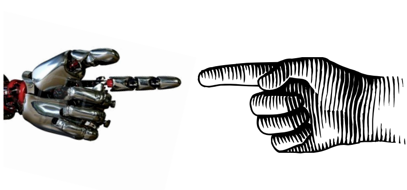
Biological Foundations of Robot Behavior



Thomas Hellström
Department of Computing Science
Umeå University

Dec 19, 2011
UMINF-11.17
ISSN-0348-0542

Contents

Introduction

Robotics made slow progress and seemed to have reached a dead-end in the end of the 1970's. A computer had yet to pass the Turing Test, and few, if any, of the self assured predictions from the early artificial intelligence era had actually been realized. The early attempts to create intelligent mobile robots did not proceed much further than the rudimentary results demonstrated by the Shakey robot at the end of the 1960's. The Stanford Cart from 1977 (Figure 1) was equipped with stereo vision and navigated using an internal map of the world. Its average speed of 10 cm/minute gave rise to the expression ”sub turtle speed”, and probably also significant stress levels in Hans Moravec's crew of robot developers at Stanford university. Not only processing speed was bothersome. Researchers had already identified fundamental problems, for instance related to the use of world models and the dependency on full and accurate knowledge of the environment and of the robot's interaction with the environment.

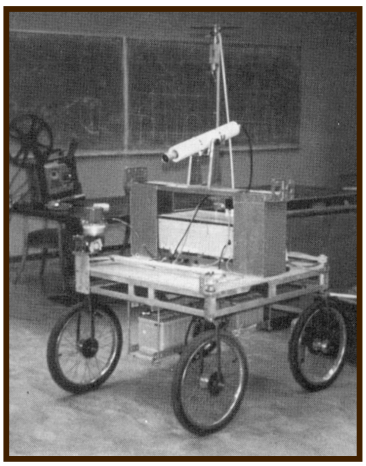


Figure 1. The Stanford Cart robot from 1977

In 1984, the Italian-Austrian cyberneticist Valentino Braitenberg published a book called *Vehicles: Experiments in Synthetic Psychology* in which he describes how hypothetical simple vehicles, can exhibit behaviors that he denoted *aggression, love, foresight and optimism*, etc. Braitenberg did not build any robots, instead he conducted *Gedanken experiment*, speculating how intelligence could evolve, and this without any sophisticated mechanisms like the ones developed and anticipated by the AI researchers at the time. The vehicles represented the simplest form of behavior based artificial intelligence, without any need for an internal memory, computers, or representations of the environment. Braitenberg's book soon became a cult among curious roboticists. Some researchers explored biology and psychology to find out what was missing in mainstream robotics research. In this compendium we will look at work by the Nobel Prize winners (1973) Nikolaas Tinbergen and Konrad Lorenz who developed an influential theory on how concurrent behaviors interact and are triggered by Innate Releasing Mechanisms (IRM). The psychologist J.J. Gibson described animal behavior without assuming any global world model, in a way that contradicts the way information is viewed in the Hierarchical Paradigm in robotics. These ideas later became the foundation for the Reactive Paradigm which took over after the Hierarchical Paradigm in the middle of the 80's. We will also look into the work of Michael Arbib, who already in the late 70's started to explore biology in the search for useful principles that could be used in robotics.

Why study animals and humans?

The arguments why a robotics researcher should search for inspiration in different areas of biology and psychology were, and still are, several and convincing. Animals and humans provide existence proofs of several aspects of intelligence. In other words: The answer is there, if we just manage to see it. Furthermore, many simple animals exhibit intelligent behavior with just a handful of neurons. In other words: There is no need to wait for more powerful computers or breakthroughs in classical areas of computer science or signal processing. A third reason to seek inspiration in biology and psychology is that these studies can yield computational models that can be implemented in robots. In other words: we hope to reverse engineer the brains of animals and humans by studying their behavior.

Still, studying animal behaviors was not the first choice for many roboticists. One argument was that “Airplanes don’t flap their wings!”. While being almost true (there are actually planes that flap their wings), almost every other aspect of a plane’s aerodynamics imitates a bird’s flight. Judging from Figure 2, it is indeed clear that the Wright brothers’ airplane was clearly inspired by the anatomy of a bird.

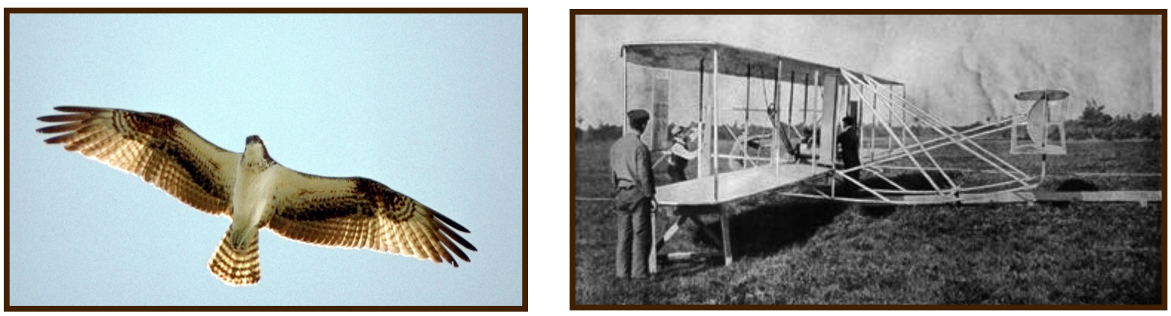


Figure 2. Comparison of the anatomy of a bird and the architecture of the Wright brothers’ airplane exhibit clear similarities.

New sources for information

Several fields within biology and psychology have shown to be useful to inspire and enlighten robotics researchers:

- Ethology – the scientific study of animal behavior. Konrad Lorenz is often said to be the founder of modern ethology.
- Cognitive psychology – explores human internal mental processes: how people perceive, remember, think, speak, and solve problems.
- Neuroscience – the study of how signals in the nervous system relate to perception and actions
- Physiology – e.g. how a hand is constructed

In the following we will describe several studies within these fields, and discuss how they can be relevant for robotics research. We will primarily focus on the study of animal behaviors.

Different types of animal behaviors

The term *behavior* refers to the actions of a system or organism in response to various stimuli or inputs, whether internal or external. Ethologists study animal behaviors and divide them into three major categories (Arkin 1990):

Reflexive behaviors are innate hardwired behaviors, e.g. the knee reflex. Another example is the flight response of some insects when legs are not touching the ground. The response comes as a direct consequence of the stimulus and can be described as a mapping from stimulus to response. This type of behaviors is therefore also denoted stimulus-response behaviors.

Reactive behaviors are learned, but are then performed without conscious effort. They may however be effected by will power. Many behaviors in sports are reactive behaviors, e.g. biking, skiing (the term "muscle memory" is also often used for these behaviors).

Conscious behaviors are deliberative and may chain other behaviors together, e.g. eating with fork and knife.

The terminology differs somewhat between ethologists and roboticists. Roboticists most often use the term *reactive behavior* to denote what ethologists call reflexive behaviors, and the term *skill* to denote what ethologists call reactive behaviors. In this compendium we will, if not stated otherwise, consistently use the words in the ethology sense.

Reflexive behaviors

The Reactive paradigm in Robotics, which took over after the Hierarchical Paradigm is built upon reflexive behaviors. We will for that reason pay special attention to this kind of behaviors.

Three categories of animal reflexive behaviors are described (Arkin 1990): Reflexes, Taxes and Fixed-action patterns. *Reflexes* are rapid, automatic, involuntary, responses triggered by a stimulus. E.g.: escape behaviors. A reflex is proportional to the strength of the stimulus and stops if the stimulus disappears. *Taxes* are behaviors that orient the animal toward or away from a stimulus. A *Fixed-action pattern* is not proportional to the strength of the stimulus. It is affected by internal states and does not stop even if the stimulus disappears. E.g.: a fleeing deer continues to run even when the danger that initiated the behavior is no longer in the visible field of the animal.

Some reflexive behaviors may fall into several categories. For instance, an animal walking towards food (a taxis) will continue to do so even if the visual contact with the food is temporarily broken (i.e. a fixed-action pattern). Taxes and Fixed-action patterns have been studied extensively with several interesting results for robotics. These two categories are further described in the following.

Taxes

Jacques Loeb (1859-1924) was fed up with the psychologists' anthropomorphic[1] view of animal behavior. His standpoint is clearly expressed by, C. Lloyd Morgan, another proponent of the same view:

"In no case is an animal activity to be interpreted in terms of higher psychological processes, if it can be fairly interpreted in terms of processes which stand lower in the scale of psychological evolution and development"

In this spirit, Jacques Loeb developed a theory of forced movements by an organism and coined the term *taxis*: movement towards or away from a stimulus source. Several taxes have been identified. A few examples are:

- Phototaxis is the movement of an organism in response to light: that is, the response to variation in light intensity and direction. For example, cockroaches move away from light sources and thereby demonstrate (negative) Phototaxis.
- Chemotaxis is a movement response caused by a chemical concentration gradient. For example, the bacteria E. Coli. demonstrates chemotaxis in response to a sugar gradient. Another well known chemotaxis behavior is demonstrated by ants navigating by tracking pheromones disposed on ground by themselves or by other ants.
- Thermotaxis is a migration along a gradient of temperature.
- Geotaxis is a response to the attraction due to gravity
- Phonotaxis is the movement of an organism in response to sound.
- Thigmotaxis is the response of an organism to physical contact.

In one of his work, Loeb describes the behavior of a coastal snail by using several taxes. The snail's behavior is illustrated in Figure 3. In its search for the feeding area above the surface, it is first guided by negative phototaxis (1) triggered by its upright pose. This will lead the snail into the dark hole in the uneven vertical wall. The negative phototaxis will turn to positive (2) when the snail is upside down, causing the snail to navigate towards the opening of the hole. When turning vertically up and facing the light, a negative Geotaxis is triggered (3), and the snail will continues to move upwards. When it is high enough not to get wet, a negative phototaxis (4) is once again triggered and the snail will move into a dark hole where the food is located.

An important conclusion from this and similar studies is that complex behaviors, even sequences of several different behaviors can be totally reactive in the robotics sense, i.e. stimulus-response mappings without memory.

---

[1] Attribution of human motivation, characteristics, or behavior to inanimate objects, animals, or natural phenomena.

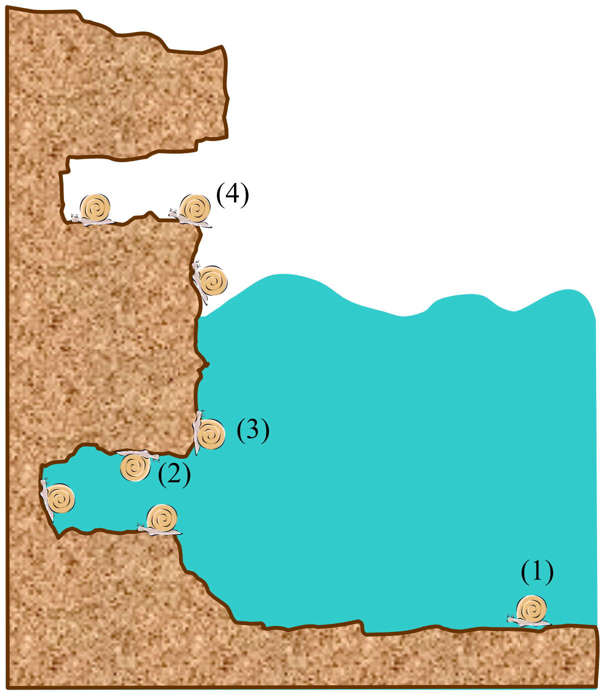


Figure 3. The behavior of the coastal snail may be described as a sequence of taxes, triggered by external stimuli. The mechanism enables the snail to find its way up from the bottom of the sea to the location of food above water level.

Fixed-action patterns

Fixed-action patterns are time-extended responses to stimuli. They are indivisible and run to completion (Campbell 1996). Many mating dances carried out by bird are examples of fixed action patterns. In a famous experiment conducted by Nikolaas Tinbergen, the Graylag Goose demonstrated another fixed action pattern. This type of goose will roll a displaced egg near its nest back to the others with its beak, as illustrated in Figure 4. The sight of the displaced egg triggers the mechanism that will continue even if the egg is taken away. This means that the animal goes on pulling its head back and forth as if an imaginary egg is still being moved by the underside of its beak. A video demonstrating the phenomena is available at
http://www.youtube.com/watch?gl=US&hl=iw&v=vUNZv-ByPkU

Another example of fixed-action patterns is illustrated in Figure 5 in which a cardinal feeds a fish, probably because its nest had been destroyed and the innate feeding behavior did not stop. This behavior reportedly went on for weeks.

Figure 4. Female goose behavior of moving eggs back to the nest. When the goose sees an egg outside the nest it begins a repeated movement of pushing the egg with its beak and neck. However, if the egg slides off the beak, or if it is removed by a curious researcher, the goose continues the movements until it reaches the nest.

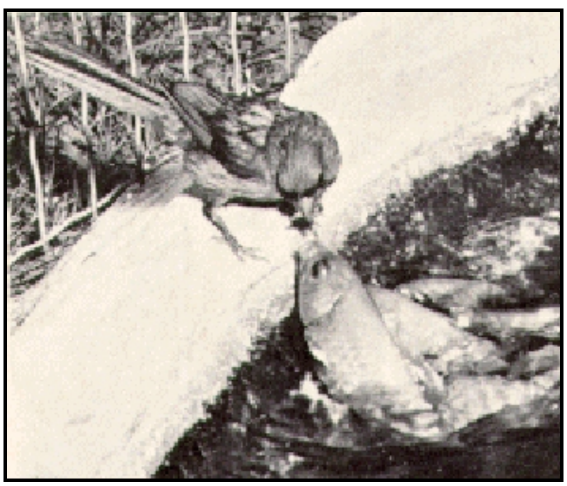
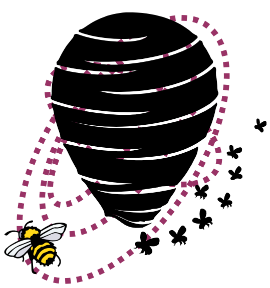


Figure 5. An example of a Fixed-action pattern where a bird feeds a fish, probably because its nest had been destroyed. (picture from *Animal Behavior*, N. Tinbergen, Time Inc, 1966).

Where do behaviors come from?

Tinbergen and Lorenz conducted intensive studies on how animals acquire behaviors, and distinguished between *innate* and *learned* behaviors. An innate behavior may comprise one *single* behavior or a *sequence* of single behaviors. One example of the former is the feeding behavior of the Arctic terns (Murphy 2000). These birds live in Arctic, which is a largely black, white and gray environment. When a baby tern is hungry, it pecks at the parent's beak, which regurgitates food for the baby to eat. This is innate behavior guided by the red spot that all grown up arctic terns have on their beaks (more on this later in the section on Perception). An example of an innate sequence of innate behaviors is demonstrated by the digger wasps. This wasp's mating cycle comprises three steps conducted in logical sequence: female mates with male, female builds nest, female lays eggs. Each individual step is an innate reflexive behavior and so is the sequencing mechanism. The wasp doesn't need to understand the meaning of what it is doing since each step in the sequence is triggered either by internal states or external stimuli.

Some behaviors may at first appear as learned, but are innate and equipped with *memory* such that they are configured for the actual task in the real world. One example is the flying behavior of young bees that live in hives (Murphy 2000). The bees have an innate behavior to start flying away from the hive and then returning. At first, only short distances but gradually further away from the hive. The conjecture is that the bee in this way learns both the location of hive and the opening of the hive. Eventually, the bee is able to find its way to the hive and the opening, from long distances and from any direction. This may of course be viewed as a form of learning, but is normally instead denoted *adaption*. The innate homing behavior is tuned to fit the location and appearance of each bee's own hive.



Lions are born without any hunting instincts and need to *learn* all aspects of this complex behavior by their mothers. This process may take several years and comprise sub-behaviors such as searching, stalking, chasing and catching the pray. The reason why the baby lions have to learn hunting is that each one of these sub-behaviors are very complicated and need adaption to both environment and the type of animal being hunted. Instead of being born with a more or less static hunting behavior, the lions are born with the ability to learn. This approach of nature is highly efficient and is present in several other animals, not least in human beings.

Coordination of behaviors

From the examples above of the arctic tern, the coastal snail, the digger wasp, and the graylag goose we can learn several things that may be useful in robotics. Simple reflexive behaviors can be combined into sequences that exhibit a highly intelligent overall behavior. The sequencing may be triggered by internal states such as hunger, sexual drive, and fear, but also by external stimuli such as the pose of the animal (the snail example) or presence of objects (the goose example). We will look into how this sequencing can be modeled and how this knowledge can be applied to robotics.

Innate releasing mechanisms

Lorenz and Tinbergen tried to clarify the mechanisms that triggers behaviors and gave them a special name *innate releasing mechanisms* (IRM). The IRM theory describes how several behaviors can co-exist in parallel and be activated by their releasers.

Figure 6 shows the common "arrows and boxes" way of illustrating a behavior. The *Behavior* is fed with *Stimuli* input and produces a *Response* as output. For the example with the Arctic tern, the Stimuli would be the location of the red blob on the parent's beak, and the Response would be the motor action that moves the baby tern's head towards the blob. However, the baby tern is not moving its head to get food all the time. Two conditions need to be fulfilled: The tern has to be hungry and there has to be a red blob in the visual field. The enabling of the Feeding Behavior is implemented as a *Releaser* as illustrated in Figure 7. The Feeding Behavior is only active if the conditions defining the releaser are satisfied. A general case is illustrated in Figure 8. The Releaser may be a combination of internal states and external sensory input.

Figure 6. Illustration of a general behavior.

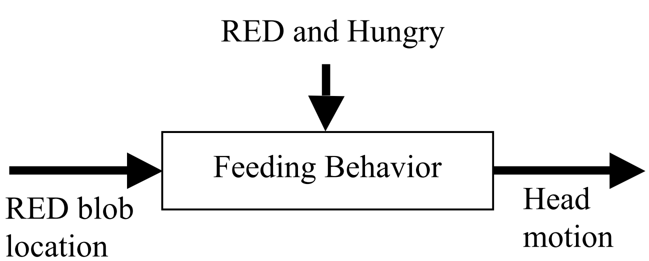


Figure 7. The specific feeding behavior of the Arctic tern. The behavior is only active if the RED and Hungry conditions are satisfied.

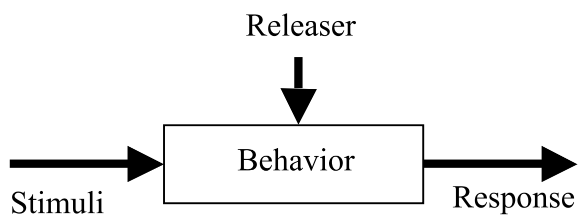


Figure 8. Illustration of a general behavior with a Releaser (IRM).

Implicit chaining

We will now look at how a sequence of behaviors can be coordinated by its releasers and the IRM. The general idea is that all behaviors exist in parallel but are passive until their Releasers are activated. In this way, simple behaviors operating independently can lead to what an outside observer would view as a complex sequence of actions.

We will use the previously described mating cycle of the digger wasp as an example. The mating cycle comprises three behaviors: Mating, Building and Egg laying. The behaviors and suggested Releaser mechanisms are illustrated in Figure 9, 10 and 11. The Mating behavior is released by a sexual drive to mate and the presence of a male wasp. This means that the Releaser is a combination of an internal state and external stimuli. The actual behavior is governed by the location of the sexual partner, and results in a response consisting of suitable mating actions. The building behavior is released by the internal state of being pregnant. It takes stimuli input corresponding to the relative location of suitable building material and the nest location, and produces a response of motor actions that realize a nest. Finally, the Egg laying Behavior is released by a combination of an internal hormonal state signaling egg laying and a stimulus saying that the nest is ready. The behavior is governed by the location of the nest, and produces actions that will cause the female wasp to move to and safely stay in the nest while laying her eggs.

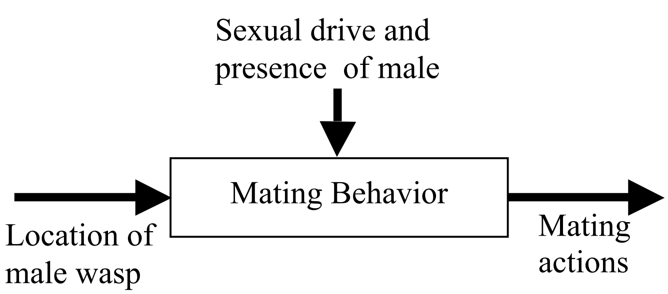


Figure 9. Mating behavior of a female digger wasp.

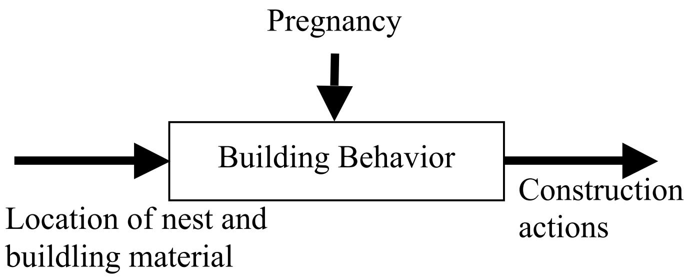


Figure 10. Building behavior of a female digger wasp.

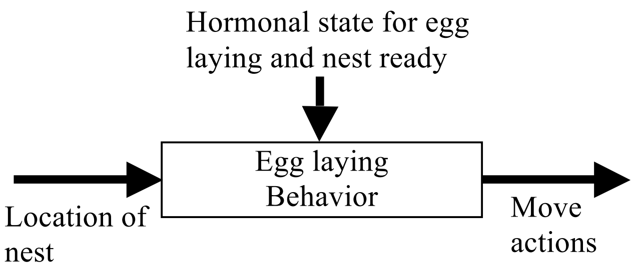


Figure 11. Egg laying behavior of a female digger wasp.

The message to robotics is that simple, often purely reactive, behaviors and also complex sequences of behaviors can be implemented by several independent behaviors that run in parallel and are activated by releasers. Both internal states and external sensor data (stimuli) can be used as releasers. These ideas have inspired several architectures in the reactive paradigm in robotics. Behaviors can be implemented as *threads*, and object orientation and modular programming techniques are highly appropriate. A nice consequence of the modular design is that the system will "degrade gracefully" if any of the modules stop working, for instance due to malfunctioning sensors.

Concurrent behaviors

According to the IRM theory described above, behaviors often execute concurrently and independently. The releasers are designed such that, most of the time, the intended compound behavior is executed, either by executing behaviors in sequence or by only allowing compatible behaviors execute at the same time. However, sometimes there are conflicts due to conflicting stimulus that have not been foreseen by evolution. In such cases behaviors are executed at the same time, although they are not designed to do so. Studies of animals in such situations can be divided into the following categories (Murphy 2005):

- *Equilibrium*: The behaviors balance each other out. This can for instance be observed in squirrels being fed by a human. If the food is close to the human, the squirrel moves towards the food until the fleeing instinct counter balances the feeding instinct. The result is that the squirrel stops.

- *Dominance*: One of the concurrent behaviors takes over control of the animal and the other is suppressed. This can be observed also in a human who is both sleepy and tired. One of the conflicting behaviors sleeping and eating is declared winner.
- *Cancellation*: ALL concurrent behaviors are cancelled out as a result of the conflicting interests. One example is the Male sticklebacks (fish) that have a defend behavior that sometimes clash with an attack behavior. This occurs when two fish's territories overlap. The defend behavior is released since another fish is intruding, and the attack behavior is released since the fish finds itself within another fish's territory. Should it defend or attack? The answer is neither. Instead the fish is often observed to start building a new nest.

Perception and behaviors

With the focus on reflexive behaviors in the previous sections, it should by now feel natural to view sensing as crucial for both natural and artificial intelligence acting in the physical world. This is certainly true, no matter what paradigm in robotics we look at, and the importance is extra highlighted in the reactive paradigm where the basic building blocks are the reflexive behavior modules (denoted reactive behaviors in robotics terminology). Sensing produces stimuli, which is the fuel that powers reflexive behaviors. The relation between sensing and perception is clarified by the following definition (Pomerantz 2003): "Perception is the process of attaining awareness or understanding of the environment by organizing and interpreting sensory information". In other words, perception processes sensor data or stimulus and generates higher level knowledge about the environment. The tight connection between perception and action was realized already in 1976 by the American psychologist Ulric Neisser in his book *Cognition and Reality*. In this section, we will have a look at relevant parts of Neisser's work and also the work of one of his colleagues James J. Gibson.

Two usages of perception

Perception may be used by a behavior in two distinct ways. First to *release* the behavior, as described above by the IRM theory. Second, perception can be used to *guide* the behavior. By this we mean that perception is needed to generate the actual actions in response to the perceived information. With reflexive behaviors expressed as S-R mappings, in combination with releasing mechanisms, these two usages of perception are indeed obvious. In Figure 7, the feeding behavior of the Arctic tern is described. The *release* of the behavior comes from a perceived red blob in the visual field, together with an internal Hunger state (which is an example of *interoceptive* sensing). Also the *guiding* of the behavior is done by perceived data, namely the perceived location of the red blob. Using the same kind of sensor information for both releasing and guiding is not at all uncommon. In robotics, the term *action-oriented perception* refers to processing of sensor data (i.e. perception) such that it fits a specific behavior. It is important to emphasize that this processing does not aim at creating a high-level world model, such as in the hierarchical approach in robotics. Rather, sensing and perception is tailored to the

specific needs of the behaviors. This may even be manifested in specialized sensor organs. Some frogs have a split retina such that the upper part works well in air and the lower part in water. In this way frogs can sit in water with half their eyes looking for food in the air and the other half in the water (Murphy 2005, p.85).
Gibson argued that it is pointless to discuss perception in isolation. Instead it should be seen as an interaction between the agent and the environment. Acting and sensing have co-evolved as agents survived in a particular environment and the functions are therefore highly intertwined. Gibson referred to his work as an "ecological approach" where the word ecology refers to the interaction between an organism and its environment. The environment affords the agent what it needs to survive, such that the perception needed to release or guide an action is directly in the environment and it does not need to be inferred or memorized. Gibson coined the term *affordance* to denote this information that the environment affords the agent (Gibson 1979). The red blob is a typical example of an affordance that is used by the animal to both release and guide the behavior. Affordances may occur in other sensor modalities than vision. When filling gas in a car, you know when the tank is almost full by simply listening to the sound, which is the necessary affordance for the behavior. Affordances should be seen as relative to the action capabilities of the agent. Soegaard (2010) gives the following example: "…to a thief an open window can have an affordance of 'climbing through' (and subsequently stealing something), but not so to a child who is not tall enough to reach the window and therefore does not have the action possibility". A short video based explanation of affordances is given by Don Norman here: http://www.youtube.com/watch?v=NK1Zb_5VxuM

Affordances are said to be obtained through *direct perception*, i.e. without signal processing, use of memory or high level interpretation of sensed data. While affordances are sufficient to describe several animal behaviors, it is not a complete description of how animals perceive. Neisser argued that there are two perceptual systems in the brain: One working by *direct perception* and one working by *recognition*. By recognition is meant perception based on higher-level cognitive operations, the use of models, and reasoning. Recognition is for instance needed when the environment contains several instances of objects that are identical in the sense that they provide the same affordances. One example would be if we want to identify one particular arctic tern among several other arctic terns. Looking for a red blob is hardly sufficient for this task. Rather, we would have to look for specific signs that we associate with the tern we are looking for: size, color shading, shape of the body, etc. This perceptual process requires higher-level operations and is hence classified as recognition.

While direct perception and affordances can be described as a bottom-up process starting from sensors, recognition can be described as working top-down, starting with models and expectations on what to perceive.

When designing robot behaviors, it is important to observe the distinction between the different typed of perception, and first of all figure out if there are affordances that can be used to release and/or guide a behavior. If this is the case, the design work will be greatly simplified and the result will be a faster operating robot.

Schema theory

Schema theory was originally a tool developed by psychologists in the early 1900's to express and model activities. In robotics, it was introduced and adopted by the neuroscientist and a computer scientist Michael Arbib in the 80's and early 90's (Arbib 1985) (Lyons and Arbib 1989). We will briefly look into how concepts in schema theory are used to describe the relation between sensing, perception and action in behaviors. Arbib describes a behavior as a schema that is composed of a *perceptual schema* and a *motor schema*. The perceptual schema maps sensory input to useful *percepts* that are made available to the motor schema. The motor schema uses the percepts to produce motor actions that execute the behavior. A releaser provides a way of activating/deactivating the behavior. The process is illustrated in Figure 12.

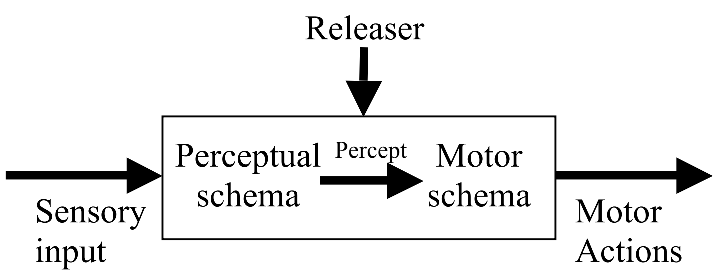
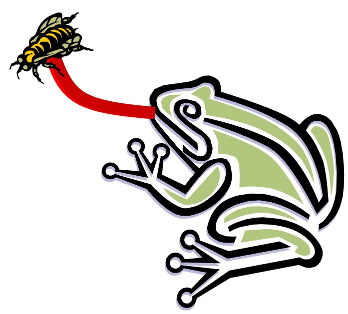


Figure 12. Behavior composed of a perceptual schema and a motor schema.



An agent may be equipped with several schemas that are active at the same time. Motor schemas always output actions in the form of vectors, and combined action is generated by simply adding the outputs from all active schemas. Arbib conducted experiments with fly catching toads and modeled the observed behavior using schema theory. When a toad sees a flying object, it turns towards the object and snaps at it as illustrated to the right. The corresponding modeled behavior, including perceptual and motor schemas, is illustrated in Figure 13. The percept, produced by the perceptual schema, is in this case an attractive force, represented by a vector pointing towards the fly and with a magnitude equal to the strength of snapping. This percept is fed to the motor schema that outputs a control vector, pretty much the same as the input percept. This vector is then transformed into muscles signals that turn the head and perform the tongue snapping.

Interestingly enough, the model manages to predict what occasionally happens when a toad sees two flies at once. In the schema theoretic spirit, each percept triggers instantiation of one schema, each one designed as illustrated in Figure 12. The outputs from the two schemas as added together as illustrated in Figure 14. In accordance with actual observations of toads, the result will be a control vector that points in between the two flies and the toad will consequently turn and snap towards that location.

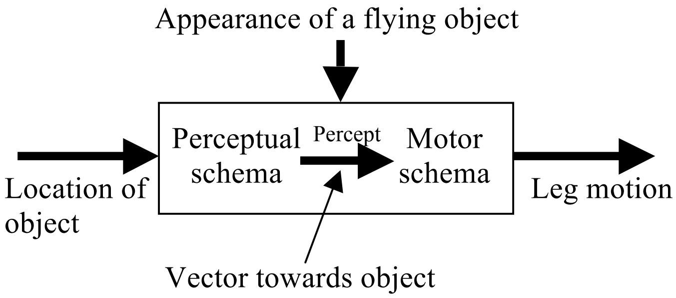


Figure 13. Schema based behavior for snapping a fly.

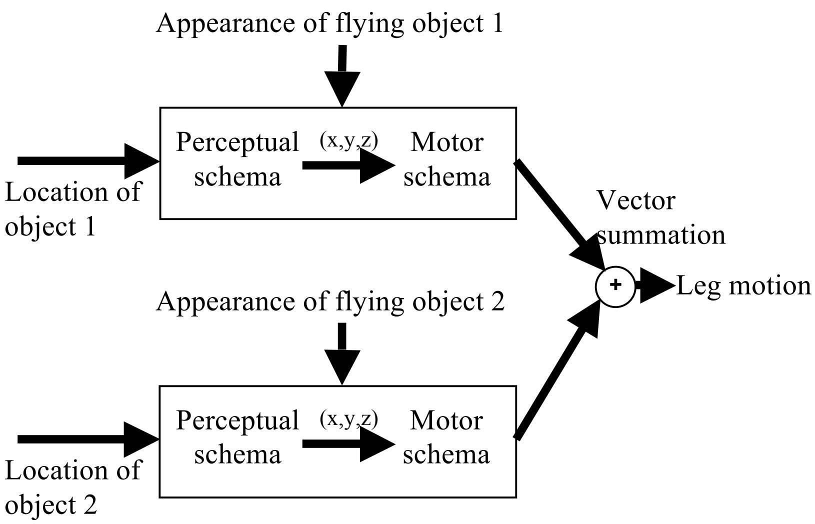


Figure 14. Schema based behaviors when frog sees two flies at the same time

The important conclusion for robotics is that we may think in terms of multiple concurrent behaviors that operate asynchronously and wait for the right percepts to activate the releasing mechanisms. There is no predefined hierarchy between different schemas or behaviors, and schemas can be activated and deactivated at any time depending on the robot's intentions, capabilities and environmental constraints. This gives a much more dynamic architecture than layered hierarchical architectures. The output from behaviors is in vector format and can be easily coordinated by vector summation.

The division into perceptual and motor schemas connects to the previous section on perception. No general world model is necessary and sensor data is converted into percepts that are directly tuned to specific motor schemas and behaviors (action-oriented perception).

References

Arbib, M. (1985), Schema Theory, in The Handbook of Brain Theory and Neural Networks, ed. M. Arbib, MIT Press, Cambridge, MA, 1995, pp. 830-834.

Braitenberg, V. (1984), Vehicles: Experiments in synthetic psychology. Cambridge, MA: MIT Press.

Lyons, D. and Arbib, M. (1989), A Formal Model of Computation for Sensory-based Robotics, IEEE Trans. on Robotics and Auto., Vol. 6, No. 3, June 1989, pp. 280-293.

Arkin, R.C. (1989), Motor Schema-Based Mobile Robot Navigation, International Journal of Robotics Research, Vol. 8, No. 4, August 1989, pp. 92-112.

Arkin, R.C. (1998), *Behavior-Based Robotics*, MIT Press.

Campbell, N.A. (1996), Biology (4th edition), Chapter 50. Benjamin Cummings, New York.

Gibson, J.J. (1979), The Ecological Approach to Visual Perception, Boston: Houghton Mifflin.

Murphy, R. (2000), Introduction to AI robotics, MIT Press.

Neisser, U. (1976), Cognition and Reality, W.H. Freeman.

Pomerantz, J. R. (2003), Perception: Overview, In: Lynn Nadel (Ed.), *Encyclopedia of Cognitive Science*, Vol. 3, London: Nature Publishing Group, pp. 527–537.

Soegaard, M. (2010), Affordances. Retrieved 13 July 2011 from Interaction-Design.org: http://www.interaction-design.org/encyclopedia/affordances.html