The Essence of Embodiment: A Framework for Understanding and Exploiting Structural Coupling Between System and Environment

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Abstract

A framework for understanding and exploiting embodiment is presented which is not dependent on any specific ontological context. This framework is founded on a new definition of embodiment, based on the relational dynamics that exist between biological organisms and their environments, and inspired by the structural dynamics of the bacterium *Escherichia coli*. The definition draws on the idea of mutual perturbation between a system (biological organism, robot, or software agent) and its environment, enabling structural coupling between the two. The framework provides a vocabulary and concepts that can be used to discuss and analyse embodiment in any kind of environment, not just the material world. Rather than blurring boundaries between disciplines and domains, this permits the characterisation of distinctions and common features between them, in a manner meaningful to all parties. Other benefits include the potential quantification of embodiment, and access to practical and theoretical ideas associated with material embodiment for those working with *non*-material systems. The relational embodiment definition is illustrated by ongoing experimental work in which the relational dynamics that exist between *E. coli* and its environment are applied in a variety of environments, both software and material, using a Cellular Automata-based system with artificial 'sensory' and 'effector' surfaces. This experimental system is also used to outline a biologically grounded, dynamical systems-based approach to the generation of behaviour in a variety of operational environments, exploiting features of the embodiment framework presented.

Keywords: Embodiment, Structural Coupling, Cellular Signal Pathways, Environmentally Coupled Cellular Automata, Emergent Behaviour.

1 Introduction

The concept of embodiment is highly significant in terms of the theoretical perspective that it engenders and its practical implications. It also lacks a precise definition. Typically, 'embodiment' is used to connote a system, either biological or robotic, that is situated in the material world (otherwise known as 'The Real World'). Whilst the notion of material situatedness is perfectly reasonable as the basis for an operational description of organisms and robots, it invites further questions that it is not equipped to answer, particularly 'what is it *about* the relationship between materially situated systems and their environments that is special?' and 'what about embodiment in non-physical contexts?' Researchers pose and answer such questions in terms that are appropriate to the operational domains in which they work. Opportunities for cross-disciplinary exchange are then lost, as potential conceptual and operational similarities are buried beneath domain-specific terminology. Even assuming a willingness to 'trade', a great deal of effort is required to translate and transpose ideas, as is evident in Kushmerick (1997).

This paper argues that being embodied in an environment is significant because of how this conditions the *relationship* between system and environment. Embodiment, and instances thereof, can be discussed in terms of features of this relationship. We identify suitable features, which are used to define precisely and minimally what it means for a system to be embodied.

This relational approach permits exploitation of the distinction between analysis and analysand. A major appeal of systemic analyses is that a single model can be applied to different instances and different types of thing. Similarly, the 'stuff' of an embodied system and the environment in which it is embodied is taken to be irrelevant except in so far as it impacts on the *relationship* between them. This is the sense in which we refer to the 'essence' of embodiment. Using such an approach, it is possible to talk of embodiment in many different domains, using a common vocabulary that articulates both commonalties and significant distinctions—for example, the noisiness and unpredictability that is associated with The Real World (Brooks, 1990).

A relational definition of embodiment also represents a valuable conceptual bridge for disciplines that wish to exploit the powerful theoretical perspective that embodiment typically represents, but which are not blessed with materially endowed systems. For example, the phenomenological underpinnings of the embodiment perspective, discussed below, are an appealing feature for many working in ALife. However, an insistence on materiality in embodiment is clearly problematic for a discipline that typically deals with *non*-material entities—a problem that becomes more serious if one adopts the position that embodiment is a necessary condition for the synthesis of at least some forms of life-like behaviour.

Crucially, the relational model proposed here is also *quantifiable*, through parameters of the system-environment relationship. This is an important feature for behavioural robotics, offering the possibility of measuring the extent of the embodiment of particular systems.

2 Embodiment in Action

In this section we look at different uses and interpretations of the notion of embodiment, from its theoretical grounding in philosophy, to its application in contemporary disciplines associated with computer science. We suggest that there is an underlying theme that exists across these different contexts. Regardless of the stance that is explicitly taken on the meaning of 'embodiment', its significance is almost invariably analysed in terms of how it impacts upon and conditions the *relationship* between an embodied system and the environment in which it is embodied.

2.1 Embodiment in Philosophy

To philosophers, embodiment represents a perspective that stands in stark contrast to the Cartesian mind-body dualism underpinning the 'traditional' forms of cognitive science and Artificial Intelligence. Rather than characterising the body as an (at best) insensible support and input/output system for the generative apparatus of the mind, the entire human agent is seen as a material system which is born, develops and reasons through material action and interaction in a material environment. As well as providing grounding for powerful critiques of traditional AI—see Dreyfus & Dreyfus (1985); Dreyfus (1979); Winograd & Flores (1986) for some classical examples—the embodiment perspective offers intriguing possibilities, for example, grounding phenomena such as semantics and intentionality in the direct interplay between agent and environment.

Why is being a material thing in a material environment so significant? To suggest that material embodiment 'just is' special amounts to physical vitalism. There must be some particular feature or features of how physical embodiment impacts on the *relationship* between embodied agent and environment. For example, a specific material form in a material world impacts on the possibility to act by making some interactions between body and world likely, others necessary, others impossible. There is nothing inherently material about the 'possibility to act', except in so far as one posits a material domain for action. Being a material agent is not directly significant, rather it is how qualities of this feature in particular cases condition the interplay between material agent and material environment that is significant. Dreyfus makes a point that supports this interpretation, with regard to Merleau-Ponty's use of embodiment. Dreyfus suggests that relatively little emphasis is placed on the actual form of the human body, but rather on qualitative features thereof, such as the capacity to act, the 'I can' — the ability to "respond to situational solicitations" (Dreyfus, 1996).

2.2 Behavioural Robotics and Sensorimotor Dynamics

Behavioural Robotics has generally been content to work with the 'materially situated system' interpretation of embodiment. This does not seem unreasonable, given that robots are just the sort of thing that people would be happy to describe as 'embodied', without worrying too much about what that might really mean: after all, robots certainly are materially situated things. A variety of researchers have established just how this fact can be meaningfully and very effectively exploited (Brooks, 1990; Mataric, 1992). Similarly, the challenges created by the fact of robots being material things in a material world are also frequently remarked upon.

However, such reflections on the *consequences* of embodiment leave untouched the question of exactly what it *means* to be 'embodied'—yet because that very term appears so often in the literature of Behavioural Robotics, this is easy to overlook.

Within Behavioural Robotics, this gap is covered, superficially at least, by the default notion of 'a materially situated thing'. The lack of a precise definition can still have troublesome consequences though—for example if one wishes to quantify embodiment, to capture more exactly the different ways in which robots can be embodied in their environments, an issue raised by Dautenhahn (1997).

A further consequence of this definitional void is that when analysing a particular embodied system or class thereof, roboticists must invent tools and a vocabulary for filling in details about embodiment. It is revealing to see how often this is achieved through appeal to the relationship between system and environment.

This is most evident in the work of Randall Beer, who appeals directly to the notion of behaviour as the interplay between coupled dynamical systems over time. Beer shows how, at least in relatively simple cases such as insect walking gaits, the emergence of behaviour can be understood by mapping out features such as the correlation between sensory and effector activity, and the trajectories of effectors through state-space (Beer, 1995; Chiel & Beer, 1997).

It is interesting to note that even those who focus explicitly on material embodiment often explain the features of their approach through appeal to both the dynamics inherent in their systems' structures, and the way in which these structural dynamics reflexively relate to the environments in which they are observed. For example:

> *The realisation of these control tasks [does] not happen by means of functional modules with clearly defined interfaces. It is achieved by dynamically interacting processes that are tightly coupled with the environment and with environmental time rather than with internal state-transition time. The system-environment coupling of robots is based on effectors and measurement devices. The use of meters marks the departure from purely formal models most clearly ... Measurement is a process in which two dynamical systems interact.* (Prem, 1997)

Similar examples appealing to dynamics of the system-environment relationship as an explanatory tool can be found in Pfeifer (1995); Smithers (1995); Hasslacher & Tilden (1996).

2.3 Embodiment in Software

In non-material domains, this lack of an explicit definition at the heart of embodiment is much more troublesome. If material properties are necessary for embodiment, this presents a serious barrier to the application of the embodiment perspective in *non*-material domains, such as that of software. In such cases, the nature of embodiment must be confronted, either tacitly or openly.

There are various types of response to this problem. Kushmerick (1997), hoping to reap for software some of the benefits of Behavioural Robotics, undertakes the impressive task of transposing techniques from Behavioural Robotics to the domain of software, by providing computational interpretations of them. The materiality clause is respected, and instead of asking 'how can we embody software in an environment' the question posed is 'how can we get in software the sort of operational benefit that roboticists achieve with material things?' Through this process however, the worldview of Behavioural Robotics and the embodiment perspective evaporates. Principles such as using the environment as its own representative by responding directly to it are abstracted to merely valuable practical and pragmatic methods and maxims, such as "exploiting task invariants to simplify reasoning" (op.cit.).

A more common response is to retain the embodiment perspective, but quietly drop the materiality requirement in favour of a generalised notion of situatedness, by tacitly accepting that situatedness can be recognised and exploited as embodiment in a medium such as software, although contrast Etzioni (1993). Franklin, for example, uses embodiment "in the situated sense of being autonomous agents structurally coupled with their environment" (Franklin, 1997). Similarly, Etzioni argues that "real softbots in real software worlds" (op. cit.) offer a test-bed for the study of intelligent agents that is just as valid as robots in the physical world.

This general approach is very similar in spirit to the framework offered here, except that we are concerned to address the issue of what it means to be embodied, head-on.

The ontological liberation of embodiment is more than wishful thinking. This is evident in experimental work in Evolutionary Robotics, where, albeit in relatively constrained environments, control systems are developed in a simulation environment, and transferred directly and successfully to robots operating in The Real World. See, for example, Mautner & Belew (1999b); Lund & Miglino (1998); Wilson et al. (1997); Miglino et al. (1995). Such cases demonstrate that the central operational principles associated with embodiment apply regardless of the ontological type of the domain in which they do so. A core axiom here might be expressed as follows: 'where behaviour emerges from the interplay between system and environment, if exactly the same system-environment relationship is instantiated in two cases then the same characteristic behaviours are seen to emerge.' This demonstrably applies even if one case exists in the material world, and the other in software.

Typical simulations in Evolutionary Robotics simulate *both* material system *and* material environment, where the material environment used is also a highly constrained subset of

The Real World. This differs from the research program outlined below, where, to develop a relational understanding of embodiment, we propose situating a *single* software system in a number of *different* environments of different ontological kinds and compare the behaviours that emerge as well as the parameters that impact on those behaviours.

Bellman and Landauer's work related to 'computational embodiment', applied in the context of Multi-User Domains (MUDs), is interesting, in so far as the nature of embodiment is openly addressed, and a software-friendly, non-material interpretation of the term is used (Landauer & Bellman, 1999). Because of this, it shares a significant feature of the framework presented here, that of applicability within any domain. However it lacks the qualities of minimalism, preciseness and quantifiability. A whole range of 'essential properties' are predicated of embodiment, some of which appear far from necessary, at least in so far as these qualities are *not* present in exemplary embodied robotic systems, such as Braitenberg Vehicle-based implementations (Hogg et al., 1991), basic subsumption architecture systems (Brooks, 1986), and BEAM robots (Hasslacher & Tilden, 1996). For example, an embodied system is required to have "a viewpoint of itself in its environment", and "a notion of its own resources, abilities and internal state". This is may be a consequence of the authors' strong orientation towards human-interaction related applications. Another problematic issue, perhaps related, is that Bellman and Landauer are writing within a computational tradition that embraces the interpretation of adaptive systems in terms of, for example, symbols and symbol manipulation, and which advocates the use of explicit internal representations and models.

3 A Framework for Embodiment

3.1 Structural Coupling

The relational definition of embodiment presented below is heavily influenced by Maturana and Varela's concept of 'structural coupling' (Maturana & Varela, 1980). Structural coupling is a systemic, relational construct, and hence suitable as an explanatory tool with regard to many different kinds of things, in the sense suggested in the introduction. Our definition of embodiment describes a minimal state of affairs whereby structural coupling is made possible.

Structural coupling is a process that occurs when two structurally plastic systems (an organism and its environment, for example) repeatedly perturb one another's structure (their constituent components and the relationships between them) in a non-destructive fashion over a period of time. This leads to the development of structural 'fit' between the systems. There is an intimate relationship between this process and the emergence of 'appropriate' behaviour from the interplay between interacting systems, because the structure of a system determines its responses to perturbatory environmental events.

A number of interesting consequences ensue if structural coupling is treated seriously. First, it emphasises that achieving appropriate behaviours that change over time is not a matter of an organism, for example, 'fitting' itself to an unchanging and unyielding environment, but is something that occurs because of the way in which the environment impacts on the organism *and* the organism impacts on the environment. Nor is it helpful to think of behaviour as something that is 'in' organisms—it is something that is observed, in the interplay between system and environment.

Structural coupling sits very comfortably with accounts of both behaviour and cognitive phenomena based on dynamical systems—cf. the Dynamical Hypothesis (van Gelder & Port, 1995)—where it can be used as an explanatory tool, as in Beer (1995). In such accounts, a direct relationship is taken to exist between the dynamics of a system and behaviours that are manifest. Similarly, 'structure' is highly significant in dynamical systems, given that global system dynamics are produced from local interactions between components. Altering constitutive components and the relationships between them has significant consequences—impacting directly on behaviour, which is generated 'bottom-up' from the interplay between all components, operating within an environment.

A similarly easy relationship exists between structural coupling and the philosophical tradition of embodiment. Structural coupling shapes a system over time as a result of interaction with an environment, such that responses to events within its environmental niche flow directly from the structural state of the system at that moment in time. In this sense, events directly solicit appropriate responses—there is no need to posit higher-level structures reminiscent of the folk-psychological constructs of cognitive science, such as symbols, representations and schemas. The structure at some point in time of a system coupled to its environment reflects a whole *history* of interaction—of the effect of environment on system, and of system on environment, which is reflected back through subsequent environmental events. See Rose (1997) and Dautenhahn & Nehaniv (1998) for deeper commentary on the significance of an agent or organism's individual history. As suggested earlier, this perspective also offers a natural handle on phenomena such as semantics and intentionality. Each can be grounded in the continual and intimate relationship between system and environment that underpins all 'actions' on the part of the system.

3.2 A Minimal Definition of Embodiment

We define what it is for a system to be embodied as follows:

> *A system **X** is embodied in an environment **E** if perturbatory channels exist between the two. That is, **X** is embodied in **E** if for every time **t** at which both **X** and **E** exist, some subset of **E**'s possible states have the capacity to perturb **X**'s state, and some subset of **X**'s possible states have the capacity to perturb **E**'s state.*

This expression articulates a relationship in terms of which instances of embodiment can be discussed. These terms are applicable regardless of the operational context in which a system happens to be instantiated. This is not the same as asserting that 'embodiment is the same in all instances.'

The expression describes minimal conditions under which structural coupling is possible: a pair of systems (one of which may constitute the other's environment) that have states, each with the potential to perturb the other.

A system-environment relationship that minimally satisfied these conditions would not reveal a particularly interesting state of affairs. Such a case would constitute an instance of situatedness, but no more—perhaps an abandoned car rusting quietly in a desert, deforming the flow of wind and the shaping of the sand enveloping it, whilst being gradually eroded. However, using the definition above, there is scope for huge variation in the relationship between system and environment, which can be expressed through the parameters of the relationship—for example, the space of possible states and the capacity to perturb and be perturbed. In the following sub-section, we look at some of these parameters, and how they might be used both to characterise and to quantify embodiment.

3.3 Characterising and Quantifying Embodiment

There are various features of the relationship between system and environment that it might be interesting to pick out and use to describe instances of embodiment. For example:

- *The size of the space of possible structural states of X and E*, where 'structure' is characterised in terms of constituent components and the relationships between them. A multi-cellular organism with some form of nervous system has a set of possible structural states orders of magnitude larger than does, for example, a prokaryotic single-cell organism. This is closely related to the cybernetic construct of 'variety'.
- *The structural plasticity of X and E.* Simple software simulations and highly constrained Real World experimental environments might be partly characterised through their lack of plasticity. An interesting feature of biological organisms is that structural plasticity is offset by homeostatic processes, such as those associated with metabolism.
- *The bandwidth of perturbatory channels between X and E.* More advanced robots tend to exploit a greater range of sensory modalities, affording potential sensitivity to a greater range of environmental events. Similarly, a robot with both wheels and a manipulator has a greater potential to perturb its environment than a robot with just a means of locomotion.

The various parameters that can be identified in the relationship are *quantifiable*. This opens up the possibility of discriminating *degrees* of embodiment, offering in turn the opportunity to maximise embodiment in particular cases. One option is to ground a metric of embodiment in the total *complexity*—as rigorously defined in Nehaniv &

Rhodes (1997), or alternatively Crutchfield (1994)—of the dynamical relationship between system and environment, over all possible interactions. Factors such as those identified above, for example the total bandwidth of the perturbatory channels between system and environment, as well as the computational power in the dynamics of their interaction, may contribute to this complexity.

Particular *kinds* of embodiment can also be characterised with reference to features of the embodiment relationship. For example, an interesting and challenging feature of The Real World, particularly in Real World Applications not present in most simulation environments is the potential for severe perturbations to a system from *outside* designed or evolved sensory channels. In a hostile or unknown terrain, there exists the risk of destructive structural perturbations through physical forces exerted as a result of falling, or being struck by a foreign object.

This is an example of how it is possible to describe instances of embodiment in a manner that recognises the potential for uniqueness, using a vocabulary and concepts that are consistent across domains. As well as facilitating a general exchange of ideas, using a common vocabulary has the advantage of unmasking similarities between domains.

The features of this relationship also apply *between* different ontological types. Not only can an embodiment relationship exist between a software agent and a software environment, but between a software agent and a physical or even a social environment. The only requirement is for potential structural coupling between system and environment.

Having theorised at some length on the nature of embodiment, it is reasonable to ask 'how does this perspective really apply in practice?' The remaining sections of the paper begin a 'fleshing out' processes, by applying our framework to a biological example of embodiment, and then using that as the basis for experimental work.

4 Embodiment in Action: *Escherichia coli*

In this section we look at the bacterium *Escherichia coli* (figure 1, below), and how its behaviour emerges from its embodiment. There are two reasons for doing this. The first is to illustrate 'embodiment in action'. *E. coli* provides an excellent biological example of the sort of relational and dynamical approach to embodiment, as a basis for adaptive behaviour, that we advocate. Because *E. coli* is a (relatively) simple organism—a single prokaryotic cell—the relationship between its structural dynamics, its perturbatory interaction with its environment, and its observed behaviour is (relatively) clear. In more complex organisms there is a temptation to fall back on features such as nervous systems or cognitive processes as explanations in their own right for complex and adaptive behaviour. The second reason is that we use this organism as inspiration and to provide a biological grounding for the experimental part of our research, described in more detail below. This involves building a software system based on *E. coli*'s signalling transduction pathways, and coupling it to different operational environments using specially designed sensory and effector surfaces.

4.1 Structural Dynamics in *E. coli*

E. coli is a remarkable organism. Compared to those of some multi-cellular organisms, its sensory and effector surfaces are extremely basic. It has non-directionally sensitive receptors, capable of binding to a variety of molecules. It is propelled by flagella, affording *E. coli* just two kinds of movement in addition to an infrequent 'rest' state: 'running' (smooth swimming), resulting from counter clockwise (CCW) flagella rotation, and 'tumbling' (rotating in place, randomly reorienting the bacterium), which occurs when at least a few flagella rotate clockwise (CW). *E. coli*'s baseline activity is a random walk in its environment. By shifting the flagella motors' rotational bias towards CCW / smooth swimming when moving up a concentration gradient of attraction, *E. coli* exhibits chemotaxic behaviour, converging on nutrient sources (Levin et al., 1998).

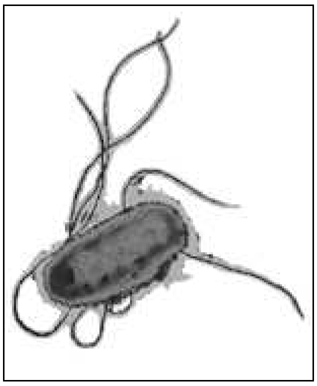

Fig. 1: A free swimming *Escherichia coli* bacterium. Flagella are clearly visible

Despite its relatively simple structure, *E. coli* is capable of highly adaptive behaviour. Its sensitivity to chemoattractants extends over 5 orders of magnitude, from 2 nM (nanomolar) to 360 µM (micromolar). After a period of time at a given concentration, the proportion of time spent tumbling increases back to the original baseline level. This range is also 'dynamic,' maintaining a constant level of sensitivity (Bray et al., 1998).

E. coli'*s* chemotaxic abilities emerge from the dynamics of its structure, operating within and in relation to its physical environment via its sensory (receptors) and effector (principally flagella) surfaces. The dynamics of two structural processes contribute to this behaviour: highly connected signalling pathways within the cell (Levin et al., 1998), and receptor clustering on its surface (Bray et al., 1998).

The signalling pathway is an archetypal complex dynamical system: a number of interconnected basic elements with relatively simple interaction rules between them, giving rise to coherent emergent phenomena. The interactions are based on the transfer of phosphoryl groups. The presence of these at motor sites encourages CW rotation (tumbling). Attractant-binding at receptor sites inhibits the generation of phosphoryl groups (autophosphorylation) within the cell, biasing the bacterium's random walk towards smooth swimming. Conversely, in the absence of attractants, increased autophosphorylation leads to a bias towards tumbling. Various feedback loops cause a homeostatic effect, so that the run / tumble bias returns to a constant base level regardless of attractant concentrations. Methyl groups play an important part here. Unmethylated receptors have a lower autophosphorylation rate, resulting in a bias towards smooth swimming. Receptors are constantly being methylated, so that at any concentration of attractants, the motor bias shifts towards CW (tumbling). At the same time, receptors are demethylated at a rate scaled by the level of autophosphorylation, preventing excessive tumbling.

Receptor clustering behaviour plays a pivotal role in *E. coli*'s dynamic range (Bray et al., 1998). At low attractant concentrations, receptors cluster together. When one receptor binds to an attractant, neighbouring receptor complexes also exhibit reduced autophosphorylation, resulting in a net response that is much greater than the contribution from the bound receptor alone. At higher concentrations, receptors disperse, providing sensitivity to attractant binding that would be effectively ignored by large clusters.

Chemotaxis as an observable behaviour only arises from the operation of these processes because of the way in which system and environment perturb one another across the bacterium's sensory and effector surfaces, and the coupling that this gives rise to. If an *E. coli* bacterium were fitted with receptors that bound to gold, for example, the consequence would be a chemotaxic response to concentration gradients of gold—although the resultant prospector bacteria would be short-lived without access to a supply of nutrients.

5 Exploiting Embodiment

The purpose of this section is twofold. First, to outline *one* particular model of how the perspective on embodiment presented might be exploited in applications[1]. Second, to describe ongoing experimental work inspired by *E. coli*, which is developing this approach, as well as our understanding of embodiment as system-environment coupling.

5.1 Generic Environmentally Coupled Dynamical Systems

Many biologically inspired approaches in both Evolutionary Robotics and Artificial Life use some form of neural network to generate an organism's structural dynamics (Mautner & Belew, 1999a; Nolfi, 1998; Menczer & Belew, 1996; Beer, 1995). However, cases such as *E. coli* demonstrate that in biological systems, adaptive behaviour is not *necessarily* grounded in the activity of neurons—much more generic

[1] It should be noted that the embodiment definition does not inherently impose any particular perspective with regard to how one ought to go about exploiting embodiment, or producing adaptive behaviour.

and perhaps simplistic dynamical activity, coupled to an environment, can be responsible. As a means of exploring this, we propose using more generic classes of embodiable dynamical systems, principally Cellular Automata (CA) based systems. Embodying CA involves creating sensory and effector surfaces that allow perturbations to flow between the CA, and some environment (defined in this context as a source of perturbations)—see figure 2, below.

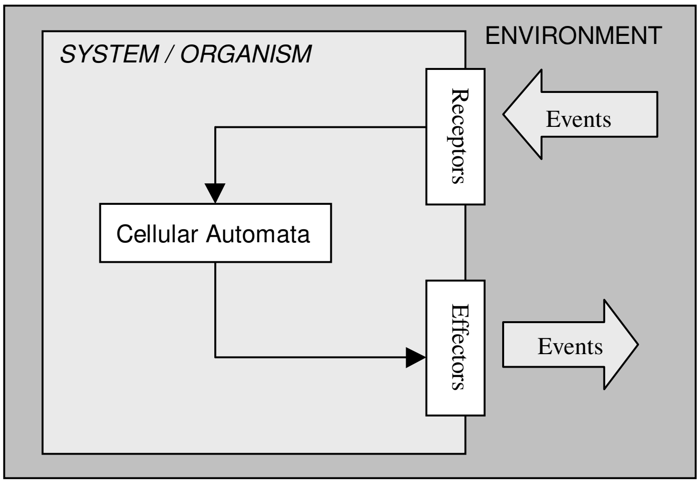

Fig. 2: An environmentally coupled CA

Precedent for environmentally coupled CA, in contrast to the more usual closed form (Wolfram, 1983; Langton, 1986) has been set by Varela's *Bittorio* (Varela, 1986)[2]—a system built as an exemplar of structural coupling. Having illustrated the close relationship between structural coupling and dynamical systems approaches to behaviour and cognition, as well as the theoretical worldview associated with the embodiment perspective, this seems to be a substantially interesting avenue of research—the pursuit of which forms the body of the first author's PhD research.

Environmentally coupled CA-based systems constitute a natural, although not the only possible, implementational model for the perspective on embodiment that has been presented here. They have a (potentially) very large state-space, the trajectory through which can be perturbed by altering the state of cells, and the topology of which can be perturbed by altering local connections between cells, and cell update rules. See Wuensche (1992) for further detail. A CA-based system can be used as a model of dynamics that are representative or constitutive of an agent's or organism's structure. A sensory surface must be provided, to allow perturbation of the system's structure by environmental events, for example by changing the state of cells, or altering cells' rule-tables or connectivity. Similarly, an effector surface must also be provided, to allow perturbation of the environment in some way, given structural states changes in the

[2] See also Sims (1991) for a demonstration of CA–environment coupling in an evolutionary context.

system. Examples of such features, based on *E. coli*'s sensory and effector systems, are provided below.

5.2 Experiments in Multiple-Domain 'Chemotaxis'

A Java program called *Phenomorph* is being developed, which implements a highly simplified version of *E. coli*'s cellular signalling pathway. In terms of the embodiment framework presented, this is a *system*, which, in experimental work, will engage in a mutually perturbatory relationship with a number of different *environments*. This perturbatory relationship is enabled by sensory and effector surfaces, described below, that are appropriate to each of those environments.

5.2.1 Experimental Aims

The goal of Phenomorph is to develop a deeper understanding of embodiment, as characterised in this paper. Phenomorph will allow us to observe the behaviour that emerges from one system embodied in a *range* of environments. This feature will help in the identification of qualities that arise from the system-environment *relationship*—they should be observed across all environments where the same relational features obtain. We will be able to address many questions to do with embodiment and the emergence of behaviour from the interplay between an embodied system and its environment. For example:

- How are features such as sensitivity, dynamic range and adaptivity effected if the parameters of the system-environment relationship, for example the system's structural plasticity, are altered?
- What sort of behavioural consequences ensue as a result of altering the system's dynamics, and why?
- To what extent is it possible to produce qualitatively and quantitatively similar behaviours in different environments, by instantiating a similar system-environment relationship in each case?

5.2.2 Implementation: Structural Dynamics

This implementation, partially completed at the time of writing, is intended initially to be minimally sufficient for the emergence of chemotaxis-like behaviour, so that basic qualities of the system and its behaviour in interaction with a variety of environments can be established before the complexity of the model is increased.

The implementation is based on a non-standard, very simplistic form of CA. This CA is one-dimensional, binary-state, has a connectivity radius of zero (each cell is connected only to itself), and a probabilistic update-rule. Cells are synchronously updated at every time step using this rule, which is oblivious to the current state of each cell, simply stating that with probability P_0, the cell will be in state 1 (active) rather than state 0 (inactive). Active cells play a role in Phenomorph modelled on the role played by phosphoryl groups in *E. coli*—they bias towards 'tumble' rather than 'run' behaviour, impacting on effector surface events. Individual cells in the CA also have an alternative form of behaviour—they can be ‘locked’ in a low-activity state, P_1 for a number of time steps. This mimics the consequences of ligand binding in *E. coli*—autophosphorylation drops sharply in effected receptor complexes, resulting in a bias towards running. In the CA, this alternative ‘low activation’ cell state is triggered by sensory events.

5.2.3 Implementation: Sensory and Effector Surfaces

A significant feature of software is that it can be built to interface with many different sorts of environment. This permits the construction of sensory and effector surfaces that can carry perturbations to and from different kinds of environment. Phenomorph has sensory surfaces that simulate ligand binding, and effector surfaces that simulate ‘run’ and ‘tumble’ for each of three experimental environments: the World Wide Web, an abstract parameter space, and The Real World. Each sensory and effector surface attempts to simulate in Phenomorph, for each different environment, the impact of ligand binding on *E. coli*, and the effect of flagella rotation on *E. coli*’s environment.

The effect of ligand binding on Phenomorph’s structure, and the effect of Phenomorph’s internal CA activation level is identical in all cases, and very similar to processes that occur in *E. coli*. Ligand binding events cause cells in Phenomorph’s CA to move to their low-probability activation state, P_1. In turn, the overall activation level (proportion of cells in an active state) expresses the probability that ‘tumble’ rather than ‘run’ behaviour will be expressed at the effector surface.

By contrast, sensory and effector mechanisms necessarily vary for each environment. The sensor and effector models to be used for each environment, again based as closely as possible on *E. coli*, are set out in table 1, below.

Of the sensory and effector surfaces outlined in table 1, the Web interface has so far been constructed and functionally tested, using an early version of Phenomorph’s internal CA-based system. Starting from either an arbitrarily selected web page or the results page of a search engine, which the Web interface system queries, Phenomorph can move from page to page, by following URLs (Uniform Resource Locators) referenced from the current page. The sensory surface parses each page for keywords, the presence of which triggers ‘ligand binding’ events, as described above. The effector surface parses each page for hyperlinks, which are weighted for estimated relevance, using features such as whether or not keywords appear in the URL and the linked text. If Phenomorph’s structure generates a ‘run’ event, the most highly weighted link is followed. If a ‘tumble’ event is generated, a link is selected at random.

System	Environment	Sensory surface	Effector surface
E. coli	3 dimensional (fluid) space	Chemical receptor complexes, detecting a range of ligands, e.g. aspartate	*Run:* CCW flagella rotation / smooth swimming *Tumble:* CW flagella rotation / random reorientation in space
Phenomorph	World Wide Web	Pattern matching to detect user-defined keywords in html documents	*Run:* Follow hyperlinks in html documents selected from a weighted list *Tumble:* Randomly select hyperlink
Phenomorph	Abstract 2D parameter space	Detection of artificial nutrients, perhaps derived from an 'error' function	*Run:* Maintain constant vector through parameter space *Tumble:* Randomly select new vector
Phenomorph	The Real World	Infrared detectors on Khepera robot[3]	*Run:* Step robot's wheels equal turns forward *Tumble:* Step each wheel randomly turns in random direction

Table 1: Sensory and effector surfaces for coupling to various operational environments

5.3 Future research

Immediate next steps are to execute the experimental aims described in section 5.2.1, by observing and experimenting with Phenomorph in each of its operational test environments.

There is a lot of scope for developing the complexity and scope of the experimental model over time, once the most basic possible case has been explored. Interesting research questions include:

– The potential of the embodied dynamical systems approach as a tool for biological prediction and modelling. For example, if further *E. coli*-like features are added to Phenomorph, how will its behaviour in various environments compare that of the real

[3] See http://www.k-team.com/ for details of the Khepera robot

bacterium and of other computational models (Bray et al., 1993; Hauri & Ross, 1995)?

- To what extent is it possible to construct different behaviours through the design of structural dynamics and sensory and effector surfaces? Might Genetic Algorthims (GAs) be effective? What sort of characteristics such behaviours have, for example in terms of adaptivity and robustness (Barkai & Leibler, 1997)?
- What are the consequences of social interactions amongst populations of such systems?

It would be particularly interesting to exploit Holland's (1998) constrained generating procedure (cgp) model in place of a CA as a basis for building generic dynamical systems that can be environmentally coupled. The cgp, and its more powerful 'variable' relative, the cgp-v, which takes a description of a cgp-v as an input and produces another as an output, represent formally defined building blocks that can be used to model any dynamical system—they are effectively 'maximally flexible' CA with respect to states, wiring and update rules. Where we have used a very simplistic form of CA to model a minimal version of *E. coli's* cellular signalling pathways (above), the formally defined cgp framework could be used to construct much more complex models.

Cellular models are becoming increasingly relevant in the field of Evolutionary Algorithms (EAs), particularly GAs, which is beginning to take notice of the non-linear relationship between genotype and phenotype in natural systems. Such models can be exploited to increase the power of genetic encodings, for example through the use of embryogeny-like growth processes (Mautner & Belew, 1999a; Bentley & Kumar, 1999). Holland shows how a cgp can be represented as a binary string—on which an EA can operate. This offers a possible means to extend the EA approach through the synthesis of cellular processes at the level of ongoing ontogeny, producing dynamics that lead to the emergence of behaviours when coupled to an environment. Such a combination of ALife and EAs offers a powerful model reminiscent biological systems, where the evolved genotype (DNA) is expressed as a highly interconnected network of interacting elements (intracellular proteins), which in turn both affects the ongoing expression of the genotype, and is perturbed by and perturbs an environment, as the basis for the production of behaviours.

6 Conclusion

Although supporting experimental work has yet to be completed, much of the embodiment framework presented in this paper constitutes a matter of perspective regarding the significance of being embodied in an environment. This perspective consists of recognising the *relational* impact of being embodied in an environment. We have suggested that in many cases, a relational approach, looking at system-environment dynamics, *is* adopted, but as an analytical tool rather than a wider framework for characterising and understanding embodiment. This is partly because of an assumption to the effect that embodiment 'just is' material embodiment. There are many benefits that follow a revision of this assumption, as this enables cross-disciplinary exchange, the quantification of embodiment and the opening of the embodiment perspective to software-based disciplines. Existing embodiment doctrine in robotics is not undermined by this shift. Rather, an opportunity is offered to express and understand these principles in terms of the underlying relationship between system and environment—terms that are also meaningful in other operational contexts even if the features so expressed cannot be instantiated.

We have also illustrated how the biological organism *E. coli* exemplifies the emergence of behaviour from the relationship between system and environment dynamics. Environmentally coupled dynamical systems offer an interesting tool for investigating and exploiting such emergence, as well as exploring the significance and developing our understanding of embodiment as a relational phenomenon. Such systems fit well with the 'bottom-up' ethos developing in many disciplines, and appears particularly interesting in the light of new approaches to cognition based on dynamical systems.

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