A Consideration of the Biological and Psychological Foundations of Autonomous Robotics

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The new wave of robotics aims to provide robots with the capacity to learn, develop and evolve in interaction with their environments using biologically inspired techniques. This work is placed in perspective by considering its biological and psychological basis with reference to some of the grand theorists of living systems. In particular, we examine what it means to have a body by outlining theories of the mechanisms of bodily integration in multicellular organisms and their means of solidarity with the environment. We consider the implications of not having a living body for current ideas on robot learning, evolution, and cognition and issue words of caution about wishful attributions *that can smuggle more into observations of robot behaviour than is scientifically supportable. To round off the arguments we take an obligatory swipe at ungrounded artificial intelligence but quickly move on to assess physical grounding and embodiment in terms of the* rooted cognition *of the living.*

KEYWORDS: Biorobotics, embodiment, Umwelt, grounding, rooted cognition, robot intelligence, adaptive robotics, evolutionary robotics.

1. Introduction

Attempts to design autonomous robots to test simple mechanistic hypotheses about the behaviour of organisms began around the mid-twentieth century (Hammond, 1918; Ross, 1938, Grey Walter, 1950; Shannon, 1951; Wallace, 1952; Howard, 1953). However, with the birth of artificial intelligence (AI) in the 1950s and the concomitant rise of cognitive psychology, attention shifted towards studying and modelling the nature of intelligent behaviour as abstracted from its natural machinery, the biological body. There was still some interest in robotics during these dark ages, but the focus was on the off-line mediation of teleological systems between sensors and effectors.

When a *new wave* of the older, biologically inspired, style of robotics appeared in the middle of the 1980s it was with a radical tone. There were cries of, ''we want intelligence without representations of the world or without reason'' from, for example, Brooks (1991a; 1991b). Indeed, arguments against traditional AI were used as a springboard with which to launch the new wave. This came at a time when AI was also having to contend with strong challenges from the rise of connectionism.

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The attacks from the new wave robotics community and the connectionists had much in common. Both schools disliked the idea of centralised control and explicit world models. Instead they both counted on the *emergence* of coherent behaviour at the global/system level from the distributed activity of multiple, simpler components working in parallel. Furthermore, they both distanced themselves from the dominant cognitivist portrayal of intelligence in terms of operations on symbolic representations. The connectionists wanted to replace these with nonsymbolic (or subsymbolic) representations that are self-organised or learned, but the more radical roboticists wanted to develop behavioural systems entirely without explicit representations, e.g. Brooks (1991b). Now some connectionists and roboticists are starting to realise their common starting point and there is open public collusion.

Like any new movement, with the excitement engendered by feelings of radicalism, there can be much unintentional spin-doctoring and hype. New terminology and techniques can bring with them old or new theory-laden baggage with consensual assumptions that can become difficult-to-unpack precepts. In this paper, we dare to examine some of the hallowed assumptions of the new wave and put them in perspective. For this we use lessons that AI had to learn the hard way; how the use of seemingly innocent terms to describe systems can be used to 'smuggle' in conceptualisations that may be unwarranted or misleading. Our criticisms are not meant as an attack on biorobotics, to which we are committed, but they are needed to ensure that the foundations of the subject are not really quicksand on which it will later flounder.

We begin with a review of some of the biological theories and ideas that underpinned the birth of biorobotics. In particular, we outline Sherrington's (1906) theory of how the neural (or reflex) mechanisms of bodily integration are used for creating solidarity in multicellular animals. We then examine two different ways of viewing the solidarity between organisms and their environments. In Loeb's (1918) view, the organism is treated as a Cartesian puppet under the control of environmental stimuli, whereas according to von Uexküll (1921), the solidarity is due to the organism's embedding in a subjective phenomenal world. The implications of these theories of bodily and agent–environment solidarity are then spelled out in an examination of biologically inspired robot implementations. This will include a critical look at some of the adaptive techniques used in modern robotics, such as artificial neural networks (ANNs), reinforcement learning and evolutionary methods, from a 'life' perspective. We then focus on what it means to have a living body as opposed to a robot body and what the implications are for such new wave notions as *embodiment*, *situatedness* and *physical grounding*. Finally, we relate our arguments to recent ideas about embodied cognition in terms of theories of *cognition as a biological process*.

2. Organism and Environment

Much of the basis for modern robotics can be seen in biological and psychological discussions from the late nineteenth and early twentieth century. Particularly influential in developing a biological basis for behaviour and cognition were Charles Sherrington (1857–1952), Jacques Loeb (1859–1924) and Jakob von Uexküll (1864–1944). In different ways they represented the discontent felt by a number of biologists about anthropomorphic explanations. After Darwin's 1859 book *The Origin of Species*, comparative psychology had attempted to find a universal key which resulted in the breaking down of the distinction between humans and

other species. This led to the attribution of human-like mental qualities to other vertebrates and even invertebrates. For example, one of the questions was, what motivates the moth's *desire* to fly into a candle flame? In stark contrast to this anthropomorphic approach, both Sherrington and Loeb developed scientifically testable theories about the interaction of organism and environment in the creation of behaviour. Von Uexküll theorised about the organism-environment interaction in terms of subjective perceptual and effector worlds, and thus contradicted anthropomorphic as well as purely mechanistic explanations. The role of these theories was to find a way to explain the behavioural unity of organisms, and their environmental embedding, based on their biology.

2.1. *Solidarity in the Organism*

Sherrington was concerned with the *solidarity* of multicellular animals and how their bodily reactions are *integrated*. He acknowledged that there are several integrative agencies at work in such organisms. There is solidarity by mechanical combination of cells into a single mass, for example, by connecting tissue and the fibrous layer of skin that encapsulates the whole body. And there is solidarity from chemical communication between cells and body parts; he used the example of the distributed reproductive system. However, Sherrington's focus was on the nervous system. His 1906 book, *The Integrative Action of the Nervous System*, gave a scientific account of the mechanisms of the central nervous system based on documented experimental findings about decerebrated monkeys, dogs, and cats.

> In the multicellular animal, especially for those higher reactions which constitute its behaviour as a social unit in the natural economy, it is nervous reaction which *par excellence* integrates it, welds it together from its components and constitutes it from a mere collection of organs an animal individual. This integrative action in virtue of which the nervous system unifies from separate organs an animal possessing solidarity, an individual, is the problem before us. (From the introduction to Sherrington, 1906.)

For Sherrington, the elementary unit of integration and behaviour was the simple reflex consisting of three separable structures: an effector organ, a conducting nervous pathway leading to that organ, and a receptor to initiate the reaction. This is the *reflex arc* and it is this simple reflex which exhibits the first grade of coordination. Sherrington was the first to say that the simple reflex is most likely to be a purely abstract conception. Since, in his view, all parts of the nervous system are connected together, no part may react without affecting and being affected by other parts.

Although Sherrington's goal was to explain integration, he was well aware of the limitations of using a decerebrate animal:

> . . . it contains no social reactions. It evidences hunger by restlessness and brisker knee jerks; but it fails to recognize food as food: it shows no memory, it cannot be trained to learn... The mindless body reacts with the fatality of a multiple penny-in-the-slot machine, physical, and not psychical. (Sherrington, 1906)

Nonetheless, the idea of chains of reflexes to form coherent behaviour became part of mainstream psychological explanation beginning with the work of the Russian psychologist Dimitri Pavlov who extended the study of reflex integration into the realm of animal learning, classical conditioning, of which we will say more later.

2.2. Solidarity Between Organism and Environment

Loeb, also committed to a scientific study of behaviour, had little patience for the physiological study of the reflexes although he sympathised with the more holistic conceptions. In his own words:

> While it may seem justifiable to construct the reactions of the organism as a whole from the individual reflexes, such an attempt is in reality doomed to failure, since reactions produced in an isolated element cannot be counted upon to occur when the same element is part of the whole, on account of the mutual inhibitions which the different parts of the organism produce upon each other when in organic connections; and it is, therefore, impossible to express the conduct of the whole animal as the algebraic sum of the reflexes of its isolated segments. (Loeb, 1918)

Loeb (1918) derived his theory of *tropisms* (directed movement towards or away from stimuli) by drawing lessons from the earlier scientific study of plants where considerable progress had been made on directed movement through geotropism (movement with respect to gravity) (Knight, 1806) and phototropism (movement with respect to light) (De Candolle, 1832). Strasburger (1868) really set the ball rolling for animal behaviour in a study of the movements of unicellular organisms towards light which he labelled *phototaxis* to distinguish the locomotory reactions of freely moving organisms from the *phototropic* reactions of sedentary plants. The study of *chemotaxis* came soon afterwards (e.g. Pfeffer, 1883) to describe attractions of organisms to chemicals.

These notions about taxis are still used in modern zoology. For example, Bray *et al.* (1998) have recently begun to model how the bacteria, *Escherichia coli* (cell body $2 \times 1\,\mu m$), respond to extremely low concentrations of attractants and can follow gradients over a range greater than five orders of magnitude at a velocity of from 20 to 40 μm per second. The behaviour of the mobile bacteria can be classified as either a *run* (swimming smoothly and with directionality) or a *tumble* (randomly changing the direction of the next swim) depending on which direction their flagella are turning (see Figure 1). Each bacterium has up to six motors connected to the filamentous flagella such that when they rotate counterclockwise, the flagella form a bundle that propels the cell forward. When the flagella are rotated clockwise they part and the cell tumbles. The fraction of time that the motor rotates in a counterclockwise direction is called the *bias* of the flagellar motor behaviour (Levin *et al.*, 1998). When molecules of aspartate bind to any of the 2000 receptor sites on the surface of the bacteria, the bias of the motors is increased. As the cell moves up a concentration gradient of attractant, the increases in the bias push it in a random walk towards the source.

Although Loeb wanted to explain the behaviour of higher organisms, those with nervous systems, he continued to use the term *tropism* rather than *taxis* to stress what he saw as the fundamental identity of the curvature movements of plants and the locomotion of animals in terms of *forced movement*. In an interesting early move that was to herald the introduction of biologically inspired robotics, Loeb (1918) described an artificial heliotropic machine constructed by J. J. Hammond. Discussing his own *mechanistic conception of life*, Loeb held that:

> . . . the actual construction of a heliotropic machine not only supports the mechanistic conception of the volitional and instinctive actions of animals but also the writer's theory of heliotropism, since the theory served as the basis in the construction of the machine. (Loeb, 1918)
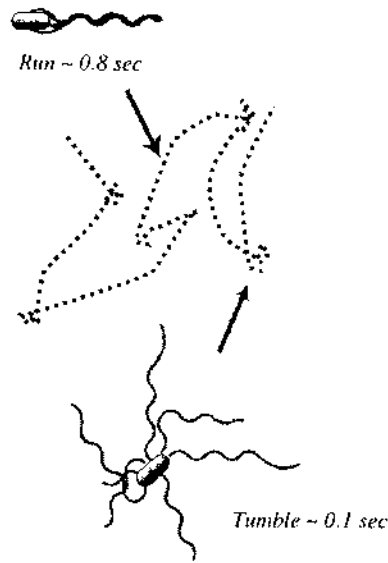
Figure 1. Run and tumble behaviour in *Escherichia coli*. The upper 'rod' represents the *E. coli* with the flagella turning counterclockwise as a single propellor. The lower 'rod' represents the *E. coli* with the flagella turning clockwise and staying individuated for the tumble behaviour.[1]

Eventually, Loeb's specific theory about animal symmetry and forced movements failed from the weight of empirical data. However, the general conception of the importance of taxis/tropism in animal behaviour was taken up by later biologists and lives on in behaviour-based robotics today. Fraenkel and Gunn's 1940 book, *The Orientation of Animals*: *Kineses, Taxes and Compass Reactions*, strongly sympathised with Loeb's position about the objective study of animal behaviour, although they argued that Loeb was wrong in implying that *purpose* in behaviour cannot be expressed quantitatively. They provide many natural examples of many kinds of taxis and show the general usefulness of the notion (Fraenkel & Gunn, 1940).

Fraenkel and Gunn proposed that the behaviour of many organisms can be explained by a combination of taxes working together and in opposition—thus heralding behaviour-based robotics (Brooks, 1986b). In this style of robotics each behaviour (or behaviour-producing module), such as *avoid obstacles* or *move towards light*, is encoded as a separate program module such that each is directly under the control of environmental circumstances rather than a central controller. For example, when there is light on the sensors, the *move towards light* module will be active until the light is occluded by an obstacle and then the *avoid obstacles* module takes over.

A concrete example of combining taxes used in the behaviour-based robotics literature (e.g., Connell, 1990), comes from Fraenkel's study of the coastal slug, *Littorina neritoides* (Fraenkel, 1927). The *Littorina* combines positive and negative *phototaxis* and negative *geotaxis* to enable it to feed and survive. Interestingly, it is negatively phototaxic when it is out of sea water and when it is oriented the right
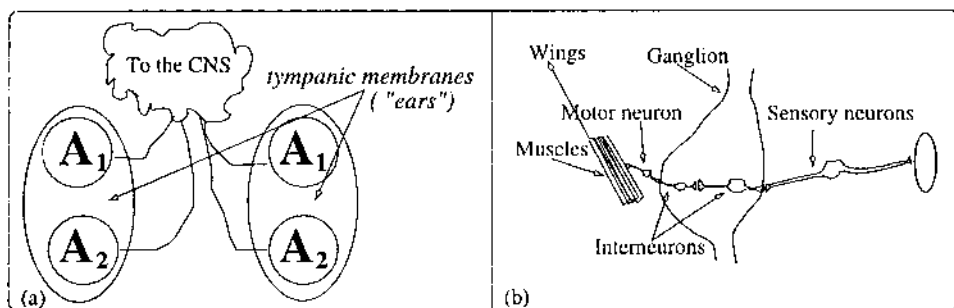
Figure 2. (a) An illustration of the moth's two membrane *ears* showing the two types of neuron, A_1 and A_2, and the connections to its central nervous system (CNS). (b) An idealised drawing of the connections from the ear to the muscles in the motor system.

way up in sea water. When it is upside down in sea water, it is positively phototaxic. In brief, *Littorina* lives on the sea floor and is attracted, by negative phototaxis, to dark rocks. It starts climbing the rocks as a result of negative geotaxis, and is attracted into the dark cracks by negative phototaxis. Then when it is upside down, it becomes positively phototaxic and crawls towards the light and on to the next crack in the rocks and so on until it reaches food where it feasts until a wave lashes it out and back onto the sea floor where it begins its ascent once more. Thus evolutionary pressure has finely tuned this organism so that the combination of its local behaviours leads to food and survival.

A similar fit between an organism and its environment is exhibited by certain noctoid moths, *Cataocala*, that selectively respond to the high frequency emissions of bats to help them avoid being eaten. The moths respond in two different ways that are determined by the intensity of the high frequency sound. If the sound is soft, the moth flies away from it and when it is loud the moth tumbles through the air in an unpredictable path which makes it difficult to catch.

Roeder and Treat (1957) found two tympanic membranes at the bottom of the thorax of the moth that serve as very simple, specially tuned, 'ears'. Each ear has only two sensory neurons as shown in Figure 2(a). Neuron A_1 is activated by the high frequency emissions of a bat coming towards it. This neuron is connected, via interneurons, to the muscles that operate the wings as shown in 2(b). This is like a reflex arc where the high frequency sounds vibrating the tympanic membrane activate the sensory neuron and impulses travel along the interneurons to the motor neuron which causes the muscle contraction and relaxation required to flap the wings of the moth. Neuron A_2, as shown in Figure 2(a), in contrast, responds only to loud high frequency emissions. Its activation simply desynchronises the wingbeats so that the moth tumbles through the air unpredictably making it difficult to catch.

Such highly adapted selective perceptual mechanisms are common and have been shown in a variety of other insects living in the bat's world, e.g. praying mantises (Yager & May, 1990) and lacewings (Miller, 1971).

2.3. Reactivity and Taxis in Robots

It was the twin ideas of reflex and taxis that first inspired the use of robots in the mechanistic modelling of behaviour. After Hammond's heliotrope, one of the first

examples of a physical test of *reactive* behaviour came from Grey Walter (1950, 1953), who built his two electronic tortoises, Elmer and Elsie, of the species *Machina speculatrix* between 1948 and 1950. Among other things, they exhibited phototaxis and 'hunger'; they re-entered their hutch to recharge their batteries as required. This work combines and tests ideas from a mixture of Loeb's tropisms and Sherrington's reflexes.[2] Although Loeb is not explicitly mentioned in the book, the influence is clear, not least from the terms positive and negative tropisms.

Grey Walter's electromechanical creatures were equipped with two 'sense reflexes'; a little artificial nervous system built from a minimum of miniature valves, relays, condensers, batteries and small electric motors, and these reflexes were operated from two 'receptors': one photoelectric cell, giving the tortoises sensitivity to light, and an electrical contact which served as a touch receptor. Elmer and Elsie were attracted towards light of moderate intensity, repelled by obstacles, bright light and steep gradients, and never stood still except when re-charging their batteries. They were attracted to the bright light of their hutch only when their batteries needed re-charging. These archetypes of the new wave in robotics exhibited a rich set of varying behaviours, including goal finding (photographed with candles on top of their shells with very lengthy exposure times), self-recognition and mutual recognition (Grey Walter, 1953).

If we were to turn the tortoise robot on its back and briefly shine a light on its sensors we would get a brief burst of motor activity and perhaps a turn of a wheel and we would observe what would appear to be a reflex action. Sharkey and Heemskerk (1997) discussed how the results of such an experiment could provide a sense-act look-up table. However, in its operational environment with a constant light we would have what appears to be phototaxis (of course these are neither reflex nor taxis, but the movements of a mechanical control system under test conditions). That is, we would *describe* the behaviour as moving towards a light source. Sharkey and Heemskerk, drawing on earlier work, referred to this distinction between the observation of a single sense-act loop and a sequence of sense-act loops respectively as *proximal* and *distal* descriptions. This is not a new distinction as pointed out by Keijzer (1998) and was emphasised by Brunswik (1952), but it is an important one. In some ways, at least with *M. speculatrix*, the distal behaviours can be seen as arising from the (moment to moment) proximal behaviours, but more of this later.

A more recent, but related robotics study, focusing on phonotaxis, has modelled the female crickets' attraction to the male song. The cricket's ears are on the forelegs (tibia) near the body which allows the female to locate a conspecific male by following its calling song (actually *stridulations*). In a series of studies, Huber investigated the neurophysiology of sound reception in female crickets (Huber, 1983). Using intracellular electrodes to a group of about 60 receptor cells in each ear, Huber found some neurons that are tuned to the specific frequency of the courtship songs of conspecific males while others appeared tuned to receive frequencies from intraspecific calls and sounds from possible predators.

In order to test the mechanistic plausibility of the phonotaxis hypothesis, Webb, Lund and Hallam built a Lego vehicle (Webb, 1995) and later used a Khepera miniature robot with a special auditory circuit (Lund *et al.*, 1997b; 1998) to physically model the phonotaxis behaviour of the cricket. The idea behind building a physical model was that it would have to achieve the same task under comparable conditions. It was shown that the Khepera model was actually attracted to live cricket stridulations, and exhibited syllable rate preference very similar to its natural

counterpart (Lund *et al.*, 1997b; 1998). But we should not think that an artificial cricket has been built. What has been demonstrated is the plausibility of a simple mechanistic model of one aspect of the crickets' behavioural repertoire.

Lambrinos *et al.* (1997) also used a robot to test behavioural models in a natural environment. They were interested in how arthropods use the sun to maintain a heading to return home after a foraging trip. Sanchi (1911) was the first to show this phenomenon with desert ants in a simple but seminal experiment. He screened direct sunlight from the ants and reflected it on them with a mirror from the opposite side. The ants adjusted their direction of travel according to this 'new' sun. Von Frisch (1949) showed that another hymenopteran, the honeybee *Apis mellifera*, used polarised skylight rather than the sun itself to navigate to food sources and to 'tell' other bees the whereabouts of food. The directions of light that has been polarised by striking particles in the outer atmosphere, the e-vectors (electric vectors), form a regular pattern across the celestial hemisphere and as the sun moves, the pattern moves with it. Thus it is possible to determine where the sun is by looking at the e-vectors in any portion of the sky. Von Frisch conducted an ingenious series of experiments in which he used a filter lens, that he had made, consisting of eight polarised filters set as triangular wedges in an octagon shape—this was derived from observations of the bees ommatidia. Placing the filter over a hole in a dark shed where the bees were, he was able to demonstrate a direct causal link between the bees' communicative dance and the turning of the filter.

In a similar move Lambrinos *et al.* (1997) built special purpose polarised light sensors based on what is known about the neural mechanisms of polarisation that the honey bee *Apis mellifera*, the field cricket *Gryllus campestris* and the desert ant *Cataglyphis bicolor* use to determine the position of the sun. Unlike von Frisch, they were not investigating the actual polarisation mechanisms of arthropods. Rather they mounted their sensors on a robot, Sahabot, and used it to test three different models of how the *Cataglyphis* maintains its heading with polarised light. The robot was required to maintain a target course direction for relatively short distances (68m or 136m) and then return to the starting position. Wheel encoders, which the ant does not have, were used to determine the distances travelled. All three models worked although there were differences.

As in the other robot studies discussed here, Sahabot was used to model only a small part of the whole process of finding the direction to the nest. It did not, for example, accommodate the movement of the sun across the sky during the day (although this information was used by the researchers to correct their data). The sun moves relative to the earth at an average of 15 deg. per hour (this varies greatly according to the time of day). Brun (1914) used this fact to show that ants both memorised the position of the sun and compensated for its movement. He found that when ants were imprisoned in a dark box for 2.5 hours and released, they deviated from their original bearing by approximately the same number of degrees as the sun had moved during their imprisonment. These findings have been borne out and refined by many more recent studies on 'kidnapped' ants (see Gallistel (1990) for a review). The findings reveal that *Cataglyphis* keeps track of the azimuth during the day and uses this information in maintaining a course.

The way in which Sahabot maintained its heading could be considered to be another form of taxis in which the animal maintains a fixed angular deflection from the source of stimulation, the sun. Indeed, it used to be called *mnemotaxis* or *solar compass reaction* to mean that the body is positioned in a remembered relation to a

source of stimulation (cf. Fraenkel and Gunn (1940)). However, this is quite
different from the taxes discussed until now. In this case the animal has to maintain
the correct angle to the sun that was 'memorised' on the outward journey. It used
that same angle when it rotates 180 deg. for returning to the nest and it also
compensates for the movement of the sun.

Zoologists and ethologists no longer discuss mnemotaxis or solar compass
reaction. Rather, animal navigation is a subject in its own right. Recent work
discusses the mixture of strategies that hymenopterans such as bees and ants use
for navigation and how they learn to use cues in their environments, e.g. Wehner
et al. (1996) and Collett (1998, this volume). There is substantial evidence that
hymenopterous insects such as ants (Wehner *et al*., 1996) and bees (Esch & Burns,
1996; Srinivasan *et al*., 1996) and also many mammals (Etienne *et al*., 1996;
Etienne, 1998) use dead reckoning to negotiate their environments. Moreover,
many of the biological systems use external references such as landmarks as well
as celestial cues and, more controversially, cognitive maps (Gould, 1986; Gallistel,
1990). For example, it appears that hymenopterans use optic flow to measure
distance travelled and a solar compass to measure their heading (Wehner, 1992).
There is also considerable recent robotics research on biologically inspired robot
navigation, e.g., Floreano and Mondada (1996), Millan (1996), Owen and
Nehmzow (1997) and Sharkey (1998), and see Schmajuk (1998) for a collection
of papers on this topic.

What we have seen here is a style of robotics following on from and testing
early notions from biology and comparative psychology. The work of Sherrington
(1906) shows how a multicellular organism gains internal solidarity through the
integrative action of its nervous system. The work of Loeb (1918) shows us the
importance of what kind of global behaviour can arise out of the minute interactions
of animal and world. The notion of a reactive robot is based on the combination
of reflex and taxis. Complex behaviour can arise out of the moment-by-moment
interaction of the robot with its environment; or, to put it another way, the distal
behaviour arises out of the *temporal integration* of local interactions.

By iterating the proximal system's short-term influence on the surroundings,
the distal behaviour is influenced in regular ways to generate patterns of events
over longer time-scales; what the observer sees as autonomous behaviour. In other
words, proximal sensory-motor couplings constitute short-term self-organising
processes which over longer time-scales converge to form what we perceive to be
the distal, functional regularities of behaviour. In living forms, it is the *results* of
proximal behaviours, finding food and mates, that receive competitive rewards in
evolution.

2.4. *The Organism as a Subject*

Given Loeb's delight with Hammond's crude heliotropic machine, he would have
been ecstatic with the sophistication of the modern machines. Sherrington, one
supposes, would be less impressed. His concern was with bodily integration and
how solidarity arises in multicellular organisms. The examination of metal machines
has little to tell us in this respect except by way of a, less than plausible, analogy
between neural integration and the wiring from sensors to controller to motors
(artificial neural network controllers are discussed in Section 3). The mechanistic
models, at present, could at most, be said to exhibit the simple reflex arc which

Sherrington admitted was really a theoretical entity since all of the reflexes are interdependent.

Moreover, the behaviour of the robots, when compared with the living, lacks meaning except in the scientific sense between data and model. For example, the cricket robot described above, attempts to model the sexual attraction of female crickets by detecting a male's stridulations and then moving towards the source. This model clearly shows the physical plausibility of the simple mechanistic theory of wiring 'ears' to 'motors' and provides a parsimonious alternative to having more sophisticated recognition and decision processes. This is similar to Roeder and Treat's theory about how the moth, *Cataocala*, evades being eaten by bats. However, the mechanical phonotaxis lacks the biological and evolutionary meaning of the animal's attraction; namely the reproduction and the survival of the species.

While not modelling a single species, much of the behaviour-based robotics research (e.g. Brooks, 1986b, 1989; Connell, 1990; Urzelai *et al.*, 1998) has been concerned with the more general development of systems of taxes or, as they are called in the robotics community, behavioural modules, that together create more interesting *emergent* behaviours. Even though the numbers of implemented behaviours have been quite small, such systems would be more likely to slightly interest Sherrington since there is some attempt to find a way of integrating 'reflexes' mechanistically in a way similar to his proposals on inhibition and excitation. Nonetheless, such mechanisms lack the behavioural coherence of even the simplest organisms; they lack bodily solidarity and attain only crude interaction with the world.

Even unicellular organisms with no nervous system exhibit more bodily integration and intimacy with their environment than current robots. They certainly demonstrate that the relationship between organism and environment is perhaps more subtle than our examples of reactive robots have indicated. The intimacy of the interaction of world and organism can be seen in the behaviour of the *E. coli* described above. It can follow a gradient through 5 orders of magnitude, relying not only on the chemotaxis itself but also on its interaction with the environment to change the way in which it is sensing. Whenever a single molecule of aspartate is bound to a receptor, there appears to be a chemical reaction that increases the probability of several neighbouring receptors being 'off' and thus the bias to swim is increased. However, without going into too much detail, because of the way in which chemical adaptation works, as the concentration gets stronger, so the size of the cluster of neighbouring 'off' cells shrinks (to as little as just the bound receptor). It is as if the bacteria were simply components in a giant environmental machine. In proximal terms, each aspartate molecule biases towards counterclockwise rotation of the flagella, while in distal terms, the bacteria 'swim and tumble' towards the highest concentration of aspartate molecules.

The seemingly tailor-made fit or solidarity between the organism's body and its environment is what von Uexküll tried to capture, starting in the 1910s, in his formulation of a *theoretical biology* (von Uexküll, 1928), and in particular his *Umwelt* theory (von Uexküll, 1921, 1957). Von Uexküll criticized the mechanistic doctrine ''that all living beings are mere machines'' for the reason that it overlooked the organism's subjective nature, which integrates the organism's components into a purposeful whole. Thus his view is to a large degree compatible with Sherrington and Loeb's ideas of the organism as an integrated unit of components interacting in solidarity among themselves and with the environment. He differed from them

in suggesting a rudimentary non-anthropomorphic psychology in which subjectivity acts as an integrative mechanism for agent–environment coherence.

> The mechanists have pieced together the sensory and motor organs of animals, like so many parts of a machine, ignoring their real functions of perceiving and acting, and have gone on to mechanize man himself. According to the behaviorists, man's own sensations and will are mere appearance, to be considered, if at all, only as disturbing static. But we who still hold that our sense organs serve our perceptions, and our motor organs our actions, see in animals as well not only the mechanical structure, but also the *operator, who is built into their organs as we are into our bodies.* We no longer regard animals as mere machines, but as subjects whose essential activity consists of perceiving and acting. We thus unlock the gates that lead to other realms, for all that a subject perceives becomes his perceptual world and all that he does, his effector world. Perceptual and effector worlds together form a closed unit, the *Umwelt*. (von Uexküll, 1957, first emphasis added)

The concept of *Umwelt* can be illustrated with reference to the noctoid moth mentioned above: part of the moth's perceptual world is, for example, the bat's high frequency emissions, which carry a particular meaning inherent to its species (danger), and part of its effector world is its capacity to exhibit protean escape behaviour that makes it difficult to catch.

Von Uexküll (1957) used the example of the tick to illustrate his idea of the organism's embedding in its world through *functional cycles*. It is three such functional cycles in "well-planned succession" which coordinate the interaction of the tick as a subject and a mammal as its object:

(1) The tick typically hangs motionless on bush branches. When a mammal passes by closely its skin glands carry perceptual meaning for the tick: the perceptual signs (*Merkzeichen*) of butyric acid are transformed into a perceptual cue (*Merkmal*) which triggers effector signs (*Wirkzeichen*) which are sent to the legs and make them let go so the tick drops onto the mammal, which in turn triggers the effector cue (*Wirkmal*) of shock.

(2) The tactile cue of hitting the mammal's hair makes the tick move around (to find its host's skin).

(3) The sensation of the skin's heat triggers the tick's boring response.

Von Uexküll 'admitted' that the tick exhibits "three successive reflexes" each of which is "elicited by objectively demonstrable physical or chemical stimuli", but as he pointed out:

> We are not concerned with the chemical stimulus of butyric acid, any more than with the mechanical stimulus (released by the hairs), or the temperature stimulus of the skin. We are solely concerned with the fact that, out of the hundreds of stimuli radiating from the qualities of the mammal's body, only three become the bearers of receptor cues for the tick.... What we are dealing with is not an exchange of forces between two objects, but the relations between a living subject and its object....
>
> The whole rich world around the tick shrinks and changes into a scanty framework consisting, in essence, of three receptor cues and three effector cues—her *Umwelt*. But the very poverty of this world guarantees the unfailing certainty of her actions, and security is more important than wealth. (von Uexküll, 1957)

Thus von Uexküll did not deny the physical/chemical nature of the organism's components, but he pointed out that they are forged together to form a coherent whole that acts as a behavioural entity, i.e. a subject which, through functional

embedding, forms a ''systematic whole'' with its Umwelt. Bourgine and Varela (1992) referred to this ''specific mode of coherence, which is embedded in the organism'' as a *cognitive self*:

> . . . the cognitive self is the manner in which the organism, through its own self-produced activity, becomes a distinct entity in space, though always coupled to its corresponding environment from which it remains nevertheless distinct. A distinct coherent self which, by the very same process of constituting itself, configures an external world of perception and action. (Bourgine & Varela, 1992)

The lesson that researchers in robotics and artificial life (e.g., Brooks, 1986a, 1991b; Clark, 1997; Prem, 1997) have learned from von Uexküll's work is that the study of the interaction between organism/agent and environment has to be based on the agent's own view of the world rather than the scientist's 'objective' view of agent and environment.

3. Robot Learning and Evolution

Previously, we discussed the successful application of robots for testing mechanistic models of simple (and often singular) taxes. However, like organisms, robots are often required to deal with complex, dynamic and unpredictable environments; but unlike living systems robot bodies do not necessarily possess any bodily integration or inherent solidarity with their environment, cf. Section 2. This can make them very difficult to build and program (cf. Nolfi, 1998, this volume). Much research is therefore concerned with the use of computational learning methods in an attempt to provide robots with a certain capacity for self-integration in interaction with their environment, i.e. to enable them to adapt or (re-) 'program' themselves to some degree. Most popular among such adaptation techniques are, perhaps due to a general conviction that ''nature knows best'', biologically inspired ones. These include reinforcement learning, evolutionary methods and neural computing. In this section we take a closer look at each of these techniques, their use in robotics and how they differ from their natural counterparts.

3.1. *Artificial Neural Methods*

Connectionist or artificial neural network (ANN) learning techniques have been used extensively for developing robot controllers for a variety of different tasks (e.g., Pomerleau, 1993; Meeden, 1996; Nolfi, 1997; van der Smagt, 1998), and there are a number of collections on the topic (Bekey & Goldberg, 1993; Omidvar & van der Smagt, 1997; Sharkey, 1997a). ANNs offer flexibility, robustness to noise and the capability of learning by example or by trial and error (reinforcement). They are therefore commonly considered to be effective mechanisms for controlling autonomous robots (e.g., Meeden *et al.*, 1993; Ziemke, 1998). Connectionist ideas also mesh well with reactive or behaviour-based robotics although this is not always appreciated.

A key feature of the use of ANNs for robot control is their capacity for learning and *self-organisation*. Unlike traditional AI methods, ANNs are not based on explicit, symbolic representations that mirror a pre-given external reality, but on self-organisation of an adaptive flow of activation between simple processing elements, and are thus compatible with an interactivist (Bickhard & Terveen, 1995) or experiential (Sharkey, 1997c) view of representation. Thus ANNs allow bottom-up

development of integrated control strategies (Meeden, 1996). In the simplest case, the self-learning capacity reduces the system designer's task to the choice of an appropriate ANN architecture for a given control task. Even in the case of supervised robot learning, the whole system may be self-organising. For example, Sharkey (1998), used an innate controller to train a supervised neural network controller.

Many consider ANN training methods to be statistical techniques that no longer necessitate contemplating the biological roots. However, when working in biorobotics it is useful to consider the biological significance of the ANN architectures and what level of relationship they have to living material.

Neural network research began towards the end of the nineteenth century when Ramon y Cajal discovered gaps or *synapses* in the neural tissue and this gave rise to the *doctrine of the neuron* (Waldeyer-Hartz, 1891). Cajal also suggested that learning involved adjustments of the connections between neurons. Soon the first real pro- posal for neural network learning came from William James (1892) who proposed that when two processes in the brain are active at the same time, they tend to make permanent connections. This is often referred to as *Hebbian learning*. However, Hebb (1949) did not set out his learning rule until more than 50 years after James and six years after the now famous McCulloch and Pitts (1943) paper, 'A logical calculus of the ideas imminent in nervous activity', which initiated the development of a formal computational approach to finding a physical basis for mind.

McCulloch and Pitts showed that, by partly ignoring and by simplifying the physical and chemical complexity of the nervous system, it was possible to build abstract model neurons into networks capable of computing all boolean functions. The reasoning behind the two main simplifications were that, (i) since the spike action potential of neurons is all or none, it fires when activity is above threshold, the neuron can be conceived of as a binary computing device; (ii) since modification of the neural synapses strengthens the connection between neurons, this connection can be modelled with numerical weightings between the binary computing ele- ments. To show how thought might be computed by a brain, McCulloch and Pitts turned to the mid-nineteenth century work of George Boole. Boole had attempted to describe the laws governing thinking by developing a system of logic in which symbolic propositions about the world could be combined to form other statements about the world using logical connectives. McCulloch and Pitts showed that binary networks of model neurons could be constructed to compute all boolean functions. However, the language of thought was not that simple and certainly did not appear Boolean. There is still considerable debate as to how thought might arise from the brain and this was particularly intense between cognitivists and connectionists, e.g. Fodor and Pylyshyn (1988) vs. Smolensky (1987).

Although Hebb cited neither James nor McCulloch and Pitts, he took a step beyond them in attempting to causally relate memory and perception to the physical world (Hebb, 1949). He proposed that the representations of objects may be considered to be states (or patterns) of neural activity in the brain. When a neural pathway is used, a metabolic change in the synaptic connections facilitates subsequent signal transmission. In this way, groups of neurons, from potentially different areas of the brain, are linked to form assemblies that support transforma- tionally invariant object recognition. Thus the synaptic connections come to *represent* the statistical correlates of experience.[3]

Thus, for biorobotics, it can be said that the whole concept of neural computing is beholding to biology and psychology for its beginnings. However, the problem now is that when a robot is equipped with an artificial neural net controller it has

to be remembered that it is a very abstract *model* of a neural network. Real neurons are living cells. As Sherrington put it in 1906:

> . . . nerve cells, like all other cells, lead individual lives—they breathe, they assimilate, they repair their own substantial waste; each is, in short, a living unit with its own nutrition more or less centered in itself.

Cells can also chemically communicate with each other by means other than induction. This might seem an obvious point, but it is worth asking in the heat of a good research day, what are the biological causal implications of using ANNs as part of a model and what is their explanatory value? It is also worth asking if one is making a commitment to a particular style of control because it carries with it an assumption that in some abstract manner that is what living computation and learning could be like. There is nothing wrong with this commitment as long as it is clear that this is all that it is. However, artificial nervous systems, as they stand now, cannot be expected to provide organismic solidarity of the type proposed by Sherrington for the reflexes. Nor can there be chemical solidarity between the artificial nervous system and the rest of the robot's body.[4]

3.2. Reinforcement Learning and Conditioning

Pavlov (1849–1936) demonstrated how the causal contingencies of reflex behaviour could be extended to include arbitrary stimuli through association (Pavlov, 1927). Conducting research on the secretions of the digestive glands of dogs, Pavlov noted that the sound of the footsteps of the caretaker bringing food elicited the same salivary reflex as the food. This led him to a series of experimental investigations of the association between unconditioned stimuli (e.g. food) and conditioned stimuli (e.g. the sound of footsteps). Perhaps the most famous experiment was carried out on a harnessed dog that heard the sound of a bell just before it received food. With repeated pairing of bell and food, the dog begins to focus on the bell when it is hungry. The sound of the bell, the conditioned stimulus, then elicits the same salivatory reflex as does the unconditioned stimulus, the food. Taking this a step further, Pavlov showed that by pairing the conditioned stimulus (the bell) repeatedly with another neutral stimulus (a light), the second stimulus would also elicit the original reflex response (salivating). With this second order Pavlovian conditioning in place, it is possible to see how reflexive behaviour could come to be adapted to the environment by a process of stimulus substitution. Flexibility comes about through a process of extinction through which the effect of the conditioned stimuli is gradually inhibited if the pairing is not repeated. However, the response to the conditioned stimuli may recover spontaneously after an absence and it will recover quickly if the pairing is repeated.

Classical conditioning was first introduced into robotics by Grey Walter (1953). By grafting the Conditioned Reflex Analogue (CORA), a learning box, onto *M. speculatrix*, described in Section 2.3, he created *M. docilis*, the easy learner. *M. docilis* had built-in phototaxis, i.e. a light elicited a movement response towards it which Grey Walter confusingly referred to as "an unconditioned reflex of attraction". When a light was repeatedly paired with the blowing of a whistle, *M. docilis* became attracted to the sound of the whistle and exhibited a phonotaxic response. In a separate series of experiments, Grey Walter repeatedly paired the sound of the whistle with obstacle avoidance and thus trained the robot to 'avoid' the sound of the whistle. He also demonstrated extinction of conditioned pairings

by presenting the conditioned stimulus repeatedly without pairing it with the unconditioned stimulus. There was also a slower decay of the conditioned response if it was not used for some time.

While Grey Walter's experiments were a little confused in the relationship between stimulus substitution for reflexes and stimulus substitution for taxes, they do show how a simple learning mechanism can extend the behaviour of a robot by bringing its reflexes under the control of substituted environmental effects. Adapting a positive phototaxis response for use as a positive phonotaxic response or adapting an object avoidance response for use as a negative phonotaxic response could be crucial for survival in a changing world. It is hardly surprising that classical conditioning has been resurrected in recent robot studies (e.g., Verschure *et al.*, 1992; Balkenius, 1995).

Many psychologists, most notably Watson (1916), believed that all learning (and experience) could be translated into Pavlovian conditioned reflexes and it was demonstrated for many species during the 1920s and 1930s. However, there were others, such as Skinner (1935), who argued that classical conditioning was just *one* rather than *the* learning paradigm. Schlosberg (1937), following a seminal series of experiments, concluded that classical conditioning produces what appear to be "diffuse prepatory responses". Thus, strictly speaking, learning and adapting by classical conditioning only works on built-in reflex responses (although there is also second-order Pavlovian conditioning). This is in tune with Sherrington's (1906) work on the reflexes in terms of the integration of coordinated movement. However, if such conditioning was the only form of adaptation, animal behaviour would be strictly limited and lacking 'creativity'. It is clear that organisms can learn patterns of behaviour leading to a reward that are not best categorised by reflex chains. In the way in which we showed the move from bodily solidarity to organism-environment solidarity through the work of Loeb and taxes, there was also a move from reflex conditioning to behaviour conditioning.

More adaptive learning was shown to be the result of the behaviour influencing the stimulation; the behaviours themselves are *instrumental* in bringing about rewards. In this way an organism can adapt its behaviour to the environment in such a way as to maximize its positive reinforcement and minimize its negative reinforcement. Reinforcement, in this context is simply defined as a stimulus which increases the probability of the response upon which it is contingent. It is this type of instrumental learning that formed the basis for machine reinforcement learning methods (RL) in the 1980s (e.g., Sutton & Barto, 1981; Barto *et al.*, 1983; Sutton, 1984; Watkins, 1989) and it is most closely associated with the 'trial and error' animal research of the early connectionist Thorndike (1898). In robotics, reinforce-ment learning of this type is used extensively, beginning in the 1950s with maze learning (Howard, 1953; Shannon, 1951), and is nowadays used for learning in unknown problem domains where supervised learning techniques are less useful (e.g. Nehmzow, 1992; Medeen *et al.*, 1993; Prescott, 1994; Ziemke, 1996; Touzet, 1997; and see Krøse (1995) for a collection of papers on robot RL).

One of the more interesting moves in current robot learning is the use of *operant* conditioning techniques developed by Skinner (1953). This involves the manipulation or *shaping* of pre-given behaviours. In particular, Skinner showed that animals could be trained to produce an experimenter-required behaviour if they were rewarded for successive approximations to that behaviour. For example, if a rat is to be trained to press a bar for food, to begin with, it would receive rewards for any reaching movement. Then by rewarding successive approximations

to the goal, the animal can be trained. In robotics this has also been called behaviour editing by Dorigo and Colombetti (1994, 1998) who have conducted most of the experimental work on this technique in robotics. An extension of this work to include incremental shaping is discussed by Urzelai *et al.* (1998, this volume). For a review of the relation between animal and robot shaping see also Savage (1998, this volume).

In a realistic approach, Saksida *et al.* (1997) successfully used operant conditioning to modify the interaction between behaviours that had been pre-programmed into a robot. This departure from using reinforcement learning as 'trial and error' to modify existing behaviours is a step towards real animal training. Furthermore, unlike most RL work, the training was conducted by a human trainer rather than a programmed reinforcer. Initially, the robot had three categories of objects: a bright orange jacket, green and pink plastic dog toys, and blue plastic recycling bins. One of its innate behaviours was to approach the plastic dog toys and pick them up. Successful (fast) shaping was shown for a number of new behaviours, including *Follow the Trainer*, *Recycling* and *Playing Fetch*.

The animal research on conditioning over a 90 year period has been extensive and experimentally detailed. Robot learning, in its modern incantation, has a lot of catching up to do on the specifics to account for the psychological research. Even the operant conditioning work has modelled only part of the process. For a detailed discussion of recent work on robot shaping see Savage (1998, this volume). For our purposes, the most important difference between robot reinforcement learning and animal learning is that animals have living bodies and have behavioural completeness. The body is important if reinforcement learning is to have realism. The robot does not experience pleasure or pain as does the animal; it experiences only modifications to its ANN weights or to its program code during learning. Thus the psychological meaning of the behaviour is lost by an absence of bodily needs and changes.

3.3. Evolutionary Robotics

Evolutionary robotics is a useful method for the 'hands off' development of robot controllers in the new wave of robotics (cf. Nolfi, 1998, this volume). The approach is abstractly based on the Darwinian principle of natural selection, the survival of the fittest, and is of particular interest to those interested in artificial life. Although evolutionary algorithms are now widely used in engineering systems as an efficient search mechanism for problems with large solution spaces, it is the relationship with natural evolution that concerns us here.

For natural organisms, as discussed in Section 2, it is essential to interact viably in solidarity with their environment. This is what enables them to exhibit coherent distal behaviour that allows them to preserve their bodily integrity, survive, and eventually reproduce. Thus the seemingly tailor-made fit between organism and environment can be seen as a result of evolutionary pressure: organisms whose bodily mechanisms allow them to interact effectively with their environments are more likely to reproduce, and thus pass on the genetic material underlying these mechanisms. Neo-Darwinians, such as Richard Dawkins, actually argue that all living creatures are essentially protein robots whose purpose is to carry self-replicating DNA (or RNA in the case of some viruses) and spread it around when appropriate opportunities arise to replicate (Dawkins, 1997). Thus, in this

view, it is the DNA that gives life a purpose, and it is the body that facilitates its realisation.

The first approach to applying evolutionary methods to artifacts was probably Friedman's (1956) master's thesis on evolving control circuits for autonomous robots. However, it was not until the 1990s that the idea of an *evolutionary robotics* was investigated systematically (e.g. Cliff *et al.*, 1993; Nolfi *et al.*, 1994). The very idea of evolving robots was well illustrated by Braitenberg (1984) who likened evolution to the following scenario. There are a number of robots driving about on a table top. At approximately the same rate that robots fall off the table, others are picked up randomly from the table, one at a time, and copied. Due to errors in the copying process, the original and the copy might differ slightly. Both are put back onto the table. Since the fittest robots, those who stay on the table longest, are most likely to be selected for 'reproduction' the overall fitness of the robot population is likely to increase in the course of the 'evolutionary' process.

Braitenberg's scenario is an example of evolving robot hardware. Currently, however, only relatively few researchers are experimenting with the evolution of physical robots. Where this is possible at all, the costs in development time and hardware resources are high. Much more research is dedicated to evolving control-lers, at least partly, in simulation for later use in either simulated robots or real robots (e.g., Nolfi, 1997; Husbands *et al.*, 1998; Urzelai *et al.*, 1998; Jakobi, 1998; but see also Floreano & Mondada, 1994, for the first example of an evolutionary process entirely carried out on a physical robot). Individual solutions, e.g. the connection weights in an ANN robot controller, are represented by the computer equivalent of gene strings, and they are reproduced on the basis of their fitness, applying mutation and crossover operators. Since selection for reproduction is biased towards genotypes with high fitness values, the average fitness tends to increase in a population of genotypes.

Nolfi (1997) presents an impressive example of a robot evolving non-trivial behaviour from very simple mechanisms. He evolved the connection weights in an ANN controller for a Khepera miniature robot equipped with distance sensors and a gripper. The task was to 'clean' an arena by picking up objects and dropping them off outside the arena. This task implies subtasks such as moving around in the arena, locating an object, picking it up, moving towards the walls, and releasing it outside the arena. The initial control structures were 100 feedforward networks with random connection weights. The robot controllers were then tested in the environment and evaluated using a fitness function that took into account how well they handled the subtasks. In each generation the 20 fittest controllers were selected, and each of them was reproduced five times (using random mutations), such that the next generation would consist of 100 new individuals. After 1000 generations, robot controllers were evolved that performed the cleaning task to a high degree of accuracy.

As in this example, in evolutionary robotics there is typically a fitness function to measure how well a particular robot or its controller performs in the context of the problem it is required to solve. Thus, robot evolution is typically viewed as the maximisation of a predefined fitness function. Natural evolution, on the other hand, can be viewed as "natural drift" (Varela *et al.*, 1991) rather than optimisation. Harvey, for example, points out that optimisation "is not in fact what goes on in natural evolution, where the 'problems' different organisms face were not predetermined at the origin of life on earth. Natural evolution can be thought of as a method for adaptive incremental improvement to organisms who are facing,

over geological time, problems that vary with the environment which significantly includes varying organisms'' (Harvey, 1997). In other words the environment and other species co-evolve with a given organism. This has been taken up in *co-evolutionary robotics*, in its simplest form with two species co-evolving. Floreano and Nolfi's work, for example, on the co-evolution of predator and prey behaviour has two different agents/species as part of each others' environment (Floreano & Nolfi, 1997; Nolfi & Floreano, 1998). Since the 'species' co-evolve, the fitness landscape is no longer static, but effectively changes from generation to generation. Thus this process can no longer be viewed as the solving of a specific problem or optimisation of a static fitness function.

A problem with the evolution of robot controllers is what Funes and Pollack call the "chicken and egg" problem of evolutionary robotics: "Learning to control a complex body is dominated by inductive biases specific to its sensors and effectors, while building a body which is controllable is conditioned on the pre-existence of a brain" (Funes & Pollack, 1997). Thus, although the specific connection weights in the Nolfi example were evolved, they were meaningful only in the context of the ANN architecture employed, the layout and type of sensors and motors, and the robot body shape. As Nolfi (this volume) points out, at least in theory, all of these parameters could be encoded by the genotype as well. If this were technically possible, then robots could be evolved as integrated bodily units with some of the solidarity of organisms, cf. Section 2. While integrated robot body units are some way off in the future, a small but growing number of researchers have begun to study the evolution of physical structures and robot morphologies (e.g., Funes & Pollack, 1997; Lund *et al.*, 1997a), in some cases in co-evolution with controllers (Cliff & Miller, 1996; Lund & Miglino, 1998). For example, Cliff and Miller (1996) simulated the co-evolution of 'eyes' (optical sensors) and 'brains' (ANN controllers) of simple robotic agents which pursued and evaded each other in a two-dimensional plane.

Nevertheless, despite recent advances in co-evolutionary robotics, real life is still far more complex than the scenarios of artificial evolution. One key difference is that, apart from co-evolving species, environments are mostly static in artificial evolution scenarios. Natural evolution really is co-evolution of nervous systems and/or chemical communication systems, bodies and complete dynamic eco-systems with multiple competing and possibly cooperating species. Furthermore, in natural organisms, every cell in the body is determined initially by the DNA that exists in every cell. The individual phenotype is the result of (a) a developmental process following genetic instructions for building a body which may include a nervous system and receptors in interaction with the environment; and (b) individual adaptation and learning. In contrast, robot 'genes' are held centrally in the computer, not in the body, and are usually specifications which are directly mapped onto behaviour-producing mechanisms, e.g. the weights in an ANN controller. It should be noted, however, that the field of evolutionary robotics is still very young, and both the integration of development (e.g., Kodjabachian & Meyer, 1998, this volume), and the interaction between learning and evolution (e.g., Nolfi & Parisi, 1997; Floreano & Mondada, 1998), are being addressed in current research.

In sum, evolutionary robotics research addresses the questions of (a) how, through an evolutionary history of *integration through mutual specification*, agent-internal mechanisms and environment come to cooperate intimately in the production of coherent behaviour, as described for living organisms in Section 2, and (b) how the mutual specification of agent and environment can be synthesised

in robots. Given the intended relationship between the behaviour of new wave robots and natural biological behaviour, the development of an evolutionary robotics is an attractive approach to the study of behaviour in artificial and natural systems (cf. Nolfi, 1998, this volume). Even from a purely engineering perspective, evolutionary methods are a useful tool for working in unknown domains (but see also Mataric and Cliff (1996) for a critique and a discussion of some of the practical problems).

4. Minds, Bodies, and Robots

So far we have examined the biological theories of animal behaviour that underpin biorobotics; theories that have arisen directly from the study of biological systems and are concerned with the integration of the body to create coherent behaviours and the solidarity of organism and environment. Even in the case of Umwelt, the organism's phenomenal world was described as tightly coupled to its physical environment. Further, we have discussed different biologically inspired techniques in robotics that allow robots to adapt in interaction with their environment. However, from the 1960s through the 1980s, the early work was divorced from the dominant themes in the mind sciences. The early biological approaches contrasted sharply with those of *cognitivism*, traditional AI and traditional cognitive psychology. Here, mind was cut off from body in a move that echoes Sherrington's decerebration of animals in reverse.

4.1. From Robots to Computer Programs and Back

In Neisser's (1967) book *Cognitive Psychology*, which defined the field, he suggested that the book might just as easily have been titled, *Stimulus Information and its Viscissitudes*. By this Neisser meant that the term *cognition* referred to all process "... by which sensory input is transformed, reduced, elaborated, stored, recovered, and used. It is concerned with these processes even when they operate in the absence of relevant stimulation, as in images and hallucinations. Such terms as *sensation*, *perception*, *imagery*, *retention*, *recall*, *problem-solving*, and *thinking*, among many others, refer to hypothetical stages or aspects of cognition." Neisser stressed that "... the task of a psychologist trying to understand human cognition is analogous to that of a man [sic] trying to understand how a computer has been programmed." The cognitive psychologist, "... wants to understand the program, not the hardware".

Taken to extremes, this analogy echoes one of the central tenets of *cognitivism* in which cognition can be thought of as a program that could be run on any machine capable of running it. Whereas behaviourists treated mind as an opaque box in a transparent world, cognitivists treated it as a transparent box in an opaque world (Lloyd, 1989). But there is more to cognitivism. According to Fodor and Pylyshyn (1988), classical models of the mind, derived from Turing and von Neumann machines, are committed to the notion that the kind of computing required for the understanding of cognition involves operations on arbitrary symbols and structured symbolic expressions (cf., Newell & Simon, 1976; Newell, 1980). So, according to the cognitivists, after transducing the sensory inputs onto symbols, the vicissitudes of information are the formal manipulation of syntactically struc-tured symbolic expressions.

In this functionalist framework having a body, living or artificial, was regarded

as a low-level implementational issue. Even connectionism of the 1980s, with its biologically inspired computation and its strong criticisms of the cognitivist stance for its lack of concern with neural hardware, was mainly concerned with explaining cognitive phenomena as separated from organism-world interaction. However, unlike traditional AI, connectionists did not promote symbolic representations that mirror a pre-given external reality. Rather, they stressed self-organisation of an adaptive flow of activation between simple processing units that is compatible with an interactivist (Bickhard & Terveen, 1995) or experiential (Sharkey, 1997c) view of representation (see also Clark (1997), Dorffner (1997)). Nonetheless, all of this cognitive work left autonomous robotics in an awkward position and cut if off from its earlier intellectual roots. The robot simply became a vehicle for carrying an AI system for planning and reasoning, as, for example, the famous Shakey robot (see Nilsson (1984) for a review).

It was not long before arguments were raised from a number of quarters that AI could not realise its goal of machine intelligence without paying closer attention to how intelligence arises from the interaction between agent and world; systems designed by researchers could never capture intelligence as developed through evolutionary pressure and adaptation to the environment. The arguments were many and varied but they all stressed similar points. For example, Searle (1980) argued that in the symbolic models of traditional AI there is no causal connection whatsoever between the representation and the represented, i.e. the internal symbols and the external world they were supposed to represent. Instead, that connection is only in the eye/mind of the designer or observer of such systems. Harnad (1990) later referred to this as the *symbol grounding problem*. But this only sidesteps the real problem and a number of other authors have pointed out that the grounding problem is not limited to symbolic representations, and should therefore be referred to as the problem of *representation grounding* (Chalmers, 1992), *concept grounding* (Dorffner & Prem, 1993), or the *internalist trap* (Sharkey & Jackson, 1994). Searle, however, did not suggest giving up the idea of intelligent machines, but argued that humans are such machines and that the main reason for the failure of traditional AI was that it is concerned with *computer programs*, but "has nothing to tell us about *machines*" (Searle, 1980), i.e. physical systems causally connected to their environments.

It was perhaps the new wave in robotics that showed the strongest alternative to ungrounded AI. A number of researchers questioned not only the techniques used by traditional AI, but its top-down approach and focus on agent-internal reasoning in general. They suggested a bottom-up approach as an alternative to the representationalist/computationalist framework of cognitivism. In particular, Brooks put forward his *behaviour-based AI* approach (Brooks, 1986b, 1990, 1991a), and Wilson formulated the *animat approach to AI* (Wilson, 1985, 1991). For a more detailed review see Ziemke (1998). In this approach, robotic agents are typically considered *physically grounded* as Brooks explains.

> Nouvelle AI is based on the physical grounding hypothesis. This hypothesis states that to build a system that is intelligent it is necessary to have its representations grounded in the physical world. ... To build a system based on the physical grounding hypothesis it is necessary to connect it to the world via a set of sensors and actuators. (Brooks, 1990)

These key ideas are also reflected by commitments to "the two cornerstones of the new approach to Artificial Intelligence, situatedness and embodiment" (Brooks, 1991a). The first commitment, to the study of agent–environment interaction

rather than representation, is reflected in the notion of *situatedness*: ''The robots are situated in the world—they do not deal with abstract descriptions, but with the here and now of the world directly influencing the behavior of the system.'' (Brooks, 1991a). The second commitment was to machines, i.e. robotic agents rather than computer programs, as the object of study, as reflected in the notion of *embodiment*: ''The robots have bodies and experience the world directly—their actions are part of a dynamic with the world and have immediate feedback on their own sensations.'' (Brooks, 1991a).

4.2. Rooted Behaviour and Rooted Cognition

The physical grounding and agent–environment interaction which come with the bottom-up approach enable so-called embodied, situated agents to 'reach out' into their environment, and directly ('autonomously') interact with it, and thus offer a way for AI research to 'escape' the internalist trap by avoiding it in the first place. Moreover, the new wave provided a link to the older biological theories described in Section 2. Here, it seems in principle, is a way for AI to move closer to biological intelligence; towards a robotic form of intelligence that could be evolved, rather than designed, and could adapt to its world without intervention by the researcher. However, while these ideas from robotics represent a significant advance in AI there is still a long way to go in the development of a lifelike artificial intelligence. In this sub-section we examine what it means for a robot to have a body and whether this body can *stand in* for a living body.

The new wave in robotics appears to be taking AI a long way towards greater and more naturalistic intelligence. However, paraphrasing Dreyfus (1979), we must be sure that we are not climbing a tree and thinking that we are on our way to the moon. Traditional AI research made the early mistake of overclaiming and falsely predicting its future. We must not make the same mistake. In 1976 McDermott, a prominent AI researcher, expressed his concerns about the labels being used to describe aspects of AI programs. He refers to these labels as *wishful mnemonics* and gives the example of a programmer writing an 'understanding' program. If in the first implementation the main loop of the program is called UNDERSTAND, then the programmer may come to believe the similarity with humans solely on the basis of the label.

Similar caution must be exercised with terms such as *embodiment* and *physical grounding*. It is one thing to use these terms to describe inadequacies in cognitivist theories and another to use them to describe a robot or a robot controller.[5] The concepts that are smuggled in with such terms can lead to theory-laden attributions of the robot behaviours; *wishful attributions*, e.g. goal seeking. If care is taken and the relationship of the terms to their living counterparts are exposed, they can be useful in finding new research directions. We now turn to discuss some of the differences between robot bodies and living bodies, and their implications.

A robot is a collection of inanimate mechanisms and non-moving parts that form a loosely integrated physical entity. The Nomad 200 and the Khepera, for example, are motor controllers with a surrounding shell; the meaning of *body*, in this sense, is really like a car body and not at all like a living body. By way of example, if you attach a hula-hoop or a bunch of clothes pegs to your body, they will clearly be objects attached to your body. With a robot, the hula-hoop or the clothes pegs could be considered part of its body. (What would it mean for a robot

to have an artificial limb?) There is not the same clear distinction between the robot body and the objects around it as there is for an organism.

This is not just a trivial matter. The chemical, mechanical, and integrating mechanisms of living things are missing from robots. Consequently, there can be no notion of multicellular solidarity, as described in Section 2, or even a notion of a cell in a current robot. Although some may argue that the messaging between sensors, controllers and actuators, is a primitive type of integration, this is very different from the dependency relationship between living cells in real neural networks. ANNs can be used as a 'stand-in' integrative mechanism between sensors and actuators. However, they are not themselves integrated into the body of the robot; most of the body is a container for the controller, a stand to hang the sensors on, and a box for the motors and wheels. There is no interconnectivity or cellular communication (or cells for that matter). In multicellular creatures, solidarity of different types of cells in the body is required for survival.

Cells need oxygen and so living bodies need to breathe, they need nutrition and so bodies need to behave in a way that enables ingestion of appropriate nutrients. This gives an organism purpose. All of this demands finely tuned distal behaviour. As pointed out earlier, the distal behaviours of an organism have evolutionary significance in terms of the survival and regeneration of the species; which genes will stay in the pool and which will be extinguished. This is not the case with robots. Their behaviour has no evolutionary significance to the species *M. speculatrix*. There is no reproduction of the body and the genome resides centrally rather than existing in every part (cell) of the body.

Due to the differences in body type, a robot does not learn like an animal. Although robots may be used for modelling operant and classical conditioning in a more realistic way than simulations, and ANNs may be used as controllers to model the mechanisms of learning, the robot is not learning anything biologically or psychologically meaningful. Without an integrated body it does not experience pleasure or pain in reinforcement learning; there are only weight changes or program changes. The actual putative 'experience' of a robot undergoing reinforcement learning is the same for both reward and punishment. The organism, on the other hand, is driven by its bodily aversions and needs.

Perhaps some of the most important issues of having a robot body arise in the thorny question of subjectivity. This is not a problem for the cognitivists since their theories require only a 'hook' into the world to ground the symbols (Jackson & Sharkey, 1996). But it is another matter for those committed to an interactionist view of intelligence. Many wish to pursue the "next step in intelligence" (Sharkey, 1997b) with cognition as an integrative mechanism. As already discussed in Section 2.4, von Uexküll strongly objected to the doctrine "that all living beings are mere machines":

> ... All our useful devices, our machines, only implement our acts. There are tools that help our senses, spectacles, telescopes, microphones, which we may call *perceptual tools*. There are also tools used to effect our purposes, the machines of our factories and of transportation, lathes and motor cars. These we may call *effector tools*.
>
> Now we might assume that an animal is nothing but a collection of perceptual and effector tools, connected by an integrating apparatus which though still a mechanism, is yet fit to carry on the life functions. This is indeed the position of all mechanistic theories, whether their analogies are in terms of rigid mechanics or more plastic dynamics. They brand animals as mere objects. The proponents of such theories forget

that, from the first, they have overlooked the most important thing, the *subject* which uses the tools, perceives and functions with their aid. (von Uexküll, 1957)

In a similar vein, Maturana and Varela (1980, 1987) challenged cognitivism with their notion of cognition as being first and foremost a biological phenomenon. In particular they claimed that "living systems are cognitive systems, and living as a process is a process of cognition" (Maturana & Varela, 1980). More recently these arguments have led to the formulation of an *enactive cognitive science* approach, (Varela *et al.*, 1991), and there is broad support in the field of *embodied cognition* where there is a reassessment of the relevance of life and biological embodiment for the study of cognition and intelligent behaviour (e.g., Clark, 1997; Chiel & Beer, 1997; Ziemke, 1997a; Prem, 1997; Wheeler, 1997; Pfeifer & Scheier, 1998).

In this framework, cognition is viewed as *embodied action* by which Varela *et al.* (1991) mean "... first, that cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities, and second, that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context". Thus, this view, like that of von Uexküll, emphasises the organism's embedding in not only its physical environment, but also the context of its own phenomenal world (Umwelt), and the tight coupling between the two. In the words of Varela *et al.*, "cognition in its most encompassing sense consists in the enactment or bringing forth of a world by a viable history of structural coupling" (Varela *et al.*, 1991).

The emphasis on structural coupling (or continual mutual specification) between agent and environment offers an interesting perspective on how environment and agent participate in producing effective behaviour. We noted earlier that when looking at the mechanisms underlying behaviour one can easily get the impression that it is the environment that is driving the organism; that the organism is a mere Cartesian puppet (cf. also Sharkey and Heemskerk (1997), Ziemke (1997b)), e.g. the aspartate that drives the *E. coli* or the bat's sound emissions that trigger certain actions in the moth. Merleau-Ponty, however, strongly rejects the notion of the organism as a puppet. He likens this idea to that of the living creature as a keyboard on which environmental stimuli play. Like von Uexküll his arguments emphasise the subjective nature of the living.

> The organism cannot properly be compared to a keyboard on which the external stimuli would play ... But it is the organism itself—according to the proper nature of its receptors, the thresholds of its nerve centers and the movements of the organs—which chooses the stimuli in the physical world to which it will be sensitive.... This would be a keyboard which moves itself in such a way as to offer—and according to variable rhythms—such or such of its keys to the in itself monotonous action of an external hammer. (Merleau-Ponty, 1963)

All of this goes far beyond the notion of embodiment as providing (only) physical grounding. Living organisms are not only physically grounded in their environment and physically situated in some "here and now", but, as bodies, they are also historically *rooted* and situated in the here and now of their *own Umwelt* which is the result of a long history of mutual specification and structural coupling between organism and environment. Living bodies embody the evolutionary and individual history of agent–environment interaction and provide an Umwelt that enables effective agent–environment interaction in the present. The reason the noctoid moth does not have to think about how to escape the bat, but can just 'go with the flow' of its bodily interaction with the world, is that the moth is rooted in its own

tailor-made world, which is the result of the interaction of generations of moths with their environment.

Robots may be *physically grounded* but they are not *rooted* in their *own* world; they are moving objects in *our world*. They exhibit behaviours that we refer to as goal seeking, obstacle avoidance, phototaxis, and so on, but these are meaningless to the robots. Anything else is *wishful attribution*.

The difference between physically grounded and rooted behaviour, can be illustrated by analogy with a secret garden inhabited by a roboticist and a gardener. The roboticist would design a non-mobile robot that in some way resembled a plant; the design would consider the types of sensors needed for appropriate phototropic movement as well as the required mechanical movements. All of the inanimate components would be purchased, assembled and tested. The finished product would then be stuck in the ground and connected to a power source.[6] There would probably be many iterations of the design process to finalise the plant for demonstrations. If it was left for long enough it might become inhabited by living creatures and plants but it will have no connection to them.

The gardener plants some seeds in the ground, waters them and watches them grow, flower, and seed to repeat the cycle. The living plant is *rooted* in its world. In some sense it has co-evolved with other plants and animals over millions of years. It takes from the sun, the earth and the atmosphere to produce, in chorus with the other plants, the atmosphere that sustains it and the other life forms on the planet. The delicate and complex interplay between plants and animals is illustrated by Dawkins in the co-evolution of the interdependent relationship between the fig wasp and the fig tree (Dawkins, 1997). The wasp depends entirely on the fig for its food and the fig depends entirely on the wasp to carry its pollen for propagation.

4.3. *Implications*

The lack of rootedness might be a minor problem where robots are used to *model* the behaviour of living systems, as in the aforementioned cases of crickets or desert ants. In the case of bio-behavioural modelling, organism and environment are often relatively well studied, and the robotic model is typically only intended to model isolated aspects of the interaction between the two (for further examples see Prescott & Ibbotson (1997), Burgess *et al.* (1998), Quinn & Ritzmann (1998)). Furthermore, as a *model*, the robot derives its embodiment at least partly from the organism it is supposed to model, and thus to some degree inherits its evolutionary rooting.

Many researchers in the fields of AI and robotics, however, would like to build robots that do not only model isolated aspects of living systems' intelligent behaviour, but robots that actually *are* intelligent and autonomous themselves. On the other hand, most researchers do not want to limit themselves to robots that mimic the physiology or behaviour of living systems. Thus robotics faces a funda-mental dilemma: a robot that is built and equipped with a body the conventional way will always be *heteronomous* in the sense that its body and its environmental embedding are not its own, but designed[7]; thus its behaviour, much like a wishful attribution, derives meaning from the intentions of its designers or observers.

Certainly we can equip robots with sensors and effectors, and some hold that this provides them with a rudimentary form of *Umwelt* (cf. Brooks, 1986a, 1991b). We know, however, very little about how to design coherent artificial organisms,

which have the solidarity of living systems and are one with their world. The key problem for the development of a truly intelligent robot is how to synthesise such a coherent self.

A possible route to achieving the autonomy and solidarity in robots, that in living systems form the foundation of cognition and intelligent behaviour, might be to 'build' robots the 'natural' way, viz. through radical bottom-up self-organisation via co-evolution of robot bodies, nervous systems (or chemical systems) and environments, as briefly discussed above. However, to what degree this approach could possibly achieve the integration and coherence of organisms is an open question.

5. Conclusions

The main focus of this paper has been on the implications of having a living body as opposed to a robot body. We began by using Sherrington's (1906) work on the mechanisms of bodily integration to show how the solidarity in multicellular animals has implications for the design of robot bodies. We then examined two different ways of viewing agent–environment solidarity. In the first, by Loeb (1918), the organism was treated as a Cartesian puppet under the control of environmental stimuli (tropisms); and, in the second, by von Uexküll (1921), solidarity was created by species-specific subjectivity. The implications of these theories of bodily and agent–environment solidarity highlighted the gap between biologically inspired robot implementations and real organisms. Next, we examined biologically inspired techniques, such as neural computing or connectionism, reinforcement learning, and evolutionary methods that enable robots to adapt in interaction with their environment and thus equip them with a capacity for a certain degree of self-integration. Finally, we considered some recent ideas about physical grounding in robotics and how they improved upon ungrounded AI. In discussing theories of *cognition as a biological process*, we pointed to differences between embodied cognition on a robot and rooted cognition in a living system. Our conclusion is that robots lack the bodily solidarity and behavioural coherence from which cognition and intelligent behaviour flow in living systems.

The intention was not to criticise the important work being carried out in biorobotics, but rather to offer notes of caution that could prevent derailment of its theoretical impetus further down the line; wishful attributions could wrong-foot the scientific enquiry. We have attempted to show that, from the modelling and general theory testing perspective and from the perspective of self-organised engineering, biorobotics is making significant advances. Much headway has been made in making robots adaptive by providing them with the capacity to learn, develop and evolve in interaction with their environments (in the *artificial* senses of these terms).

For those wishing to build artificial life forms and robot intelligence, an aim which is attractive to most practitioners in the field, there is still a very long way to go and a lot of difficult problems still have to be solved. But, then again, this is what makes biorobotics so attractive. To stay within the garden metaphor, making robots adaptive could be likened to the roboticist's attempt to provide an artificial seed that can grow in the living garden and thus become an integral part of it. Our worry, however, is that unless the body itself, not only its controller, is allowed to self-organise into an integrated unit and grow into a meaningful whole consisting of body and environment, a robot may never have a coherent autonomous self comparable to even the simplest organism. Robots, like organisms, need to be rooted.

Acknowledgements

Notes

1. We thank Dennis Bray from the Department of Zoology at the University of Cambridge for providing us with this figure.
2. Nowadays the term reflex is reserved for movements that are not directed towards the source of stimulation whereas taxis and tropism are used to denote movements with respect to the source of stimulation.
3. It was not until 1973 that Bliss and Lomo first reported, in detail, that following brief pulses of stimulation, there is a sustained increase in the amplitude of electrically evoked responses in specific neural pathways, that is *long term potentiation.*
4. For an example of neuroscientifically inspired robot controllers modelling chemical influences to some degree see Husbands *et al.* (1998, this volume).
5. It is sometimes unclear in the literature whether it is the controller that is embodied in the robot or the robot that is embodied in the world.
6. In this context, the cognitivist would merely say, "who needs plants for a beautiful garden anyway".
7. For a discussion of the distinction between autonomy and heteronomy in an artificial life/robotics context see, e.g., Bourgine and Varela (1992), Prem (1997).

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