

Universal Principles of Biological Cognition

By Marc van Duijn, Ph.D.

Distinction-making or discrimination is a fundamental aspect of sensation and perception. Several classical psychophysical laws such as Weber's law and Gestalt principles are based on our ability to make distinctions in sensory input. In the first issue of *JSP*, Joel Isaacson¹ introduced the notion of *Recursive Distinctioning* (henceforth RD) as a natural law that applies to all naturally evolved cognitive agents. According to Isaacson, RD is a universal principle that underlies all perceptual and cognitive processes. What happens in RD is that an agent capable of spatial and/or temporal distinction-making makes local discriminations on raw proximal sensory inputs and subsequently uses this new pattern, made up of local distinctions, as an input for another round of distinction-making. This process can in principle be repeated indefinitely; hence the recursive nature of RD.

The identification of this and other universal principles of intelligence can not only be used to come to a more coherent theoretical understanding of what natural cognition is as a biological phenomenon, but can also be used as biologically plausible constraints on thinking about the nature of extraterrestrial forms of intelligence. That is, the identification of such universal principles of cognition could be used to form a biologically plausible picture of the organization of intelligent extraterrestrial organisms; these principles would have to hold for the perhaps to be discovered (micro)organisms in, say, the oceans of Jupiter's moon Europa, or other intelligent life forms on exoplanets.

As a theorist working on biological cognition, I am interested in general principles of biological cognitive organization, which is why I was drawn to Isaacson's RD hypothesis. In my dissertation, I develop a modern theoretical framework for understanding biological cognition that incorporates similar universal principles of biological cognition. There is a growing need for such a modern, revised framework because of the paradigm shift that is currently taking place in modern-day cognitive science.

This paradigm shift is fundamentally changing the way in which many cognitive (neuro)scientists and philosophers have come to define what constitutes a cognitive system. Since roughly the mid-1950s, the received view holds that cognition boils down to computation or symbol manipulation. On this view, cognition is shared by digital computers and organisms with advanced brains capable of symbolic representation. Since the early 90s, however, a competing paradigm of cognition has emerged and scholars from various disciplines have increasingly argued against a purely computational view of cognition.^{2,3} Although there is still no strict consensus on the status and the contents of the new paradigm, three main theoretical changes are

¹ J. D. Isaacson, "Nature's Cosmic Intelligence," *Journal of Space Philosophy* 1, no. 1 (2012): 9.

² H. Dreyfus, *What Computers Still Can't Do* (New York: MIT Press, 1992).

³ R. Penrose, *The Emperor's New Mind* (Oxford: Oxford University Press, 1989).

prominent with respect to the classical view. These three major theoretical changes are rooted in ideas that have circulated within the cognitive sciences for a long time and now seem to re-surface partly because of new empirical evidence that vindicates these views:

(1) Cognitive science seems to be converging towards a more embedded and embodied view of cognition by also incorporating morphological, biomechanical, situational, and dynamical factors in the study of cognition. On this view, cognition is not so much a brain-bounded computational process, but rather involves the co-evolution of neuronal variables, bodily variables, and environmental parameters: cognitive systems are viewed as dynamic brain-body-environment systems that are not necessarily fully understood as computational systems.⁴ This approach also stresses the importance of perception-action coupling in the study of cognition: the different ways in which organisms adaptively coordinate perception and action is thought to be constitutive of cognition.

(2) There is a strong shift from linguistic-, logic-, and computer-based approaches to cognition to more biologically oriented bottom-up explanations of cognition. These approaches assume that biological cognition is first and foremost a biological property that first evolved in comparatively simple organisms. On this so-called biogenic view,⁵ natural cognition is a form of adaptation that confers certain selective advantages for organisms, such as allowing them to cope more efficiently with environmental complexity.⁶ Typically human cognitive skills such as thinking and reasoning are very advanced cognitive capabilities and these highly advanced skills probably do not provide a suitable theoretical starting-point for understanding the evolutionary origins and biological functions that biological cognition serves. Biogenic approaches aim to gain more headway on answering fundamental questions regarding the relationship between life and cognition as adaptive mechanisms, by attempting to specify better which adaptive functions cognition serves and to investigate how more basic forms of biological cognition are related to more advanced human-like forms of cognition.

(3) The common *brain-based* view of cognition asserts that the evolution of cognition advances with the evolution of the brain or that it coincides with some more advanced stage in brain evolution. On this brain-based view, cognition is a property that developed relatively late in evolution and is associated with typically human cognitive skills such as abstraction, symbolization, and language. The brain-based view is contested by empirical research from a variety of disciplines, as there is convincing evidence for cognitive-like abilities in single-celled organisms.⁷ The complexity of the

⁴ R. D. Beer, "The Dynamics of Brain-Body-Environment Systems: A Status Report," in P. Calvo and A. Gomila, eds., *Handbook of Cognitive Science: An Embodied Approach* (Amsterdam: Elsevier, 2008), 99-120.

⁵ P. Lyon, "The Agent in the Organism: Toward a Biogenic Theory of Cognition," PhD thesis, Australian National University, Canberra, 2006.

⁶ P. Godfrey-Smith, *Complexity and the Function of Mind in Nature* (Cambridge: Cambridge University Press, 1996).

⁷ E. Ben Jacob, I. Becker, Y. Aspira, and H. Levine, "Bacterial Linguistic Communication and Social Intelligence," *Trends in Microbiology* 12 (2004): 366-72.

behavior of unicellular organisms has long been underestimated by behavioral scientists. However, recent microbiological evidence shows that single-celled organisms already exhibit complex capabilities that are often presumed to be cognitive, like memory, learning, and action-selection. The idea that single-celled organisms are already capable of cognitive-like behaviors suggests that what we call biological cognition represents a phylogenetically ancient adaptive process that evolved long before nervous systems did.

The framework for biological cognition I develop in my dissertation⁸ is based on these aforementioned theoretical developments and is an attempt to integrate them into a coherent framework. The thesis is based on the assumption that sensorimotor coordination (SMC) is a necessary and sufficient feature of biological cognition. The notion of SMC is rooted in the work of John Dewey, whose work forms the foundation of the embedded/embodied approach to cognition. Dewey claimed that perception is not passive and stimulus-driven, but that it is fundamentally action-based; perception is a way of acting that involves SMC. By performing motor actions, organisms partially determine the sensory changes they perceive. Self-induced movements can therefore generate law-like patterns in sensory-information, which simplifies learning and facilitates cognitive processes⁹.

SMC is ubiquitous in the animal kingdom and is also exhibited by organisms without a brain or central nervous system. For example, bacterial chemotaxis is a form of SMC that provides a good example of *minimal cognition*, the most elementary form of biological cognition.¹⁰ By detecting and moving along gradients of chemicals, bacteria such as *E. coli* are able to self-optimize the conditions of their external physico-chemical environment for the benefit of their metabolic functions. By way of temporal comparison, using a form of memory that can last from seconds to several minutes, bacteria such as *E. coli* are able to detect extremely subtle changes in gradients of many superimposed chemicals and to travel up or down these gradients by alternating between running and tumbling behaviors in order to obtain nutrients or to avoid toxins or other harmful circumstances.

The two-component signal transduction system, or TCST, is a molecular sensorimotor mechanism that also operates as a molecular form of memory required for bacterial chemotaxis. The TCST system is made up out of two separate but interacting “branches” or signaling pathways: one that mediates perception, the phosphotransferase or perception pathway, and one that mediates adaptation by providing feedback on the bacterium’s receptors, the methylation pathway. The interaction between the fast-paced perception pathway, which operates at the level of milliseconds, and the slower-paced methylation pathway, which functions on the level of seconds, up to minutes, gives rise to intricate feedback cycles between the two

⁸ M. van Duijn, “The Biocognitive Spectrum – Biological Cognition as Variations on Sensorimotor Coordination,” PhD thesis, RijksUniversiteit Groningen, 2011.

⁹ R. Pfeifer and C. Scheier, *Understanding Intelligence* (London: MIT Press, 1999).

¹⁰ M. van Duijn, F. A. Keijzer, and D. Franken, “Principles of Minimal Cognition: Casting Cognition as Sensorimotor Coordination,” *Adaptive Behavior* 14, no. 2 (2006): 157-70.

pathways¹¹. Due to the interaction of both pathways on different time scales, the methylation level of the receptors is “compared” to the level of attractor and repellent occupancy at the receptors, which biases their motor responses and ultimately allows the bacterium to engage in SMC.

The key role of sensorimotor behavior in the development of human cognition was emphasized by Piaget and Vygotsky, who both claimed that the first two years of human development are entirely devoted to SMC and that the development of reasoning skills crucially depends on early sensorimotor stages. Recent research dovetails with the view that many human cognitive abilities are intimately tied to and ultimately dependent on SMC. For example, research in developmental psychology demonstrates that SMCs play a crucial role in the development of higher cognitive functions such as Theory of Mind, imitation, language, imagination, conceptual thought, and abstract thought. This research shows that many advanced ‘off-line’ cognitive abilities, which are temporarily decoupled from overt behavior, are intimately tied to and ultimately dependent on SMC. In my thesis, I argue that SMC therefore forms the phylogenetic and ontogenetic basis of human cognition.

There are fundamental similarities between the behavioral strategies of single-celled organisms and those of more complex organisms equipped with centralized nervous systems. Our claim is that these behaviors are grounded in analogous SMC mechanisms that have evolved through convergent evolution on different scales of biological organization. On this view, a plausible scenario is that due to strong selection pressures, nervous systems evolved in the first place to enable SMC at the level of Metazoa: nervous systems merely provide a practical substrate for SMC that is tailored to relatively large multicellular organisms, whereas TCST-systems and ion-channels are required for enabling SMC at the level of single-celled organisms¹². The evolution of the brain was therefore not the watershed in the evolution of biological cognition, but enabled comparatively large multicellular organisms to exhibit similar SMC strategies to those that can be found at the bacterial level. With the evolution of the nervous system the organization of biological cognition could be expanded in unprecedented ways. SMC thus provides a universal organizational principle for biological cognition that throughout evolution has taken on a wide variety of forms, yielding a broad biocognitive spectrum from bacteria to humans.

How does this approach relate to other existing biogenic approaches to biological cognition? Previous biogenic approaches often adhered to the brain-based view of cognition,¹³ or equated cognition with autopoiesis¹⁴ or life itself.¹⁵ However, I agree with

¹¹ J. J. Falke, R. B. Bass, S. L. Butler, S. A. Chervitz, and M. A. Danielson, “The Two Component Signaling Pathway of Bacterial Chemotaxis: A Molecular View of Signal Transduction by Receptors, Kinases, and Adaptation,” *Annual Review of Cell and Developmental Biology* 13 (1997): 457-512.

¹² F. Keijzer, M. van Duijn, and P. Lyon, “What Nervous Systems Do: Early Evolution, Input–Output, and the Skin Brain Thesis,” *Adaptive Behavior* 21, no. 2 (2013): 67-85.

¹³ A. Moreno and A. Lasa, “From Basic Adaptivity to Early Mind,” *Evolution and Cognition* 9, no. 1 (2003): 12-30.

Margaret Boden¹⁶ that the latter approach conflates adaptation with cognition. Although SMC is ultimately dependent on the adaptive processes that sustain life itself, in my dissertation I argue that SMC constitutes a higher-order adaptive strategy that can be distinguished from other forms of adaptation, such as metabolic adaptation, phenotypic plasticity, and genetic adaptation. Bacterial taxis behaviors are not directly part of (epi)genetic alterations or adaptive changes in growth patterns and morphogenesis (although these behaviors are of course ultimately dependent on their outcome), but rather constitute a higher-order adaptive strategy that enables bacteria to optimize the external conditions for these other adaptive processes through SMC. On this view, there is still a deep phylogenetic continuity in biological cognition, but there are also specific boundary conditions in the form of SMC mechanisms that clearly demarcate the domain of biological cognition.

Another universal principle that I discuss in my dissertation is *cognitive bow-tie architecture*. This principle is derived from work in systems biology that has identified bow-tie architecture as a universal organizational feature of biological systems.¹⁷ Bow-tie architecture is an organizational feature that is found in the vertebrate immune system, gene-protein networks, metabolic networks, and signal-transduction systems. Bow-tie architectures are global control systems that are characteristically organized around a core of closely coupled, phylogenetically conserved processes, which provide a versatile interface for a wide array of input and output processes. According to Csete and Doyle,¹⁸ the benefit of these conserved cores is that they facilitate high flexibility in the peripheral input and output parts of the bow-tie structure. These peripheral parts can therefore be more susceptible to epigenetic modulation, which allows bow-tie control systems to adapt flexibly to local conditions. This kind of architecture is the result of evolutionary optimization processes that promote organizational efficiency, robustness, and evolvability.

Bow-tie architectures are usually hierarchically organized structures made up out of several nested bow-ties. For example, Zhao et al.¹⁹ found that the topology of the metabolism of bacteria such as *E. coli* consists of a hierarchy of nested bow-tie control systems that are integrated in the global metabolism. Several authors argue that this nested hierarchical bow-tie pattern is the result of evolutionary optimizing processes and that this type of recurrent bow-tie organization is an efficient way of biological organization that enhances robustness.

¹⁴ H. Maturana and F. Varela, *Autopoiesis and Cognition: The Realization of the Living*, Boston Studies in the Philosophy of Science, vol. 42, ed. Robert S. Cohen and Marx W. Wartofsky (Dordrecht: D. Reidel, 1980).

¹⁵ E. Thompson, *Mind in Life. Biology, Phenomenology, and the Sciences of Mind* (Cambridge, MA: Harvard University Press, 2007).

¹⁶ M. A. Boden, "Autopoiesis and Life," *Cognitive Science Quarterly* 1 (2000): 117-45.

¹⁷ H. Kitano, "Biological Robustness," *Nature Reviews: Genetics* 5 (2004): 826-37.

¹⁸ M. Csete and J. Doyle, "Bow Ties, Metabolism and Disease," *Trends in Biotechnology* 22 (2004): 446-50.

¹⁹ J. Zhao, H. Yu, J. Luo, Z. Cao, and Y. Li, "Hierarchical Modularity of Nested Bow-Ties in Metabolic Networks," *BMC Bioinformatics* 7 (2006): 386.

My hypothesis is that *cognitive bow-tie architecture* is an important organizational feature of natural cognitive systems. Cognitive bow-tie architecture refers to the feedback control architecture that regulates the SMC capabilities of organisms. This type of architecture characterizes the make-up of the bacterial two-component-signal-transduction system (TCST), a highly versatile signal-transduction system that has been co-opted by many different processes, including gene regulation and chemotaxis. I hypothesize that cognitive bow-tie architecture is also a fundamental organizational feature of the human brain and, more broadly, the human cognitive system.

Given the high metabolic expenditure of brains, the principles of “using least wire” and limiting connections and energy consumption are important organizational constraints on the evolution of complex nervous systems and brains. Centralized brain mechanisms limit connection costs in brain wiring and also accommodate the need for specialized action-selection structures that co-ordinate different action subsystems that compete against each other for behavioral control.²⁰ The cores of the cognitive bow-tie architecture are phylogenetically conserved, hierarchically organized neuronal core systems, which govern progressively higher levels of sensorimotor control. Different structures along the neuraxis, such as the medial reticular formation (mRF) in the core of the brain stem, the basal ganglia, and the forebrain, provide such substrates for action-section that supplement each other and exhibit aspects of hierarchically organized or “layered” cognitive bow-tie architecture.

From a theoretical perspective, cognitive bow-tie architecture provides an economical solution for coordinating a wide variety of sensory systems, motor systems, emotional systems, and memory systems and involves reusing and sharing efficient resources such as centralized control systems. The core mechanisms are robust, evolutionary stable, highly constrained organizational units, while the peripheral mechanisms are only softly constrained structures, which form flexible sensory input and motor output pathways that are more susceptible to epigenetic modulation. This combination of evolutionary stable core systems and highly flexible peripheral systems optimizes the relation between adaptability in the short run and evolvability in the long run. We assume that cognitive bow-tie architecture is a universal feature of brain and cognitive organization and that this principle provides a way to understand how features such as modularity, hierarchical organization, co-option, and epigenetic organization are related and integrated in a global SMC control architecture.

I was contacted by Prof. Joel Isaacson a few months ago, with the question whether, and if so how, RD would fit into my framework. We are currently collaborating on an article for a future edition for JSP. We believe that there is compelling evidence that three highly evolvable co-dependent features: (1) sensorimotor coordination, (2) recursive distinctioning, and (3) cognitive bow-tie architecture are ubiquitous throughout the phylogenetic tree of life and provide universal features of biological forms of cognition, from bacteria to humans. Our assumption is that SMC is ultimately dependent

²⁰ T. J. Prescott, “Forced Moves or Good Tricks in Design Space? Landmarks in the Evolution of Neural Mechanisms for Action Selection,” *Adaptive Behavior* 15 (2007): 9-31.

on an organism's ability to perform the RD function and that RD also lies at the very foundation of cognitive bow-tie architecture.

We are aware that at this stage some of our claims are purely hypothetical, but also that these claims can easily be empirically validated or falsified. There are already computational models (Turing machines) that show that RD processors exhibit oscillatory properties that are similar to those found in bacterial receptor systems. With regard to investigating the validity of cognitive bow-tie architecture, it will be necessary to map the connectivity architecture of the human brain and the brains of other organisms to see if these do indeed exhibit nested bow-tie architecture.

It is clear that more research is required to prove beyond a reasonable doubt that these principles are truly universal biological mechanisms and organizational principles. If validated, these universal principles of biological cognition could provide a significant contribution to cognitive science. Moreover, the discovery of universal principles of biological cognition could help us to go beyond mere speculation, so that we can come to a biologically plausible understanding of how intelligent life on other planets might have evolved.

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Postscript by Dr. Louis H. Kauffman, Professor of Mathematics, University of Illinois at Chicago: Comment on “Recursive Distinguishing”

This remark will be in two parts. The first part points out that using the concept of distinction as a foundation for cognition is necessarily circular – because cognition is required to understand distinction. This is the conceptual level of this discussion. The second part is devoted to some speculation about what happens in practice when we take the point of view that systems are based in certain key distinctions. Then things flip over and it becomes clear that it is very fruitful to think in terms of distinctions and recursive production of distinctions from levels of distinction.

Part 1. Epistemology

There is a problem in identifying recursive distinguishing (RD) as a natural law. Let me put this as simply as possible. In order to have recursive distinguishing we must have distinguishing. Once there is distinguishing, then it can be applied recursively. There can be no problem with that and once one has a given system of distinctions that can be reliably performed: then systems of recursive distinguishing arise naturally and they do so arise. However, the problem is in knowing what is meant by distinguishing itself and locating just how and where this apparent act occurs in organisms and cognitive systems. What is an act of distinction? In using language this way, we come close to the limits of language itself.

There can be no definition (in the sense of mathematical definition) of the idea of distinction. To see this, note that a definition is itself a certain form of distinction. Thus any definition of distinction will be circular, involving the concept in its own articulation. In other words, distinction cannot be the basis or the natural law behind cognition because having distinction already assumes cognition and understanding. Thus there is no way to take distinction as a theoretical basis for cognition and we are left to ask and to continue to investigate how acts of distinction, acts of creation, arise in cognitive systems.

If one takes sensory motor coordination (SMC) as a necessary and sufficient condition for biological cognition, as does Dr. van Duijn, then this assumes that our ability to make distinctions arises from and is completely encapsulated by physical biology. Then, again, the distinction-making that we do as cognitive organisms is secondary to the SMC and is not at the level of basic natural law. One can point to operations of a physical system and call them “the making of distinctions,” but in fact such operations are seen to be the making of distinctions only in the eyes of an observer whose cognition is already assumed to be present before such explanations begin.

Part 2. Systems and Distinctions

Having stated this point of view about the epistemology of distinction and cognition, let us continue and comment on how it impacts scientific observation. We take an observational stance in looking at any biological or computational system and within this stance we see or design systems of distinctions that can be seen to operate in the mechanism of the system. At this level, the idea of describing such systems as

recursive distinguishing is fundamental and very useful in sorting out both the structure of the system and its creative action. This includes studying cognition, where we can see in many instances that complex cognitive structures arise by the way they produce distinctions and act upon them to produce new distinctions. In this sense recursive distinguishing can be regarded as fundamental to biological cognition. The circularity in the epistemology is fundamental also to the subject and is one of the reasons why cognition will never be explained from some set of mathematical axioms.

An example may be useful at this point. There is a famous model of autopoiesis due to Maturana, Uribe, and Varela²¹ where one makes a computational substrate consisting of “molecules” that like to bond with one another in the presence of a “catalyst.” These molecules are distributed randomly in a plane space. The result is that over time, the catalysts become surrounded by circularly closed rings of bonded molecules. These rings are seen by an observer as “protocells.” Due to the properties of the model, bonds have a certain probability to decay and molecules wander about, but with the parameters set appropriately, the protocells have lifetimes and can even be observed to interact. The key point about this model and the exciting point about it is that the distinctions (between inside and outside with the catalyst on the inside) that arise in the form of protocells do so ON THEIR OWN. Thus we see an example of a system where distinctions arise without a mind to direct them and these distinctions are then seen by an external observer. This is one way of thinking about it. The other way of thinking about it is to say that there are no distinctions between inside and outside occurring in this model except as seen by an observer.

Now consider another example. The biologists Cozzarelli, Spengler, and Stasiak devised a technique in the 1980s for coating DNA molecules with protein in such a way that the DNA appears thick and ropy under the electron microscope. They then used this technique to produce electron micrographs of DNA that convinced everyone that DNA could be knotted! One sees the weave in the electron micrograph and becomes convinced that this weave is a reality in the molecular biology. Now we all agree that it requires observers to obtain this information. We have to look at the electron micrograph and decide that the weave is knotted. But we do not, as scientists, assert that the weave does not exist without the observation. The logical sequence for us is that the observation implies the existence of the weave. The knot is implicated by our observation and becomes, through that observation, a real knot in the biochemical world.

By the same token, we must admit that many systems operate on distinctions and even make distinctions. These distinctions become real for us because we can stably observe them and, of course, we may be in the position of having created them.

What about cognition? Well again, it depends upon where you draw the line. Do you see the human visual system as an RD automaton making distinctions with distinctions and producing the high-level summaries that we take to be our vision? Then you draw a

²¹ F. Varela, H. Maturana, and R. Uribe, “Autopoiesis: The Organization of Living Systems, Its Characterization and a Model,” *Biosystems* 5 (1974): 187.

line where cognition appears through the visual system. But also vision appears through the conceptual lenses that we wear (the Kantian *a priori* if you will) and this is also an RD system. And so we back up and put that on the automatic side of the line. We can do this again and again until there is nothing left on the other side except our awareness and our understanding. Awareness and understanding are described by us as whole-system properties and so we come full circle.

There are those who believe that awareness and understanding are whole-system emergent properties of the underlying RD automaton of our biology. There are those who do not believe this and imagine that there is something extra. And there are those who reason as I have reasoned above and conclude that cognition is fundamentally circular and that it is illuminated by a combination of the automatic and the aware.

At this point I will read this essay again from Part 1 and I suggest that the reader rethink these issues as well.

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Response to the Postscript by Joel Isaacson

Dear Lou,

I followed your suggestion and read your comments thru a number of rounds. Following are the thoughts that occur to me.

In regard to Part 1, Epistemology, your pointing out the circularity between a first distinction and primordial cognition is important. This, indeed, represents a fundamental dilemma. The question though is: does this basic dilemma warrant conclusions about RD as a natural law? My thinking at this time is no.

To see this, I invoke the classic chicken-or-egg dilemma (COED) which shares the same circularity as the dilemma that you pose. For all I know, COED is undecidable. Yet, no one who deals with COED concludes that nature does not produce both chickens and eggs in abundance. So, there is separation between logical undecidability and the natural phenomena in question.

(As a side comment, I think that assuming linear-precedence logic in inherently circular situations, i.e., A entails B and B entails A, may be part of the problem in formulating and resolving COED. Some sort of dialectical logic, where both A and B are co-dependent and concurrent, perhaps in rapid oscillation, may be worthwhile. But I make no claim to resolving COED.)

Now, RD as natural law is advanced as a hypothesis, subject to verification or falsification. So, the issue of whether or not RD is a natural law is not acute for practical purposes. The issue is whether RD, especially when expressed as an automaton, is practically useful for the cybernetic study of biological cognition. I think that, in Part 2, you amply indicate that it is.

Your comments on the requirement for an aware observer are acceptable to me, as is your comment on symbiosis between RD automata and aware humans. Here, the tree-in-the-forest dilemma may be invoked, where some people can argue that in the absence of a hearing agent no noise would be generated by such an event.

In RD automata the role of an observer is perhaps more subtle. Looking back at how RD automata have been developed, it is clear to me that the automaton, by itself, is not aware of its performing RD. I have happened to be the observing agent who constructed after the fact, thru meticulous observation and awareness, the patterns of RD that are generated by RD automata. So, I am inclined to accept that a mix between the automatic and the aware is, as you propose, a good way to go in thinking about these matters.

So, with all your reservations and caveats from both Part 1 and Part 2, I think that the bottom line is that RD automata are potentially useful for the study of biological cognition.

In as much as RD concepts are missing so far from cybernetic thinking (there certainly has been a lot of talk about distinction and about recursion, but not on the tight combination of recursive distinguishing) I think that it would be important to inform our cybernetic community on the potential of RD. Perhaps add it to your thematic list that you proposed recently.

Best,

Joel

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About the Author: Marc van Duijn studied experimental and theoretical psychology at Leiden University and the University of Toronto. In 2012, he received his PhD in theoretical philosophy at the University of Groningen, the Netherlands. His research focusses on the interrelationship between biology and cognitive science. Currently, he is a lecturer at the Faculty of Sciences at the Free University of Amsterdam. Email: Marc.van.Duijn@gmail.com.



Editors' Postscript: The leadership of Kepler Space Institute and *The Journal of Space Philosophy* thank Dr. Joel Isaacson, Dr. Marc van Duijn, and Dr. Louis Kauffman for each of their contributions to the science of this critically important subject for all of humanity and for those in the Space Sciences planning the future of humans in Space.

We want to make an important macro point. Stephen Hawking and Leonard Mlodinow, in their 2013 book *The Grand Design*, write the following:

Philosophy is dead. Philosophy has not kept up with modern developments in science, particularly physics. Scientists have become the bearers of the torch of discovery in our quest for knowledge.²²

While Stephen Hawking and Leonard Mlodinow were right in that general statement about the relevance of philosophy to science, in that philosophy is often some way behind the cutting edge, refocusing philosophy to make it more relevant might be a better solution than abandoning it. That is exactly why we have dedicated *The Journal of Space Philosophy* to staying ahead of modern developments in the Space sciences. The discoveries by Dr. Joel Isaacson of *Nature's Cosmic Intelligence*, this related article by Dr. Marc van Duijn on *Universal Principles of Biological Cognition*, and the comments above by Dr. Louis Kauffman all place them as the bearers of the torch of discovery in the sciences of Intelligence and Cognition. Our Kepler Space Institute Team members are privileged to document their discoveries and their theories. Assisting in creating needed new research to advance the discoveries and the theories of Space sciences is a major part of Kepler Space Institute's mission and vision. [Bob Krone and Gordon Arthur](#).

²² Stephen Hawking and Leonard Mlodinow, *The Grand Design* (New York: Bantam Books, 2013), 1.