It Is Time to Dissolve Old Dichotomies in Order to Grasp the Whole Picture of Cognition

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Abstract. Models of efficient computation aiming for artificial general intelligence routinely draw a wealth of inspiration from the human brain and behavior. This applies to many diverse details and building blocks, and the most notable ones so far are artificial neural networks. As soon as it comes to more general architectural and algorithmic questions difficulties arise as there is a wide variety of models purportedly describing the basis and the working of specific mental processes. Here, it shall be sketched how a novel cognitive architecture under the name of the Ouroboros Model allows the reconciliation of many competing views by offering an overall conception, in which earlier attempts can be traced to specific and limited perspectives focusing on particular features, tasks and contexts. It is claimed that the Ouroboros Model constitutes a novel and promisingly comprehensive approach, which is still waiting exploitation for detailed formalization, modelling and working implementations.

Keywords: Cognition · Schemata · Iterative cyclic processing
Discrepancy monitoring · Consistency curation · Self-reflective
Self-steered · Autocatalytic

1 Introduction

Since their start, the human brain has served as a model and source for inspiration for endeavors to understand abstract cognition and to create an artificial thinking machine. Phrenology as developed by Franz Joseph Gall more than 200 years ago probably was not the first attempt to link anatomical features of a skull to traits in character and cognitive performance of an individual. Nowadays, deep neural nets, inspired by living neural networks in brains, constitute the summit of artificial cognition with computer programs beating world top champions in chess, GO and *Jeopardy!*

There is still room for improvement, e.g., relating to learning and the requirement of extensive training on a large body of material, – in stark contrast to one-shot learning available to living brains. In order to further advance general artificial intelligence it thus seems wise to again look to brains for clues. The problem that immediately arises is that there is not one accepted theory of how a human brain produces cognition. Rather, incoherent patchworks of models for different parts and functions with contradictory detailed assertions have been proposed over time. This makes it difficult for reverse engineering and to select some functionality for promising formalization.

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2 Dichotomies, All Over

Various disciplines contribute to our investigations of minds, often incommensurably, and riddled by many disparate approaches. Examples, where two options, even if fuzzy, are viewed as mutually exclusive alternatives span a vast range of levels of abstraction. In the following, a selection of well-known dichotomies is briefly presented. Emphasis is on providing an overview, aware that the choice and descriptions of the highlighted features cannot be comprehensive; still, it is meant to be representative in a sense, considering key areas and multiple telling perspectives.

Analog – Digital. Many proposals have been made concerning the code(s) employed by single nerve cells and the human brain as a whole. Noisy neurons, continuously, sometimes erratically, varying input signals, and population codes contribute an analog flavor while stable percepts, gestalts, and decisions show digital qualities [1, 2].
Bottom up – Top Down. Whether early influences from sensory signals or biases imposed by later and higher stages are seen as most important seems to be an eternal chicken-and-egg question. In a modern guise, top-down accounts have been become fashionable under the label of predictive coding [3, 4].
Parallel – Serial. This distinction runs along similar lines as the ones between bottom-up and top- down processing and also early versus late deployment of attention; earlier a more principled question, it lately is seen as pertaining mainly to multitasking [5, 6].
Cognition – Affect. Although often posited in popular accounts as irreconcilable opposites, there is plenty of evidence that (human) rational decisions involve and demand substantial emotional underpinning [7, 8].
Two Systems: Fast – Slow. Related, but not completely along the same rift as between cognition and affect, runs the purported distinction between fast, automatic, effortless and unconscious processing (by "System 1") and slow, considerate, effortful and conscious processing (by "System 2") [9, 10].
Emotion: Early – Late. Often regarded as a most specific characteristic of humans, of animals at the most, "true" emotions were long taken as impossible to be understood on a deep level or to be genuinely exhibited by artifacts [11–13].
Attention: Early – Late. Agreement appears to develop in the literature that attention has several facets and attentive processes work on different levels of abstraction [14].

Questions touching on possible implementations like embodied/embedded or in hard-/software further add to the complexity. As an example, just looking at the wide variety of the diverse memory systems and functions, which have been proposed, exhibits a rather unsatisfactory state of affairs and highlights the necessity of some overarching frame and comprehensive approach.

One commonality, though, appears to be shared by all the enlisted dichotomies: not one has been concluded with the same intransigence as shown during the height of their respective discussions, i.e., just agreeing on one alternative and fully rejecting the other for good. It rather looks everywhere as Gordon Logan once summarized [5]: "it depends". Common dichotomies surface under different titles; the proclaimed distinctions obviously are not mutually independent.

How these dependencies can be understood and how they could all be covered under the overarching framework of one cognitive architecture and thus provide evidence for that particular conceptualization is proposed after it has been shortly introduced in the next section.

3 The Ouroboros Model in Brief

3.1 Memory Organization

The Ouroboros Model holds that memory records are organized into cohesive chunks, schemata [15]. New entries as distinct records of any concurrent activation, preferentially committed to storage at times, which are experienced as important and meaningful to an agent [16].

A rather well-defined parcellation of memory content allows the confined activation of complete entries from fragments of the original content, i.e., pattern completion, the generation of anticipations and relevant predictions, and, at the same time, an activated frame enables straightforward appraisal of current activity in the light of previous experience. Information thus is easily available to Bayesian processing, and this is not restricted to actually encountered features but applicable also to ones, which are expected in a context but do not actually occur [15, 17, 18].

3.2 Iterative Processing

The Ouroboros Model has as its backbone a self-reflective and self-referential recursive process with alternating phases of data-acquisition and -evaluation, comprising the main steps: … anticipation, action/perception, evaluation, and new anticipation, … These steps are concatenated into full repeating cognitive cycles each build-ing on its predecessors and thus evolving over time with a clear forward direction.

A central monitor-process termed ‘consumption analysis’ is intermittently checking how well expectations triggered at one point in time fit with subsequent activations.

The outcome of this monitoring, a universal form of consistency checking, marks discrepancies and entails impacts on various (time-) scales: short-term, it highlights “open slots”, i.e., attributes that belong to the one selected schema (task set) but are not yet confirmed by currently available input, and, partly more long-term, it provides feedback for an actor on how matters develop, both as basis for autonomously directing future steps and the also meaningful allocation of (attentional) resources [19].

The set-up with one fundamental consumption analysis process working in the same way on all content, which is available in the format of schemata, allows a straightforward implementation of process-hierarchies, self-reflection and many other meta-levels as the hierarchy of the schemata is simply “inherited”.

Strictly adhering to their order and succession of non-overlapping time-frames for full activation precludes possible problems, which might arise from simple concurrent circularity. Not everything, which is computable, is also meaningfully predictable.

4 Dichotomies Dissolved

In the following it shall be tried to show how the above purported dichotomies can be reconciled and thus made effectively disappear by changing from myopic views centered on isolated opposites to a wider imbedding in a single comprehensive model, which offers a markedly different compound of alternating perspectives.

The Ouroboros Model can be seen as schema-, i.e., model-based as well as data-, i.e., input- or event-driven, and also as value-guided, as values and goals are just examples of peculiar high-level abstractions and schemata. Overcoming in essence static perceptions, bottom-up and top-down activity unfolds incrementally in iterative cycles progressing in time. This interplay is effectively implementing Bayesian mechanisms and approximates optimum performance [15, 17–19].

The overall processing in the Ouroboros Model brings forth a self-organized direction and prioritization towards what is currently experienced as relevant and also expected to be so in the future. Consumption analysis triggers the allocation of attention, gives rise to emotions, determines what is put into (long-term) memory storage and calls for stronger (conscious) engagement in cases where automated responses or habits do not suffice [16]. This directly opposes any "echo chamber" effect: the emphasis self-consistently is on widening the mind frame, especially if such need arises.

4.1 Analog – Digital

The Ouroboros Model of cognition is based on hybrid representations. It holds that the initial predominant mode of operation at the procedural level is analog, and dis-tinct digital (abstracted) representations are built thereupon. Snapshots and schemata by definition mean chunks with boundaries, which bundle (at least partly analog) representations; schemata thus qualify as being of a hybrid analog-and-digital nature. The consumption analysis process, as most processing by neurons generally, first involves analog values (e.g., during evidence accumulation); thereupon, by means of employing thresholds and nonlinearities, 'digital' abstractions are built up.

A proposal of how fine-grained and continuous intermediate values might then again be calculated, i.e., interpolated and extrapolated, from inevitably patchy and stepped representations in vertebrate brains (with content sparsely coded in distributed arrangements over wide-spread cortex areas) by cerebellar structures, has been presented recently [20]. In that context, the massive signals conveyed by climbing fibers would be clearly of 'digital' quality when signaling the coincidence between a supporting value and an ongoing interpolation.

4.2 Bottom up – Top Down

The Ouroboros Model naturally explains these two processing directions as segments of one integral general cognitive loop, where the respective emphasis is put on distinct points in time, which are selected as relevant and highlighted as the begin of distinguished phases.

Predominantly bottom-up effects like the capturing of attention by movement are a straight extension of directly wired reflexive responses. Top-down modulation consists in the guiding of activity by an activated schema, which can facilitate the detection of a specific attribute but can also mean more global orientation from high-level plans or aims; open slots generally bias specific constituents.

The direction of the processing stream appears to change intermittently; basic periodicity and alternating phases can be easily discerned.

Over the last years, a top-down approach called "predictive coding" has gained some popularity [21]. Whereas the different conceptions under this name certainly constitute an advancement over earlier uni directed bottom-up/feature → Gestalt accounts, they still are rather one-dimensional (and predominantly serial), just reversing the main direction of the purportedly dominant information flow postulated as decisive. This branch can be understood as a limited view of the "backward-directed" phase of the Ouroboros Model; how some flaws of this picture can be understood and corrected by taking a comprehensive view has been outlined recently [22]. The situation here is somewhat similar to that with respect to production systems, which emphasize if → then rules and do not so much put in the foreground the levels, which are involved. Conditionals can in any case be mapped to the filling of an open slot in an active schema [15, 19].

Emphasizing the interplay between features belonging to different levels of abstraction in the hierarchy of schemata, and outlining the all-important iterative processing thereupon, the Ouroboros Models breaks any one-dimensionality and obviates simple and always-dominating forward or backward directions.

Shedding light on inconclusive discussions, some fundamental complication arises immediately: when cutting a full circle open in twain in order to obtain a linear succession of steps, it is possible to pick out various points as beginnings or ends, yielding in turn quite dissimilar perspectives and interpretations.

In front of the background of longer time scales, the whole machinery, which makes a particular sensory signal pop out, does this on the basis of tuned sensory channels, and can be understood as evolved as a consequence of lengthy bottom-up processes [23]. The higher levels providing their bias had first to be established by a proper combination of signals and tokens representing lower level components for a species in animals' brains when adapting to prevailing (living-) conditions. Learned categorizations reiterate the process in the short time frame available to an individual.

4.3 Parallel – Serial

There cannot be any doubt that over longer intervals and for complex tasks cognitive processing steps are performed in an overall serial succession. On the other side of the coin, given the long time constants of neural hardware, formidable parallel processing must be harnessed by brains in order to achieve the observed high performance and speed in many difficult tasks.

According to the Ouroboros Model, a basic recursive process progresses in real time in a piecewise serial fashion while concatenating stages, which are intrinsically parallel, into one principal iterative loop [15]. For non-trivial tasks, some nesting of loops will be demanded; this is in the focus of ongoing research, and only a simple draft picture without recursion is presented here.

With one promising schema selected (in parallel), consumption analysis draws together all activity at specific assessment points in time, one after the other; then, all concurrent activation (in parallel) is considered. The monitoring of overall consistency at regular intervals enforces a succession of phases and steps at the global level.

4.4 Cognition – Affect

Consumption analysis as described in the Ouroboros Model lies at the very core of efficient rational cognition. The proposed lay-out is implementing Bayesian reasoning and constraint satisfaction; this, on different time scales and levels of abstraction, it points out specific discrepancies, directs attention, and it delivers a feeling-component as an overall result of an appraisal process [19]. The feeling-quality of emotions is thus explained as indispensable global feedback from consumption analysis. Emotions are a fundamental result of and ingredient to all ongoing (mental) activity; they set the principal stage for subsequent actions. Emotions, and in particular, moods, are a more long term addition to the immediate "cognitive" effects of pointing out specific discrepancies and biasing specific open slots in an activated schema.

As one of their essential constituents, feelings associated with previous experience 'mark' basically all schemata. Emotion-tags are components of concepts, very similar to other attributes. Action in a healthy brain is thus guided and biased not only on a short time scale by the momentary feedback and prevailing emotion just as by other relevant dimensions, but also essentially, more generally and long-lasting, relying on previously established affective values. On top of this comes the new (overall) feedback on global performance and well-being.

Many constellations involving diverse inherited tags and ongoing evaluations are possible; this might even lead to akrasia, i.e., acting "against one's better judgment".

Affect and cognition are inseparably intertwined; curiosity might serve as an example: any frame invites for the inspection of its holes and boundaries, - at least for such inclined agents. The unknown can be alluring and/or scary. Even in the absence of any strong urge to investigate, perception, as described by the Ouroboros Model, is predominantly an active process. If actions yield results as anticipated or even better, positive emotions are evoked [15]. Mismatches, e.g., concerning the effect of an action, yield a negative feeling component.

4.5 Two Systems: Fast – Slow (Pre-/Un-Conscious – Conscious)

A principal contrast between fast automatic intuitive unconscious and assumed parallel (implicit) versus (explicit) slower, effortful deliberate, analytical and serial working stages of human cognition, has been postulated as effective during perception, in particular, for visual search, and also for many other processes [9, 10].

In the context of discovery, an influential model of intuition has been suggested some time ago [24]; Bowers and colleagues started from the observational fact that subjects can often respond discriminatively to tacit perception and a hunch of coherence that they cannot yet identify. They claim that subliminal detection of coherence is what guides such decisions and propose a two-stage model. First, clues to coherence would activate relevant material with, second, a threshold for consciousness potentially

being crossed with increasing activation. Mainly unconscious processing would be a precursor to a distinctly different process of conscious checking whether a suspicion holds. The transition between these two states would be often experienced as sudden gestalt-like perception or insight.

Over the last years experiments have been performed by different groups showing good correspondence with Bower's ideas [10, 24]. A straight-forward interpretation of the experimental results fits perfectly with the Ouroboros Model.

Starting with a first percept, this activates a schema resulting from a competition between different options. In case there is no doubt about the winner and the selected schema is very well established, open slots will be biased strongly, and action will be triggered without much further iteration. In particular, no extensive spreading of activation and no excitation in higher personal and language-levels will occur: fast intuition of an expert typically yields good results. Only at the end or in hindsight the actor becomes conscious of the event as the threshold for action has been crossed [25].

If, however, it is not so clear from the start what schema to consider and how to delineate and fill-in slots activation has to spread and evolve in many iterations. This raises the general level of activity, and High Personality Activation (HOPA) ensues [25]. This tedious process certainly requires effort and time: conscious dedication. Thus, the Ouroboros Model offers a specific and well-motivated version of a type Global Workspace or Higher Order Global State theory and sheds light on some of their main tenets [26–28].

Funny enough, for cases where effortful search and thinking does not yield any satisfactory result, i.e., consumption analysis signaling that discrepancies remain and no fit with a consistency-value above the demanded threshold has been found, decisions, when forced to be taken, are again experienced as "intuitive". This might be the case under severe time-constraints when action will be taken on the best basis, which is available at that point in time, i.e., the schema, which has received most activation up to that moment. Clearly, both manifestations of intuitive action share some "jumping to a conclusion" without taking time (or being able) to deliver a consistent narrative and justification, associated with a certain feeling of uneasiness due to un-filled gaps.

Important to note: there is one memory organized into schemata and one consistency-curation process involved. What is different and gives rise to the impression of qualitatively distinct processes is the relative, quantitative, strength of schema activations and the detailed way to (satisfactory) highest level consistency. No mystic ingredient is required for escalating from very simple perception → reaction connections to the highest human performance levels of conscious rational thought.

Whereas there is complete agreement on a coarse scale with two-systems accounts, i.e., concerning the apparent succession of two dominating principal stages, the Ouroboros Model posits firstly quantitative differences in the required operations during each stage over time, with wide-ranging iterations only for "System 2".

4.6 Emotion: Early – Late

According to the Ouroboros Model, emotions are compound activations with se-mantic content and context including bodily (re)actions and sensations and a "feeling" - component with qualitative and quantitative features like positive/negative value and strength. Focusing on the valence, i.e., the sign, of an emotion, it is hypothesized that this is nothing but a more general part of the feedback delivered by the consumption analysis process. Matters can develop as expected; progress can be worse or even better than hoped for. Such assessment is stored with all other concurrent activations when an entry for a particular occasion is fixed in memory. Never-seen-before content thus obtains its first affective qualification; in this case, emotions clearly come after some appraisal and evaluation of a situation.

Upon later reactivation, semantic content and also the associated emotional tags are effective; a concept has inherited emotional dimension(s). For previously encountered schemata an affective component might be activated significantly faster than semantic attributes, especially for strongly marked content; in this case, emotions are evoked fast and before any substantial activation of a percept and its (new) evaluation.

It is claimed that this sketch of an analysis can explain why it was possible that eminent researchers had fierce arguments on the primacy of emotions versus cognitive contributions; both sides were right (but only partly, each for their perspective) [11, 12]. So, as before, potential discrepancies and misconceptions derive from cutting at different points through overall cyclic processes.

4.7 Attention: Early – Late (Bottom-up – Top-Down)

This closes a circle and brings the argument back to brief time scales. Diverse models have been proposed for set-ups with more than one bottleneck for attention, which are explained as resulting from serial processes and (the transition between) different stages of perception [14, 29].

Taking vision as example, attention can be triggered automatically by an approaching movement, and it can be devoted to something as the result of extensive conscious deliberations. The first, according to the Ouroboros Model, arises from the immediate triggering of an established schema and pattern completion; the latter means attempts of filling-in open slots in schemata, revising experienced gaps or inconsistencies.

As described under the headings parallel – serial and top-down – bottom-up, selections between available alternatives (in parallel) occur at several processing levels in iterations. According to the Ouroboros Model, the basic neural (higher up: cognitive) processes stay the same, irrespective of the involved content; what changes, are the employed schemata and their relevant dimensions. Loops will be nested. A comparison between actual input and expectations based on previous experience, i.e., consumption analysis, determines where to boost the sensitivity for further input and what schemata and components to inhibit, respectively [15, 19].

Biases thus can effectively be exerted from all levels, not only the "higher" ones in the associated hierarchy. Depending on the sophistication of an activated concept or percept, fully grasping it might require several iterations, and the required associated attributes might be situated lower (earlier) and/or higher (later) in the processing hierarchy (and sequence) when starting from an arbitrary fresh input. Analysis and synthesis are inevitably and inseparably intertwined.

As one last example and closing that loop, it was only to be expected that attention has also been characterized as being an "effect", rather than a "cause" [30]. Following the assessment of the current state of an animal and its environment, a filter-like function is claimed to result from the workings of a conserved circuit motif for value-based decision making, which employs the basal ganglia (preceding the emergence of neocortex); – fitting nicely as implementation detail with highlighting features in an activated schema [15, 19].

5 Conclusion and Future Work

A pervasive human predisposition to think in black & white, i.e., in pairs of dichotomies, can be overcome for the case of cognition by dissolving mistaken contradictions and thus accommodating previously incompatible alternatives in one overarching framework as given in the Ouroboros Model. Details still need to be worked out but it can be stated already that many of the features of a postulated standard model are incorporated, and some key differences can quickly be outlined [31]. Most important, the cognitive cycle is "put to work" in a meaningful way, surpassing by far a mere adjustment of predictions; outcomes of iterations have well-defined functional roles in advancing the behavior and also the future set-up of an agent. One structured memory is the substrate for all actions, only the detailed demands, circumstances and the activation in iterative phases produce the impression of disjunct entities. This also applies to other attempts of comprehensive conceptualizations with even more elaborate distinctions of memory functions [32].

Time is the decisive factor for un-reflected action following simple rules as well as for full rationality at its highest (meta-) levels. Self-steered autocatalytic growth and (self-) consciousness take time. Bayesian accounts intrinsically include a temporal dimension; on a qualitative level, the fit of priors with schemata, and consumption analysis as implementing belief-updating (and action selection), appears compelling [17–19]. Collaborations to quantitatively elucidate these links and to formalize the tenets of the Ouroboros Model are most welcome.

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