

Advancing Knowledge of Cognitive Development Sequences in Infancy

Frank Guerin¹

Abstract. Human adults have relatively sophisticated cognitive abilities, and manage vast quantities of diverse knowledge. The amount of data in the genome, and the differences with other species, show that a relatively small amount of information must code a system that can bootstrap itself to this high level of sophistication. How this bootstrapping process works remains largely a mystery. The technique of computational modelling opens up the possibility of developing a complete model of this bootstrapping process which could allow us to understand the whole developmental sequence, starting with infancy. Existing computational models of infant development typically only model one episode in one area of competence, and these individual episodes have not been linked up; yet, the process by which new developments build on earlier achievements is central to the bootstrapping, and remains a mystery. This paper looks at what work needs to be done to take forward the idea of attempting to explain cognitive development at a level which could account for long sequences of development. We argue that in order to understand the developmental processes underlying longer sequences we first need to determine what these possible sequences are, in detail; existing knowledge of such sequences is quite sketchy. The paper identifies the need to discover a directed graph of behaviours describing all the ancestors of sophisticated behaviours. The paper outlines some experiments that may help to discover such a graph.

1 Introduction

Human cognitive development from infancy through to adolescence shows a fascinating dramatic increase in the sophistication of behaviours displayed. Arguments purely from the amount of data in the genome, and the differences with other species, show that a relatively small amount of information must code a system that can bootstrap itself to a high level of sophistication. How this bootstrapping process works remains largely a mystery; it must involve some process of incrementally building new knowledge on top of old knowledge structures. This “incremental building” is a process which is currently very poorly understood, and is therefore our focus of investigation. Computational modelling would probably be the most precise way to describe this development (if it is possible to reach such a level of precision). A computational model could make clear what learning mechanisms are in operation in cognitive development, and what mechanisms can account for multiple developments, building on each other.

In this paper we look at how we might advance our knowledge of the incremental building which happens during cognitive development in infancy, through studies involving both computational modelling and experimental psychology. The process starts with obser-

vations and theories from psychology. Computational modelling is necessary to test these theories and show up impossibilities and gaps in knowledge, where more precision is required to specify the developmental mechanism. This leads to the specification of further psychological experiments, and the cycle continues. The ultimate goal is to have a precise description of the mechanism which could account for some of the major cognitive developments which take place during infancy. The precision required is at the level of a running computer program, such that the program could be placed in a simulated world², and could interact with the world, and develop cognitively, recapitulating the development of the infant. In this paper, as a first step in this process, we examine existing psychological results to see how useful they are for computational modelling, and what additional information would be desirable, and finally the type of psychology experiments which might reveal this information.

Computational modelling of cognitive development is nothing new of course; however there is no work which has attempted to model substantial sequences of development in detail. For example Schlesinger et al. [12] or Cohen et al. [5] model one part of development in some detail, while [6] models a longer sequences, but in very poor detail, i.e. Drescher’s simulated world was very simplified and precludes the modelling of many behaviours. One of the essential features of infant cognitive development is that it is *ongoing*; i.e., what is learnt in one learning episode is built on and forms the starting point for a subsequent learning episode. A computational account of the development must explain how one acquisition feeds into the next, in an ongoing sequence. This is a tough requirement to meet, and implies a large research programme, because each individual development modelled must be done with a view to subsequent developments, and must acquire knowledge structures in some representation which can feed into the next episode of learning.

In order to limit the scope of our research to a manageable chunk, the research programme we consider here is to be able to model the development from basic sensorimotor schemas such as Piaget’s sec-

² Rodney Brooks [2] has argued for the need to develop Artificial Intelligence (AI) with robots in the real world, rather than simulation. Brooks makes strong arguments for why relying on human introspection about how the world should be represented can lead to serious problems; this means that in building simulations we must be careful not to impose our representation on the AI system, but to expose it to data as might be seen by a vision system (for example), so that it solves the problem from the raw data, and does not have a human specified shortcut to higher representations. Rich Sutton’s verification principle [15] strengthens this point by pointing out that any human imposed shortcut could not be revisited by the AI system to be reformulated if necessary, hence the system would be brittle and restricted to scenarios the human had foreseen. However no strong argument has been made against simulation itself, provided it is done without “cheating”. There is no reason to believe that AI research (including computational modelling) cannot progress through work in simulations (past failures do not prove any general law).

¹ University of Aberdeen, Scotland, email: f dot guerin at abdn dot ac dot uk

ondary circular reactions (Piaget's stage 3, beginning at roughly 4 months), right through to tertiary circular reactions (Piaget's stage 5, running to roughly 18 months). The kinds of behaviours exhibited towards the start of this sequence would include striking objects, grabbing them, shaking them, etc. By the end we would see advanced behaviours such as retrieving a distant object with a stick. The aim is to create a computer simulation which could begin with the abilities at the start of this sequence, and could "play" in a simulated world, and with no further intervention from a programmer, could autonomously develop, through experiences in the world, to arrive at the behaviours marking the end of the sequence. Cognitive development in infancy involves both learning based on experience in the world, as well as the arrival of new competences through maturation of the nervous system. The focus of this paper is especially on the learning mechanism which builds knowledge based on experiences. However, our simulation will also need to be some modelling of maturation, which could take the form of a scripted sequence of developments which unfold at specific times.

The research agenda proposed in this paper would fall under the heading "developmental psychology". The main input from Artificial Intelligence (AI) to this paper (and hence the link to this symposium's theme) is *the very idea* of attempting to understand a developmental mechanism underlying long sequences of development. This is a very computational idea; i.e. that there could be a program, with a limited amount of initial information, which by gathering information from the environment, and modifying itself, can become very sophisticated. This computational perspective leads one to ask questions about long sequences of development, and the intermediate levels of competence, and training sequences that cause transitions. The questions thrown up by this attempt are questions which psychologists are not currently investigating.

Much of the developmental psychology literature about infancy probes the infant's competences at various ages. The focus of the proposed investigation is on *development*, rather than competence at any particular age. (Assessing competence at particular ages is only interesting for the information it gives about the development which must have taken place between those ages.) We argue that there is a need to conduct research on infancy which identifies ordered sequences of intermediate competences, and the training experiences which lead to development from one intermediate level of competence to the next. Research to identify training experiences which can lead to development has been carried out with older children, but very rarely with infants.

2 Requirements: Precise Models of Infant Cognitive Development

The ultimate aim of the research which this paper is concerned with is to have a complete mechanistic description of infant cognitive development; i.e., working computer model, which could recapitulate the development of a human infant. Various levels of detail can be envisaged; the most detailed being a realistic infant-like robot which interacts with real human caregivers, while simpler versions could include simulated robot infants in simplified simulated worlds which could recapitulate some of the main themes of development. This paper considers the simpler end of this spectrum, and focuses on just some of the developments which take place. We are particularly interested in developments relating to fine motor skills rather than gross motor skills. This section of the paper looks at the shortcomings of existing work in psychology, and looks at what knowledge may be needed from further psychological investigations in order to guide

the development of a computational model.

2.1 Shortcomings of Piaget's Theory

Piaget's theory would seem to be useful for informing the construction of computational models of infant development, because it describes a learning function which operates at all ages, and which constructs new knowledge structures. There are some problems with it however, as described in this section. Piaget's theory groups the behaviours of the first two years into six sensorimotor stages [10]. In explaining his theory about the development between the different stages he tends to describe the development in general terms, rather than describing how individual behaviours belonging to a particular stage lead to some other behaviours from the next stage. There are a number of problems with this.

Firstly it is not certain that it is sensible to group the behaviours into the six stages which he groups them in. Take for example Piaget's fifth sensorimotor stage. In this stage he group together (1) the behaviour of the support (e.g. pulling a towel in order to bring an object resting on it closer); (2) the behaviour of the string (pulling a string which is attached to an object, in order to bring this object closer); (3) the behaviour of the stick (using a stick to retrieve a distant object). These behaviours tend to occur at quite different ages, the behaviour of the stick in particular is much more difficult than the string or the support, and can occur four months later. Furthermore, many of these behaviours have a number of different levels of competence within them, for example the support can occur in the fourth sensorimotor stage as a means-end behaviour, without full understanding of the situations in which it will work; the string can also occur in a similar fashion, and there can be a considerable gap between competence on the string on a horizontal surface and vertically [16]. A second example is the objective knowledge of space, which Piaget groups with the fifth sensorimotor stage. This clearly will not arrive all together, but many fragments of objective knowledge must be built up during this stage, and this detail is not described. This suggests that Piaget's grouping is at best too coarse grained (and therefore not very useful), or at worst mistaken and misleading. The questionable utility of sensorimotor stage 5 is further illustrated by considering the results of an acceleration study by Wishart and Bower [18]. In this study the viewing of training displays accelerated infants' development of the stage 5 behaviour of correctly retrieving hidden objects; however it is extremely doubtful (although the tests were not carried out) that these infants would be capable of other stage 5 behaviours, such as experimental discovery of new means (one of the hallmarks of stage 5). This calls into question the utility of Piaget's grouping because some stage 5 behaviours can develop seemingly independently of others. (Piaget's stage 5 has just been used as an example here, similar comments could be made for stages 3 and 4, which also pack in quite a variety of different behaviours.)

Secondly, the frequency of behaviours exhibited from each Piagetian stage take the form of overlapping waves, much like Siegler's theory of development [3, see p. 7]. This is roughly sketched in Figure 1; one can see that at a particular age (say one year) an infant will display behaviours from a number of different stages. As a child enters a new stage the behaviours of that stage gradually start to become more frequent, but those of the previous stages may not decline appreciably for quite some time. This means that Piaget's theory does not make it clear which behaviours necessarily precede which others. For example a late stage 4 behaviour may well first occur after an early stage 5 behaviour, furthermore Piaget does not go into details

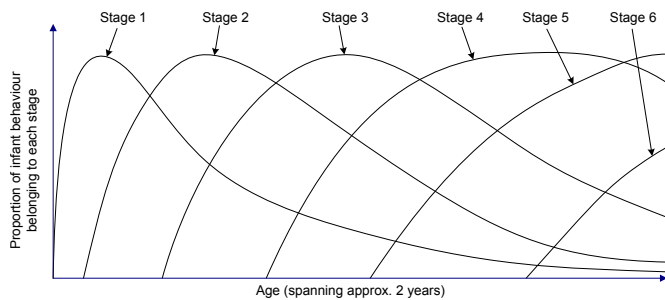


Figure 1. Piaget’s sensorimotor stages as overlapping waves.

about the necessary order of most behaviours within a stage. This is problematic because we would ideally like to know the ordered sequence of development for each individual behaviour and intermediate level of competence. Uzgiris and Hunt [16] proposed an alternative categorisation which suggested instead six parallel tracks of development, such that development on one track could proceed faster (or slower) than on other tracks. The order of acquisitions within any track cannot change, but between tracks, variations in relative order are possible, and this is where Uzgiris and Hunt can differ from Piaget; Piaget lumps a number of acquisitions together in one stage, and does not view them as independent tracks. There is evidence to support Uzgiris and Hunt’s view [16, p. 134 and p. 138].

Given the question marks over the suitability of Piaget’s grouping of the behaviours in his sensorimotor stages, it is problematic that he tends to mostly describe development in general terms. For example, in his description of how stage 5 develops from the infant’s earlier knowledge, he describes how the new ability to experiment is derived from the ability to recognise the results of experimental acts, because these results match schemas learnt previously [10, Chap. 5, Sec. 1, especially p. 276-277]. However, he does not describe which earlier schemas in particular permit the recognition of which results, thus facilitating a particular type of experimentation. Thus Piaget has a sort of grand unified general theory of development, without having a detailed account of how some specific behaviours develop. This is a little suspect, as one would like to see a grand unified theory built on a foundation of detailed knowledge of specific instances. Piaget’s general theory may or may not be accurate, but certainly we will need more detail before we can make this judgement, and Piaget’s evidence falls far short of what would be required to support his theory as a credible explanation of all of infant development.

For the work proposed in this paper we would like to postpone the formulation of a general theory, and instead focus exclusively on trying to explain in detail the mechanism which can account for some specific acquisitions. When a great deal of this specific research is done it may be possible to see the big picture, and compare with Piaget’s theory. It is likely that Piaget’s description will eventually turn out to be accurate for certain developments, but that much more is needed to explain other aspects. Piaget’s genius may lie in the fact that he was able to see the outline of a general theory without needing to know all the details.

Note that the shortcomings of Piaget’s theory described here were found by taking a computational perspective on the problem. The computational perspective leads one to think about how to formulate a learning mechanism in precise terms, which in turn leads one to realise how hopelessly vague Piaget’s description of stage transition

can be. This leads to the effort to find concrete precise descriptions of transitory behaviours, in order to give sufficient data to guide the search for a computational mechanism which could account for the transition. Thus it is an example of how adopting an AI perspective can lead to new research programmes which may answer some of the core issues which concern developmental psychologists (in this case the search for a mechanistic explanation for cognitive development).

2.2 Shortcomings of More Recent Psychology Research

With regard to more recent work in infant cognitive development, there is a lot of work on probing infants’ competences at various ages (for example [1]), but very little work addresses the issue of *development*, and explains what leads to the changes in competences. Chen and Siegler [3] have noted this gap, and also note a contrast between the types of research carried out on infants’ and toddlers’ thinking when compared with research on the thinking of older children. With older children, we also see research on competences, but in addition, we see “studies aimed at revealing mechanisms of change” [3]. Part of the reason for this difference is the different experimental paradigms used. For example, with older children it is common to ask them for explanations for their decisions; obviously these techniques do not translate easily to infancy research. However, Chen and Siegler are of the opinion that the gap between the two types of research is unnecessary, and many techniques applied to older children can work with infants (some of these techniques are described in Section 3 below).

Chen and Siegler advocate closing the gap with new experiments on infants, using appropriate experimental paradigms, to answer questions such as “Through what process of change do children become able to do X”. To this end they have conducted a study on children as young as 18 months to analyse the strategies they use to retrieve a distant object, when provided with an array of tools (some useful and some not). The studies we advocate however will need to experiment with younger infants, as we want to examine how skills such as tool use are first acquired. The methods of Chen and Siegler will be very useful for our proposal.

2.3 Requirements for Machine Learning

From a computing perspective, the task of creating a computational model of infant cognitive development could be seen primarily as a machine learning problem. To define the machine learning problem we need to specify the tasks to be performed, and the training experience. The tasks are simply the types of behaviours which an infant is capable of at 18 months, and incapable of at 4 months say. For example, one can use some of the types of tasks documented by Piaget, which 18 month-olds are typically capable of, such as the behaviour of the stick (retrieving an out-of-reach object by means of a long stick). The training experience is varied and complex, and most of the training period is spent attempting other intermediate tasks, some of which lead to learning which is useful for performing the 18 month tasks. For this reason it may make more sense to look at a sequence of separate machine learning problems, each with its own training experience, and target tasks, and where the learning on earlier problems in the sequence facilitates later learning. What the computer modeller needs from psychology then is information about a sequence of these learning problems. Each of these learning problems will involve the transition from some competences at a particular age to a more advanced version at a later age, and ideally the

gap between these two ages should not be too large, so that we are modelling small steps in development. Psychology experiments will need to find the sequence of competences, and the training experiences which lead to developments. For computer modelling we also need to decide on what sensorimotor abstractions and representations to use. This is much more difficult to determine from psychological experiments, but it may be sufficient to simply guess, and refine those guesses as needed in order to be able to model a whole sequence of developments. The more detailed our knowledge of the sequence of behaviours and the training experiences is, the more well informed our guesses about representations will be.

2.4 The Graph of Development

An analogy between evolution and cognitive development helps to explain the idea here. In looking at the many organs which different animals have evolved it is often difficult to imagine the path along which they evolved. The organs are quite complex (for example the eye), and if one were to guess at the mechanism of evolution based on scant evidence, one might conjecture a much more sophisticated mechanism than necessary. However, if one sees all the precursors in the fossil record for an organ, such as the eye, then the development pathway becomes more clear, and the mechanism which could account for the evolution can be simpler. Similarly, in looking at the sophisticated abilities of a toddler, and the large gap between those and a young infant's abilities, one might conjecture an overly complex learning mechanism to account for it; however, if the path of development can be traced out in detail, showing small developments between intermediary abilities, then the development might be explained with a simpler mechanism.

In evolution there is a tree, and each species (or organ) can be an ancestor for one or more others. In cognitive development the analogy of the species (or organ) is a knowledge structure, which could be a schema in Piagetian terminology, or could be a concept or skill or sensorimotor abstraction. Each knowledge structure may have multiple immediate ancestors (unlike evolution) because new structures are often built from relationships among existing ones (see for example Cohen's theory [5]). This means that in place of evolution's tree, cognitive development has a *directed acyclic graph*. The nodes of the graph represent knowledge structures, which could include for example a sensorimotor abstraction, allowing recognition of some situations where an action has a certain effect, or a motor control policy allowing performance of a skilled action. The directed edges of the graph have the meaning that the set of immediate ancestors of a node are the necessary and sufficient precursors of that node. The graph can then be supplemented with a new type of node to describe the training experiences that can lead to developments, i.e. a new training experience node can be inserted between a set of ancestors, and the descendent which they can give rise to. Finally we would specify machine learning algorithms which can start with the knowledge of some ancestor nodes, and use the training experience to generate the descendent nodes.

The above description of a development graph is a sort of gold standard, which could serve as a long-term goal for research in the field. In the medium term it is probably unreasonable to pursue it given our present poor state of knowledge about infant cognition. In particular we know very little about knowledge structures existing at various stages of development, and all we can directly observe are the behaviours which the infant is capable of. For this reason it may be more feasible to attempt to find a graph of behavioural milestones. This would again be a directed acyclic graph, but each node

describes observable behaviour; i.e., a certain behavioural milestone, or training experience (these no longer need to be different types of nodes as all nodes describe behaviour now). The directed edges of the graph have the meaning "is a necessary precursor"; i.e. the later behaviour should not be possible if the infant is incapable of the earlier behaviour. We would not claim that the immediate ancestors of a node are sufficient to enable the later behaviours, as this is a graph that will need to be built up incrementally; we can test behaviours to determine if they are necessary as ancestors, but we will not know if we are missing some.

Some additional factors complicate the infant development graph. Firstly, not all infants develop along the same paths, thus there are some later behavioural milestones (say milestone m) which have more than one set of possible immediate ancestors. This could be handled by having the behavioural milestone m represented by more than one node in the graph, i.e., once for each unique set of possible ancestors which could lead to it. The various nodes representing the milestone could then link to a single one, so that this would be a unique ancestor on which later behaviours could build. In any event, the issue of alternative paths need not be a great concern for initial investigations, because it may suffice to discover one possible developmental progression. The second complicating factor is that not all new behaviours are derived from others; some arise due to maturation, or due to a combination of maturation, and a certain level of development having been attained. This means we may include nodes in the graph which do not have ancestors or which are not arrived at via training experience.

For each intermediate competence, and each node describing a training experience, we need a fairly precise description of the behaviour, in order to avoid ambiguity. We must describe standard objects to be used, and detail the movement expected of the infant. For example, in a retrieval behaviour using a stick we must specify the dimensions of the stick (as the behaviour with a short stick is much easier than a long one for a more distant object), we must also specify the rigidity and weight of the stick; for the object to be retrieved we must specify the shape, dimensions, weight, colour, and frictional coefficient with the supporting surface (an object that rolls or slides easily is more difficult to retrieve, as the infant's poorly controlled swipes will put it out of reach); for the surface we must also specify the pattern (as it may be that a pattern with some visual landmarks is used to help interpret relative motion); for the remainder of the environment we should specify any other objects in the scene, and what background is visible in the room.

Note that this call for precise specification is not intended to create an artificial micro-world in which problems can be solved without tackling the full complexity that is entailed by the variation in the real world. The precise specification is necessary so that the same experiments can be repeated with different infants, and so that ambiguity will not result in another experimenter using different materials and unwittingly testing a qualitatively different behaviour. We are here describing experiments for infants, who naturally have a strong ability to generalise, and handle minor variations in materials and conditions. If such a detailed specification of behaviours could be made for the graph, then it would also be extremely useful for experiments in developmental robotics. Again, this is not an attempt to define an artificial micro-world, but rather to show a sequence of behavioural competences and training experiences which lead from one to the other, which form a potential developmental trajectory, which roboticists could attempt to follow.

In summary, we may not yet be ready to formulate a complete theory of infant development, explaining the knowledge structures

built, and the mechanism which builds them; however, as a first step, it may be useful to come up with a directed graph which shows which behaviours build on which others. Such a graph would be useful for computational modelling efforts, as it sets the sequences of tasks which need to be modelled, along with the training experience, and it gives insight into the incremental learning required; i.e. how early learning transfers to later learning. Computational modelling would then begin the process of guessing at the types of knowledge structures which are responsible for the competences shown at each node of the graph, and the learning algorithms which can build these knowledge structures, given the appropriate training experiences.

2.4.1 *Potential Criticism of the Approach*

The development graph we propose may feel like a bit of a step backwards for two reasons. Firstly it is a little behaviourist, in that we are relying solely on observable behaviour as guidance for computational modelling, even though a number of works in the psychological literature have already made conjectures about knowledge possessed by infants at various ages (see for example [1]). There is however considerable controversy about the claims made about infant knowledge [4, 7, 8], so it may be safer to rely on observable evidence from infants acting, and then to let the computer modelling come up with the simplest models which could account for the behaviour observed. Much of the work which purports to show advanced competences in infants might be criticised in the same way that a lot of early artificial intelligence work was criticised by Brooks [2]. Researchers may be too quick to assume an adultlike mind within the infant. This is simply a case of transferring the adult's model of his/her own thinking (known only by introspection) across to the infant; but this is by no means the simplest explanation for an infant competence, and science should always prefer the simplest explanation. Ascribing an adult world model to the infant may seem like the simplest explanation if one overlooks the enormous complexity of adult reasoning. A further point is that, as adults, we might well not be solving problems in the way we think we are solving them. We may be in fact solving the task subconsciously in the same way as we learnt during infancy, and then fitting an adult rationalisation on top of the solution after the fact. This means that it may be really a long time before an infant has an adultlike concept of object permanence for example, or perhaps never (if the adult's idea of the concept from introspection is not in fact what the adult is reasoning with). In summary we should not presume what is inside the infant's head based on adult introspection, we should just make the simplest model that can account for the behaviour, and adjust it whenever it is inadequate.

The second reason why our proposal may seem a bit of a step backwards is that we are proposing to make no assumptions about the general features of the mechanism of development, even though theories such as Piaget's have made conjectures about this mechanism. For example, if following Piaget's theory we would perhaps explicitly focus on modelling his sensorimotor stages, and the transitions between them. However, given the concerns described about his theory above, we believe that it may be better to start computational modelling from scratch, guided purely by evidence from behaviour. This process begins with some of the infant studies already carried out, such as Willatts's [17], discussed in the next section.

2.4.2 *Work Already Done*

This section briefly looks at some existing work which gives some fragments of a development graph. The work of Piaget [10, 11] has identified a partially ordered sequence of behaviours which build on each other. Much of Piaget's writing on this is speculative, and experiments have yet to be carried out to test many of his specific conjectures. An example of one of his conjectures is as follows. Piaget's son Laurent acquired the ability to discard one object in order to grasp another, at about 7 months, 29 days [10, Obs. 125]. Piaget conjectured that this behaviour derived from the ability to set aside an obstacle which prevented him from grabbing a desired object (this behaviour having been acquired just previously). This idea of one behaviour being derived from the other does not seem to have been investigated subsequently (and there are many more such examples yet to be investigated).

The work of Uzgiris and Hunt [16] (mentioned above) provides more fine grained detail, and the beginnings of a development graph, with six parallel branches. This defines a partial ordering of behaviours, and is what we require, except that we need to know more about behaviours intermediate between those they describe, and the training experiences which go between them. (Uzgiris and Hunt's interest was more in devising tests, rather than gaining insight into the mechanism of cognitive development.)

For determining training experience, Willatts's work on means-end behaviours [17] provides excellent evidence for the training experience which can lead an infant to knowledge of the means-end action which can retrieve an object supported by a towel. The above works are all useful steps on the way towards the directed graph which we envisage. These works however represent exceptions, as the main thrust of research in cognitive development is more concerned with determining competence's at specific ages. We believe that those works which specifically identify developments which lead to other later developments give some of the most useful knowledge to inform computational modelling efforts.

3 **Promising Experimental Paradigms**

This section briefly looks at the experimental paradigms which are most promising for taking forward the research agenda we are concerned with.

3.1 **Testing of Sensorimotor Skills**

Simple tests of behaviour will be an essential part of any experiments to discover the graph of development. Tests can simply involve observing the spontaneous behaviour of the infant with some objects, or setting the infant a task, such as to retrieve a toy which interests the infant. There are a great number of examples of these tests in Uzgiris and Hunt's book [16]. Once an infant can retrieve a toy in a situation, further variations can be used to probe the infant's competence in more detail. For example, if the infant can retrieve an out of reach toy placed on a towel, by pulling the towel, then the experimenter can hold the toy just above the towel and see if the infant continues attempting to pull the towel. Some experiments are also done by first demonstrating a procedure to the infant, and then examining if the infant is capable of imitating the procedure.

Willatts [17] introduced a further technique in tests by not only recording success or failure on the task, but also monitoring the infant's gaze, in order to have an objective measure which could discriminate between accidental success, or intentional success. This

was used on the task of pulling a towel to retrieve a supported toy. Younger infants (about six months) tend to give up on the toy and play with the towel instead, but in doing so they often accidentally bring the toy into reach. Willatts was able to monitor the infant's gaze, and to show that there was a transition: whereas the younger infants gave up on looking at the toy, as they got older, there were more glances towards the toy, suggesting that pulls of the towel were intentional in order to retrieve the toy.

3.2 Intervention to Accelerate Development in Longitudinal Studies

An intervention which can accelerate development of one group of infants relative to a control is one of the clearest ways to identify the experience which can lead to a development (which is required in our development graph). In a longitudinal study by Wishart and Bower [18] a group of infants was trained by watching a series of displays at regular sessions over a number of weeks, and tracking the objects seen in the displays. There were three displays: (1) an object which moved over a platform, i.e. coming into contact with the platform, and moving on past it; (2) an object that moved behind a screen and re-emerged from the other side; (3) an object which moved through a hollow cylinder and re-emerged. These infants were then tested on standard Piagetian object retrieval tasks, using the classic "A not B" problem. The tasks included an object placed on platforms, an object hidden behind screens, and an object hidden under a cup. These tasks belong to Piaget's fifth sensorimotor stage. The infants showed a dramatic acceleration in development, and succeeded on all three tasks well before the average ages at which success is typically achieved on these tasks. This study then very clearly shows the type of training experience which can lead to development from one level of competence to another in a very specific task. Such studies are resource intensive as infants must be studied over a relatively long period of time, however they give probably some of the best evidence which could be used to find the development graph of Section 2.4. The basic idea of accelerating development has also been used over shorter timescales in the microgenetic studies of Siegler and colleagues as described next.

3.3 Microgenetic Studies

Siegler has pioneered the microgenetic method [14]. The method is defined by three characteristics (reproduced from [3]):

1. an observation period spanning the time from the beginning of the period of rapid change to the stable use of target ways of thinking;
2. a high density of observations during this period, relative to the rate of change; and
3. intensive, trial-by-trial assessments of ongoing changes, both qualitative and quantitative.

The method seems to have rarely been used on infants, apart from the study of Chen and Siegler [3] which went as low as 18 months of age. By looking at some studies on older children, we can get an idea of how we might translate the same ideas to infancy. Siegler and Chen [13] have carried out a study to probe children's reasoning about how much water will be displaced by various objects. This study ran over two consecutive days, children were tested at the start and the end, and underwent training in the middle. Part of the training was designed to accelerate development; some of the children were asked to explain only their own answer, whereas others were asked

to explain correct and incorrect answers; this latter group were more likely to notice the roles of the variables in the problem, and more of them developed to the stage of correct answers within the period of the study. The general pattern of development here could translate to infancy experiments: noticing new variables, formulating more advanced approaches that incorporate the new variables, and generalising discoveries to new problems. For example in an infant tool use experiment, the infant must notice the position of the end of the tool relative to the infant's hand; younger infants will overlook this, but older infants know how to orient the tool, for example to maximise reach. A microgenetic study could experiment with various training experiences to determine which will lead the infant to pay attention to this variable. We cannot ask the infant for explanations, but we can expose the infant to situations where distracting aspects are removed, and it is more clear that the relative position of the end of the tool is the important variable across trials.

In looking at Chen and Siegler's study on tool use [3], one can also see methods that could be employed in studies of younger children. Chen and Siegler have outlined five steps in the acquisition of new strategies (reproduced from [3]): (1) acquiring the strategy of interest, (2) mapping the strategy onto novel problems, (3) strengthening the strategy so that it is used consistently within given types of problems where it has begun to be used, (4) refining choices among alternative strategies or alternative forms of a single strategy, (5) executing the strategy of interest increasingly effectively. In their study they looked at strategies for retrieving a distant object placed on a table when tools were available. Strategies used by the children included reaching across the table, or climbing on it, using a long tool, or turning to the parent for help. The same methods might be used where strategies are more fine grained, as required for our purposes. For example one could analyse the strategies that can be used with a long tool, during the phase where the infant is not yet competent in its use. In this case strategies will include: directing the stick towards the object; hitting the object; getting the end of the stick behind the object; repeated hitting on one side to bring gradually closer; changing the side of hitting when the object moves too far to one side.

Combining the experimental paradigms described here, a complete research methodology for determining the development graph could proceed as follows:

1. Initial longitudinal studies to graph a sequence of developments, with microgenetic studies to observe transition periods.
2. Formulation of hypotheses about which behaviour acquisitions may be used by later acquisitions.
3. These hypotheses could then be tested via studies which attempt acceleration of developments.

4 Some Specific Sub-Graphs to Investigate

The three Piagetian stage 5 behaviours mentioned above (i.e., string, support, stick) could be a starting point for investigating sub-graphs of the complete development graph. Each of these behaviours is a node which forms the endpoint of a subgraph containing all behaviours which lead to it. For each of the behaviours we already could sketch an outline of a sequence of developments leading to it.

For the behaviour of the stick we can sketch an outline sequence of some behavioural milestones as follows (not all behaviours here are in a strict ordering).

- The ability to grab an object;

- The ability to manipulate the object, to turn it and grab different parts (especially when this is applied to long objects, such that the near part can be pulled in order to bring the far part into range for detailed investigation);
- The ability to repeat the action of hitting a grabbed object against a surface to produce a noise (if discovered by chance);
- The ability to hit a grabbed object against another stationary object to produce a sound (if discovered by chance);
- The ability to intentionally grab an object in order to use it to hit another object (at this stage the grabbed object is considered to be located only at the fist, even if a long object);
- The ability to hit the other object with the end of the (long) grabbed object, when the long object happens to have been grabbed in such a way that it already extends forward;
- The ability to direct the end of an object (i.e. an object with a rod-like shape) towards another (this entails The ability change the angle of an object, relative to the hand);
- The ability to use a short rod as an extension of the hand, to manipulate rattles, blocks, etc.;
- The ability to use a short rod to retrieve objects just out of reach, by a single motion which “scoops” the object into reach;
- The ability to release a rod and re-grasp it in a better place, in order to extend the reach;
- The ability to retrieve with a longer rod;
- The ability to use a long stick to bring a distant object by a series of successive hits to each side of the object. (This is quite advanced compared to the behaviours above, and many intermediates between them need to be found.)

Existing knowledge of these intermediate abilities is quite sparse, and many studies remain to be carried out to find relative orderings and the training experiences to cause transitions. The specification for each test of intermediate behaviour must be quite detailed, to specify the conditions under which success can be achieved or not. Even the final competence of our sequence will not have the same capability to retrieve objects in tricky situations, when compared with an adult using the same stick; therefore the behaviour test must make clear exactly the minimum requirement to pass.

The sequence of behaviours for the stick above is mostly a straight ordering, and is missing the branching out that we expect to occur as we trace through the ancestors. Some of Piaget’s general hypotheses about stage transition can be used to guide the search for further necessary behaviours in this sub-graph; we can test if the general hypotheses hold true in the specific behaviours we analyse. For example, in the fifth sensorimotor stage there is an ability to recognise little motions caused by chance (e.g. when the stick hits the object and it moves a little closer, or a little further away). Piaget hypothesises that these recognitions are possible because of schemas that were learnt during the third and fourth stages. In fact Piaget does give a little more detail on what he suspects is the developmental sequence in these specific behaviours. In the retrieval with a long stick, the recognition of a movement closer or further away is hypothesised to rely on understanding of these motions which were gathered during experience with displacing objects by the support and the string [10, p. 302, top]. The understanding of the motion during acquisition of the behaviour of the support is hypothesised to rely on the behaviour of moving objects by means of a string during the third sensorimotor stage [10, p. 288]. Obviously not all infants need to learn the support and the string before graduating to the stick; in the case where the stick is learnt without the other two, the interpretation of motion (produced fortuitously) must rely on knowledge of rela-

tionships learnt earlier, probably in the fourth sensorimotor stage, such as perhaps the relationship “in front”. The basic understanding of one object being in front of another, and removing an occluder is rather simple and acquired long before the behaviour of the (long) stick. There is likely a relatively long developmental sequence to be worked out here, which could be explored by suitable tests to determine which motions can be distinguished by the infant, and recognised as leading to an object coming closer, and into reach.

This section has just outlined some behaviours that could be investigated in order to produce a graph of development. The main point of the paper is that this detailed graphing is essential in order to discover the mechanism of cognitive development via accurate computational modelling, i.e., to find the learning function which builds new knowledge structures. If we do not have detailed knowledge of behavioural sequences, then we are very unlikely to chance upon the actual mechanism in use by infants, and a computational modeller is more likely to insert inappropriate knowledge and representations, and to be misled by introspection, and the way we expect infants should reason.

Discovering a mechanistic description of cognitive development (via computational modelling) is a contribution to research in biology, because it is giving a detailed understanding of a biological system. The methods to be used will come from AI, as AI has already done a lot of work in machine learning and various representations, which can be borrowed for the modelling task.

5 Infancy Studies as a Gateway to Complete Models of Development

Infancy research holds the promise of helping to advance the larger enterprise of understanding cognitive development in humans at all ages. Infancy research may help us to gain insight into the mechanism of knowledge building at an age where it may be easier to guess at what builds on what, due to the limited set of possibilities in infancy (relative to other ages). When modelling development on humans older than infants one can only model a very small portion of the knowledge of the human, and so tasks involving selecting appropriate knowledge are overly simplified.

Reasoning by analogy is one useful example to illustrate this. Analogy is recognised to be an integral part of human cognition, but studies which investigate it [9, for example] cannot model all the knowledge which an agent has. The typical task in analogy studies is to be given an example related pair of objects “ x is to y ” and to be given a third object p , the subject must then find a fourth object q such that p is to q as x is to y . However, the object q is typically selected from a small handful of possible candidates, sometimes as low as two. This is clearly missing a major part of the problem facing a human with a more complete set of knowledge. The human must select from a vast array of possible candidates, and must choose a representation which is appropriate to the problem. At the present time one could hardly hope to model all the knowledge of an adult, and thus solve the complete problem including selection from many alternatives. However, it may be feasible to model all the fine object manipulation abilities of a young infant, and to build on these, so as to have a reasonably complete model of the infant’s knowledge; analogical tasks (such as finding analogous objects or parts of objects for manipulation) could then be studied in a more complete system.

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