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On Bots and Bacteria: Ontology Independent Embodiment

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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 *Escherichia coli* bacteria. Recognition is given to the role played by physically instantiated bodies, but in such a way that this can be meaningfully abstracted within the constraints implied by the term 'embodiment', and applied in a variety of operational contexts. This is supported by ongoing experimental work in which the relational dynamics that exist between *E. coli* and its environment are applied in a variety of software environments, using Cellular Automata (CA) with artificial 'sensory' and 'effector' surfaces, producing qualitatively similar 'chemotaxic' behaviours in a variety of operational domains.

1 Introduction

This paper is concerned with the nature of embodiment, offering a definition of the term that allows the concept to be extended to and exploited in non-material domains. The approach advocated here involves asking *what is it that is special about the relationship between bodies and the world?*, and then putting that relationship to use in other ontological contexts.

Robots, biological organisms and other *physical* systems are held by proponents of embodiment to enjoy a special kind of relationship with the environments within which they exist [1]. Material embodiment conditions the nature of interaction between a system and its environment in a number of ways, which creates challenges for, and can be exploited by both biological organisms and the designers of artificial physical systems [2].

In the context of Artificial Life (ALife), advocacy of embodiment represents an uncomfortable position [3-5]. To the extent that ALife constitutes a digression from the tradition of symbol manipulation in Artificial Intelligence (AI) [6, 7], the non-Cartesian European tradition within which advocates of embodiment often stand can represent a compelling theoretical grounding. However, if *physical* embodiment is a necessary condition for the emergence of at least some life-like behaviour, this bodes ill for the synthesis of such behaviours in non-physical media — a common theme in ALife [8].

The framework presented here diffuses this tension. Whilst it abstracts from physical embodiment by focusing on the *relationship* between physical systems and their environments, it also recognises the part played by material structures.

In the following section, we illustrate how embodiment is interpreted in current research in a variety of operational contexts, before going on to articulate an explicit definition of the term. The practicality of this definition is then illustrated in an experimental context that draws inspiration from biological systems. Additional benefits and possibilities are discussed, and an ongoing program of research is described.

2 System – Environment Dynamics

There exists a pervasive assumption that only materially endowed entities can be 'embodied.' However, to insist on materiality as a necessary condition for embodiment amounts to physical vitalism. Unless there is some mysterious quality possessed by material things beyond those that follow from the way that being a material thing in a material environment conditions and shapes interaction, there is no need for embodiment to be ontologically constrained.

It is revealing to see how in a number of research areas, ideas about embodiment find expression in terms of dynamical systems and relationships that exist between them, despite initial appearances to the contrary.

Sensorimotor Dynamics in Behavioural Robotics and Physical Autonomous Agents. Those who champion embodiment, even those who focus very specifically on material embodiment in robots, often explain the deeper significance of their approach through appeal to both the dynamics inherent in their systems' physical structures, and the way in which these structural dynamics reflexively relate to the environments in which they are observed. Striking examples can be found in [1, 9-12], and particularly in Beer's work where particular emphasis is placed on the role of sensorimotor dynamics and structural coupling in autonomous behaviour in robotic systems [13, 14]. Sensorimotor coordination also features in research emphasising the evolution of neural control systems [15].

Software Agents. Applying ideas about embodiment in the domain of software necessitates an ontological shift, simply because software is not based on the manipulation of physical matter.

Kushmerick offers a detailed discussion of embodiment in the context of software, but emphasis is placed on transposing practical *techniques* for exploiting physical embodiment into the domain of software [16], rather than on addressing directly the nature of embodiment.

Franklin comes close to the perspective advocated here, referring to embodiment in terms of "autonomous agents structurally coupled with their environment" [17]. Etzioni takes a similar stance, arguing that "real softbots in real software worlds" offer a test-bed for the study of intelligent agents that is just as valid as robots in the physical world — softbots offer "easy embodiment," based on the provision of software sensors and actuators within a software environment [18].

Phenomenology. Dreyfus illustrates a significant point with regard to Merleau-Ponty's use of embodiment in his *Phenomenology of Perception* [19], where little emphasis is placed on the actual form of the human body, but rather on qualitative features such as the capacity to act, the 'I can' — the ability to "respond to situational solicitations" [20]. The significance of the embodiment perspective is in terms of the ongoing relationship between embodied actor and situational context.

Relinquishing the insistence on materiality for embodiment also strikes a blow to dualism. Where the significance of the body itself is seen as a dynamical system, body and mind can be grounded in a single phenomenon — coupling between dynamical systems (cf. the *Dynamical Hypothesis* in Cognitive Science [21]).

3 Embodiment as Structural Coupling between System and Environment

Maturana and Varela's influential [13, 14] notion of structural coupling underlies the definition of embodiment presented here. Structural coupling is an ontologically non-specific concept, arising as a consequence of mutual perturbation over time between structurally plastic systems. In their work, it is the basis of ontogenic variation and adaptation in individual autonomous entities [22, 23].

A Minimal Definition of Embodiment. The following definition is proposed for embodiment, establishing a basis for structural coupling by requiring the potential for mutual perturbation between system and environment:

> *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 with respect to **X** have the capacity to perturb **X**'s state, and some subset of **X**'s possible states with respect to **E** have the capacity to perturb **E**'s state.*

This definition is minimal, saying nothing about the way in which any particular embodied system relates to its environment or vice-versa, simply that *if* such a relationship exists, *then* system ***X*** is embodied in environment ***E***, whatever the respective ontological status of ***X*** and ***E*,** and whatever effect ***X*** and ***E*** happen to have on each other.

An important feature of this definition is that embodiment is identified as a *relational* concept, rather than a fundamental property of 'special' kinds of objects such as robots. Embodiment is only a feature of objects with respect to their environments (cf. [13]). It is as feasible for such a relationship to hold between a softbot and its environment as between a robot and the material world.

Degrees of Embodiment. The mere fact that an object is embodied in an environment is insufficient to guarantee that any interesting interaction will occur between the two. Embodiment simply affords perturbatory exchange between system and environment. A biological system bristling with active and sensitive sensory and effector surfaces is likely to be much more tightly coupled to its environment than an inanimate object. Highly complex structurally plastic systems such as organisms with nervous systems are likely to exhibit a particularly complex range of behaviours as a result of coupling between nervous system, body and environment [14, 22, 23].

Under this framework, 'extent' of embodiment[1] could be quantitatively measured, for example, in terms of the total complexity (as defined in [25, 26]) of the dynamical relationship between system and environment over all possible interactions. Various qualities of both system and environment might contribute to this, all of which may vary over time, such as:

- total bandwidth of the perturbatory channels between system and environment, defined by the number and efficacy of the system's sensory and effector surfaces;
- structural complexity of system and environment, defined as the number of constituent components, and plasticity with regard to the configuration of those components in relation to one another.

Cellular Automata as a Generic Class of Embodiable Dynamical System. In contrast to the specific models involved in dynamical software techniques such as Artificial Life Neural Networks (ALNNs) [27] and some evolutionary models [28, 29] that recognise the significance of system - environment interaction, it is proposed that Cellular Automata (CA) are appropriate for capturing the structure and inherent dynamics of embodied systems, of whatever form or ontological status (cf. [30]). Boolean Networks, a close relative of CA, have previously been used to explore the general phenomenon of stability in genetic networks [31, 32], and more recently to model genetic activation networks [33].

Whilst CA have traditionally been studied as closed systems [34], providing for their embodiment requires features analogous to sensory and effector surfaces, as a basis for a mutually perturbatory relationship with an environment (Fig.1).

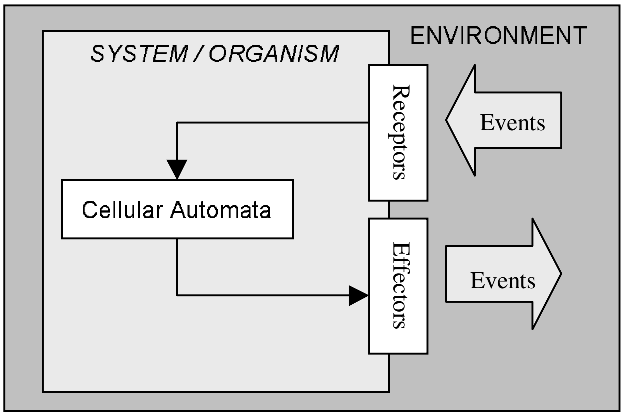

Fig. 1. CA-based System embodied in an environment via sensory and effector surfaces

Precedent for this has already been set by Varela's 'Bittorio', a simple CA exhibiting parity detection as an emergent feature when perturbed by environmental binary values [35, 36]. Varela presents this as an example of an operationally closed [2] system, capable of structural coupling (cf. [37]).

[1] For a discussion of variability in embodiment, see [24].

[2] In the autopoietic sense (roughly) of being structure determined, and hence autonomous.

4 Bots and Bacteria — *E. coli* on the Internet

In this section we present *E. coli* as a case study in embodiment, and then describe an environmentally coupled CA based on *E. coli*. The initial goal is to establish the basic feasibility of the abstract definition of embodiment by investigating the emergence of behaviour via structural coupling in non-materially embodied systems.

Structural Dynamics in *E. coli*. The bacterium *E. coli* (Fig.2) 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), occurring when at least a few flagella rotate clockwise (CW). By shifting the flagella motors' rotational bias towards CCW when moving up a concentration gradient of attraction, *E. coli* is able to exhibit chemotaxic behaviour, converging on nutrient sources [38].

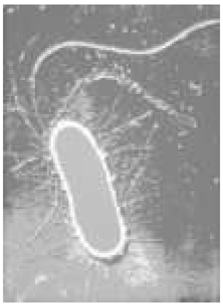

Fig. 2. A free swimming *Escherichia coli* bacterium. Flagella are visible (*top*)

Despite having less structural complexity than a single neuron, *E. coli* is capable of highly adaptive behaviour. Its sensitivity to chemoattractants extends over 5 orders of magnitude, from 2 nM (nanomoles) to 360 μM (micromoles). This range is 'dynamic,' maintaining a constant level of sensitivity [39].

E. coli's chemotaxic abilities emerge from the dynamics of its structure, operating within and in relation to its physical environment via its sensory and effector surfaces. The dynamics of two structural processes contribute to this behaviour: highly connected signalling pathways within the cell [38], and receptor clustering on the surface of the bacteria [39].

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 absence of which at motor sites inhibits CW rotation (tumbling). Attractant-binding at receptor sites inhibits autophosphorylation processes, biasing the bacterium's random walk towards smooth swimming. Conversely, in the absence of attractants increased autophosphorylation leads to a bias towards tumbling. Feedback loops cause a homeostatic effect, so that the run / tumble bias returns to a constant base level regardless of attractant concentrations. Methyl groups also play an important part. 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 plays a pivotal role in *E. coli*'s dynamic range [39]. At low attractant concentrations, the receptors cluster together. When one receptor binds to an attractant, neighbouring receptor complexes also exhibit reduced autophosphorylation, resulting in a net response 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 penicillin, the consequence would be a chemotaxic response to concentration gradients of penicillin. If one were to alter the flagella motors so that phosphorylation led to CCW rather that CW rotation, chemoattractants would act as repellents.

***E. coli* on the Internet.** Suppose that instead of swimming and tumbling in physical space, *E. coli* were to traverse and randomly re-orient in the information space of the World Wide Web (hereafter referred to as the Web). Suppose that instead of having receptors sensitive to ligands such as aspartate, they were to react to the presence of certain words or phrases on web pages.

A Java programme, PhenoMorph, has been implemented with just this relationship with the Web. The purpose is not to achieve optimal search on the Web, nor to model exactly the structural dynamics of *E. coli* (cf. [40, 41]). The bacterium is used as an approximate implementational basis for studying ontology independent embodiment.

At the heart of PhenoMorph is a uniform 1D binary state CA, generating dynamics very roughly analogous to those embedded in *E. coli*'s signalling pathways and receptor clustering mechanisms. The CA has two non-standard features. First, it has variable connectivity between cells, simulating receptor clustering. Connectivity is inversely proportionate to keyword concentration. Second, it has a variable rate methylation function that can force cells into an 'off' state. This increases the likelihood of tumbling, as cells in a 'on' state are used, conversely, to represent nutrient bound receptors, and the associated reduced autophosphorylation. Each cell in the CA applies the simple logical rule OR to its inputs to calculate its next state.

Keyword 'nutrients' are defined at run-time. For every keyword that PhenoMorph encounters in the HTML[3] (HyperText Markup Language) source of a web page, an inactive cell is activated. Nutrient absorption is simulated by preventing PhenoMorph from detecting keywords on a particular page more than once.

Starting from an arbitrarily selected web page or search engine results page, sites are visited and parsed for keywords and hyperlinks. URLs (Uniform Resource Locators) referenced from a given page are ranked against the likelihood that they contain further keyword instances. This is estimated through the application of weightings to links, based on features such as whether or not keywords appear in the link and the linked text.

[3] See specification at http://www.w3.org/TR/REC-html32.html

Running and tumbling are triggered by the global state of the CA, and achieved by emitting HTTP[4] (HyperText Transfer Protocol) requests. The proportion of active cells is used as an expression of the probability that the system will run rather than tumble. In the case of running, PhenoMorph traverses to a highly ranked URL. If a tumble event is generated, a link is chosen randomly. This is repeated at every page visited.

Evaluation. Initial results suggest that the approach adopted has the capacity to produce complex behaviours from the interaction between structural dynamics and environment, even given the relatively simple CA used, and the low bandwidth of the perturbatory channels involved.

The features of system - environment interaction associated with physically embodied systems [11] can be observed in the relationship between PhenoMorph and the Web. These features are not simulated by or coded into the software [16], but emerge directly from the mutual perturbation between PhenoMorph's dynamics and the Web, via the software's sensory and effector surfaces.

PhenoMorph is situated in its environment, responding directly to features such as the presence of keywords. It does not rely on abstract descriptions — keyword concentration gradients are not explicitly represented in any way. It 'experiences' its world directly via its sensory and effector surfaces, and its actions have an immediate impact on its own subsequent 'experiences.' For PhenoMorph to exhibit infotaxis[5] requires appropriate dynamics in the interactions between system and environment to produce an appropriate relationship with its environment, in the eye of some observer.

The embodiment relationship both enables and constrains system - environment interaction. Constraints arise primarily because of the nature of the sensory and effector surfaces. For example, PhenoMorph is only capable of being perturbed by certain features of its environment. Only established keywords can trigger its sensory surface and affect its structure. Similarly, its capacity to generate environmental perturbations is limited to a small subset of the HTTP protocol. In this way, environmental complexity (in the sense of variety) is filtered by the form of the system's embodiment. The embodiment relationship is enabling because of the immediacy of the relationship between system and environment — each continually deforms the dynamic trajectory of the other [13]. Responses to events flow directly from the structural state of each at any moment in time.

5 Conclusions

Conceptual Consequences. Defining embodiment in terms of the possibility of mutual perturbation between a system and its environment negates the requirement for embodied systems to be materially endowed, and so the concept can conceptually cohabit with ALife. Under this definition, it is meaningful to talk of embodiment in the context of software. This shift does not detract from the insights into embodiment made in behavioural robotics, but makes those insights accessible in other ontological contexts. The framework also provides a solid basis for understanding degrees of

[4] See specification at http://www.w3.org/Protocols/History.html

[5] An informatic counterpart of chemotaxis. PhenoMorph has yet to attain a level of behavioural 'fitness' that can be compared with that of the acutely honed *E. coli*.

embodiment, a significant issue in robotics [24], through appeal to the potential for structural coupling afforded by the plasticity of a system's structure and the bandwidth of its sensory and effector surfaces.

Practical Benefits and Implications. The CA driven model presented here is a relatively simple example of a technique that may have potential as a way of producing dynamical systems of a generic sort, able to couple to a wide range of operational environments, given suitable internal dynamics and sensory and effector surfaces.

With the raw possibility of ontology independent embodiment established, there is scope for exploiting structural coupling across ontologically distinct domains, for example, between social and software systems. Human social systems are a high level expression of the actions of groups of people, and so there is a basis for a perturbatory relationship with structurally dynamic software. Other practical benefits include the robustness that follows from behaviour based on distributed processes [42], and the possibility of using Evolutionary Algorithms to develop much more complex emergent behavioural strategies by tuning parameters such as connectivity and update rules (cf. [43]).

Flesh for the Framework: Future Research. The next step in PhenoMorph's development is to establish a minimal set of dynamics expressed as CA rules, sufficient to produce basic infotaxis. A consequence of an ontologically non-specific model of embodiment is that we would expect to see similar behavioural phenomena across a range of environments provided that in every environment, the effect that system and environment have on the others' dynamics is similar. PhenoMorph has a highly Object-Oriented architecture, separating its sensory and effector surfaces from the CA responsible for generating structural dynamics. This will permit the embodiment of the system in an arbitrary range of environments, provided that sensory and effector surfaces can be defined that are appropriate for any given environment. In particular, we plan to embody the infotaxis CA system in two other operational contexts. First, an abstract parameter space where an error function takes the place of nutrients at the sensory surface, and run and tumble are implemented as movement in parameter space. Second, a physical space, where a robot provides a sensory and effector interface to the material world.

With this research, we hope to further develop our understanding of embodiment as a relationship between a dynamical system and an environment, as well as the nature of structural coupling across distinct ontological domains and the practical opportunities offered by ontology independent embodiment.

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