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Minds, machines and science:

Animal spatial intelligence and limits of current AI and neuroscience.

Invited talk for "Web and Philosophy" workshop
(PhiloWeb 2021 -- Presentation on 22nd June 2021)
http://web-and-philosophy.org/event/philoweb-2021-schedule/
http://web-and-philosophy.org/

This was originally part of 13th ACM Web Science Conference, 22-25 June 2021
https://websci21.webscience.org/

NOTE ADDED 29 Jun 2021: WORKSHOP VIDEO RECORDING
A recording of the complete PhiloWeb workshop (about 8.5 hours)
is now available online, here:
https://www.youtube.com/watch?v=mj4GbPG2Mok
My (somewhat chaotic) talk starts at around 25:00,
followed by discussion, ending at around 55:00.

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Note

This talk was allocated 30 minutes, so many details had to be omitted. Links below refer to further information. Much of the work I presented goes far beyond relevance to the internet.
A longer presentation, followed by discussion, was given on 2nd June, hosted by Tubingen University, with recording included here:
https://www.youtube.com/channel/UCaG1Q8TEuLN5OJZXaTL28PQ
NOTE: an unannounced change in zoom, requiring cable-connected machines to use TCP, prevented screen sharing for the Tubingen talk, so I had to give a long, unprepared, "talking head" presentation, without any slides, diagrams or videos to help. The discussion following the presentation was also recorded and is available at:
https://www.cs.bham.ac.uk/research/projects/cogaff/movies/tub/as-discuss.mp4

A closely related presentation will be given at the Worcom workshop in September 2021:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-morcom.html
Mike Levin, at Tufts University has agreed to take part:
https://wyss.harvard.edu/news/mike-levin-on-electrifying-insights-into-how-bodies-form/

Installed: 22 Jun 2021 (Updated several times since then.)
This document is
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-PhiloWeb.html

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TALK AT PHILOWEB WORKSHOP

22 Jun 2021
http://web-and-philosophy.org/event/philoweb-2021-schedule/
This is part of

13th ACM Web Science Conference 2021 June 21st -- June 25 https://websci21.webscience.org/
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EXTENDED ABSTRACT

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 constitutionally incapable of discovering or representing impossibility or necessity, which are not extremes of probability.

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 I think Immanuel Kant, reacting to David Hume's account of types of knowledge had some deep insights -- and at at least partly understood the difficulty of finding complete explanations. More on Kant below.

I think we still cannot explain all the processes and mechanisms involved, but I shall try to share some ideas about the problem and a possible (future) answer. Parts of my answer are inspired by features of the internet and the extent to which its functioning depends on profound use of increasingly complex and sophisticated forms of ***virtual*** machinery. A similar comment can be made about attempts to understand processes of cognition in humans and other species, and the mechanisms that make them possible.

What happens inside a bird's egg?

I claim, though this talk is too short for a detailed argument, that 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. including powerful forms of virtual machinery required to control assembly processes. (I'll enlarge on that diversity and complexity below, though I suspect many important details are unknown).

Another important feature of processes inside an egg is that in many species the in-egg processes produce individuals with complex forms of spatial intelligence that are required for interacting with the immediate environment after hatching, as illustrated by the avocets shown in the video below.

There are other striking examples of complex shape changes triggered by features of the environment, such as the behaviour of slime molds (spelt "moulds" in an earlier version of this paper). 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 sphericality, but the intricate internal details constantly become more complex and more diverse.

This image (not shown in the conference presentation) crudely indicates stages of development in a chicken egg:

Here's a video showing some of what goes on inside a chicken egg during the hatching process: https://youtu.be/PedajVADLGw
Courtesy of: Cobb Ltd

Some of the stages
DAY 1: Appearance of embryonic tissue.
DAY 2: Tissue development very visible. Appearance of blood vessels.
DAY 3: Heart beats. Blood vessels very visible.
DAY 4: Eye pigmented.
DAY 5: Appearance of elbows and knees.
DAY 6: Appearance of beak. Voluntary movements begin.
DAY 7: Comb growth begins. Egg tooth begins to appear.
DAY 8: Feather tracts seen. Upper and lower beak equal in length.
DAY 9: Embryo starts to look bird-like. Mouth opening occurs.
DAY 10: Egg tooth prominent. Toe nails visible.
DAY 11: Cob serrated. Tail feathers apparent.
DAY 12: Toes fully formed. First few visible feathers.

DAY 13: Appearance of scales. Body covered lightly with feathers.
DAY 14: Embryo turns head towards large end of egg.
DAY 15: Gut is drawn into abdominal cavity.
DAY 16: Feathers cover complete body. Albumen nearly gone.
DAY 17: Amniotic fluid decreases. Head is between legs.
DAY 18: Growth of embryo nearly complete. Yolk sac remains outside of embryo. Head is under right wing.
DAY 19: Yolk sac draws into body cavity. Amniotic fluid gone. Embryo occupies most of space within egg (not in the air cell).
DAY 20: Yolk sac drawn completely into body. Embryo becomes a chick (breathing air with its lungs). Internal and external pipping occurs.

My thanks to: https://www.backyardchickens.com/

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 interconnection going on inside the developing animal, leading to production of bones, nerve fibres, heart, lungs, veins, arteries, and capillary networks. 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 into veins. Both sets of veins and sets 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.

These functions can include transfer of types of physical matter such as nutrients, waste products and chemical signals (e.g. hormones). Moreover during development of an embryo inside an egg, the diversity, complexity, and types of function of the components of the foetus, and the types of connectivity between different parts continue growing. This is very different from the types of changing self-organisation exhibited by shape-changing organisms such as slime mold, illustrated in many online tutorial videos, e.g. this one https://www.youtube.com/watch?v=40f7_93NIgA with caption "What self-driving cars can learn from brainless slime mold"!

> *Is this what Alan Turing was really interested in when working on morphogenesis?*
> Turing's 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 physiological structures (as discussed above), though he did not wish to provide information on work in progress in that paper. I suspect he was far more interested in problems such as how a chick is assembled in an egg, than problems about formation of 2D patterns. But he wasn't ready to make that work public in 1952. He died two years later without publishing anything more on morphogenesis, as far as I know.

I suggest that there is no product of human engineering that is smaller than a major chemical plant and has 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.

How many years would it take? 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?

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.

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, available shortly after hatching. Most current theories I have encountered that attempt to explain such competences assume all competences have to be learnt by acting in the environment and collecting information about what does and does not work, etc.

Current theories attempting 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.

Post-hatching displays of intelligence in avocet chicks
(thanks to BBC Springwatch, 1st June 2021):
https://www.cs.bham.ac.uk/research/projects/cogaff/movies/avocets/avocet-hatchlings.mp4
The video 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, to swim and paddle, to detect prey items and to catch them and swallow them.

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?

Turing 1952
Alan Turing's 1952 paper 'The chemical basis of morphogenesis', discusses chemistry-based pattern formation on the surfaces of plants and animals, but I suspect it was intended as precursor to a much deeper publication on the role of chemical mechanisms in thought processes. I.e. he 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.

What are the requirements for such an explanatory mechanism, and what might the benefits be?

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 are well studied and understood, and propagating local interactions among molecules seem to suffice. But we need something much richer and more powerful to explain later stages of development.

The internet is relevant at last!
We can use the concept of virtual machinery, which has been constantly changing and growing richer since the simplest versions in mid 20th Century.

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, ...

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.

Here's an example involving two stone rings forming a chain on an old Indian temple: Vaideshwara temple at Talakad:

FIG 2 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.

It appears that each of the rings is made of a single piece of solid stone that has never been divided into two or more pieces and then recombined. Given that: here's a question for the reader *Could the two rings have been cut out of two separate blocks of stone and then assembled?*

o How do you know the answer to this?

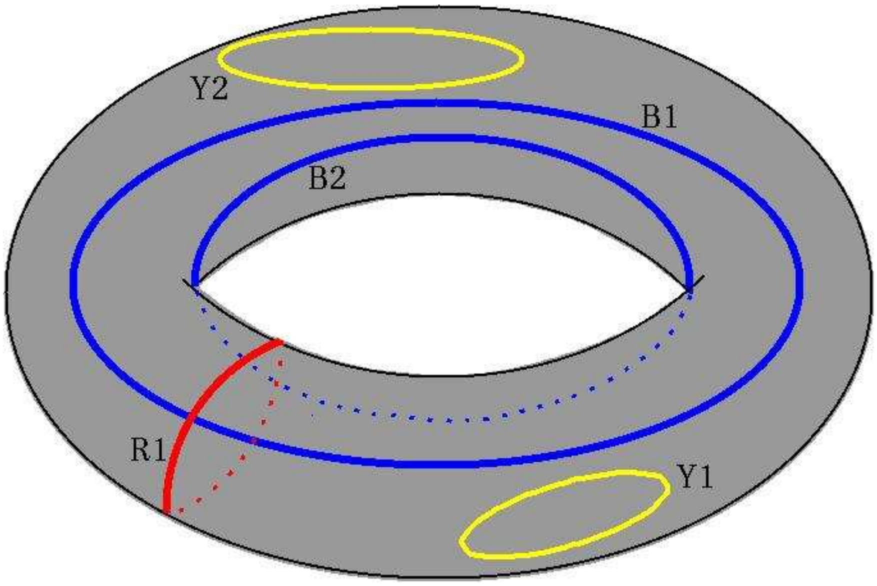
Curves on the surface of a torus

(Skip during workshop presentation)

In a planar or spherical 2D surface S, if C is a (non-self crossing) closed curve, then C 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.

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 closed curves: they have no free ends.



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?

Note added 22 Jul 2021
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? What sort of brain makes 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 curves? Does any current robot have an artificial brain with such powers? Could you design such a robot?

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 abilities. They can make use of spatial possibility, impossibility, and necessity in selecting and performing actions, though they cannot communicate their knowledge, and may not have brain mechanisms required for reflecting on what is known, or describing such knowledge.

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 after my presentation 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 Hilbert axioms using logic, as the great mathematician David Hilbert did when he "axiomatized" Euclidean geometry Hilbert(1899).

But 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.

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

I suspect, and I think Turing thought, that those ancient, and not so ancient, spatial reasoning processes cannot all be replicated/modelled in logic based systems. In effect Immanuel Kant made related claims about some forms of mathematical reasoning in 1781, but my claims in this presentation do not depend on whether purely symbolic, logic-based, reasoning *cannot* replicate the *results* of the ancient forms of mathematical reasoning. I claim only that there were ancient (and not so ancient) mathematicians whose geometric reasoning went beyond use of logic and definitions.

Kant vs Hume

Immanuel Kant’s characterisation of ancient mathematical knowledge, in his Critique of Pure Reason (1781) drew attention to three features of such cognition, using three distinctions that are ignored in current psychology, neuroscience and neural-net based AI: the non-empirical/empirical, analytic/synthetic, and necessary/contingent distinctions.

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 it 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.

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.

REFERENCES AND LINKS
To be extended

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