An interesting path still fraught with uncertainty

« 7 » Totaro and Ninno are ambitious, as they decided to tackle a most central problem in the theory of cognitive systems. We have to commend their *panache*, more than 50 years after the publication of DMSV, since they want to derive – from first principles – how the nervous system constructs the conceptual categories of the discrete and the continuum. Their partial solution, to untangle the self-referential recursion (*Obs, Obs*(*Obs*), *Obs*(*Obs*(*Obs*)), …), is a small step in increasing our ability to manipulate the Umwelt that we are continuously building, but much more is needed. The problem of formalizing *self-fabrication* and *cognition as action* is extraordinarily complex, and we are still at the very beginning of this path (Valdés-Zorrilla, Letelier & Soto-Andrade 2023).

« 8 » What Totaro and Ninno write in §41 underlines the complexity of the task at hand. There they claim that they have formalized the concept of *observing* (à *la* Maturana and Varela) using notions of recursion, organization and structure. Furthermore, in Footnote 2, they claim that they have created a framework called "Environment Generative Operator" (EGO), which incorporates notions from autopoiesis, George Spencer Brown's indicational calculus and Donald Hebb's notions of neural assemblies. While there was not enough space in their target article to present the details of the EGO framework, they have shown a pathway, a possible *route* in the language of mountaineering, that we should follow and complete. Perhaps this pathway, hinted at but not yet traversed, is the *Schwerpunkt* that needs to be pursued.

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As a Professor at the Universidad de Chile, I enjoy my time doing quantitative neurophysiology at various organizational levels (from single-cell recordings to EEG). I also devote some of my time to thinking about how living systems construct their world by acting upon their multifaceted perceptions, and sometimes I build very practical gadgets.

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Distinguishing Two Kinds of Recursion in Maturana's Theory: A Necessary Step Before Addressing the Continuum/Discrete Distinction

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> Abstract • As it is a central element in Totaro and Nino's hypothesis, I critically examine Maturana's concept of recursion and its relation with the emergence of the observer. I suggest that two different types of recursion should be distinguished, i.e., linear and hierarchical, each of which has different properties and explanatory roles. The latter type is the one that serves as a generative mechanism of language and observing systems. I suggest that accepting this conceptual distinction as useful could refine Totaro and Nino's hypothesis.

Handling Editor • Alexander Riegler

« 1 » Paolo Totaro and Domenico Ninno (T&N) aim to explain how the properties of the continuum and the discrete emerge in our experience as observers. They propose recursion, understood in terms of Humberto Maturana's biology of cognition, as the key process in the generation of the experiences of the continuum and the discrete (§3). The proposal, built on a mathematical formalization of Maturana's theory of the observer, is ambitious, complex, and has many aspects that deserve an extended discussion that goes beyond the scope of this commentary. Here, I focus on the notion of recursion and its relation with the observation process, given the centrality of this relation in T&N's hypothesis. While remaining agnostic about the specific content of T&N's thesis, I would like to draw attention to the concept of recursion presented by Maturana, as it has a critical but usually overlooked ambiguity. Clarifying this ambiguity may require us to review, rethink and reformulate T&N's thesis regarding the cognitive origins of the continuum and the discrete.

Observing, language, recursion

« 2 » I agree with T&N that, in Maturana's theory of the observer, the concept of recursion plays a central role. On the one hand, according to Maturana, an observer is essentially a languaging system that makes distinctions in its experiential flow. Humans, for example, are observers to the extent that (and while) they "make distinctions in language" (Maturana 1988: 26). So, there is no observer without language. On the other hand, recursion is the key generative mechanism of language (Maturana 1978). Maturana characterizes language as a recursive phenomenon in the consensual coordination of behaviors between organisms (Maturana 1978, 2002; Maturana & Varela 1987). So, there is no language without recursion. Thus, we have, by implication, that there is no observer without recursion, as recursion is, ultimately, the generative engine of observing.

« 3 » All this looks coherent and straightforward within Maturana's conceptual framework, and T&N seem to rely on this appearance in using the concept of recursion to hypothesize on the origins of the continuum and the discrete. However, the concept of recursion in Maturana's theory is not univocal. It comes in two different senses: linear and hierarchical. Unfortunately, neither Maturana nor the secondary literature sufficiently distinguish these two senses and routinely conflate them. In their target article, T&N do not seem to escape this situation either. If this is so, the question that naturally arises is: exactly what kind of recursion, linear or hierarchical, is behind the generation of the observer and her observations? And, if T&N's hypothesis is convincing, what kind of recursion is behind the experiences of the continuum and the discrete? Note that answering this question proves critical for T&N's hypothesis, which is built precisely on the relation between recursion and observing processes (§13).

Linear and reflective recursion

« 4 » Linear recursion occurs every time an operation is applied to the result of its previous application. One way of viewing this kind of recursion is as a historical phenomenon. Scanning a picture over and over again using the same original picture is an instance of (mere) repetition. Scanning the product of the previous scan over and over again is an instance of recursion. Whereas, in the first case, the copies are not historically linked, in the second case, they form a historical chain. Biological evolution (or natural drift, to use Maturana's term), is an example of this kind of recursion (Maturana & Varela 1987). Another way of viewing linear recursion is in terms of the coupling of a repetitive (circular) process to a linear one.

> "When a repeating circular process becomes coupled with a linear one that displaces the circumstances of the repetition, the repetition of the circular process becomes a recursion, and a new phenomenal dimension appears." (Maturana, Mpodozis & Letelier 1995: 3)

This recursion is taken to be fundamental in living beings:

> "In biological systems, recursion is a fundamental dynamic, because of the circular character of biological processes and the linear character of the relations between a living system and its changing medium." (ibid)

« 5 » T&N seem to follow this interpretation when introducing and analyzing the recursive processes characteristic of living beings (§3). Yet, however fundamental for living beings, this recursion cannot be the one that explains the emergence of the observer (through the emergence of language) because, once examined, it proves to be a trivial condition of any physical change or transformation. The classic examples of this kind of recursion offered by Maturana, in which the cyclic operation of wheels (or legs) placed on the ground generates the displacement of a body (Maturana, Mpodozis & Letelier 1995; Maturana 2000; Maturana & Poerksen 2004), applies indeed to any change or transformation in the physical domain. Any displacement, movement, or change of any entity, biological or not, can be described as recursion in this linear (sequential) sense. Moving a pendulum once and again from point A to B is a repetition process. Producing molecule C by combining molecules A and B, then combining molecule C and B to produce molecule D, and so on, is a recursive one. Autopoiesis and any other biological process, whether exhibiting a circular fashion or not, prove to be trivially recursive in this sense.

« 6 » Maturana (1978, 2002) asserts that language and observing emerge through a recursive process in the domain of communicative behaviors, but this cannot be simple linear recursion. To explain how or why languaging and observing are specifically different from simple communicative interactions in which non-languaging (or pre-languaging) organisms merely trigger one another over time in a coordinated way, a different type of recursion is needed, i.e., *hierarchical* recursion. Hierarchical recursion escapes linear logic and entails creating a second-order operational level that subsumes a more basic one. An example of this hierarchical relation can be found in Ross Ashby's (1960) notion of ultra-stability. An ultra-stable system is a system with two interconnected homeostatic circuits, the first one controlling one or more variables, and the second one controlling the first homeostatic circuit. From the point of view of control theory, this means having a hierarchical system where a control system is, in turn, controlled. According to Maturana, when this kind of recursion occurs in the domain of linguistic behavior, language arises as a meta-level of consensual behavioral coordination.

> "When linguistic behavior takes place recursively, in a second-order consensual domain, in such a manner that the components of the consensual behavior are recursively combined in the generation of new components of the consensual domain, a language is established." (Maturana 1978: 50f)

And, in turn, "with languaging observing and the observer arise" (Maturana 1988: 46). As with any recursive process in the physical domain, hierarchical recursion trivially has a linear dimension, too, i.e., it acts upon the result of its previous application. In addition to this recursive dimension, it creates a new, higher level that operates over a more basic one. It is this second sense of recursion, the hierarchical one, that does the distinctive explanatory job in Maturana's theory of language and observing.

« 7 » I suggest that this is the type of recursion that T&N should explore as the cognitive origin of the continuum and the discrete in our experience. Hierarchical recursion appears as the generative process of

observing. Or should we assume that T&N's hypothesis builds on a different, broader picture where both kinds of recursion are explanatorily important in their own right? Q1

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Challenges for Connecting Life and Computation

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> Abstract • Totaro and Ninno explore a central relationship between mathematical reasoning and the biological foundations of life. While the argument is grounded in embodiment, I raise experiential, enactivist, and practical challenges to the generalizability of the argument to axiomatizations of biological processes. Incorporating scientific practice in how modeling tools are used, and connecting it to coarse-graining in philosophy of mind and science could provide a valuable alternative interpretation.

Handling Editor • Alexander Riegler

« 1 » Paolo Totaro and Domenico Ninno make a compelling argument for locating the origin of continuous and discrete perception, building on Humberto Maturana and Francisco Varela's early work on autopoiesis and self-organization. They view mathematical reasoning as a biologically grounded practice that could benefit from an analysis of the basic observational and sensory processes of biological organisms, because it is an error to keep "mathematics separate from our body and its phylogeny" (§2). The question they seek to answer "concerns the 'biological' conditions of possibility that make the experiences of the discrete and the continuum comprehensible" (ibid). The assumption here is that recursion in biological perception arises from the dynamics involved in maintaining the system's own autopoietic processes, and the question arises of whether this recursiveness is, in principle, necessary for mathematical understanding as well. The authors aim to reconnect mathematics with the embodied roots of our thinking, which offers an interesting enactivist view of formal sensemaking.

« 2 » The argument presented in the article starts from the assumption that subjective experience emerges from recursive loops in biological self-organization:

> "[B]iological processes are recursive because they operate to preserve their ability to operate, that is, to keep unchanged the relations between their components that ensure such an ability." (§3)

While this is consistent with the work of Maturana and Varela, it is an open question how well the argument generalizes when we consider contemporary perspectives on the emergence of experience. Currently debated models of conscious experience discuss its origin as computational or neurobiological processes that do not explicitly depend on recursion:

- Integrated information theory (Tononi et al. 2016), proposes that subjective experience arises from a specific integration of information in a neural network;
- Global workspace theories (e.g., Baars 1988) locate conscious experience in a specific brain structure that acts as a transmitter for unconscious parallel neural processes; and
- Dendritic integration theory (Bachmann, Suzuki & Aru 2020) provides evidence for the emergence of experience at the level of individual cortical pyramidal cells.

These are just a few of the highly cited approaches that present the origin of experience as not necessarily dependent on recursion as presented by autopoietic research. Since these recent approaches suggest that biological recursion may not be necessary for experience, does the argument presented in the target article explicitly depend on the assumed autopoietic origin of experience? How could it be generalized to other theoretical approaches to conscious experience? Q1

« 3 » In terms of the broader scope of the argument presented and the biological metamathematics proposed, the target article appears at a time in cognitive science when computationalist and embodied approaches exist in parallel. After the conceptual challenges of enactivism to the previously dominant cognitivist and computationalist paradigms, the expected paradigm shift has not occurred, and representational approaches without embodied dimensions are still dominant in computational neuroscience and machine learning. Enactivist researchers need to rethink how to communicate their formal challenges to computational functionalism