DRAFT LIST

Transitions in biological information-processing
or
Varieties of evolved, developed, learnt, invented... forms of biological computation

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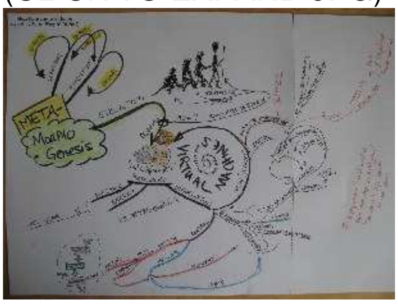
NOTE ADDED 18 Jan 2017/24 Nov 2018
Some parts of this are superseded by or expanded in the discussion of the role of construction-kits in biological evolution and development:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html (also pdf)
A discussion of roles of compositionality in evolution is also relevant:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/sloman-compositionality.html (also pdf)

On 5th Jun 2012, Stuart Wray, after reading a draft paper
on Meta-morphogenesis and the Creativity of Evolution:
http://www.cs.bham.ac.uk/research/projects/cogaff//12.html#1203
produced this sketch of the ideas in the project ...
(CLICK TO EXPAND JPG)



CLICK HERE FOR PDF VERSION.

This is part of the Turing-inspired Meta-Morphogenesis project:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/bio-math-phil.html
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/toddler-theorems.html
http://www.cs.bham.ac.uk/research/projects/cogaff/11.html#1106d
See also video of tutorial on Meta-Morphogenesis at AGI Dec 2012
http://www.youtube.com/watch?v=BNul52kFI74
Developing theory of evolved construction-kits begun late 2014:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html
The central, crucial, roles of mathematical structures and competences in evolution:
Multiple Foundations For Mathematics

(DRAFT: Liable to change: Please do not save copies -- save a pointer.)

Installed: 15 Oct 2012
Last updated:
22 Jun 2014; 26-27 Jul 2014; 8 Aug 2014; 15 Aug 2014 (Wray, Birner); 18 Jan 2017; 27 May 2018;
25 Oct 2012; 2 Nov 2012; 19 Nov 2012; 25 Nov 2012; 30 Dec 2012; 3 Jan 2013; 14 Jan 2013;
6 Feb 2013; 5 Mar 2013; 2 Aug 2013; 19 Aug 2013; 8 Jan 2014; 27 Apr 2014

This file is
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/evolution-info-transitions.html
A PDF version derived from the html (possibly a bit older):
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/evolution-info-transitions.pdf

A partial index of discussion notes is in
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/AREADME.html
(Please do not save copies of this document -- as they will get out of date quickly.)

CONTENTS (Partial contents list)

Abstract: (Revised 2 Mar 2013; 19 Aug 2013)

It is not uncommon for biologists and others interested in evolution to discuss and investigate evolutionary transitions that produced new **physical forms**, or new **sensorimotor organs**, or new **physical behaviours**. What is not so common, and is much harder to do, is to identify transitions that produced new forms of **information-processing**, including new information contents, new forms of representation, new sources of information, new ways or transforming or deriving information and new ways of using information.

The attempt to identify and analyse those transitions in information-processing is the Meta-Morphogenesis project, so named because the mechanisms that produce the transitions sometimes produce new mechanisms for producing such transitions: for instance, some of the types of evolution, learning and development that exist on earth now are themselves products of evolution, learning and development, and did exist in the earliest life forms.

This document presents and attempts to explain the importance of a growing collection of examples of transitions in information-processing capabilities in evolution, in development, in learning, in society/culture, and perhaps also in ecosystems. The transitions created by information engineers since the 1940s could also be regarded as products of biological evolution (like the cathedrals built by termites), but for now they are used merely to illustrate types of information-processing phenomena. Recent information-processing technology provides several pointers to problems and solutions that previously turned up in biological evolution (e.g. the advantages of control by virtual machines rather than physical machines, when virtual machines are easier to design, monitor, debug, modify, extend and combine with other mechanisms, as explained here.)

Others have asked some of the questions raised here, but I am trying to collect a wide variety of examples of transitions that may show patterns not visible to researchers in a single discipline focusing on narrower sets of examples.

The key idea (Added 8 Aug 2014)

The key idea: evolution changes evolutionary processes and mechanisms, development changes developmental processes and mechanisms, individual learning changes individual learning processes and mechanisms, cultural evolution changes cultural evolutionary processes and mechanisms. Moreover, each of these processes and mechanisms of change can impact on the others over appropriate time-scales. If all that is correct, attempts to characterise any of those processes or mechanisms in a **uniform** way will lead to erroneous theories.

For example, natural selection may seem to be a uniform process, but what it does depends both on the mechanisms generating options between which selections can be made, and the selection mechanisms. The points summarised above imply that both the types of options and the selection mechanisms can change dramatically.

For discussion of ways in which learning and development in an organism can produce results that combine with genetic mechanisms to influence later development see Chappell and Sloman (2007). Closely related ideas are in Karmiloff-Smith(1992)

A major extension since early 2015: Evolution's use of fundamental and derived construction kits.

http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html
Still under development

Some related work (a tiny subset)

Although the scope of this project seems to be larger than most others, this is not the first work to be concerned with evolution of information processing mechanisms.

A similar concern can be found in many other publications, e.g. here's a tiny sample:

Modularity in Development and Evolution
Eds. Gerhard Schlosser, Gunter P. Wagner
University of Chicago Press, Chicago, 2004

Living is information processing; from molecules to global systems,
K.D. Farnsworth and J. Nelson and C. Gershenson, 2012,
http://arxiv.org/abs/1210.5908

Stuart Kauffman,
At home in the universe: The search for laws of complexity,
Penguin Books, 1995,

Chapter 15 of Margaret A. Boden,
Mind As Machine: A history of Cognitive Science (Vols 1--2),
Oxford University Press, 2006,

Note added 2 Aug 2013: I have been reading Merlin Donald's 2002 book
A Mind So Rare: The Evolution of Human Consciousness
The book is spoilt by excessive rants against reductionism, and a seriously ill-informed account of symbolic computation, but is a superb introduction to many of the evolutionary transitions that involve information-processing, e.g. Chapter 4. Donald seems to understand the importance of the fact that what exists now, e.g. in human minds, builds on many layers of previously evolved function and mechanism which may be shared with many other species. He raises many important questions about how and why various features of human minds evolved, even though he lacks (or lacked) the engineering expertise to provide deep answers.

Beyond the organism's boundaries

A common thread in the work on evolution of information processing is the importance not only of the sensorimotor morphology of organisms, and the mechanisms in brains and nervous system, but also the nature of an organism's environment, the problems it poses, the opportunities it provides, and the kinds of information-processing systems required for dealing with it.

In the last few decades there has been much emphasis on the importance of embodied cognition, or enactivism. I think it will turn out that much of the work done under that banner, especially the polemical pronouncements, merely illustrate the dangers of following narrow fads instead of trying to get a deep understanding of the variety of design requirements for organisms and robots, and the variety of possible solutions and their trade-offs.

In particular a narrow approach to the study of embodied cognition tends to emphasise the importance of "online intelligence" as if "offline intelligence" either did not exist or had no major biological function, whereas I argue that offline intelligence is crucial to understanding the variety of types of affordance and their perception and use (going far beyond the ideas of James Gibson on affordances). This is also essential to understanding human mathematical and scientific theory-building competences, for example. The distinction between online and offline information-processing is discussed further below.

For a more detailed critique see:

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Some Requirements for Human-like Robots:
   Why the recent over-emphasis on embodiment has held up progress
In Creating Brain-like Intelligence,
Eds. B. Sendhoff, E. Koerner, O. Sporns, H. Ritter, and K. Doya, pp. 248--277,
http://tinyurl.com/BhamCosy/#tr0804
```

Sources of variety in types of Meta-Morphogenesis:
For any biological (e.g. genetic) changes B1, B2, B3,.. etc. and for any environmental states or changes E1, E2, E3,... there can be influences of the following forms ...

- E changes B
- B changes E
- Bi changes Bj
- Combinations of Ei, Bi, Bj, ... cause changes in Bk, BL, ... etc., etc.

These and other patterns need to be used to drive research into new patterns of influence.

Background

If Turing had lived longer he might have asked: What collection of changes in **information-processing mechanisms** would have been required to produce life as we know it and how could they have come to exist?

It is clear that evolution, learning, development, and cultural changes produce new biological information used in reproduction and in many forms of behaviour.

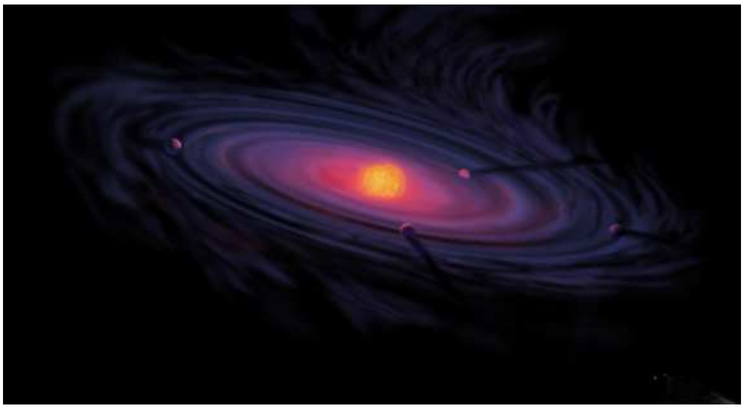
However, the mechanisms for producing new forms of information-processing have themselves been changed -- including new forms of reproduction, learning, development, cultural change, and "unnatural selection" mechanisms such as mate-selection, animal and plant breeding, and more recently cloning and use of genetic manipulation to control reproduction.

The meta-morphogenesis project seeks to identify (a) all such changes in information contents, and information-processing mechanisms and their consequences, especially the many unobvious changes that are needed to answer old philosophical questions and shed light on the relations between nature and nurture and relations between minds and brains, and (b) the processes and mechanisms that drove those changes.

If identifying all (including future) changes is impossible, we can attempt to identify as diverse a range as possible, with as many intermediate points as possible, along as many divergent evolutionary lineages as possible.

It may be necessary to start with relatively coarse-grained transitions and gradually home in on details.

From ashes and dust



Ideally where we should start....
(Picture by NASA on Wikimedia: protoplanetary-disk.jpg)

In the earliest phases of evolution, the mechanisms, and the changes in information processing that they produced, could be understood in terms of physics and chemistry, but as evolution progressed the information contents, and the information-processing mechanisms, including virtual machinery, became increasingly important -- at least for the most complex organisms -- much as the products of human engineering have increasingly involved information and information contents, including the products that are used to produce new products. The latest generation of cpus could not have been produced without using earlier cpus controlled by changeable software. Likewise, the most complex software products could not be designed, developed, tested, debugged, maintained, etc. without the use of earlier software products, including compilers, interpreters, type-checkers, development tools, etc.

Conjecture: In similar ways, new products of biological evolution, and products of its products, enhance evolution's ability to produce more complex products.

This document presents some examples of transitions in information-processing competences, starting with very simple cases and moving to increasingly complex examples, but without presuming that there's a fixed order in evolution, or development. The diversity of possible trajectories, is clearly indicated by human learning and development and by differences in evolutionary lineages. Whether there are any absolute restrictions on possible trajectories is a question to be investigated later.

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NOTE: A failure to recognise diversity in developmental and learning
trajectories can ruin educational systems for many learners.
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Many of the transitions in biological information-processing are closely connected with deep philosophical problems, including questions raised by Immanuel Kant (Critique of Pure Reason, 1781) in his philosophy of mathematics, since a number of biological transitions were required to produce organisms capable of making mathematical discoveries, as discussed further in connection with "Toddler theorems" discussed below and capabilities that seem to have been needed for the developments that led to Euclid's Elements over 2,300 years ago.

Some of the competences are illustrated and discussed briefly here:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/triangle-theorem.html

Other transitions in information-processing were required to allow attention to be switched between objects, events and processes in the environment and objects, events and processes in perceivers, for example the ability to notice, when looking at unchanging external structures from a moving viewpoint, the changeable intermediate results of perceptual processing, such as aspect ratios, optical flow patterns, texture gradients, and assumed but unperceived parts, e.g. 'far sides' of objects. Such changes in contents of awareness have produced philosophical puzzles about the relationships between experience and reality, since ancient times. (Think of Plato's Cave, for example.)

But those are much later developments certainly in evolutionary time, and possibly also in individual development of humans, since it's not obvious that newborn infants have such capabilities.

High level, partial overview [Revised 26 Jul 2014]

Some of the important transitions to be discussed in more detail later include:

- New types of **information contents** that can be represented and used (i.e. changing ontologies)

- New forms of syntax, new forms of syntactic manipulation, new forms of semantic content, new ontologies, new additions to or modifications of old ontologies (e.g. merging, splitting, etc.)

- New types of **forms of representation** that can be used for expressing or storing information -- including the use of **virtual** machinery in which information structures are created, manipulated, and used

- New types of **forms of derivation** of new information from old

- New types of **mechanisms for exploring** varieties of information contents

- New types of **sensory mechanisms** that are available for acquiring information of various sorts (including information about internal states of the organism).

- A variety of such transitions are concerned with the need to deal with **noise in sensors**. Noise, or randomness, is a common feature of many biological sensory systems, and mechanisms for coping with noisy sensors or randomness in the environment seem to be found in many organisms. A number of examples can be found in a series of lectures by William Bialek: the Salam Lecture Series 2013 available at:
  http://www.youtube.com/playlist?list=PLoxv42WBtfCAY8icy7uChz_kpBXpWoMwk

- **Motor signals can also be noisy**, and mechanisms for 'taming' the noise in order to produce fine grained control have also evolved.

- **Beyond noise: (Added 26 Jul 2014)**
  There are many things that are structured features of the environment or of the perceiver's actions, that can modify or interfere with perception of some object

or process, and they need mechanisms totally different from noise reduction, or probabilistic inference. For example, another object or a different part of the same object (if it rotates or bends) or part of the perceiver (e.g. a grasping hand), or motion of the perceiver to a new point of view, a new direction of view, a new, distant, location can all make a difference. Understanding these processes and taking account of them requires the perceiver to have, to acquire, to extend, the syntactic and semantic (ontological) resources needed to represent the environment and its place in it. See also http://www.cs.bham.ac.uk/research/projects/cogaff/misc/simplicity-ontology.html

- New types of **control mechanisms** that are available for producing actions using motor mechanisms and internal mechanisms, such as attention-switching mechanisms, motive generating mechanisms, and many more

- New types of **uses** to which information can be put
  (this can include extensions to new physical environments that can be perceived, created, controlled, or modified)

- New types of **architectures** of information processing systems
  (e.g. changes that allow new kinds of processing to occur concurrently, or new kinds of interactions between different sub-systems, such as one sub-mechanism monitoring or modulating another, or changes that allow task- and environment-dependent changes of architecture.)
  See the CogAff project

- New types of ability to deal with **other information-processors**
  The requires evolution or development of meta-semantic competences of various kinds, some of which may be inwardly directed, others used for representing and reasoning about information processing in others (as Jane Austen clearly understood). (Search for her name below.)
  (See examples below.)

- New types of **collaborative** information-processing, including communication
  There are complex 'emergent' features of collaborative or collective information-processing in swarms, flocks, hives, and the production of termite cathedrals.
  There is a different sort of collaborative information processing when small numbers of individuals, e.g. a few carnivores hunting grazing mammals, or two humans discussing how to solve a problem.
  here must have been complex communications between internal subsystems long before whole individuals communicated as humans do.

- Additions to verbal/linguistic forms of representation used for thinking, perceiving, communicating, and possibly other purposes. A readable overview document by Bill Woods implicitly (and unintentionally) provides reminders of some of the unobvious types of complexity that might have been added over evolutionary time to language-using capabilities, including transitions that now happen much more quickly during individual language learning/development, supported in some way by genetic meta-competences:

William. A. Woods, Meaning and Links,
AI Magazine, 28, 4, pp. 71--92, 2007, AAAI,
http://www.aaai.org/ojs/index.php/aimagazine/article/viewArticle/2069
See also Chappell and Sloman (2007)

NOTE: not all changes are *extensions* -- some forms of evolution or development may involve *loss of previous capabilities* -- e.g. loss or reduction of ability to learn a new language, as learners get older.

NOTE: Hayek also had ideas about evolutionary transitions expressed in his book
F.A. Hayek, 1952, *The Sensory Order* (available online)
https://www.mises.at/static/literatur/Buch/hayek-the-sensory-order.pdf

For example, he wrote (page 82):
4.13. *It is perhaps worth stressing that the problem of purposive adjustment of organisms to changes arises long before the problem of its purposive behaviour with regard to external objects.*
[E.g. homeostatic control mechanisms come before abilities to think about how to act in an external environment containing enduring objects that continue to exist while not being sensed. (A.S.)]
and later (page 85):
We must probably assume that, in the course of evolution, the original direct connexions between particular stimuli and particular responses are being preserved, but that control mechanisms are being superimposed capable of inhibiting or modifying these direct responses when they are inappropriate in view of other simultaneously acting stimuli.
Note added 29 Dec 2022
This seems to be closely related to the Symbiogenesis theory of Lynn Margulis
Lynn Margulis, *The Symbiotic Planet: A New Look at Evolution*, 1998, Weidenfeld and Nicholson, London
Lynn Margulis and Dorion Sagan, *What is life?*, 1995, Simon and Schuster, New York

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Note on the concepts "Representation" and "Information" used here

There have been many confusions related to usage of the words "representation" and "information". In particular, for some people "information" has its old meaning which allows information received to be true, false, precise, vague, hypothetical, predictive, consistent, inconsistent, entailed by something else, explanatory, confusing, etc.

The concept of "information" used by the Meta-Morphogenesis project is not the technical concept introduced by Claude Shannon in 1948. The older, more familiar non-technical concept of information about something, with content that may be correct or incorrect, and which can be used in formulating questions, forming intentions, controlling actions, forming explanations, making predictions, and helping others, was already familiar to Jane Austen in 1813, as demonstrated in
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/austen-info.html

In that sense information is what is sometimes called "meaning", or "semantic content".

This is completely different from the relatively new usage of the word introduced by Shannon, in 1948, which subsequently confused philosophers, composers, scientists, and many others. In this document I **never** use the word in Shannon's sense.

Moreover, most of the attempts to **define** the older meaning are either erroneous, or circular, or else misleading in various ways. Like many powerful theoretical terms (e.g. "matter", "energy", "gene", "electrical charge", "valence",...) the word "information" cannot be explicitly defined. Rather it is implicitly defined by the theories in which it occurs, which through their structure partially identify a class of models, which can be more precisely identified by adding links with observation and experiment to the theory -- a process I call "theory tethering", not to be confused with the seriously misleading notion of "symbol grounding". The concept of information is discussed more fully in

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A. Sloman, What's information, for an organism or intelligent machine?
     How can a machine or organism mean?,
In, Information and Computation, Eds. G. Dodig-Crnkovic and M. Burgin,
World Scientific, pp.393--438, 2011
http://www.cs.bham.ac.uk/research/projects/cogaff/09.html#905
```

The notion of "representation" is often defined in a very narrow way, e.g. by specifying that only humans, or only conscious users, can create or use or interpret representations, or by assuming that these representations refer only to things or states of affairs. However, scientists, engineers, and many others now use the words "represent", and "representation" much more broadly, in discussing how information is conveyed, stored, expressed, manipulated or used. I use representation in what I think is the broadest widely used sense, to refer to any vehicle, or medium, or bearer of information, whether physical or in a virtual machine (e.g. datastructures in virtual machines can be representations), and whether the information is produced or communicated intentionally or not. E.g. a rock can provide an organism with information about its size, shape, location, material, weight, etc. if the organism has suitable sensory motor apparatus with which to perceive or investigate it, and suitable information-processing mechanisms to make use of the information.

Information and control

The most basic and, biologically most important use of information is for control. Many other uses of information, e.g. to refer, represent, predict, explain, instruct, request, command, question, challenge, hypothesise, imagine, and so on, can be shown to provide potential uses for control. For very simple organisms, the only use of information is for control, e.g. in chemotaxis, or in uses of feedback control. As organisms get more complex, and have more capabilities for internal or external actions, more varieties of information and more uses become possible. That's the topic of the rest of this document, though a **full** discussion of possible varieties and uses of information is not possible here. See also:

A. Sloman, 'The mind as a control system',
in **Philosophy and the Cognitive Sciences**,
Eds. C. Hookway and D. Peterson, pp. 69--110, CUP, 1993,
http://www.cs.bham.ac.uk/research/projects/cogaff/81-95.html#18

A. Sloman,
What enables a machine to understand?,
Proceedings 9th IJCAI, Los Angeles, pp. 995--1001, 1985,
http://www.cs.bham.ac.uk/research/projects/cogaff/81-95.html#4

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Added: 14 Jan 2013
Place holder: roles of information in control
We can distinguish different sorts of functional roles for mechanisms involved in use of information for control, in biological and non-biological systems. Examples:

- sensing some state, or event, or process
- allowing sensory information to trigger a response through direct physical causation, e.g. mouse-trap, Watt-governor, use of wind direction to rotate a windmill to face the wind
- selecting a response to a trigger state on the basis of some other state information (i.e. responses are conditional)
- performing analysis or interpretation or integration of sensed (or sensory-motor) information before allowing response to be triggered
- allowing different connections between response selection and response production, e.g. direct physical causation vs sending an instruction to an effector
- allowing responses to be produced by different effectors (e.g. grasping with hand vs biting, running away vs flying away).
- allowing response to be produced by coordinating different motor subsystems e.g. two hands and mouth when peeling bark off a broken branch
- allowing different sorts of responses meeting different sorts of needs to be integrated (e.g. when hungry and thirsty modify walking route to pass nearer fruit on way to river)
- allowing conditions for selecting responses to be extended and varied
- allowing time of response to be varied (e.g. select action but postpone it)
- allowing urgency, importance, costs, etc. of different selected responses to be compared in selecting when, whether or how to respond,
- allowing a new type of response to be created (e.g. planning of various kinds)
- altering/extending the ontology used for interpreting sensory information
- altering/extending the ontology used for specifying actions and goals
- performing collaborative actions (e.g. pack hunting, swarming, mating, guarding or feeding infants, etc.)
- extending temporal or spatial distance between information being available and information being used, i.e. extending need for various kinds of communication in control systems

(Compare the importance of multi-window perception and multi-window action, as opposed to peep-hole perception and action, in the CogAff framework.)

Many thinkers discussing information processing or computation consider only formal manipulations of structures within some sort of machine, e.g. a Turing machine or computer. This raises questions about how any semantic content can be involved in what the machine does. We can answer those questions by explaining how information can be related to control, whether in organisms or human-made machines. Ian Wright attempts to present and extend these ideas in this slideshare presentation (slides and audio):
http://www.slideshare.net/wrighti/sloman2011-slides

Warning: everyday concepts can be traps causing deep muddles

Many researchers pose questions about evolution or development in terms of everyday language, e.g. When/how/why did consciousness/emotions/thinking/language/tool-use or whatever evolve?

Such uses of everyday language in asking scientific questions can be seriously misleading because the concepts are not based on a deep explanatory theory, and as a result group together things that are superficially similar but deeply different (like sharks and whales, both originally thought of as fish) or treat as different things that have deep commonalities, e.g. use of manufactured tools, like hammers, cutters, spears, and use of kinds of pre-existing matter to perform manipulations on other objects, including the use of body parts.

For example, use of one hand to hold an object that is being peeled by another hand, has deep structural and functional (mathematical) similarities with the use of a space between two rocks to hold something, or use of a manufactured vice to hold the object being manipulated.

Of course, there are also differences, but without understanding how the differences and similarities interact (e.g. providing extra functionality in some cases) it’s possible to miss important cognitive processes.

More subtly, asking questions about whether or when human infants, or other animals, have or acquire concepts like "enduring object", "causation", "false belief", "number", "error", or "emotion", will typically cause researchers to group together processes, competences and mechanisms that are deeply different, or fail to notice similarities between examples that are superficially different, like the similarities between marine mammals and land mammals that were initially not noticed.

Another source of deep traps is the word (or concept) "language". When researchers ask

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    which animals can learn or use a language?
or
    when do children start to use language?
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they nearly all make use of a shallow common-sense notion of "language" as primarily concerned with communication, possibly enhanced by some famous proposal such as that the signs of a language are all arbitrary (totally ignoring the non-arbitrary link between semantic contents and complex signs using a compositional semantics). Many researchers never dream of the possibility that there may be languages that have nothing to do with communication **between** individuals but everything to do with information processing **within** an individual, like a programming language interpreted by a running computer. For more on this see below.

Another example is the ordinary concept "teaching", which some biologists have attempted to apply to animal behaviours often ending up squabbling about what is or is not real teaching. (Compare Nigel Franks on Teaching in tandem-running ants)

Since I have no option but to use ordinary language for most of this project, still in its early stages, I try to specify what I am asking, conjecturing, or proposing by giving examples. But in many cases I am likely to be guilty of the mistakes I have just criticised, and I welcome critical analysis of examples, from the point of view of a designer of working systems, showing that my examples need re-organisation or re-labelling. The ultimate test will be ability to contribute to a broad, deep and precise, explanatory theory that can be applied to both the explanation of natural phenomena and to the construction of working models.

Conjecture: Learn about possibilities before learning about utility
The more complex the organism and the more possible internal and external actions available, the more important it is to explore possibilities and their consequences **before** those explorations have any evident utility. (See the discussion of architecture-based motivation, below.)

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Incomplete preliminary/draft list of transitions

(Starting with microbes -- and growing?)

Below is a very sketchy summary list of examples of transitions in biological information processing in evolution, development, learning, etc., some of which also involve transitions in physical structure or new sensors, many of which are related to changes in the environment, e.g. new problems, challenges, dangers or opportunities. In some cases the transition is initially merely related to acquisition or manipulation of information, without any practical application, though, as the history of mathematics shows repeatedly, such 'useless' changes can later provide the basis for massive practical advances.

[**NB**: the numbering of points below is likely to change, as new items are inserted and old ones rearranged, or merged, or split.]

1. **Ontological changes support changes in information processing**
   [Added 27 Jul 2014]
   Many researchers work on systems that learn. Different sorts of things can be learnt, including abilities of many kinds, and applications of those abilities. Different abilities require different ontologies, and the ontologies used by organisms have changed in many ways during

evolution. I suspect the list of types of change here is only a tiny subset.

Changes in abilities and ontologies include (in no significant order): Ontologies required for learnable abilities including: abilities to label, abilities to describe, abilities to predict, abilities to manipulate directly or to control indirectly, abilities to perform actions of varying complexity and difficulty, abilities to classify, abilities to explain, abilities to evaluate, abilities to appreciate, abilities to plan, abilities to carry out plans, including modifying or extending them during execution, abilities to design things, abilities to make things to satisfy a need, abilities to prove things, make inferences, calculate or reason, abilities to discover things, abilities to communicate (using language or other media), abilities to understand communications, abilities to teach or assist others, abilities to collaborate as leader or subordinate or equal, abilities to empathise, abilities to introspect in various ways, abilities to resolve conflicts, within oneself or between individuals, and many more related abilities.

All those abilities are generic and may have sub-cases that have to be learnt separately, and in some cases the learning can include increasing speed, fluency, reliability and accuracy of performance.

Intelligent abilities require use of knowledge about types of things that can exist or happen, i.e. knowledge of an ontology. A simple homeostatic controller, e.g. a thermostat, may use a very simple ontology perhaps including contents of a form of sensory input (e.g. temperatures) and contents of a form of output e.g. 'raise' or 'lower' signals to a heater or cooler.

Organisms (and future robots) with multiple modes of sensing and acting on a complex independently existing environment need ontologies that straddle modes of perception and action, for instance the ability to express where something is or how it is moving, irrespective of how the object's location is sensed or changed.

If we had a better understanding of how various ontologies used for various purposes in organisms evolved, and how they develop in individuals, we might be better able to design machines with intelligence that matches those of animals, including humans. Instead we can now only produce machines with very shallow and restricted abilities, that often turn out to be very brittle when dealing with novelty. For more on changes in ontologies and associated forms of representation, see:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/simplicity-ontology.html

2. Developing the ability to use information about increase or decrease in osmotic pressure to select a defensive response.

    E. Bremer
    "Synthesis and uptake of compatible solutes as a microbial defence against osmotic and temperature stress",
    http://www.uni-marburg.de/fb17/fachgebiete/mikrobio/mpireport_bremer.pdf

    It is likely that several homeostatic mechanisms developed in the earliest life forms and perhaps their precursors.

3. **Making continuous control more intelligent. [Added 4 Jan 2014]** Since continuous homeostatic control can be more or less intelligent, there are likely to be changes in how control works, during evolution, during development and in some learning processes. For example, someone steering a boat or other vehicle towards a target while changing winds

continuously tend to force a change of direction, may learn patterns in the changing wind and use those to anticipate changes and resist their effects using counteracting forces, including anticipatory control changes. Someone driving a car into a garage may use more or less intelligent variations in accelerations and braking controls so as to get the car close to the rear wall without hitting it and without taking a vary long time.

It seems very likely that during evolution of some species several changes of continuous control mechanisms occur, either directly through alterations in the genome, or indirectly through improved learning mechanisms. However this document is more concerned with intelligent deliberation where control is not continuous. [To be expanded]

4. Getting information about contact with food or something noxious and reacting accordingly e.g. absorbing, rejecting or moving away ("chemotaxis")
5. Developing new physico/chemical sensors or extending the competences of old ones.
6. Getting information that instead of distinguishing good, bad and neutral items, allows more categories to be distinguished and more response options than merely absorb, retreat/repel, ignore, ...
7. Detecting and using information about gradients (e.g. changing concentration of a desired chemical) and using that to select direction of motion.

    (There are very many biological mechanisms that do this, some relatively simple, e.g. phototropism, geotropism, hydrotropism??, others much more complex, e.g. carnivores seeking prey that can move, or animals seeking mates.

    Note that in general change detection requires more complex mechanisms than detection: e.g. it may require storage of previous information to be compared with new information. So puzzlement about change blindness is mis-directed: change detection, not non-detection, is what primarily requires explanation.)

8. Developing various techniques for improving ability to follow gradients, e.g. faster or with greater precision, possibly using newly evolved sensory motor subsystems or merely using old ones more effectively (better information processing).
9. Detecting correlations between sensor values and **immediate** consequences, so that preferences that can drive the above mechanisms change.
10. Detecting correlations between sensor values and **later** consequences, so that preferences that can drive the above mechanisms change. More generally: detecting correlations across temporal gaps.
11. Detecting approach of some good or bad discrete entity, and using the information to control approach or avoidance behaviour.
12. Developing detectors that can operate in parallel with inputs that can be

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-- combined to detect more complex phenomena
-- used to detect unrelated phenomena in parallel, leading
   to possible conflicts in reactions (e.g. choosing what
   to consume, what to avoid).
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13. Progressing from detection of presence or absence of properties to
    - selection from multiple categories (apple, orange, plum, ...),
    - use of ordered categories, e.g.
        - infant, child, teenager, adult, elder, ...,
        - unpleasant, harmful, dangerous, fatal
    - use of ordered (comparable) intervals between ordered categories
    - use of scalar values that can vary continuously (e.g. pressure, temperature, chemical concentration, illumination,...)
    - Use of vectors of values (collections of labels) to describe an entity, e.g. "big, red, heavy, soft, immobile, ..."

    Compare S.S. Stevens' "scales" of measurement (1946).

14. Changes in the reverse direction: from continuous sensing to categorization or discretization. Examples:
    - Developing abilities to chunk portions of a range of variation into different categories, e.g. tiny, small, medium, big, huge, or different degrees of loudness, or different stages in development (infant, toddler, child, youth, adult, elder ...), or perhaps colour categories;
    - Developing abilities to produce "fuzzy chunking" (discretization) of **continuous changes**, e.g. into phases of expansion, contraction, pulsation, translation, rotation (etc.) of some or all of an object or surface.
    - Developing ability to produce "fuzzy chunking" (in L. Zadeh's sense?) of **continuous surfaces**, into sub-surfaces, e.g. bumps, dents, grooves, ridges and other extended surface features that can be straight, curved, wiggly, spiral-shaped, etc.

    Some of these kinds of discretization will be done by individuals separately, while others may depend on developing a consensus among members of a community, and others may result from species differentiation -- producing different ways of dividing a continuum (plants and their pollinators?).

15. Adding relations to the spatial/causal ontology: e.g. in, above, overlapping, between, containing, touching, nearer to, pushes, resists, supports, prevents, ...

    Far more **relations** are important in interacting with a complex environment than **unary predicates**, yet very many writers seem to assume that all or most concept formation is formation of unary concepts (predicates), e.g. straight, square, box, shoe, house, dog, etc. Contrast different ways of generating new concepts:
    - use of ordered collections of simultaneous values (vectors of values)
    - use of structural descriptions involving relationships of many kinds between objects, their parts, their features, their composition, their capabilities, etc.

      Unfortunately current AI students seem not to learn about some of the deep pioneering work done in the late 1960s and early 1970s in which use of structural descriptions, including comparisons of structural descriptions was central, for example the work by T.G. Evans on a geometric analogy program which inspired work by P. Winston on learning structural descriptions from examples, and G.J. Sussman on A

Computational Model of Skill Acquisition, referring to thinking skills, not physical skills (both of which are important in humans and many other species).

- use of forms of representation allowing structural variability, and varying complexity (e.g. lists, trees, graphs, sentences), possibly based on a generative grammar (which could be implicit in the ways certain mechanisms work).
- use of representations of sub-regions in a continuous space of topologically equivalent structures E.g. string, sausage, horseshoe, hook, toroid, sphere, ellipse, bowl, spiral, helix, and many more. (E.g. seeing leaves, petals, sand-dunes or hairless torsos.)

Does anyone know which organisms were first able to detect, represent and make use of relationships?

16. Developing the ability to represent **processes**, again moving through various kinds of complexity: change of value in a set of values, or on a linear scale, or changes of a vector of values, or changes of structures or relationships, or parallel unrelated changes (e.g. two animals moving), or structurally/causally related parallel changes, e.g. two meshed gear wheels rotating or a person pulling a card up a hill, shape changes, e.g. changes of curvature of a portion of surface, ...

17. Developing ability to represent processes under the perceiver’s control.

18. Developing ability to produce "fuzzy chunking" (in L. Zadeh’s sense?) of **continuous surfaces**, into sub-surfaces, e.g. bumps, dents, grooves, ridges and other extended surface features that can be straight, curved, wiggly, spiral-shaped, etc.

19. Developing related abilities to produce "fuzzy chunking" of **continuous changes**, e.g. into phases of expansion, contraction, pulsation, translation, rotation (etc.) of some or all of an object or surface.

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20. Placeholder: **Varieties of information-processing in microbes**
Referred to as cognition in microbes by James Shapiro e.g. in this presentation: here. (**Added**: 27 Nov 2012 - Thanks to John Doyle for the pointer.)

21. Developing abilities to use information to control manipulators e.g. jaws, claws, hands, feet, tusks, tails, etc. (Including moving food into mouth, dis-assembling or breaking food into pieces, removing unwanted portions, moving obstacles, assembling shelters, nests, etc. of ever increasing complexity.)

22. Acquiring abilities to move away from predators or competitors (Walking, crawling, running, climbing, hiding, ...)

23. Acquiring abilities to out-smart predators or competitors Using evolved, automatic responses, or using newly invented plans, strategies, traps, hiding places, etc.

24. Acquiring abilities to perform various actions required for mating. (Wittingly or unwittingly.)

25. Acquiring abilities to perform various actions required for caring for young, or collaborating with conspecifics. (Wittingly or unwittingly.)

26. Acquiring information about extended spatial structures on various scales (compare SLAM techniques in robotics http://en.wikipedia.org/wiki/Simultaneous_localization_and_mapping)

27. Acquiring and using information about environmental contents not accessible by sensory mechanisms (and not definable in terms of sensory-motor statistics, e.g. properties of matter like rigidity, flexibility, elasticity, strength, liquidity, chemical composition, combustibility, ...) e.g. "baby stuff".

28. Acquiring abilities to represent enduring individuals in the environment, including mobile individuals that can interact causally with their environment, and individuals that can endure while not visible. (And later the ability to ask questions about identity of indistinguishable items encountered at different times, or identity of entities whose important features can change, e.g. through growth or injury.)

29. Acquiring and using information about empty regions of space e.g. the passable space between two large rocks, the space into which some object could be moved in order to simplify some task (e.g. standing on it to look over another object), the space out of sight where something wanted might be located. the possible spatial trajectory of an armchair that will not fit through a doorway without a complex 3-D rotation.

30. Acquiring information about possibilities and impossibilities (necessities) (Very many kinds. See papers on toddler theorems, triangle theorems , actual possibilities, and types of affordance.) The ability to represent what can happen but is not happening allows the possibility of puzzlement about why something is or is not happening.

    One of the deep questions related to this is how the differences are represented between
    - X is occurring (e.g. rain is falling);
    - X is occurring but might not have occurred (e.g. rain might not have fallen now);
    - X is not occurring but could occur (e.g. it might have been raining but isn't)

    and similar examples relating to past and future, or different locations (what could or could not happen here and there).

    It is sometimes proposed that such information contents require use of a modal logic, that adds operators such as "possible", "impossible", "necessary" and "contingent" to a formalism for expressing facts. But that presumes that all information is represented propositionally (in a form expressible in sentences), but, for many reasons, including observations about mathematical competences below I suspect the ability to think and reason about counterfactuals uses **architectural** extensions (illustrated by the work of John Barnden and Mark Lee on counterfactuals and ATT-Meta).

31. Going from representing a set of possibilities to discovering some invariant feature of the set -- as in many mathematical discoveries, e.g.
    - http://www.cs.bham.ac.uk/research/projects/cogaff/misc/triangle-theorem.html
    - http://www.cs.bham.ac.uk/research/projects/cogaff/misc/triangle-sum.html

- http://www.cs.bham.ac.uk/research/projects/cogaff/misc/torus.html
- http://www.cs.bham.ac.uk/research/projects/cogaff/misc/knots

32. Acquiring abilities to represent past events and compare them with present events, in various ways, for various purposes.

    Frank Guerin informed me that his three and a half year old son asked at a restaurant "Why didn't we get them last time?" when the restaurant provided wet serviettes for wiping children's hands. This requires
    - the ability to store information about previous events
    - the ability to compare stored and new events,
    - the ability to consider possibilities that have not occurred, and to ask "Why not?" (Mentioned above.)

33. A related example (also connected with the ability to build up information about extended spatial structures): A child was taken for a walk and then when the route taken joined up with an earlier part of the route, he said, with great delight, something like "We came here earlier".

    There are anecdotes about other animals being able to remember past events involving individuals who have helped or harmed them. [REFs needed.]

34. Ability to use mappings between collections of objects, e.g. performing two discrete sequences of actions in step (e.g. touching objects and making a noise for each one, or allocating a portion of food to each nestling). Later versions of this can lead to the concept of cardinal number and then arithmetical operations on numbers, not to be confused with concepts of measures.

    Compare: toddler theorems about numbers and numerosity (often confused by researchers).

35. Ability to use meta-semantic and meta-cognitive information about information and information-users (including oneself).

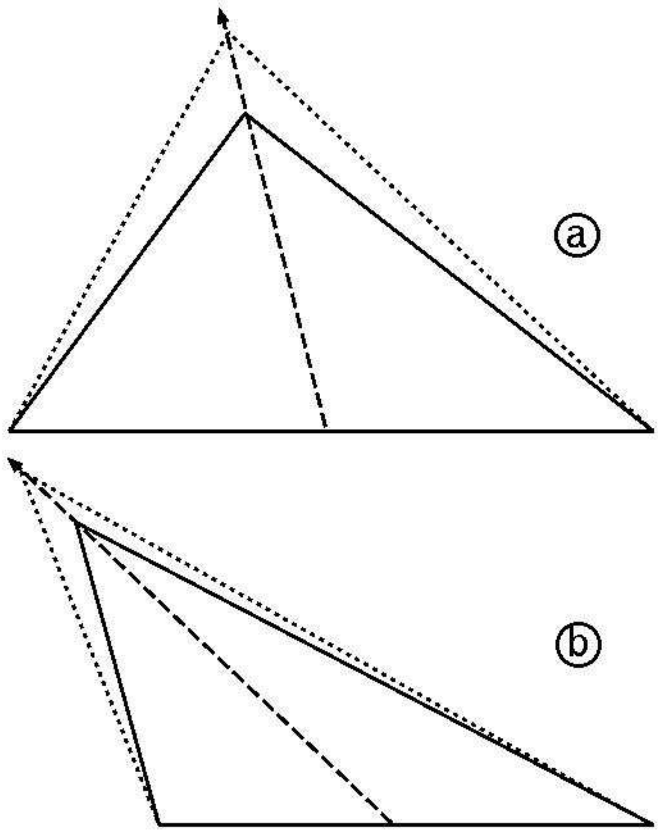
36. Various kinds of self-knowledge, including meta-meta-knowledge

37. Developing abilities to monitor, reason about and control the contents of and causal interactions within virtual machinery (apparently produced by evolution long before human engineers began to understand the need for and uses of virtual machinery with causal powers since mid 20th century). Example: Merlin Donald mentions the importance in humans of voluntary control of access to stored information -- deciding which memories to retrieve in various contexts. This is a special case of the general tendency to evolve more and more flexible and sophisticated forms of access to stored information.

    Some ideas about this are presented in this discussion of the speed, power, and flexibility of human visual processing:
    A Multi-picture Challenge for Theories of Vision
    http://www.cs.bham.ac.uk/research/projects/cogaff/talks/#talk88

38. Developing the particular forms of meta-cognition involved in mathematical discovery.

How do you know that if a vertex of a planar triangle moves along a median away from the opposite face the area of the triangle **must** increase, no matter what the size, shape, orientation, colour or location of the triangle? Compare the two cases (a) and (b) in the figure below? I suggest this uses deep functions of animal vision that have mostly been ignored.



Abilities to perceive and reason about **possibilities** and **constraints** on possibilities in a mathematical context are deeply connected with the ability to perceive and reason about affordances, which must have evolved earlier. This sort of requirement is one among many aspects of cognition that are blindly ignored (as opposed to being temporarily postponed) by most researchers on "embodied" or "enactive" cognition. More examples are e.g. here, here and here. Compare "toddler theorems" about how what’s visible through a doorway to another room changes as you move your location relative to the doorway in various directions.

39. Transitions in functions of biological visual information processing. Most vision researchers seem to think it is obvious what the functions of vision are (e.g. as spelled out by David Marr in 1981). However, as far as humans and similar animals are concerned, the problems of specifying exactly what the functions of visual perception are, how they vary, how they develop in individuals, and how those functional requirements are met by the information processing mechanisms available (e.g. brain mechanisms) remain unsolved problems: which is part of the reason why machine vision is so limited compared with animal vision (including human vision).

For example, I know of no animal whose visual system uses a lens to project light onto a regular rectangular grid of optical sensors, as almost all artificial visual systems do. The physical and functional design features of biological eyes may provide deep clues to the information processing functions and mechanisms of natural vision systems that have largely been ignored.

An overview of some of the functions of vision in humans is under construction here and http://www.cs.bham.ac.uk/research/projects/cogaff/misc/vision

A larger project is to identify major transitions in biological visual information-processing since the earliest forms. I have many online papers and presentations related to functions of vision, and will later attempt to organise them. One way to do that is in terms of the 3x3 CogAff Schema grid, (outlined here), which combines three **columns** of functionality:

- perception,
- central processing, and
- action

and three **layers** of functionality, listed here from the bottom up:

- evolutionarily old reactive mechanisms,
- newer deliberative mechanisms (able to represent and reason about things that are not currently perceived and also possible alternatives to things that are perceived or known to exist
- still newer meta-semantic, meta-cognitive and meta-management mechanisms (able to represent and reason about things that represent and reason, including other agents and oneself.

Many evolutionary and developmental transitions are concerned with either adding new kinds of functionality within these layers or columns, or connecting functionality in different parts of the grid, across columns or layers, to develop more complex systems, e.g. producing social actions (such as smiling, beckoning, teaching, that involve not just the low level motor control system but also meta-semantic competences generating intentions and actions, and visually interpreting actions and responses of other agents.

Because of the nature of this grid there are many possible sequences in which particular competences can be added by evolutionary and developmental processes.

Although the CogAff grid/schema provides a useful framework for thinking about design alternatives it must be considered as a very crude approximation, especially the obviously inadequate implication that there are only 9 major subdivisions among types of information processing.

40. **Place holder: (14 Jan 2013, revised 2 Nov 2014)**
Transitions related to Arnold Trehub's ideas.
Several features of human information processing, especially visual information processing, that are not widely acknowledged are discussed in Arnold Trehub's 1991 book **The Cognitive Brain**, now online here with related papers http://www.people.umass.edu/trehub/.

In particular, he attempts to explain how human vision (and presumably also vision in some other animals), can use the information sent to the primary visual cortex which is constantly changing because of saccades and other eye movements as well as head movements and movements of the whole body. His "retinoid" theory proposes a constantly changing mapping between the retinal information in V1 and the enduring information structure that encodes what is seen.

I would summarise this by saying that instead of regarding F1 as the first level of visual processing in the usual manner, we should regard it as an extension of the hardware evolved for collecting visual information (collecting photons).

It is part of a "sampling" mechanism for rapidly sampling different portions of the *optic array* (Gibson), using saccades, with the samples immediately "forwarded" to several other subsystems for further processing and for absorption into various enduring information structures holding different sorts of information about contents of the environment, not contents of retinal stimulation -- which would be of far less importance to many subsystems in an intelligent animal or machine. Since the main sampling is done by the high resolution fovea, and the fovea will not find any gaps in the optic array, the other subsystems do not obtain information about gaps that one might suppose the "blind spot" on the retina would produce.

A corollary is that theories that associate contents of self-consciousness (contents of visual self-awareness) with contents of V1 (in humans) may be completely misguided, since useful meta-cognitive mechanisms for inspecting current contents of visual processing will normally need to know now what the raw, unprocessed data are, but what various results of intermediate data are. (Compare the sort of visual self-awareness needed by a good artist drawing or painting realistic pictures.)

Whether all the details are correct (including Trehub's proposal that information is stored in regular grid structures, which I doubt) a theory of that general sort has several merits in addition to explaining why no "blind spot" is perceived, even during monocular vision. There are still many unanswered questions about forms of representation used and types of processing associated with various aspects of visual intelligence.

We may be in a better position to answer them after the meta-morphogenesis project has uncovered many more intermediate stages in the evolution of current animal vision systems. [REF DISCUSSION PAPER IN PREPARATION]

41. Place holder: Transitions involving "Alarm" mechanisms. (Discussed in Cogaff papers, including mechanisms concerned with the five "F"'s: feeding, fighting, fleeing, reproduction and freezing -- often omitted from the list).

42. Transitions towards binocular visual perception. One of the wonders of biological evolution is both the diversity of evolved designs for eyes and also the way certain design features (e.g. use of lenses) evolved independently more than once (briefly summarised in http://en.wikipedia.org/wiki/Evolution_of_the_eye).

    Much is known about physical, chemical, and morphological aspects of many kinds of eyes, and also about their functions, which typically depend on the needs of the organism, its optical sensor morphology, the features of the environment (including available food, predators, mate-features), the actions of which the organism is capable, and the available types of information processing mechanism.

Several animals have two or more eyes, and in some cases these seem to operate as independent sensors. But humans, and various other animals, including primates, hunting mammals, and many birds seem to be able to use two eyes pointing roughly in the same direction to drive two collaborating streams of information processing to compute distances of perceived objects by triangulation.

Unfortunately, Julesz and others discovered that humans are able to see 3-D structures in random dot stereograms, and this led many researchers to assume that the methods required for doing that, by first finding low level correspondences in the images, are used for all stereo vision. However, most natural scenes do not produce random dot patterns on the retina, and it is easy to confirm that a great deal of 3-D structure can be seen monocularly (e.g. try wearing an eye-shield for a few hours). So it is at least possible that animal systems use the results of monocular perception to identify corresponding locations in the left and right percepts and use those correspondences to perform triangulation. I offer this merely as an illustration of how easily an experimental discovery leading to a large tranche of computational modelling can distract research attention away from an important biological function.

Conjecture: binocular depth perception first occurred as a transition from monocular perception that made use of monocular structure to find corresponding items in left and right visual fields to use for triangulation. Later, additional mechanisms evolved to deal with cases like textured surfaces or sand dunes, where the monocular percepts do not provide sharp points of comparison. Normally the two mechanisms function in parallel. If this conjecture is correct it could lead to much improved stereo vision systems in robots, primarily using the results of monocular vision. (Perhaps that has already been done.)

Some references on evolution of binocular vision (Added 2 Nov 2014)
Wilfred Harris (1953) Evolution of Binocular and Stereoscopic Vision in Man and Other Animals *Br Med J.* Aug 8, 1953; 2(4831): 297-301. PMCID: PMC2029017
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2029017/

Pettigrew JD (1986) Evolution of binocular vision. *Visual Neuroscience* (Sanderson KJ, Levick WR, eds.), pp 208-222. Cambridge, UK: Cambridge University Press.
http://www.uq.edu.au/nuq/jack/BinocVisEvol.pdf

Andrew N. Iwaniuk Peter L. Hurd (2005) The Evolution of Cerebrotypes in Birds Brain Behav Evol 2005;65:215-230 DOI: 10.1159/000084313
http://www.psych.ualberta.ca/~phurd/papers/BBE_05.pdf

43. Place holder: Issues related to representation of shape and affordances
It is often assumed that perception of a 3-D configuration of objects requires either or both of isolation and labelling of image regions corresponding to different object-types (recognition) and construction of an internal model of the portion of the 3-D environment currently perceived.

Both of these miss the requirement to identify 3-D features of shapes that may or may not be visible from all views, and which may or may not be relevant to possible uses and behaviours of the object, and may take account of various combinations of topological properties of the objects, metrical properties of the object, qualitative semi-metrical properties, e.g. constancy, increase or decrease of curvature of part of a surface, or "phase transitions" in orientation or curvature, e.g.

regions where curvature changes from concave to convex or vice versa, regions where curvature is constant, and many more.

--

a) In what ways can the objects be grouped perceptually?
   -- As regards spatial structure (topological, metrical)
   -- As regards kinds of curvature change in various parts
   -- As regard planes and axes of symmetry
   -- As regards optical properties of the material
   -- As regards height above the supporting surface
   -- As regards distance from the viewer
   -- As regards surface markings
   -- As regards affordances (possible uses, possible actions: e.g. graspability by viewer's left or right hand, use for pouring contents into a narrow container, use for drinking out of, ...)
b) Which objects have been moved between the two photographs, and in what ways?
c) How have the viewpoint and viewing direction changed?
d) In the scene depicted on the right, which objects would be easier to pick up with the viewer's left hand and which would be easier with the right?

When can a typical human infant use vision to take in the information required to answer such questions? Which other species can do it? What forms of representation and capabilities had to evolve to make such tasks possible?

44. Place holder: Issues related to acquiring and representing information about spatial layouts. How were organisms first able to learn about an enduring spatial configuration of resources, obstacles and dangers, only a tiny fragment of which can be sensed at any one time? What changes occurred to meet that need?
    - Use of "external memories" (e.g. stigmergy)
    - Use of "internal memories" (various kinds of "cognitive maps")
    - Use of "social memories" (collaborative route finding and following)

45. Place holder: Issues related to representation of space -- (metrics vs semi-metrically enhanced partial orderings). Sophisticated animals can make use of information about spatial structures, sizes, shapes, relationships, part-whole structures, orientation, location, relative distances, motions, effects on motions (e.g. obstructing, diverting, etc.).

    Many mathematically well educated researchers assume that animals (and intelligent machines) must express all those spatial properties and relationships using an ontology that assumes an all encompassing space, with global metrics for length, area, volume, curvature, orientation, angle, etc.

    However, it is far from obvious that many animals (or any animals) can do that, and moreover there are many unsolved problems about how to derive such information from visual and other sensor data. Perhaps that is a poor analysis of the problems evolution and its products solved.

    For various reasons, to be explained later, I suspect that the ability to think about, make use of, or acquire information expressed in terms of such global metrics, e.g. using a global cartesian coordinate frame, or a global polar coordinate frame, is a very late, relatively sophisticated achievement (only developed in 1637 and thereafter by Descartes, Fermat, and their successors -- without which Newton's mechanics would have been impossible).

    An alternative ontology might instead make use of collections of spatial and topological relationships between objects, and object parts, where the relationships could be binary, ternary, etc., with **partial orderings** of size, area, volume, angle, distance, direction, straightness, curvature, regularity, where some of the relationships are detected and represented in far more detail than others, e.g. relationships between objects or surfaces (including surfaces of manipulators) in the immediate environment, or relationships between objects on which actions are being, or are intended to be performed. A network of partial orderings of size, distance, could be enhanced by semi-metrical relationships, e.g. A is longer than B, and the difference is more than three times and less than four times the length of B. If B is a pace for a walking animal that could be relevant to choosing routes for walking. Different kinds of information about partial orderings might be relevant to grasping and manipulating objects in the immediate environment.

    There's lots more to be said about the alternatives, their biological uses, their evolution, their development in individuals, the forms of representation used, the forms of reasoning, their roles in perception of different sorts (visual, haptic, auditory, or multi-modal perception, or a-modal reasoning), and about how organisms differ. E.g most of this would be impossible for microbes.

I suspect this ability to perceive and reason about semi-metrical partial orderings is part of what accounts for the early discoveries leading to Euclidean geometry, including the examples summarised here, and that in humans many transitions in representation of spatial structures, relationships, processes and interactions occur in the first few years of life that have not been noticed or studied by developmental psychologists. (Though Piaget seems to have thought about some of them.) They also have not been noticed by roboticists, especially 'enactivist' roboticists who focus mainly on online intelligence ignoring offline intelligence, briefly mentioned below.

46. Place holder: Issues related to use of matter to manipulate matter. ("Tool use" is a special case of this.) There are many kinds of affordance, perceptual competences, planning competences, plan-execution competences, action control competences (e.g. servo-control), and representational competences related to the use of one piece of matter (whether part of the body or something else) to manipulate or constrain the possible motion of another piece of matter. Most of such competences found in many animals are far beyond the competences of current robots. Unfortunately asking questions about which animals, or which infants, show tool-use can divert research attention from deeper questions about those common matter-manipulation competences.

    Too often researchers think that what they do effortlessly needs no explanation -- so they look for explanations of failures (e.g. change blindness, lack of "conservation", etc.) instead of *first* looking for explanations of successes, without which it is impossible to construct explanations of what goes wrong.

    Some examples of matter-manipulation competences:
    - Sample grasping scenarios
    - Orthogonal Recombinable Competences Acquired by Altricial Species

47. Place holder: Issues related to evolution of different kinds of visual architectures, including pipe-line architectures, and architectures supporting concurrent multi-layer, multi-functional, visual contents, with mechanisms for rapid reorganisation (possibly using constraint propagation), illustrated here and here.

48. Place holder: Issues related to the speed, variety, and complexity of multi-level perception. Some examples are in chapter 9 of *The Computer Revolution in Philosophy* and here.

49. Place holder: Issues related to transformations from procedural/implicit to declarative/explicit information. Many AI programmers and others have found from experience that a program structure that works can often be made more general and more efficient if in the instructions are repackaged in a different way, allowing more decisions to be taken at run time on the basis of what has been learnt so far by the running program, instead of the programmer trying to work out an optimal strategy to cover all cases. For example, a program may search for a solution by constantly trying ways of extending partial solutions, then "backtracking" to previous "choice points" on encountering dead ends, where the ordering of choices is determined in advance by the programmer. Instead the program could be restructured so that it does some preliminary investigations of options and their strengths and weaknesses (e.g. peeking over a wall to gain information before deciding whether to follow the wall to the left or to the right.

I suspect that biological evolution changed the information processing architectures of some organisms so as to allow more intelligent 'look ahead' to guide choices, or to allow different exploration strategies to be selected explicitly on the basis of information available instead of being 'hard-wired' in search strategies.

Such transitions have happened many times in the history of programming language development. An example was the transition from the Planner AI language to the Conniver language at MIT in the early 1970s.
[Ref Sussman and McDermott, 1972

There are other transitions where failures discovered during a search process can be found to be detectable at an earlier stage, an example being the process of "compiling critics" modelled in Sussman's Hacker program [[REF]].
Compare recording 'ill-formed' substrings during parsing to constrain future search, and the development of 'caching' mechanisms, mentioned below.
[[Other examples of transitions from cognition to meta-cognition needed.]]

Finding out when such transitions occurred in evolution will be much harder. Some cases of occurrence in individuals may turn out to be examples of what Karmiloff-Smith refers to as "Representational Re-description" in Beyond Modularity (1992)

Conjecture: There are MANY more transitions made explicitly by programming language designers that are analogous to transitions made implicitly in changes of biological information processing.

50. Place holder: transitions from individual to collective or collaborative actions. This can include swarming, flocking, foraging, migrating as a herd.

    - **Collective** behaviours: the individuals merely react to what is happening in their environment, including what conspecifics are doing.
    - **Collaborative** behaviours: the individuals share goals and deliberatively make use of what others are and are not doing in controlling their own behaviour so as to achieve the goals.

    There are probably many different intermediate cases, and overlapping cases, with both features.

51. Place holder: Issues related to altricial precocial tradeoffs, e.g. discussed in this paper.

52. Place holder: Issues related to transitions from Humean to Kantian understanding of causation. I.e. from being able to use correlations to understanding underlying mechanisms See these presentations (with Jackie Chappell), from a workshop in 2007:

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http://www.cs.bham.ac.uk/research/projects/cogaff/talks/wonac
    1. Evolution of two ways of understanding causation:
       Humean and Kantian. (PDF),
    2. Understanding causation: the practicalities
    3. Causal competences of many kinds
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53. Place holder: Issues related to Annette Karmiloff-Smith's notion of types of "Representational redescription" discussed here.

54. Place holder: Issues related to distinctions between architectural layers and types of deliberative competence, as discussed here.

55. Place holder: Issues related to evolution and development of different kinds of motivation, e.g. reward-based and architecture-based motivation discussed here.

56. Place holder: More complex issues concerned with various types of motive generator, motive comparator, and varieties of meta-management. [Refs; Beaudoin, Sloman, Simon and others.]

57. Place holder: Motivations and competences related to things enjoyed It's very likely that simplest organisms merely do certain things and attempt to avoid other things. But they do not have an information processing architecture that supports states and processes involved in liking, enjoying, disliking, wanting to prevent, etc. I suspect those all require information processing architectures supporting concurrent processes in which some are concerned with managing, monitoring, comparing, initiating, preventing, taking decisions about others, including some management of the management processes (called Meta-Management by Luc Beaudoin in his PhD thesis (1994)).

    These mechanisms, and related mechanisms involving architecture-based motivation discussed above, are probably deeply involved in the later development of processes involving aesthetic enjoyment -- creating, observing, taking part in processes and structures that do not necessarily directly serve any obviously biological need, e.g. some of the play in young mammals. [Much more needs to be said about this.]

58. Place holder: Evolutionary issues related to muddles about consciousness, qualia, emergence, downward causation, the explanatory gap, and the evolution of self-monitoring self-modifying virtual machinery, discussed here.

59. Place holder: Issues related to differences between "online" and "offline" intelligence, e.g. servo-control vs deliberating, planning, explaining, or describing.

    For example, servo control can make use of physical/mechanical compliance (as in use of padded skin, or physically compliant manipulators) or **virtual compliance** e.g. allowing perceived/sensed changes in relationships and in forces to affect changes in applied forces, where the perceptual component could be haptic/tactile, kinaesthetic or visual. See http://www.cs.bham.ac.uk/research/projects/cogaff/misc/information-based-control.html

    Such advances in *online* intelligence do not necessarily provided advances in *offline* intelligence, e.g. the ability to think about the past, or future, or what might have happened under different conditions.

    Varieties of deliberation are discussed here.

    Many products of robotic research show very impressive online intelligence without any offline intelligence, e.g. the amazing BigDog robot built by Boston Dynamics.

See also this discussion of some of Karen Adolph’s work on young children: http://tinyurl.com/CogMisc/online-and-offline-creativity.html

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Note (modified 25 Nov 2012):
  Serious muddles about ventral and dorsal "streams" of visual processing arise
  from failure to understand the different information processing requirements for
  (a) servo-control based on transient, constantly changing (mostly scalar?)
      information, and
  (b) acquiring and storing information for possible multiple uses at different
      times, including describing, planning, answering questions, etc.

  Referring to these as "where" and "what" functions betrays a deep but common
  failure to understand requirements for working systems of different sorts. The
  more recent replacement of these labels with the labels "action" and "perception"
  betray a failure to appreciate the variety of functions of perception, including
  its role in online intelligence.
  See On designing a visual system
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60. Place holder: Transitions in brain functionality from control of behaviour to many other functions -- including counterfactual-metacognition. This is closely related to the previous point.

    Examples: a robot, like Boston Dynamics’ BigDog produces very impressive behaviours. But it does not know what it has done, what it will do, what it hasn’t done but could have done, why it did the one and not the other, what would have happened if it had selected a different option, what options might be available in a few seconds time, what the consequences of those various options are, and many more.

    Many questions need to be answered: What sorts of evolutionary transitions led to such counterfactual-metacognitive capabilities in humans? Which other animals have them? At what stage do they develop in children, and how?

    How does all that relate to the "proto-mathematical" ability to look at a triangle and ask what would happen to the area if one of the vertices moved relative to the opposite side, as illustrated here?

    Note: there is much more to be said about "offline intelligence" and how almost all the research inspired by a concern with embodiment, dynamical systems, enactivism (etc.) fails to address some of the deepest aspects of biological intelligence (a recurring theme here).

61. Place holder: Issues related to evolution of language, especially the importance of uses of generalised (internal) languages (GLs) for **internal** purposes, such as expressing the contents of perception, intentions, plans, puzzles, questions, spatial structures, etc., and the likely evolution of sign languages before spoken languages as argued here. Many theories of language evolution and/or development ignore the fact that a prerequisite of communication is having something to communicate, which requires some non-communicative information bearer (form of representation) **before** the development of uses of language for communication.

    So the ordinary concept of "language" like the ordinary concept of "tool-use" does not pick out a well defined scientifically useful class of phenomena, and diverts attention away from deep similarities between things for which we do not use the same label in ordinary speech. (Compare the unobvious similarity between graphite and diamond.)

Infinite competence behind finite performances. (Inserted: 22 Jun 2014) A feature common to both (a) human languages (spoken, signed, or written) and (b) internal forms of representation required for percepts, goals, preferences, plans, questions, puzzles, explanations, ... including some of the contents of non-human animal minds, is that a type of form of representation is required that allows

(i) structural variation in what is represented,
(ii) variation in complexity of what is represented,
(iii) no fixed limits on the complexity that can be accommodated,
(iv) some sort of compositional semantics insofar as the content represented in a complex structure is systematically related to the contents of the parts of the structure and the current context.

Condition (iv) is essential for coping with structural novelty, e.g. perceiving, or thinking about, or intending to construct, something never previously encountered. If everything perceived, intended, hypothesised, explained, or predicted could be adequately represented by a collection of N scalar measures then all variability would be accommodated by the possible set of values those measures. But many animals evolved abilities to cope with environments in which objects, processes, and actions exist with much more complex forms of variation, including structural variation (illustrated by the variety of plant and animal forms and the variety of ways in which different collections of plants, animals, non-living matter can be assembled and interact -- for instance the variety of processes involved in assembling a nest from twigs, or weaving a nest from leaves).

An observation due to Chomsky half a century ago (although he did not express it like this) is that any economical solution to the problem of being able to cope with the kinds of variation that can occur in human experiences will have the potential to cope with infinite variation. We now know that infinite potential (or competence) can exist in a computer, for example insofar as it includes and can execute a recursive definition of the factorial of a number) despite it having performance limits due to memory limits, or memory addressing limits. Those performance limits can co-exist with the infinite competence in the factorial procedure, which works in principle for any integer input, no matter how large. How biological information processing systems actually implement that infinite competence is an empirical question. How many forms of solution to that problem and by what evolutionary pathways is a problem for the M-M project.

Eventually a deep theory of evolution of forms of information processing will need to account for the various intermediate stages that can occur, both in evolution and in individual development, both in humans and in other intelligent species. A particular requirement that follows from (iii) is that no matter what the size limits of individual brains, the organisms need forms of representation and mechanisms of operation, that in principle have infinite generative competence. As Chomsky noticed in connection with human languages, actual performance may be limited by various aspects of the implementation.

Some of the issues are discussed in connection with human language in
http://ling.auf.net/lingbuzz/001611
Ian Roberts, 2009,
The Mystery of the Overlooked Discipline: Modern Syntactic Theory
and Cognitive Science,

Unfortunately, most linguists who understand this point don’t seem to realise that it is a special case of requirements for animal intelligence encountered long before the evolution of human intelligence and human language. See also Chappell and Sloman (2007)

Immanuel Kant had similar ideas in relation to human mathematical competences.

62. Place holder: Transitions from Computing to Caching (storing useful results for future use) There are many aspects of human intelligence that depend on having memorised things that could in principle be worked out when required. Familiar examples include results of addition and multiplication of numbers. A great deal of numerical thinking would be very seriously hampered if only the basic principles were stored and results computed whenever required. Playing frequently used sequences of notes on a piano from memory (e.g. learnt scales, arpeggios, etc.), and many other types of physical behaviour are examples of different sorts. Frequently used phrases may be stored as if they were parts of the vocabulary (referred to by Joe Becker as ’The Phrasal Lexicon’ in 1975) also illustrate this.

    Sometimes educational policies that try to emphasise ’understanding’ at the expense of ’memorising’ miss an extremely important function of memorising as an aid to altering the level of complexity of what the learner can understand.

    Presumably there was some sort of evolutionary transition between being able to work out plans or solutions to problems and having mechanisms for storing results of such computations for future use.

    A closely related, but more subtle development is the ability to remember discoveries about what does not work, so as to reduce the risk of following false trails in planning, reasoning, designing, doing mathematical reasoning, etc. Compare the work of Sussman on ’compiling’ critics mentioned above.

63. Place holder: From caching specifics to caching Patterns A store of learnt useful information about what does and what does not work may contain only specific instances to be re-used or avoided. A more powerful capability could replace instances with generic patterns that cover a wider range of cases. That requires development of a form of representation for expressing patterns in a usable form, and suitable mechanisms for detecting when new cases match a stored pattern.

    Transitions of this sort occurred several times during the development of programming languages in the 20th century. A tutorial introduction to use of patterns in programs manipulating list structures is here.

64. Place holder: From Patterns to Grammars Atomic labels are not rich enough to express structural features. Patterns can express some structural features. Use of grammars can express features of unbounded complexity and great variability as in goals, plans, descriptions of perceived items, beliefs, etc.

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    Grammars can be used not only for linear structures, like sentences, but also
    for things like networks. Some of the early AI research in vision (in the 1960s)
    made use of "web-grammars", i.e. grammars for networks or graph-structures, to
    express the contents of visual percepts.
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    Many researchers seem to assume that grammars are relevant only to languages used for communication, ignoring requirements for *internal* information processing in animals and machines.

65. Place holder: Precocial to Altricial transitions Most species have most of their behavioural and information processing competences specified genetically (pre-configured), possibly enhanced with some adaptive mechanisms that allow a generic specification to be tailored to the details of the individual's morphology and environment.

    For more complex species, evolution seems to have "discovered" the advantages, especially as life-spans increase, of more powerful ways of enhancing the genetically specified design, to cope better with threats, opportunities and constraints in each individual's environment, i.e. replacing pre-configured with meta-configured competences.

    In some cases, e.g. in humans and some other altricial species, evolution also seems to have discovered the advantages of not only slowing down physical development while information processing mechanisms adapt to each individual's circumstances, but also *staggering the onset of various kinds of later learning* that build on the products of earlier learning: delayed activation of a meta-cognitive learning mechanism allows it to start looking for patterns in what "lower order" mechanisms have discovered when the patterns are richer and more stable, instead of wasting effort analysing patterns that are spurious, because based on too few instances and tests. This may be specially important in cases where learning cannot easily be undone. These ideas are developed in a little more detail in Chappell and Sloman (2007).

    These are crude analyses: far more details, based on far more examples, are needed.

66. Place holder: Issues related to meta-semantic competences Semantic competences are concerned with abilities to acquire, manipulate, transform, use, information: what this document is all about. Meta-semantic competences are concerned with abilities to use information about information, about information bearers, about information uses, about information manipulation (e.g. inference, reasoning, planning).

    All living things have semantic competences insofar as they can use any information at all, whether with external or purely internal referents. A subset seem to have meta-semantic competences regarding themselves or others. These competences may be genetically fixed for some species and in others may develop under multiple influences (meta-configured competences, mentioned above). In humans many kinds of social/cultural education, and in some cases therapy can enhance meta-semantic competences, whether self-directed or other-directed (e.g. getting better at telling whether your actions are upsetting someone).

    Human infants (and perhaps the young of some other species) need to develop a variety of meta-semantic competences, some self-directed some other-directed, some combined with counterfactual reasoning (e.g. "what could I have done differently?", "How would A have responded if I had not done X?", "Can A see this part of X?", "Can A tell what I can see?", "What does A think B did?"). Psychologists have used the label "mind-reading" for this sort of capability, but mostly restricted it to a small set of competences involved in working out what another believes or thinks, especially in situations where they don't have up to date evidence. This is just one of many cases where a fashion for a particular kind of research has spread because it is easy to vary experimental details, without ever thinking about the kinds of mechanisms required to make any of the competences involved possible at all.

For example, meta-semantic competence requires an architecture that supports referential opacity as well as referential transparency -- the usual default. Referential transparency refers to properties of representations where replacing item A in a larger representation referring to object O with item B also referring to O makes no difference to what is represented by the whole structure, and whether it is true or false. For example, if Fred is chairman of the club, then if it’s true that the chairman of the club is a cricketer, then it is also true that Fred is a cricketer. But in a referentially opaque context, e.g. "Joe believes that the chairman of the club is a cricketer" replacing "the chairman of the club" with "Fred" can turn a true statement into a false one, or vice versa.

Some researchers favour trying to model such effects by extending the language used with a new operator (e.g. "believes that") and modifying normal inference rules. I suspect that what is really needed is a change in the architecture, to support a separation between information structures accepted as true (beliefs) and the information structures that represent possibilities that are not accepted. This is essential for planning, and for perception of affordances.

67. **Added 8 Nov 2014** Place holder: The development of logical reasoning. Because of the way logic is often taught to philosophy students, using natural deduction systems in which operators, like **NOT**, **AND** and **OR** are introduced by rules, such as introduction rules and elimination rules, the misconception seems to be widespread that logical reasoning depends on abilities to follow such rules. I think it would be better if propositional logic were taught using truth-tables and intuitions about validity were used to justify the truth tables (at least for the above three operators - **IF ... THEN ...** is more complex). But the a child does not need to learn the truth tables in order to make logical inferences. If he sees that John is in the kitchen and sees that Mary is in the pantry then he can use that as a basis for answering a question about their whereabouts by saying

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"John is in the kitchen and Mary is in the pantry"
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Moreover if he is in a corridor looking for his mother and shouts "Where are you?" and hears an answer from the end of the corridor "I’m here" then he knows she is either in the kitchen or in the pantry because those are the only two rooms leading off the end of the corridor and he can see that she is not in the corridor. If he then goes and looks in the kitchen, and finds that she is not there, he correctly infers that she is in the pantry. In order to do that he does not need to follow some rule:

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P or Q
Not-P

Therefore Q
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Rather he merely needs to reason that as there were only two possible locations and one is ruled out the other one is the correct one. He may use the word "must" to express this "She must be in the kitchen". That is the "must" of logical necessity, but it doesn’t come from a rule -- it comes from constraints linking the alternatives and the observed facts in this situation. The rule may later be formulated as a generalisation of the inferences made in such situations. But the articulated rule need not be involved in understanding the necessity that makes the inference valid.

A. Sloman, 1968/9, Explaining Logical Necessity,
Proceedings of the Aristotelian Society, 69, pp. 33--50,
http://www.cs.bham.ac.uk/research/projects/cogaff/07.html#712

68. Place holder: The Baldwin effect and its inverse/reverse The Baldwin effect (discussed critically by David Papineau here) refers to useful competences that start off being learnt by individuals, and, as a side effect, certain genetic changes providing those competences become selected for. This could speed up the availability of the competence in individuals, for example.

    A reverse process seems to me to be far more common and far more important: some feature or competence is produced in members of a species by natural selection. Then later, because the genetically-specified competence is too specific to be useful in enough different situations, the competence may be split into some general framework, provided by the genome, and context-specific details acquired by some sort of adaptation to the details of the environment. (E.g. locomotion that evolved for relatively flat terrain might be replaced by a general competence to acquire locomotion suited to the individual's environment, which may be rocky, or on a mountain slope, etc.

    In some cases this could lead to an inherited group of partly similar competences being split into a number of inherited sub-competences that can be combined in different ways, using learning mechanisms to find the combinations that are useful for an individual's environment. (EXAMPLES NEEDED. REF Deacon?).

    In more sophisticated cases, instead of learning (e.g. by experimentally finding out what works), a process of creative problem-solving or planning may enable individuals to *work out* new ways of combining fragments of old (learnt or inherited) competences. This could have the effect that parts of the genome specifying a particular combination of competences might become redundant because individuals who need that combination can synthesise it through planning or learning, when needed, and perhaps synthesise a combination better tailored to the particular environment than the previously evolved version.
    NOTE:
    This is an extension of Kenneth Craik's idea, in Craik (1943), that being able to "run" internal models of parts of the environment to find out the consequences of certain actions could save time, effort, injury, and even life). However, it is not clear that Craik had worked out the full implications of use of internal models, including their role in exploring what is possible and what is impossible.

    In particular, running a model could not in general prove that something is impossible. And while running a model could show that particular values of variables are possible, more than running is required in order to partition possible and impossible sets of configurations. Likewise running a model cannot show that some relationship necessarily holds. E.g. exploring a variety of particular triangles by deforming triangular shapes cannot show that the internal angles of a (planar) triangle will necessarily always sum to half a rotation (180 degrees). For more on this see: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/impossible.html

69. Place holder: Transitions in biological information-processing architectures There are evolutionary transitions, developmental transitions, learning transitions, social transitions, cultural transitions, transitions in sets of requirements (niches) as well as transitions in designs for meeting those requirements. A particular set of transitions concerns changes in the information processing architecture and the requirements they meet or fail to meet (transitions/trajectories in design space and niche space). Some ways of thinking about spaces of architectures and transitions in architectural designs are in the Cognition and Affect papers, e.g. the overview.

70. Place holder: Transitions in fitness criteria Closely related to the previous points, and to tradeoffs, below.

71. Place holder: Major tradeoffs, in evolution, learning, development, etc. A well known example is the R/k tradeoff between quality of offspring and number of offspring. How many tradeoffs are there in relation to designs/options for information processing in various kinds of organism. (A few are mentioned elsewhere in this document.)

72. Place holder: forms of evolution involving the "extended phenotype" (Dawkins)

73. Place holder: forms of evolution involving the "extended genotype"
(Ron Chrisley, in conversation circa 2001, unpublished)

74. Place holder: Co-evolution of multiple interacting designs and niches A niche is best viewed not as a physical environment, but as a collection of requirements against which designs (and their instances) are evaluated, e.g. regarding ability to compete, survive and reproduce, since a mouse and a midge have very different niches even when they are physically very close together. As organisms modify their designs, or their environments they alter the niches for other organisms, which may as a result modify their designs, producing changing networks of mutual influences generating interacting trajectories in "design space" and "niche space".

75. **Reproduction-related and metabolism-related (brainless) information-processing**

    This covers a vast mixture of types of process, mechanism, form of representation, information content, and uses of information, on many scales, for many purposes.

    The vast majority of successful organisms on this planet, whether measured by individual numbers, variety of species, or biomass, **lack brains**. Brainless organisms provide both the base of food pyramids for others, and in some cases essential forms of symbiosis (e.g. bacteria in the human gut.) Lacking brains does not stop them processing information, e.g. in controlling their reactions to their immediate environment and internal processes, including reproduction and growth.

    Even in organisms that have brains there is a vast amount of sub-organism control (including homeostasis) and learning (adaptation) that does not use brain mechanisms, e.g. in metabolism, reproduction, growth, brain development, immune reactions, and many more -- but I suspect that only a tiny subset has so far been identified.

    The majority of such cases, and certainly all the earliest cases, historically and developmentally, seem to rest on molecular information-processing, for example processes required for building brains, which, at least initially cannot use brains, though later on in life that can change in various ways as discussed briefly in [*].

76. Place holder: Changes in uses of information to enable and control different sorts of development of an embryo -- epigenetic information processing.

77. Place holder: Changes in use of information in immune systems and other defensive control mechanisms.

78. **Changes in sources of information**

It is commonplace to ask how the physical changes (e.g. construction of new complex molecules, or changes in the availability of oxygen) occurred.

But it is also important to ask "Where does all the information come from?" -- e.g. the information specifying complex organisms used in their reproduction.

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Compare Paul Davies,
The Fifth Miracle: The Search for the Origin and
    Meaning of Life, 1999
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We should not assume the information all came in one large dollop when the earth was formed, or when the universe was formed: for it is possible that the structure of matter and the space it occupies provides a platform for certain kinds of interactions and (positive and negative) feedback loops to create novel information (not in Shannon's sense, but in the sense of content that refers).

Exactly what information emerges may not be totally determined in the initial state, if some of the interactions leading to new physical structures and new types of information processing are physically unpredictable.

Another possibility is that external perturbations (e.g. asteroid impacts, changes in radiation reaching the planet, could significantly alter the environment in which already evolved organisms continue evolving -- including changing the physical properties of the environment or eliminating or reducing other relevant species, e.g. prey or predators.

The latter would be a special case of a process that happens continually, namely the environment for any species can be changed as a result of evolutionary changes in other species in that environment, including prey (food), predators, parasites, symbiants, etc.

79. **Place holder: changes in information processing mechanisms used for reproduction**
(Wild speculation?)
As methods of reproduction changed, the information processing requirements and opportunities changed. Here are some illustrative, speculative, possible changes.

- Early forms of reproduction involves self-assembly of a new structure within an old one until it becomes detached and self-sustaining (possibly continuing to grow). The information about the design of the copy is implicit in the mechanisms that allow (possibly random) chemical processes within the original organism to have the side effect of growing a copy.
- Another form, presumably later, involved assembly within the "parent" of specifications for offspring, which can be assembled into a structure that is excreted, possibly with a small initial food supply, and which thereafter continues self assembly in an external medium from which it extracts nutrients. This mechanism would allow each individual to produce offspring that grow in parallel, enabling production of far more offspring in any time than the previous mechanism. This mechanisms requires the information given to the offspring to include information about how to pass on the information -- an early example of meta-morphogenesis.
- A variant for external assembly of a copy is to produce the reproductive information for growing a new individual, and also a protective shell, and a store of nutrients in the shell.

This would allow new copies to become larger and more complex before requiring the ability to absorb, or seek and find, nutrients in the environment.

- Another variant is parasitic insertion of the instructions for building a copy into another living organism from which the offspring can gain nutrients, and perhaps also other benefits such as temperature control and in some cases different resources at different stages of development.
- A variant of a parasite using a host of a different type could be a parasite using a host of the same general type, which might have the advantage of providing a development environment better suited to the copy -- conspecific parasitism(?).
- This might have led to development of insertion appendages, and later still to defensive mechanisms that enabled hosts to use inserted embryos to carry some of their own reproductive information and later still sexual differentiation that replaced mechanisms for exploitation with mechanisms for cooperation in reproduction.
- In that case a subset of the transmitted information would have to be of two kinds, one for production of a new host for developing embryos and one for providing some of the reproductive information and possibly other functions, e.g. protection. (Of course, this is wild speculation, merely intended to illustrate very crudely some possible varieties of information processing in reproduction. There are many more detailed transitions)

80. **Adding "secondary qualities" to the world**
(First draft: 2 Mar 2013)
Early biological detectors evolved with abilities to discriminate between things in the environment that the organisms needed to treat differently, e.g. allow some to enter the membrane, repelling or moving away from some, and perhaps ignoring others. Those detectors may have been reacting to particular chemical structures, but they had no ability to encode detailed information about the chemical structures, for instances which molecules they contain, how they are arranged spatially, what chemical bonds exist. ... to be continued...

81. **Generalising the notion of "Meme": more powerful change-drivers**

Memes are self-reproducing information structures that move between information users with capabilities for communication, imitation, teaching, learning, and related competences.

A full discussion would need to include the transitions that led to production of information-processing machinery capable of supporting meme construction and reproduction -- very different from the mechanisms involved in encoding, copying, transmitting, using, interpreting information in genes.

- Memes (originally defined by Dawkins) were supposed to be information structures that were "replicators" that could be passed from individual to individual.

- Copying information content is a special case of something more general, and more subtle, since the possession, provision or use of information by one individual A can trigger use of a different, but related, kind of information by something else B, that observes, manipulates, or interact with A.

- That sort of influence can operate genetically on a species, or cognitively on an individual.

- The influence can take very different forms, some involving very specific directly triggered responses (eye blink in response to rapid motion towards the eye), others involving highly context-sensitive, goal related, intelligent responses (e.g. saccades during searching) possibly involving creative planning or problem-solving.

- Interactions over time between predator and prey, or collaborators, parents and siblings, and extended interactions can lead to new strategies for catching, avoiding being caught, collaborating, tending, etc.

- Such invoked new forms of information and information-processing, can then, in turn trigger further new forms in prey, predators, etc. This is an old idea studied, for example, in connection with evolutionary "arms races", but it is often used to investigate "evolutionarily stable strategies", whereas my point is that there need not be anything stable about the process: in some cases it may generate constant novelty, but not only through competition, as in arms races.

    - items in the environment can have potential affordances that influence the evolution of species so as to enable them to detect and use those affordances.

    - individuals detecting affordances in objects or situations may work out goals, or strategies for making use of those affordances, in a systematic way. E.g. pickability of berries can lead to strategies for picking the berries by hand in one species, and by mouth in another, because of morphological differences.

    - Typical behaviours of one species (or individual) can influence evolution or learning of information processing competences of other species (or other individuals), for example competences of predators, prey, collaborators, parents, or offspring. (So-called evolutionary 'arms races' are a special case of this.)

      Note: learning by imitation can be seen as a special case of this more general kind of learning by external provocation and detection of new affordances. (The information-processing requirements for learning by imitation are ignored by many who regard that as an explanatory category.)

82. **Place holder (added 16 Jan 2013):**
    Kinds of minds and kinds of freedom
    Daniel Dennett and I have both emphasised the need to understand transitions in biological evolution and in particular the need to understand ways in which evolutionary changes produced new kinds of freedom (disposing of some old philosophical debates about "free will"), and new kinds of mental competence. See the references here
    http://tinyurl.com/CogMisc/meta-morphogenesis.html#dennett
    and this 1992 discussion based on an earlier usenet posting:
    "How to Dispose of the Free-Will Issue",
    http://www.cs.bham.ac.uk/research/projects/cogaff/81-95.html#8

83. **Place holder (5 Feb 2013): Transitions concerned with time** I was reminded of the importance of this when reading part of Gardenfors (2003). This is also discussed by Merlin Donald (2002).
    - At various stages organisms must have developed abilities to control speeds of processes, e.g. speed of motion, if self-propelled, and in articulated parts, controlling speed of motion involves controlling temporal coordination of moving parts, e.g. legs, wings, fins, etc.
    - Various rhythmical internal processes can also be speeded up or slowed down, such as

heart beats and breathing.

- Organisms that depend on cooperation of various sorts need to be able to control and coordinate times of action, e.g. mating swarms of some insects, flashing of fireflies, migration in birds, coordinated hunting by dolphins and some sharks.
- A hunter trying to intercept a moving prey animal has to control speed so as to arrive at location where the two trajectories intersect at the same time as the prey.
- Some tasks require estimates of time for something unseen to happen, e.g. something coming back into view after going behind an obstacle.
- Speech requires complex coordination of timing of breathing, tongue movements and other mouth movements.
- Sign language also involves coordination of different parallel movements.
- Additional time competences are required for building histories: information about what happened when and where, and temporal relations (e.g. "I left before he arrived"), and abilities to reason about the future and make and compare plans. Some plans only have temporal ordering with no reference to how long each step takes. Some specify time intervals.
- to be continued ...

84. **Added 20 Aug 2013**
    Place holder: Issues related to measurement of time
    Evolution of mechanisms for measuring light changes in various forms of life were discussed in a BBC Radio 4 programme on 20 Aug 2013:

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    Russell Foster, Professor of Circadian Neuroscience at Oxford University, is obsessed
    with biological clocks. He talks to Jim al-Khalili about how light controls our
    wellbeing from jet lag to serious mental health problems. Professor Foster explains
    how moved from being a poor student at school to the scientist who discovered a new
    way in which animals detect light...
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[[lots more to be added]]
[TO BE CONTINUED]

Related work
(Added: 25 Nov 2012 -- last Updated: 15 Aug 2014)

- Kenneth Craik, (1943), *The Nature of Explanation,* 1943.
- Merlin Donald (2002) *A Mind So Rare: The Evolution of Human Consciousness*
  W W Norton & Co Inc.
- Peter Gärdenfors (2003), *How Homo Became Sapiens: On the Evolution of Thinking*, OUP
- John McCarthy’s 1996 paper "The Well Designed Child" is very relevant:
  http://www-formal.stanford.edu/jmc/child.html
  (Later published in the AI Journal, 172, 18, pp 2003--2014, 2008)

  > "An important part of the "learning" required to deal with the three dimensional world of objects, processes, and other beings was done by evolution. Each child need not do this learning itself.

"Evolution solved a different problem than that of starting a baby with no a priori assumptions."

"Animal behavior, including human intelligence, evolved to survive and succeed in this complex, partially observable and very slightly controllable world. The main features of this world have existed for several billion years and should not have to be learned anew by each person or animal."

"In view of evolution, one would expect the fact of being hungry to be represented both chemically and in the language of thought."

- Ulric Neisser wrote, in *Cognition and Reality,* W.H. Freeman, 1976.

  "... we may have been lavishing too much effort on hypothetical models of the mind and not enough on analyzing the environment that the mind has been shaped to meet."

- Karl Popper became enthusiastic about Darwin and natural selection
  after having criticised the work earlier.
  http://www.informationphilosopher.com/solutions/philosophers/popper/natural_selection_and_the_emergence_of_mind.html
  Popper's Darwin Lecture: (Linked here 15 Aug 2014)
  Natural Selection and the Emergence of Mind
  Delivered at Darwin College, Cambridge, November 8, 1977
  Kindly made available on Bob Doyle's web site: http://www.informationphilosopher.com/

- 15 Aug 2014: Jack Birner drew my attention to his paper
  Jack Birner (2009).
  "From Group Selection to Ecological Niches: Popper's rethinking of evolutionary theory in the light of Hayek's theory of culture." In
  Z. Parusnikova & R.S. Cohen (eds.), *Rethinking Popper*, Springer.
  PDF available here.
  From the Abstract:
  Hayek's *The Sensory Order* contains a physicalistic identity theory of the mind. Popper criticized it, saying that it could not explain the higher functions of language. Hayek took up that challenge in a manuscript but failed to refute Popper's arguments. Drawing upon the same manuscript, Hayek developed a theory of behavioural rules and cultural evolution. Despite his criticism of the theory of mind on which this evolutionary theory was based, Popper adopted Hayek's idea of group selection. He transformed it into a theory of the selective power of ecological niches. This became a central element of Popper's theory of evolution. The chapter traces the influence Popper and Hayek had on each other in the fields of the philosophy of mind and evolutionary theory. ...

  NOTE: an online PDF version of Hayek's The Sensory Order is available here:
  https://archive.org/details/sensoryorderinqu00haye
  (The 'BW/PDF' version is smaller and slightly more readable.)

- John C. Doyle's research group at Caltech

- See also references to Karmiloff-Smith's work, above.

- Dirk Trossen organised a workshop on thinking architecturally.
- Research on Molecular Haematopoiesis and Epigenetics
- ....

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Other documents

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Other documents introduce the general project and discuss conjectures about overlaps
between mechanisms originally used (pre-historically) to produce the mathematical
knowledge accumulated in Euclid's elements and mechanisms involved in non-human
animal intelligence and types of discovery pre-verbal children can make ("toddler
theorems"), which I think have unnoticed connections with J.J.Gibson's claim that a
major function of perception is discovery of affordances.


[*] Some very sketchy theoretical ideas about the nature-nurture issues related to toddler
theorems are presented in this paper published in IJUC in 2007:
    http://tinyurl.com/BhamCosy/#tr0609
    Jackie Chappell and Aaron Sloman
    Natural and artificial meta-configured altricial information-processing systems

There's more on toddler theorems here
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to be completed....

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- Tanya Goldhaber kindly read and commented usefully on a draft of this document in November 2012, in particular pointing out the need for more context to be provided in several sections.

This file is also accessible as http://tinyurl.com/CogMisc/evolution-info-transitions.html
Partial index of discussion notes: http://www.cs.bham.ac.uk/research/projects/cogaff/misc/AREADME.html

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