Diversity of Developmental Trajectories in Natural and Artificial Intelligence

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Abstract

There is still much to learn about the variety of types of learning and development in nature and the genetic and epigenetic mechanisms responsible for that variety. This paper is one of a collection exploring ideas about how to characterise that variety and what AI researchers, including robot designers, can learn from it. This requires us to understand important features of the environment. Some robots and animals can be pre-programmed with all the competences they will ever need (apart from fine tuning), whereas others will need powerful learning mechanisms. Instead of using only completely general learning mechanisms, some robots, like humans, need to start with deep, but widely applicable, implicit assumptions about the nature of the 3-D environment, about how to investigate it, about the nature of other information users in the environment and about good ways to learn about that environment, e.g. using creative play and exploration. One feature of such learning could be learning more about how to learn in that sort of environment. What is learnt initially about the environment is expressible in terms of an innate ontology, using innately determined forms of representation, but some learning will require extending the forms of representation and the ontology used. Further progress requires close collaboration between AI researchers, biologists studying animal cognition and biologists studying genetics and epigenetic mechanisms.

Tabula Rasa or Something Else?

It may be of interest to see what can be done by giving a robot no innate knowledge about its environment and only a completely general, environment-neutral, learning mechanism, such as reinforcement learning, or some information-reduction algorithm, to see what it can learn in various environments. However, it is clear that that is not how biological evolution designs animals, as McCarthy states:

> "Evolution solved a different problem than that of starting a baby with no a priori assumptions.
> ....
> Instead of building babies as Cartesian philosophers taking nothing but their sensations for granted, evolution produced babies with innate prejudices that correspond to facts about the world and babies' positions in it. Learning starts from these prejudices. What is the world like, and what are these instinctive prejudices? (McCarthy 1996)

It is likely that evolution discovered more design problems and more design solutions than most learning researchers have so-far considered. This paper aims to generalise McCarthy's point, asking how different sorts of environment determine different sorts of design requirements for an animal or robot, using a comparative design stance to expand both normal AI research methodologies and the comparative approach in Dennett's survey of 'kinds of minds' (1996).

An extreme illustration of McCarthy's point, in our world, is that members of most species are born or hatched with all the competences they will ever need (though they may be able to tune parameters, to increase speed or accuracy, and some can be trained, with great effort, to make new connections between perceptual and motor competences).

Spectacularly, some grazing mammals can walk to the mother's nipple and run with the herd very soon after birth, and chicks that are ready to hatch fight their way out of the egg unaided, and can peck for food, imprint on a hen (or any moving object with about the right size, shape, and motion patterns) and follow her about. These are labelled 'precocial' species by biologists. Their competences are genetically determined, but need not be fully specified in DNA, if further details are determined by a common, predictable environment during early development (e.g. conditions in a womb or egg). We could regard those parts of the environment as implementations of an 'enlarged genome'.

The fact that some species start so competent provokes the question: *Why do other species, such as primates, hunting mammals and nest-building birds, start so helpless and incompetent?* Such species are labelled 'altricial'.

This is especially puzzling in the case of altricial species whose members, as adults, seem to perform more cognitively sophisticated and varied tasks, such as: hunting down, catching, tearing open, and eating another animal; building stable nests made of fairly rigid twigs (as opposed to lumps of mud) high in trees[1]; leaping through treetops; using hands to pick fruit in many different 3-D configurations – and, in the case of humans, far more. It would seem that if adults of certain species are going to have very sophisticated physical

*Much of this work was done jointly with Jackie Chappell

[1]Could you do it if you could bring only one twig at a time?

and cognitive competences, evolution should make them as advanced as possible from birth or hatching.

The appearance of starting totally incompetent and ignorant may be very deceptive, if the prior knowledge of the environment provided by evolution in those cases is more subtle and abstract than in the case of foals and chicks. And there may be good reasons why that sophisticated method of learning should start work in a physically and cognitively under-developed individual. Those reasons will in part depend on the nature of the environment, and in part on the kind of niche into which the species has evolved, e.g. what sorts of prey and predators it has. Moreover, evolution did not jump directly to any of the existing designs. There were very many intermediate designs and what is possible at any stage will to some extent be constrained by what has evolved so far. Thus the existing features of a species are as much a part of the niche that constrains further development as the features of its prey, predators and other features of the environment. In particular, individual features of a species form part of the niche for other features.

Not one problem with one solution: We can shift the precocial/altricial distinction from species to competences (Sloman & Chappell 2005; Chappell & Sloman 2007) allowing some competences in a species to be 'precocial' – i.e. pre-configured in the genome, for instance sucking in humans, and some late-maturing mating behaviours – while others are 'altricial' – i.e. meta-configured, produced epigenetically by pre-configured meta-competences interacting with the environment.[2] By considering variations in sophistication and specificity of initial competences instead of whole individuals we allow a much wider variety of designs than would be the possible if every species was either entirely pre-configured or entirely meta-configured.

We also need to analyse in greater depth the environments in which species evolve. As Neisser wrote (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." (Of course, this does not imply that we should disregard the information-processing mechanisms and architectures.)

Varieties Of Worlds To Learn In

Soup dwellers: We can reason from features of an environment to requirements. Consider an organism living in a soup of non-uniformly distributed nutrient chemicals where, at every point in the soup, each chemical can be present but their concentrations differ, and their concentration gradients have different directions and magnitudes. The organism can consume available nutrients (required for energy, for repair, for growth, for reproduction, etc.) at a rate that depends both on present need and the local concentration. So something not currently needed will not be consumed even if the concentration is high, though at a later time it might be consumed rapidly. Suppose the organism's sensors can detect the gradients and its effectors can produce motion in any selected direction. At each moment the organism has varying internally sensed needs for each of the nutrients and it chooses the one for which the need is strongest and moves in the direction of increasing concentration of that nutrient. Nutrients that have been consumed are stored in the organism, and different nutrients are consumed at different rates that depend on whether the organism is moving, sensing, reproducing, consuming, etc.

Deciding how such an organism should act at any time is a non-trivial problem expressible fairly simply in terms of how to map a changing vector containing internally and externally sensed states onto a changing vector of effector outputs so as to maximise the expected life-span. Different patterns of variation of nutrients and changing requirements could make this a more or less difficult task. Evolution may be able to 'learn' how the concentrations and gradients change in this world (e.g. if each nutrient's concentration peaked at a fixed depth) and produce a strategy that maximises reproductive fitness. However the representational requirements for such organisms would be very simple: a fixed collection of continually varying measures are the only things available to be represented, and the only decisions to be made are local 'hill-climbing' decisions.

Varying soup-challenges: Problems for individual organisms and for evolution can be made harder in many ways, even before other organisms are introduced. If an organism has mass then dynamic control mechanisms are needed to prevent over-shooting preferred locations. If concentrations of the various chemicals are constantly changing unpredictably everywhere, then there is little to be learnt about the distribution of chemicals in the soup. However if concentrations and gradients are somehow kept fixed then it would be useful to be able to learn and remember where the various sorts of nutrients are available so that short cuts can be taken to the desired locations instead of gradient ascent being the only option. The ability to acquire, store, and make use of that geographical information requires major additions to the information-processing capabilities of the organism, not discussed here. There will be a trade-off between evolutionary processes gradually acquiring information equivalent to a fixed map that can be used by all individuals that inherit the information, and evolutionary processes that produce the ability to learn the geographical layout. If the layout changes slowly during the life of each individual but is significantly different from one generation to another, then that will tend to favour acquisition of a learning mechanism rather than acquisition of a fixed map in the genetic material.

Noxious and walled soups: Things get more complex if there are also noxious chemicals (henceforth referred to as 'noxients') with varying effects, some transient and some persistent, such as interfering with sensing, with ability to move, with reproduction, with ability to make use of nutrients etc. If their distribution in the soup also remains fixed then there will be significant benefit in learning where they are, though this will be a different task from learning the locations of the nutrients, since it will not generally be desirable to find out where the harmful chemicals are most highly concentrated by hill-climbing.

[2] The importance of epigenesis in cognitive development is stressed by (Jablonka & Lamb 2005), who also argue that epigenetic factors can be inherited. Cf. (Sloman & Chappell 2007).

Fixed, impenetrable barriers to motion can also add opportunities to benefit from the ability to learn and remember their locations. The barriers impose rigid constraints on motion whereas the noxients impose soft constraints: the organism may sometimes find it useful to go through low concentrations of noxients to get to a high concentration of a nutrient. All of these environmental differences affect the requirements for information-processing capabilities, and the tradeoffs between different options, as well as tradeoffs between learning and evolution.

Atomic sensors: If new types of substance are introduced from time to time, then the problem for evolution is much harder. It must allow the information-processing architecture and the contents of representations to be take different forms in different generations. There are two main ways of doing this. If the changes are slow enough then, as the soup-world changes, the fixed architecture of the organisms can slowly vary from generation to generation, and over time some sequences of variation may produce surviving sequences of organisms in the new environments. If environmental changes occur faster, then individual organisms need to be able to learn about the new substances. That requires sensors to have more generality: e.g. by being able to detect 'lower-level' features that are common to different sorts of substance. For example if there are only N fixed chemicals in the soup then N detectors for those chemicals will be useful, whereas if new chemicals can be introduced it may be better for the organism to have detectors for atoms and for relations between atoms, so that different combinations and arrangements of atoms can be distinguished, including new combinations as new chemicals are introduced.

A similar point can be made about requirements if there are 3-D objects of different sorts in the environment. If only a fixed set of shapes ever exists, then sensors could evolve for those. However if new shapes can turn up that need to be distinguished because the objects with different shapes have different properties that are important for the organism, then the organism can benefit from having detectors for shape-fragments (e.g. for portions of surfaces, and ways in which different surface fragments can be combined). This requires additional, costly, cognitive machinery for discovering and representing different combinations of these features, but the ability to cope with novel structures can compensate for the cost. Biological immune systems have something like this capability. Some of their sensors are also effectors: in sensing pathogens they combine with and neutralise them. There could be similar combined sensing and consuming processes in some organisms.

From Moving to Manipulating: So far we have considered only organisms that sense, move and consume. But there is another possibility: some environments not only provide ready-made complex objects of different sorts that provide opportunities for and threats to the organism, but, also make it possible for smaller fragments to be combined to form larger fragments that are useful, or for larger fragments to be disassembled if they are harmful, or if their parts are potentially useful in combination with other fragments. This has profound implications, not widely appreciated.

The possibility of benefiting from being able to assemble, disassemble and reassemble complex structured 3-D objects provides yet more challenges for evolution and learning. The effectors need to be more complex, so that objects or their parts can be moved together or apart or rearranged. This requires the ability either to move one object to another that is held fixed by the environment or to be able to hold one object and move another, or to move both at the same time. It is interesting that this sort of ability has evolved not only in vertebrates (including birds) but also in many invertebrate species, including insects.[3]

In addition to requiring additional sorts of physical components, such as articulated parts that can be moved in different directions concurrently, these opportunities also substantially extend the requirements for information-processing. Whereas previously the only control decisions concerned motion of the whole organism, there may now be a need to control articulated parts moving in different ways at the same time. Whereas previously an organism needed to know only where it was (and perhaps which way it was facing if that affected movement or sensing) some now have to know where their various independently mobile parts are, as well as where the graspable and separable parts of objects are, and how all those things are moving.

Further, whereas previously the only kind of future to be considered in formulating goals or predicting consequences of actions was a future in which the organism's location[4] had changed and the array of sensor values had changed, it is now also necessary to consider possible futures in which external 3-D objects and parts are rearranged in relation to one another. If planned objects can be more or less complex, that will require the ability to construct more or less complex representations of objects, instead of using only fixed-size, fixed-complexity vectors of measurements.

Moreover, as structured 3-D objects move in relation to one another, many relationships change in parallel, in ways that are constrained both by the shapes of the objects and the type of relative motion. I have previously described these as 'multi-strand' processes because different relationships change in parallel, some continuously and some (e.g. topological relationships) in discrete steps.[5]

Exosomatic ontologies: Exactly how these new structures should be represented is debatable. Much research on visual recognition and action in robots attempts to represent information about the environment in terms of conditional probabilities linking patterns of sensor and motor signals with future sensor signals, sometimes described as sensory-motor contingencies. An organism that can represent only

[3]The abilities of insects to build nests and other structures, such as termite 'cathedrals', are examples of the ability to detect and manipulate matter in the environment. However it is not clear whether any can perceive and plan new 3-D structures. Do termites perceive the cathedrals that they build, or plan any substructures?

[4]If the organism's sensors are not uniformly distributed in all directions, or if the direction in which it can move at any time depends on which way it is facing, then it also has to be able to detect whether its orientation needs to be changed.

[5]See, for example, this presentation: 'Architectural and representational requirements for seeing processes and affordances': http://www.cs.bham.ac.uk/research/cogaff/talks/#compmod07

relations between signal-patterns within its body uses only a 'somatic' ontology. If an animal or machine uses an ontology that refers to things that can exist or occur independently of how they are sensed or acted on by that agent, it uses an 'exosomatic' ontology.

Although deriving amodal exosomatic information from sensorimotor information can be difficult, there are many advantages to exosomatic ontologies, including their economy in representing what is common to many situations viewed from different locations or produced by different actions, and their ability to refer to hypothetical past or future events independently of how they are sensed or produced. This facilitates construction of plans, predictions and explanations. It also allows the same ontology to be used for one's own actions as for actions produced by others, which can support both learning and teaching, and caring for young learners by anticipating the consequences of their actions, i.e. perceiving 'vicarious' affordances.[6]

From Inheriting to Discovering: Such an environment allows different options for evolutionary development. If the kinds of object and kinds of manipulation required in a particular environment do not change much then it is possible for evolution to produce combinations of sensors, effectors, and information-processing mechanisms, including forms of representation, forms of perception, ways of forming goals, ways of relating goal execution to varying states of the environment, and so on. This is what we observe in precocial species that are born or hatched highly competent. The fact that something is genetically pre-configured does not imply that the cognitive processing is simple. The competences of new born grazing mammals and newly hatched chicks and ducklings currently far surpass what any robots can do. But if, as discussed in (Sloman & Chappell 2005; Chappell & Sloman 2007) either the physical environment changes faster than evolved designs can, for instance by providing new sorts of materials, or new configurations of objects, new ranges of temperature, etc., or if members of the same species move between different locations with different opportunities and dangers, or if rival species (prey, or predators, or competitors for the same food or habitats) adapt quickly, or if new ones move into the environment, then it will not be possible for evolution to hard-code all the required competences, even if the sensors and effectors provided are very general.

Structured structure-learners: In those cases, evolved pre-configured competences cannot match what individual learning can achieve, if fast learning methods are available. This needs not a completely general learning mechanism, but the ability to learn kinds of things that are specific to a complex 3-D environment in which there are different kinds of material, different kinds of shape and different kinds of process involving changes of many sorts, and specific to a particular bodily form, including sensors and effectors.

Evolution seems to have produced specific modes of learning adapted to those things, including specific ways of using 3-D parts of the organism to play with objects in the environment to find out what sorts of things they are and how they react to various ways of being acted on. This is highly dependent on having good ways to represent static and changing 3-D structures and their causal interactions. This is much more specific than a general learning mechanism that assumes nothing about the environments and is equally applicable to all environments. Such a general method is bound to be very slow, depending heavily on random exploration since it cannot use information about the organism or the environment.

Manipulation Changes What Can Be Learnt

An important complication has not yet been mentioned: In a 3-D world, as more and more complex objects are constructed by assembling available components, those complex objects themselves can be parts of still more complex objects. So the fact that certain objects have been made makes it possible to discover that there are new kinds of objects that can be made in fairly small steps that could not previously be made in small steps. Likewise as actions are produced that assemble such objects, 'chunked' sequences of actions become available to be used as components in more complex actions, where sometimes the complexity involves doing longer sequences of things, and at other times it involves doing more things in parallel, using cooperative agents. The value of such chunking in reducing complex search spaces has been well known in AI for decades.

As objects become larger the problems of manipulating them change, making it necessary to use more than hands, claws or beaks to move things. Thus, learning to make things can constantly result in new, increasingly complex, opportunities to learn new things, requiring qualitatively different and more complex actions, and more and more complex forms of representation to encode percepts, goals, actions, sequences of actions, and their results. Often new opportunities are far from obvious: brilliant ancient Greek architects did not discover the advantages of using keystone arches over horizontal beams.

Ontology extension: The ontology of the learner may also have to be extended to include new kinds of design, new kinds of tool, new kinds of construction process, new ways of collaborating with others, providing new contents for thinking, seeing, planning, and learning processes.

Watching young children playing with toys of various sorts shows that things that seem obvious to older children may be completely incomprehensible to younger ones for a while, such as why putting a puzzle piece back in the location from which it came is not sufficient to make it fit into the recess. At that point the child may not have in its ontology the notions of (a) the boundary of a recess, (b) the boundary of a piece, and (c) two boundaries being aligned.

I have seen an eleven month old child apparently mystified as to why he could not transfer yogurt from a spoon to his leg or to the carpet as easily as he could transfer it to his mouth (Figure 1): He apparently had not understood that the bowl of the spoon separated the yogurt from the target

[6] Perhaps mirror neurons should have been called something like 'exosomatic abstraction' neurons? The requirement for exosomatic amodal ontologies is discussed in online discussion papers on sensory-motor contingencies and orthogonal competences here: http://www.cs.bham.ac.uk/research/projects/cosy/papers/

Figure 1: *Yogurt can be food for the mind as well as for the body in an 11 month old scientist.*

surface and that he needed to invert the spoon for the yogurt to be transferred. I have seen an 18 month old child with toy wooden trucks each with a hook at one end and a ring at the other, trying to join two rings and getting mystified and angry at his failure. Presumably he had not yet developed in his ontology representations of the different causal roles of rings and hooks, so that he could not understand why one of each was needed. A few weeks later he had learnt how to do it. What changed in him? In contrast, researchers in Oxford watched in amazement as Betty, a New Caledonian crow spontaneously made a hook in order to lift a bucket of food out of a tube (Weir, Chappell, & Kacelnik 2002).[7]

Learning begets new needs: We started with pressures to develop new learning abilities to cope with rapidly changing environmental threats and opportunities. We now see that by enabling the learner to produce novel structures, those learnt abilities themselves rapidly produce new opportunities (and sometimes threats – since new constructions can be dangerous as well as useful), possibly requiring another 'layer' of learning. The learning capabilities that produced the early competences will not always suffice for producing the newer more complex ones. It seems that somehow this was discovered by evolution and the result is 'staggered' development of brains, at least in humans, so that as opportunities for new kinds of learning result from the earliest forms, new portions of the brain come into play, and they somehow support new forms of learning from what has previously been learnt – new ways of thinking and controlling thought processes have to be learnt. It is clear that what humans can learn at various stages changes significantly. The idea that some meta-competences are the product of interactions between results of earlier meta-competences and the environment is crudely represented towards the right side of Figure 2.

Layered meta-competences

Not all meta-competences are genetically pre-configured: some are produced by meta-meta-competences. For example, the ability to learn a particular language is significantly extended by learning that language's way of representing facts about language (one of many meta-semantic competences humans acquire), so that the learner can ask questions about what something means, or how to express something, thereby learning things that could not have been learnt at an earlier stage. From this viewpoint, there can be extended hierarchies of meta-competences and whatever has been learnt at any stage can provide a platform for building new meta-competences and meta-meta-competences.

Meta-meta-competences build on the early acquired competences to produce new meta-competences that extend the individual's learning ability. A university student studying theoretical physics could not have learnt the same material soon after birth. The ability to learn to learn can iterate, as indicated graphically in the figure.

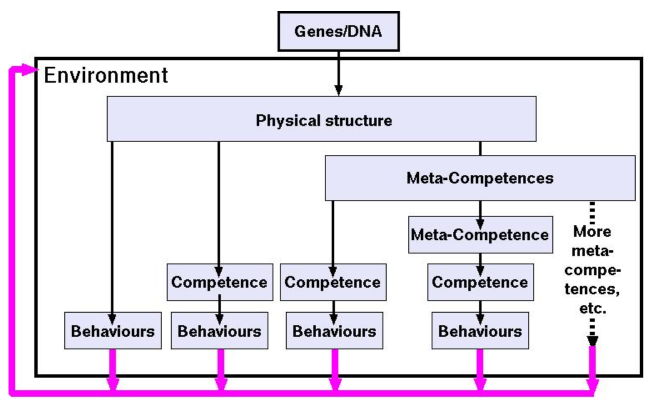

Figure 2: *Possible routes from genome to behaviours. All the processes represented within the box are capable of being influenced by the environment, including the environment's responses to actions by the learner. (Needs to be more precise.) (From (Chappell & Sloman 2007))*

In order to understand why anything like that might be required or why it may have evolved, it is worth considering the demands made on evolution by different sorts of environment. I have tried to sketch some of the possible evolutionary tradeoffs, though nothing presented here proves anything. It suggests new kinds of research in human and animal development, that perhaps may lead to reinterpretation of some archeological and paleontological evidence, and, more importantly, can direct new forms of AI research in robotics, though the problems are very hard.

[7]Videos of the crow, Betty, spontaneously making hooks in several different ways, are available online at the Oxford zoology web site. Use a web search for "betty", "crow" and "hook".

More detailed analysis would reveal more architectural and representational requirements, including requirements for meta-semantic competences.

Innate Context-Specific Meta-knowledge: If the previous arguments are correct, then some meta-competences that enable or facilitate the acquisition of new competences (or new meta-competences), far from being general learning algorithms, are specifically tailored to finding things out about restricted environments. As McCarthy implied, it is not surprising that millions of years of evolution should have produced learning mechanisms for discovering biologically useful things about physical environments containing 3-D configurations of objects and processes. So an important research task suggested by these considerations is deeper analysis of the requirements for learning about a world of manipulable 3-D objects made of many different kinds of materials in many different kinds of shapes for many different kinds of purpose.

Definitional vs Substantive Ontology-Extension

Some learning about new kinds of stuff, new properties, new relationships, new events, and new processes requires development of concepts that are not definable in terms of genetically provided ontologies. This needs learning mechanisms that support *substantive* as opposed to mere *definitional* ontology extension.[8]

Some learning mechanisms assume an initial collection of concepts (including relational concepts) and learn that among the many ways of constructing new concepts defined in terms of the initial ones, there is a particular subset of constructed concepts that is useful in the environment. A feature of this kind of learning is that it does not really *extend* the expressive competence of the learner, but merely provides some re-usable shorthand. Likewise, there are learning algorithms that use collections of facts expressed using some available set of concepts to discover laws linking instances of those concepts. An example is using existing concepts of 'pressure', 'volume', 'temperature', 'increase', 'hold constant', to learn from experiments that if pressure on a volume of gas is increased while the temperature is held constant, the volume decreases. Those methods of learning concepts and laws are essentially mechanisms for picking out useful subsets from the very large space of possible concepts and possible laws already expressible in the learner's ontology (and syntax).

Substantive concept learning: In contrast, *substantive* concept learning produces new concepts that are not definable in terms of the initial set, allowing construction of new theories or hypotheses that were not previously expressible. Some previously known facts may later turn out to support or contradict those theories, and old puzzles may be explained by the new theories. Such cases are familiar from the history of science. It has often been conjectured (e.g. by T.S.Kuhn) that something similar happens during development of children though attempts to determine in more detail that it happens and how it happens, and how to model it in AI systems, have made slow progress.

Substantive ontology extension includes learning about different kinds of matter and properties of various materials that are not detectable using available sensors, for instance, solubility or electrical conductivity. What is learnt through the application of meta-competences includes what sort of ontology is useful in the environment, as well as which laws using that ontology work well for making predictions in the environment. But it is not a simple algorithmic process, for it involves exploratory search for new explanatory constructs. This is one reason why some of that learning can take many generations, though once it has been achieved it can be passed on more quickly to subsequent learners, thereby also speeding up the process of learning to learn.

Which layers of competence develop in an individual will depend not only on the learner's innate meta-competences but also on the particular features of the environment in which learning takes place. A three-year old child in our culture can learn many things about computers and electronic devices that were not learnt by most of her ancestors. They probably started with the same sort of learning *potential* but developed it in different ways: bootstrapping (cognitive epigenesis) can be highly context sensitive.

Forms of representation for 'inner languages'

In (Sloman 1979) and more recently in (Sloman & Chappell 2007), it was suggested that in some species the kinds of perceptual, planning, problem-solving, and plan execution competences that develop require sophisticated internal forms of representation that we call 'generalised-languages' abbreviated as 'g-languages', or GLs. The word 'generalised' acknowledges that most people restrict the word 'language' to human languages used for communication. The concept of a GL is more general because it includes both communicative 'external' languages and internal languages used for other purposes. However, we require any GL to have two features often assumed to exist only in human languages, namely, a GL is a form of representation (or, for people who do not like the word 'representation', a form of information-encoding) that has both (a) *structural variability* and (b) *compositional semantics*. We generalise the latter notion to allow context sensitivity, as follows:
(a) Structural variability in a GL allows the construction of complex information structures with varying numbers of parts in varying relations. This includes the use of lists, trees, and networks containing different sorts of items of information. It also includes distributed as well as localised and geometrical as well as logical forms of composition.
(b) Compositional semantics in a GL allows any information structure to occur as parts of several different larger information structures, where the information (meaning) expressed in the larger structure will be determined by (i) the structures of which it is composed, (ii) how they are organised, along with (iii) relevant contextual information.

Different notions of part, whole and composition to form complex information structures are possible. There

[8] This would be impossible if 'symbol-grounding' theory (concept empiricism) were true! See this presentation: 'Ontology extension in evolution and in development, in animals and machines' http://www.cs.bham.ac.uk/research/projects/cosy/papers/#pr0604

is no requirement that the syntax used in a GL should use linear sequences, or that it should be be logical, or discrete, or that the semantic rules should be those of logic. For example, the notations used for circuit diagrams, for flow-charts, for maps of city transport systems, for geographical maps, for chemical formulae, for parse trees, are all GLs. I am not claiming that human brains use any one of these or even that anyone knows which GLs are used in biological brains. An example of use of a GL would be seeing a configuration of objects (stones, twigs, mud) and thinking of a different configuration involving a subset of those objects rearranged, or a configuration involving those objects with some additional, out of sight objects. Representations in an internal GL of the still future configuration could be used to guide a complex sequence of actions to produce an example of the configuration. The GL would also be used in comparing a partially constructed configuration with the intended configuration in order to determine a suitable next action to perform. This seems to be a requirement for constructing a rigid nest from twigs of many shapes and sizes. Use of a GL is essential for 'fully deliberative' architectures (described in http://www.cs.bham.ac.uk/research/projects/cosy/papers/#dp0604).

The parts in an intended configuration of objects could include parts of the animal, e.g. hands, feet, or jaws, which might be required in intermediate phases of the production of some new complex object. Animals building nests, peeling bananas, or using two rocks to crack open something edible, may in some cases use only rigid genetically determined action sequences instigated without any representation of a goal state (e.g. termites?). Alternatively such actions may depend on using a GL to represent a new goal which is then used to control actions constructing, disassembling or rearranging objects, using representations of the intermediate configurations to determine what to do next. Very few types of animal can do this. Deciding which ones can do it may require very complex indirect inferences from observations of what they can do, especially observations of apparently intentional, goal directed (non-random) novel solutions to problems. The problems Kohler (1927) gave his apes seem to be examples, and inspired much early research in AI.

It should be obvious that no structure or process *intrinsically* represents anything else. Representation is always for an information user and constrained by that user's information-processing capabilities.

GLs precede Ls: If both animals that do not talk and pre-linguistic human children can use internal GLs for perceiving, thinking, forming goals, planning actions, controlling actions, formulating questions to be answered, etc., *then those GLs must have evolved for internal use prior to the evolution of human language* – though their use for external communication probably accelerated their development.

If semantically rich information structures with compositional semantics are available in children prior to the learning of human languages, that transforms the nature of the language learning task: for the learner already has rich, structured, semantic contents available to communicate, including possibly questions, and goals, depending on what the GL is used for. This contrasts with theories of language learning that assume the child has to learn both how to mean and what to mean at the same time as learning how to communicate meanings.

It must be stressed that GLs are not restricted to linear strings of symbols or to Fregean languages using a syntactic form composed entirely of applications of functions to arguments. On the contrary, in (Sloman 1971) it was suggested long ago that analogical representations using other modes of composition are sometimes useful for representing and reasoning about spatial configurations. Analogical representations, including diagrams and maps are capable of supporting structural variability and (context sensitive) compositional semantics since parts of diagrams can be interchanged, new components added, etc., producing changes in what is represented. As explained in that paper, analogical representations need not be isomorphic with what they represent, as should be obvious from the fact that 2-D pictures can represent 3-D objects (e.g. the Necker cube). The relationship is more subtle and complex than isomorphism, and can be highly context sensitive. Internal GLs may use analogical representations not yet known to science. The use of such representations externally (e.g. on paper, in 3-D models) usually has to be learnt or developed – the representations only work for people, animals, or machines that have suitable information-processing mechanisms.[9]

Learning About Causation

Discussion notes and presentations on the CoSy web site (http://www.cs.bham.ac.uk/research/projects/cosy/) make a further claim, namely that the ability to manipulate (possibly analogical) representations of spatial structures can be the basis of a kind of causal competence that enables a reasoner to understand why a certain event or process *must* have certain effects. A Humean, purely correlational, concept of causation is involved in discovering that twiddling some knobs on a sealed box causes other knobs to move, or that pressing a light switch makes a light go on or off. In contrast, someone who sees gears meshed, and understands the notion of wheels being made of rigid and impenetrable material, and who can reason geometrically, can *work out* that one wheel turning makes the other turn the opposite way: the conclusion is not merely a summary of empirical observations.

This uses a Kantian conception of causation that involves more than mere reliable correlation: there is a geometrical necessity in the relation between cause and effect. A different sort of geometric causation is the fact that drawing a line between a vertex of a triangle and the midpoint of the opposite side causes the triangle to be divided into two triangles that have the same area even if they have different shapes.

This seems to be the kind of understanding of causation proposed by Kant(1781), in opposition to Hume's view that

[9]For more on this, and an attack on symbol-grounding theory see
http://www.cs.bham.ac.uk/research/projects/cogaff/talks/#models
http://www.cs.bham.ac.uk/research/projects/cogaff/talks/#inf

the notion of 'cause' refers only to observed correlations, which is also the predominant analysis of causation among contemporary philosophers and scientists, who have generalised Hume's concept to include conditional probabilities, as represented in Bayesian nets.

Progress in science typically starts with Humean causal discoveries in each new domain, and then as deep theories regarding underlying mechanisms are developed, the understanding of causation in that domain becomes more Kantian, allowing reasoning about structural interactions to be used, for example, to predict the effects of new events in new situations. In contrast, Humean causation supports only predictions concerning instances of previously observed types of events, or interpolations between them.

In humans, this Kantian understanding of causation is closely related to the ability to learn and do mathematics and to reason mathematically, especially the ability to acquire and use competence in proving theorems in topology and Euclidean geometry. We don't know to what extent other animals are capable of Kantian reasoning, but the creativity shown by some of them suggests that they do have a Kantian understanding of causation in at least some contexts. Moreover, it is clear that for robots to have the same abilities as humans (or even nest-building birds?) they too will need to be able to acquire kinds of ontologies, forms of representation, and theories, that allow them to use Kantian causal understanding in solving novel problems.

It is not easy to determine what forms of representation and inference are used in animals (or children) that cannot talk. Some of the problems of investigating causal understanding in non-human animals, were discussed by Jackie Chappell in her WONAC presentation: http://www.cs.bham.ac.uk/research/projects/cogaff/talks/wonac

Conclusion

This is an incomplete, hastily written paper produced after being invited to give a talk at the workshop on 'Computational Approaches to Representation Change During Learning and Development' at the 2007 AAAI Fall Symposium. Getting some of the ideas in print may provoke a few people to work on challenging and extending them. Building machines that have the more sophisticated features discussed here will not follow easily from the experiments in insect-like (or less than insect-like) robots that currently dominate the field.

We should not assume that the problem is simply a collection of inadequate tools, and immediately start trying to develop new tools, which has happened repeatedly in the history of AI. The real gap in our knowledge is understanding of the *problems*, or, in engineering terms, the *requirements*. That includes, but is not restricted to, understanding the problems of learning and acting in a richly structured, changing 3-D environment. Other tasks that I have not mentioned involve the requirement of an intelligent animal or robot to develop a meta-semantic ontology in order to perceive, think about, reason about or act on its own or other individuals beliefs, desires, preferences, intentions, moods, learning processes, and so on.

If we can specify more of the problems to be solved, by analysing in detail the opportunities and constraints arising in different sorts of environment (not just soup-worlds) that may help to point us in the direction of building new tools, or perhaps using existing tools to achieve new goals. Without doing the requirements analysis, building new tools, even biologically inspired tools, can lead us up blind alleys.[10]

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[10]The list of references below is merely illustrative. There is far more relevant work than can be mentioned here.