The early evolution of spatial behaviour: robot models of trace fossils*

Tony J. Prescott and Carl Ibbotson
Department of Psychology
University of Sheffield
Western Bank
Sheffield S10 2TP

email: t.j.prescott@sheffield.ac.uk
http://www.shef.ac.uk/~abrg/tony/

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Abstract

The evolutionary history of nervous systems can provide useful insights for biologically-inspired robot design. The study of trace fossils, the fossilised remains of animal behaviour, reveals interesting parallels with recent research in behaviour-based robotics. This paper reports robot simulations of the meandering foraging trails left by early invertebrates which demonstrate that such trails can be generated by mechanisms similar to those used for robot wall-following. We conclude with the tentative suggestion that the capacity for intelligent behaviour shown by current behaviour-based robots is similar to that of animals of the early Cambrian period approximately 530-544 million years ago.

Introduction

Biology is widely regarded as an important source of inspiration for robotics. Animals are seen as offering working examples of robust, embedded autonomous agents, and their neural circuitry, and sensor and motor structures, are viewed as providing models for designing similar components for robots. The premise of this paper is that robotics can gain further insights from biology by taking a closer interest in evolutionary history—the study of the phylogenetic relationships between animals and the nature of evolutionary change from one animal form to another. Invaluable insights for robotics should be gained if we can understand how complex neural circuits were derived from simpler ones, a question that can only answered by investigating the evolutionary history of nervous systems. Of course, brains and behaviour don't make good fossils. This gives evolutionary neurobiologists the difficult task of inferring the architecture of early nervous systems from clues found in comparative and developmental studies. Only occasionally does the fossil record provide any direct evidence of the behaviour of ancient animals. Here, however, we are concerned with fossil evidence of exactly this sort which has provided important insights into the early evolution of animal spatial behaviour. Perhaps unsurprisingly, we see that the first nervous systems generated behaviour with some remarkable similarities to that of recent behaviour-based robots.

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Trace Fossils

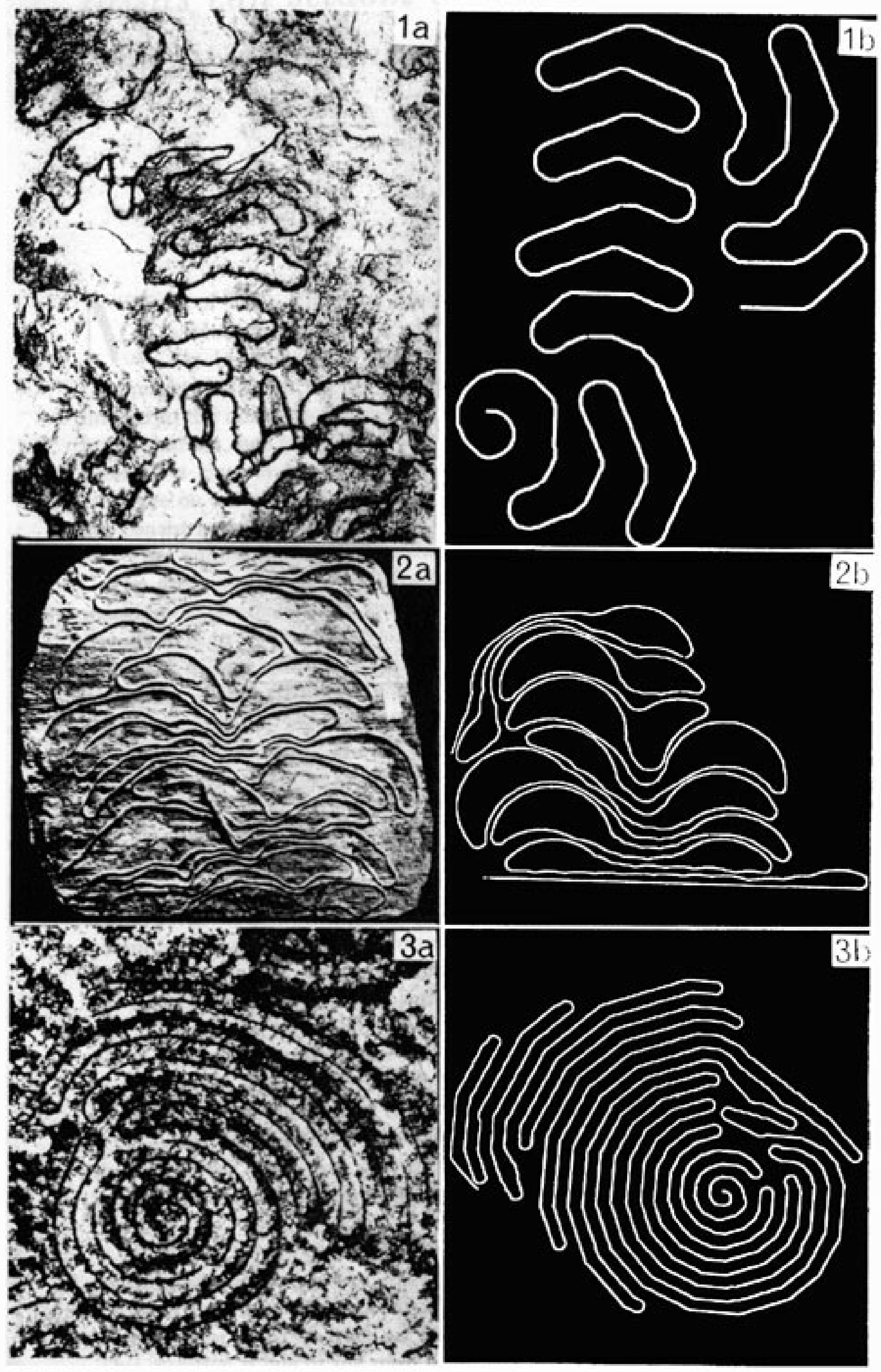
The common ancestor of all modern, bilaterally symmetric, metazoans (multicellular animals) was probably a roundish worm that lived on the ocean floor during the Precambrian period 550 to 600 million years ago (mya) (Valentine, 1994). Such creatures left no actual fossils as they had virtually no hard body-parts. Fortunately, however, they did leave a fossil record of sorts—some of the tracks, trails, and burrows that these early invertebrates left in the sediment were preserved forming what are now called trace fossils. The commonest forms of trace fossil record foraging trails left on, or just below, the ocean bed. The earliest traces reflect simple 'scribbling' behaviours, with tracks that often cross themselves, and indicate relatively crude and inefficient foraging methods. By the early Cambrian however, 530-544 mya, more regular trails appear that form spirals or 'meanders' that loop back on themselves without crossing. Complex burrows also begin to appear around this time with multiple levels and branches. These changes reflect three important developments: an increase in the diversity of animals, improvements in burrowing capabilities, and most importantly, an increase in the complexity of neural circuits. The beginning of the Cambrian is, of course, also recognised as marking the origin of the contemporary metazoan phyla. The Cambrian 'explosion' saw the rapid emergence, over the course of ten to twenty million years, of a diversity of body forms equipped with relatively complex sensory and nervous systems. Trace fossils therefore represent our primary source of insights into the sequence of evolutionary events that anticipated the appearance of the modern fauna.

Computer models of trace fossils

In attempting to infer the perceptuo-behavioural capabilities of the ancient animals that left fossil traces, it seems reasonable to seek the simplest mechanisms that will reproduce the observed patterns. Following Braitenberg's (1986) advice that "when we analyze a mechanism we tend to overestimate its complexity" the methodology of synthetic psychology—building model systems that generate similar behaviours—seems an appropriate strategy. In fact, synthetic approaches were applied some time ago to the understanding of trace fossil behaviour, the computer simulations of Raup and Seilacher (1969) standing out as an early, and rarely acknowledged, example of what might now be termed Artificial Life.

The most consistent fossilised foraging patterns were formed in areas of the sea bed with an even distribution of food particles in the sediment. This environment favors compact trails with maximal coverage and minimal recrossing of existing tracks. Compared with straight-line movement a meandering pattern also helps to keep the animal within its preferred environment and may reduce the likelihood of encountering predators. Raup and Seilacher based their models of these trace fossils on a combination of three reactive behaviours: *thigmotaxis* that makes the animal stay close to previously formed tracks; *phobotaxis* that causes it to avoid crossing existing tracks; and *strophotaxis* that causes it to make 180° turns at various intervals. Their simulations demonstrated that the interaction between these behaviours is sufficient to generate the tightly coiled meandering patterns characteristic of many foraging trails. Figures 1-3, taken from Raup and Seilacher (1969), show some typical foraging trails generated by their program together with the trace fossils they were designed to emulate.

The principle of a complex behaviour pattern emerging from the competitive interaction of a number of simple reactions is a characteristic that Raup and Seilacher's work clearly shares with the behaviour-based robotics approach of Brooks and others (e.g. Brooks, 1986, Maes, 1992). Indeed, the meandering behaviour generator is not unlike a robot wall-following mechanism in which the object being followed, rather than being a fixed contour, is the trail of disturbed sediment generated by the animal's own movements.



Figures 1-3. Trace fossil meanders and comparable computer output. (From Raup & Seilacher, 69)

Figure 2 has the interesting feature that the thigmotaxis response is particularly weak—following a U-turn the animal takes some time to restore contact with its earlier track. This relatively inefficient foraging behaviour, a characteristic of early fossils, is taken by Raup and Seilacher as evidence that thigmotaxis and phobotaxis are "genetically distinct behavioural reactions". Like wall-following in behaviour-based robots (see, e.g. Maes, 1992) the foraging meander is seen as an emergent pattern arising from the environment-mediated interaction of two distinct behavioural competences. Evidence for flexibility in the foraging behaviour is demonstrated by the fact that the "lobes" of the meandering patterns (the straight sections between turns) are not always of constant length. Seilacher (1967) speculated that this may sometimes be due to contact with an obstacle which triggers a higher priority "avoid" behaviour. It therefore seems likely that the activity of these animals was controlled by a hierarchy of behavioural competences.

Seilacher (Seilacher, 1967; Raup and Seilacher, 1969; Seilacher, 1986) suggested a number of further models for different types of foraging trace, and proposed that the variation between some fossil traces, and their increased efficiency over the course of evolution, can be modelled by manipulating key parameters of the various component reactions. For instance, the turning radius of the animal, the mean distance between tracks, and the relative strengths of phobotaxis and thigmotaxis, can each be varied to generate trails with different characteristic patterns and varying degrees of foraging efficiency. One of the implications of these studies is that evolution operated as much on the sensory and motor systems used to implement the reactive behaviours as on the behaviours themselves.

Robot models of trace fossils

A step towards enhancing the realism of trace fossil modelling, that would introduce the constraints of genuine sensorimotor coordination, is to model the generation of fossil trails using a mobile robot. We are currently engaged in some preliminary investigations of this nature using a customised Lego robot to generate and follow trails across the laboratory floor. The sediment feeders we are attempting to model probably used chemical and mechanical sensory systems to detect and follow their tracks and burrows. However, as a first approximation to these mechanisms we are using light sensors to detect a trail of paper which is dispensed by the robot as it moves. As illustrated in figure 4 the two arms of the robot each carry a pair of light detectors.

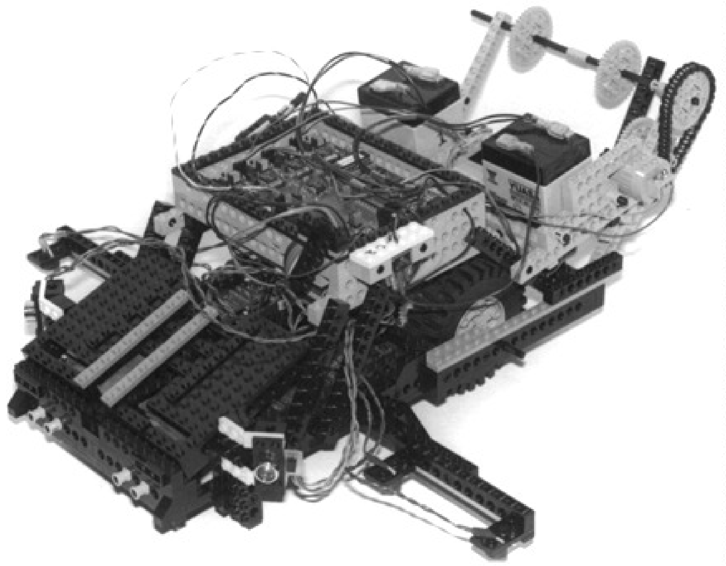


Figure Four: The Lego Robot. The motorised dispenser on the back of the robot releases a stream of paper when the robot is moving. Two light detectors on each of the side arms measure reflected light from the floor and control the thigmotaxis (toward track) and phobotaxis (away from track) behaviours.

Figure 5 shows a simulation of behaviour generated by the combination of phobotaxis (avoid track re-crossing) and thigmotaxis (follow existing track). Thigmotaxis is triggered when the value of the outermost sensor drops below a threshold, and phobotaxis when the value of the innermost sensor goes above a threshold. Without strophotaxis (U-turns) the robot's behaviour is simply to spiral outwards following the pattern of its paper trail (compare figure 6, a spiralling trace fossil).

Figure Five: A spiral 'foraging' trail generated by the Lego robot.

Figure 6: Trace fossil of a spiral foraging trail (from Seilacher, 1967).

Figure 7 shows the effect of adding the strophotaxis (U-turns) behaviour. Changes in the parameters of the behaviours, particularly the relative strengths of thigmotaxis and phobotaxis generate meanders of varying compactness. In the bottom right picture an avoid behaviour has been added that overrides the meandering behaviour in the vicinity of an obstacle.

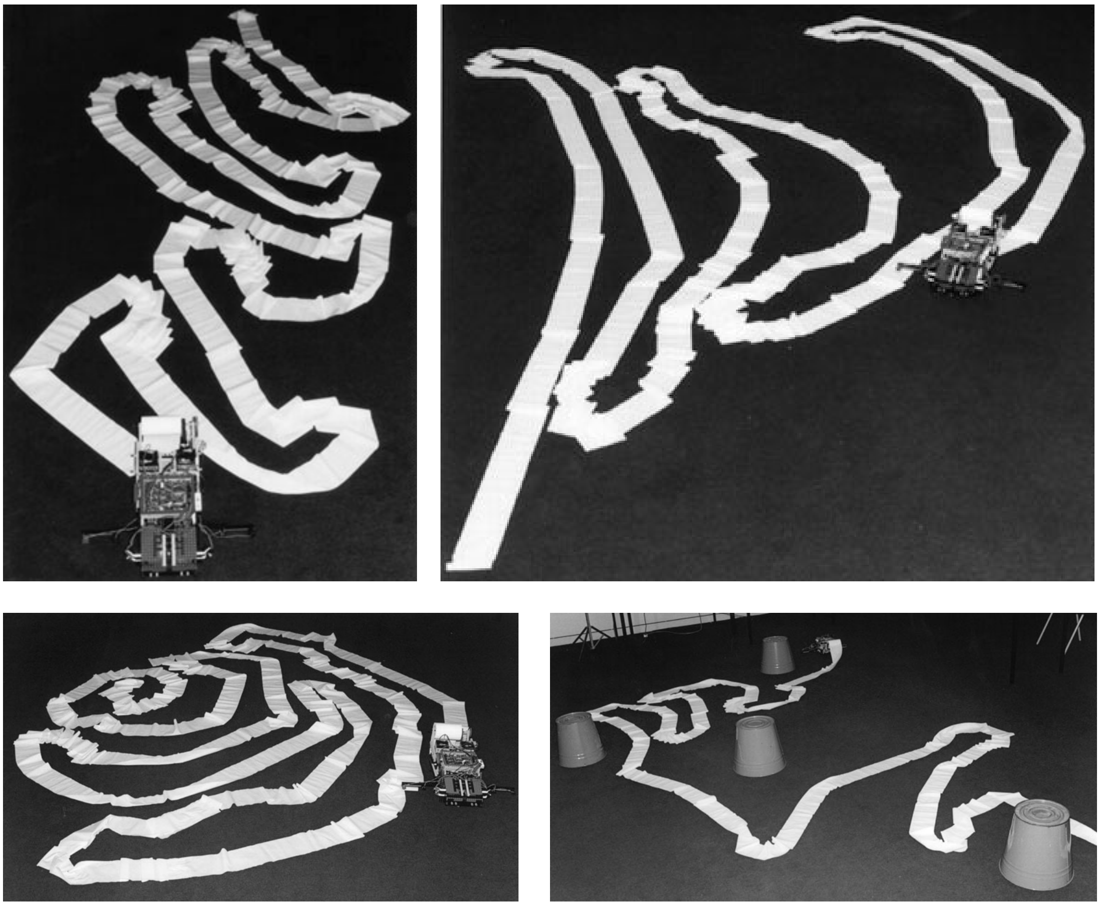


*Figure 7: Meanders generated using thigmotaxis, phobotaxis, strophotaxis, and (bottom-right only) avoid obstacle behaviour*s.

A 'Cambrian explosion' of behaviour-based robots?

The value of these demonstrations perhaps lies less in discovering that relatively simple mechanisms can be used to implement robot 'foraging' trails and more in simply pointing out the similarities between the sensorimotor behaviour of ancient animals and that of simple reactively-controlled behaviour-based robots. This similarity locates the behaviour of such robots at a grade similar to animals of the early Cambrian[1]. This period of perhaps less than twenty million years saw the explosive development of many different body forms and complex nervous systems. The organisms of this fauna achieved a great diversity of methods of locomotion, had an abundance of different sensory mechanisms including compound eyes, and possessed a wide range of

[1]Seilacher (1967, 1986) has suggested that the complexity of trace fossil behaviour increased gradually for 100 million years or so after the start of the Cambrian period, however, recent finds have caused this conclusion to be revised and it is now thought likely that diversity increased during the Cambrian radiation and has been relatively constant since (Crimes, 1992; Raff, 1996).

behavioural repertoires including predation (Conway Morris, 1989; Miklos, 1993). In other words, many of these animals had very mobile and active lifestyles, were capable of effective sensing in different modalities, and exhibited complex and appropriate reactions to varied stimuli. Comparative and paleo-neurobiological studies indicate that 'groundplans' for the neural circuitry of the different phyla were established in this period that placed significant constraints on subsequent evolution. For instance, the basic pattern of insect nervous systems was probably present in Arthropod ancestors of the Cambrian, and has since shown primarily quantitative rather than qualitative change[2]. It also appears likely that the basic plan for the vertebrate nervous system was established at an early stage (Jerison, 1973; Stahl, 1977; Sarnat and Netsky, 1981; Hodos, 1982), and within 100 million years of the initial Cambrian explosion. Miklos (1993) who has referred to this period of rapid evolution as a “big bang” in the evolution of complex nervous systems, suggests that:

> "Complex brains were unlikely to have been painstakingly 'wired-up' synapse by synapse over hundreds of millions of years. We are faced with the exciting prospect that nervous systems can be constructed rapidly".

That the evolution of nervous systems in the early Cambrian metazoa proceeded at such a cracking pace should give encouragement to the designers of robot control systems. However, a number of cautions should be entertained with regard to the prospect of an imminent 'explosion' of behaviour-based robots. First, we should recognise that robotics currently lacks building materials with the versatility and intelligence of the eukaryotic cell (itself the outcome of three billion years of evolution). Second, much work in the design of robot control circuitry is not far above the level of specifying individual synapses—such methods can expect slow progress and bear few similarities with the sophisticated development processes that control gene expression in neural circuitry[3]. Finally, we might consider whether an explosion of behaviour-based robots has already occurred in that a wide variety of platforms that exhibit mobility and reactive behaviour have already been built and demonstrated. This is not to suggest that we have achieved the morphological or neural complexity of the early Cambrian fauna, but we may not be far off replicating their grade of intelligent behaviour.

Conclusion

Trace fossil research demonstrates that the evolutionary history of early invertebrates contains interesting parallels with current work in behaviour-based robotics. This observation encourages the belief that a close examination of early metazoan evolution could provide further valuable insights for an evolution-inspired robot design process. For instance, Brooks Brooks, 1986 has proposed building complex robot control systems by progressively incrementing an initially simple system with extensive testing and debugging of each intermediate architecture. This ‘layering’ process has been offered as roughly analogous to the processes of natural evolution (Brooks, 1991). An examination of the evidence concerning the sequence of evolutionary events that produced complex nervous systems should allow us to evaluate and refine this analogy, and determine strategies for robot design that might more accurately reflect the evolutionary history of intelligent life on earth.

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[2] Edwards (Edwards, 1977; Edwards and Palka, 1991) describes the evolution of the nervous systems of insects as having been “astonishingly conservative”, despite remarkable variations in body plans, with perhaps the most signficant trend being towards miniaturization of the neural circuitry in some species, and the most variation being in the relative volume of sensory processing.

[3]Modellers and robot-builders are now beginning to take an interest in simulating the processes of neural development (e.g. Dellaert and Beer, 1996). Progress in the area could have important consequences for the automated construction and evolution of complex control systems.

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