then tells us everything generally and nothing in particular.

Another way to respond is to say: That's interesting, maybe there is some sense in which it might be reasonable to speak of intelligence in plants. But then you have to move beyond thinking in terms of definitions. Definitions generally want to create crisp boundaries so that you have a way to determine what falls within the definition and what is excluded. They are in this sense mental boxes. When you peruse these 70-plus definitions of intelligence, what you discover is a spectrum or a continuum and no hard-and-fast boundaries. In this sense, such a compellation facilitates a movement beyond thinking in boxes.

If we are not focused on including or excluding different kinds of beings based on a definition of intelligence, we can shift our perspective. We consider the idea of the ability to adapt to the environment itself. Everything we designate as a "thing" is also embedded in a world we call "environment." Every "thing" relates to its world. It might change in relation to changes in the environment, and when it changes, the environment might also change. The concepts of "thing" and "environment" are inextricably connected. They belong together; they presuppose each other. Nothing exists in isolation. Nothing exists without a larger world to which it belongs. So when we delve into any realm of phenomena, we focus on something particular and in our attempt to understand it, we strive to move beyond our ignorance of it by discovering, if we can, the meaning-filled (meaningful) relations of which it is a part.

At the same time, we see that the meaning of "adapt" or "environment" modifies depending on what kind of entity or organism we are considering. Water for a rock is something very different from water for a plant. This may pose a bothersome problem for a mind that wants to start with a clear definition as the basis for including or excluding phenomena within the definitional concept. For us it is exciting to engage in a project in which our concepts may grow with each encounter.

Moreover, while we may discover distinct features of intelligence in, say, plants and animals, we may also find different qualities of what we might call intelligence within a given type of organism.

It is easy to recognize how human beings participate "intelligently" in the world in ways that remain beneath the surface of the reflective, intellectual mind. Imagine dashing madly through an overgrown field. You push through thickets of shrubs, attempt to evade brambles, and focus on finding openings that allow you to navigate the overgrowth in the most expedient manner. You breathe more deeply and your heart rate increases. When you arrive at the other side, you discover scratches on your arms and legs that you barely noticed as you were running. Some are still bleeding, others begin to crust over. Healing processes begin immediately following an injury regardless of whether you are aware of them or not. When the skin is punctured, the surrounding or damaged blood vessels immediately contract, reducing the flow of blood. Platelets converge on the locus of the wound and release fibrin proteins that form a tangled web resulting in a clot sealing the wound. Once the wound is sealed the blood vessels expand, bringing white blood cells to the wound area. As the healing process continues, fibroblast cells produce collagen that scaffolds the placement of new skin cells formed by the division of cells in the surrounding dermal tissue.

All of this takes place inside of us and is done by us beneath the surface of what we consider to be conscious. It happens without our conscious input. We are not deciding or making choices. As with most of what happens in the living world, our self-conscious understanding of these highly meaningful and dynamic processes is extremely limited. Yet they are at the heart of our existence as living beings. And do they not provide the organic basis of our ability to think about the world, to employ our conscious intelligence?

There are apparently different layers or dimensions of "intelligence" within human beings. Realizing this helps free us from the limitation of thinking of intelligence solely in terms of reflective human consciousness. It makes us keenly aware of the pitfall of limiting the inquiry to one particular expression of human intelligence and projecting it into all other forms of life.

From this perspective, the question of intelligence in nature shifts away from applying a specific definition to different types of beings in the world to asking: What are different ways of being in the world and what do they reveal? The notion of intelligence can in this way become more nuanced and grow when we take different kinds of creatures on earth seriously in their specific ways of being. Our primary focus in the coming year or so will be on plants. As our inquiry proceeds, we may find that we need terms other than intelligence to express the different qualities of organism-environment relations. We leave that open.

References

Calvo, Paco (2016). "The Philosophy of Plant Neurobiology: A Manifesto." *Synthese* vol. 193, pp. 1323-43. doi 10.1007/s11229-016-1040-1

Calvo, Paco, et al (2020). "Plants are Intelligent, Here's How." *Annals of Botany* vol. 125, pp. 11-28. doi: 10.1093/aob/mcz155

Darwin, Charles (1859/1979). *The Origin of Species* (first edition). New York: Penguin Books. Online: http://darwinonline.org.uk/conten/frameset?itemID=F373&viewtype=text&pageseq=1

Darwin, Charles (1880/1989). *The Power of Movement in Plants*. "The Works of Charles Darwin", Volume 27. Edited by Paul. H. Barrett and R. B. Freeman. New York: New York University Press, pp. 572-73. Online: http://darwinonline.org.uk/content/frameset?itemID=F1325&viewtype=text&pageseq=1

Darwin, Francis (1908). "The Address of the President of the British Association for the Advancement of Science-I." *Science* vol. 28, pp. 353-62. Online: https://www.jstor.org/stable/1636207

Gagliano, Monica, et al. (2014). "Experience Teaches Plants to Learn Faster and Forget Slower in Environments Where It Matters." *Oecologia* vol. 175, pp. 63-72.

Gallusci, Philippe, et al. (2023). "Deep Inside the Epigenetic Memories of Stressed Plants." *Trends in Plant Science*. https://doi.org/10.1016/j.tplants.2022.09.004

Kutschera, Lore, et al. (1997). *Bewurzelung von Pflanzen in verschiedenen Lebensräume*. Bd. 5 der Wurzelatlas-Reihe, Stapfia 49.

Legg, Shane and Marcus Hunter (2007). "A Collection of Definitions of Intelligence." *Frontiers in Artificial Intelligence and Applications*, vol. 157, p. 17. https://arxiv.org/pdf/0706.3639.pdf

Mallet, Jon, et al. (2021). "Debunking a Myth: Plant Consciousness." *Protoplasma* vol. 258, ppl. 459-76. https://doi.org/10.1007/s00709-020-01579-w

Mancuso, Stefano, and Alessandra Viola (2015). *Brilliant Green — The Surprising History and Science of Plant Intelligence*. Washington, DC: Island Press.

Taiz, Lincoln, et al. (2019). "Plants Neither Possess nor Require Consciousness." *Trends in Plant Science* vol. 24, pp. 677-87. https://doi.org/10.1016/j.tplants.2019.05.008

Trewavas, Anthony (2017). "The Foundations of Plant Intelligence." *Interface Focus* vol. 7: 20160098. https://doi.org/10.1098/rsfs.2016.0098

How Do Biomolecules "Know" What To Do?

Stephen L. Talbott

Physicists, before recovering their balance after all the turbulence roiling their discipline during the first half of the twentieth century, faced "insane" questions seemingly without coherent answers. But they eventually turned their perplexity into an exhilarating freedom of thought. Having broken through the narrow confines of pre-quantum era (nineteenth century), solid-particle, materialistic thinking, they — or some of them anyway — allowed their imaginations to soar into previously inaccessible realms. So it was that in 2005 a Johns Hopkins University professor of physics and astronomy, Richard Conn Henry, could publish in *Nature* — that dignified matriarch of scientific reporting — an article with the risque title, "The Mental Universe." Referring to lessons learned during the quantum revolution, including the primacy of observation over theorizing about submicroscopic "things" — things that seem inherently non-observable — he remarked:

> Someone who has learned to accept that nothing exists but observations is far ahead of peers who stumble through physics hoping to find out "what things are."

Urging the importance of educating the wider public about the changes in physics, Henry expressed the hope that physicists can "pull a Galileo," so as to change the way people think about the world around them (Henry 2005).

I cannot vouch for Henry's vision of material reality. And I don't know who among physicists, or what confluence of events, will sooner or later "pull a Galileo" with the general public. But I do have some suspicions about the "insane" questions that just might transform biology in a wonderfully bracing way. And I am convinced that here, too, transcending the limitations of materialistic thought is the decisive opportunity — and may prove even more transformative than it has in physics. After all, problems of mentality, consciousness, thought, and intention are more obviously central to biology than they are to physics.

Here I wish to articulate just one of the "impossible" questions. A question, if it is truly a question and not part of a disguised brief for a ready-made answer, is always open-ended; one is free to take it up or not, and never knows for sure where it might lead.

Of course, no inquiry is ever *completely* open-ended. To begin with, the choice of a topic says something about the direction of thought motivating the inquiry. And I have just now admitted that I am already convinced about our need to leave behind an older, materialistic way of thinking. I well realize that if this admission encourages some few to engage with the thoughts I am putting forward, it will discourage very many others. Fair enough. It will presumably turn out that the one group or the other will be on the side of history. We will see.

Meanwhile, there is (for me, anyway) the joy of the pursuit — the wrestling with perplexities that, one way or another, need to be penetrated by human understanding. This is despite the difficulty of glimpsing, at the moment, how the penetration might even be possible. But I am convinced that every question disturbing the human heart will sooner or later find its answer.

Let's begin by looking briefly at two research topics in molecular biology:

Example 1: Topoisomerases

As the usual comparison has it, packing the DNA of a human cell, with its 21,000 or so genes, into the cell nucleus is like stuffing 24 miles (40 kilometers) of thread into a tennis ball, with the thread divided into 46 separate pieces (chromosomes) averaging roughly a half mile each in length. Appropriate gene expression entails an elaborate, three-dimensional structuring of these chromosomes into loops and different sorts of contact domains that bring specific genes and regulatory DNA sequences into relationship with one another and also with endlessly diverse collections of effector molecules in the nucleus.

If you or I were managing the thread, it's fair to say that we would be clueless about how to establish and maintain the intricate and intertwined functional relationships among the millions of significant loci along these strings. But there are enzymes called "topoisomerases" that somehow manage just fine as they deal expertly with one part of the problem — namely, with the knots, tangles, and the ever-changing (and potentially disruptive) helical twist of the two-stranded chromosomes. Some topoisomerases cut one of the two DNA strands of a single chromosome, allowing the cut strand to unwind or wind (untwist or twist) further around the uncut strand, then "healing" the cut. Other topoisomerases untangle knots by cutting both strands, passing a loop of the chromosome through the gap, and then sealing the gap.

No one knows how it is possible for a "dumb" molecule to perform these chores sensibly amid all the seemingly unreadable complexities of the dense mass of chromosomes. James Wang, currently a Harvard biochemist, discovered the first topoisomerases in the 1970s and has more recently written about the function of the enzymes:

> When we think a bit more about it, such a feat is absolutely amazing: An enzyme molecule, like a very near-sighted person, can sense only a small region of the much larger DNA to which it is bound … How can the enzyme manage to make the correct moves, such as to untie a knot rather than make the knot even more tangled? How could a nearsighted enzyme sense whether a particular move is desirable or undesirable for the final outcome? (Wang 2009, p. 41)

Or, for that matter, what can we make of the enzyme's capacity to "sense" anything at all? What is implied by that casual and oh-so-natural — yet oh-so-unnatural — use of words? And then there is the problematic reference to an outcome that is either desirable or undesirable. "Desirable" and "undesirable" are not physical categories. Yet here is a perfectly competent physical scientist driven to use such words. Perhaps we should pay attention.

In any case, we can assure ourselves that, sooner or later, someone will trace all the physically lawful activity through which the task is accomplished. It will make sense. Everything will turn out to be "routine" and "as expected" from a physical point of view. And because we find it so easy to interpret lawfulness as offering a more encompassing necessity than it can actually underwrite, we may then think that everything has been properly accounted for.

Does Biological Organization and Coordination Require Special Explanation?

It is true that the lawfulness of physical interactions reflects a kind of necessity. But this is an extremely limited sort of necessity. A rather fantastic thought might help to clarify the matter. Suppose there is a small, squirrel-sized hole in the left-field fence of a baseball stadium, and suppose further that a batter hits a line drive that passes precisely through the hole. It's a very low-probability event. Yet it could happen.

And if it did happen, we would rightly think that everything must have been lawful, from the velocity and spin of the pitched ball, to the angle of impact of the ball upon the bat, to the ball's flight through the resistance of the air, to the lack of any bird or insect in the flight path, and so on to every smallest detail of muscular performance of the batter and pitcher. The pattern of lawful interactions would reflect a certain "chain of necessity," even though what we mean by "necessity" in this case seems rather difficult to pin down. (The batter *could* have swung the bat slightly differently; a bird or insect *could* have gotten in the way; the ball *could* have encountered an unusual little gust of wind; a fan in the stands above the fence hole *could* have dropped a glove that interfered with the ball …)

But now suppose that, during practice, a batter hits 257 successive pitches as line drives striking the left field wall. Suppose further that chalk marks on the fence indicating the places of impact neatly spell out the sentence, "What Is The Meaning of Life?" Given such an occurrence, it's safe to say we would feel a need for explanation going beyond the physical lawfulness of each of those 257 drives. If someone suggested that a djinn suddenly emerged from a bottle and coordinated everything, we would doubtless reject the idea as ludicrous. And if we were told that this was one of the most amazing magician's tricks ever pulled off — we knew not how — then we just might believe it. It would be either that or else keep looking for another explanation.

But what good does it do, you may be asking, to summon such an impossible picture? How could a falsely imagined occurrence help us with a real biological problem?

It's true that the 257 line drives just now hypothesized would never happen, so that we would never actually need the looked-for explanation. The story was given in fantastic form only to point out as vividly as possible the difference between two varieties of explanation. An explanation beyond the lawfulness of physical interactions is required whenever we need to account for a kind of coordination or organization or meaning of events that physical lawfulness seems unable to support — *if indeed such coordination ever occurs*.

It is perhaps relevant here that magicians, unlike djinns, really do exist, and sometimes present us with perplexingly clever performances. When we try to understand those performances, most of us assume that everything was physically lawful. But we still want to know, "How did the magician pull this off?" The *trick* is not explained by its lawfulness.

So now we return to biology. What about the "trick" of the topoisomerases — whose accomplishment in managing complex and deeply contextualized meanings we still need to make sense of, and whose difficulty for human understanding we still need to remove. Unlike in the fanciful case of the baseball batter, we know that the "impossibly" intelligent and meaningful management of knots, tangles, and twists by topoisomerases actually occurs. Although everything is physically lawful, this lawfulness, by all accounts, knows nothing of the needs, interests, and purposes of the cell and organism, which the topoisomerases seem to be "aware" of. The purposive and intricate coordination of molecular events by topoisomerases in service of the cell's needs is well attested, so we can't simply reject the picture as fantastic and unbelievable.

What is a conscientious biologist to do, if not look for the missing aspects of a proper understanding? Fortunately, she might not warm to the idea of a djinn (or of a magician, or of any other external agent or designer). But what then? Ought we at least to keep the explanatory problem in mind? What is it about the current state of biology that so easily allows such problems to drop out of sight?

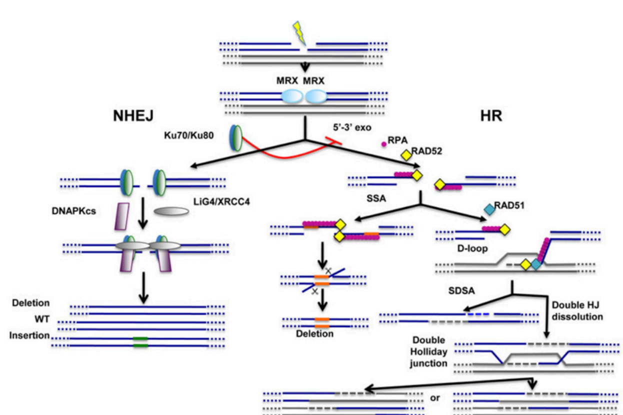
Example 2: DNA damage repair

The DNA of a human cell incurs, on average, tens of thousands of molecular lesions per day. These can occur through internal agents such as reactive oxygen species, or environmental agents (smoke, radiation, natural toxins, or man-made mutagenic chemicals). Without the cell's ability to repair nearly all this damage, our lives would be extremely short, if we even survived to birth.

The various means of repair that a cell can bring to bear upon these diverse sorts of damage are so unthinkably complex and difficult for the human mind to follow that I would not attempt to capture that complexity here even if I were capable of it. I merely present in Figure 1 a biologist's summary representation of two methods employed in dealing with a single kind of DNA damage — double strand breaks. Figure 2 is an elaboration of a small section at the lower right of Figure 1. The highly schematized figures, completely devoid of the massively complex biochemical details, are intended for those with training in genetics, and I imagine that trying to follow the depicted pathways of coordinated molecular surgery must have caused innumerable headaches in graduate students of molecular biology.

I would advise readers not to bother much with these figures. A vague and general impression is enough. But I will have a few things to say, usefully I hope, about the problem of DNA damage repair.

Figure 1, below (Note to readers: This figure and the following one don't need to be understood. See main text.) Figure 1 depicts two general pathways for the repair of DNA double-strand breaks: non-homologous end-joining (NHEJ) and homologous repair (HR). Each pair of blue or gray horizontal lines represents the two strands of one complexly structured DNA molecule (double helix). Sections of these strands may be swapped around, and one molecule may be employed in the repair of a second, damaged molecule. Each of the steps shown may be accomplished by a large number of protein molecules working cooperatively. Figure 2 expands slightly on just one of the steps of homologous repair, involving the formation of a Holliday junction.[1]



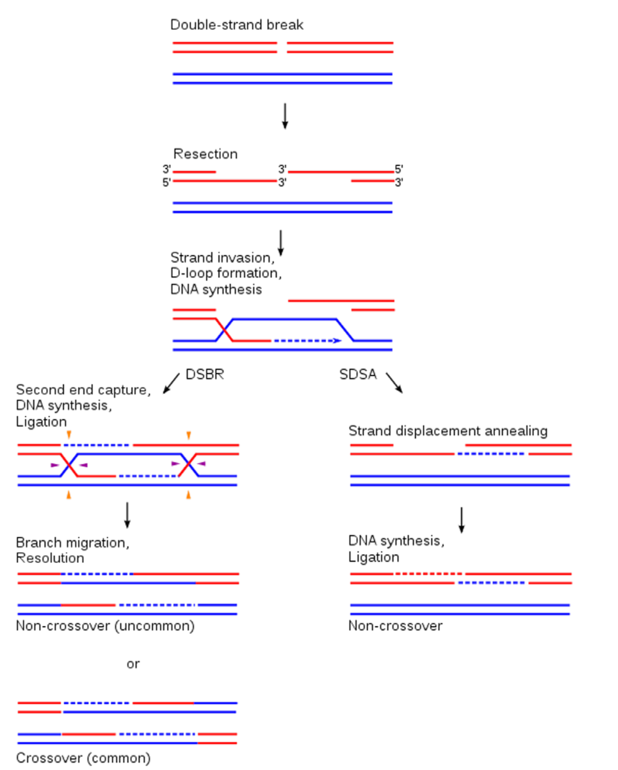


Figure 2. Schematic diagram showing Holliday junctions in two pathways of homologous DNA repair: the double-strand break repair pathway (top and left), and synthesis-dependent strand annealing pathway (top and right).[2]

Huge numbers of protein molecules are involved, directly or indirectly, in the intricate repair. Perhaps the first task for each molecule is to "understand" with which of many possible repair pathways, for which of many types of damage, and with which of countless possible cooperating repair molecules, it is "supposed" to engage itself. Then there are the other molecules that must "know" how to repeatedly modify these protein molecules along the way, so as to make them "fit" for the successive stages of their work. Then there are all the molecules that need to "watch" the process from outside so that they can collectively "decide" how well the whole process is proceeding in all its aspects, and whether the damage is too great for repair, so that a process of cell death "needs" to be initiated.

If we were to think that genes hold the secret of life, this thought would immediately be contradicted by the companion thought that, whatever the complex capabilities of genes, the cell must stand "knowledgeably" above them, with its ability to repair such complex entities and recommit them to their "proper" roles — or else to "decide" that the irreparably damaged genes are not up to their job and that the cell therefore needs to "sacrifice" itself and recycle its contents for the general "good."

The quoted terms in the preceding descriptions should be taken as mere placeholders. They are (as often read, anyway) improper — hard to reconcile with the language of respectable scientific description. As placeholders they are merely reminders that we need *some* terms in those places — either by investing the given words with proper meaning, or by finding better words. And it is the clarifying task of biologists to find those meanings and words. With this understanding I will continue using such terms, both quoted and unquoted.

Recognitions of the Problem

It feels misleading to single out examples such as the ones given above, since all physiological processes, when looked at in sufficient depth, involve something like the same complexity, meaning, and end-directedness. The general capacity of biological molecules to contribute holistically and lawfully to functional order and organization rather than to go their own disinterested ways could be considered definitive of life. The molecules are continually "spelling out," as it were, the open question governing all biological research: "What is the meaning of life?"

The opportunity for biologists is to ask themselves, "What can we say about the not-yet-understood wisdom that shines through organic activity at every level of observation?" The question remains after the physical lawfulness of all the activity is demonstrated, since it is not a question about this lawfulness, but rather about the meaningful and expressive organization of the activity. It seems clear enough that biological processes require us to seek principles of understanding that go beyond the non-violation of physical laws.

What can we say about the not-yet-understood wisdom that shines through organic activity at every level of observation?

We don't see the same sort of organizing in the non-organic cosmos or in earth's solar system, or in the sciences of geology and chemistry. But we see it everywhere in biology. No textbook describes DNA damage repair without central reference to the purposiveness of the entire process — the wholeness and healthy functioning of the genome being "aimed at." Cells and organisms achieve this aim only with a considerable expenditure of energy — that is, only by making a well-directed "effort."

As I'm sure nearly all biologists would agree, the coherence of such well-organized activity needs a proper scientific accounting. And, in fact, there is a common thought that, somehow, evolution by natural selection must give us the required account. However slowly and however indirectly, it must have supervised the emergence of all the necessary capabilities.

Evolution is said to be a tinkerer, and over time (so the thought goes) it tinkered with all the biological mechanisms constituting the present organism until those mechanisms became more or less efficient at doing the needed thing, whatever that might be. After all, organisms that do the right thing are the ones that survive and reproduce best, so it is not surprising that we see everywhere organisms that have the basic tools for survival. How could it be otherwise? So where's the problem in that?

But this line of thought leaves untouched the problem we're looking at now. An evolutionary tinkering with mechanisms that are preserved into the future so that they can be perfected through further tinkering is hardly relevant. All these interacting molecules in a fluid medium must coordinate their intricately organized activity on the fly and in this very moment, without the external guidance of any evident gears, levers, or mechanical contrivances engineered in the distant past.

If we are looking for controlling mechanisms to regulate the activity of topoisomerases or DNA repair enzymes, we are out of luck. There are no such mechanisms to be found, and I am not aware of anyone claiming to have found them. It seems impossible even to conceive the existence of such devices. So what enduring material *mechanism* is evolution supposed to have been working on, and where do we see any such mechanism guiding the topisomerases in their second-by-second "brain surgery"?[3] To say that evolution fosters the development of needed traits, *whatever they might be* (regardless of their physical implausibility), is much the same as appealing to magic, or saying "Everything is as it is because God made it so."

The question all this molecular activity poses is not about the prior evolutionary selection of particular mechanisms or structures, but rather about an apparent wisdom that must be brought to bear in a currently unknown fashion upon exactly this moment's ever-changing, somewhat chaotic, and evolutionarily unprecedented configuration of diverse molecules within the cell's swirling plasm. Everything must proceed discriminatingly and without the guidance of any accessible record of historical transactions in similar (but never identical) situations. And this unscripted performance must continue, unpredictably, past the present moment and on to the next, and the next, and the next, without end (until death) — all in order to keep the organism healthily functioning. It is an amazing choreography without an evident choreographer. Yet, just such a performance is uniquely inherent in every different sort of organism. What are we to make of this?

Paul Weiss and the "Restraint" of the Whole

There are two angles I haven't mentioned yet, from which we might look at the puzzle we are confronting. One was offered to us by the twentieth-century cell biologist and National Medal of Science honoree, Paul Weiss. Reflecting on the degrees of freedom molecules possess in a fluid medium, he concluded that it made no sense, physically, for collections of organic molecules not to go their own way, as opposed to carrying out an endless series of stunningly detailed, functionally efficient, expertly organized performances.

But Weiss had no desire to go beyond the observed facts or to explain them from a position of ignorance. He merely remarked rather dryly that "The resultant behavior of the population [of cellular constituents] as a whole is infinitely less variant from moment to moment than are the momentary activities of its parts." And so "the system *as a whole* preserves its character" (Weiss 1962, p. 6). That is what he observed.

Or, in somewhat different words: when we examine the form and physiology of an organism, we see how "certain definite rules of order apply to the dynamics of the *whole* system … reflected [for example] in the orderliness of the overall architectural design, which cannot be explained in terms of any underlying orderliness of the constituents." (Weiss 1971, p. 286)

Weiss sums up the situation in a way that highlights the non-mechanical uniqueness of the molecular configuration in a cell at every moment of the cell's existence:

> Small molecules go in and out, macromolecules break down and are replaced, particles lose and gain macromolecular constituents, divide and merge, and all parts move at one time or another, unpredictably, so that it is safe to state that at no time in the history of a given cell, much less in comparable stages of different cells, will precisely the same constellation of parts ever recur …Although the individual members of the molecular and particulate population have a large number of degrees of freedom of behavior in random directions, the population as a whole is a system which restrains those degrees of freedom in such a manner that their joint behavior converges upon a nonrandom resultant, keeping the state of the population as a whole relatively invariant. (Weiss 1962, p. 6)

We are particularly invited to pause and weigh our ignorance in the presence of these words: "the population as a whole is a system which restrains those degrees of freedom." What do we actually know, in our present science, about such restraint? Here, perhaps, is one of the opportunities for future biologists to "pull a Galileo" (as Richard Conn Henry put it above) and move biology into a new era of previously unimagined thinking.

The Decisive Role of Context

A second additional angle on our topic is expressed in a current mantra recited time and again in molecular biological writing: just about every molecular interaction in a living cell, we're told, is context-specific (or context-dependent, or context-sensitive). An alternative word would be "holistic," if it weren't anathema in biology. After all, being sensitive to a context just means acting consistently with, or in harmony with, the larger whole in which one finds oneself.

The phrase "context-specific" makes no sense unless it refers to some kind of top-down ("formal") causation — that is, causation relating to the part's participation in, and conformity to, the pattern or form or meaning of the whole. This is not the kind of causation that old habits of thought encourage us to acknowledge. That's why "context-specific," despite occurring almost everywhere in the biological literature, is defined almost nowhere.

The idea that the whole interpenetrates its parts, thereby helping them to become what they are, reminds us of the way the meaning of speech and text works. It's as if individual words "pay attention" to the meaning of their context, and adapt themselves to it — or, we might say, the context imposes its own meanings upon the words. Or perhaps the adapting and imposing are really a single, harmonious, and indivisible play of meaning. This play must, of course, occur both in the actual production of the speech or text, and in our understanding of it.

It doesn't take a lot of reflection to realize that, if biological activity is context-sensitive, the whole must have something like a causal influence on the part. This is not the usual conception of parts acting upon parts and therefore summing up to the whole. It looks rather more as if the idea or meaning of the whole informs and governs its parts. But to give idea or meaning a causal role in this way is foreign to contemporary scientific thought. Or is it, really? How easy it is to forget that a great part of conventional science consists of explanatory *ideas*, many of which nearly all scientists are perfectly happy to regard as belonging to our causal understanding of the world! This is certainly true, for example, of the mathematical ideas (equations) expressing our conventional understanding of the basic physical forces.[4]

Short of reckoning with the molecular conundrum presented by the topoisomerases as a *problem of meaning*, no one seems to have even a tentative approach to it, and so it fades into the unspoken (and, perhaps, largely unthought) background of biology. Maybe we are approaching a place where we can do better than that.

Unanswered Questions Are a Part of Any Healthy Science

We might put the question we have been dealing with this way: *How do molecules gain whatever passes for their "awareness" of — their ability to interact intelligently in light of — the meanings of the larger cellular and organismal context in which they find themselves?* The problem is that making the question explicit is enough to show that it does not sit comfortably with the acceptable explanatory apparatus of today's biology.

One option is simply to turn from biology to the sciences of the inanimate while assuming that the continuing elucidation of physically lawful processes will sooner or later carry us beyond the stubbornly persistent questions facing biologists. But this no longer looks like a solution once we have recognized the fundamental difference between questions of physical lawfulness and those of meaningful coordination and organization in relation to an organism's needs, purposes, and interests. Perhaps the "stubborn persistence" of the questions simply reflects this fact.

Yet we must, I think, refuse the idea that molecules, or even cells, have anything we are likely to want to call "awareness" in close analogy with human awareness. But, as I mentioned earlier, we have no choice but to find *some* way to substitute for, or qualify, that word (and others like it). And we are certainly free to ask ourselves whether this problem points us toward the possibility for a refreshingly new science of biology in the future.

I have been suggesting that we cannot account for biological organization merely by tracing a sequence of physically lawful processes. Something "above" that is required. But saying that something more is required is not to explain how the requirement is fulfilled. And I am not about to explain it now, simply because I am not capable of it. It is always good to acknowledge the limits of one's current understanding.

I do, however, recognize at least some of the reasons why we should expect the question or problem we have been looking at — how do biomolecules "know" what to do? — to prove insoluble in the context of today's biology. After all, the most obvious terms in which we might approach the question have long been ruled out by the materialistic commitment implicit in today's biology. That's why the question we are considering is not even being posed by contemporary working biologists — certainly not with any clarity. Where a science lacks the resources even to pose a pressing question, we can hardly expect it to possess the resources for answering that question.

I have already mentioned one root of the problem: biologists have a great difficulty with the notion that ideas — or, more generally, what we might refer to as the *interiority* of the organism (which needn't refer to conscious awareness) — can play anything like a causal role in its life. Ideas are scarcely thought to be real in any fundamental (ontological) sense, let alone to possess some sort of causal power.

Another aspect of the problem lies in the fact that scientists since Galileo have unapologetically tried to rid science of qualities. The problem is that, if they could somehow succeed in this crazily impossible project, they would be left with no observation-based science at all, since all observation of the material world is irreducibly qualitative.[5] Nor would they have any content from which to abstract quantities. In and of themselves, of course, quantities are not material entities. (Talbott 2023).

To whatever degree we succeed in arriving at quality-free explanatory laws (and it is never 100%), those laws become abstract, universal, and silent about particular things, because things in their particularity simply aren't there to be recognized in the terms of such laws.

So the seemingly insuperable problem we now face is this: if respectable science can hardly bear to deal at all with observable things in their own, irreducibly qualitative terms — if the world's lawfulness is required to be universal and detached from the qualities and meanings that distinguish one thing from another — how can we even begin to talk about the "something more" that is the unique, unfolding form and highly coordinated way of being of a trillium or snail or cellular life cycle? The problem is simply invisible to anyone raised up according to the quantitative and materialistic ideals of our present science.

Notes

1. Figure 1 credit: Decottignies 2013, (CC BY-SA 3.0).

2. Figure 2 credit: emw2012 (CC BY-SA 3.0).

3. It is interesting that evolutionary discussions of physiological processes tend to focus on how new or modified proteins arise in evolutionary history. The focus is on *things*. And yet the more directly relevant question is how the proteins that are there manage to *do what they do*.

4. The ideas bearing on the force of gravity or, say, the dynamics of billiard balls are, of course, a long way from the formative ideas we see at work in organisms. But why should the ideas governing disparate realms of being all be of the same sort? No one has demonstrated inherent limits upon the kinds of ideas that might be embodied in the various phenomena of the material world. Just as we indisputably "see" the mathematics of gravity in planetary motions, we also and with equal persuasiveness "see," for example, the striving for life evident in all organisms. This is always a species-specific striving that seems quite able to guarantee, for example, the infinitely complex, distinctive, and qualitative pathway from a tiger zygote to a mature tiger.

(Regarding the distinctive way of being for a species, see Craig Holdrege's whole-organism studies: https://natureinstitute.org/whole-organism-biology. And also his book, *Seeing the Animal Whole — And Why It Matters:* Holdrege 2021.)

As far as possible, the physicist tends to seek universal laws that apply to objects without reference to their own character. Hence the appeal to abstracted, universal quantities such as mass and energy. Things with their own character are invisible to such laws. A 5-kilogram meteor and a 5-kilogram groundhog — they're pretty much the same thing as far as the law of gravity is concerned. On the other hand, biology deals with qualitative behaviors arising from the internal and differentiated characters of the uniquely expressive, more or less individuated "objects" (organisms) it deals with. The biologist's knowledge of a groundhog is not at all the same as the physicist's knowledge of a rock. The formative ideas are very different in the two cases.

Where physics gives us universal principles of regularity, biology gives us, over evolutionary time, the ever more distinct focal agency of organisms. And this agency can be meaningfully exercised — it can actually *be* agency and culminate in freedom — only in a world of physical regularity. Without such predictable regularity, no act of an agent could mean anything since the consequences of the act could not be known in advance. This complementarity between two very different sorts of formal causation is one of the ways in which organisms and the inanimate world must be understood in relation to each other.

5. If you are thinking of an instrument that provides only a numerical output, don't. If the reading of the instrument is to be of any scientific use, it can only be because a scientist has employed it in relation to a qualitatively describable phenomenon and then interprets the numbers in terms of that phenomenon. A presentation of numbers by themselves means nothing. Just imagine that I read off to you a series of numbers without any context. What would they mean?

References

Decottignies, Anabelle (2013). "Alternative End-joining Mechanisms: A Historical Perspective," *Frontiers in Genetics* (April). https://doi.org/10.3389/fgene.2013.00048

Henry, Richard Conn (2005). "The Mental Universe," *Nature* vol. 436 (July 7), p. 29. doi:10.1038/436029a

Holdrege, Craig (2021). *Seeing the Animal Whole — And Why It Matters*. Great Barrington MA: Lindisfarne.

Talbott, Stephen L. (2023). "How the World Lends Itself to Our Knowing," in *Organisms and Their Evolution: Agency and Meaning in the Drama of Life*. Available online at https://bwo.life/bk

Wang, James C. (2009). *Untangling the Double Helix — DNA Entanglement and the Action of DNA Topoisomerases.* Cold Spring Harbor NY: Cold Spring Harbor Laboratory Press.

Weiss, Paul (1962). "From Cell to Molecule," in *The Molecular Control of Cellular Activity*, edited by John M. Allen, pp. 1-72. The University of Michigan Institute of Science and Technology Series. New York: McGraw-Hill.

Weiss, Paul A. (1971). *Within the Gates of Science and Beyond: Science in Its Cultural Commitments*. New York: Hafner.

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"We Americans are reluctant to learn a foreign language of our own species, let alone another species. But imagine the possibilities. Imagine the access we would have to different perspectives, the things we might see through other eyes, the wisdom that surrounds us. We don't have to figure out everything by ourselves; there are intelligences other than our own, teachers all around us. Imagine how much less lonely the world would be." – Robin Wall Kimmerer, *Braiding Sweetgrass*