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Complexity and Functionality: A Search for the Where, the When, and the How

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We discuss three approaches to a study of complexity: the reductionist stance; a search for new laws; and a search for a new aspect of reality, besides space and time. We focus on the latter, introducing the term 'sense' as a candidate for such a third aspect. We point out some of the ramifications of such a move for the subject/object relationship in physics and in biology.

1 Complexity with an Attitude – but which one?

How do complex phenomena such as life and especially consciousness fit into our scientific world view, based on physics as the most fundamental of the natural sciences? Is biology more than a complex form of applied physics? In general, what is the character of 'emergent properties'? There are three fundamentally different attitudes that we can take with respect to these questions.

1) the reductionist stance. We can deny that there is any problem, remaining satisfied with the 'explanation' that ultimately the most complex phenomena are, after all, layered upon some physical substratum, a dance of matter and energy in space and time. Whatever it is that is thus layered on top is seen as mere icing on the cake, nothing 'substantial', and hence nothing special, from a basic point of view.

2) a search for new laws. Accepting that physics in its current state is unable to capture phenomena such as life and consciousness, although it may suffice to describe the behavior of the physical substrata, it is natural to search for something else, something with which to augment physics. A natural move is then a search for new laws of physics, additional principles that may help explain properties such as autonomous agency and adaptive behavior.

3) a search for a new aspect of reality, besides space and time. This is the move that we are exploring in this paper. At first, this move may seem bewildering. What could there possibly be, in addition to space and time, and equiprimordial with space and time, irreducible to either or both? The answer may lie along the lines of intention, agency, cognition/feedback, relationship, and functionality.

In a nutshell, the move from space and time to a third aspect of reality can be motivated as follows. A movie shows motion in time, but does so by freezing temporality into a series of purely spatial snapshots. Similarly, a biological treatment of a living cell shows that cell's functionality, through a series of snapshots at different 'levels' of complexity, from that of atoms to that of molecules to that of organelles, etc. Where a movie freezes and carves up the time dimension, an analysis of a complex biological system freezes and carves up the different levels of description of emergent properties.

A single snapshot can be described spatially, but such an analysis fails to capture fully the temporal coherence of the series of snapshots. Similarly, a single level of description of a cell, on the molecular level, say, can be performed using physics, based purely on spatial and temporal concepts. However, such an analysis fails to capture in full the 'dimension' of functionality of a living cells, the intrinsic coherence between the different levels of description, that which gives the cell its unity, deserving the single name 'cell'.

2 Reductionism

Physics describes a world of complex reactions between a handful of simple entities (particles, fields, ...), situated in space and time.

On the one hand, physics is very successful: everything we see around us seems to have a place within the physics fold, if we restrict ourselves to objective (inter-subjective) phenomena. Even so-called secondary quantities such as the color of an object, can now be calculated from first principles, given the material composition: we can derive the fact that the sky is blue and the grass is green. That is to say, that their light has a wave length distribution corresponding to blue and green.

On the other hand, there a few aspects in which physics is not (yet) successful:

- the subjective experience of a color, the 'quale', may correlate with an objective description in terms of wavelength, but is clearly something else. In the near future, we may find a more and more accurate correlation with an intermediary phenomenon, between the wavelength and the quale of a color, in the form of

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a detailed description of the firing pattern of neurons corresponding to that color. But even if we would have the complete wiring diagram of the brain, and what is more, a full understanding of the data processing involved, we would still not have reached the quale.

- physics is an abstraction of reality, or better: actuality. It is the result of pushing actuality through the filter of physics, taking only what is objectifiable and repeatable. Ethics and esthetics are thus lost. The best that physics can hope for, it seems, is to reconstruct the objective counterparts to esthetic and ethical experiences in terms of a detailed understanding of the corresponding neurological processes. As is the case with color, there seems to be a rift between an understanding of such processes and 'the real thing'. Even more than with color, the internal logic of ethics and of esthetics seems to be lost here.

- even on the level of biological processes, anything with a function, aim, need, or intention already fails outside the purview of physics, based on a purely causal explanation. The very term self-organization that is used to describe the processes of maintenance and reproduction in organisms implies a self that perpetuates a distinctive type of organization, the living condition. This goes beyond current physics in two ways: 1) life involves an emergent organizational property which has yet to be precisely defined in physical terms and is not reducible to causal molecular interactions (including the template and coding properties of DNA)(Goodwin 1994; Kauffman 1995); 2) the self of an organism can be described as an autonomous agent that acts on its own behalf and in so doing it invokes a world which it knows and in which it can function successfully (see Kauffman, Investigations; Maturana and Varela 1992). Clearly the terms 'know', 'act on its own behalf', 'evoke', and 'function' take us into a territory of internal agency or subjectivity that transcends the terms of reference of causal explanation in physics, even allowing for an observer.

Let's take a closer look at those three objections. The root cause for all three to arise is the opening move of reductionism: to want to start with (what appears to be at a given moment in the history of physics) the most fundamental building blocks. A while ago, atoms and molecules seemed to be the most fundamental. We then descended to wave functions and relativistic quantum fields, and we may soon arrive at an even deeper level, perhaps given by string theory. Reductionism considers those 'deeper' levels to provide a foundation for the 'higher' levels of analysis of complex systems: physics founding biology founding chemistry.

This notion of the natural sciences as stacked on top of each other, with logic in the basement, math on the ground floor, physics on the second floor, and so on, provides a rather curious metaphor. Time and again, the 'underlying principles' of physics have changed dramatically, and yet the building never collapsed as a result. The switch from classical to relativistic mechanics replaced some 'fundamental' assumptions of physics, and yet most chemistry and biology went on with business as usual, on the higher floor. The switch to quantum mechanics provided an even greater change in 'basic' assumptions, but this, too, did not mean that we had to rebuild chemistry from scratch. The vast body of knowledge built up so far in chemistry did remain valid: verified phenomena remained verified, and so did their empirical relationships.

What type of building is it, this grand structure of the natural sciences, that you can cheerfully replace the foundations or first floor without affecting the higher floors? It sure would be a convenient building to work on, for architects and construction workers who had trouble making up their mind! The conclusion we draw from this picture is that the whole notion of 'foundations' is greatly flawed. Rather, the building seems to be held up in the middle, or better, all over the place. The real support for any scientific theory ultimately comes from experience: from experimentation in the lab, or from observations in nature.

What science provides is a divide-and-conquer strategy. Starting with the full buzzing and confusing diversity of phenomena in daily life, a severe filtering operation leads us to isolate the principles of mathematics first, then of physics and then of the more complex branches of natural science. If there is any real 'grounding' in this whole operation, the ground is provided by 'what happens', and by the relationships between these happenings, which can be described by carefully specifying where, when, and how each happening happens. Everything else, no matter how elegant and simple it may seem at any given time, is derivative (Nishida 1911, James 1912, Husserl 1913, van Fraassen 1994, Hut and Shepard 1996).

The where, when, and how of these happenings are always described by a human agent - one of us - busy doing, acting and constructing, as well as describing. As we climb the building through levels of complexity, we reach the level where we turn our probings on ourselves and describe the happenings that we can observe - as outside observers.

Here we encounter the agent that sets up the experiments defined by specific relationships between the observer and the observed happenings. This agent is also part of reality, and there is no way it is going to disappear in the dance of happenings that it itself has choreographed. The doings of a causal agent cannot be reduced simply to a set of happenings. Why not? Because an agent has a point of view, a framework of action, a relationship to actuality that gives direction to its doings. Happenings just happen - they do not serve any agent's purpose. Doings involve both the effects of outside influences on an agent and the point of view, the framework of action that defines the agent as an actor in the world.

To make these ideas clearer, consider a concrete biological example - a bacterium swimming towards a source of sugar that it has detected. Here is an example of an autonomous agent able to act on its own behalf in an environment defined by its selected relationship to the world. Going to get dinner! Good. A bacterium appears to be "just" a physical system. However, when we examine this agent in more detail we realize that it has a very interesting property: it is able to perform work cycles that perpetuate its own distinctive organization. There is a logical closure within such systems that allows the agent to make more of itself. Of course it can only do this within an environment that satisfies its needs - such as sources of sugar for energy to drive the work cycles that generate more of the structures that constitute the organization of the agent itself. The very language of description here is self-reflexive, revealing the logical cycle that defines closure. Such as agent can act on its world - swim towards a source of dinner, eat it, and in so doing change its world. These are "doings": they serve the specific purposes of the agent in perpetuating and propagating its distinctive organization.

When the bacterium does work in swimming to get dinner, its swimming slightly warms the liquid medium and jiggles other creatures. The warming and jiggling are happenings, not doings, for they do not serve the bacterium's purposes.

So we see the distinction between doings and happenings. The agent has a point of view underlying its actions, and its actions literally change the world. The agent has embodied knowhow - the knowhow to make its way in the world. That knowhow of doings that tend to sustain and propagate the bacterium are its mode of navigation in its world. None of this is standard physics. All of it is under our noses. All of it is true. But where does it take us in relation to new laws or new basic postulates of science?

3 In Search for New Laws

Let us look more closely at that question of what makes biology more than physics. Whence intention? We'll leave the first two questions of section 1 (reductionism) for later, but keep them in mind as part of our motivation to grope for something beyond physics.

A living cell, a living organism, a living ecosphere: all seem to be composed out of known building blocks. On the atomic level, we have an intricate network of a handful of molecules, mostly H, C, O, N, and a few others. This may seem to suggest that we just have a complicated calculation at our hands, an advanced exercise in applied physics, nothing more.

Well, let's pause for a moment. In physics itself, what counts as the understanding and deriving of results is quite different in different fields. In particle physics, the drive is towards more and more fundamental levels of insight, in terms of finding more and more primitive building blocks. But in solid state physics, say, the drive is to find effective laws, emergent properties, laws that are layered on the underlying properties of the next layer of more primitive building blocks, but that cannot be understood purely in terms of the building blocks. The latter are needed, and show up when things break down, but fade out of view as long as we focus on the higher-level machinery in full action.

So, perhaps biology, too, has its own logic, its own laws, equally 'real' or 'fundamental' as the laws of, say, quantum field theory.

But wait, there is something funny going on here. If the most fundamental laws of physics already 'cover' everything, then where is there room for more laws? How can there be more 'fundamental laws' than an already complete set? And don't those extra laws hold sway over a substratum that perfectly runs by the existing laws as such? Isn't this picture of 'extra laws' not a bit like that of a child in the passenger seat, holding a toy steering wheel, turning it whenever the car turns, in great delight, but without adding anything to the dynamics of the car.

4 Where and When and How

How about an even bolder move. Perhaps biology can point the way to something extra, not on the level of laws, but on the level of the composition of reality itself. Instead of viewing space and time as fixed, and all of physics and biology as a game played within space and time according to given rules, we can question the notion of space and time as catching the whole picture. In other words, instead of searching for new rules of the game, we could search for ways to widen the playing ground itself (Hut 1996, Hut and Shepard 1996, Hut and van Fraassen 1997; cf. Tarthang Tulku 1977).

So let us introduce a third aspect of reality. Besides the 'where' of geometry and physics in the limit of statics, and the additional 'when' of physics in general, including dynamics, we want to ask a third question, characteristic for biology. What sets apart biology from physics is the fact that any living system has a functional structure. In physics, once you have specified the dynamics and the initial conditions, the system evolves in time. How it evolves is specified in the universal laws that are obeyed by the system under consideration. In biology, however, any particular system has its own 'how'. The bacterium mentioned above has an efficient 'how' for the question of how to get dinner: swimming in the direction of increase of sugar concentration.

In physics, the 'when' of dynamics does not negate the fact that we can still ask about the 'where' of moving objects. Time does not replace space as a mysterious alternative type of fluid or ether, spread out 'in' space; rather, time is fully complementary to space, and a complete description of dynamics needs a specification in both space and time. Similarly, the 'how' of biology, we propose, does not negate the fact that a living cells still partakes in the 'where' and 'when' of physics. We can still describe the cell on a molecular level, as an exceedingly complex dynamic system in terms of physics. The third aspect (meta-dimension?) is simply complementary to the first two, space and time. Just as time and space don't bite each other, so the 'how' of biology does not interfere with the 'where' and 'when'.

We propose to use the simple term 'sense' to give a name to this third aspect of reality. The answer to how? is then: through sense (in its aspect of 'meaning', not that of 'sense experience'). In order to interpret what is happening, we have to 'make sense' out of the situation. This is already implicitly the case in physics, where any form of experiment or observation entails particular choices on the side of the experimenter or observer, who plays the role of subject. Any description, no matter how objective, is a description made by a subject trying to make sense. Even though the relationships between subject and object were rarely discussed in classical physics, relativity theory and quantum theory have forced us to make them more explicit. Especially in biology, the polarity between an agent and its environment is prominent. It makes sense for a bacterium to look for a source of its dinner. Already in order to stay alive, organisms explore the 'everyhow' of relational possibilities side by side with the everywhere of space and the everywhen of time.

This provides an alternative direction, complementary to the search for 'laws of complexity' and 'emergent properties', mentioned in the previous section. Of course, the choice between 'extra laws' and 'an extra aspect of reality' is not mutually exclusive. On the contrary. If it is reasonable to talk about an extra 'dimension' of reality, then that dimension has been there already from the outset. Just as time is still there when we analyze a static configuration, sense has been there all along, when doing physics. So biology simply uses more of what is already there, and physics less, and geometry even less. Seen in that light, physics could be viewed as a specialization of biology, rather than the other way around.

5 From Where to When

An analogy may help us here. The first time we hear about the possibility of a fourth dimension, it is hard to imagine what a four-dimensional world would look like. It is easier to go in the other direction, from three to two dimensions, and imagine how the world would appear for two-dimensional beings. Specifically, we can then ask ourselves how such beings could try to imagine the hypothetical existence of a third dimension. After thus getting some experience in flexing our 'dimension imagination muscles', we are then ready to move up, to contemplate the move from three to four dimensions.

In our case, too, rather than trying to figure out what our third aspect of reality may look like, let us descend to an understanding of the world, based purely on space. Imagine that we would encounter a group of scientists who would look at the world as a geometric landscape, aware of the subtleties of space, but more or less oblivious of time. Of course, they would know motion, change, origination and decay, but imagine that they never made the jump to postulating a background time, a single something that can act as the condition of possibility for *any* type of change or motion or occurrence to occur.

How could we possibly go about trying to convince this tribe of geometers that there is something else besides their beloved space, something called time that is really on a par with space, with neither of the two being reducible to the other? Let us imagine a dialogue between one of the geometers (G) and a physicist (P) who is trying to point to the existence of time.

G: So you are saying that there is something very important, something called time, but which is invisible, and in general, unmeasurable as such?

P: Yes and no; time as such cannot be measured, but what we can measure is the progress of time, reflected in all motions around us.

G: Do you mean that time is some sort of field, that is especially strong and concentrated around fast moving objects?

P: No, time is everywhere, equally present for static bodies as for bodies in motion.

G: So you mean that time is like space? Is it equal to space, or is it a type of subtle ether, something that is filling space everywhere equally?

P: Neither of the above. You're searching in quite the wrong direction. Hmm. How can I explain this. In a way, space and time are such basic concepts, you can almost feel them. If you wave your hand, you are waving through space, but at the same time, it takes time to wave your hands, so you are waving through time as well. Each breath you take, your chest moves rhythmically through space and time; it is exactly the balance between the spatial and temporal motions that defines the presence of rhythm.

G: Now you are really mystifying things. Are you really asking me to believe that there is anything more to motion that what can be analyzed in a series of snapshots? What more can there possibly be, over and above snapshots? I bail out. This is getting just too ridiculous.

6 From Where and When to How

After this warm-up exercise, let us now switch to the topic of our present paper. Let us imagine a similar dialogue between a physicist (P) and a biologist (B). For definiteness, let us call the third aspect of reality 'sense.'

P: So you are saying that there is something very important, something called sense, but which is invisible, and in general, unmeasurable as such?

B: Yes and no; sense as such cannot be measured, but what we can measure are the many types of relational behavior, reflected in any and all biological processes around us.

P: Do you mean that sense is some sort of field, that is especially strong and concentrated around living objects, A type of vital spirit?

B: No, sense is everywhere, equally present for inanimate and animate bodies, and already implied by the existence of mass-energy in space.

P: So you mean that sense is like space? Is it an aspect of space, built into it, perhaps on the level of vacuum fluctuations or the like?

B: No, you're searching in quite the wrong direction. Hmm. How can I explain this? In a way, space and time and sense are all such basic concepts, you can almost feel them. If you wave your hand, you are waving through space, but at the same time, it takes time to wave your hands, so you are waving through time as well, and while doing all this, you are in some way 'making sense' within space and time. Each moment, you are making sense of your world in a different way, and so you can be said to move through a dimension of sense. When we talk about exploring the 'depth' of meaning, we use just one of many metaphors that point to meaning or sense as having a type of geometric interpretation. Similarly, each breath you take is an act, something that makes sense for you as an organism, whether you are conscious of it or not. And the most relaxed way of breathing, in fact, occurs when space, time, and sense are all in perfect balance, expressing and revealing the appropriate ratios that define the inherent know-how or embodied rationality of the action. Indeed, that way of breathing is most sensible.

P: Now you are really mystifying things. Are you really asking me to believe that there is anything more to life that what can be analyzed by physical processes occurring in space and time? What more can there possibly be, over and above the dynamics of matter and energy? I bail out. This is getting just too ridiculous.

7 Conclusion and Outlook

In retrospect, adding time to space to get motion and dynamics is such an obvious move that you wonder why it wasn't done before Newton and Leibnitz. However, inventing an effective analytical structure such as the differential calculus, and an appropriate conceptual framework for space and time, was difficult and continues to challenge the scientific imagination, since time remains an enigma.

Similarly, the addition of sense to space and time seems obvious and, at first sight, trivial. However, its consequences grow rapidly in depth and significance as the implications are pursued. They lead directly to the dilemma of the observer and the subject, which is put to one side by physics but must be faced in biology where the intentional actions of agents, their purposes and functions, are ever-present aspects of reality. Developing an appropriate conceptual structure for space, time, and sense, and effective methodologies of investigation that allow us to make progress in understanding and explaining these properties of organisms and of nature in general, is the hard work that faces us on this path. We are convinced that something along the lines suggested is the move that is now required, and we invite anyone interested to indicate how they believe that we can proceed further.

References

[1] GOODWIN, Brian, *How The Leopard Changed its Spots*, New York: Simon and Schuster (1994).

[2] HUSSERL, Edmund, *Ideen zu einer reinen Phaenomenologie and phaenomenologischen Philosophie I, Erstes Buch* (1913), translated as *Ideas Pertaining to a Pure Phenomenology and to a Phenomenological Philosophy, first book*, Dordrecht: Kluwer (1982).

[3] HUT, Piet, "Structuring Reality: the Role of Limits", in *Boundaries and Barriers*, eds. J. Casti and A. Karlqvist, Reading, MA: Addison-Wesley (1996), pp. 148-187.

[4] HUT, Piet, and Roger SHEPARD, "Turning 'The Hard Problem' Upside Down & Sideways", *Journal of Consciousness Studies*, **3** (1996), 313-329.

[5] HUT, Piet, and Bas VAN FRAASSEN, "Elements of Reality: A Dialogue", *Journal of Consciousness Studies*, **4** (1997), 167-180.

[6] JAMES, William, *Essays in Radical Empiricism* (1912), reprinted in *Essays in Radical Empiricism & A Pluralistic Universe*, Gloucester, MA: Peter Smith (1967).

[7] KAUFFMAN, Stuart, *At Home in the Universe*, New York: Oxford University press (1995).

[8] KAUFFMAN, Stuart, *Investigations*, in press (1997).

[9] MATURANA, Humberto R, and Francisco J. VARELA, *The Tree of Knowledge*, Boston: Shambala (1992).

[10] NISHIDA, Kitaro, *Zen no Kenkyu* (1911), translated as *An Inquiry into the Good*, New Haven: Yale Univ. Pr. (1990).

[11] TARTHANG TULKU, *Time, Space, and Knowledge*, Berkeley: Dharma Publ. (1977).

[12] VAN FRAASSEN, Bas, "The World of Empiricism", in *Physics and our View of the World*, ed. Jan Hilgevoord, Cambridge: Cambridge Univ. Pr. (1994), pp. 114-134.