Dealing with the Unexpected

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Abstract

Typically, we think of both artificial and natural computing devices as following rules that allow them to alter their behaviour (output) according to their environment (input). This approach works well when the environment and goals are well defined and regular. However, 1) the search time for appropriate solutions quickly becomes intractable when the input is not fairly regular, and 2) responses may be required that are not computable, either in principle, or given the computational resources available to the system. It may seem that there is no way to deal with these conditions, but if we think of systems as dynamical non-equilibrium autonomous entities, there are ways to deal with the unexpected and irregular by taking advantage of self-organising and self-preserving capacities of such systems. A generalised force acting on a system far from equilibrium will cause the system to reorganise itself in the direction of the generalised force in such a way as to minimise its effects (Nicolis and Prigogine, 1977), but there can be unpredictable effects in different generalised directions in the system's phase space. In order to preserve system integrity, these effects must be damped or used for further self-reorganisation, possibly starting a cascade effect that leaves the system in a substantially different state in which it can handle further instances of this sort of information. This model is similar to and extends the theoretical model of accommodation and assimilation of Piaget, derived from his observations of the development of intelligence in children.

Keywords: systems, self-organisation, adaptation, unpredictability, autonomy

1 Introduction

Typically, we think of both artificial and natural computing devices as following rules that allow them to alter their behaviour (output) according to their environment (input). This approach works well when the environment and goals are well defined and regular. Simple examples are thermostats controlling heating and cooling devices, and governors on engines that control their maximum speed. Even complex problems, such as playing chess, have been implemented on computers to the extent that they can beat expert humans. At some level, we could devise a machine that could compute any computable function, and consequently deal with any regular input and goal. However, 1) the search time for appropriate solutions

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quickly becomes intractable when the input is not fairly regular, and 2) responses may be required that are not computable, either in principle, or given the computational resources available to the system. In other words, in the second case, the goals may not be defined in advance. It may seem that there is no way to deal with these conditions, but systems that are dynamical non-equilibrium autonomous entities have ways to deal with the unexpected and irregular by taking advantage of self-organising and self-preserving capacities of such systems.

The way such systems deal with these conditions is similar to the model of accommodation and assimilation developed by Jean Piaget (1963, 1971) in which, as a continuation of the biological processes of variation, selection and retention (VSR) the structure qualities and dynamics of the external environment come to be represented or encoded in the organism itself. Piaget's views can be construed as requiring a priori categories of development, but he is deeply ambiguous about this, and I will construe him as regarding mental development as contingent on input and the current state of development and organising resources of the organism (the human child in most of Piaget's studies).

I will suggest that variation, selection and retention are not sufficient to explain the accommodation and assimilation of the unexpected, partly because they are just too slow to explain the speed of mental development, but also because it is increasingly recognised that self-organising processes play a significant role in biology itself (for instance, see Brooks and Wiley, 1988; Kauffman, 1993; Depew and Weber, 1995; Collier, 1998). If mental development is a continuation of biological processes at the more flexible level of mental adaptation, then we might expect self-organisation to play a role there as well. Part of the reason why VSR processes are slow is the separation of the various stages, in which the variants have to be compared to a selective template, and then retained. Self-organisation involves self-selection by the same processes that both produce the variants and lead to stabilisation and retention, combining the separate VSR processes into one self-supporting process.

2 The Unexpected

Much of the environmental input to a system will not matter to the system, either because it is irrelevant or else it is so disruptive that the system does not have enough energy or finesse to avoid its destructive power. We might call this *noise*. For example, taps on a thermostat are not part of its designed input. They might not affect its operation at all. On the other hand, they may be strong enough to make it malfunction or even destroy its operation. Ironically, a tap on a malfunctioning thermostat may set it back to proper functioning. This would be a case of an unplanned input realigning the components of the system so that it functions properly. This sort of input and consequence, familiar to most people who work with machines, is accidental, in the sense that it is not a part of the intended design of the device. (I find my computer responds well in this way when, if it suffers regular lockups, I turn off the power and tap the motherboard and some of its components lightly.) The beneficent results of the tap are coincidental, though it would be possible to design thermostats that would tend to respond favourably to light taps when they are malfunctioning. In this case the tap is more akin to a third sort of input. This sort of input the system accommodates by rearranging its internal state, and perhaps its behaviour as well, via information the system has already encoded as rules, either deterministic or heuristic. We might call this *signal*. Perhaps the most familiar example these days is the input to a digital computer in the form of a program and data. Other examples that are less deterministic are inputs to trained neural nets, which sometimes output the correct result, but sometimes do not. Speech recognition devices have this property. Their rules are heuristic, though their operation is deterministic.

This paper is concerned with inputs that are neither signal nor noise, that is, inputs to which the system can, under the right conditions, creatively adapt to and preserve its overall functionality. We might call this the *unexpected*. Strictly, unexpected inputs are not anticipatable, but as I shall argue, the organisation of a system can make a huge difference in how successfully it can deal with the unexpected. At a very simple level, for example, while driving a car we might scan the sides of the road and rear view mirrors in order to deal with unexpected events, such as a child running out on the road. I say this is a simple case, since the only thing that distinguishes it from the signal case is that the particular circumstances determine the appropriate evasive action, and there may be no rules for what is correct in every situation. A creative reaction like steering into a lamp standard instead of hitting the child might be the best solution. In more complex cases, the input may not even be recognised as a signal, but the effects on the system would be disruptive unless action within the scope of the system's capacities were taken. I will focus on the sort of system organisation required to deal with this sort of unexpected input.

3 Accommodating the Unexpected: Physical Systems

These more complex cases require the creation of new information within the system that allows it to both accommodate and assimilate the unexpected input (see Piaget, 1963, 1971). Any system that can create new information must do this through self-organising processes. This places certain requirements on the system, especially that it be both energetically and informationally away from equilibrium (see Collier and Hooker, 1999). A generalised force acting on a system far from equilibrium will cause the system to reorganise itself in the direction of the generalised force in such a way as to minimise its effects (Nicolis and Prigogine, 1977; Prigogine and Stengers, pp. 146-159), but there can be unpredictable effects in different generalised directions in the system's phase space. In order to preserve system integrity, these effects must be damped or used for further self-reorganisation, possibly starting a cascade effect that leaves the system in a substantially different state in which it can handle further instances of this sort of information. When the process is complete, the system reaches a new quasi-steady-state, and has assimilated the unexpected input. Ideally, this should occur in such a way that prior function is not lost, and the new functions are integrated into the overall functionality of the system. This places fairly severe constraints on the sort of system organisation required. Modularity (the partial decoupling of system self-interactions) helps by limiting the spread of unpredictable effects. Furthermore, a certain amount of vertical integration is required to coordinate the various changes.

3.1 Effects of Forces on Far From Equilibrium Systems

Non-equilibrium thermodynamics can be thought of in terms of forces and flows, like all dynamical systems. It is often simpler to use generalised coordinates rather than standard Cartesian or polar coordinates, since these reflect better the actual organisation of the system, and generally simplify models by eliminating invariant constraints. A simple example is a bead constrained to move on a hoop. In polar coordinates, we have the radius an angle, but if we consider the constraint to movement on the hoop, the problem becomes one dimensional. In near to equilibrium thermodynamics, in which the fluctuations are greater than the gradient, it is possible to use standard equilibrium methods, and deduce that the system will produce minimal entropy locally (Prigogine , 1961). For far from equilibrium systems, the dynamics are much more complicated. Prigogine hypothesised that the entropy production in the generalised direction of the application of a force, in this case an entropy gradient, the entropy production in a coordinate in the generalised direction is minimised, but that in other coordinates the entropy production is not, in general, predictable (Prigogine and Stengers, p. 140, 145). Each particular situation has to be treated as a separate case in terms of its long term behaviour. This is a consequence of the non-linear interactions among fluxes and forces in such systems. In near to equilibrium systems, the system reaches a steady state, but in far from equilibrium systems this cannot be taken for granted. Effects will propagate through the system until the applied force is fully dissipated. If the applied force is applied over time, the system may never reach a steady state. Interestingly, however, in certain systems fluctuations can lead to phase changes in which the whole system reorganises, and falls under a new dynamics. The classical example is the simple Bénard cell transition from the conducting to convecting state. Due to the constraints on the system (implying low dimensionality), Bénard cell dynamics are highly regular.

3.2 Self-Organisation and the Formation of New Levels

Self-organisation in systems like Bénard cells, and the Brusselator and its relatives are by now so well known that I will not take up space describing the processes involved. These systems are also of fairly low dimension, and show consequent overall order. More complex systems the reorganisations can cascade, leading to changes far from the original source. In each of these case, new organisation is formed that is at a higher level that previously. By this I mean that the order of the new organisation in terms of its Shannon redundancy level, the size of the units required to recognise the redundancy, increases. This implies a larger scale integration caused by the imposed forces. A similar effect can be obtained in lower dimensional systems by increasing the applied force, resulting in a larger gradient. At low gradients, the system can bifurcate into cells that may have differing properties and dynamics. As the gradient is increased, further bifurcations occur, until at a certain limit it goes into chaos. The mathematician, Jonathan Smith, has shown that this limit is fully analysable combinatorially. For continuous systems, however, in which the cells can interact with each other non-linearly, it is not clear that such a combinatorial treatment is possible. Thus the bifurcation route to chaos in relatively low dimensional systems should not be confused with what might happen in more complex systems. This does not mean, however, that more complex systems cannot reach a new steady state, with non-linear interactions among its cells providing an even higher order of integration. Certainly this result is not necessary; it is only possible under certain conditions. The system must be so organised that it preserves its overall cohesion as it accommodates the impinging forces. This is exactly the sort of system that I have called *autonomous* in previous papers for CASYS (Collier, 2000a, 1999, also 2000b). Autonomy is characteristic of biological systems, with their low energy wells, and high organisation, permitting them to be sensitive and adaptive to inputs, but as I emphasised in these papers, the same ideas can be applied to machines and their design. Complex systems without autonomy are much more likely to respond to impinging forces with increasing disorganisation, and even disintegration.

3.3 The Accommodation of Impinging Forces

There are basically three ways that far from equilibrium systems can respond to impinging forces (or information, which is a form of energy with special properties). If the system is relatively simple and well-constrained, it is likely to reach a steady state with a new higher level dynamics, with further bifurcation into independent cells as the applied force increases the gradient. Most complex systems will respond by breaking up into cells with complicated and disorganised non-linear interactions, perhaps even leading to their disintegration. Autonomous systems, however, accommodate impinging forces by reorganising themselves through a cascade away from the direction of the applied force, just like the previous sort of system, but they can respond with increasing organisation among the cells, creating even higher levels of integration. These changes assimilate the unexpected forces, since the new level of integration will merely be perturbed if the same sort of force impinges again, since their new organisation allows these forces to be channelled through the same pathways that were formed, reducing its effect, and at best producing redundant effects that fall under the highest level of newly formed organisation. The analogy to Piaget's process of accommodation and assimilation in the development of intelligence and understanding in terms of stages and levels is too striking to ignore, and I will now turn to the examination of the analogy.

4 Piaget's Process of Accommodation and Assimilation

Piaget's views on the development of intelligence and knowledge are closely tied to biological ideas. They are basically adaptation by other means, and he considers them to be continuous with biological processes (Piaget, 1963, 1971). On the other hand, Piaget was strongly influenced by structuralism, which does not sit well with the dynamical approach

I have taken in discussing physical systems and impinging forces they were not designed to accommodate. We might take this to be a strong disanalogy, making any analogy superficial. On the other hand, Piaget regarded development as a process, which is surely a dynamical idea, in fact a process continuous with biological processes. Some of his examples are certainly structural in nature, but this, I will argue is due to the highly constrained aspects of the processes. Piaget's work has been criticised both empirically and theoretically for its emphasis on stages and the formation of structures within the developing child. A close reading of *The Origins of Intelligence in Children*, however, shows a lot of hedging on these issues, not to mention some outright denials that stages proceed in a definite and regular way. Furthermore, to some extent structure and organisation are interchangeable, though their connotations are certainly different. In essence, I am going to argue that the analogy is quite strong, if not an identity.

4.1 Assimilation and Accommodation

Piaget regards adaptation as an equilibrium (more correctly, a steady state) between assimilation and accommodation. First the organism assimilates an input and then accommodates to it by reorganising itself (in simple cases, altering its behaviour), so that it can deal with future similar inputs in a regular way. He regards this process as continuous with biological adaptation, on which he has a Lamarckian view that modifications in behaviour can lead to genetic changes. His view is not derogative in the usual sense of Lamarckianism, but is compatible with current biological theory, including views of the interaction of genes and culture (Lumsden and Wilson, 1981; Boyd and Richerson 1985). One of his primary examples is the shell-less mollusc Limulae, which take an elongated form in placid environments, but take a circular form in turbulent environments. The circular form eventually becomes fixed genetically. We might say that the Limulus assimilates the turbulent environment, and then accommodates to it. Piaget does not deny natural selection, but he is more interested in processes in which behaviour plays a role in adaptation. This is partly to support the continuity of biological and neurological processes. For this reason, he pays much attention to reflex and instinct, which are primary biological functions with behavioural effects (Piaget, 1971). Neurological adaptation builds on these to produce mental development.

Reflex is highly constrained, and in (Piaget, 1963) it forms the basis for the first stage of mental development. At that time he did not give such a large role to instinct. Since reflex is highly constrained, by the reasoning of section 3.3, the effects on the organism to unexpected inputs will be a relatively rapid approach to steady state, which is what we find in the first stage of development, which occurs in young babies. For example, Piaget describes sucking reflexes, which is first stimulated by a variety of things, and comes to be primarily focussed on the nipple, though there are wide variations in the process. Accommodation results from the modification of the activity of the reflex to focus on the source of nutrients. The result is the adaptation of the sucking reflex for nutrition (though other variants also occur). Because reflex is so constrained, the process looks rather mechanical, and fits easily into models Pavlovian conditioning, or behaviorism. As Piaget summarises, "Accommodation exists because ... the reflex mechanism needs the environment. Assimilation exists because, through its very use, it incorporates to itself every object capable of supplying what it needs, and discriminates even these objects ... Finally, Organisation exists, inasmuch as organisation is the internal aspect of this progressive adaptation. Piaget calls these adaptations "primary circular reactions", and also applies the notion to the development of vision and the ability to focus on interesting objects. His observations strongly support the progressive nature of these adaptations: they are neither sudden not efficient.

On the other hand, instinct is much more like acquired intelligence, in that it works with *schemata* that need to be filled out with environmental information. Instincts are also often social in nature (consider for example the sexual instinct), and require trans-individual coordination, much like acquired intelligence. Instincts differ from acquired intelligence, however, in that the schemata are innate, based in fixed aspects of the organisational structure of members of a species. Schemata play a major role in phenotypic and cognitive adaptations (Piaget, 1971). It should be noted that schemata are not purely cognitive, any more than instincts are. They contain both cognitive elements and motivational elements that give direction to cognition. Schemata are thus dynamical elements, and are subject to dynamical principles. Adaptation is basically the formation of new schemata that are integrated into the overall organisation of the organism, which maintains its overall organisation (what I have called in previous papers a kind of cohesion called autonomy Collier, 1999). I don't have the space here to go into a detailed account of Piaget's empirical observations or stages of development, which have been criticised at any rate. Some degree of stages are required for the recursive process of development, and the disagreements are mostly about the details. The more significant aspect of his work for this paper is the coordination of assimilation and accommodation to change the organisation of the organism so that it can make future anticipations. Piaget notes that neither assimilation nor accommodation can exist on its own to produce adaptations, since in either case the change is only temporary. The dual process is required for adaptation through changes in the organisation of the organism.

4.2 Non-Equilibrium in Piaget

I now turn to the role of non-equilibrium processes in Piaget's account of adaptation. Firstly, as Piaget notes, the neurological system is open, receiving information (stimuli) from the environment. This is a primary condition of self-organising systems. Secondly, the original state is not random (at informational or thermodynamic equilibrium), since instinct, reflex and other hereditary factors have a definite but flexible structure, creating a difference between maximum entropy and actual entropy of the young organism. Lastly, there are many potential neurological connections that are not fixed, and only certain of these connections are made in the adaptive process.

On my interpretation of Piaget within the framework of non-equilibrium systems, assimilation is a response to a force applied, whit the initial response being a reduction of entropy production in the generalised direction of the applied force. This permits the relevant neurological circuits to respond to the stimulus by reducing their difference from the stimulus. Side effects, however, are a cascade of peripheral forces throughout the neurological system. This leads to further assimilations in different dimensions. Eventual dissipation of the initial stimulus leads to an equilibrium state. Assuming that the organism is autonomous, this does not disrupt its overall organisation, but it does have the potential through self-organising processes to produce higher level order within the nervous system. This has two aspects. The first is the formation of local accommodations, and the second is due to the non-linear interaction of these local accommodations to produce higher level integration through a continuing process of self-organisation. The overall result is a steady state in which the assimilated stimulus is fully accommodated. Note that in agreement with Piaget's claim that assimilation and accommodation are inseparable, the cascade of assimilations and accommodations constitute a continuous process leading to steady state in which it is possible to deal with further similar stimuli without altering the organisation of cognition, and anticipation becomes possible through the integration of local assimilations and accommodations.

4.3 Some Requirements for Non-destructive Adaptation

As mentioned above, one possible response to impinging stimuli is the disorganisation or even complete disruption of the system. This is probably possible even in autonomous systems, since there are limits to their cohesion. If we consider the mind alone, possible results are various forms of mental illness, most of which have an environmental component, even if they have a hereditary component as well. A less severe response is continuing cognitive dissonance, which may or may not be resolved eventually, sometimes by the adoption of bizarre or superstitious beliefs.

In order to avoid such problems, autonomy should have considerable logical depth, meaning that it is highly organised and integrated at a high level. A further way to damp non-adaptive or maladaptive response is through modularity of function, so that disturbances of one function does not disturb other functions. There is evidence that the structure of the brain supports such functional modularity through the separation of various linguistic functions, visual functions, and sensorimotor functions. Further modularity may exist that is not structurally evident, since function and structure are only loosely related. This sort of modularity has been proposed by Collier and Hooker (1999), and seems to be required for logical depth, though it does not imply it.

Another aspect of the assimilation/accommodation model of adaptation is the rather slow progress of the process. Self-organisation is inherently more gentle than forced organisation in the same way that a forced oscillator away from its resonant frequency requires more power input than it does near its resonant frequency (Collier, 1999; Collier and Burch, in press). This principle applies generally to self-organisation, which depends only on the properties of the system. Thus we might expect the assimilation/accommodation process to be fairly gentle in most cases.

5 Conclusions

The ability to adaptation to unexpected and anticipatable input places certain constraints on a system, including the ability to self-organise both energetically and informationally, the ability to limit unexpected results of this self-organisation, modularity, and the ability to vertically integrate new organisation, ideally all without losing prior functionality. The model presented is based in far-from-equilibrium dynamics in which the system first accommodates and then assimilates the information in the unexpected inputs. This model is similar to and extends the theoretical model of accommodation and assimilation of Piaget, derived from his observations of the development of intelligence in children. The model presented here does not depend on cognitive factors, merely an underlying dynamics of the right sort, so it should apply as well to biological and mechanical systems, and not just humans.

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