A GENERATIVE APPROACH TO THE UNDERSTANDING OF COGNITIVE SKILLS *

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Abstract

We describe a new approach to understanding the functioning of the nervous system, unifying previous ideas of Josephson and Hauser [1], Baas [2], and Brooks [3]. Its basis consists in analysing the total developmental process into basic components of development, whose corresponding mechanisms (skill constructors) are organised together into a coherent total system.

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1 Introduction

In this paper we describe a new approach to understanding the functioning of the nervous system, developed from previous work of Josephson and Hauser [1] and Baas [2]. Its essence lies in envisaging mature capabilities as the cumulative outcome of a large number of small advances in capability. Each such advance is assumed to be associated with a particular generative mechanism, so that the nervous system as a whole can be viewed as an organised collection of such generative mechanisms, each specialised to some particular generative process. Just as in the case of a factory, the products of one kind of generative mechanism are handed on to other such mechanisms for further constructions to be carried out.

The research agenda associated with the approach indicated above is essentially the following: (i) the developmental process is analysed into elementary steps of development (ii) models are made of mechanisms that could mediate such steps and (iii) on the basis of these models, the elementary mechanisms are integrated into an entire system. The mechanism aspect is essential in this approach, since it is mechanisms that integrate elementary functions into more complex ones (elementary illustration: a lighting system consists of three functional systems, the electricity supply, light sources and switches. These components must be connected together in the right way for the individual components to function correctly).

Such mechanisms might be modelled at a variety of levels, of differing degrees of abstraction, models at one extreme being highly mathematical, and ones at the other attempting to reflect closely the details of the actual nervous system.

2 General principles

2.1 Self-organisation and diagnosis

Models of this general kind, with complicated mechanisms being built up from simpler components having a simpler function, have been developed previously by workers such as Marr (models of vision) [4] and Brooks (robotics) [3], and these indicate the meaningfulness and practicality of such an approach. What is proposed here differs crucially from the work of Marr and

Brooks, however, in the *self-organisation* aspects of the mechanisms concerned. The mechanisms, by examining their own performance, are able to diagnose imperfections in the functioning and make changes that improve on them. We do not have to start off with skilful machines; it is sufficient to have primitive mechanisms that crudely approximate to what is needed, combined with diagnostic mechanisms adequate to repair the defects in the initial performance, until an acceptable level (acceptable in terms of the kind of environment in which the organism will find itself) of competence is eventually reached.

In this latter kind of picture, it is not enough that the system as a whole contain various mechanisms for constructing skills. It must at the same time deploy the mechanisms concerned in an appropriate manner, that is to say at the appropriate times, and to the right extent. Thus the *processes of development* involve more than the *mechanisms of construction* already considered. Many factors will affect the efficiency of the constructive processes, for example the way the person concerned searches for new situations in which to attempt to develop skills, and the ability to utilise the knowledge obtainable from others. In the last analysis, these factors must all be implicit in the nervous system design. To design such a system without any clues from nature would be extremely difficult, but the knowledge of how children develop in actuality can simplify the task of understanding these matters.

We hypothesise that for each construction mechanism, and process constructed, there is an associated activation of the nervous system, which triggers off particular secondary processes, and leads to the system having a specific orientation for the relevant period of time, generally persisting as long as the system receives reinforcing cues indicating that it is being effective, but modulated by other relevant factors. Over the course of time, higher order skills develop that use earlier constructions and take over command of their use (cf. [3]).

We have indicated that development occurs partly through the agency of mechanisms able to diagnose imperfections. In general, diagnosis can be defined as any process that leads, through the results of observation, to the improvement of a system or skill. On this basis we can distinguish between innate diagnostic systems that have evolved through natural selection, and diagnostic systems acquired during the life of an individual or culture as a result of the observation that a certain action in a given situation has beneficial consequences. The ‘credit assignment problem’, that of deciding whether a particular process is actually the one responsible for a particular improvement, seems to be solved in practice by having a mechanism that treats such a process as tentative (making a 'provisional link') and observes its effects over an extended period, developing a tendency to excite or inhibit that process as a result. Eventually such a process may be linked in to the system in such a way that the process is activated automatically, the system then being in the position of having to find ways of coping with any adverse consequences of so doing.

2.2 Illustration of a generative mechanism

As an illustrative example of a specific generative mechanism, take the process of rising to a vertical position, which has a pivotal role of providing the initial situation in which locomotion by means of walking can take place. We hypothesise that there are specific circuits to mediate this process. When they are activated they may, in the earlier developmental stages, activate certain 'instinctive movements' possessing the feature of causing the body to tend to rise, combined with holding on to objects for support. They then evaluate the outcomes in particular ways and make modifications in the direction of rising as far as possible, and being as nearly balanced as possible (which can be judged in terms of the amount of effort involved in holding on to a support). The proprioceptive system can be primed to learn these nearly balanced states and thus guide further attempts, which can be made with gradually reduced support from objects.

2.3 Top-down considerations

In the phrase 'construction of skills', there lies implicit both bottom-up and top-down mechanisms. The word construction implies putting components together to make larger units, leading by a process of accumulation to the formation of a hyperstructure as described in [2]. On the other hand, a prescribed skill can be considered as a whole that, given mechanisms that cause the skill to emerge, places constraints on how the parts behave. There is an analogy between this and the way that in a laser the microscopic systems create the macroscopic field, while at the same time the macroscopic field acts back on the microscopic systems. In human systems there are a number of high level systems that behave in this kind of way, for example the life that an individual chooses to live (which is partly a product of his skills and partly the determiner of the skills that he acquires), the modes of being of a society, the particular language of a society and so on. To take the laser analogy further, the selection of a process to attempt corresponds in the laser to selection of a mode to excite, while errors correspond to attenuation mechanisms, so that effective diagnoses have the effect of reducing errors and hence allowing the relevant mode to grow.

At a less all-embracing level there are cases of limited specific fields of endeavour, as can be typified by the example of rock climbing. Such a category of projects poses especial difficulties, the overcoming of which can be equated with the possession of particular skills. Acquisition of such skills expands the range of problems that can be tackled in the given domain. The mutual relationships between skills and domains of endeavour provides a natural mechanism for the marking out of particular domains for development by an individual or by a culture, which selection has marked effects on subsequent advances, especially facilitating particular possibilities.

3 Further examples of construction mechanisms

So far we have been discussing constructive mechanisms almost entirely in general terms. It is now time to consider more specific examples in detail. The main principle in analysing these is firstly the idea that there are very specific skills that play a pivotal role in development and act as stepping stones to higher achievements, and secondly the concept that there should be interrelationships between skills that facilitate the construction of one skill on the basis of the possession of others.

3.1 Walking

Our first example is the process of learning to walk, where we have already discussed the potentiating skill of rising to a vertical position (itself supported by the auxiliary skill of getting support from objects). Subsequent pivotal skills include being able to stand without support, taking single steps, progressing without support and without falling over, walking to a visible object where there are no intervening obstacles, etc. These skills have the desired feature that it is in some sense a straightforward task to advance from possession of one skill to the next. For example, when the above progression has reached the stage where the child is able to assume a standing position for a moment then further processes can be invoked centred around the process of balance involved in sustaining such a situation over a period of time. Again, after the skill of balancing in a standing position has been achieved then, given the appropriate hardware, the compensations that apply to ensure balance while standing can be usefully used as components of a system to avoid falling over while walking. On this basis, initially small but gradually greater steps in the direction of expert walking can then be taken, under the control of the generative system that oversees this part of the process.

Let us now skip a few stages, and go on to consider the transition from the ability to walk without falling over to the skill of walking to a location which is visible and where there are no intervening obstacles, again a pivotal skill in that it gives the person some ability to be located in a place other than where he currently is should another location be more suitable for what he wants to do. This transition can be modelled in terms of Brooks' concept [3] of adding additional layers to an existing system to give it more advanced capabilities. A basic walking system contains no provision for making changes in direction, but this can readily be included by adding new systems to the design. Firstly there can be incorporated into the system architecture signals intended for directional control, which affect the motor centres in such a way as to cause a person standing or walking to change direction. Such movements will affect balance and so the systems responsible for balance must relearn balance again in the new situation. When this has happened, a new specialised diagnostic system can become active that is sensitive to relationships between the direction of walking and objects in the visual field. Training algorithms can then teach a system driven by appropriate visual information to generate the appropriate directional signals, the ultimate aim of such a system being that of being able to achieve a 'balanced' situation where walking without applying directional control leads to a situation where the direction of the selected object does not change significantly when one approaches it (or alternatively one of controlled unbalance leading to passing on the side of an object).

3.2 Thematic mechanisms

How does the cognitive system develop beyond the stages discussed so far (leading to being able to walk directly to a visible location)? We explain these processes in terms of the nervous system having built-in capacities to handle particular *themes*, such as obstacle, gap, search, route, preference and alternative. These themes correspond to particular abstractions that can be usefully made in particular situations, and which are able to mediate further constructions of various kinds.

3.2.1 The route theme

As an example, the route or sequence theme is one that can be invoked to record, using some symbolic representation, the sequence by which a certain situation is arrived at. The hardware that does the recording must have the feature that the sequence information can be unpacked on a later occasion and used to repeat the sequence either exactly or in some modified form, e.g. with skips or insertions.

Informally, the sequence mechanism is able to mark the route the first few times until the person has had a chance to learn to retrieve the route without having to make use of this dedicated mechanism. The mechanism thus acts as a *bridge* between a simpler situation and a more advanced one. One may for example first of all be in a situation A and get to a situation C via an intermediate situation B, and then later when one is at A evoke, using the sequence mechanism, the sequence ABC again, and then follow it up in actuality if the outcome C is a desired one. Bottom-up constructive mechanisms of this type combine with mechanisms that try to adapt the totality of what is learnt to the demands of higher level skills, as a result of which there is strong selection in favour of what is most useful in an individual's life.

3.2.2 The obstacle/problem theme

Equally crucial is the theme of there being an obstacle or problem, an occasion for the theme being invoked being the failure of a process that normally succeeds. There may be various diagnostics specific to locating or defining a problem, and special mechanisms are required for integrating the resolution of the problem that may be found into the original activity. Again we have the situation where specialist mechanisms can form a bridge between a simpler situation and a more advanced one.

3.3 Symbolic activity

We move on now to consider a different avenue of development, that associated with symbol use. We conceive of symbols in the following terms. A symbol has power through its having a referent or referents. The kinds of constructive processes we have been referring to lead accumulatively, through an exploration of what is *possible*, to the symbols being related to their referents in more and more subtle ways, always consistent with the demands of utility. For example, a symbol may initially be created in response to a perceived object, and a link formed between it and the activities of the nervous system related to the actual perceiving of that object. Other links may be created with more complex situations involving the object, for example with the skill of *looking for* the object; in such a way the invocation of the symbol can become a means of finding the object, and then built into higher skills. Or, again, it may be used in connection with the process of *anticipating* an event. Further possibilities have been described in the theory of language due to Josephson and Blair [5].

4 Innate vs. constructed mechanisms

We hope that the above has given a hint of the way powerful structures can come into being on the basis of a collection of basic constructive mechanisms. The answer to the question of how many there are in the collection would seem to be ‘as many as are needed to do an efficient job’. The discipline of artificial intelligence has shown that many different processes are required to do even the simplest operations effectively. But these processes do not all have to be innate if they can be constructed, and if they can select themselves out of the many possible constructions by virtue of their effectiveness in the life of the advancing child.

5 Transformation and emergence

We conclude with a more mathematical, or at least pre-mathematical, account of what has been described above (cf. [2]). The generative mechanisms mediate *transformations* on existing behaviour, and these transformations lead to the emergence of new features. There is selection in favour of particular features, the totality being end-directed: in other words, the features selected for must be such that a chain of transformations can lead to the desired end result. This account is however a gross oversimplification, in that a relevant feature such as 'capacity to understand a language' is not a simple Boolean variable but some kind of distribution of competence.

One may also see the transformations as opening up windows into spaces of possibilities. The spaces must be large enough to include the domains that are of value, but there must also be restrictions that ensure that the period of development is a period of time that is effectively spent. In this the individual's culture plays an important role, since a culture, with its collective experience of many individuals over many generations, can know about what is useful to know in a way an individual of that culture cannot.

6 Concluding remarks

The approach advocated here differs from most in the emphasis it places on the *constructive* capacity of the nervous system, and the advantages of flexibility that results from the course of development not being laid down in detail but discovered by trial and error. On the other hand, it insists that development is not a process of *blind* trial and error: it is desirable for particular processes to be performed, and advantageous to have mechanisms designed especially for them. However, it avoids postulating ill-specified mechanisms such as a 'language acquisition device' by insisting (in line with the analysis in [5]) that these complex developments be broken down into their elementary steps of progress, and that these be understood individually. In this way we may hope to have arrived at a very practical way of probing the extreme complexities of the development of human cognitive abilities.

References

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