A Microworld for Robot Awareness

John H Andreae

Department of Electrical & Electronic Engineering
University of Canterbury, Christchurch, New Zealand
(E-mail: j.andreae@elec.canterbury.ac.nz)

Abstract

The Squash-Pop microworld is designed for experiments in robot awareness. Robot behaviour in this microworld is analysed in terms of various conditions for consciousness suggested by philosophers, psychologists and neuroscientists. It is found that robot design demands more precise conditions than these.

Keywords: Robot, Consciousness, Microworld.

Introduction

Philosophers, psychologists and neuroscientists are hot on the trail of consciousness, but the last word may come from an engineer talking to his or her robot and finding out what it is like for it to be aware of itself. Interestingly, it is not impossible to question animals about their awareness. Monkeys have indicated that they have blindsight by pressing a 'no light' panel when a light was shown in their (expected to be) blind hemifield, and rats can press a lever to 'say' that they 'knew what they were doing'. [12]. This is remarkable, but their lack of language is likely to limit what can be discovered in this way. Of course, robots have a long way to go and neuroscientists will learn more from animals before we learn much from robots.

Here are some suggested conditions for consciousness:

C1. "For a creature (or a machine for that matter) to possess visual awareness, what is required is that, in addition to exercising the mastery of the relevant sensorimotor contingencies, it must make use of this exercise for the purposes of thought and planning." [10]

C2. Multiple drafts model: "Human consciousness is ... best understood as the operation of a 'von Neumannesque' virtual machine implemented in the parallel architecture of a brain that was not designed for any such activities."[7]

C3. Global workspace model of consciousness: "consciousness reflects the operation of a global integration and dissemination system, nested in a large-scale, distributed array of specialized bioprocessors;" [5]

C4. "Experience and feeling arise at the level of the outputs from the sensory modules and the inputs to a cognitive system." [11]

C5. "What distinguishes a conscious state from a non-conscious state, he [Rosenthal] argues, is ... the straightforward property of having a higher-order accompanying thought that is about the state in question." [7]

C6. "It is the very achieving of the ability to make a commentary of any particular event that is what gives rise to awareness and it is what we mean by being conscious." [12]

C7. Consciousness is the operation and monitoring of plans. [5]

I regret that these conditions do not do justice to the extensive proposals offered by the authors. Many other ideas which I found less applicable to the robot situation had to be omitted.

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Most of the authors of these suggestions would, I expect, be happy to admit that they have not set down sufficiently precise conditions for the development of a conscious robot, and most of them would not have had that aim in mind. An engineer requires precision and in this paper I use the results of an experiment to illuminate conditions C1-C7 and to consider the future development of a robot 'brain' that will give a robot consciousness. As I have argued in [4], the key aspect of consciousness for the engineer is for the robot to 'know what it is doing'. Further, I argued there that the target for the development should be a robot that can give answers to its own questions about its own intentions. A conscious robot must be its own interpreter of its own information processing. I will assume that most of the 'feel' of consciousness (phenomenological consciousness, qualia, etc.) comes from the requirements of sensorimotor contingencies (C1), but that a small basic remnant – due to the physical implementation – would distinguish the subjective experiences of robots in real and simulated bodies. (Sensorimotor contingencies are defined in [10] as "the structure of the rules governing the sensory changes produced by various motor actions.") Perhaps, if satisfying the rules is like satisfying a set of differential equations, the appearance of subjective experience needs a physical basis, just as the solution of the differential equations needs boundary conditions.

The Microworld

A microworld and body have been designed for a robot with a PP (short for PURRPUSS, [1,4]) learning 'brain' to enable simulation experiments on robot awareness to be carried out. Because of the speed limitations of simulating a parallel 'brain' on a serial computer, the body and microworld have to be painfully simple, while incorporating significant features, such as movable objects, targets for hunger and thirst, another moving entity, and an eye which can see the robot itself.

In the Squash-Pop Microworld, two robots move about on a 3 x 3 squared board surrounded by wall squares. The squares are aligned in a North-South and an East-West direction. The size of the board can be increased when that becomes desirable. Robot A has a PP 'brain', while robot B can be programmed to behave as we wish. Robot B can be used to help robot A to learn. Robot A has an eye 'a', while robot B has an eye 'b'. Only one of two objects, food 'O' or drink 'Q', is on the board at any time. Each robot faces North, East, South or West. It can move forward into a square in front of it, or rotate 90º left in its square, or rotate 90º right. A food or drink object can be 'consumed' by one robot pushing the object into a corner of the board, while the other robot prevents the object from being squeezed out of the corner. When the object is 'squashed' in this way, it vanishes and reappears in a random empty square of the board. After 20 squashes, a food object reappears as a drink object, or vice-versa.

Each robot has 'hunger' and 'thirst' drives which are controlled by its food and drink reserves, each having values in the range 0-100%. Food and drink reserves are incremented by the robot 'squashing' a food or drink object, respectively. If a reserve is moved up past a threshold of 95% by the consumption of food or drink objects, the drive switches off due to satiation. The reserves are used up by the actions of the robot, the food reserve by forward actions and the drink reserve by all actions. When the reserve drops below 80%, the drive switches on again. Each robot has a drive stimulus, telling it if it is hungry, thirsty, both or neither.

Each robot has an eye that it can move over the board. The 'fovea' stimulus shows what occupies the square immediately under the eye. The 'wide' stimulus shows what occupies the four squares in front, to the right, behind, and to the left of the foveal square, relative to the direction of the robot body. All squares outside the central 3 x 3 are wall squares. The 'direction' stimulus is the relative direction of the other robot if it appears in the fovea or wide stimuli, otherwise it is null. Proprioception is the relative displacement of the eye from the body.

Each robot can 'feel' whether there is an object, a robot, a wall or nothing immediately in front of it, or either side of it. A robot can also make sounds and hear both its own and the other robot's sounds.

Robot B's relationship with robot A is intended to be like that of mother and child, where robot B, like a mother or carer, helps an infant (robot A) to achieve goals that come from robot B but end up as goals of robot A [6]. Now, both robots have a bottom-level, random body movement mode which avoids moving a robot forward into a wall or into another robot. Any action chosen by robot A's PP 'brain' takes precedence over its random action, and robot B's programmed behaviour takes precedence over its random actions. Both robots have the same bottom-level, random eye movement mode, which tends to keep the eyes on robots and objects. The first part of robot B's programmed behaviour is to substitute a simple deterministic strategy in place of its random body moves so that robot A will find it easier to predict what B is doing. The strategy is "If robot or wall ahead, or if wall on right, turn right. If nothing ahead and food or drink object on right, turn right. If food or drink object ahead and last action was forward, turn left (to let robot A squash object). Else move forward."

The second part of robot B's programmed behaviour is to 'say' what body movement it is making, but only if it has heard nothing from robot A. This needs explaining. Robot A starts without knowing there are sounds it can make. A process, which I called 'mimic speech' in [1] and have used ever since, enables PP to make sounds that it hears by having those sounds, which it hears when it itself is silent, stored in memory as though it had made them. Thus, the result of robot B making sounds corresponding to its actions is that robot A will make those sounds in similar situations in the future. Then, when robot B hears these sounds from robot A, the third part of robot B's programmed behaviour comes into effect with it doing the corresponding body moves. Not only can robot A learn to make these sounds in new situations but it learns to use them to control robot B for its own purposes, as in the plan of Figure 2. The fourth part of robot B's programmed behaviour has it 'telling' robot A what action to perform, but this is only when robot A is in its fovea and robot A is not hungry or thirsty. Robot B gives a spoken GOOD reward when robot A performs two consecutive actions corresponding to robot B's telling. Altogether, robot A is expected to learn to move to get food and drink, to learn to control robot B by sounds, and to learn to do what robot B tells it.

The operation of the PP 'brain' in robot A has been described in detail in [4], so a minimal account will suffice here. Think of the PP 'brain' as a cortical sheet with a number of labelled areas, which we will here call CortAreas (called templates in [4]). Each CortArea has input (afferent) bundles from certain sensory processors and/or motor proprioception and/or other CortAreas; it has an output (efferent) bundle going to a motor output processor (and possibly to another CortArea). The connections to and from a CortArea determine what rules (associations) it can learn, each rule being of the form: IF these input events (one from each bundle) occur together, THEN this output event is likely to follow. The input events can be delayed versions of stimulus or action events, so a rule condition (IF context) is a spatio-temporal sample of event space.

In this experiment we use only one CortArea for predicting body and eye movements, by lumping each body action and eye action together in a composite body-eye action. A second CortArea is used for predicting sound actions. Eight CortAreas predict the seven stimuli, the direction stimulus having an extra one for reasons to be given, as shown in Figure 3.

After choosing its body-eye and sound actions, robot A makes a plan (unless it is already following a plan). First, the stimuli following the actions are predicted, then the next actions are selected, then stimuli predicted, and so on. The plan succeeds if an active goal rule is reached. A plan is abandoned if predictions can't be made or the plan goes into a loop. There are four kinds of goal-rule. A rule is marked as a goal rule (i) if it is hungry and the rule has contributed to its squashing a food object, (ii) if it is thirsty and the rule has contributed to its squashing a drink object, (iii) it is not hungry or thirsty but the rule has contributed to its getting a GOOD reward, and (iv) if it is a new rule being stored in memory, in which case it is called a novelty goal. Robot A receives a GOOD reward if robot B makes the sound GOOD. One can imagine that it has to be made with the appropriate emotional intonation.

PP forms separate networks with the rules of the body-eye predicting CortArea and the rules of the sound predicting CortArea. There is a node in a network for each different rule condition (context), so a node includes the rules with that particular context. Each rule in the node is connected to those nodes which follow it in the behaviour of the robot and probabilities are continuously estimated for the transitions corresponding to those connections. This makes possible an expectation calculation, called 'leakback', which evaluates the desirability of each rule of each node. When the current situation corresponds to a particular context, PP chooses the action corresponding to the THEN part of the most desirable rule in the node for that context.

Results of the experiment

Figure 1 shows the results of a learning experiment with the Squash-Pop microworld, in which robot A steadily increases the rate at which it squashes food and drink objects so that it is left with more time to learn to get GOOD rewards for doing what robot B tells it. The graph for GOOD rewards has been halved to keep the graphs distinct. The number of nodes allowed per CortArea is 5000. When this limit is reached and a new rule has to be stored, the rule with all its connections that has not been used for the longest time is deleted. This begins happening around step 200, 000, as can be seen in the second figure. There is a levelling off of learning above step 1 million. I could discuss these and other results at some length, but space is limited, so I will take one plan (typical of its hundreds of better plans) that PP made on step 2000008 and discuss that in some detail. A plan is a good indicator of the reasons for PP's actions and the state of PP's memory. Figure 2 is a minimal summary of the plan. A number of points can be made about the plan.

P1. At the start of the run, robot A knows nothing about the sounds that robot B makes, but later robot A learns to use them to control robot B, as illustrated in this plan.

P2. In the plan, robot A's eye has robot B within view all the time. Although the food object O is not seen until the last two moves, robot A can feel the presence of O at the beginning.

P3. Robot A controls the movement of robot B by making the appropriate sounds it has learned from robot B, while moving itself into the right position to squash the food object.

P4. Although space has prevented me from listing the predicted stimuli, which are part of the plan, these show that robot A is using all the 'sensorimotor contingencies' (cf. C1 above) available to it.

P5. The extra CortArea for the direction stimulus allows robot A to gather specific information about the movements of robot B, when it can see robot B. Two consecutive directions identify what action robot B has made.

P6. Robot A has never been told what the sounds mean (I could have used any sounds in place of Forward, Left and Right, but these help us!) but the sounds seem to have acquired some meaning for it through learning.

P7. Robot A's plan is a trajectory through its memory, that memory being an active model of the world including both robot B and itself. According to Hofstadter [8, p.62], "what's really crucial for a conscious machine is that it should incorporate a well-developed and flexible self-model."

P8. The plan shows that robot A is aware of itself and robot B in the sense that it sees both and has control of both, but surely it is not conscious.

Robot Consciousness

I see the seven conditions for consciousness C1-C7 as compatible and reinforcing, rather than competitive. The following proposed developments for PP amount to my conception of a conscious robot and I will try to indicate how they relate to the seven conditions. The precise requirements of robot design will be seen to demand stricter conditions than the seven offer.

D1. Increase the number of CortAreas and the complexity of the robot body and world as more computing power becomes available. PP can already be seen as a Multiple Drafts brain (C2), but this will become clearer as more Cort Areas can be included, especially if it can be implemented in parallel hardware. PP is a design for parallel hardware. C3 will be a guide to the choice of CortAreas and supporting special processors (modules).

D2. Provide adaptive modules for processing raw sensory data so that the brain has inputs at the object-space-time-world level, as required by C1, C3 and C4. One could say that this is already the case – in a simple way – for the Squash-Pop experiment, because PP is 'seeing' objects rather than pixels. Time will be represented better when CortAreas include more delayed events (examples in [1] and [4]). The extra CortArea predicting the direction stimulus processes rules of the form "IF drive is HT, direction is D, body move is M, and it says S THEN direction may be D'." If neither D nor D' is null, such a rule records a move of robot B, so it can be seen as an object level rule. It is not so easy to imagine object level processes when there are varying numbers of moving objects in the robot's visual field, but we humans do seem to be able to keep tabs on more than one object in our visual field, although we have difficulty.

D3. Use of second-order events which process the events at the first-order, object-space-time-world level. This was illustrated briefly in [4] with 'contexts of contexts' where rules were treated as events. I don't myself see how condition C5 makes the first-order events conscious, but it is reasonable that such second-order events would be outside consciousness if they cannot be represented in the object-space-time-world space.

D4. Plan monitoring is not easy to arrange because PP has to monitor its own plans. An interesting possibility only tried out very briefly [2] is to have PP talk its way through plans. The idea is that speech in a plan is real speech which enters into the event space of the robot's real actions, unlike the other actions which are inner, 'imagined', not-implemented actions. This speech-within-plans would be like thinking aloud and it could affect the plans themselves by altering the speech part of contexts and by setting up goals. Speech was used to set up a goal in 'The ROOMS Task' in [1]. In my view, plan-monitoring (C7, and see [3]) is the most promising area for progress.

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D5. Ensure that the amount of memory available for storing rules is sufficient for the complexity of the robot body. A condition for this sufficiency is that the robot can look around its current sensory environment without finding (after the first scan or so) that new rules are being stored. In this condition it will have learned the 'sensory-motor contingencies' of C1. If rules are having to be discarded because of lack of available memory space, the robot will not be able to achieve our illusion of seeing the world around us all the time. My own guess is that special memory (perhaps cortical maps?) will be needed to hold the spatial positions and trajectories of objects in the object-space-time of the immediate environment (cf. 'Painted vision' in [4]).

D6. The introduction of processed sensory signals at the object-space-time-world level to indicate intensity of light, sound and touch, together with pain signals to cause closing of eyes, protection of ears and withdrawal of limbs when the intensities are excessive. I have no idea as to what feelings these might give the robot. All that I think we need worry about is that the signals appear in the object-space-time-world at the point on the robot's body where they originate. (If we prick a finger we feel the prick in the finger.) I think that it is quite likely that there should be (are, in us) inbuilt (innate) modules for this kind of stimulus processing, as required by C4.

D8. Language. PP has Turing Machine power so language is within its competence, but a great deal of experimentation will be needed to find out if a 'language module' or 'Universal Grammar' is needed and, if so, what it should provide. Some initial experiments are reported in [4]. It may be possible to find out whether a robot without language is conscious in the same way as is being attempted with animals [12], but see the next section. The impossibility of subjective access is the same for the animal mind as for the robot mind, even if we have perfect knowledge of the working of the latter.

The reader may notice that I do not talk about 'attention', even though this is usually treated as an important psychological process and some theorists see it as part of consciousness. It does not seem to be a problem with PP. PP attends to whatever information is drawn in by its actions. Attention is not a particular process separate from its own actions and inbuilt reflexes.

Conscious Rat?

The general underlying strategy in the commentary-key approach is similar to a much earlier one used by Beninger et al. (1974), who asked laboratory rats if they 'knew what they were doing'. On any trial, the experimenter waited until rats made one of four possible, and highly probable responses: face-washing, rearing, walking, or remaining immobile. There were no constraints on which of the four was allowed. But in order to get food, the rat had to press one of four different response levers to indicate which of the four responses they had just made. Rats can learn to do this. [12, p.89]

Could we set up an experiment in which we asked a PP robot a similar question to that asked of the rat? My experience, as in the experiment on the communication of intentions in ch.6 of [4], has been that a psychological experiment transferred to a robot situation can lose some of its force. We don't expect much of a robot and so we are unlikely to assume as much of the subject of an experiment if it is a robot. Now, before making disparaging remarks about the rat experiments, I should stress that Weiskrantz's argument about commentaries is based on far more than the above quotation.

The Squash-Pop microworld was not designed with this kind of experiment in mind. Robot A has no innate behaviours corresponding to the rat's face-washing, rearing, or immobility. However, it does learn different behaviours and, if it has information in some of its rules which distinguishes the behaviours, and if it is provided with actions for making responses, then it will be able to learn to respond appropriately. The experiment would be trivial and the result of little consequence. We would have no more reason than now to consider robot A to be conscious, nor to conclude that it knew what it was doing. As argued in [4], even simple expert systems can give quite involved answers to questions about their recommendations and reasoning, and nobody would ascribe consciousness to them.

Conclusions

Conditions for consciousness must be more precise than C1-C7 if they are to help the engineer develop a conscious robot. C1 is satisfied by sensorimotor contingencies encapsulated in learned rules in the CortAreas, and these have been shown to be used in planning. Yet, I doubt that the reader would accept robot A as being conscious. C2, C3 and C4 are compatible with the architecture of PP. The best chance seems to be in the direction of plan-monitoring, which is supported by C5, C6 and C7, but even here we need a better prescription of what counts as thought-about-thought, commentary, or monitoring to avoid satisfaction of these conditions by a trivial experiment.

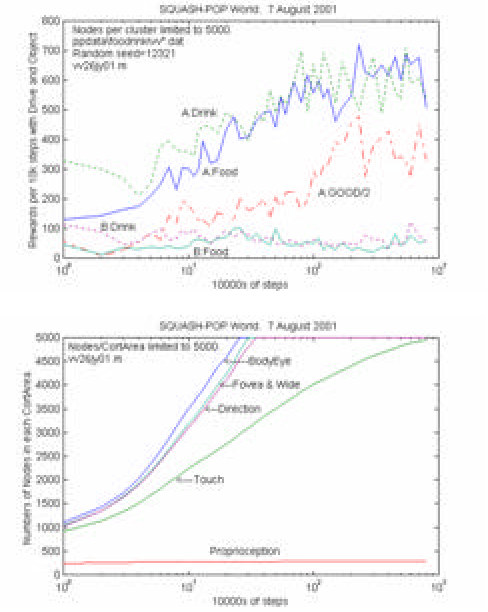

Figure 1. Learning in Squash-Pop Microworld.

Board position (1): Robot **B** faces east in the top left square, and the eye **a** of robot **A** is over the same square. The food object **O** is in the middle right square. Robot **A** faces south in the middle square with eye **b** of robot **B**.

(2): **A** moves forward, holds its eye **a** still, and says Forward. **B** moves forward to the east, and moves its eye in the same direction. It says nothing. Robot **A** now makes a 4-step plan to a food goal, which it proceeds to follow. Since the plan is followed accurately, only the following of the plan is shown. Some movements of robot **B** are implicit in the plan, but **A** does not see **b** (where robot **B** is looking) in this experiment, so eye **b** is not even implicit.

(3): Plan step 1: Robot **A** to turn right and its eye **a to** move east. Say 'Forward'. (Robot **B** to move forward. This movement of **B** is implicit in the plan because **B** is seen by **a**.)

(4): Plan step 2: Robot **A** to turn left and to move its eye **a** east. Say 'Right'. (Robot **B** to turn right.) The 'x' indicates that **a** and **b** are over the same square.

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+-----------+     +-----------+
¦aB?¦   ¦   ¦(1)  ¦ a ¦ B?¦   ¦(2)
¦---+---+---¦     ¦---+---+---¦
¦   ¦?Ab¦ O ¦     ¦   ¦   ¦bO ¦
¦---+---+---¦     ¦---+---+---¦
¦   ¦   ¦   ¦     ¦   ¦?A ¦   ¦
+-----------+     +-----------+
+-----------+     +-----------+
¦   ¦ a ¦ B?¦(3)  ¦   ¦   ¦?Bx¦(4)
¦---+---+---¦     ¦---+---+---¦
¦   ¦   ¦bO ¦     ¦   ¦   ¦ O ¦
¦---+---+---¦     ¦---+---+---¦
¦   ¦?A ¦   ¦     ¦   ¦?A ¦   ¦
+-----------+     +-----------+
+-----------+
¦   ¦   ¦   ¦(5)
¦---+---+---¦
¦   ¦   ¦?Bx¦
¦---+---+---¦
¦   ¦?A ¦ O ¦
+-----------+
```

(5): Plan step 3: Robot **A** to turn left again and to move its eye **a** south. Say 'Forward'. (Robot **B** to move forward.) Robot **A** is ready 'for the kill'!

Plan step 4: Robot **A** to move forward, to squash the food object and, being hungry, to be rewarded.

(Plan stimuli and other details omitted.)

Now robot **A** is at configuration (2) ready to carry out the plan. In this case, the plan was followed perfectly.

Figure 2. Plan made on step 2000008, 29 july 2001.

IF wide, fovea, direction, touch, proprioception, hearfo THEN body-eye moves.

IF wide, fovea, direction, proprioception, body move THEN make sound.

IF wide, fovea, touch, body move THEN touch.

IF proprioception, body-eye moves THEN proprioception.

IF wide, fovea, direction, touch, body-eye moves THEN fovea.

IF wide, fovea, direction, touch, body-eye moves THEN wide.

IF wide, fovea, direction, touch, body move THEN direction.

IF drive, direction, body move, say THEN direction.

IF hear, say THEN hear.

IF touch, drive, body move THEN drive.

Note: hearfo is the sound made by the other robot if any, else its own sound.

Figure 3. CortAreas used in the experiment.

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