Progress report on the Turing-inspired Meta-Morphogenesis project

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Abstract. The Turing-inspired Meta-Morphogenesis project was proposed in the final commentary in *Alan Turing - His Work and Impact* a collection of papers by and about Turing published on the occasion of his centenary[6]. The project was also summarised in a keynote talk at AISB2012, suggesting that an attempt to fill gaps in our knowledge concerning evolution of biological information processing may give clues regarding forms of computation in animal brains that have not yet been re-invented by AI researchers, and this may account for some of the enormous gaps between current AI and animal intelligence, including gaps between ancient mathematicians, such as Euclid and current AI systems. Evolution of information processing capabilities and mechanisms is much harder to study than evolution of physical forms and physical behaviours, e.g. because fossil records can provide only very indirect evidence regarding information processing in ancient organisms. Moreover it is very hard to study all the internal details of information processing in current organisms. Some of the reasons will be familiar to programmers who have struggled to develop debugging aids for very complex multi-component AI virtual machines. The paper presents challenges both for the theory of evolution and for AI researchers aiming to replicate natural intelligence, including mathematical intelligence. This is a partial progress report on attempts to meet the challenges by studying evolution of biological information processing, including evolved construction-kits.[2]

1 INTRODUCTION

This partial progress report on the Meta-Morphogenesis (M-M) project, now also called the Self-Informing Universe project[3], extends ideas presented at AISB2012 (Turing Centenary)[4].

The M-M project was based partly on my interest in defending Kant's philosophy of mathematics since my 1962 DPhil thesis [20][5], and partly on a conjectured answer to the question: "What would Alan Turing have worked on if he had not died two years after publication of his 1952 paper on Chemistry and Morphogenesis [31]?", reproduced and discussed in Part IV of [6] — the most cited of his publications, though largely ignored by philosophers, cognitive scientists and AI researchers. It has stimulated research in physics, chemistry, mathematics and biology, especially in the last decade. In it, Turing demonstrated mathematically that, in principle, interaction between two liquids diffusing at different rates through a developing organism could produce a very wide variety of surface patterns and 3-D structures, including many found in living forms.[6]

I suspect that if Turing had lived on he would have tried to understand forms of information processing needed to control behaviour of increasingly complex organisms. Controlled production of complex behaving structures needs increasingly sophisticated information processing, both in the processes of growth and development and for control of behaviour of complex organisms reacting to their environment, including other organisms.

In simple cases control uses presence or absence of sensed matter to turn things on or off or sensed scalar values to specify and modify other values (e.g. chemotaxis[7]). Many artificial control systems are specified using collections of differential equations relating such measures. One of several influential attempts to generalise these ideas is the "Perceptual Control Theory (PCT)" of Powers[18]. Turing's Morphogenesis paper also focused on scalar (numerical) changes, but as a pioneer of modern computer science he was well aware that the space of information-using control mechanisms is not restricted to *numerical* control systems.

In the last half century human engineers have discovered, designed and built increasingly complex and varied additional forms of control in interacting physical and virtual machines, including control based on grammars, parsers, planners, reasoners, rule interpreters, problem solvers and many forms of automated discovery and learning. Long before that, biological evolution produced and used increasingly complex and varied forms of information in construction, modification and control of increasingly complex and varied behaving mechanisms. [26] suggested that if Turing had lived several decades longer, he might have produced new theories about intermediate *forms of* information in living systems and intermediate *mechanisms for* information-processing: intermediate between the very simplest forms and the most sophisticated current forms of life.

This might fill a gap in standard versions of the theory of natural selection: namely, it does not explain *what makes possible* the many forms of life on this planet, and all the mechanisms they use, including the forms that might have evolved in the past or may evolve in the future. It merely assumes such possibilities and explains how a subset of realised possibilities persist and consequences that follow. For example, the noted biologist Graham Bell wrote in [1]: "Living complexity cannot be explained except through selection and does not require any other category of explanation whatsoever". This ignores the need to explain (a) what mechanisms make possible all the options between which choices are made, and (b) how what is possible changes, and depends on previously realised possibilities.[8]

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[2] An extended abstract for a closely related invited talk at the Symposium on computational modelling of emotions is also available online at http://www.cs.bham.ac.uk/research/projects/cogaff/aisb17-emotions-sloman.pdf

[3] http://goo.gl/9eN8Ks

[4] http://events.cs.bham.ac.uk/turing12/sloman.php

[5] http://www.cs.bham.ac.uk/research/projects/cogaff/sloman-1962

[6] https://en.wikipedia.org/wiki/Reaction%E2%80%93diffusion_system

[7] https://en.wikipedia.org/wiki/Chemotaxis

[8] Since the "official" final version of this paper I have made available a first draft survey of types of foundation for mathematics, including

2 USES OF EVOLVED CONSTRUCTION KITS

To meet this criticism, the M-M project was expanded in 2014 to include investigation of (a) the nature and potential of the "Fundamental Construction Kit" (FCK) provided by physics and chemistry before life existed and (b) the many and varied "Derived construction kits" (DCKs) produced by combinations of natural selection and other processes, including asteroid impacts, tides, changing seasons, volcanic eruptions and plate tectonics.[9]

As new, more complicated, life forms evolved, with increasingly complex bodies, increasingly complex changing needs, increasingly broad behavioural repertoires, and richer branching possible actions and futures to consider, their information processing needs and opportunities also became more complex. Somehow the available construction kits also diversified, in ways that allowed construction not only of new biological materials and body mechanisms, supporting new more complex and varied behaviours, but also new more sophisticated information-processing mechanisms, enabling organisms, either alone or in collaboration, to deal with increasingly complex challenges and opportunities.

Deep discoveries made by evolution include designs for DCKs that make new forms of information processing possible, with important roles in animal intelligence, including perception, conceptual development, motivation, planning, problem solving and topological reasoning about effects and limitations of possible continuous rearrangements of material objects: much harder than planning moves in a discrete space. Different species, with different needs, habitats and behaviours, use information about different topological and geometrical relationships, including birds that build different sorts of nests, carnivores that tear open their prey in order to feed, and human toddlers playing with (or sucking) body-parts, toys, etc.

Later on, in a smaller subset of species (perhaps only one species?) new meta-cognitive abilities gradually allowed previous discoveries to be noticed, reflected on, communicated, challenged, defended and deployed in new contexts. Such "argumentative" interactions may have been important precursors for chains of reasoning, including the proofs in Euclid's *Elements*.[10]

This is part of an attempt to explain how it became possible for evolution to produce mathematical reasoners. (The importance for science of explanations of *possibilities* and *limits* of possibilities was discussed in Chapter 2 of [22].[11])

Deeper theories, explanations, and working models than we can now produce should emerge from investigation of preconditions, biological and technological consequences, limitations, variations, and supporting mechanisms for biological construction kits of many kinds. For example, biologists (e.g. Coates [5]) have pointed out that specialised construction kits, sometimes called "toolkits", supporting plant development were produced by evolution, making upright plants possible on land (some of which were later found useful for many purposes by humans, e.g. ship-builders). Specialised construction kits were also needed by vertebrates and others by various classes of invertebrate forms of life. Construction kits for biological information processing have received less attention. One of the early exceptions was Schrödinger[19].

More general construction kits that are tailorable with extra information for new applications can arise from discoveries of parametrisable sub-spaces in the space of possible mechanisms – e.g. common forms with different sizes, or different ratios of sizes, of body parts, different rates of growth of certain body parts, different shapes or sizes of feeding apparatus, different body coverings, etc. Using a previously evolved construction kit with new parameters (specified either in the genome, or by some aspect of the environment during development [11]) can produce new variants of organisms in a fraction of the time it would take to evolve that type from the earliest life forms.

Similar advantages have been claimed for the use of so-called Genetic Programming (GP) using evolved, structured, parametrised abstractions that can be re-deployed in different contexts, in contrast with Genetic Algorithms (GAs) that use randomly varied flat strings of bits or other basic units.[12]

Instead of using only continual modification of parameters of a fixed pattern to control development of individuals from birth or hatching, evolution sometimes produces specifications for two or more different designs for different stages, e.g. one that feeds for a while, and then produces a cocoon in which materials are transformed into a chemical soup from which a new very different adult form (e.g. butterfly, moth, or dragon fly) emerges, able to travel much greater distances than the larval form to find a mate or lay eggs. These species use mathematical commonality at a much lower level (common molecular structures) than the structural and functional designs of larva and adult, in contrast with the majority of organisms, which retain a fixed, or gradually changing, structure while they grow after hatching or being born, but not fixed sizes or size-ratios of parts, forces required, etc.

Mathematical discoveries were implicit in evolved designs that support parametrisable variable functionalities, such as evolution's discovery of homeostatic control mechanisms that use negative feedback control, billions of years before the Watt centrifugal governor was used to control speed of steam engines.[13] Of course, most instances of such designs would no more have any awareness of the mathematical principles being used than a Watt-governor, or a fan-tail windmill (with a small wind-driven wheel turning the big wheel to face the wind) does. In both cases a part of the mechanism acquires information about something (e.g. whether speed is too high or too low, or the direction of maximum wind strength) while another part does most of the work, e.g. transporting energy obtained from heat or wind power to a new point of application.

Such transitions and decompositions in designs could lead to distinct portions of genetic material concerned with separate control functions, e.g. controlling individual development and controlling adult use of products of development, both encoded in genetic material shared across individuals.

Very much later, some meta-cognitive products of evolution allowed individuals (humans, or precursors) to attend to their own information-processing (essential for debugging), thereby "re-discovering" the structures and processes, allowing them to be organised and communicated – in what we now call mathematical theories, going back to Euclid and his predecessors (about whose achievements there are still many unanswered questions).

If all of this is correct then the physical universe, especially the quantum mechanical aspects of chemistry discussed by Schrödinger

cognitive and biological foundations, here: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/maths-multiple-foundations.html

[9] http://goo.gl/eFnJb1

[10] E.g. http://goo.gl/Zz2O1l and http://www.cs.bham.ac.uk/research/projects/cogaff/misc/trisect.html

[11] http://www.cs.bham.ac.uk/research/projects/cogaff/crp/#chap2) While finalising this paper I learnt that the physicist David Deutsch is developing what he calls "Constructor theory", making related points. Use search engines to find recent videos and publications.

[12] http://www.genetic-programming.org/

[13] https://en.wikipedia.org/wiki/Governor_(device)

in 1944[19], provided not only a construction kit for genetic material implicitly specifying design features of individual organisms, but also a “Fundamental” construction kit (FCK) that can produce a wide variety of “derived” construction kits (DCKs) some used in construction of individual organisms, others in construction of new, more complex DCKs, making new types of organism possible.

Moreover, as Schrödinger and others pointed out, construction-kits that are essential for micro-organisms developing in one part of the planet can indirectly contribute to construction and maintenance processes in totally different organisms in other locations, via food chains: since most species cannot synthesise the complex chemicals they need directly from freely available atoms or sub-atomic materials. So effects of DCKs can be very indirect.

Functional relationships between the smallest life forms and the largest will be composed of many sub-relations. Such dependency relations apply not only to mechanisms for construction and empowerment of major physical parts of organisms, but also to mechanisms for building information-processors, including brains, nervous systems, and chemical information processors of many sorts. (E.g. digestion uses informed disassembly of complex structures to find valuable parts to be transported and used or stored elsewhere.)

So far, in answer to Bell, I have tried to describe the need for evolutionary *selection* mechanisms to be supported by *enabling* mechanisms. Others have noticed the problem denied by Bell, e.g. Kirschner and Gerhart[15][14] adding some important biological details to the theory of evolved construction-kits, though not (as far as I can tell) the ideas (e.g. about abstraction and parametrisation) presented in this paper. Ganti’s “chemoton” theory [8], is also relevant, as is Kauffman [14], possibly also [7, 10, 33]. and probably others unknown to me!

3 BIOLOGICAL USES OF ABSTRACTION

As organisms grow in size, weight and strength, the forces and torques required at joints and at contact points with other objects change. So the genome needs to use the same design with changing forces depending on tasks. Special cases include forces needed to move and manipulate the torso, limbs, gaze direction, chewed objects, etc. “Hard-wiring” of useful evolved control functions with mathematical properties can be avoided by using designs that allow *changeable parameters* – a strategy frequently used by human programmers. Such parametrisation can both allow for changes in size and shape of the organism as it develops, and for many accidentally discovered biologically useful abstractions that can be parametrised in such designs – e.g. allowing the same mechanism to be used for control of muscular forces at different stages of development, with changing weights, sizes, moments of inertia, etc.

Even more spectacular generalisation is achievable by re-use of evolved construction-kits not only across developmental stages of *individuals* within a species, but also across *different species* that share underlying physical parametrised design patterns, with details that vary between species sharing the patterns (as in vertebrates, or the more specialised variations among primates, or among birds, or fish species). Such shared design patterns across species can result either from species having common ancestry or from convergent evolution “driven” by common features of the environment, e.g. aspects of spatial structure and visual perception of structure common to all locations on the planet, despite the huge diversity of contents. Such use of abstraction to achieve powerful re-usable design features across different application domains is familiar to engineers, including computer systems engineers.

The Darwin/Wallace idea that variations between partly similar species can evolve by splitting a lineage, without each variant having to evolve separately from the most primitive organisms, implicitly assumes re-use of important design abstractions in evolution. “Design sharing” explains why the tree of evolution has many branch points, instead of everything having to evolve from one common root node. Symbiosis also allows combination of separately evolved features. [15]

Similar “structure-sharing” often produces enormous reductions in search-spaces in AI systems. It is also common in mathematics: most proofs build on a previously agreed framework of concepts, formalisms, axioms, rules, and previously proved theorems. They don’t all start from some fundamental shared axioms.

A different kind of abstraction can be found in connection with what are sometimes (misleadingly) called “non-functional requirements” or “ilities”, e.g. engineering design requirements such as usability, maintainability, repairability, efficiency, understandability, ... that are not specific to particular functions or designs. They were labelled “meta-functional requirements” in [28].

If re-usable abstractions can be encoded in suitable formalisms (with different application-specific parameters provided in different design contexts), they can enormously speed up evolution of diverse designs for functioning organisms. This is partly analogous to the use of memo-functions in software design (i.e. functions that store computed values so that they don’t have to be re-computed whenever required, speeding up computations enormously, e.g. in the Fibonacci function). Another type of re-use occurs in (unfortunately named) “object-oriented” programming paradigms that use hierarchies of powerful re-usable design abstractions, that can be instantiated differently in different combinations, to meet different sets of constraints in different environments, without requiring each such solution to be coded from scratch: “parametric polymorphism” with multiple inheritance.

This is an important aspect of many biological mechanisms. For example, there is enormous variation in what information perceptual mechanisms acquire and how the information is processed, encoded, stored, used, and in some cases communicated. But abstract commonalities of function and mechanism (e.g. use of wings) can be combined with species specific constraints (parameters).

Parametric polymorphism makes the concept of *consciousness* difficult to analyse: there are many variants depending on what sort of thing is conscious, what it is conscious of, what information is acquired, what mechanisms are used, how the information contents are encoded, how they are accessed, how they are used, etc.[16] Mathematical consciousness, still missing from AI, requires awareness of possibilities and impossibilities not restricted to particular objects, places or times – as Kant pointed out in [12]. (See examples in Note 10.)

Mechanisms and functions are also shared across groups of species, such as phototropism in plants, use of two eyes with lenses focused on a retina in many vertebrates, a subset of which evolved mechanisms using binocular disparity for 3-D perception. That’s one of many implicit mathematical discoveries in evolved designs for spatio-temporal perceptual, control and reasoning mechanisms, using the fact that many forms of animal perception and action occur in 3D space plus time, a fact that must have helped to drive evolution

[14] Briefly reviewed in http://www.americanscientist.org/bookshelf/pub/have-we-solved-darwins-dilemma

[15] Compare the theory of symbiogensis https://en.wikipedia.org/wiki/Symbiogenesis

[16] An overview is in preparation here: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/family-resemblance-vs-polymorphism.html

of mechanisms for representing and reasoning about 2-D and 3-D structures and processes, as in Euclidean geometry.

In a search for effective designs, enormous advantages come from (explicit or implicit) discovery and use of mathematical abstractions that are applicable across different designs or different instances of one design. For example a common type of grammar (e.g. a *phrase structure grammar*) allows many different languages to be implemented including sentence generators and sentence analysers re-using the same program code with different grammatical rules. Evolution seems to have discovered something like this.

Likewise, a common design framework for flying animals may allow tradeoffs between stability and maneouvreability to be used to adapt to different environmental opportunities and challenges. These are mathematical discoveries implicitly used by evolution. Evolution's ability to use these discoveries depends in part on the continual evolution of new DCKs providing materials, tools, and principles that can be used in solving many design and manufacture problems. In recently evolved species, individuals e.g. humans and other intelligent animals, are able to replicate some of evolution's mathematical discoveries and make practical use of them in their own intentions, plans and design decisions, far more quickly than natural selection could. Only (adult) humans seem to be aware of doing this.

Re-usable inherited abstractions allow different collections of members of one species, e.g. humans living in deserts, in jungles, on mountain ranges, in arctic regions, etc., to acquire expertise suited to their particular environments in a much shorter time than evolution would have required to produce the same variety of packaged competences "bottom up". This flexibility also allows particular groups to adapt to major changes in a much shorter time than adaptation by natural selection would have required.

This requires some later developments in individuals to be delayed until uses of earlier developments have provided enough information about environmental features to influence the ways in which later developments occur, as explained later in Section 3.3. This process is substantially enhanced by evolution of *metacognitive* information processing mechanisms that allow individuals to reflect on their own processes of perception, learning, reasoning, problem-solving, etc. and (to some extent) modify them to meet new conditions.

Later, more sophisticated products of evolution develop meta-meta-cognitive information processing sub-architectures that enable them to notice their own adaptive processes, and to reflect on and discuss what was going on, and in some cases collaboratively improve the processes, e.g. through explicit teaching – at first in a limited social/cultural context, after which the activity was able to spread far and wide – using previously evolved learning mechanisms. As far as I know only humans have achieved that, though some other species apparently have simpler variants. These conjectures need far more research! Human AI designs for intelligent machines created so far seem to have far fewer layers of abstraction, and are far more primitive, than the re-usable designs produced by evolution. Studying the differences is a major sub-task facing the M-M project (and AI). This requires a deep understanding of what needs to be explained.

3.1 Designing designs

Just as the designer of a programming language cannot know about, and does not need to know about, all the applications for which the programming language will be used, so also can the more abstract products of evolution be instantiated (e.g. by setting parameters) for use in contexts in which they did not evolve. One of the most spectacular cases is reuse of a common collection of

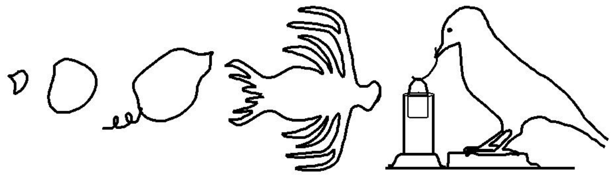

Figure 1. Many discontinuities in physical forms, behavioural capabilities, environments, types of information acquired, types of use of information and mechanisms for information-processing are still waiting to be discovered.

language-creation competences in a huge variety of geographical and social contexts, allowing any individual human to acquire any of several thousand enormously varied human languages, including both spoken and signed languages. A striking example was the cooperative creation by deaf children in Nicaragua of a new sign language because their teachers had not learned sign languages early enough to develop full adult competences. This suggests that what is normally regarded as language *learning* is really cooperative language *creation*, demonstrated in this video:
https://www.youtube.com/watch?v=pjtioIFuNf8

Re-use can take different forms, including re-use of a general design across different species by instantiating a common pattern, and re-use based on powerful mechanisms for acquiring and using information about the available resources, opportunities and challenges during the development of each individual. The first process happens across evolutionary lineages. The second happens within individual organisms in their lifetime, as explained later, in Section 3.3. Social/cultural evolution requires intermediate timescales.

Evolution seems to have produced multi-level design patterns, whose details are filled in incrementally, during creation of instances of the patterns in individual members of a species. If all the members live in similar environments that will tend to produce uniform end results. However, if the genome is sufficiently abstract, then environments and genomic structures may interact in more complex ways, allowing small variations during development of individuals to cascade into significant differences in the adult organism, as if natural selection had been sped up enormously. This was recognised in plants in [11]. A special case is evolution of an immune system with the ability to develop different immune responses depending on the antigens encountered. Another dramatic special case is the recent dramatic cascade of social, economic, and educational changes supported jointly by the human genome and the internet!

3.2 Changes in developmental trajectories

As living things become more complex, increasingly varied types of information are required for increasingly varied uses. The processes of reproduction normally produce new individuals that have seriously under-developed physical structures and behavioural competences. Self-development requires physical materials, but it also requires information about what to do with the materials, including disassembling and reassembling chemical structures at a sub-microscopic level and using the products to assemble larger body parts, while constantly providing new materials, removing waste products and consuming energy. Some energy is stored and some is used in assembly and other processes.

The earliest (simplest?) organisms can acquire and use information about (i.e. sense) only internal states and processes and the immediate external environment, e.g. pressure, temperature, and presence of chemicals in the surrounding soup, with all uses of information taking the form of immediate local reactions, e.g. allowing a molecule through a membrane.

Changes in types of *information*, types of *use of information* and types of *biological mechanism for processing information* have repeatedly altered the processes of evolutionary morphogenesis that produce such changes: a positive feedback process. An example is the influence of mate selection on evolution in intelligent organisms: mate selection is itself dependent on previous evolution of cognitive mechanisms. Hence the prefix "Meta-" in "Meta-Morphogenesis". This is a process with multiple feedback loops between new designs and new requirements (niches), as suggested in [23].

As Figure 1 suggests, evolution constantly produces new organisms that may or may not be larger than predecessors, but are more complex both in the types of physical action they can produce and also the types of information and types of information-processing required for selection and control of such actions. Some of that information is used immediately and discarded (online perceptual intelligence) while other kinds are stored, possibly in transformed formats, and used later, possibly on many occasions (offline perceptual intelligence) — a distinction often mislabelled as "where" *vs* "what" perception. This generalises Gibson's theory [9] that perception mainly provides information about "affordances" rather than information about visible surfaces of perceived objects.

These ideas, like Karmiloff-Smith's[13], suggest that one of the effects of biological evolution was fairly recent production of more or less abstract construction kits that come into play at different stages in development, producing new more rapid changes in variety and complexity of information processing across generations as explained below in Section 3.3 and Figure 2.

It's not clear how much longer this can continue: perhaps limitations of human brains constrain this process. But humans working with intelligent machines may be able to stretch the limits. At some much later date, probably in another century, we may be able to make machines that do it all themselves – unless it turns out that the fundamental information processing mechanisms in brains cannot be modelled in computer technology developed by humans.

Species can differ in the variety of types of sensory information they can acquire, in the variety of uses to which they put that information, in the variety of types of physical actions they can produce, in the extent to which they can combine perceptual and action processes to achieve novel purposes or solve novel problems, and the extent to which they can educate, reason about, collaborate with, compete against conspecifics, and prey or competitor species.

As competences become more varied and complex, the more *disembodied* must the information processing be, i.e. disconnected from current sensory and motor signals (while preserving low level reflexes and sensory-motor control loops for special cases). This may have been a precursor to mathematical abilities to think about transfinite set theory and high dimensional vector spaces or modern scientific theories. E.g. Darwin's thinking about ancient evolutionary processes. was detached from particular sensory-motor processes. This applies also to affective states, e.g. compare being startled and being obsessed with ambition. The fashionable emphasis on *embodied* cognition may be appropriate to the study of organisms such as plants and microbes, or even insects, but evolved intelligence increasingly used *disembodied* cognition, most strikingly in the production of ancient mathematical minds. (Compare Kirsh[16]).

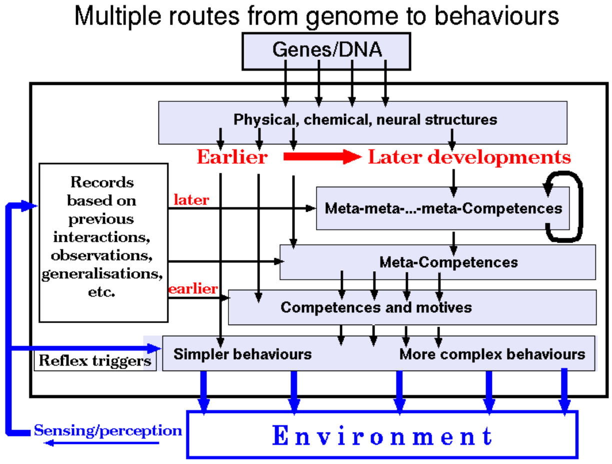

Figure 2. Cascaded, staggered, developmental trajectories proposed in [3]. Early genome-driven learning from the environment occurs in loops on the left. Downward arrows further right represent later gene-triggered processes during individual development modulated by results of earlier learning via feedback on left. (Chris Miall suggested the structure of the original diagram.)

3.3 Variations in epigenetic trajectories

The description given so far is very abstract and allows significantly different instantiations in different species, addressing different sorts of functionality and different types of design, e.g. of physical forms, behaviours, control mechanisms, reproductive mechanisms, etc.

At one extreme the reproductive process produces individuals whose genome exercises a fixed pattern of control during development, leading to "adults" with only minor variations.

At another extreme, instead of the process of development from one stage to another being fixed in the genome, it could be created during development through the use of more than one level of design in the genome. E.g. if there are two levels then results of environmental interaction at the first level could transform what happens at the second level. If there are multiple levels then what happens at each new level may be influenced by results of earlier developments.

In a species with such multi-stage development, at intermediate stages not only are there different developmental trajectories due to different environmental influences, there are also selections among the intermediate level patterns to be instantiated, so that in one environment development may include much learning concerned with protection from freezing, whereas in other environments individual species may vary more in the ways they seek water during dry seasons. Then differences in adults come partly from the influence of the environment in selecting patterns to instantiate. E.g. one group may learn and pass on information about where the main water holes are, and in another group individuals may learn and pass on information about which plants are good sources of water.

If these conjectures are correct, patterns of development will automatically be varied because of patterns and meta-patterns picked up by earlier generations and instantiated in cascades during individual development. So different cultures produced jointly by a genome and previous environments can produce very different expressions of the same genome, even though individuals share similar physical forms. The main differences are in the kinds of information acquired and used, and the information processing mechanisms developed. Not all cultures use advanced mathematics in designing buildings, but all build on previously evolved understanding of space, time and motion.

Evolution seems to have found how to provide rich developmental variation by allowing information gathered by young individuals not merely to select and use pre-stored design patterns, but to create new patterns by assembling fragments of information during early development, then using more abstract processes to construct new abstract patterns, partly shaped by the current environment, but with the power to be used in new environments. Developments in culture (including language, science, engineering, mathematics, music, literature, etc.) all show such combinations of data collection and enormous creativity, including creative ontology extension (e.g. the Nicaraguan children mentioned above in Section 3.1).

Unless I have misunderstood her, this is the type of process Karmiloff-Smith[13] called "Representational Re-description" (RR). The general idea is crudely depicted in Figure 2 (extending the version published in 2007[3]). Genome-encoded previously acquired abstractions "wait" to be instantiated at different stages of development, using cascading alternations between data-collection and abstraction formation (RR) by instantiating higher level generative abstractions (e.g. meta-grammars), not by forming statistical generalisations. This could account for both the great diversity of human languages and cultures, and the power of each one, all supported by a common genome operating in very different environments.

Jackie Chappell (co-author of [3]) noticed the implication that instead of the genome specifying a fixed "epigenetic landscape" (proposed by Waddington[32]) it provides a schematic landscape and mechanisms that allow each individual (or in same cases groups of individuals) to modify the landscape while moving down it (e.g. adding new hills, valleys, channels and barriers). In such cases *measures* of percentage contributions of genome and environment to cognition are nonsensical, unlike *descriptions* of influences.

Though most visible in language development, the process is not unique to language development, but occurs throughout childhood (and beyond) in connection with many aspects of development of information processing abilities, construction of new ontologies, theory formation, etc. This differs from forms of learning or development that use *uniform statistics-based methods* for repeatedly finding patterns at different levels of abstraction.

Instead, Figure 2 indicates that the genome encodes increasingly abstract and powerful creative mechanisms developed at different stages of evolution, that are "awakened" (a notion used by Kant in [12]) in individuals only when appropriate, so that they can build on what has already been learned or created in a manner that is tailored to the current environment. For example, in young (non-deaf) humans, processes giving sound sequences a syntactic interpretation develop after the child has learnt to produce and to distinguish some of the actual speech sounds used in that location. It is a remarkable fact that young humans seem to be able to learn two (or more) languages with different speech sounds and different grammatical structures in parallel. However, there must be an upper limit to the number of languages a child can acquire concurrently.

In social species, the later stages of Figure 2 include mechanisms for discovering non-linguistic ontologies and facts older members of the community have acquired, and incorporating relevant subsets in combination with new individually acquired information. Instead of merely absorbing the details of what older members have learnt, the young can absorb forms of creative learning, reasoning and representation that older members have found useful and apply them in new environments to produce new results. In humans, this has produced spectacular effects, especially in the last few decades.

The evolved mechanisms for representing and reasoning about possibilities, impossibilities and necessities were essential for both perception and use of affordances[9] and for making mathematical discoveries, something statistical learning cannot achieve.

3.4 Space-time

An invariant for all species in this universe is space-time embedding, and changing spatial relationships between body parts and things in the environment. The relationships vary between water-dwellers, cave-dwellers, tree-dwellers, flying animals, and modern city-dwellers. Representational requirements depend on body parts and their controllable relationships to one another and other objects. So aeons of evolution will produce neither a tabula rasa nor geographically specific spatial information, but a collection of generic mechanisms for finding out what sorts of spatial structures have been bequeathed by ancestors as well as physics and geography, and learning to make use of whatever is available (McCarthy[17]): that's why embodiment is relevant to evolved cognition.

Kant's ideas about geometric knowledge are relevant though he assumed that the innate apparatus was geared only to structures in Euclidean space, whereas our space is only approximately Euclidean. Somehow the mechanisms conjectured in Figure 2 eventually (after many generations) made it possible for humans to make the amazing discoveries recorded in Euclid's *Elements*, still used world-wide by scientists and engineers. If we remove the parallel axiom we are left with a very rich collection of facts about space and time, especially topological facts about varieties of structural change, e.g. formation of networks of relationships, deformations of surfaces, and possible trajectories constrained by fixed obstacles.

It is well known (though non-trivial to prove!) that trisection of an arbitrary angle is impossible in Euclidean geometry, whereas bisection is trivial. However, some ancient mathematicians (e.g. Archimedes) knew that there is a fairly simple addition to Euclidean geometry that makes trisecting an arbitrary angle easy, namely the "neusis" construction that allows a movable straight edge to have two marks fixed on it that can be used to specify constraints on motion of the edge.[17] They proved this without modern logic, algebra, set theory, proof theory etc. However, there is no current AI reasoner capable of discovering such a construct, or considering whether it is an acceptable extension to Euclid's straight-edge and compasses constructs.

If we can identify a type of construction-kit that produces young robot minds able to develop or evaluate those ideas in varied spatial environments, we may find important clues about what is missing in current AI. (See the documents referenced in Note 10.) Long before logical and algebraic notations were used in mathematical proofs, evolution had produced abilities to represent and reason about what Gibson called "affordances"[9], including possible and impossible alterations to spatial configurations: such as the (topological) impossibility of solid linked rings becoming unlinked, or vice versa. I suspect brains of many intelligent animals make use of topological reasoning mechanisms that have so far not been discovered by brain scientists or AI researchers.

Addition of *meta-cognitive* mechanisms able to inspect and experiment with reasoning processes may have led both to enhanced spatial intelligence and meta-cognition, and also to meta-meta-cognitive reasoning about other intelligent individuals.

[17] http://www.cs.bham.ac.uk/research/projects/cogaff/misc/trisect.html

3.5 Other species

I conjecture that further investigation will reveal varieties of information processing (computation) that have so far escaped the attention of researchers, but which play important roles in many intelligent species, including not only humans and apes but also elephants, corvids, squirrels, cetaceans and others. In particular, some intelligent non-human animals and pre-verbal human toddlers seem to be able to use mathematical structures and relationships (e.g. partial orderings and topological relationships) unwittingly.

Mathematical **meta-meta...**-cognition seems to be restricted to humans, but develops in stages, as Piaget found[18], partially confirming Kant's ideas about mathematical knowledge in [12]. However, I suspect that (as Kant seems to have realised) the genetically provided mathematical powers of intelligent animals make more use of topological and geometric reasoning, using analogical, non-Fregean, representations, as suggested in [21] than the logical, algebraic, and statistical capabilities that have so far dominated AI and robotics. (NB "analogical" does not imply "isomorphic".) For example, even the concepts of cardinal and ordinal number are crucially related to concepts of one-one correspondence between components of structures, most naturally understood as a topological relationship rather than a logically definable relationship [22, Chap.8].

All this shows why increasing complexity of physical structures and capabilities, providing richer collections of alternatives and more complex internal and external action-selection criteria, requires increasing *disembodiment* of information processing.

The fact that evolution is not stuck with the Fundamental Construction Kit (FCK) provided by physics and chemistry, but also produces and uses new "derived" construction-kits (DCKs), enhances both the mathematical and the ontological creativity of evolution, which is indirectly responsible for all the other known types of creativity.[19] This counters both the view that mathematics is a product of human minds, and a view of metaphysics as being concerned with something unchangeable. The notion of "Descriptive Metaphysics" presented by Strawson in [29] needs to be revised.

I also conjecture that filling in some of the missing details in this theory (a huge challenge) will help us understand both the evolutionary changes that introduced unique features of human minds and why it is not obvious that Turing-equivalent digital computers, or even asynchronous networks of such computers running sophisticated interacting virtual machines, will suffice to replicate the human mathematical capabilities that preceded modern logic, algebra, set-theory, and theory of computation.[20] It will all depend on the precise forms of virtual information processing machinery that evolution has managed to produce, about which I suspect current methods of neuroscientific investigation cannot yield deep information. Compare [25].

Current AI cannot produce reasoners like Euclid, Zeno, Archimedes, or even reasoners like pre-verbal toddlers, weaver birds and squirrels. This indicates serious gaps, despite many impressive achievements. I see no reason to believe that *uniform, statistics-based* learning mechanisms will have the power to bridge those gaps. Whether the addition of logic-based reasoners will suffice is not clear, for reasons given in [22, Chap 7]. The discoveries made by ancient mathematicians preceded the discoveries of modern algebra and logic, and the arithmetisation of geometry by Descartes.

Section 3.3 gave reasons for believing that evolved mechanisms that use previously acquired abstract forms of meta-learning with genetically orchestrated instantiation triggered by developmental changes, may do much better. These mechanisms depend on rich internal languages that evolved for use in perception, reasoning, learning, intention formation, plan formation and control of actions before communicative languages.[21] This generalises claims made by Chomsky in [4], and his later works, focused only on development of human spoken languages, ignoring how much language and non-linguistic cognition develop with mutual support [27].

3.6 The importance of virtual machinery

Building a new computer for every task was made unnecessary by allowing computers to have changeable programs. Initially each program, specifying instructions to be run, had to be loaded (via modified wiring, switch settings, punched cards, or punched tape), but later developments provided more and more flexibility and generality, with higher level programming languages providing re-usable domain specific languages and tools, some translated to machine code, others run on a task specific virtual computer provided by an interpreter. Later developments provided time-sharing operating systems supporting multiple interacting programs running effectively in parallel performing different, interacting, tasks on a single processor. As networks developed, these collaborating *virtual machines* became more numerous, more varied, more geographically distributed, and more sophisticated in their functionality, often extended with sensors of different kinds and attached devices for manipulation, carrying, moving, and communicating.

These developments suggest the possibility that each biological mind is also implemented as a collection of concurrently active non-physical, but physically implemented, virtual machines interacting with one another and with the physical environment through sensor and motor interfaces. Such "virtual machine functionalism" could accommodate a large variety of coexisting, interacting, cognitive, motivational and emotional states[22], including essentially private qualia as explained in [24] and [25].

Long before human engineers produced such designs, biological evolution had already encountered the need and produced virtual machinery of even greater complexity and sophistication, serving information processing requirements for organisms, whose virtual machinery included interacting sensory qualia, motivations, intentions, plans, emotions, attitudes, preferences, learning processes, and various aspects of self-consciousness.

4 THE FUTURE OF AI

We still don't know how to make machines able to replicate the mathematical insights of ancient mathematicians like Euclid – e.g. with "triangle qualia" that include awareness of mathematical possibilities and constraints[23] or minds that can discover the possibility of extending Euclidean geometry with the *neusis* construction (see

[18] He did not know enough about computation to characterise the stages accurately

[19] Boden [2] distinguishes H-Creativity, which involves being historically original, and P-Creativity, which requires only personal originality. The distinction is echoed in the phenomenon of *convergent* evolution, illustrated in https://en.wikipedia.org/wiki/List_of_examples_of_convergent_evolution. The first species with some design solution exhibits H-creativity of evolution. Species in which that solution evolves independently later exhibit a form of P-creativity.

[20] Why did Turing write in his [30] that chemistry may turn out to be as important as electricity in brains?

[21] http://www.cs.bham.ac.uk/research/projects/cogaff/talks/#talk111

[22] http://www.cs.bham.ac.uk/research/projects/cogaff/

[23] http://www.cs.bham.ac.uk/research/projects/cogaff/misc/triangle-theorem.html

Note 17). It is not clear whether we simply have not been clever enough at understanding the problems and developing the programs, or whether we need to extend the class of virtual machines that can be run on computers, or whether the problem is that animal brains use kinds of virtual machinery that cannot be implemented using the construction kits known to modern computer science and software engineering. As Turing hinted in his 1950 paper: aspects of chemical computation may be essential.

Biological organisms also cannot build such minds directly from atoms and molecules. They need many intermediate DCKs, some of them concrete and some abstract, insofar as some construction kits, like some animal minds, use virtual machines.

Evolutionary processes must have produced construction kits for abstract information processing machinery supporting increasingly complex multi-functional virtual machines, long before human engineers discovered the need for such things and began to implement them in the 20th Century.[24] Studying such processes is very difficult because virtual machines don't leave fossils (though some of their products do). Moreover details of recently evolved virtual machinery may be at least as hard to inspect as running software systems without built-in run-time debugging "hooks". This could, in principle, defeat all known brain scanners.

"Information" here is not used in Shannon's sense (concerned with mechanisms and vehicles for storage, encoding, transmission, decoding, etc.), but in the much older sense familiar to Jane Austen and used in her novels e.g. *Pride and Prejudice*[25] in which *how information content is used* is important, not how information bearers are encoded, stored, transmitted, received, etc. The primary use of information is for control. Communication, storage, reorganisation, compression, encryption, translation, and many other ways of dealing with information are all secondary to the use for control.

Long before humans used structured languages for communication, intelligent animals must have used rich languages with structural variability and compositional semantics *internally*, e.g. in perception, reasoning, intention formation, wondering whether, planning and execution of actions, and learning.[27]

We can search for previously unnoticed evolutionary transitions going beyond Figure 1 – e.g. between organisms that merely react to immediate chemical environments in a primaeval soup, and organisms that use temporal information about changing concentrations in deciding whether to move or not, or new mechanisms required after the transition from a liquid based life form to life on a surface with more stable structures (e.g. different static resources and obstacles in different places), or a later transition to hunting down and eating mobile land-based prey, or transitions to reproductive mechanisms requiring young to be cared for, etc.? Perhaps we'll then understand how to significantly extend AI.

Compare Schrödinger's discussion in [19] of the relevance of quantum mechanisms and chemistry to the storage, copying, and processing of genetic information.[26] I am suggesting that questions about evolved intermediate forms of information processing are linked to philosophical questions about the nature of mind, the nature of mathematical discovery, and deep gaps in current AI.[27]

[24] Anticipated over a hundred years before Turing by Ada Lovelace.
[25] As documented in http://goo.gl/zMelDg
[26] Annotated extracts: http://goo.gl/6DHTJAl
[27] For more on that see http://www.cs.bham.ac.uk/research/projects/cogaff/misc/maths-multiple-foundations.html

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