Virtual Machinery and Evolution of Mind (Part 3)

Meta-Morphogenesis: Evolution of Information-Processing Machinery[1]

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Abstract

Much of Turing's work was about how large numbers of relatively simple processes could cumulatively produce qualitatively new large scale results e.g. Turing machine operations producing results comparable to results of human mathematical reasoning, and micro-interactions in physicochemical structures producing global transformations as a fertilized egg becomes an animal or plant. In the same spirit, this paper presents a first-draft rudimentary theory of "meta-morphogenesis" that may one day show how, over generations, interactions between changing environments, changing animal morphologies, and previously evolved information-processing capabilities might combine to produce increasingly complex forms of "informed control", starting with control of various kinds of physical behaviour, then later also informed control of information-processing. Eventually, this could explain philosophically puzzling features of animal (including human) minds, such as the existence of "qualia"; and also enhance our still incomplete understanding of requirements for future machines rivalling biological intelligence. This will require us to explore the space of *possible* minds, and the requirements different sorts of minds need to satisfy – many of which are unobvious. These ideas point to some consequences of embodied cognition that often go unnoticed.

Key words: Architecture, Causation, Cognition, Consciousness, Darwin, Designer Stance, Evolution, Explanatory Gap, Informed control, Layers, Mind, Morphogenesis, Qualia, Turing, Virtual Machinery

[1]This was the first paper on the Meta-Morphogenesis project, written in 2011, as the first draft of Part 3 of a sequence of related invited contributions on virtual machinery, evolution, and the nature of minds, to *Alan Turing – His Work and Impact* (Eds. S.B.Cooper and J. van Leeuwen, published by Elsevier in 2013. For details see http://www.cs.bham.ac.uk/~axs/amtbook. The previous chapters, published in the same volume are referenced here as "Part 1" and "Part 2", available at http://www.cs.bham.ac.uk/research/projects/cogaff/11.html#1106 A fourth paper criticised claims that Turing had proposed a *test* for intelligence in 1950. The current website for the Meta-Morphogenesis project is http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html

1. Introduction: Types of emergence

Turing made major contributions to our understanding of certain types of emergence, by showing how a Turing machine can be set up so as to generate large numbers of very simple processes that cumulatively produce qualitatively new large scale results e.g. TM operations producing results related to results of human mathematical reasoning Turing (1936).

Later work by Turing and many others led to electronic computing machinery allowing very large collections of a relatively small set of very simple operations to produce very many kinds of novel, useful, complex, and qualitatively varied results – a phenomenon that we now take for granted in many aspects of everyday life. His work on Universal TMs had also shown that both the construction of *mechanisms* and the construction of *things on which mechanisms operate* can in some cases be handled in a uniform way, by having mechanisms that can construct and manipulate mechanisms (e.g. computer programs that construct, modify and use computer programs, including themselves).

Turing's 1950 paper suggested, but did not argue, that in a newborn human or new robot a small set of learning capabilities could generate all forms of human knowledge and expertise (as some AI researchers believe). In my paper on the Mythical Turing Test in this volume, I argued that that was an error, to which I'll return below.

As far as I know Turing's last work on micro-macro emergence was the 1952 paper on morphogenesis, discussing some of the processes by which micro-interactions in physicochemical structures could account for global transformations from a fertilized egg to an animal or plant, within a single organism.

All those ways in which complex configurations of simple structures and processes can have qualitatively new features are examples of micro-macro relationships that can be labelled as "emergent" (Cohen and Stewart,1994).

It is now clear that physical and chemical mechanisms involved in biological reproduction can, like computational machinery, include specifications not only for (partially) controlled construction of new physical mechanisms (where some of the control comes from the environment) but also production of new construction specifications, and new mechanisms for using such specifications, as well as development and learning mechanisms for growing and modifying already functioning machinery, and mechanisms for detecting damage and producing repairs. The combined products of all these mechanisms, including ecosystems and socio-economic-political systems, together constitute the most complex example of emergence on our planet, and perhaps in the universe.

Much research on evolution and development has focused on production of new physical forms and new physical behaviours. However, we also need to understand micro-macro relationships involving creation and use of *new forms of information-processing*, without which much of the complexity could not have arisen[2]. There is much knowledge and expertise about information processing in computer science, software engineering and more generally computer systems engineering, but relatively little understanding of the corresponding biological phenomena, especially the information processing mechanisms involved in producing biological novelty which I'll label "meta-morphogenesis" (MM).

2. Computational creativity

Anyone who creates working computing systems has to be able to find new micro-macro relationships, built from a limited set of micro components: types of hardware or software structure, a small collection of possible processes associated with those components, and ways of ways of combining processes and structures using syntactic composition methods. The resulting new macro components (e.g. electronic circuits, or computer programs) have more complex and more varied structures, and are capable of producing new types of complex and varied processes, some of which provide "platforms" for constructing further layers of complexity. As argued in Part 1 (this volume), the functions, states and processes in the new layers often cannot be defined in the language that suffices for the lower levels (e.g. the language of physics and chemistry, or digital circuits). In that sense although the new layers may be fully implemented in the old ones, they are not reduced to them. E.g. the concepts "win" and "lose", required for describing a running chess program, are not definable in the language of physics. So the chess machine is implemented in, but not reducible to physical machinery.

Achieving such micro-macro bridges requires understanding the deep and unobvious generative potential of the initial fragments and their

[2]For an answer to "What is information?" see Sloman (2011).

possible relationships. Most of that potential was unobvious in the early days of computing, but new programming languages, new development environments, new operating systems, new re-usable packages and, above all, new problems, have continually revealed new, more complex, achievable targets. Specifying designs for 21st century computing devices on the basis of the micro-features available to programmers in the 1950s would have been totally intractable. The complexity we now take for granted was achievable only through *layered* development of tools and techniques. Some later layers could not be designed without the help of earlier layers. Similar constraints must apply to biological evolutionary and developmental trajectories, including those leading to new information processing mechanisms and functions.

Creation by humans of new layers of computing machinery is in part a response to *external* pressures from application domains, with which new computing systems have to interact, e.g. using sensors (e.g. cameras, pressure sensors, etc.), effectors (e.g. grippers, wheels, paint sprayers, etc.), or network connections. Similar, still unidentified, environmental pressures led to new emergent mechanisms and processes in biological evolution. Other pressures can come from *internal* requirements to improve speed, reliability, energy efficiency, easy of monitoring, ease of debugging and ease of extension.

3. Possible trajectories

Like new computing applications, many of the biological mechanisms, structures and functions that developed recently could not have occurred in earlier times, despite the availability of all the required *physical* materials, because many small intermediate changes were required in order to produce the *infrastructure* for newer more complex mechanisms.

The physical universe is able to produce objects of varying complexity, from subatomic particles through molecules, planets, galaxies and the like. Large lumps of solid or liquid matter can be produced by the materials concurrently being brought together. But some of the intermediate sized structures of great complexity, including organic molecules and organisms of many kinds, require special mechanisms of construction, or intermediate scale components, that are not always directly available wherever the physical materials are available. Instead, some of the more complex systems need to be assembled over time using precisely controlled selections from among physically and chemically possible alternatives. For example, there was no way the matter on this planet several billion years ago could have immediately reorganised itself into an oak tree or an orangutan.

Some sceptics about evolution have misconstrued the reliance on random changes as implying that a tornado could assemble a 747 airliner from a junkyard full of the required parts. However, just as assembling an airliner requires not only prior assembly of smaller parts, but also machinery for producing the various intermediate structures, and also maintaining them in relationships required for subsequent operations, so also does biological evolution require intermediate stages including intermediate mechanisms of reproduction and development. (This is related to the way later stages of a mathematical proof depend on earlier stages, preventing simultaneous discovery of all parts of the proof.) In particular, insofar as both the eventual products and the intermediate stages require many increasingly complex forms of information processing, biological evolution, like computer systems engineering in the last half century, must have involved many intermediate forms of information processing.

Successive information-processing mechanisms must have had successively more complex physical components, forms of representation, ontologies, algorithms, architectures, and functions, especially information processing functions relating to the environment. We need to understand those intermediate forms in order to understand the later forms that make use of them.

This tornado fallacy and other considerations have led some to assume that there must be a single master designer controlling such processes of assembly of complex living structures from inanimate matter. But the development of software engineering sophistication over the last six decades did not require some super-engineer controlling the whole process. There wasn't one: only a very large collection of successively discovered or created bootstrapping processes engaged in a multitude of forms of competition and co-operation partly driven by a plethora of new more complex goals that became visible as horizons receded. In that process we stumbled across more and more complex ways in which previous achievements could be extended.

Natural selection had much in common with this, except that there were no designers detecting new targets until species emerged with sufficient intelligence to engage in mate selection and other selective breeding activities – for their own or other species.

4. Types of biological complexity – and meta-morphogenesis

We can generalise Waddington's 1957 "epigenetic landscape" metaphor to include a wide range of types of development. Then, a general feature of growth of complexity is that as new mechanisms and mechanism-components are developed some of them can transform, and hugely simplify, large subsets of the opportunities for subsequent developments, as illustrated for individual cognitive development in Chappell and Sloman (2007). Related points were made in Cohen and Stewart (1994). New mechanisms, new forms of representation, new architectures, can sometimes be combined to provide new "platforms" bringing entire new spaces within (relatively) easy reach. Examples of such transitions in the history of computing include development of new operating systems, new programming languages (with their compilers or interpreters), new interfacing protocols, new networking technologies, new constraints and requirements from users, including requirements for reliability, modifiability, security, ease of learning, ease of use, etc. We don't know what the corresponding new pressures were that influenced developments of biological information-processing mechanisms, both in evolution and in individual development, though we can guess some of them.

Developments in biological information processing were much slower, and did not require any goal-direction, only random "implicit" search (implicit because there were no explicitly formulated goals, only opportunities that allowed certain changes to be relatively advantageous). Identifying those opportunities and the evolutionary changes they helped to select is a major research project. A simple example is the difference between a organism in an amorphous chemical soup and an organism whose environment has distinct enduring parts with different properties (e.g. providing different, persistent, nutrients and dangers, in different locations). Only the second organism could benefit from mechanisms for acquiring and storing information about those enduring structures, information that would necessarily have to be built up piecemeal over time. If the organism had visual mechanisms it could rapidly take in information about complex structures at different distances. If it only had tactile/haptic sensors the information would have to be acquired in much smaller doses with more movements required. Compare the discussions in Gibson (1979).

5. Changes in biological information-processing

Some computing developments, such as the creation of a new notation, or the introduction of a new ontology (e.g. for types of communication, or types of event handler, or types of data-structure), or the creation of a new type of operating system, can provide a “platform” supporting a very wide range of further developments.

There were probably also many different kinds of platform-producing transitions in biological evolution, including, for example, development of new means of locomotion, new sensors, new manipulators, new forms of learning. Some of these were changes in physical form or structure or forms of motion, or types of connectivity (Maynard Smith and Szathmáry (1995)) while others were changes concerned with information processing. Maynard Smith and Szathmáry discussed changes in forms of *communication*, but there must have been many more transitions in information processing capabilities and mechanisms, some discussed in Sloman (1979, 2015).

When a new multi-function platform is developed, searches starting from the new platform can (relatively) quickly reach results that would have involved totally intractable search spaces without the benefit of the new platform. For example, programmers who have learnt a powerful language like Prolog can very quickly produce programs that would have been very difficult to express using earlier languages. Different high level programming languages add different new opportunities for rapid advances. Likewise, as Dawkins and others have pointed out, some biological developments, including new forms of information processing, could, in principle, dramatically shorten time-spans required for subsequent developments, even though there is no goal directed design going on. Even random search (though not a tornado?) can benefit from a billion-fold reduction in size of a search space.

6. Less blind evolutionary transitions

Some animals are capable of formulating explicit goals or preferences and selecting actions in accordance with them. The evolution of that capability can provide a basis for selecting actions that influence reproductive processes, for example selecting mates, or favouring some offspring over others, e.g. bigger, stronger or more creative offspring. When animals acquire such cognitive capabilities, such choices can be used, explicitly or as a side-effect of other choices, to influence selecting breeding, in ways that may be as effective as explicit selective breeding of other species, e.g. domestic cattle or hunting dogs. Which types of selective breeding a species is capable of will depend on which features they are capable of recognising. If all they can distinguish among prospective mates or their offspring is size or patterns of motion, that could speed up evolution of physical strength and prowess. If they can distinguish differences in information processing capabilities that could lead to kinds of selective breeding of kinds of intelligence. (N.B. I am merely trying to describe what is possible, not recommending eugenics.)

These are examples of ways in which production of a new platform can transform something impossible into something possible, overcoming limitations of pre-existing mechanisms of composition. That can include bringing within reach yet more platforms for further development, as has happened repeatedly in computer systems engineering when new tools allowed the construction of even more powerful tools – e.g. using each new generation of processor design to help with production of subsequent designs.

A major research task in biology is to identify evolutionary and developmental transitions that facilitate new subsequent evolutionary and developmental transitions. Innate learning capabilities produced at a late stage in evolution may include important pre-compiled partial information about the environment that facilitates specific kinds of learning about that sort of environment. (Compare Chomsky's claims about human language learning capabilities, and Karmiloff-Smith (1992).) Special-purpose kinds of such evolved learning systems may, on this planet, outstrip all *totally general*, domain-neutral learning mechanisms sought in both models of evolutionary computation based on a single type of algorithm, or models of learning based on a single powerful learning process. Turing thought the latter might be possible Turing (1950), which I find surprising. Contrast the suggestion in McCarthy (2008) that evolution produced new, specialised, learning capabilities, required for human learning in a human lifetime, in certain sorts of changing 3-D environments.

7. From morphogenesis to meta-morphogenesis

Without attempting to match Turing's mathematical detail I have tried to sketch, in the same general spirit as his paper on morphogenesis, a rudimentary theory of "meta-morphogenesis" showing that the sorts of development that are possible in a complex system can change dramatically after new “platforms” (for evolution, or development) have been produced by pre-existing mechanisms.

Biological evolution is constantly confronted with environmental changes that reduce or remove, or in some cases enhance, the usefulness of previously developed systems, while blocking some opportunities for change and opening up new opportunities. In that sense the environment (our planet) is something like a very capricious teacher guiding a pupil.

Initially the “teacher” could change only physical aspects of the environment, through climate changes, earthquakes, volcanic eruptions, asteroid collisions, solar changes, and a host of local changes in chemical soups and terrain features.

Later, the teacher itself was transformed by products of biological evolution, including global changes in the composition of the atmosphere, seas, lakes, and the land-water distribution influenced by evolution of microbes that transformed the matter with which they interacted.

As more complex organisms evolved, they formed increasingly significant parts of the environment for other organisms, of the same or different types, providing passive or active food (e.g. prey trying to escape being caught), new materials for use in various forms of construction (e.g. building shelters, protective clothing, or tools) active predators, mates, and competitors for food, territory, or even mates.

Likewise, as a species evolved new physical forms and new information-processing mechanisms, those new developments could make possible new developments that were previously out of reach, for example a modification of a control mechanism might allow legs that had originally evolved for locomotion to be used for digging, fighting or manipulation. As new control subsystems evolved, they could have produced new opportunities for system architectures containing those subsystems to develop, allowing old competences to be combined in novel ways.

In that way, developments in the “learner” can be seen as also developments in the “teacher”, the environment. Two concepts used in educational theory, Vygotsky’s *Zone of proximal development* (ZPD) and Bruner’s notion of “scaffolding” can therefore be generalised to evolution. Evolutionary and other changes can modify the ZPD of an existing species and provide scaffolding that encourages or supports new evolutionary developments. Further details would contribute to a theory of meta-morphogenesis.

8. Evolution of information processing: beyond Gibson

Almost all organisms are control systems, using stored energy (sometimes externally supplemented, e.g. when birds use up-draughts) to produce internal and external changes that serve their needs. The control details depend on information acquired through sensors of various kinds, at various times. So organisms are "informed control systems".

Information available, and also the control possibilities, varied enormously: from the simplest micro-organisms, mostly responding passively in chemical soups, to animals with articulated bodies and multiple sensors, who were capable of performing many different sorts of action, and requiring increasingly complex information processing to notice opportunities, to select goals, to select ways of achieving goals, to carry out those selected actions, to deal with unexpected and previously unknown details of the environment that are detected during execution, and to learn from the experiences of performing successful and unsuccessful actions, and from observation of other things occurring in the environment. A full account of these transitions requires several generalisations of James Gibson's notion of "affordance", some of them explained in Sloman (2009).

We need to extend not only Turing's work but also the work of Maynard Smith and Szathmáry (1995) on transitions in evolution, to include detailed investigation of transitions in types of *information processing*. Transitions in forms of communication are often noted, for instance the development in humans of communication using syntactic structures, but there are far more processes involving information in biology than communication (internal or external). The need for many types of information processing in organisms will be obvious to experienced designers of intelligent, autonomous robots. The information processing requirements for robots include interpreting sensory information, controlling sensors, learning, forming plans, dealing with conflicts, evaluating options, and many more Sloman (2006).

Many of the requirements are not obvious; so it is too easy for researchers to notice only a tiny subset and therefore to underestimate the problems to be solved – as has happened repeatedly in the history of AI. An extreme example is assuming that the function of animal vision is to provide geometric information about the reflective surfaces in view (Marr (1982)), ignoring the functions concerned with detecting affordances, interpreting communications, and continuous control of actions (Gibson (1979)).

A particularly pernicious type of myopia is connected with research in robotics, biology, psychology, neuroscience and philosophy that focuses entirely on the continuous or discrete *on-line* interactions between organism (or robot) and objects and processes in the immediate environment, ignoring requirements for planning, explaining, and reasoning about things going on in other locations, and past and possible future events Sloman (2006, 2009).

Overcoming this myopia can be very difficult, but progress can be improved if instead of focusing attention on single organisms or particular robot designs, we examine *spaces of possibilities*: possible sets of requirements for organisms and robots, and possible sets of design features capable of meeting those requirements. For example, noticing an organism or individual failing to do something may draw attention to the problem of explaining how others succeed – a requirement that may previously have gone unnoticed. A special case of this is the work of Jean Piaget on the many partial or missing competences of young children, which help to draw attention to the hidden complexities in the competences of (normal) adults. Likewise the strange behaviours following brain damage or psychiatric diseases can expose unobvious aspects of normal cognition.

Simply observing organisms or dissecting them will not inform us as to all the ways in which they use information: we also need to engage in detailed analysis of differences between different environments and different morphologies, showing how, as environments change, a succession of increasingly complex demands and opportunities can arise that make possible cumulative changes not only in physical structure, size, strength, and behaviours, but also in the kinds of information available, the kinds of information processing mechanisms, and the uses of such information.

We also need to identify different requirements for belief-like and desire-like states that inform behaviours as discussed (incompletely) in Sloman et al. (2005). Changes in the environment can affect the goals that are essential or useful for an organism to pursue. In some cases goals remain the same, but the information processing and behaviours required to achieve them change: for example if drought or competition makes a certain kind of fruit more scarce, requiring the animals to travel further, climb higher up trees, and in some cases physically engage with competitors attempting to obtain the same food.

In other cases, changes in the environment may produce new constraints or new opportunities, making it useful to acquire new types of goal. For example, a new kind of food may become available, and if food is scarce the species that acquire desires to find and consume the new food will benefit.

However, the physical actions required to obtain and consume that food (e.g. breaking open a shell) may benefit from new forms of control, thereby allowing yet another genetic change to be useful – if it occurs.

Even if neither the environment nor the sensorimotor morphology of a species changes, changes in the *mode of processing* of the information available may provide benefits, for example

- acquiring new ways of learning correlations linking contents of sensorimotor signals
- acquiring new actions that provide or refine information about the environment – e.g. approaching objects, viewing them from new locations, rotating them, acting on them by prodding, pushing, squeezing, twisting, pulling apart, etc. Gibson (1966, 1979).
- developing a new ontology and mapping old information into the new ontology (e.g. developing an exo-somatic ontology of 3-D structures and processes that exist independently of being sensed, developing an ontology that allows information about the past or the future or states of affairs out of sight to be represented).
- developing new explanatory theories about the materials, structures, processes, and causal interactions in the environment.
- developing ways of exploring future possible actions to find good plans before initiating behaviours Craik (1943); Sloman (2006).
- developing new meta-semantic competences that allow the information processing of other organisms to be taken into account (e.g. prey, predators, conspecifics, offspring, mates).

9. Monitoring and controlling virtual machinery

Some of those developments produce new needs for informed control or detailed monitoring of information-processing. This can include operations on the intermediate virtual machine structures in perceptual sub-systems. Contributions to parts 1 and 3 of this volume point out that such biological developments involving virtual machinery can explain philosophically puzzling features of animal (including human) minds, such as the existence of "qualia"; and also enhance our still incomplete understanding of requirements for future machines rivalling biological intelligence. We need to explore the space of *possible* minds, and the different requirements different sorts of minds need to satisfy – a very difficult task, since many of the requirements are unobvious. In particular, I hope it is now clear that not all the requirements for embodied organisms (and future robots) are concerned with real-time, continuous, online interactions with the immediate environment, except for very simple organisms with very simple sensory-motor capabilities Sloman (2006, 2009).

Turing was interested in evolution and epigenesis and made pioneering suggestions regarding morphogenesis – differentiation of cells to form diverse body parts during development. As far as I know he did not do any work on how a genome can produce *behavioural competences* of the complete organism, including behaviours with complex conditional structures so that what is done depends on internal and external sensory information, nor internal behaviours that extend or modify previously developed information processing architectures, as discussed in Karmiloff-Smith (1992).

Even if we can understand in the abstract that evolution produces behavioural competences by selecting brain mechanisms that provide those competences, explaining how it actually works raises many deep problems, especially where the competences are not themselves behavioural.

The human-produced mechanisms for constructing more and more complex computing systems from a relatively small set of relatively simple types of components are all examples of "emergence" of qualitatively new large-scale structures and processes from combinations of much simpler building blocks.[3] Perhaps a deeper study of the evolution of tools, techniques, concepts and theories for designing complex systems in the last half century will stimulate new conjectures about the evolution of natural information processing systems, including those that build themselves only partly on the basis of an inherited specification. I suspect that people who predict imminent singularities underestimate the extent of our ignorance about what evolution has achieved, and some of the difficulties of replicating it using known mechanisms.

[3] Part 1 introduced a distinction between implementation and reduction, where a Running Virtual Machine (RVM) can be fully implemented in physical machinery (PM) even though the concepts required to describe the processes in the RVM cannot be defined in terms of concepts of physics. In that case the RVM is implemented in but not reduced to physical machinery. Part 2 showed how this might account for the existence of mental phenomena such as qualia.

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