NOTE (25 May 2022)

There will be a new presentation, to a bio-engineering group in Singapore, probably on a Thursday morning (UK time) in June 2022. For further information check this page:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/singapore-2022.html

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This is
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-CCB-2022.html
A derived PDF version is also available (which may be temporarily out of date):
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-CCB-2022.pdf

This is a much revised version of a document created for a zoom presentation on Wed 23rd March 2022 at the
Centre for Computational Biology (CCB)
University of Birmingham

I am very grateful for all the questions and comments.

After the CCB presentation this web page was modified and extended for a new presentation:

On Friday 8th April 2022. 10.00am-12.00noon (UK Time/BST),
there was an online Zoom-based meeting of IRLab (Intelligent Robotics Lab),
School of Computer Science, University of Birmingham, UK:
https://www.birmingham.ac.uk/research/activity/computer-science/artificial-intelligence/intelligent-robotics-lab/index.aspx

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Title of talk (unchanged since previous presentations):

Recently hatched ideas about hatching and intelligence

Using very low energy physics and chemistry at "normal" temperatures in egg-laying vertebrates

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NB THIS IS STILL UNDER CONSTRUCTION AND LIKELY TO CHANGE
A later version may be given a new title.

A recording of the talk on 8th April 2022, including discussion, is available here, along with recordings of other IRLab talks:

https://www.youtube.com/playlist?list=PLKnAIE0gedEklvwT7IF2LxVEc82hfE5WI

The video recording of this talk is also directly accessible here:
https://www.youtube.com/watch?v=VJh_zkNnX1o

A revised, improved, version of a complex figure used in the talk is now available here:
http://www.cs.bham.ac.uk/~axs/fig/multi-multi-stage-evo-devo.jpg
The new diagram, including its textual components, should be regarded as a replacement for the portion of the recording between 22:03 to 27:07.

Abstract

The ideas presented here are restricted to egg-laying vertebrates, which assemble themselves disconnected from their mothers, while contained in an eggshell, in which they go through striking changes in a hatching process until the new hatchling emerges.

The restriction to vertebrates rules out egg-laying insects, for example, although their development is also very interesting, including changes in physical form and behaviours produced by metamorphosis in cocoons -- which will not be discussed here.

Hatching in an egg starts with a fertilised egg, which is mostly composed of a few varieties of fairly amorphous matter, apart from a minute cell containing DNA, whose processes of division, replication, and differentiation eventually produce a new very complex organism that emerges from the shell. What are the morphogenesis mechanisms that produce such remarkable transformations?

In contrast, metamorphosis (e.g. in insects) is a phase between a larval stage and an adult stage. During metamorphosis the animal changes itself from one form with a collection of behaviours to a completely different form with very different behaviours, including new feeding behaviours, flying in some cases, and mating behaviours, depending on the type of organism.

Many vertebrates lay eggs in which new hatchlings develop until they emerge with complex, highly differentiated bodies and sophisticated behavioural abilities, including abilities to feed themselves, and later to mate, and in many cases look after their own hatchling offspring (e.g. birds that whose eggs hatch in nests where food needs to be brought to hatchlings).

Reproduction by laying eggs is used by a large variety of animal species that differ widely in their physical forms, behaviours and habitats. This presentation draws attention to some abstract but important generalities across various egg-based reproductive mechanisms in vertebrate species, including chickens, ducks, avocets, swans, alligators, turtles, crocodiles, pythons, and many more.

These abstract common features help to explain how enormously complex construction processes enclosed within eggshells can transform a fairly small variety of chemicals into a wide variety of different chemical substances reassembled to form a large collection of physiological structures in an enormously complex intricately interconnected highly functional animal body which starts life after hatching already in possession of important competences required for finding and consuming food, without having to learn to do it e.g. by training neural networks.

In contrast, processes in mammals, with rich mother-infant interaction during development of the foetus, differ widely in what they achieve. E.g. some new-born mammals can run with the herd if chased by a predator shortly after birth, i.e. without having to learn how to do that. Others are

extremely helpless for a long time after birth. The trade-offs between alternative modes of reproduction of vertebrate species will be discussed elsewhere.

One of the main questions arising from consideration of hatching processes in a variety of egg-laying vertebrate species is this:

What features of fundamental physics are essential to the explanation of how such hatching processes (including complex chemical transformation and assembly processes) are possible?

The ideas are complex and messy and not easy to present in a summary web site like this.

This Document
This document is located at:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-CCB-2022.html
A PDF version is also available:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-CCB-2022.pdf

NOTE:
Earlier versions of this document were used for presentations on 23rd March and 8th April, 2022. However, some of the details were incomplete at that time and have been extended since then. The rest of this document is a much modified version of the original document.

Development of this document has continued since those presentations, especially some of the detailed claims about relationships between stages in evolutionary history and stages in individual development in eggs of vertebrate organisms.

The ideas are related to, but more subtle than, the familiar old conjecture that "Ontogeny recapitulates phylogeny". The claim is not that individual developing organisms repeat their evolutionary history, by taking on a succession of features of their ancestors.

Instead, I propose that a succession of in-egg assembly mechanisms controlling individual development in eggs, dealing with increasingly complex assembly tasks, partly replicates and combines transitions in assembly mechanisms and processes in the evolutionary history of the species.

So the individual organism does not take on successive shapes, capabilities, or behaviours of its ancestors, but the successive assembly mechanisms constructed in the egg during hatching, use modes of in-egg assembly that were used in the evolutionary history of the species.

So evolution produces not only new organisms with new structures, but also new structure-building mechanisms, and new mechanisms for building structure-building mechanisms... etc. Aspects of that evolutionary process (modes of assembly of increasingly intricately related body parts) are replicated during the hatching process.

These ideas are sketched in an impressionistic fashion in the diagram below. This diagram uses ideas suggested privately by Professor Susan Stepney (York University) a few weeks before this presentation, in response to my attempt to explain to her what I was thinking about.

The diagram has been repeatedly extended in an attempt to make the ideas more explicit. The current version, below, was produced after the presentation on 8th Jan 2022.

Consequently, this presentation significantly extends ideas developed and presented during 2020 and 2021, in talks about mechanisms providing intelligence in newly hatched vertebrates, such as reptiles and birds, including the presentation (alongside a talk by Mike Levin) at the MORCOM Workshop on 15th Sept 2021
https://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-morcom.html
(MORphological COMputing of Cognition and Intelligence)

This new presentation is also closely related to a talk on Compositionality given in 2018 Sloman(2018) and to earlier work on the Meta-Morphogenesis project
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html
to the theory of construction kits evolved and used by biological evolution:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html
and also to work on the meta-configured genome theory (developed with Jackie Chappell starting shortly after she came to Birmingham from Oxford in 2004):
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-configured-genome.html
(I'll say more about that theory later.)

Jackie unfortunately had other obligations at the time of this presentation and was not available to help me answer questions!
https://www.birmingham.ac.uk/staff/profiles/biosciences/chappell-jackie.aspx

Many other individuals, including students and colleagues in Birmingham and other places, have helped me in various ways, including sending comments, criticisms or questions relating to my publications or online papers, or commenting on talks, especially zoom talks given at various events during 2021.

Note added 13 Apr 2022
Jackie Chappell has informed me about Homeobox genetic mechanisms, which appear to be directly relevant to topics in this document. See the Wikipedia Entry.
This seems to be closely related to the mechanisms postulated in the meta-morphogenesis project outlined here (also pdf):
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html
Homeobox mechanisms may be essential components of the mechanisms postulated in this paper. Ideas developed in collaboration with Jackie Chappell about what we called Meta-Configured genomes in our 2007 paper are directly relevant, though at the time we did think of applying them to processes in eggs. More generally, there is already a considerable amount of literature on Evolutionary Developmental Biology, to which the ideas in this presentation need to be related. E.g. see
https://en.wikipedia.org/wiki/Evolutionary_developmental_biology

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Original motivation: explaining biological forms of spatial intelligence
For many years, originally inspired by reading Immanuel Kant's views in his (1781), I have been claiming, using many sorts of examples, that ancient mathematical discoveries depended on evolved forms of spatial intelligence that could not be explained by any current theories/models of

intelligent processing, whether based purely on logic, or on neural-net based mechanisms, or a combination. I now claim that the answers are related to questions about how chemical processes are used to assemble new organisms, including animals that emerge from eggs with complex forms of spatial intelligence, such as the newly hatched avocets shown in the videoclip below.

[I believe Alan Turing was working on a Chemistry-based theory of intelligence shortly before he died. I suspect that his recently widely cited 1952 paper, on chemical morphogenesis of 2D patterns, was probably a side-effect of his deeper research on chemistry-based learning and reasoning mechanisms, and perhaps the role of chemistry in supporting various forms of life and reproduction.]

Example: spatial competences of newly hatched avocets
The newly hatched avocets in the 35 second videoclip below clearly have some complex spatial competences that they have not had time or opportunity to learn after hatching. I take that as an indication of the power of chemistry-based assembly mechanisms used in hatching.

The videoclip is from a BBC Springwatch programme in June 2021:
https://www.cs.bham.ac.uk/research/projects/cogaff/movies/avocets/avocet-hatchlings.mp4

The full Springwatch episode, showing the avocet hatchlings, is on Youtube at:
https://www.youtube.com/watch?v=FV6ZHe0CiHw
The section on "Avocet Island" starts at about 12min 23sec.
The 35 second extract, above, above, showing competences of newly hatched avocets, starts at about 12mins 30secs.

Conjecture: Relevance to ancient discoveries in geometry and topology
I conjecture that ancient human mathematical competences that led to major discoveries in geometry, including Pythagoras' theorem, first discovered and proved centuries before Pythagoras was born(!) are not explained by any currently fashionable mechanisms in AI, psychology, or neuroscience, but depend on forms of chemical information processing that were originally required to solve the problems of coordinating parallel assembly of many parts of new organisms, including ancient, and not so ancient, vertebrates grown inside eggshells, like the avocets in the video-clip above.

How many people at this meeting (or readers of this document) learnt at school, or university, to find geometric proofs and constructions?

As Immanuel Kant pointed out, in opposition to David Hume (explained in more detail later) those were not discoveries about probabilities: they were about what is necessarily the case or impossible, and could include things that are known to be possible before examples are encountered.

However, such discoveries were not purely logical consequences of definitions, i.e. "analytic truths" in Kant's terminology. And although the ideas may be triggered by empirical discoveries the knowledge gained is not empirical knowledge, and it is not about empirical generalisations, but about what is impossible or necessarily the case.

As anyone with a good mathematical education will be aware (alas less common now than in my youth), making such a discovery is a totally different process from establishing that something has a very high or very low probability on the basis of empirical evidence: the focus of a massive amount of recent and ongoing research on natural and artificial neural networks. I regard much of that research as seriously misguided and anti-scientific, for reasons that I hope will become clear on the basis of this presentation.

That will include unrecognized features of many discoveries about geometry, made by ancient mathematicians, and used by many scientists and engineers since then.

(Unfortunately there are serious gaps in the mathematical education that many otherwise highly intelligent researchers have experienced.)

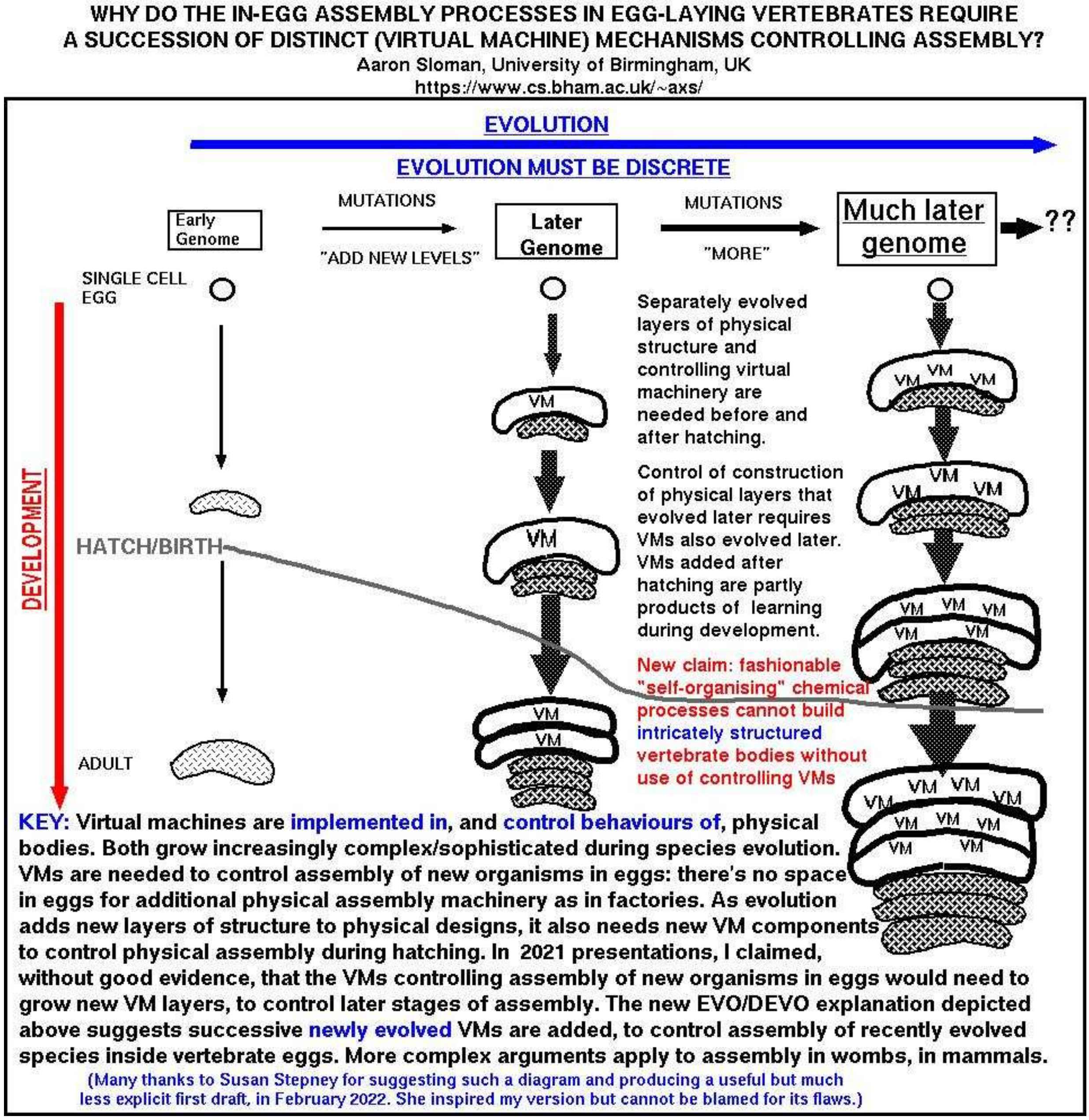
This talk: A new Evo-Devo set of ideas

I shall try to present a rather complex collection of ideas most of which have been presented in earlier papers and talks in this project along with some very new ideas (new since January 2022).

When I mentioned the new ideas in a message to Susan Stepney she sent me a photo of a hand drawn diagram summarising what she had understood from our communication. During the zoom presentation on 8th January I tried to explain her ideas using a fairly complex diagram that I had created the previous night.

However I was not satisfied with the diagram and after the presentation produced a new version now displayed as Figure Evo-Devo, below, although no such diagram can adequately specify all the ideas in the theory. Moreover, the theory is still under development, and much of what is in this document, including the diagram, may need to be revised.

Figure Evo-Devo



The importance of virtual machinery in the above mechanisms

One of the largely unheralded achievements of computer science and computer systems engineering since the 1960s was the invention, design, implementation, and use of increasingly complex forms of virtual machinery, including virtual machinery that could continue running on complex hardware systems while the components of those systems were being replaced, either because of faults or because new technology provided benefits such as greater speed, greater reliability, lower cost, or new kinds of functionality e.g. online conferences linking many participants using many different kinds of computers and running on networks that constantly adjust themselves to achieve load balancing or compensate for local hardware failures.

This document refers to virtual machinery used in biological organisms, which I suspect includes not yet understood chemistry based techniques providing greater robustness and reliability with much lower requirements for physical space, physical materials, external power supplies, heat dissipation, etc. and also more sophisticated self construction and self repair mechanisms than any current human-engineered forms of virtual machinery. A major largely unacknowledged feature of biological hatching processes is creation of use of a wide variety of species specific types of virtual machinery required for assembling animals of many different types while they hatch in eggs, and also providing important kinds of information-processing functionality after hatching. [This paper does not attempt to defend that claim.] See also .Sloman(2013++) (In need of revision, e.g. to include points made here.)

The above diagram does not indicate differences between animals that reproduce using eggs, as opposed to being carried in the mother till they are born, in some cases utterly dependent on a carer/feeder and in others less dependent (e.g. foals that can run with the herd shortly after birth).

Many egg-using species, like the avocets in the video above, produce new hatchlings that already have sophisticated spatial competences that they do not need to learn, I am not aware of any work attempting to explain how chemical assembly processes in eggs can produce hatchlings with such competences, nor how evolution can produce the required chemical machinery in eggs.

I'll try to explain some profound implications of that fact below. During 2021 I gave a series of talks drawing attention to facts about competences of many species that reproduce using eggs, from which emerge hatchlings with significant spatial competences. The competences of avocet hatchlings shown in the video above are just one example among many. When discussing such phenomena in 2020 I speculated that the processes of assembly in eggs must go through a series of transitions that require increasingly complex modes of control of assembly. I tried to justify this in terms of the increasing complexity of the assembly *tasks*.

But not everyone was convinced and several audience members suggested that mechanisms explaining processes of self-modification in simple organisms being studied in various laboratories, such as the work of Mike Levin and familiar work on Slime molds could suffice.

These countered my claims that hatching processes in vertebrate egg-layers could not all be based on a uniform mechanism of self-organisation. The new arguments below counter the objections by pointing to discontinuities in evolution that produce discontinuities in foetal assembly mechanisms. But I am aware that a great deal more evidence from organic chemistry, microbiology, immunology, developmental biology and ethology than I can present will be needed to substantiate these claims.

The above "Evo-Devo" diagram indicates crudely that some species use what Jackie Chappell and I called Meta-Configured genomes, which produce multiple stages of gene-expression, where later stages make use of information acquired from the environment during earlier stages of gene expression.

In the case of animals hatched in eggs, as in humans and other mammals, some of the processes of gene expression may continue after birth, or hatching, with consequences mentioned in the theory of meta-configured genomes mentioned below.

The importance of modal concepts Impossibility and Necessity

Many mathematical discoveries involve detection of necessity or impossibility. This has critical implications for theories of cognition based on neural nets, because:
Detection of necessity and impossibility, cannot be achieved by neural net mechanisms, since necessity and impossibility are not simply high and low probabilities.

Despite being highly fashionable, neural net mechanisms that collect statistics and derive probabilities cannot lead to discoveries of spatial necessity or impossibility, including ancient mathematical discoveries of geometrical and topological facts since those facts are not concerned with high and low probabilities.

For example necessity is not the same thing as a very high degree of probability.

Impossibility is not a very low degree of probability.

Many scientific researchers investigating cognition seem to have had a mathematical education that failed to provide them with an understanding of the roles of necessity and impossibility in mathematical discovery, as opposed to high and low probabilities.

Hybrid neural plus logical mechanisms can do more, but I don't think they explain the phenomena discussed here: there are forms of necessity and impossibility discovered by ancient geometers that are not cases of purely *logical* necessity or impossibility. That includes many cases of *spatial* necessity or impossibility (e.g. transitivity of spatial containment).

Example: superimposing spirals

Here's a new version of an old example of spatial intelligence. What brain mechanisms make it possible to detect the impossibility below?

Figure Spirals

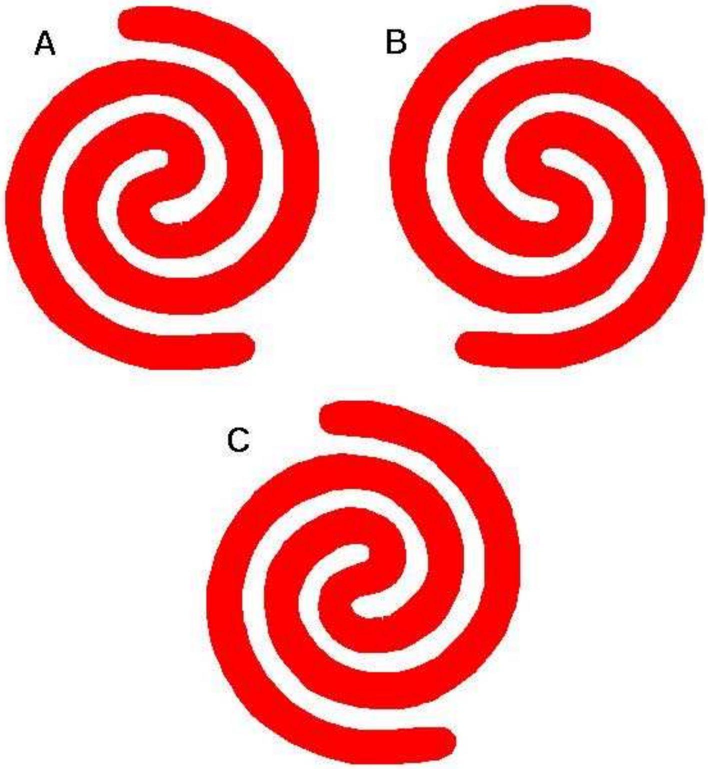


FIG: Spirals
By sliding object C around in the surface, including both translating and rotating it in the plane, clockwise or counter-clockwise, without changing its shape or "flipping" it over in 3D space, is it possible to get C exactly superimposed on either A or B or both?

How can you know that one of the alternatives is possible and the other impossible?

I claim that Immanuel Kant's views about this, around 1781, were basically correct, though lacking in detail, and it seems that he despaired of our ever understanding the mechanisms involved: "This schematism of our understanding, in its application to appearances and their mere form, is an art concealed in the depths of the human soul, whose real modes of activity nature is hardly likely ever to allow us to discover, and to have open to our gaze" *Critique of Pure Reason*, translated by Kemp Smith. I am proposing a research project that will eventually allow us to understand those "real modes of activity", after we have understood its evolutionary history.

Most philosophers of mathematics now mistakenly think Kant's views were refuted by 20th century developments in relativity theory, proposed by Einstein and later confirmed by Eddington's solar eclipse observations in 1919. I've been arguing (since my 1962 DPhil Thesis), that Kant was right and they were wrong.

I'll try to show later how that refutes claims about the explanatory power of neural-net mechanisms that collect statistical evidence and derive probabilities. Necessity and impossibility are not points on probability scales!

A full defence of Kant's view requires advances in our understanding of reproductive mechanisms. I shall try to show that assembly processes in vertebrate eggs provide important clues.

Question about the Spirals Figure

The spiral superposition impossibility illustrates Kant's claims about (currently unknown) brain mechanisms that can discover spatial impossibilities. But the mechanisms that make such discoveries possible are still unknown.

I suggest that similar mechanisms are used by human and non-human animals with high spatial intelligence -- soon after hatching in the case of many bird species, like the newly hatched avocets in the video above. Additional mechanisms allow us to detect that certain things are necessarily true, or necessarily false, as illustrated by your ability to reason non-empirically about the Compare the Stone rings problem, below.

What difference would a curved space make?

If the Spirals figure were reproduced on the surface of a sphere, instead of on a planar surface, and a portion corresponding to object C was able to slide around on the surface of the sphere, would that make any difference to the answers to the question above? Would that allow object C to coincide with the figure that it cannot coincide with on a planar surface? How can you tell? What brain mechanisms enable (some) humans (but not human infants, for example) to answer that question?

[I have no idea whether my questions about spherical or toroidal versions of the original problem have ever been discussed previously. One of the facts about mathematical minds that remains to be explained is: *What mechanisms enable them to come up with new questions?*]

How were those mechanisms created and to what extent are they shared by non-human species with high spatial intelligence?

If the figure were replicated in the obvious way on the surface of a torus, instead of a planar or spherical surface, would that make a difference to the answers?

What brain mechanisms make it possible to think about these variants of the original problem, and other variants readers may think of?

More generally, what brain mechanisms made it possible for us, and also ancient mathematicians who lived centuries before Pythagoras, to discover "interesting" mathematical problems and theorems in geometry and topology, including many different proofs of Pythagoras' theorem?

Spatial intelligence is not restricted to mathematicians, or humans.

Spatial intelligence in many non-human animals, and pre-verbal human children, enables them to avoid wasting time trying to achieve a goal using actions for which success is impossible, e.g. moving directly toward a visible object through a hole that is too small to pass through.

Many humans without mathematical training can detect that it is impossible to push a table through a doorway while the table top remains horizontal.

Some of those humans can also work out that rotating the table in space so that the top is no longer horizontal may make it possible to move the table through the doorway. This is obvious if the legs are shorter than the width of the doorway. But even if the legs are longer, a sequence of translations and rotations of a tilted table can make it possible to get the table through the doorway. (I hope most readers are familiar with this problem and its solution, or can work out the solution from this description.)

Statistics-based neural nets cannot detect, or even represent, the fact that the original task (getting the table through the doorway while it remains vertical) is *impossible*, or that a certain sequence of rotations and translations will *necessarily* solve the problem, so that processes of trial and error are not required to discover what will work.

Neural nets derive probabilities from statistical evidence. They cannot establish necessity or impossibility: those are not degrees of very high and very low probability -- a fact that is ignored by many researchers studying natural or artificial neural-net mechanisms.

Recent steps toward a new theory

In presentations given during 2021, I claimed that spatial competences of newly hatched animals of several different species, e.g. competences used to obtain food very soon after hatching, showed that chemical assembly mechanisms in eggs could achieve results that many scientists assume require learning based on interaction with the physical environment, e.g. training neural nets in brains after hatching.

In those presentations I conjectured that in order to achieve such results the in-egg assembly mechanisms had to be changed as the developing foetus grew more complex, making the assembly control tasks more complex and more difficult. I also suggested that the in-egg assembly mechanisms could also produce brain mechanisms providing competences required shortly after hatching, like the competences of those newly hatched avocets.

But that was a weak argument for changing layers of mechanism controlling in-egg assembly processes. Moreover, it did not answer the question how the assembly mechanisms decide when to add a new layer of control and what additional control functions to provide -- different action-control processes are required by different species that emerge from eggs, e.g. chickens, alligators and turtles.

This new presentation poses more questions than answers. But it substantially extends the previously presented ideas by paying more attention to the detailed requirements for assembly processes in eggs of vertebrates (e.g. reptiles, birds, and others), and the evolutionary changes that were required to produce those changes in assembly mechanisms and processes.

In particular, to understand the assembly processes in eggs we need to understand

> how the requirements and the in-egg assembly mechanisms change across generations, during evolution of the species.

For this we need to understand
--- the stages that occur during evolution of the species

and how those evolutionary changes relate to
--- changing requirements for control of assembly during the hatching process.

Those control requirements are not obvious. For example, they cannot easily be inferred from pictorial representations of slices through a foetus at different stages of development such as this:
https://www.cs.bham.ac.uk/~axs/fig/chicken-egg-devel.jpg

Such an image sequence doesn't indicate the complexity of the chemical processes that produce state changes, and the forms of control that are required at various stages of assembly of the new animal.

Among other limitations, such images don't show the requirements for assembling the neural connections, the various types and locations of blood vessels (including capillary networks), the mechanisms for production and distribution of hormones, the mechanisms for extracting nutrients from food and distributing them via the blood supply, the mechanisms for waste disposal, including disposal of carbon dioxide produced around the body, and many other details that can vary:

- across species,
- across evolutionary stages within the history of a species, and
- across stages of development of individuals while hatching is going on in eggs.

Studying only products of hatching or birth ignores important mechanisms

Psychologists and neuroscientists have put much effort into studying processes of learning by interacting with the environment that occur after birth or hatching, usually ignoring what happens in eggs or wombs and how those pre-natal processes with different evolutionary histories contribute to post-natal competences.

Such research is inherently "blinkered".

In particular, early availability of competences after hatching, illustrated by the avocets, above, must result from processes that occur inside the egg, before hatching. The avocets have no need to learn after hatching, and they don't have the time to train themselves using trial and error. They already know what to do -- like the post-hatching young of many (vertebrate) species that reproduce using eggs. How do they know?

Likewise, early competences of a new-born mammal, such as a foal that can run with the herd shortly after birth, must be products of chemical assembly processes inside wombs: they cannot be products of learning after birth during a few hours without any running or practice avoiding obstacles.

However, understanding the assembly of mammals in wombs is a far more complex challenge that understanding assembly in eggs: because in eggs all the assembly mechanisms are included within the eggshell, whereas a mammalian foetus is constantly involved in rich and complex interactions with a variety of mechanisms inside the mother.

Eggs are sophisticated self-constructing chemical factories

Within eggs, during hatching, chemicals provided by the mother before the egg is laid, are disassembled and the atoms reassembled to form the extraordinarily complex and intricate collection of highly differentiated physiological structures that exist by the time the new hatchling emerges from the egg, e.g. a new chick, duckling, alligator, turtle, python, etc.

The challenge

How are the processes of decomposition of millions of molecules followed by use of the resulting particles to assemble a new organism in the egg controlled as required to produce a new physical machine with a huge variety of newly created components in highly intricate relationships, including blood vessels, glands, nerve fibres, tendons, bones, muscles, skin, skin-coverings (e.g. fur, or feathers, or shells, or scales, or skin), along with internal and external sensors, brain structures, heart, lungs, stomach, etc.

During 2020 and 2021 I produced weak arguments that in-egg assembly processes required a sequence of increasingly sophisticated virtual machines controlling assembly of increasingly complex physiological structures required for production of the infant organism in the egg, ready for hatching.

I also tried to show that competences of newly hatched animals supported claims made by Immanuel Kant (around 1781) about the nature of mathematical intelligence -- claims, summarised below, that are widely, but mistakenly, believed to have been refuted by the 20th discovery that physical space is not Euclidean.

It is intuitively clear that the chemical assembly processes in eggs must go through stages of increasing complexity as the foetus becomes more complex -- a result of some kind of bootstrapping process during hatching.

But we need better arguments for those claims, and more detailed theories explaining what the mechanisms are and what they achieve.

If we study and compare hatching processes in many different egg-laying species, and also study how *post hatching competences* of members of those species evolve over time, as do the *anatomical structures* of those species, we may be able to learn more about both the assembly of physical structures in new organisms and assembly of the mechanisms providing behavioural competences in the organisms.

This may help us understand how these structures, mechanisms, and competences in egg-laying vertebrate species vary across species and how they produce individuals with complex species-specific competences that are available for use soon after birth or hatching,

(The issues are different for invertebrate egg-laying species, e.g. insects -- and will not be discussed here.)

NOTE on sexual reproduction

Most standard presentations of biological evolution mistakenly show only forward-branching evolutionary trees.

But each individual produced by sexual reproduction has both maternal and paternal ancestors, that are different, though there may be some overlap. So the normal depiction of evolution as a tree that branches out over time is misleading for species in which each individual has two parents.

Evolution of current species using sexual reproduction, such as humans and other vertebrates, must have involved a discrete backward branching evolutionary network of male and female ancestor organisms, going back to a variety of simplest ancient ancestors using sexual reproduction. However those ancestors may have been produced by forward branching evolution. Diagrams of evolution that I have seen do not include the backward branches.

Moreover, evolution of species with parent-child relationships cannot be *continuous*: it must be *discrete*. Between an individual and any of its ancestors there will be a discrete sequence of distinct ancestors. So evolution of increasingly complex egg-laying organisms must involve discrete, backward-branching histories.

I suggest that as more complex organisms evolve, discrete changes during reproductive processes correspond to those discrete evolutionary change

There may also be some evolutionary branches in which complexity decreases because of environmental changes, but they are not relevant to our topic.

So, if each individual requires two parents then there will be a backward-branching tree of ancestors, contradicting standard presentations of evolution as simply forward branching in time, which would be true of species that don't use sexual reproduction.

THE NEW CLAIM: Differing roles of chemistry in reproduction and evolution.

If the organism created in an egg goes through a sequence of stages of construction corresponding to the evolutionary stages in the history of the species, then those developmental/construction stages may make use of a sequence of chemistry based assembly control mechanisms that evolved at different times.

In such cases, in-egg synthesis is not a uniform process, using a fixed collection of mechanisms, but requires use of a sequence of increasingly powerful assembly mechanisms, namely the mechanisms that evolved at different times, in the history of the species, and which develop at different stages during production of a new organism inside an egg.

The earliest stages of reproduction, involve duplication of DNA and production of new chemical products controlled by DNA templates using molecular mechanisms that can operate only across short distances. That may have sufficed for the simplest ancestors of egg-laying organisms.

But as more complex organisms evolved, with greater numbers of distinct body-parts and relationships between parts, including functional mechanisms, such as neural systems or the mechanisms of blood supply that operate across large spatial structures, with increasing numbers of cells, the problems of controlling assembly became more complex.

The more different things have to be assembled in the right relationships, the more constraints have to be monitored during assembly.

Evolution by creation of new individuals is essentially a discrete process. And the evolutionary history of vertebrate organisms composed of discrete parts made of many different materials must have involved discrete design changes, which would have required discrete changes in the in-egg assembly mechanisms.

Those changes in assembly will be different in different evolutionary lineages. The later assembly processes, e.g. producing shape differences, or differences in body covering, or differences in behaviour control mechanisms in brains will differ more across species than the earlier assembly processes that merely involve duplicating portions of DNA and producing relatively small new molecules interacting in a cell.

But as the number and variety of distinct cells increases, as a result of evolution of more complex species, the problems of controlling assembly require more spatial relationships to be monitored and controlled, e.g. modified in order to correct misalignments, or ensure adjacency relationships.

There is a lot of impressive work being done on chemical mechanisms controlling growth of organisms, including self modifying or self-extending organisms of many sorts, illustrated by the important work being done by Michael Levin's group on xenobots.

But I don't know of any laboratory working on creating self monitoring, self repairing, self-extending organisms that compare in complexity with the body of a chick during later stages of hatching, with a huge variety of highly differentiated internal components being assembled in parallel with important constraints on relative sizes, shapes, connectivity, and neighbourhood or contact relations, etc.

Yet somehow, biological evolution has managed to produce a huge variety of organisms each requiring extraordinarily complex and varied chemical assembly processes to occur in parallel and with a large amount of coordination, without which deformities or worse consequences can occur.

This suggests a need for a substantial new multi-disciplinary collaborative research project, attempting to identify the changes in evolved reproductive mechanisms, including mechanisms that provide new species-specific competences for newly hatched individuals, and especially the changing mechanism for controlling and coordinating multiple sub-processes in parallel.

RELEVANCE TO KANT'S PHILOSOPHY OF MATHEMATICS

I'll try to show below that these ideas potentially provide support from developmental biology for Immanuel Kant's philosophy of mathematics (around 1781) claiming, in opposition to David Hume, that there are forms of reasoning that are neither empirical, nor based solely on logic and definitions, that can establish mathematical truths, including geometric discoveries made centuries before Pythagoras, for example.

At present this is a conjecture requiring further research rather than a strong argument.

OVERVIEW OF NEW CLAIMS

This talk presents new ideas developed since early 2022, relating phylogeny and mechanisms of ontogeny (especially mechanisms controlling development in eggs), placing some of the conjectures in my earlier talks in a new evolutionary context, aiming to explain both similarities and differences between developmental processes in different vertebrate species using eggs for reproduction.

The key new idea (in 2022) is that the in-egg processes assembling a new vertebrate hatchling are composed of stages with different levels of control corresponding to discrete transitions in the evolutionary history of the species.

Evolution of organisms that reproduce using eggs cannot be a continuous process, since between any organism and any of its descendents there can only be a finite (integral) number of intermediate individuals that emerge from eggs.

The earliest eggs using shells must have produced organisms with relatively simple structures and relatively simple behavioural competences.

Later descendants with more complex structures that evolved over many generations will require more complex assembly processes in their eggs.

I'll present some of the implications of those facts.

More information is provided below than I'll have time for in the presentation. The organisation and content may(?) be improved later.

The ideas are presented in connection with egg-laying vertebrates, which including birds and reptiles (among others) but do not include mammals, such as humans and other primates.

The key ideas are also relevant to mammals, but in many/most mammals the rich chemical interactions between unborn foetus and parent add complexities that will not be discussed here.

Mammalian examples closer to the animals discussed here are foals that walk unaided to suckle at a standing mother, and soon after that can run with the herd to escape a chasing predator.

Some of the complexities not discussed here are investigated in the Meta-Configured Genome theory (developed in collaboration with Jackie Chappell), summarised in
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-configured-genome.html
(also PDF).

NOTE
These notes for a (zoom) talk on Friday 8th April at 10am to the IRLab (Intelligent Robotics Lab), School of Computer Science, University of Birmingham, organised by Mohan Sridharan, are a revised version of notes for a talk given to the Centre For Computational Biology on 23rd March.

In this talk I try to spell out some implications for research in AI and Robotics, whereas the earlier talk was mainly about evolution of intelligence in animals, not robots. This web site has been revised, accordingly.

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THE REST OF THIS DOCUMENT IS STILL UNDER DEVELOPMENT

Recently hatched ideas about hatching and intelligence
- These ideas have implications for
- Philosophy of mathematics,
- Philosophy of mind,
- Biological theories of evolution and development of complex organisms such as vertebrates,

- Mechanisms of morphogenesis during biological reproduction,
- Evolution and reproduction of spatial forms of intelligence,
- AI Mechanisms required for intelligent machines, especially robots with various types of spatial intelligence,

and closely related:
- Mechanisms underpinning ancient human mathematical (geometrical and topological) discoveries.

> Only reproduction in a subset of vertebrates will be discussed here, namely vertebrates that use eggs enclosed in shells for reproduction, and emerge from their shells already equipped with important forms of spatial intelligence, e.g. required for feeding, foraging, walking and in some cases paddling or swimming, such as chickens, ducks, swans, alligators, turtles, crocodiles, pythons, and many more.
>
> So the following claims about embryo development in eggs are not intended to apply without modification to ALL egg-laying species, e.g. insects.
>
> Some examples illustrating the variety of egg-laying snakes are presented here:
> https://www.instagram.com/p/CSm_tthr8fe/?utm_source=ig_embed

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EXTENDED ABSTRACT

BACKGROUND: Discovering necessary truths about geometry and topology

Many researchers investigating intelligence nowadays ignore the deep observations of Immanuel Kant (in *Critique of Pure Reason* (1781) around 240 years ago) about both ancient forms of mathematical intelligence and everyday spatial intelligence in humans and other animals, concerning what is impossible or necessarily the case.

For example:
-- It is necessarily true that

if S1 S2 and S3 are spatial regions, **and** S1 contains S2, **and** S2 contains S3,
then (necessarily) S1 contains S3.

-- It is also necessarily true that

if C1 C2 and C3 are non-overlapping collections of objects, of any kind, and there is a one-to-one correspondence between members of C1 and C2, and a one-to-one correspondence between members of C2 and C3,

then there is also a one-to-one correspondence between members of C1 and C3.

So concatenating two 1 to 1 correspondences produces another 1 to 1 correspondence.

Note:

It is widely, but mistakenly, believed that Kant's claims about mathematical cognition were refuted by the work of Einstein and Eddington in the 20th Century demonstrating that physical space is not Euclidean. But that no more refutes Kant's ideas than the discovery that the surface of a torus or a teapot is non-Euclidean, as pointed out in Sloman (1962).

Our ability to make intelligent use of our natural number system for counting and reasoning about discrete collections of any kind depends on the fact that one-to-one correspondence is necessarily symmetric and transitive: exceptions are impossible.

What mechanisms make knowledge of such facts possible?

I suggest that there are deep, but indirect, connections between

ancient abilities to discover some logical and mathematical (e.g. geometric and topological) necessary truths and impossibilities

and

mechanisms involved in biological reproduction using eggs, e.g. mechanisms producing extraordinarily complex vertebrate animals, that have surprising forms of spatial cognition not based on learning after hatching,

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Conjecture
Ancient mathematical (geometrical and topological) reasoning abilities, including abilities to discover and prove Pythagoras' theorem [in several hundred different ways] centuries before Pythagoras was born, use chemical mechanisms related to the chemistry-based developmental control mechanisms that make it possible for processes in eggs to produce hatchlings that not only have extremely complex physiological systems and structures, like all animals, but also have sophisticated (species specific) spatial competences that they could not have learnt.

Many researchers seem to believe (mistakenly) that such forms of intelligence have to result from learning processes in which neural networks collect statistical data from which they derive probabilities. Those theories are deeply misguided because statistics plus probabilistic reasoning cannot explain ancient mathematical discoveries that something is necessarily true, or impossible. Necessity and impossibility are not extreme degrees of probability. Their discovery (and use) require more powerful mechanisms than networks that derive probabilities from statistical evidence.

Another example, the ancient concept of number (cardinality of a collection) used in connection with counting processes, is based on the fact that the one-to-one correspondence relation is necessarily transitive and symmetric: exceptions are impossible, not merely improbable. Current statistics-based neural net mechanisms therefore cannot explain our understanding of numerical relationships between collections.

What are the alternatives to neural networks? What brain mechanisms can explain such non-statistical, non-probabilistic mathematical discoveries about spatial impossibility or necessity? It might be thought that currently widely used logic-based formal systems of reasoning provide the answer: but those were not created by human mathematicians and logicians until very recently, and I know of no evidence that ancient mathematicians and engineers used them, e.g. in designing and constructing very complex massive ancient structures, which must have used arithmetical, topological and geometric reasoning processes. (That may not be obvious to people who have never designed, built and repaired or modified physical machines whose capabilities depend on relationships and constraints between their parts and the things they operate on. Construction kits such as Tinkertoy, Meccano and Fischer-Technik, and even plasticene used to provide such challenges.)

THE POWERS OF CHEMICAL ASSEMBLY MECHANISMS IN EGGS

I suggest that not yet understood chemical information processing mechanisms (on which Alan Turing was working shortly before he died) will turn out to provide answers to my questions, though it may turn out that current physical theory needs to be extended, in order to provide detailed explanations of chemistry-based control-systems in eggs, and in brains, after hatching, or birth.

Starting from facts about spatial competences of newly hatched members of egg-laying species (e.g. the avocets, above) I shall draw attention to some hard to explain features of in-egg development, and present some still incomplete ideas about the very complex chemistry-based mechanisms required.

Those assembly mechanisms need to be created during the hatching process. They perform very complex tasks, which become more complex as the embryo becomes more complex. I suggest that the mechanisms controlling assembly have multiple layers, and that successive more complex sub-mechanisms controlling more complex assembly tasks are themselves created step by step during the hatching process.

The simpler assembly mechanisms used during early stages of hatching have older evolutionary histories than the more complex assembly mechanisms used during later stages of assembly. The assembly control mechanisms used in later stages of foetus assembly are produced as by-products of the earlier stages of assembly. They are also products of later stages of evolution of the species.

So the foetus assembly is not a uniform process: the assembly mechanisms used during hatching are created step by step in the egg as by-products of earlier stages of foetus-creation, during a multi-stage hatching process.

And the powers of the mechanisms used later during hatching are products of later stages in the evolutionary history of the species.

Note

There are many online images showing actual or depicted stages in the development of embryos in eggs. One example is here:
https://www.cs.bham.ac.uk/~axs/fig/chicken-egg-devel.jpg
(Kindly made available by Cobb-Vantress, Inc.)
It shows transformations from a relatively unstructured, undifferentiated, collection of chemicals inside the egg through increasingly differentiated and complex structures. But such images cannot show all the intricate concurrently grown microscopic and sub-microscopic 3-D

structures including nerve fibres, blood vessels, tissue boundaries, outer coverings, and other structures that are grown inside the eggshell, or the mechanisms controlling all that coordinated growth.

Meta-ontogeny recapitulates phylogeny
Ontogeny of organisms cannot recapitulate phylogeny. E.g. embryo ducklings hatching in eggs do not go through transformations in which they take on adult forms of all their evolutionary ancestors.

However, my claim is that the processes of construction of mechanisms of ontogeny in eggs (i.e. the processes constructing chemical assembly mechanisms in eggs) correspond in a systematic, but unobvious and extremely complex way, to the evolutionary history of the species -- its phylogeny.

We can summarise this as:
Meta-ontogeny recapitulates phylogeny. In-egg development of assembly mechanisms recapitulates evolutionary history of assembly mechanisms used by the species.

As the foetus grows more complex the processes of assembly need to use more complex, and increasingly species-specific, types of information about its current state in order to select and control appropriate new assembly actions.

I shall try to show how these ideas about evolution, development, and chemistry-based reasoning and control during development, contradict widely (but not universally) accepted theories about how neural networks trained after birth or hatching are thought to explain intelligence, including spatial intelligence of new hatchlings and mathematical intelligence in humans.

The new ideas about processes occurring in eggs are also relevant to non-egg-laying species, e.g. mammals, but their developmental mechanisms are more complex and more varied, and involve interactions between mother and embryo *in-utero* that are more complex and varied than the processes that occur in eggs.

But the claims about eggs give an indication that current theories about intelligence in humans and other intelligent mammals could be badly mistaken, because they ignore the powers of evolved assembly mechanisms. The problems and solutions are less constrained when there isn’t an eggshell limiting abilities of mechanisms in mothers to influence assembly of the new embryo, including its brain.

There are deep, and still only partly understood, implications concerning the evolution and development of mechanisms of spatial reasoning which, in humans, provide the basis for ancient mathematical discoveries in geometry and topology, about which Immanuel Kant made his deep, but incomplete, and widely ignored or misunderstood, comments.

Note
The ideas presented here are closely related to what I learnt about gene expression from Jackie Chappell in the school of Biosciences after she arrived in 2004 (from the Oxford University ecology group in the department of Zoology). That interaction led to our idea of a "Meta Configured" Genome Chappell and Sloman 2005.

More recently I have learnt from colleagues in the School of Computer Science and elsewhere. But the most recent ideas (only weeks old) came from thinking about stages that must occur in eggs of vertebrates.

I gave a much shallower CCB presentation related to these ideas a few years ago, before I had thought about processes in eggs!

There are still major gaps in these ideas, some of which may involve deep features of quantum physics that I don't yet understand!

One of the questions arising is whether previously unnoticed facts about biological assembly processes in eggs also have previously unnoticed implications for fundamental features of physics?

No current human-designed machines for manufacturing complex physical machines are capable of being compressed to the size of an egg or capable of going through processes of repeated self-extension with no external influences apart from absorption of a small amount of thermal energy and small amounts of atmospheric gases. And no human-designed machine produced so far can construct a machine with the competences of a baby avocet, chicken, duckling, turtle, alligator, python, etc., let alone do it in such a small space, so quickly, and with so little externally supplied energy, using mechanisms that can be varied so as to enable reproduction in a very wide variety of egg-laying vertebrates.

I don't know whether that combination of features challenges current theoretical physics.

I hope the talk will provoke suggestions from researchers with much deeper knowledge of biochemistry and physical theory, including quantum physics, than I have.

Overview of some background ideas
(Still to be revised.)
There is a vast amount of research on various aspects of morphogenesis and self-organising abilities of living organisms, such as slime-molds and more recently xenobots (developed in Michael Levin's lab).

As far as I can tell, NO current theory answers the specific questions raised here about how chemical mechanisms involved in reproduction contribute to forms of spatial intelligence in many animals, including competences required for ancient mathematical discoveries in geometry and topology (centuries before Pythagoras, for example).

My talk draws on many strands of research over many years, since completion of my Oxford DPhil thesis (Sloman(1962)), in which some of the key problems, originally posed by Immanuel Kant around (1781) were discussed -- a discussion continued in several later publications, including Sloman(1978)).

Kant's ideas about mathematical discovery, triggered in response to David Hume, are an important part of the background, as explained below. His insights are generally ignored nowadays, for bad reasons.

Related talks
A precursor to this talk was presented, using Zoom, at the University of Sussex, on 16th Feb, 2021, as described here:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-chemneuro-sussex.html
(Including a link to the recording.)

A shorter, less detailed, presentation was given at the PhiloWeb 2021 Workshop on 22nd June 2021, as part of the 13th ACM Web Science Conference 2021. My talk and the following discussion starts shortly after 25:00 and ends at 55:00 in this recording of the complete day-long event:
https://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-PhiloWeb.html

Yet another presentation was given at the Morcom Workshop on 15th September, with a reply by Mike Levin. (A link will be added here later.)

Kant vs Hume Unlike most researchers on low level mechanisms of reproduction and control of development, I think these mechanisms are relevant to a disagreement between David Hume and Immanuel Kant regarding the nature of mathematics.

Immanuel Kant's characterisation of ancient mathematical knowledge, in his *Critique of Pure Reason* (1781) and other writings drew attention to three features of such cognition, using three distinctions that are ignored in current psychology, neuroscience and neural-net based AI, namely the distinctions between:
-- non-empirical and empirical knowledge
-- analytic and synthetic propositions (the former have truth values that are determined solely by the definitions of the words used and logical implications of the definitions), whereas discovery of synthetic truth requires discovering some non-linguistic truth about the subject matter, e.g. spatial structures and processes in the case of geometry.
-- necessary and contingent truths and falsehoods. It is impossible for things that are necessarily true to be false, and impossible for things that are necessarily false to be true.

Kant thought, rightly or wrongly, that Hume had failed to understand those three distinctions, and therefore mis-characterised the varieties of truth and falsity.

David Hume and Immanuel Kant (from Wikimedia)

Very crudely, David Hume, depicted above, on the left, claimed that there are only two kinds of knowledge:

1. empirical knowledge that comes through sensory mechanisms, possibly aided by measuring devices of various kinds; which he called knowledge of "matters of fact and real existence";
2. what he called "relations of ideas", which we can think of as things that are true by definition, such as "All bachelors are unmarried", and (if I've understood Hume rightly) all mathematical knowledge, for example ancient knowledge of arithmetic and geometry, which Hume's words seemed to suggest was no more informative than the bachelor example.

"True by definition" applies to all truths that can be proved using only logic and definitions.

An example is "No bachelor uncle is an only child", which can easily be proved from the definitions of "bachelor", "uncle" and "only child", using only logical reasoning.

Hume famously claimed that if someone claims to know something that is neither of type 1 (empirical) nor of type 2 (mere relations between ideas, or definitional truths) we should "Commit it then to the flames: for it can contain nothing but sophistry and illusion", which would have included much theological writing. and much philosophical writing by metaphysicians.

[I apologise to Hume and Hume scholars: this presentation over-simplifies Hume's position in order to contrast it with Kant's claims, below.]

Immanuel Kant's response (1781)

In response to Hume, Immanuel Kant, depicted above, on the right, claimed, in his *Critique of Pure Reason*, that there are some important kinds of knowledge that don't fit into either of Hume's two categories ("Hume's fork"), for they are not mere *matters of definition*, nor *derivable from definitions by using logic*.

Kant pointed out that instead of Hume's single distinction between two categories of knowledge we need to take account of three different distinctions:

the analytic/synthetic distinction,

the empirical/non-empirical (empirical/apriori) distinction, and

the necessary/contingent distinction.

(For a more detailed explanation of the three distinctions see Sloman 1965).

Using Kant's distinctions, we can locate ancient mathematical discoveries in relation to three different contrasts:
[SKIP DURING PRESENTATION!]

- The mathematical truths such as Pythagoras' theorem and others proved by Euclid are not analytic but synthetic, i.e. they are not provable simply using definitions and logic -- for example spatial reasoning is required. and

- They also are not derived from sensory experiences by generalising from examples, in such a way that if the experiences had been different the knowledge acquired would have been different, like the knowledge that eating berries with a certain appearance can make you feel ill. You cannot discover that fact simply by reasoning about berries, whereas mathematical discoveries e.g. about numbers or triangles can be discovered by reasoning, so they are apriori not empirical. (Note that "apriori" does not imply "innate". It merely rules out knowledge being *derived* from observations of the world that could have yielded different results, as is true of most of our knowledge about the world.)

- Moreover, the world could not have been different in ways that would have made our mathematical discoveries false: they are necessarily true, not contingently true, like propositions that are true but could have been false, such as the proposition that we are in the midst of a Covid-19 pandemic. That could have been false, perhaps if certain human behaviours had been different.

  Another example: I am now in Birmingham in England. In principle I could now have been somewhere else at this time, e.g. in Berlin, in Germany. So that is a *contingent* truth.

  If something is a *necessary* truth, then there are no possible circumstances in which it could be false.
  There are also necessary falsehoods. E.g. **3 + 5 = 9** is false and could not have been true in any circumstances (without changing the meaning of what is being said. So it is necessarily false and its negation is necessarily true.

In short: Kant replaced Hume's single division of types of knowledge into two categories, with a much richer analysis making use of three different divisions, producing six categories. Not all combinations are possible, however. E.g. something cannot be both apriori and necessarily false.

People who have been deprived of the traditional type of mathematical education normally fail to discover these distinctions themselves, and may not understand them if they read about them in Kant, or commentators.

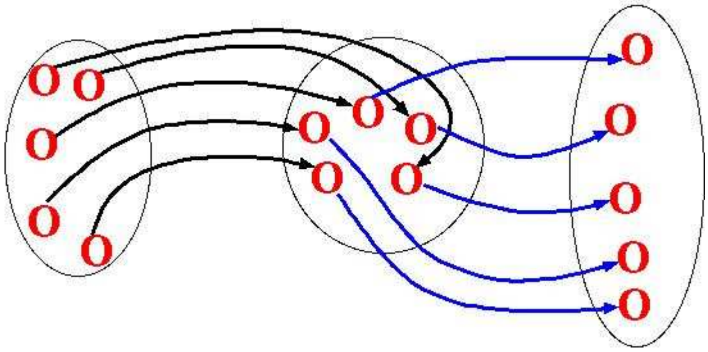
Both logic-based and neural-net-based AI systems are incapable of replicating the ancient aspects natural intelligence that allow discoveries based on spatial reasoning. Moreover, the ancient mathematical capabilities described by Kant are usually ignored in currently fashionable theories and models of mathematical cognition in psychology, neuroscience, philosophy and AI, including theories that focus on social aspects of mathematics.

Theories at odds with Kant's insights include both 'formal', logic-based, characterisations of mathematics, used in modern automated theorem provers, that reason by manipulating discrete symbolic structures, and also neural theories that attempt to explain or model mathematical discovery processes in terms of neural networks that collect statistical evidence that is used to derive probabilities. Necessity and impossibility are not extremes on probability scales.

As Kant realised, ancient knowledge of geometry, (including mathematical discoveries made centuries before Euclid), is neither simply composed of results of empirical generalisation from experience of special cases (i.e. empirical knowledge of probabilities), nor mere logical consequences of definitions. I.e. they are non-empirical (a priori), and synthetic (not derivable from definitions using only logic, and the truths they identify are non-contingent, despite some claimed counter-examples.

It is less obvious that he was also right about arithmetical knowledge, insofar as ancient number knowledge was derived from properties of the one-to-one correspondence relation, e.g. the fact that the one-to-one correspondence relation is necessarily transitive and symmetric -- which young humans seem to be unable to grasp before the age of five or six, as shown by Piaget in (1952).

Figure Mapping-Trans



[Compare Piaget's later work on children's understanding of possibility and necessity (1981,1983). I don't think he ever succeeded in formulating explanatory theories.]

This refutes theories about innateness of knowledge of cardinality, unlike knowledge of numerosity, which lacks the precision of cardinality. The numerosity of a visible part of the environment can be thought of as roughly the product of the average density (e.g. of leaves visible on a tree, or light-points visible in a portion of the night sky) and the proportion of the visual field occupied. That product gives an approximate but unreliable estimate of the actual number of distinct items visible. It can be applied to scenes where there are too many objects to count, such as leaves visible on a tree or stars/planets visible in a region of the sky at night. The numeracy estimate does not make use of one-to-one correspondence.

My talk will raise questions about mechanisms available for explaining spatial intelligence in humans and other animals based on hitherto unexplained facts about spatial competences of newly hatched animals, such as chicks, ducklings, turtles and crocodiles, whose abilities cannot be explained by neural networks trained after hatching. They must be explained by chemical mechanisms inside their eggs, available before hatching. I'll raise questions about the nature of those mechanisms linking many different sorts of parts of a developing organism and how they can be accommodated inside a fully occupied egg.

BACKGROUND NOTES

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Assembly details not shown in standard images and videos
The description of the hatching process summarised above says much about the division of different parts of the embryo into new sub-types, but very little about the huge amount of very intricate interconnection going on inside the developing animal, leading to production of bones, nerve fibres, heart, lungs, veins, arteries, and capillary networks each of which has complex and precise relationships to other structures growing in the embryo.

For example, both blood vessels and nerve fibres are distributed over all parts of the developing organism. Blood vessels need to be developed to carry blood to and from nearly all parts of the body, using arteries and veins transmitting blood in opposite directions with capillary networks fanning out from arteries and back into veins. Groups of veins and groups of arteries can perform different sorts of functions depending on where they are located and which major organs they interact with, e.g. picking up or delivering nutrients, oxygen, hormones, waste products, and thermal energy.

All the physiological substructures are functionally related to others, in some cases only to immediate neighbours (e.g. muscles exerting forces on body-parts to which they are attached) and in other cases long distance transfer of nutrients or information, using chemicals or electrical signalling.

The increasingly differentiated components of an embryo perform a wide, and changing, variety of functions, both during development of the embryo and later, while interacting with the environment after hatching.

During development inside the egg, these functions include both transfer of types of physical matter such as nutrients, waste products and chemical signals (e.g. hormones) and also transfer of information, some of it based on chemical signals some not.

During development of an embryo inside an egg, there is a steady increase in diversity, complexity, and types of function of the components of the foetus. There are also many increases in diversity and complexity of types of communication and coordination between components.

These processes are richer/more complex than the processes in shape-changing organisms such as slime mold, mentioned above.

Work by Michael Levin and others demonstrates processes relevant to the formation of a complete new organism with many new intricately interrelated functioning parts, as opposed to a mere shape-changing organism.

He mentions the example of metamorphosis: one physical form (e.g. caterpillar) transforming itself through chemical rearrangements into another form (e.g. butterfly). This process must include mechanisms of the sort discussed here, insofar as the emerging butterfly has not only a completely new physical form, but also competences related to flying and mating that were not relevant to its previous form.

However, I don’t think any of the mechanisms I’ve seen described, including the mechanisms discussed by Levin, are capable of explaining all the developmental phenomena described below. Those include production of human mathematical abilities based on ancient forms of spatial reasoning, described by Immanuel Kant, in opposition to David Hume’s ideas. as outlined below. My main novel suggestion is that there are close connections with mechanisms in eggs that control production of a new, highly complex organism, by decomposing and then re-using components of chemical structures included in eggs by the mother.

The enormous multi-layered complexity of those chemical disassembly and assembly processes, implies that a very high level of construction competence is somehow encoded in the mechanisms produced in eggs during hatching processes, based on chemical structures and mechanisms previously provided by the mother.

This implies that reproduction of complex competent organisms using eggs involves types of information processing mechanisms that are ignored by almost all currently fashionable theories of human-like intelligence, but should not be ignored.

Kant vs Hume {}
The title for this talk is "How can physical machinery enable biological evolution to produce chemical machinery that can create a foetus that grows up to be a mathematician making discoveries in logic?"
A satisfactory answer will need to address many different questions, including:

> *How do chemical processes in eggs produce* ***both*** *complex physiological structures* ***and*** *various types of spatial intelligence in new hatchlings?*

I shall try to show how that question is linked, in surprising ways, to some deep metaphysical problems, concerning what is and is not possible in this universe, and why ..... which in turn is related to the nature of mathematics, especially ancient forms of mathematics involving geometry and topology.

I'll give reasons for thinking that the mechanisms involved in understanding impossibility and necessity, including examples of spatial necessity and impossibility discovered by ancient mathematicians, long before Euclid, cannot be based on probabilistic neural nets.

There are also reasons why they cannot be based entirely on purely logical structures and mechanisms.

They are more likely to depend crucially on chemical information processing machinery, although I cannot yet specify details. That remains a major research problem. I'll present some clues below.

Long before such discoveries were made by ancient humans many of them must have been made implicitly by biological evolution in order to produce both
-- complex functional designs for animals of many types that interact appropriately with physical structures in their environment and
-- the enormously complex mechanisms for assembling such animals in eggs, and later, after further evolution, in the mother's uterus.

Immanuel Kant's philosophy of mathematics indicates that he had a deep understanding of some of the key points I am making. I'll defend some of his ideas that are now unfashionable for bad reasons. As a result, many researchers know nothing about Kant's views, or have picked up distorted versions.

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Ancient mathematics
In humans, mechanisms of spatial cognition enabled ancient mathematicians, centuries before Euclid, to make discoveries regarding possibility, impossibility and necessity in spatial structures and processes, without making use of modern mathematical formalisms in which theorems are derivable using only logical inferences: instead they used spatial forms of reasoning, e.g. reasoning based on real or imagined spatial structures rather than logical/algebraic formalisms.

Some intelligent non-human animals (e.g. squirrels, some nest-building birds, octopuses) also seem to have such (species specific) abilities. They can make use of spatial possibility, impossibility, and necessity in selecting and performing actions.

However, they don't have the additional ability that some humans have, namely to communicate their knowledge to others, and may not have brain mechanisms required for reflecting on what is known, or expressing such knowledge in a linguistic format.

Young children also have, and make use of, much knowledge of spatial possibilities and impossibilities that they cannot articulate verbally, but can use in choosing, rejecting or reflecting on possible actions. Additional examples of "toddler theorems" can be found in Sloman (2013). Piaget's last two books (1981,1983), published posthumously, on *Possibility* and *Necessity* explored such abilities in children of various ages. However, he was unable to propose explanatory mechanisms.

Many philosophers of mathematics seem to believe that everything that could be done using ancient spatial reasoning mechanisms can be replicated in modern discrete, logic-based, reasoning systems. It's possible that the ancient forms can be **modelled** in the new forms, but without being **replicated** (e.g. using physical mechanisms with similar speeds and energy costs).

During the discussion of this point after my presentation in a previous conference, Pat Hayes commented that a great deal of geometry and topology has been expressed in logic-based formal systems using only discrete symbols and discrete operations on symbols. The most obvious and well known example is the great mathematician David Hilbert's "axiomatization" of Euclidean geometry Hilbert(1899).

I am not claiming that discrete, logic-based formalisms *cannot* be used to replicate (or model) ancient geometric discoveries. I claim only that there are *alternative* mechanisms using spatial reasoning rather than symbolic manipulations, that were used by ancient mathematicians, engineers, architects and also ordinary folk, long before humans discovered the space of formal systems developed in the 19th and 20th Centuries, including Hilbert's logic-based formalisation of the subset of geometry captured by Euclid's informal axiomatisation. I suspect, but cannot (yet) demonstrate, that those older mathematicians were using chemical mechanisms related to the chemical mechanisms used to control complex assembly processes in eggs.

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Mathematical contents of everyday spatial intelligence.

Mathematical (but not meta-mathematical) insights involving topology and geometry are involved in surprising ways in the competences of very young children and many highly intelligent non-human animals, although they are not able to think about their intelligence: they lack required forms of meta-cognition. Examples are presented below.

Moreover, currently fashionable neuroscience and neurally inspired AI are totally incompetent at explaining such abilities, because they focus mainly on discovering and using statistical information and derived probabilities, ignoring discoveries of necessity and impossibility, which cannot be derived from statistical evidence.

For example, how can a child who has not studied topology at school understand the transitivity of "contains", or the impossibility of linking or unlinking, without damaging, solid rings? I'll return to such questions below.

Here's an example involving two stone rings forming a (short) chain on an old Indian temple:

Fig: Stone Rings

From Wikipedia
http://en.wikipedia.org/wiki/Group_of_temples_at_Talakad,_Karnataka
Picture by Hari, Ganesh R, subject to
Creative Commons Attribution-Share Alike 3.0 Unported license.

Each ring appears to be made from a single piece of solid, rigid, stone.
Could the two rings have been cut out of two separate rigid blocks of stone and then assembled as shown, without any cutting and rejoining, and without use of any mechanism that allows one piece of stone to pass through another? (I doubt that such a mechanism is possible in this universe.)

How do you know the answer to this?

NOTE: A comment on this by Luc Beaudoin is below.

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Bad answers, and better answers

Currently fashionable neural net theories explain only types of knowledge involving probabilities that are derived from previously collected statistical evidence. But explanations of probabilities cannot be explanations of necessity or impossibility.

Therefore such neural mechanisms, unaided, cannot explain forms of spatial reasoning used by ancient mathematicians, for instance in several hundred different proofs of Pythagoras' theorem discovered by mathematicians centuries before Pythagoras was born -- all demonstrating that in a right angled triangle the area of the square on the hypotenuse is necessarily, i.e. it MUST BE, equal to the sum of the squares on the two smaller sides. It is impossible for the third side to be longer or shorter than that sum, assuming the triangle is on a flat surface, e.g. not on the surface of a sphere or a teapot.

An example proof is available on this Wikipedia page
https://en.wikipedia.org/wiki/Pythagorean_theorem.
Click on the box on the right of the section labelled "Rearrangement proof" for a demonstration.

For similar reasons, neural nets cannot explain the spatial abilities of intelligent species such as squirrels, crows, elephants, pre-verbal humans, that involve recognition of necessity or impossibility, about which I'll say more below in commenting on differences between the philosophies of David Hume and Immanuel Kant.

Less obviously, trainable neural networks cannot explain the spatial intelligence of newly hatched creatures, like the foraging competences of young avocets in this video clip from a BBC Springwatch programme[*] in June 2021.
https://www.cs.bham.ac.uk/research/projects/cogaff/movies/avocets/avocet-hatchlings.mp4

Processes inside eggs cannot train neural nets to interact with the waterside environment since that environment is inaccessible in the egg. And, after hatching, the chicks clearly do not need to train their neural networks before they walk to water and start foraging. How are those competences implemented in their brains and what mechanisms put them there?

[*] The full Springwatch episode, showing the avocet hatchlings, is on Youtube at:
https://www.youtube.com/watch?v=FV6ZHe0CiHw
The section on "Avocet Island" starts at about 12min 23sec. The above 35 second extract, showing competences of newly hatched avocets, starts at about 12mins 30secs.

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Steps toward better answers
The competences of newly hatched birds must have been produced by in-egg pre-hatching processes using unknown chemistry-based mechanisms. What else could be available inside eggs?

What additional mechanisms could help? Below, I'll discuss conjectured chemistry-based reasoning mechanisms whose details are still unknown.

There are many aspects of common-sense spatial reasoning that are concerned with impossibility and necessity. E.g. containment in space is necessarily transitive. So the search for explanatory mechanisms presented below is relevant to far more than mathematical competences, as Immanuel Kant pointed out in his Critique of Pure Reason (1781). I'll give a tiny subset of examples -- far more are available online, e.g. in
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/impossible.html and documents referenced therein.

Neural net mechanisms are assumed by many researchers to provide the explanations of mathematical and other forms of cognition.

But those researchers fail to realise that neural nets cannot represent, let alone prove, spatial impossibility or necessity, since they merely collect statistics and derive probabilities.
Necessity is not equivalent to an extremely high probability.

Statistics-based neural nets therefore cannot match or explain important aspects of human and non-human spatial intelligence based on detection or creation of examples of impossibility, necessity, or possibility.

Modern logic-based reasoning can establish necessity or impossibility, but most of the relevant reasoning processes were discovered by humans only in the last few centuries. There is no evidence that they were used by the ancient geometers, or other intelligent animals, centuries before Euclid. hilbert

I'll suggest below that currently unknown chemical mechanisms may suffice. Moreover, I'll give reasons for thinking that related processes must occur inside eggs that assemble enormously complex interconnected structures and mechanisms. Perhaps the mechanisms in the brains of ancient mathematicians studying geometry had features related to the construction processes in eggs.

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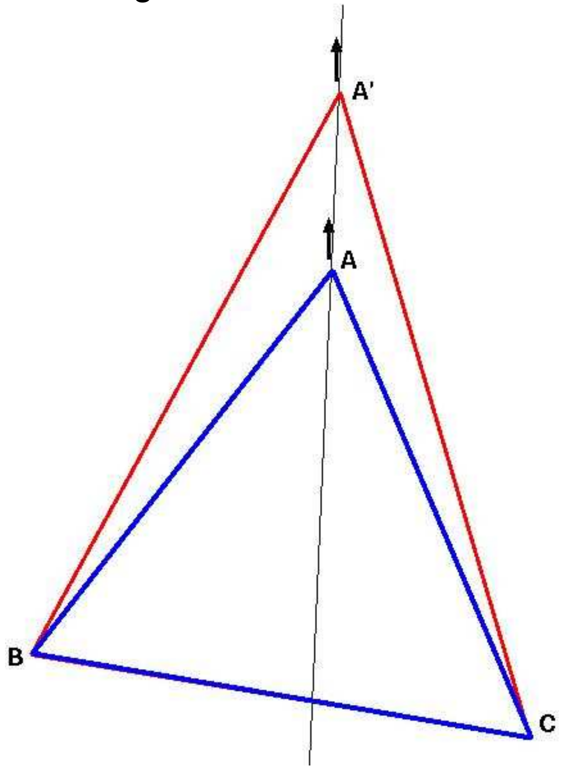
Deformed triangle example

Here is a simple example of necessity/impossibility involving a deformable triangle. If a straight line passes through a vertex of a triangle and through the interior of the triangle and the opposite side of the triangle and the vertex is moved along that line towards or away from the opposite side, what happens to the size of the angle at the vertex?

Figure: Stretch-internal



In Fig Stretch-internal what happens to the size of the angle A, on triangle ABC, if A is moved away from the opposite side (BC), along a fixed line that passes through the opposite side, between vertices B and C, until A reaches location A'. If the locations of vertices B and C do not change while A is moved further away, does the size of angle A increase, decrease or remain unchanged?
How do you know? What sort of brain makes such reasoning possible?
Is it simply an empirical generalisation that may be refuted next week?

If the line of motion, along which vertex A moves does not intersect the base of the triangle inside the triangle, i.e. between B and C, but intersects it at point outside the triangle, answering the question is a more difficult task, related to an ancient geometric theorem of Apollonius presented here: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/deform-triangle.html

Graphical demonstrations illustrate spatial necessities/impossibilities using diagrams.
Non-graphical demonstrations might manipulate equations relating numerical coordinates of points or parameters of lines. Ancient geometers used graphical proofs (e.g. proofs of Pythagoras' theorem) long before the numerical representation of Euclidean geometry, based on numerical coordinates for points, lines, etc. was discovered.

Many more examples of spatial and mixed reasoning are included in this document:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/impossible.html

A related collection based on spatial reasoning competences of young children, including pre-verbal children, is available as a collection of Toddler theorems.

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As Immanuel Kant implied in his (1781), necessity and impossibility are not very high and very low probabilities. "Necessarily true" and "Impossible" are not points on probability scales. I'll say more about Kant, and his opposition to Hume, below.

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Moreover, recently developed, logic-based, formal reasoning mechanisms account for only a subset of mathematical discoveries. They cannot explain spatial reasoning abilities of ancient humans, e.g. ancient pyramid builders and ancient mathematicians, or even pre-verbal children, like this crawler with a pencil

Exploring topology/holes

GIF VIDEO (TEMPORARILY DISABLED)
child+pencil+hole

The above child (age about 17.5 months) seems to be exploring topology. She spontaneously crawled towards the sheet of card while holding a pencil, picked up the card, pushed the pencil through the hole, pulled the pencil out, moved the pencil up and over the edge of the card while rotating the card toward the pencil then pushed the pencil through the hole from the opposite side, then removed the pencil, reverted to the original side and finally pushed the pencil in then pulled it out again.

The above 'gif video' may not work for you in this context. The episode can also be viewed in this video, which includes a commentary and some slow motion: small-pencil-vid.webm

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The abilities of pre-verbal toddlers, and many other intelligent animals, seem to indicate an intuitive (proto-mathematical) grasp of possibilities, impossibilities and necessary connections, though the children do not notice and cannot describe their own competences. This is also true of most adults. It takes a reflective mind like that of Immanuel Kant to notice surprising features of some human powers of reasoning and discovery. His ideas are summarised and contrasted with David Hume's, below,

The well known physicist, Roger Penrose, mentioned below, has made related claims about important kinds of mathematical discovery, but without specifying explanatory brain mechanisms, though he suggests that the mechanisms cannot be Turing-equivalent forms of computation, and must use quantum physics. For very different reasons, another physicist Erwin Schrödinger (1944) pointed out that reliable biological reproduction depends on quantum physics.

Below I'll suggest that some unnoticed facts about reproductive processes in eggs also depend on quantum mechanisms, that Alan Turing may have been thinking about before he died.

A familiar (adult) "domestic" example
I suspect many people have encountered the impossibility of pushing a wide armchair through a doorway that's too narrow, and the creation of a new collection of possibilities by turning the armchair on its side, which (for some chairs) makes it possible to push the chair through the doorway while rotating it about a vertical axis.

Children learn to manipulate spatial necessity and impossibility by playing with appropriate toys, including construction kits -- of varying richness. E.g. contrast Tinker Toys with Meccano.

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How did ancient (and not so ancient) mathematical brains achieve their discoveries?

I suggest that hitherto unnoticed chemistry-based mechanisms, required for biological assembly, obviously required in eggs, also underpin some complex, species-specific, forms of intelligence. An example is the intelligence of newly-hatched animals, e.g. the avocet hatchlings shown in the BBC Springwatch programme on 1st June, mentioned above.

> I suspect that a similar conjecture formed the unstated motivation for Alan Turing's work on chemical morphogenesis (1952) in the last few years before his death in 1954. If so, his 1952 paper on chemistry-based pattern formation was just a digression from his unstated deeper research problem. There is a brief hint about this in the sentence about brain chemistry in his well known 1950 paper ('Computing machinery and intelligence').

What chemistry-based mechanisms can enable mathematical reasoning about spatial structures and processes? How do they do it? I suspect nobody knows at present.

Is current theoretical physics sufficiently rich to explain all the phenomena I'll be talking about today, or all the geometric phenomena presented by Michael Levin in his talk? There's some overlap in our interests though so far I don't think he has attempted to describe or explain ancient forms of mathematical cognition. Perhaps his ideas will turn out relevant to that in surprising ways.

More detailed questions:
How do the competences and explanatory mechanisms differ in production of hatchlings of different species, such as the young of different bird species, and also baby alligators or turtles, which have very different physical forms and very different capabilities.

Are there any key features that the different species-specific mechanisms have in common?

In particular, for different species, what chemical processes completely enclosed in eggs can determine both construction of complex physical forms (including extremely intricate multi-material, internal physiology) and also the competences used in complex, species-specific, physical behaviours, often produced very soon after hatching --- unmatched by current robots? (Unless there have been recent developments I've not heard about.)

Production, within an egg, of physical components, e.g. bones, tendons, muscles, glands, nerve fibres, skin, hair, scales, or feathers, and other structures, including intricate networks of blood vessels, nerve-fibres and other physiological structures, is clearly chemistry-based, and far more complex than chemistry based behaviours of shape changing organisms, such as slime molds, in ways that are not immediately obvious, which I'll try to explain in the presentation.

Moreover, the combination of complexity, compactness, energy-efficiency, and speed of production of processes in an egg are also unmatched by human designed assembly-lines.

The recent work on "xenobots" (to be reported in Michael Levin's talk) may be an important (early?) step toward adequate explanatory mechanisms. But, as far as I know, they have not yet been shown to be capable of producing hatchlings with the combination of spatial intelligence and complex and intricate, multi-material, physiological structures created in eggs.

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Gene-expression is not a uniform process

EARLY STAGES of gene expression that are common across species that use DNA for reproduction are well understood and at first involve only one cell, then a few cells,.... [Provide link or reference]

But as a developing foetus becomes more complex, with millions of cells of many kinds, the gene-expression requirements and mechanisms become more complex (because more complex changes become possible) and also become more specific to the type of organism. E.g. later stages of gene expression in a developing foetus will be very different in a flea, an earthworm, a chicken, an alligator, a dandelion, a giant redwood tree, and so on.

Moreover, even in a particular individual, as it becomes more complex with more different body parts, the processes of gene expression in different parts will be different, though different parts may need to be coordinated -- e.g. development of bones, muscles, tendons, nerve-fibres, arteries, veins, glands, skin, mouth, waste exits, etc., and the coordination requirements will be different for adjacent parts, e.g. parts of a limb, or adjacent vertebrae, and for non-adjacent parts, e.g. linkage of blood vessels between heart, lungs, brains, digestive system, and other body parts.

Moreover, the cross-body coordination requirements will be different for different species. For example, some vertebrate eggs produce organisms with no legs (e.g. snakes) some with two legs and two wings (e.g birds), some with four legs (e.g. horses, crocodiles), some with two legs and two arms, and so on.

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Increasing kinds of long-distance coordination

It is unlikely that all that coordination can be achieved simply by chemical processes reacting to the contents of their immediate neighbourhoods -- in complex organisms increasingly complex forms of cross-organism coordination are required as the embryo develops, and they will need to change as sizes, weights, strengths, distances, etc. change.

The later processes of gene expression will produce highly complex species-specific physical configurations and forms of coordination between body parts, while still in the egg, and will have to continue extending them after hatching as the new hatchling's sensor and body parts are used in interaction with different sorts of objects in different environments -- e.g. while sheltered under the hen, while walking across dry land, while moving into water and starting to paddle or swim, and while pecking or diving for food, then manipulating it in beak or mouth, then swallowing, etc. How are all these extraordinarily complex assembly processes controlled? Notice that because the physiological structures, body sizes, environments, behaviours and food needs differ across species, the mechanisms of co-ordination and control will also differ, and will need to be constructed differently for different species.

{}

Developing requirements for centralised control

I cannot see how all those interactions can simply be emergent cumulative results of many local interactions between body parts. Brains, eyes, mouth or beak and leg muscles need to be coordinated in appropriate ways in the presence of static food, catchable prey or a threatening predator. Different forms of cross-body coordination are needed during in-egg development processes, subsequent growth after hatching or birth, and interactions with resources and dangers in the environment.

I'll suggest that the later stages of development in eggs are controlled by a succession of increasingly complex virtual machines with hitherto unknown, non-space-occupying mechanisms, whose construction needs to be boot-strapped via multi-layered assembly processes that are far more complex than anything achieved in human designed assembly plants.

In particular, the later more sophisticated virtual machines required to control assembly are not directly specified in the genome, but have to be boot-strapped by earlier stages that produce new mechanisms required for the later stages.

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The meta-configured genome (MCG) hypothesis

All the above comments illustrate features of what Jackie Chappell and I call "A meta-configured genome", about which I'll say more below. (There are also several freely available online documents and videos about these ideas that can be found using internet searches.)

A feature of the MCG hypothesis is that different assembly mechanisms are required for assembly at different stages of development of a foetus. So the assembly mechanisms need to produce new assembly mechanisms while they produce new physical/chemical components in the foetus.

Another key feature is that the specifications for later stages of development, especially development of information processing systems for dealing with perception, motivation, action-selection, planning, control of actions, and accumulating various kinds of knowledge about the environment and its contents may be left partly unspecified by the genome, so that missing specifications can be derived or constructed by making use of information that is acquired during various stages of development.

In particular, some of the motive-generation machinery, instead of being specified in the genome may have to be developed in relation to each individual's environment, using "architecture-based-motivation" mechanisms e.g. those proposed in Sloman(2009) (or its later revisions).

These mechanisms enable young individuals to discover that it is good to be motivated by certain perceived opportunities, because of the benefits gained by acting on those opportunities. So the genome itself does not specify all the top level goals that are useful for individual members of the species. Instead they can depend on the environment.

To illustrate this: the kinds of motivation that were useful for children of ancient cave dwelling humans are very different from the kinds of motivation that are useful for young humans developing in 2021, when the opportunities and benefits are totally different.

{}
Eggs vs factories
The processes in eggs, however, use far less matter and energy in their operation than processes in human designed factories producing complex machinery.

Developing explanatory theories will need new forms of multi-disciplinary collaboration, and are likely to have profound implications for theories of brain function, replacing current theories that cannot explain ancient mathematical discoveries.

I suspect it will turn out that current physical theory needs to be extended to explain how the processes sketched below can occur in eggs.

The mechanisms must be primarily chemistry-based, since neurons are created relatively late by chemical mechanisms in eggs. Powerful chemical assembly mechanisms play important roles in bodies and brains throughout development -- performing tasks that neural nets cannot perform, including underpinning mathematical insight.

We need an entirely new form of brain science giving far more credit to chemical processes whose computational powers exceed those of both digital computers and neural nets.

Is that why Alan Turing was exploring chemistry-based morphogenesis shortly before he died? Turing(1952)

Some key ideas (to be reorganised)

(There will not be time for all of this.)

There are aspects of spatial intelligence in humans and other animals, that are ignored in most current theories in neuroscience, psychology, philosophy of mind philosophy of mathematics, and also in all the AI models that I know of.

These aspects include abilities to detect and make use of varieties of spatial possibility, necessity and impossibility.

Currently fashionable "neural net" - based models, collect statistical evidence and derive probabilities. They are therefore constitutionally incapable of discovering or representing **impossibility** or **necessity**, which are not extremes of probability, but, as kant pointed out, are key features of ancient mathematical discoveries.

Logic-based models of geometric reasoning fail to model human spatial intelligence in different ways -- but most were not intended as models of cognition.

Around 1781, Immanuel Kant, reacting to David Hume’s account of types of knowledge had some deep insights -- and at least partly understood the difficulty of finding complete explanations. There’s more on Kant below.

We still cannot explain all the processes and mechanisms involved in spatial reasoning in humans and other animals, which provided the *infrastructure* for ancient mathematical discoveries in geometry and topology, centuries before Pythagoras and Euclid. However, I'll present some ideas about the problem as steps toward a possible (future) answer. There is evidence that Alan Turing was working on related ideas shortly before he died. His 1952 paper on chemistry-based morphogenesis was about development of 2D surface patterns. I Think that was a fairly shallow side-track in a much deeper investigation that he failed to complete before he died (in 1954).

I am no Turing, but I can make some observations and vague (meta-level) suggestions about assembly processes in eggs that may help future researchers to explain production of hatchlings with significant spatial competences required for moving around, finding, and eating food.

The ideas are also potentially relevant to animals produced in wombs, where the division between the developing embryo and active individual is not so sharp.

Some of the proposed mechanisms are inspired by features of complex, multi-layered mechanisms such as the internet, and the extent to which its functioning depends on profound use of increasingly complex and sophisticated forms of ***virtual*** non-space-occupying machinery, implemented in frequently changing physical machinery. However, the conjectured control processes eggs will need to be far more complex and subtle than anything created so far by human engineers.

A similar comment can be made about how mechanisms that make possible processes of cognition in humans and other species are related to brain mechanisms. If the key ideas of this paper are correct, sub-neural chemical processes in brains will turn out to be far more important in explaining aspects of human spatial intelligence, including ancient mathematical intelligence, than statistics-based neural mechanisms.

Some intelligent non-human animals with powerful spatial reasoning abilities may turn out to have more in common with ancient mathematicians than anyone has noticed.

What happens inside a bird's egg?

Some of the things that go on inside eggs must involve powerful mechanisms for assembling very complex/intricate structures, like the body of a newly hatched chick, including many microscopic and sub-microscopic subsystems such as the circulatory system (including arteries, veins, capillary networks, and interfaces to many organs that interact with and through that system) along with many other subsystems providing different facilities, such as the structural roles of bones, muscles, ligaments, etc.

I'll also present evidence that those chemical assembly mechanisms not only produce extremely complex physical/physiological structures (and functions) but (in some species) also provide information-processing capabilities required for performing complex actions in the environment shortly after hatching, actions using competences that many theorists seem to assume must be the result of learning what does and does not work in the environment, e.g. by training neural networks.

Initially the mechanisms controlling gene expression are chemical interactions within a single cell, but as the mechanisms being added or extended grow more complex and more spatially extended (across multiple cells of different types), the machinery for controlling the development must also grow more complex.

That requires the processes controlling development within the egg to be repeatedly extended by producing new layers of control mechanism. These new mechanisms obviously cannot take up extra space in the egg (which would require a space-occupancy explosion).

In previous presentations I was not able to provide a good explanation for the existence of multiple layers of control during assembly of a foetus in an egg: I merely argued that new levels of complexity in the assembly process required addition of new forms of assembly mechanisms.

I now have a much stronger argument based on the diverging evolutionary histories of increasingly complex varieties of egg-using vertebrate species.

Ancient ancestors of current egg-using vertebrates must have had much simpler physiological structures than current species.

So perhaps evolution discovered, long before humans did, the importance of virtual machinery controlling large physical machines, as illustrated by many internet mechanisms, such as email systems, banking systems, online reservation systems, which share a great deal of physical infrastructure, but perform different functions using that infrastructure. Moreover, the virtual machines that run on physical internet hardware are constantly being extended and diversified.

Sometimes this can be done without significant physical changes to internet mechanisms. But in other cases the speed and capacity of internet mechanisms need to be extended to support new virtual machinery -- e.g. high speed games in virtual environments played by humans on different continents.

Egg-based future-proofing machinery!

An important feature of processes inside an egg is that in many species the in-egg processes constructing a new embryo produce individuals with complex forms of spatial intelligence that are required for interacting with the immediate environment after hatching, without any special training or learning, as illustrated by the avocets shown in the video clip above.

> So the mechanism-building machinery in the egg must be able to create not only new physical structures in the embryo but also powerful new information processing mechanisms for use after hatching, including genetically provided information about quite detailed aspects of the environment, and how they can be made use of by performing appropriate actions.
>
> Could the post-hatching mechanisms for controlling behaviours in external spaces share some of the pre-hatching mechanisms for controlling relatively large scale assembly and coordination processes within the egg, since both involve abilities to make use of information about spatial relationships?
>
> I suggest that those abilities are not built into a single monolithic spatial understanding machine inside the egg, but assembled from a variety of spatial reasoning mechanisms that evolved at different times, and are used at different stages of development -- including constructing later layers of virtual machinery.

There are some well-known and striking examples of organisms capable of complex shape changes triggered by features of the environment, such as the behaviour of slime mold shown in many online tutorial videos, such as https://www.youtube.com/watch?v=40f7_93NIgA with (over-optimistic?) caption "What self-driving cars can learn from brainless slime mold"!

However, there are deep differences between behaviours of slime molds (as I understand them) and the chemical construction processes that go on inside eggs, where the global shape (of the egg) does not change much, apart from growth in size and deviation from sphericity, but the intricate *internal* details constantly become more complex and more diverse in a growing collection of highly parallel processes.

The control and coordination of all those intricately interrelated structures and processes is not a uniform control process.

> *As the foetus grows more complex, the tasks become more varied, more complex, and straddle more scales, e.g. over time sizes of structures that need to be related become larger, and distances between connections increase.*
>
> *So in parallel with construction of new parts of the organism, there must be construction of new mechanisms controlling assembly. But there is no space inside the egg for extra controlling machinery (like the robotic arms alongside production-lines in human-built factories).*
>
> *So it appears that biological evolution found ways to construct new virtual machines that can control assembly processes without occupying additional space!*
>
> *Could such biological virtual machines share some features with the increasingly complex and varied virtual machines added to the internet that operate to perform new tasks without changing the physical structure of the internet -- e.g. setting up a zoom conference connecting pre-existing computers using pre-existing internet connections and user peripherals?*
>
> Of course, in the embryo there are also physical processes constructing new parts or changing shapes and sizes of existing parts as the organism develops, so that requires additional complexity beyond what the internet needs.

I don't yet know enough to decide whether the mechanisms described in Levin's work suffice to explain all of that, or whether additional ideas are required, perhaps even revisions of fundamental physics to explain the possibility of such high speed, low energy, richly controlled, multi-layer virtual-machine assembly controllers.

Note on "minimal" conditions for life (Tibor Ganti)

A topic that is not discussed in this document, but is closely related to the discussion of the roles of varieties of information in varieties of types of life, is the question whether there is a well defined "minimal" combination of features required for life. One of the best-known and most interesting attempts to answer this question is the work of Tibor Ganti(2003), although the requirements he specified are not met by viruses, for example. Whether viruses should be classed as a form of life is to some extent an uninteresting question of definition though how they are similar to and different from other entities that are regarded as definitely alive or definitely not alive is of some interest -- as discussed in this BBC tutorial: https://www.bbc.co.uk/bitesize/articles/zkcvhcw

This talk does not attempt to draw a boundary. My topic is more a matter of characterising differences between entities that do and do not make use of information of different kinds for different purposes in different contexts, e.g. for growth, reproduction, protection, and other biological functions. But there are different views on what information is, and on that point I am definitely not using "information" in the sense defined by Shannon.

Not Shannon Information!
Control requires use of information to determine what needs to be done at each stage.

This paper makes repeated essential use of the notion of "information". However, it is important to stress that I am not talking about Shannon information, a concept that goes back to about 1944, and refers to information bearing capacities in physical or virtual structures, not to their semantic content.

There is a very much older semantic concept of information used repeatedly by Jane Austen in her novels, a century before Shannon, as discussed in Sloman (2013--2018) (and other papers referenced therein).

Unfortunately, Shannon's choice of the label "information" (rather than something like "information-capacity") has misled and confused many thinkers in many disciplines, though Shannon himself was not at all confused.

Is whole-organism development what Alan Turing was really interested in when working on morphogenesis?

Turing's much-cited 1952 paper on the chemical basis of morphogenesis mentioned below was about development of 2D surface patterns. I suspect that paper was merely an interim progress report on a much deeper problem concerned more with development of 3D biological structures (as discussed above), and chemical mechanisms for thought processes, though it seems that he did not wish to provide information on work in progress in the 1952 paper. He died two years later without publishing anything more on morphogenesis, as far as I know. I suspect Turing's analysis of chemically controlled embryo development would have gone much further and deeper than Schrödinger's in (1944).

I think Turing had unwittingly rediscovered Kant's problem and begun to develop an answer. Perhaps we'll never know how far he had got by the time he died. This talk presents a few small steps in the direction of providing answers.

There's a tangled web of processes going on inside a developing embryo, with increasing levels of complexity as new layers of structure and control develop.

The earliest stages of morphogenesis are well studied and understood, including propagating local interactions among molecules within a cell. But we need something much richer and more powerful to explain later stages of development as both the number but also the variety of types of cell explode.

I think it is useful to apply what we have learnt about the importance, and diversity, of types of virtual machinery, designed and deployed since mid 20th Century. The earliest examples were merely software simulations of one (possibly not yet built) physical computer in another computer.

But the complexity, variety, and types of application of virtual machinery have continually expanded since then, and especially during the last two decades, driven by the increasing power and variety of applications using the internet -- most recently virtual conferences using tools like zoom, but also banking systems, multi-national company information systems, airline reservation systems, many kinds of sales and marketing systems, government information systems, flight control systems, and many more.

I suggest that biological evolution discovered and made sophisticated use of virtual machinery long before we did, notably in processes of reproduction of and control of increasingly complex organisms, and in some cases collections of organisms.

The evolving concept of "virtual machinery"
Far more sophisticated forms of virtual machinery have been developed for use in providing services across the internet that "float persistently" above the constantly changing particular physical mechanisms at work, but without occupying additional space.

E.g. think of all the (constantly changing) physical processes supporting an ongoing Zoom-based workshop by routing messages across multiple virtual pathways using possibly changing physical infrastructure.

Did evolution "discover" the possibility, and powers of such machinery long before human engineers did? What are the implications for current theories of basic physics?

And biology, neuroscience, philosophy, ...

As far as I know, there is no human-designed structure, e.g. no major chemical plant, whose products have diversity and complexity of internal structure and function comparable to a developing embryo in a chicken egg during later stages of hatching. Perhaps not even the largest chemical plants match the internal structural and functional complexity of an egg during the later stages of embryo development?

And there is no combination of known technologies that could assemble a machine as complex as a newly hatched chick in a space (including assembly machinery) as small as a chicken’s egg, or even the space of a larger egg, such as a crocodile egg! Moreover nothing with comparable complexity of structure and function could be assembled in three weeks, using current human engineering mechanisms, and consuming so little energy in the process!

How many years would it take for us to build machines that replicate the functionality of a single chicken egg? Can it be done using current technology? Could a comparable much larger self-organising egg-like machine be built using current scientific knowledge and technology? I suspect not.

Another question raised by all this, is whether there are aspects of current physical theory, especially the theory of very low-energy physics, that need to be extended in order to explain the details of reproduction of chickens and other animals.

How are the assembly processes controlled?
A major challenge is to explain how production of all that internal diversity is controlled so that things grow into the "right" sets of relationships, where parts of some objects e.g. lungs, heart, are functionally closely related to many other parts, e.g. all the detailed portions of veins, arteries and

capillary networks.

In addition to creation of physical structures, the processes of development in the egg result in provision of sophisticated spatial competences (e.g. perception, reasoning, action selection, control of action) in the chick, or other animal, available shortly after hatching, as illustrated by the avocet video above.

Currently popular theories in psychology, neuroscience and AI that I have encountered, attempting to explain complex abilities to interact with objects in the environment, assume that everything has to be learnt by acting in the environment and collecting information about what does and does not work, etc. This is the basis of neural net models of learning. (Not all psychologists share this view, e.g. Piaget, referenced below.)

Most theorists I have encountered who claim to explain spatial cognition and spatial skills seem to me to underestimate deeply the roles of innate (but self-extending) mechanisms using powerful ancient forms of virtual machinery -- not yet understood, though I think Alan Turing was working on relevant ideas shortly before he died, and Kant seems to have understood some of the *requirements* for explanations that most 21st Century theorists ignore.

Post-hatching displays of intelligence in avocet chicks
The video-clip above illustrates the commentator’s remark about behaviours soon after hatching: "They head down to the water straight away and they start to forage". This happens without any process of learning to walk, to find water, and to walk or paddle about in the water detecting prey items which they catch and swallow.

What are the implications of the fact that such complex competences can be provided for the new organism while it is being grown inside an egg?

How is that possible? There are questions about how such mechanisms evolved, how they develop inside a hatching egg, and how they actually work: how are the competences represented in the genome? How is that information used in producing a new physical implementation? How does that produce complex useful interaction with the environment shortly after hatching, or shortly after birth in some other species, e.g. foals that run with the herd to escape a predator shortly after birth.

What does all this imply about how much explanatory progress has been made in current AI and neuroscience?

More Examples of spatial - non-discrete reasoning:

As is obvious to young children, it is impossible to separate two linked rings made of solid impenetrable material simply by moving them around in space, without breaking open either of the rings.

Curves on the surface of a torus
(Skip during conference presentation?)
You probably find it obvious that in a planar 2D surface S, if C is a (non-self crossing) closed curve lying entirely in S, then no matter where C is located in S, or how large or how small C is, it *necessarily* divides the surface S into two non-overlapping portions, S1 and S2, and every continuous line L in the surface that joins a point in S1 and a point in S2 *must* also cross the curve

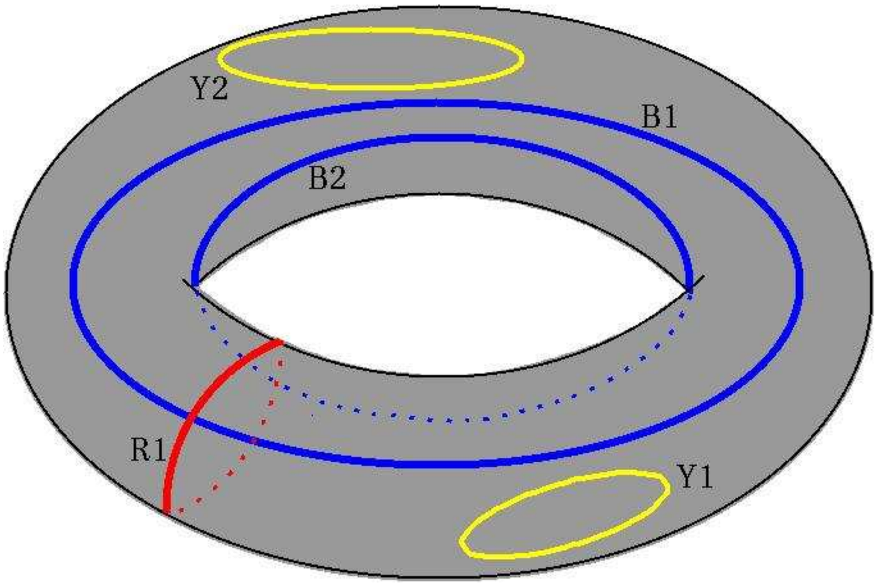
C.

There are infinitely many such closed curves in any surface. How can you know that the above statement is true of all of them: i.e. no exceptions are possible?

What mechanisms allow your brain to derive infinitely many consequences (summarised in a single statement using "all") from the the specification of C as closed and non-self-crossing?

If S is a toroidal surface, e.g. the surface of a ring, then the above is true for some closed curves in S but not all. (Think of closed curves drawn on the surface of the inflated inner tube of a car wheel.)

Now consider the figure below, containing five curves, B1, B2 both blue, R1 red, and Y1, Y2 yellow. These are all simple closed curves: they have no free ends, and none are self-crossing.



Closed curves on a torus

You can probably tell that the two yellow closed curves Y1 and Y2 are mutually continuously transformable: each can be smoothly moved in the surface of the torus to occupy the exact location of the other. How do you convince yourself that it is possible? Do you have to physically create a succession of intermediate curves, or is it enough to imagine them? Do you have to imagine all of the intermediate locations? Is the equivalence obvious at a more abstract level? What brain mechanisms could discover such obviousness?

A challenge

Suppose there are two non-self-crossing continuous closed curves C1 and C2 on the surface of a torus, we can say they are in the same "equivalence class" if C1 can be continuously deformed into C2. Is it possible for C1 to be continuously deformable into C2, but not vice versa? How could you know such asymmetry is impossible? A new question arises out of this:

How many equivalence classes of continuous closed curves are there on the surface of a torus?

What brain mechanisms make it possible for you to work out the answer simply by thinking about the problem, without having to be trained on thousands, or millions, ... or an infinite supply ... of different sets of curved lines on curved surfaces? Does any current robot have an artificial brain with similar powers? Could you design such a robot?

N.B. AI Neural Net mechanisms cannot provide such powers, since they collect statistical evidence and derive probabilities. Such a mechanism is incapable of representing, let alone discovering, that something is impossible or necessarily true.

Cem Tezer's online presentations

There are still modern mathematicians who present proofs that are based on spatial reasoning, supplemented with verbal commentaries, such as the wonderful demonstrations by mathematician Cem Tezer in these two video presentations on properties of triangles and related structures:

https://www.youtube.com/watch?v=AJvjtK2mmpU
MATH 373 - Geometry I - Week 1 Lecture 1

https://www.youtube.com/watch?v=1hNR-iCuw7g
MATH 373 - Geometry I - Week 1 Lecture 2

The great modern physicist, Roger Penrose, has also been exploring and attempting to explain such ancient human reasoning capabilities for many years, as illustrated in these lectures, and many others available online:
https://www.youtube.com/watch?v=eKjZ2W7eXlo
https://www.youtube.com/watch?v=th3YMEamzmw
https://www.interaliamag.org/audiovisual/roger-penrose-how-drawing-is-used-for-maths-and-science/
I have not encountered a specification for an explanatory brain mechanism in his work.

I suspect (and I think Turing also thought) that those ancient, and not so ancient, spatial reasoning processes cannot all be replicated/modelled in logic based systems, including digital computers, because they use chemistry-based information processing mechanisms combining discrete and continuous processes (a conclusion I did not reach until writing a paper for a Turing centenary volume). Roger Penrose implicitly makes similar claims, but as far as I can tell has not yet presented any explanatory mechanism.

In effect, Immanuel Kant, as explained below, made related claims about some forms of mathematical reasoning in 1781. My Kant-inspired claims in this presentation do not imply that purely symbolic, logic-based, reasoning *cannot* replicate the *results* of the most ancient forms of mathematical reasoning. Logic-based reasoning can lead to discoveries in logic-based branches of mathematics that are structurally related to, though different from, the original topological and geometrical discoveries discussed here. Reasoning using logic (or algebra) depends on the exact formal properties of the symbols use: a minor modification can turn a valid logical inference into an invalid one. In contrast, minor modifications in geometric proofs, e.g. a slight increase in thickness of a line, or a slight difference in radii of two circles drawn, will not necessarily render the geometric proof, as understood by a competent mathematician invalid. In fact human-produced diagrams *cannot* include examples of the mathematical structures referred to, with infinitely thin lines, for example.

I claim only that there were ancient (and not so ancient) mathematicians whose geometric reasoning was not based solely on use of logic and definitions, and I conjecture, partly because of the spatial reasoning capabilities of many newly hatched animals, such as the avocets mentioned above, that many mathematical brains use chemistry-based forms of representation and reasoning that are related to the chemistry-based control mechanisms and structures produced by chemical processes creating animals in eggs.

Ancient mathematical discoveries concerning geometric and topological impossibility or necessity could not have been based on the use of neural nets, since those merely collect statistics and derive probabilities. They cannot establish necessity or impossibility. They cannot even *represent* those concepts.

(My comments don't apply to hybrid systems in which neural nets are combined with other mechanisms, e.g. logical theorem provers.)

Construction kits built during development (epigenesis)

A key feature of the Turing-inspired Meta-Morphogenesis project, introduced here:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html
is the use of increasingly complex evolved construction kits: mechanisms for creating objects of a particular (more or less general) type -- including construction-kits for building new construction-kits Sloman 2014(+many updates).

Some new construction kits are products of evolution of a species and are initially shared only between a few members of the species, alongside other species-specific and cross-species construction kits (shared between species), such as those used in mechanisms of reproduction and growth in related species.

Evolution also seems to have discovered the benefits of "meta-construction-kits": mechanisms that allow members of a species to build new construction kits during their own development. One of the most striking examples is language development in humans: which often includes individual variation.

Examples include mechanisms for learning that are initially generic mechanisms shared across individuals, and developed by individuals on the basis of their own previously encountered learning experiences, which may be different in different environments for members of the same species.

Human language learning is a striking example: things learnt at earlier stages make new things learnable that might not be learnable by an individual transferred from a different environment, part way through learning a different language.

This contrast between genetically specified and individually built capabilities for learning and development was labelled a difference between "pre-configured" and "meta-configured" competences in Chappell and Sloman (2007), summarised below in the Meta-configured Genomes section, including Figure EVO-DEVO, below.

What we label "meta-configured competences" are partly specified in the genome but those partial, abstract, specifications are instantiated in combination with information derived during development from individual experiences in various domains, of increasing abstraction and increasing complexity. We originally offered this conjecture as a more general alternative to Waddington's notion of "an epigenetic landscape", which he thought of as providing a fixed collection of developmental options for all members of a species. The meta-configured genome theory suggests that developing individuals construct that landscape while interacting with their environment.

The new theory of hatchling development adds hypothesized evolved mechanisms and processes that occur during hatching, to prepare the embryo hatchling for species-specific interactions with the environment shortly after hatching: e.g. feeding behaviour (illustrated by the avocets above) or abilities to follow a parent.

Biological evolution is often thought of as a process of continuous change, like the growth of a plant, but for species that reproduce by producing offspring, there can only be a finite number of individuals between an organism and each of its ancestors. So evolutionary changes must be discrete. A key new feature of the theory (in 2022) is that the evolutionary changes that produce such a species must have happened in the course of a history of

(Mathematical development and language development in humans both seem to be special cases of growth of such meta-configured competences. But that's a long story...)

Meta-Configured genomes

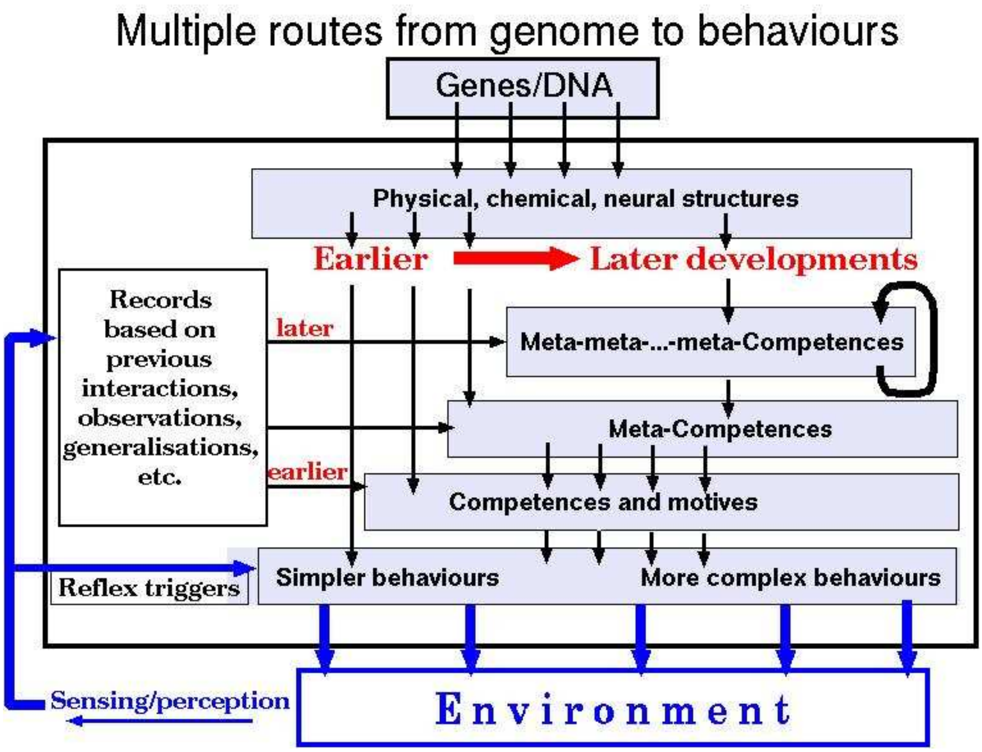


Figure 3: Figure EVO-DEVO:

A particular collection of construction kits specified in a genome can give rise to very different individuals in different contexts if the genome interacts with the environment in increasingly complex ways during development, allowing enormously varied developmental trajectories. Precocial species use only the downward routes on the left, producing only "preconfigured" competences. Competences of members of "altricial" species, using staggered development, may be far more varied within a species. Results of using earlier competences interact with the genome, producing "meta-configured" competences shown on the right. This is a modified version of a figure in Chappell & Sloman (2007).

Construction kits used for assembly of new organisms that start as a seed or an egg enable many different processes in which components are assembled in parallel, using abilities of the different sub-processes to constrain one another. Nobody knows the full variety of ways in which parallel construction processes can exercise mutual control in developing organisms. One implication of Figure EVO-DEVO is that there are not always simple correlations between genes and organism features.

The main idea could be summarised approximately as follows:

> Instead of the genome determining how the organism reacts to its environment, the environment can cumulatively determine how the genome expresses itself: with different sorts of influence at different stages of development. This should not be confused with theories that attempt to measure **percentages** of genetic *vs* environmental influence in individual development. Numerical measures in this context are much shallower than specifications of structures and their interactions. Compare: expressing the *percentage* of one composer's influence on another (e.g. Haydn's influence on Beethoven) would give little understanding of *what* the later composer had learnt from his or her predecessor. Often emphasising measurement over precise description can obfuscate science instead of deepening it. Likewise emphasising *correlations* can get in the way of understanding *mechanisms*.

Explaining the many ways in which a genome can orchestrate parallel processes of growth, development, formation of connections, etc. is a huge challenge. Fig. 3 summarises a framework allowing abstract specifications in a genome to interact with details of the environment in instantiating complex species-specific designs in a way that is relevant to the environment.

Some of these species-specific mechanisms could include genetic mechanisms that trigger desires, which in turn lead to changes in the genome in future generations, as proposed in Popper(1976), which suggested that newly evolved desires of individual organisms (e.g. desires to reach fruit in taller trees) could indirectly and gradually, across generations, influence selection of physical characteristics (e.g. longer necks, abilities to jump higher) that improve success-rates of actions triggered by those desires.

Such mechanisms may allow individual members of a species to partially construct and repeatedly modify their own epigenetic landscapes instead of merely following paths in a landscape that is common to the species. Mechanisms that increase developmental variability may also make new developmental defects possible (e.g. autism?), as well as allowing various kinds of creativity, including mathematical creativity in humans.

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

2.4 The variety of biological construction kits

As products of physical construction kits become more complex, with more ways of contributing to needs of organisms, and directly or indirectly to reproductive fitness, they require increasingly sophisticated control mechanisms. New sorts of control often use new types of information. Processing that information may require new mechanisms. That may require new construction kits for building new types of information processing mechanism.

The simplest organisms use only a few types of (mainly chemical) sensor, providing information about internal states and the immediate external physical environment. They have very few behavioural options. They acquire, use and replace fragments of information, using the same forms of information throughout their life, to control deployment of a fixed repertoire of capabilities.

More complex organisms acquire information about enduring spatial locations in extended terrain, including static and changing routes between static and changing resources and dangers. They need to construct and use far more complex (internal or external) information stores about their environment, and, in some cases, "meta-semantic" information about information processing, in themselves and in others, e.g. conspecifics, predators and prey.

What forms can all the intermediate types of information take? Many controlled systems have states that can be represented by a fixed set of physical measures, often referred to as "variables", representing states of sensors, output signals, and internal states of various sorts. Such systems have many engineering applications, so many researchers are tempted to postulate them in biological information processing. Are they adequate?

Relationships between static and changing state-components in such systems are often represented mathematically by equations, including differential equations, and constraints (e.g. inequalities) specifying restricted, possibly time-varying, ranges of values for the variables, or magnitude relations between the variables. A system with N variables (including derivatives) has a state of a fixed dimension, N. The only way to record new information in such systems is through static or changing values for numeric variables -- changing "state vectors", and possibly alterations in the equations.

There are many well understood special cases, such as simple forms of homeostatic control using negative feedback. Neural net based controllers often use large numbers of variables clustered into strongly interacting sub-groups, groups of groups, etc. Are these structures and mechanisms adequate for all biological information processing -- including human perception and reasoning?

For many structures and processes, a set of numerical values and rates of change linked by equations (including differential equations) expressing their changing relationships is an adequate form of representation, but not for all.

That’s why chemists use *structural* formulae, e.g. diagrams showing different sorts of bond between atoms, and collections of diagrams showing how bonds change in chemical reactions.

Linguists, programmers, computer scientists, architects, structural engineers, map-makers, map-users, mathematicians studying geometry and topology, composers, and many others, work in domains where structural diagrams, logical expressions, grammars, programming languages, plan formalisms, and other *non-numerical* notations express information about structures and processes that is not usefully expressed in terms of collections of numbers and equations linking numbers.

CLOSELY RELATED RESEARCH
To be extended

Minimal Intelligence Lab (MINT Lab)
Studying Plant Intelligence (and other forms)

http://www.um.es/web/minimal-intelligence-lab/
http://www.um.es/web/minimal-intelligence-lab/contenido/manifesto
Expanded Manifesto (PDF):
http://www.um.es/documents/2103613/2107123/MANIFESTO_PLANT+NEUROBIOLOGY+AND+ITS+PHILOSOPHY.pdf
The Minimal Intelligence Team:
http://www.um.es/web/minimal-intelligence-lab/contenido/the-team
"Frontiers" page on Minimal intelligence across Eukaryota
http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01329/full

The Meta-Configured Genome (MCG) theory
Some of the key ideas of the MCG theory were first published in: Jackie Chappell and Aaron Sloman (2007), Natural and artificial meta-configured altricial information-processing systems, in *International Journal of Unconventional Computing*, 3, 3, 2007, pp. 211--239,
http://www.cs.bham.ac.uk/research/projects/cogaff/07.html#717

Abstract:
The full variety of powerful information-processing mechanisms 'discovered' by evolution has not yet been re-discovered by scientists and engineers. By attending closely to the diversity of biological phenomena, we may gain new insights into

(a) how evolution happens, including how it extends the mechanisms of evolution by evolving new construction-kits, meta-construction-kits, meta-meta-construction-kits, etc.
(b) what sorts of mechanisms, forms of representation, types of learning and development, and types of architectures have evolved,
(c) how to explain ill-understood aspects of human and animal intelligence,
and perhaps, if our technology is sufficiently extendable:
(d) new useful mechanisms for artificial systems.

We analyse trade-offs common to both biological evolution and engineering design, and propose a kind of architecture that grows itself, using, among other things, genetically determined meta-competences that deploy powerful symbolic mechanisms to achieve various kinds of discontinuous learning, often through play and exploration, including development of an 'exosomatic' ontology, referring to things in the environment - in contrast with learning systems that discover only sensorimotor contingencies or adaptive mechanisms that make only minor modifications within a fixed architecture.

We sometimes refer to this collection of ideas as "The Meta-Configured genome". Paul Davies(2012) seems to have developed related ideas, though without the theory of construction-kits (including construction-kits for producing or modifying construction kits).

PROVISIONAL LIST OF REFERENCES

This list of references will later be improved (if/when I get time!). Please feel free to send suggestions for addition, preferably in plain text or bibtex format. If I simply receive a web link with no description to help me assess its relevance I may ignore the suggestion, for lack of time.

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differentiation during early embryonic development, thus mutations in homeobox genes can cause developmental disorders."

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