# How can we reduce the gulf between artificial and natural intelligence?

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**Abstract.** AI and robotics have many impressive successes, yet there remain huge chasms between artificial systems and forms of natural intelligence in humans and other animals. Fashionable "paradigms" offering definitive answers come and go (sometimes reappearing with new labels). Yet no AI or robotic systems come close to modelling or replicating the development from helpless infant over a decade or two to a competent adult. Human and animal developmental trajectories vastly outstrip, in depth and breadth of achievement, products of artificial learning systems, although some AI products demonstrate super-human competences in restricted domains. I'll outline a very long-term multi-disciplinary research programme addressing these and other inadequacies in current AI, cognitive science, robotics, psychology, neuroscience, philosophy of mathematics and philosophy of mind. The project builds on past work by actively seeking gaps in what we already understand, and by looking for very different clues and challenges: the Meta-Morphogenesis project, partly inspired by Turing's work on morphogenesis, outlined here: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html

**Keywords:** evolution,information-processing,meta-morphogenesis,Turing

## 1 Introduction

There are many impressive successes of AI and robotics, some of them summarised at `http://aitopics.org/news`. Yet there remain huge chasms between artificial systems and forms of natural intelligence in humans and other animals – including weaver-birds, elephants, squirrels, dolphins, orangutans, carnivorous mammals, and their prey.[1]

Fashionable "paradigms" offering definitive answers come and go, sometimes reappearing with new labels, and often ignoring previous work, such as the

[1] Nest building cognition of a weaver bird can be sampled here: http://www.youtube.com/watch?v=6svAIgEnFvw

impressive survey by Marvin Minsky over 50 years ago [6], long before computers with suitable powers were available.

Despite advances over several decades, accelerated recently by availability of smaller, cheaper, faster, computing mechanisms, with very much larger memories than in the past, no AI or robotic systems come close to modelling or replicating the development from helpless infant over a decade or two to plumber, cook, trapeze artist, bricklayer, seamstress, dairy farmer, shop-keeper, child-minder, professor of philosophy, concert pianist, mathematics teacher, quantum physicist, waiter in a busy restaurant, etc. Human and animal developmental trajectories vastly outstrip, in depth and breadth of achievement, the products of artificial learning systems, although AI systems sometimes produce super-human competences in restricted domains, such as proving logical theorems, winning at chess or Jeopardy.[2]

I'll outline a very long-term multi-disciplinary research programme addressing these and other inadequacies in current AI, robotics, psychology, neuroscience and philosophy of mathematics and mind, in part by building on past and ongoing work in AI, and in part by looking for very different clues and challenges: the Meta-Morphogenesis project, partly inspired by Turing's work on morphogenesis.[3]

## 2 First characterise the gulf accurately

We need to understand what has and has not been achieved in AI. The former (identifying successes) gets most attention, though in the long run the latter task (identifying gaps in our knowledge) is more important for future progress.

There are many ways in which current robots and AI systems fall short of the intelligence of humans and other animals, including their ability to reason about topology and continuous deformation (for examples see [7] and http://www.cs.bham.ac.uk/research/projects/cogaff/misc/torus.html). Don't expect any robot (even with soft hands and compliant joints) to be able to dress a two year old child (safely) in the near future, a task that requires understanding of both topology and deformable materials, among other things.[4]

Getting machines to understand **why** things work or don't work lags even further behind programmed or trained abilities to perform tasks. For example, understanding why it's not a good idea to start putting on a shirt by inserting a hand into a cuff and pulling the sleeve up over the arm requires a combination of topological and metrical reasoning: – a type of mathematical child-minding theorem, not taught in schools but understood by most child-minders, even if they have never articulated the theorem and cannot articulate the reasons why

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[2] Though it's best not to believe everything you see in advertisements http://www.youtube.com/watch?v=tIIJME8-au8

[3] http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html This project is unfunded and I have no plans to apply for funding, though others may do so if they wish.

[4] As illustrated in this video. http://www.youtube.com/watch?v=WWNlgvtYcEs

it is true. Can you? Merely pointing at past evidence showing that attempts to dress a child that way always fails does not explain why it is impossible.

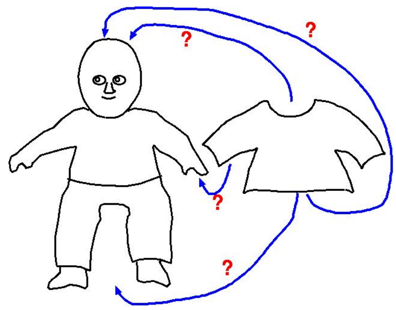


**Fig. 1.** What sequence of movements could get the shirt onto the child if the shirt is made of material that is flexible but does not stretch much? Why would it be a mistake to start by pushing the head through the neck-hole? What difference would it make if the material could be stretched arbitrarily without being permanently changed?

In more obviously mathematical domains, where computers are commonly assumed to excel, the achievements are narrowly focused on branches of mathematics using inference methods based on arithmetic, algebra, logic, probability and statistical theory.

However, mathematics is much broader than that, and we lack models of the reasoning (for instance geometrical and topological reasoning) that enabled humans to come up with the profoundly important and influential mathematical discoveries reported in Euclid's *Elements* 2.5 millennia ago – arguably the single most important book ever written on this planet. The early pioneers could not have learnt from mathematics teachers. How did they teach themselves, and each other? What would be required to enable robots to make similar discoveries without teachers?

Those mathematical capabilities seem to have deep, but mostly unnoticed, connections with animal abilities to perceive practically important types of affordance, including use of mechanisms that are concerned not only with the perceiver's possibilities for immediate action but more generally with what is and is not possible in a physical situation and how those possibilities and impossibilities can change, for example if something is moved. A child could learn that a shoelace threaded through a single hole can be removed from the hole by pulling the left end of the lace or by pulling the right end. Why does combining two successful actions fail in this case, whereas in other cases a combination improves success (e.g. A pushing an object and B pushing the object in the same direction)? Collecting examples of explanations of impossibilities that humans understand but not yet current robots is one way to investigate gaps in what has been achieved so far. It is also a route toward understanding the nature of human mathematical competences, which I think start to develop in children long before anyone notices.

Many animals, including pre-verbal humans, need to be able to perceive and think about what is and is not possible in a situation, though in most cases without having the ability to reflect on their thinking or to communicate the thoughts to someone else. The meta-cognitive abilities evolve later in the history of a species and develop later in individuals.

Thinking about what would be possible in various possible states of affairs is totally different from abilities to make predictions about what will happen, or to reason probabilistically. It's one thing to try repeatedly to push a shirt on a child by pushing its hand and arm in through the end of a sleeve and conclude from repeated failures that success is improbable. It's quite another thing to understand that if the shirt material cannot be stretched, then success is impossible (for a normally shaped child and a well fitting shirt) though if the material could be stretched as much as needed then it could be done. Additional reasoning powers might enable the machine to work out that starting by pushing the head in through the largest opening could require least stretching, and to work this out without having to collect statistics from repeated attempts.

## 3 Shallow statistical vs deep knowledge

It is possible to have a shallow (statistical) predictive capability based on observed regularities while lacking deeper knowledge about the set of possibilities sampled in those observations. An example is the difference between (a) having heard and remembered a set of sentences and noticed some regular associations between pairs of words in those sentences and (b) being aware of the generative grammar used by the speakers, or having acquired such a grammar unconsciously. The grasp of the grammar, using recursive modes of composition, permits a much richer and more varied collection of utterances to be produced or understood. Something similar is required for visual perception of spatial configurations and spatial processes that are even richer and more varied than sentences can be. Yet it seems that we share that more powerful competence with more species, including squirrels and nest-building birds.

This suggests that abilities to acquire, process, store, manipulate, and use information about spatial structures evolved before capabilities that are unique to humans, such as use of spoken language. But the spatial information requires use of something like grammatical structures to cope with scenes of varying complexity, varying structural detail, and varying collections of possibilities for change. In other words visual perception, along with planning and acting on the basis of what is scene, requires the use of internal languages that have many of the properties previously thought unique to human communicative languages. Finding out what those languages are, how they evolved, how they can vary across species, across individuals, and within an individual during development is a long term research programme, with potential implications for many aspects of AI/Robotics and Cognitive Science – discussed further in [8].

Conceivably a robot could be programmed to explore making various movements combining a shirt and a flexible, child-shaped doll. It might discover one or more sequences of moves that successfully get the shirt on, provided that the shirt and doll are initially in one of the robot's previously encountered starting states. This could be done by exploring the space of sequences of possible moves, whose size would depend on the degree of precision of its motion and control parameters. For example, if from every position of the hands there are 50 possible 3-D directions of movement and the robot tries 20 steps after each starting direction, then the number of physical trajectories from the initial state to be explored is

$$50^{20} = 95367431640625000000000000000000000$$

and if it tries a million new moves every second, then it could explore that space in about 302408000000000000 millennia. Clearly animals do something different when they learn to do things, but exactly how they choose things to try at each moment is not known.

The "generative grammar" of spatial structures and processes is rich and deep, and is not concerned only with linear sequences or discrete sequences. In fact there are multiple overlapping space-time grammars, involving different collections of objects assembled, disassembled, moved, repaired, etc. and used, often for many purposes and in many ways. Think of what structures and processes are made possible by different sorts of children's play materials and construction kits, including plasticine, paper and scissors, meccano, lego, tinkertoys, etc. The sort of deep knowledge I am referring to involves grasp of the structure of a construction-kit with generative powers, and the ability to make inferences about what can and cannot be built with that kit, by assembling more and more parts, subject to the possibilities and constraints inherent in the kit.[5]

There are different overlapping subsets of spatio-temporal possibilities, with different mathematical structures, including Euclidean and non-Euclidean geometries (e.g. the geometry of the surface of a hand, or face is non-euclidean) and various subsets of topology. Mechanisms for acquiring and using these "possibility subsets", i.e. possible action sequences and trajectories, seem to be used by pre-verbal children and other animals. That suggests that those abilities, must have evolved before linguistic capabilities. They seem to be at work in young children playing with toys before they can understand or speak a human language. The starting capabilities extended through much spatial exploration, provide much of the subject matter (semantic content) for many linguistic communications.

Some of the early forms of reasoning and learning in young humans, and corresponding subsets in other animals, are beyond the scope of current AI theorem provers, planners, reasoners, or learning systems that I know of. Some of those forms seem to be used by non-human intelligent animals that are able to perceive

[5] An evolving discussion note on this topic can be found here: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html

both possibilities and constraints on possibilities in spatial configurations. Betty, a New Caledonian crow, made headline news in 2002 when she surprised Oxford researchers by making a hook from a straight piece of wire, in order to lift a bucket of food out of a vertical glass tube. Moreover, in a series of repeated challenges she made multiple hooks, using at least four very different strategies, taking advantage of different parts of the environment, all apparently in full knowledge of what she was doing and why – as there was no evidence of random trial and error behaviour. Why did she not go on using the earlier methods, which all worked? Several of the videos showing the diversity of techniques are still available here: http://users.ox.ac.uk/~kgroup/tools/movies.shtml. The absence of trial-and-error processes in the successful episodes suggests that Betty had a deep understanding of the range of possibilities and constraints on possibilities in her problem solving situations.

It is very unlikely that you have previously encountered and solved the problem posed below the following image, yet many people very quickly think of a solution.

**Fig. 2.** Suppose you wanted to use one hand to lift the mug to a nearby table without any part of your skin coming into contact with the mug, and without moving the book on which the mug is resting, what could you do, using only one hand?

In order to think of a strategy you do not need to know the exact, or even the approximate, sizes of the objects in the scene, how far away they are from you, exactly what force will be required to lift the mug, and so on. It may occur to you that if the mug is full of liquid and you don't want to spill any of it, then a quite different solution is required. (Why? Is there a solution?).

The two pictures in Figure 3 present another set of example action strategies for changing a situation from one configuration to another. At how many different levels of abstraction can you think of the process, where the levels differ in the amount of detail (e.g. metrical detail) of each intermediate stage. For example, when you first thought about the problem did you specify which hands or which

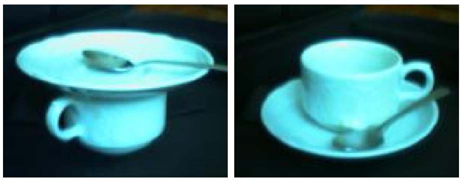

**Fig. 3.** Consider one or more sequences of actions that would enable a person or robot to change the physical configuration depicted on the left into the one depicted on the right – not necessarily in exactly the same locations as the objects depicted. Then do the same for the actions required to transform the right configuration to the left one.

fingers would be used at every stage, or at which location you would need to grasp each item? If you specified the locations used to grasp the cup, the saucer and the spoon, what else would have to change to permit those grasps? The point about all this is that although you do not normally think of using mathematics for tasks like this, if you choose a location at which to grasp the cup using finger and thumb of your left hand, that will mathematically constrain the 3-D orientation of the gap between between finger and thumb, if you don't want the cup to be rotated by the fact of bringing finger and thumb together. A human can think about the possible movements and the orientations required, and why those orientations are required, without actually performing the action, and can answer questions about why certain actions will fail, again without doing anything.

These are examples of "offline intelligence", contrasted with the "online intelligence" used in actually manipulating objects, where information required for servo-control may be used transiently then discarded and replaced by new information. My impression is that a vast amount of recent AI/Robotic research has aimed at providing online intelligence with complete disregard for the requirements of offline intelligence. Offline intelligence is necessary for achieving complex goals by performing actions extended over space and time, including the use of machines that have to be built to support the process, and in some cases delegating portions of the task to others. The designer or builder of a skyscraper will not think in terms of his/her own actions, but in terms of what motions of what parts and materials are required.

### 3.1 Limitations of sensorymotor intelligence

When you think about such things even with fairly detailed constraints on the possible motions, you will not be thinking about either the nervous signals sent to the muscles involved, nor the patterns of retinal stimulation that will be provided – and in fact the same actions can produce different retinal processes depending on the precise position of the head, and the direction of gaze of the eyes, and whether and how the fixation changes during the process. Probably the fixation requirements will be more constrained for a novice at this task than for an expert.

However, humans, other animals, and intelligent robots do not need to reason about sensory-motor details if they use an ontology of 3-D structures and processes, rather than an ontology of sensory and motor nerve signals. Contrast this with the sorts of assumptions discussed in [2], and many others who attempt to build theories of cognition on the basis of sensory-motor control loops.

As John McCarthy pointed out in [4] it would be surprising if billions of years of evolution failed to provide intelligent organisms with the information that they are in a world of persisting 3-D locations, relationships, objects and processes – a discovery that, in a good design, could be shared across many types of individuals with very different sensors and motors, and sensory motor patterns. Trying to make a living on a planet like this, whose contents extend far beyond the skin of any individual, would be messy and highly inefficient if expressed entirely in terms of possible sensory-motor sequences, compared with using unchanging representations for things that don't change whenever sensory or motor signals change. Planning a short cut home, with reference to roads, junctions, bus routes, etc. is far more sensible than attempting to deal, at any level of abstraction, with the potentially infinite variety of sensory-motor patterns that might be relevant.

This ability to think about sequences of possible alterations in a physical configuration without actually doing anything, and without having full metrical information, inspired much early work in AI, including the sorts of symbolic planning used by Shakey, the Stanford robot, and Freddy, the Edinburgh robot, over four decades ago, though at the time the technology available (including available computer power) was grossly inadequate for the task, including ruling out visual servo-control of actions.

Any researcher claiming that intelligent robots require only the right physical mode of interaction with the environment, along with mechanisms for finding patterns in sensory-motor signals, must disregard the capabilities and information-processing requirements that I have been discussing.

## 4 Inflating what "passive walkers" can do

Some (whom I'll not mention to avoid embarrassing them) have attempted to support claims that only interactions with the immediate environment are needed for intelligence by referring to or demonstrating "passive walkers",[6] without saying what will happen if a brick is in the way of a passive walker, or if part of the walking route starts to slope uphill. Such toys are interesting and entertaining but do not indicate any need for a "New artificial intelligence", using labels such as "embodied", "enactivist", "behaviour based", and "situated", to characterise their new paradigm. Those new approaches are at least as selective as the older reasoning based approaches that they criticised, though in different ways. (Some of that history is presented in Boden's survey [1].)

[6] E.g. http://www.youtube.com/watch?v=N64KOQkbyiI

The requirements for perception and action mechanisms differ according to which "central" layers the organism has. For instance, for an organism able to use deliberative capabilities to think of, evaluate, and select multi-step plans, where most of the actions will occur in situations that do not exist yet, it is not enough to identify objects and their relationships (pencil, mug, handle of mug, book, window-frame, etc.) in a current visual percept. It is also necessary to be able to "think ahead" about possible actions at a suitable level of abstraction, including consideration of objects not yet known, requiring a potentially infinite variety of possible sensory and motor patterns.

## 5 The birth of mathematics

The ability to reason about possible actions at a level of generality that abstracts from metrical details seems to be closely related to the abilities of ancient Greeks, and others, to make mathematical discoveries about possible configurations of lines and circles and the consequences of changing those configurations, without being tied to particular lengths, angles, curvatures, etc., in Euclidean geometry or topology. As far as I know, no current robot can do this, and neuroscientists don't know how brains do it. Some examples of mathematical reasoning that could be related to reasoning about practical tasks and which are currently beyond what AI reasoners can do, are presented on my web site.[7,8]

In 1971 I presented a paper at IJCAI, arguing that the focus solely on logic-based reasoning, recommended by McCarthy and Hayes in [5] could hold up progress in AI, because it ignored forms of spatial reasoning that had proved powerful in mathematics and practical problem solving. I did not realise then how difficult it would be to explain exactly what the alternatives were and how they worked – despite many conferences and journal papers on diagrammatic reasoning since then.

There have also been several changes of fashion promoted by various AI researchers (or their critics) including use of neural nets, constraint nets, evolutionary algorithms, dynamical systems, behaviour-based systems, embodied cognition, situated cognition, enactive cognition, autopoesis, morphological computation, statistical learning, bayesian nets, and probably others that I have not encountered, often accompanied by hand-waving and hyperbole without much science or engineering. In parallel with this there has been continued research advancing older paradigms for symbolic and logic based, theorem proving, planning, and grammar based language processing. Several of the debates are analysed in [1],

## 6 Other inadequacies

There are many other inadequacies in current AI, including, for example the lack of an agreed framework for relating information-processing architectures

[7] http://www.cs.bham.ac.uk/research/projects/cogaff/misc/torus.html
[8] http://www.cs.bham.ac.uk/research/projects/cogaff/misc/triangle-sum.html

to requirements in engineering contexts or to explanatory models in scientific contexts. For example attempts to model emotions or learning capabilities, in humans or other animals, are often based on inadequate descriptions of what needs to be explained, for instance poor theories of emotions that focus only on emotions with characteristic behavioural expressions: a small subset of phenomena requiring explanation or poor theories of learning that focus only on a small subset of types of learning (e.g. reinforcement learning where learners have no understanding of what's going on). That would exclude the kind of learning that goes on when people make mathematical discoveries or learn to program computers or learn to compose music.

Moreover, much AI research uses a seriously restricted set of forms of representation (means of encoding information) partly because of the educational backgrounds of researchers – as a result of which many of them assume that spatial structures must be represented using mechanisms based on Cartesian coordinates – and partly because of a failure to analyse in sufficient detail the variety of problems overcome by many animals in their natural environments.

Standard psychological research techniques are not applicable to the study of learning capabilities in young children and other animals because there is so much individual variation, but the widespread availability of cheap video cameras has led to a large and growing collection of freely available examples.

## 7 More on offline and online intelligence

Researchers have to learn what to look for. For example, *online* intelligence requires highly trained precisely controlled responses matched to fine details of the physical environment, e.g. catching a ball, playing table tennis, picking up a box and putting it on another. In contrast *offline* intelligence involves understanding not just existing spatial configurations but also the possibilities for change and constraints on change, and for some tasks the ability to find sequences of possible changes to achieve a goal, where some of the possibilities are not specified in metrical detail because they do not yet exist, but will exist after part of the plan has been carried out.

This requires the ability to construct relatively abstract forms of representation of perceived or remembered situations to allow plans to be constructed with missing details that can be acquired later during execution. You can think about making a train trip to another town without having information about where you will stand when purchasing your ticket or which coach you will board when the train arrives. You can think about how to rotate a chair to get it through a doorway without needing information about the precise 3-D coordinates of parts of the chair or knowing exactly where you will grasp it, or how much force you will need to apply at various stages of the move.

There is no reason to believe that humans and other animals have to use probability distributions over possible precise metrical values, in all planning contexts where precise measurements are not available. Even thinking about such precise values probabilistically is highly unintelligent when reasoning about topological relationships or partial orderings (nearer, thinner, a bigger angle, etc.) is all that's needed[9] Unfortunately, the mathematically sophisticated, but nevertheless unintelligent, modes of thinking are used in many robots, after much statistical learning (to acquire probability distributions) and complex probabilistic reasoning, that is potentially explosive. That is in part a consequence of the unjustified assumption that all spatial properties and relations have to be expressed in Cartesian coordinate systems. Human mathematicians did not know about them when they proved their first theorems about Euclidean geometry, built their first shelters.

## 8 Speculations about early forms of cognition

It is clear that the earliest spatial cognition could not have used full euclidean geometry, including its uniform metric. I suspect that the metrical version of geometry was a result of a collection of transitions adding richer and richer non-metrical relationships, including networks of partial orderings of size, distance, angle, speed, curvature, etc.

Later, indefinitely extendable partial metrics were added: distance between X and Y is at least three times the distance between P and Q and at most five times that distance. Such procedures could allow previously used standards to be subdivided with arbitrarily increasing precision. At first this must have been applied only to special cases, then later somehow (using what cognitive mechanisms?) extrapolated indefinitely, implicitly using a Kantian form of potential infinity (long before Kant realised the need for this).

Filling in the details of such a story, and relating it to varieties of cognition not only in the ancestors of humans but also many other existing species will be a long term multi-disciplinary collaborative task, with deep implications for neuroscience, robotics, psychology, philosophy of mathematics and philosophy of mind. (Among others.)

Moreover, human toddlers appear to be capable of making proto-mathematical discoveries ("toddler theorems") even if they are unaware of what they have done. The learning process starts in infancy, but seems to involve different kinds of advance at different stages of development, involving different domains as suggested by Karmiloff-Smith in [3].

For example, I recently saw an 11 month old infant discover, apparently with great delight, that she could hold a ball between her upturned foot and the palm of her hand. That sort of discovery could not have been made by a one month old child. Why not?[10]

Animal abilities to perceive and use complex novel affordances appear to be closely related to the ability to make mathematical discoveries. Compare the

[9] As I have tried to illustrate in: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/changing-affordances.html

[10] A growing list of toddler theorems and discussions of their requirements can be found in http://www.cs.bham.ac.uk/research/projects/cogaff/misc/toddler-theorems.html

abilities to think about changes of configurations involving ropes or strings and the mathematical ability to think about continuous deformation of closed curves in various kinds of surface.

Not only computational models, but also current psychology and neuroscience, don't seem to come close to describing these competences accurately or producing explanations – especially if we consider not only simple numerical mathematics, on which many psychological studies of mathematics seem to focus, but also topological and geometrical reasoning, and the essentially mathematical ability to discover a generative grammar closely related to the verbal patterns a child has experienced in her locality, where the grammar is very different from those discovered by children exposed to thousands of other languages.

There seem to be key features of some of those developmental trajectories that could provide clues, including some noticed by Piaget in his last two books on Possibility and Necessity, and his former colleague, Annette Karmiloff-Smith [3].

## 9 The Meta-Morphogenesis project

Identifying gaps in our knowledge requires a great deal of careful observation of many forms of behaviour in humans at various stages of development and many other species, always asking: "what sort of information-processing mechanism (or mechanisms) could account for that?"

Partly inspired by one of Alan Turing's last papers on Morphogenesis [10], I proposed the Meta-Morphogenesis (M-M) project in [9], a very long term collaborative project for building up an agreed collection of explanatory tasks, and present some ideas about what has been missed in most proposed explanatory theories.

Perhaps researchers who disagree, often fruitlessly, about what the answers are can collaborate fruitfully on finding out what the questions are, since much of what needs to be explained is far from obvious. There are unanswered questions about uses of vision, varieties of motivation and affect, human and animal mathematical competences, information-processing architectures required for all the different sorts of biological competences to be combined, and questions about how all these phenomena evolved across species, and develop in individuals. This leads to questions about what the universe had to be like to support the forms of evolution and the products of evolution that have existed on this planet. The Meta-Morphogenesis project is concerned with trying to understand what varieties of information processing biological evolution has achieved, not only in humans but across the spectrum of life. Many of the achievements are far from obvious.[11]

[11] A more detailed, but still evolving, introduction to the project can be found here: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html

Unfortunately, researchers all too often mistake impressive new developments for steps in the right direction. I am not sure there is any way to change this without radical changes in our educational systems and research funding systems.

But those are topics for another time. In the meantime I hope many more researchers will join the attempts to identify gaps in our knowledge, including things we know happen but which we do not know how to explain, and in the longer term by finding gaps we had not previously noticed. I think one way to do that is to try to investigate transitions in biological information processing across evolutionary time-scales, since its clear that types of information used, the types of uses of information, and the purposes for which information is used have changed enormously since the simplest organisms floating in a sea of chemicals.

Perhaps some of the undiscovered intermediate states in evolution will turn out to be keys to unnoticed features of the current most sophisticated biological information processors, including humans.

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