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BIOMIMICRY – A REVIEW

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ABSTRACT

A broad and brief introduction to biomimetics is presented. The review has two aims: to provide a general appreciation of the different areas of biomimicry, and to facilitate the construction of a 'Biomimicry Technology Tree'.

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1 INTRODUCTION

Biomimetics is essentially the practise of taking ideas and concepts from nature and implementing them in a field of technology such as engineering, design or computing – for example the development of machines that imitate birds, fish, flying insects or even plants. The concept of borrowing ideas from nature for engineering purposes is very old and has recently gained fresh impetus due to broad advances in science and technology which allow us to at least attempt to approach the sophistication of biological systems; this is coupled with a growing interest in learning lessons from nature for engineering purposes, driven by our civilisations increasing requirement for 'green' technological solutions to contemporary problems.

Biology has had to solve countless engineering problems since the appearance of life on Earth [Ball, 2001]. In forms of increasing complexity and order from simple *protozoa* to higher order *metazoan* creatures such as mankind itself, design and function in plants and animals have been incrementally optimised under evolutionary pressures over millions of years. Given that we enjoy many biological forms, are impressed by their abilities, and are inspired and stimulated by their designs, patterns and structures, then it is logical to see what biology has to offer in terms of design for the engineering purposes of humanity.

Living organisms provide inspiration for innovations in many different fields and for entirely different reasons. Solar energy is stored in a chemical form by plants with almost 100% efficiency; animal muscle is an efficient mechanical motor capable of an exquisite degree of control; transmission of information within the nervous system is more complex than the largest telephone exchanges; and problem solving by a human brain exceeds the capacity of the most powerful supercomputers. The array of mechanisms, processes, structures and materials used by nature is vast, and their potential application to human engineering equally so.

1.1 CENTRAL CONCEPTS IN BIOMIMETIC ENGINEERING

Biomimetic engineering is, like any organism or function that it is imitating, highly multidisciplinary in nature, and embraces aspects related to materials, structures, mechanical properties, computing and control, design integration, optimisation, functionality and cost effectiveness (see section 1.1). Because of the staggering complexity of even just a single *prokaryotic* (not possessing a nucleus) cell it is still impossible, and unnecessary, to copy natures features exactly, partly because nature is so incredibly complex, but also because it often has totally different goals. Since we can for example make excellent fibres already, there is no need to imitate *exactly* spider silk. Nylon and Kevlar are very silk-like in many ways and have superb mechanical properties. What is more interesting about spider silk is the manufacturing process used by the spider to give the silk such superb mechanical properties [Vollrath & Knight, 1999] (phenomenal tensile strength, impact load resistance etc.), working out how those properties are imparted to the silk, and designing those properties into Kevlar production processes, which is a material which we can make already with much simpler technology, is a good example of pragmatic biomimetics.

Consequently, an essential philosophy to adhere to when attempting biomimetic engineering from biological examples is to formulate the ‘’analogy’’ at an appropriate level of abstraction [Benner, 2003]. The chosen level of abstraction must allow capture of the *desired* characteristics of the biological system from which inspiration has been taken, whilst trying to avoid complexity in implementation as much as possible. It must also be realised that, in the pursuit of imitation of a particular characteristic of a biological system, that the system is invariably highly integrated and performs a number of different functions. For example, a bird’s wing has many functional roles in addition to simply providing lift; these additional functions include thermal regulation, control and sexual signalling amongst others. Neglecting to realise that the wing fulfils these other functions whilst trying to extract the characteristics that allow production of lift could lead to the situation where needless complexity is brought into the engineering process.

However, it should be realised that as biomimetics progresses, the level of integrated functionality of designs will increase; it is tight integration and multi-functionality that after all allow biological systems to attain such stunning levels of performance. At present biomimetic engineering typically tries to isolate and reproduce one single aspect of a biological system (in itself often very difficult). However, the incredibly integrated nature of biological systems is perhaps the major long-term goal of biomimetics, and the chief design characteristic of natural systems that is being copied - multi-functionality, robustness and elegance.

In terms of implementation, biomimetic engineering, like any other type of engineering, should be task-led, and therefore encapsulated within a systems engineering context. Taking as an example systems engineering methodology the SMAD [Larson & Wertz, 1996] process (and appreciating that there are many different techniques to systems engineering), the general form of the systems engineering process can be broadly described by four key steps, shown in figure 1.1.

Biomimetic solutions to the system-engineering problem will then be identified and chosen in step 2, in which alternative mission concepts and architectures are characterised; these biomimetic solutions may be competing alongside other, more traditional engineering concepts. This raises the important point, sometimes forgotten, that whilst biomimicry does indeed have the potential to provide elegant and superior solutions than more traditional engineering techniques, biomimetic solutions are not always going to be the best choice. Distinctly un-biomimetic engineering artefacts such as the jet or rocket engine have allowed human-engineered systems to perform far beyond biological systems in many ways. Simple observation of the wheel illustrates that nature does not always have the best ideas (although, in fact, rotational motion does exist in one form in the biological realm - the flagellum of bacteria). Biomimetic solutions to the system engineering question should not be allowed primacy because they are biomimetic and therefore ‘in vogue’, and practical satisfaction of the broad mission requirements and objectives should be the ultimate objective, not the construction of a biomimetic system because it is pleasing to do so.

How to actually formulate biologically inspired concepts or architectures is, of course, a separate question. At the fundamental level, the motivation behind all phenomena in the natural world can be considered to be the maximisation of the survival of the genes of the life form [Dawkins, 1977]. This translates to maximisation of offspring, and maximisation of the proportion of those offspring that themselves manage to breed. This quantity of genetic reproduction can be encapsulated within the *fitness* of the life form, an extremely important concept throughout biology. All aspects of a life form, from physiology through to behaviour, are ultimately concerned with genetic propagation and hence with increasing *fitness*. This ultimate figure of merit for any biological system is not obviously suitable for a human engineered system, which will typically have other goals than reproducing itself. The mission objectives defined in step 1 from figure 1.1 will provide these other figures of merit. Taking the lower-level metrics that biological systems fulfil as sub-tasks to their ultimate goal of genetic propagation (for example food gathering, locomotion, sensing etc.), and matching these to mission/task metrics defined by the engineering problem that is being addressed, is a sound point at which to start the process of biomimetic engineering.

Following on from the notion of fitness, another fundamental concept in the study of animal physiology and behaviour is encapsulated within the *Least Energy Principle*. Whilst attempting to secure a genetic future, all biological forms operate on the *least energy principle*. In order to survive in competition with each other, life forms have evolved ways of living and reproducing using the least amount of resources and energy; this involves efficiency both in metabolism and optimal allocation of energy between the various functions of life. Using a simple example, a life form that evolves energy efficient locomotive gaits will have more energy available for reproduction [McNeill Alexander, 2002]. Thus energy efficiency in locomotion is critical to reproductive success. A similar situation obtains with engineering, where cost is usually the most significant parameter facing the engineer. Engineering to minimum cost involves, for example, selecting efficient materials, approaching tolerances in structures, and employing efficient manufacturing processes; all tricks used extensively in natural systems. It seems likely then that ideas from nature, suitably interpreted and implemented, could improve the efficiency (and hence cost) of engineering at many levels.

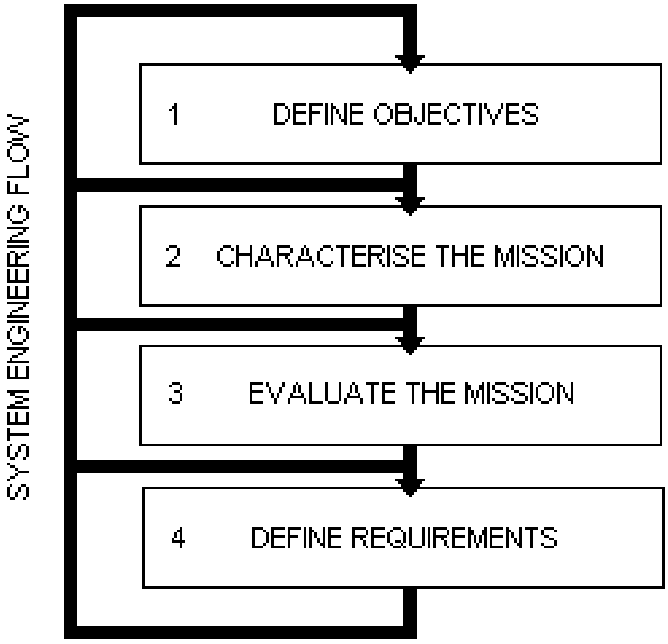

Figure 1.1 – a typical systems engineering process (adapted from [Larson & Wertz, 1996]).

1.2 AREAS OF BIOMIMETICS

Biomimetics as a field does not lend itself too easy categorisation, for two main reasons. One is that the number of biological systems from which to potentially draw inspiration is so massive, and secondly is that the central premise of the discipline is multi-functionality. Therefore clean categorisation into separate disciplines is difficult. However, consideration of the gross engineering issues which both animals and human engineered systems have constantly had to address has allowed the following format for this report to be presented, in accordance with the agreed categorisation of the biomimicry study within the Advanced Concepts Team at the European Space Agency:

Structures and Materials	(6100)
Mechanisms and Power	(6200)
Behaviour and Control	(6300)
Sensors and Communication	(6400)
Generational Biomimicry	(6500)

There is considerable overlap between these subject areas; for example, generational mechanisms from 6500 find application in learning classifier systems in 6300; where appropriate, these areas of commonality will be highlighted throughout this report.

2 STRUCTURES AND MATERIALS (6100)

2.1 STRUCTURES

In tandem with using composite materials spanning a wide range of properties, biological systems also utilise a hugely varied array of structural techniques and mechanisms [Srinivasan, 1996], that are optimised to the task in hand. For example, in the human *femur* (thigh bone), the orientation and density of the *trabeculae* (structural load-bearing ridges within the bone) corresponds to the lines of stress, or directions of tension and compression, in the loaded structure (see figure 2.1).

Optimised structures such as the human *femur* are partially predefined genetically, but adaptive mechanisms that direct the growth of the structure over time are of utmost importance. These are complex cellular feedback mechanisms, which direct the accretion of material to places where it is most needed, resulting in adaptive structures. The shape of a tree for example can be viewed as a historical record of the forces that were acting on it while it grew [Beukers & Hinte, 1998].

Structure obviously underpins many natural processes, particularly locomotion. For example, many structures in the natural world are composed of fluids separated into compartments [Seibert et al., 2001], and the principle of a fluid enclosed in a membrane being made to do useful work can be seen in the human muscular system, plants, and in the skin of worms. The skin of a worm is effectively a cylinder comprised of fibres that are wound in a crossed helical form around and along the worm's body. By contracting the muscles in the body wall and increasing its internal pressure the worm is able to change shape, with the fibres in the skin allowing the worm to go from short and fat to long and thin. This is the basis of a worm's locomotory mechanism, and can be considered analogous to the McKibben artificial muscle (section 3.1.1.4).

2.1.1 Novel Structures

Examples within this area are topological/surface characteristics of structures that allow desirable characteristics to be passively exhibited. For example, the millions of tiny hairs covering the toes on gecko's feet stick to most surfaces because of attractive forces between the molecules in their feet and the molecules of the surface they are clinging to. The molecules have areas of slight positive and negative charge – thus the gecko's toes are, in effect, covered by an immense number of mini-magnets [Geim et al., 2003].

Novel surface topologies can allow hydrophobic surfaces to be constructed. The fundamental law governing the shape of a liquid drop on a surface is governed by the angle θ between the water drop and the solid surface, termed the *intrinsic contact angle* of the drop. Different limiting cases are apparent for large and small values of θ. In the case of high energy surfaces, θ will approach 0°, and the drop will flatten out to form a film; for low energy surfaces, θ will approach 180°, and the surface remains dry. Chemical modification of a surface can increase intrinsic contact angles to around 120°. To further improve the hydrophobic nature of a surface, the topology has to be altered. In general, roughening an already hydrophobic surface will increase the effective intrinsic contact angle. This phenomenon can be observed in the case of the Lotus leaf, which employs a mixture combining a waxy surface chemistry with structural features to produce a completely hydrophobic surface. On the Lotus leaf (figure 2.2), water droplets not only simply roll off the leaf, but also transport particulate contaminants with them [Barthlott & Neinhuis, 1997], providing a cleaning effect that is currently being commercial exploited by the *Lotus* consortium.

This effect has application in the production of self-cleaning surfaces, and additionally, the combination of hydrophilic and hydrophobic surfaces allows the possibility of constructing micro fluidic systems based upon droplet transport over a hydrophobic/hydrophilic substrate [Blossey, 2003]. A natural example of such an arrangement exists in the form of the desert tenebrionid beetle *Stenocara*, which tilts its body into the wind in order to collect water by utilising the bumpy surface of the carapace which is composed of alternating hydrophobic, wax-coated and hydrophilic regions (figure 2.3). On the macroscopic scale, the *elytra* (wing casings) of the beetle are covered with a random array of bumps. At the microscopic level, these bumps are smooth, whilst the depressions between the bumps are covered with a microstructure coated with wax. The microstructure is composed of flattened hemispheres arranged in a hexagonal array, creating a super-hydrophobic surface. Water droplets form on the hydrophilic peaks. When these droplets cover the entire hydrophilic region, the ratio of their mass to their surface contact area increases rapidly until the capillary action that binds the droplet to the region is overcome – at this point the droplet detaches and rolls down onto the hydrophobic regions and towards the beetles mouth. This system has been replicated using glass spheres partially embedded into wax-coated glass slides [Parker & Lawrence, 2001].

Novel topologies at a microscopic scale can also improve other functions. The skin of the shark is composed of a ribbed texture that provides fluid dynamic efficiency relative to a smooth surface due to way the corrugations affect the viscous boundary layer of the water passing over it (figure 2.4). This principle has been applied to drag reduction in aircraft, through the application of a plastic coating with a similar topology. Aircraft drag is reduced by up to 8%, translating to a fuel saving of 1.5%. The surface is also highly hydrophobic, and therefore largely self-cleaning [Ball, 1999].

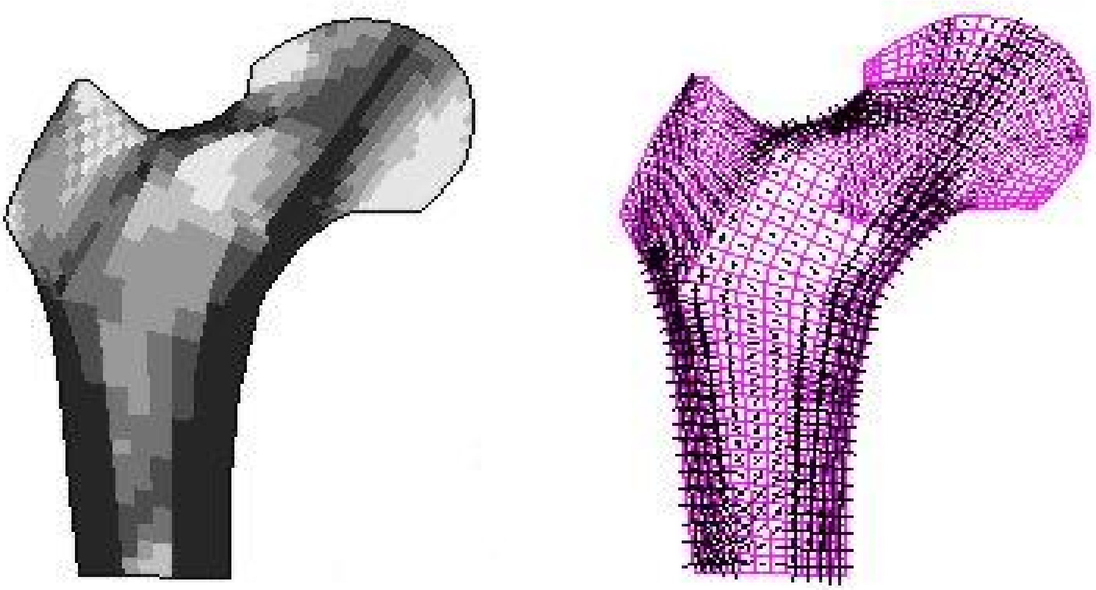

Figure 2.1 – the head of the human femur. The left image shows the bone density (darker areas are denser) whilst the right image shows the arrangement of the trabeculae.

Figure 2.2 – a water droplet on the surface of a lotus leaf (image adapted from [Blossey, 2003]).

Figure 2.3 – photograph of desert tenebrionid beetle Stenocara showing the bumpy surface of the carapace wh

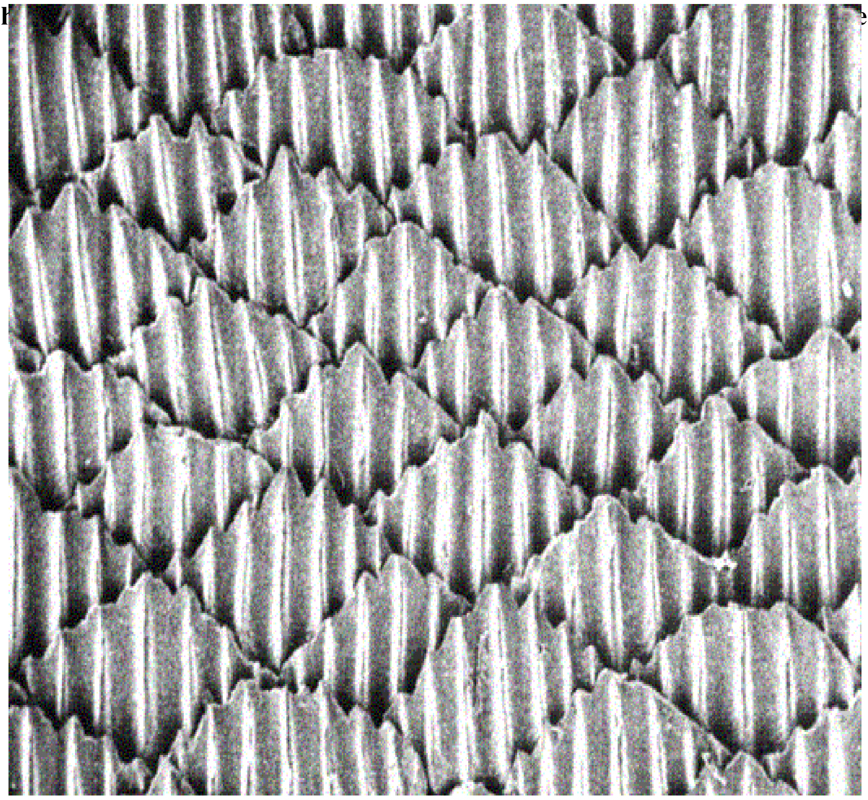

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Figure 2.4 – microscopic view of the corrugated ribs of sharks skin (flow direction is upwards in this image). Image adapted from [Ball, 1999].

2.1.2 Deployment, folding and packing

Natural systems have evolved very efficient techniques for packing, folding and deploying structures, according to the minimum energy principle (section 1.1). Packing and deployment are crucial tactics for protecting structures when they are not required or in danger of damage. For example, away from tropical regions many plants have evolved sophisticated deployment and packing mechanisms to allow deployable structures such as leaves to avoid frost damage. The leaves of most plants are also rolled or folded during growth and must be deployed safely and without damage. Many different packing strategies exist; examples include the simple corrugation of the Hornbeam (*Carpinus betulus*) leaf, to the complex longitudinal and transverse roll mechanism employed by the Fiddlehead (*Matteuccia struthiopteris*) fern (see figure 2.5). Analysis of the Hornbeam leaf deployment has led to the unusual discovery that the area of the leaf exposed during the unpacking process increases slowly at first, until the latter stages at which point the exposed surface area increases rapidly. This is surmised to be due to the advantage of low surface exposure in case of rapidly changing conditions (e.g. the onset of a frost) during deployment [Kobayashi et al., 1998].

Packing is also concerned with making the maximum use of available space. The sunflower (*Helianthus annuus*) along with numerous other plant species, packs seeds according to Fibonacci's golden ratio, j=1.618034. In the case of the sunflower, the seeds grow radially from the centre of the bud and expand radially (figure 2.6). Optimum packing of the seeds is achieved by an angular displacement for newly formed seeds that is j fraction of a circle (0.618034*360, about 222.5°). The apparent opposing spirals of seeds observed in sunflowers are an optical illusion due to the fact that ratio of the successive Fibonacci members approximates j. This packing regime allows the sunflower to produce and fit as many seeds as possible within the seed-head, thereby minimising the amount of materials and energy that have to be used in constructing the seed-head, an important though ancillary structure when compared to the seeds themselves.

Within the animal kingdom, all winged insects, upon transformation to the adult stage, have to deploy their wings from highly folded bags into very thin and stiff membranes with a large surface area. The extension of wings during transformation to adulthood takes it most extreme example in insects that undergo pupation (figure 2.7). Upon exit from the pupa, the wing is partially pulled straight. Within minutes of emergence, a hormonal mechanism reduces the stiffness of the folded cuticle by an order of magnitude, which allows the wing to be stretched plastically. Once flat, the cuticle dries and becomes stiffer and much stronger. This system is sensible from an energetic perspective (see section 1.1) because it does not require pressure generated from the body (originally thought to be the mechanism responsible). Adult winged insects are then able to pack their delicate and precious wings often under *elytra* (wing casings), in order to minimise the risk of damaging them when they are not being used.

Biologically inspired packing and deployment has led to the conceptual design of new methods for packaging and deployment of large membranes and antennae in space [Miura, 1980], in particular rigid-surface antennae, such as the TRW Sunflower, which consists of a series of rigid panels arranged around a central hub, that deploy in a manner that imitates the deployment of a flower head [Guest & Pellegrino, 1996].

Figure 2.5 – the hornbeam (Carpinus betulus) and the fiddlehead fern leaf (Matteuccia struthiopteris) The

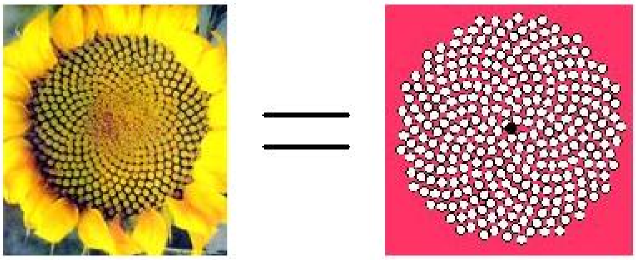

Figure 2.6 –Sunflower head packs seeds according to the Fibonacci sequence

Figure 2.7 – a Monarch butterfly (danaus plexippus) emerging from the chrysalis.

2.2 MATERIALS

Materials engineering is a huge field that has produced an enormous range of materials to fulfil a wide range of roles. Many of the materials that have been hitherto developed have superb qualities with regard to their function. However, natural materials, or their derivatives, are still used extensively, partially because of their cheapness and availability, but also because they have specific characteristics that make them superior to synthetic materials.

Why are natural materials in many instances superior? Looking at the basic materials used by organisms to provide the properties needed for various mechanical functions it is interesting to note that they are comparatively few (most natural structures use fibres as their fundamental building block), far fewer in fact than what is available to the engineering community. They do not have any especially outstanding characteristic compared to many engineering materials. In other words they cannot be classed as "high performance materials", although they do have much lower densities than most. They are successful not so much because of what they are but because of the way in which they are put together; *composites* can legitimately be considered the key to the success of biological materials. The implication is not only that animals and plants have to work hard to win the raw materials - sugars, amino acids, salts - from their environment, but that their control over the assembly and shaping of these materials is much more complete than ours [Beukers & Van Hinte, 1998].

2.2.1 Composites

The composite approach to material engineering is what allows natural systems to produce materials with such excellent properties. Bone is very tough, particularly antler bone, and bird bone is very stiff, yet birds still manage to fly. The ceramic content of bird bone is extremely high and this has been studied in greater detail with a view to considering the nature of the stiffness of bone, and whether it can be mimicked. The toughening mechanisms of antler bone suggest ideas for tougher helmets and general impact protection. Similarly, wood also has toughening mechanisms, which can be incorporated into composite materials that will have high resistance to impact. Wood has many desirable qualities that make it an excellent structural material, including resistance to crack propagation of stress fractures. This has led researchers to develop wood analogues; for example development of a wood-like substance composed of glass fibres in a resin matrix – capturing the low-density cellular nature of wood through corrugation of laminated layers [Gordon & Jeronimidis, 1980].

Seashells are also extraordinarily tough and have unique crack and shatter-resistant properties. Nacre (mother of pearl), for instance, is chiefly made of calcium carbonate, which is organized into multisided aragonite tablets that are closely packed in layers; a rubbery polymer glues the tablets together and serves as a cushion between the layers (see figure 2.8). The shells don't break because when a crack forms it propagates along complicated paths, which diffuse the crack and allow the polymer to absorb the damage. Thus nacre comprises both organic and inorganic compounds – hard mineral plates interleaved with sheets of proteins and other macromolecules [Sellinger et al., 1998]. Nanocomposite materials such as nacre are widespread in biological systems; insights into the micro architecture of natural materials such as these could help make ceramics that are lightweight, tough and shatterproof [Clegg et al., 1990].

The bulk of the mechanical loads in natural materials are carried by polymer fibres such as cellulose (wood and plants), collagen (animals), chitin (insects, crustaceans) and silks (spider's webs). The fibres are bonded together by various substances (polysaccharides, polyphenols etc.), sometimes in combination with minerals such as calcium carbonate (mollusc shells) and hydroxyapatite (bone). A major problem with fibres is that they are most efficient when they carry pure tensile loads, either as structures in their own right (ropes, cables, tendons, silk threads in spider webs) or as reinforcement in composite materials used as membrane structures in biaxial tension. Being slender columns, fibres cannot carry loads in compression because of buckling, even when partially supported laterally by the matrix in composites. In the case of polymer fibres, micro buckling at the microfibrillar level within the fibre results also in very poor compressive strengths. This problem is common to both man-made and biological composites. The main issue which plagues the design of composite structures is their low compressive strength, which limits the exploitation of their high specific modulus, and strength in tension. Since nature has found no alternative to fibres as building blocks, it has had to find ways of offsetting the low efficiency of fibres in compression in order to expand life beyond the limits of invertebrate species or aquatic environments.

Because fibres are good in tension and bad in compression (and hence in bending), using them in tension either by pre-stressing them or by stabilising them laterally using ceramic materials of high modulus or extensive cross-linking with suitable matrices allows the above-mentioned problems to be avoided. All these tactics are used in biological systems; for example many animals with flexible skins (worms, sharks, tunicates) use hydrostatic skeletons where the pre-stressing of fibres in tension is balanced by compression in a fluid (usually water).

2.2.2 Smart Materials

Beyond simple material characteristics, materials in the natural world often have 'intelligent' properties, including the ability of plants to adapt their shape in real time (for example, to allow leaf surfaces to follow the direction of sunlight), reflexivity to heat and pain, and healing. The materials and structures involved in natural systems therefore contrast sharply with current 'dumb' man made components, by having the capability to sense their environment, process data, and respond in an appropriate manner.

So called smart materials have possible application in many areas. In aerospace engineering, sensing materials could allow an aircraft to monitor it's own performance to a level beyond that of current data recording, and provide ground crews with enhanced health and usage monitoring. Sensual materials and structures also have a wide range of potential domestic applications, for example in food packaging that monitors both safe storage and cooking. The above examples address only structures that incorporate innate sensing ability. However, biomimetic materials and structures offer in addition the possibility of structures that not only sense but also adapt to their environment. Such adaptive materials/structures benefit from 'sensuality', but in addition would have the capability to move, vibrate, and exhibit a range of other real-time responses. Applications of such adaptive materials/structures range from the ability to control the aero elastic form of an aircraft wing, thus minimising drag and improving operational efficiency, to vibration control of lightweight structures such as satellites. Another important area of research into adaptive materials concerns those that incorporate some type of healing ability. Several concepts for biomimetic healing materials now exist, the majority of which involve embedding repair materials within a polymeric material or polymer matrix composite (figure 2.10). The repair agent is held in liquid form inside microcapsules, which rupture upon structural damage to the polymer, allowing the repair agent to flow out into the cracks, where it subsequently cures and bonds to the structure, preventing further damage. [White et al., 2001], [Kessler & White, 2001].

The ultimate integration of this kind of smartness into a material is where the functionality occurs at the micro structural or atomic/molecular scale (as is the case with most natural materials). There are few examples of truly smart materials at present, although the familiar photochromic spectacle glass can illustrate the function of such a material. Such glasses have inbuilt sensing and response, but with only a one stimulus - one response function. The development of truly smart materials at the atomic scale, which possess many responses to a broad range of stimuli, is still some way off, although the enabling technologies are under development.

2.2.3 Bio-incorporated Composites

Moving beyond synthetic smart materials, the possibility exists to merge natural materials with synthetic constructs – the field of bio synergic engineering [Ahmad & Mark, 1998]. As biomimicry continues to approaches a molecular scale, the ‘natural’ tendency will obviously be to begin to incorporate actual biological elements into the engineered system. An example of this type of biomimetic engineering is the mimicry of spider silk. Spider silk has outstanding mechanical properties that rival benchmark synthetic polymers such as polyaramid (a substance used to produce bullet proof clothing, reinforced composite panels for aircraft). It has been suggested [Vollrath & Knight, 1999] that artificial silk production could be achieved using dope solutions composed of genetically modified natural proteins, provided that the essential morphological characteristics of the spiders spinning process are effectively reproduced. Thus actual biological components are incorporated into the biomimetic material.

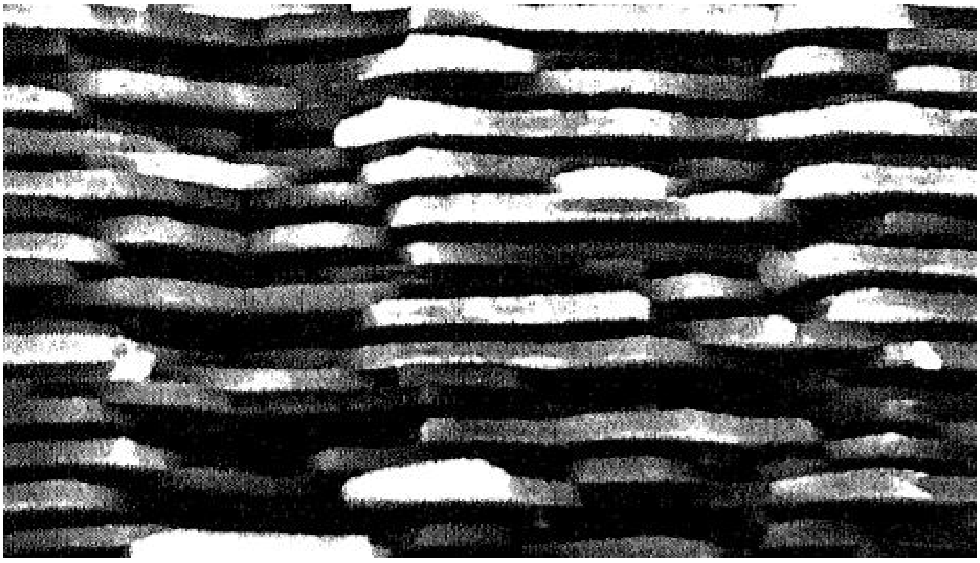

Figure 2.8 – SEM image of the structure of Nacre showing the aragonite bricks (taken from [Kaplan, 1998])

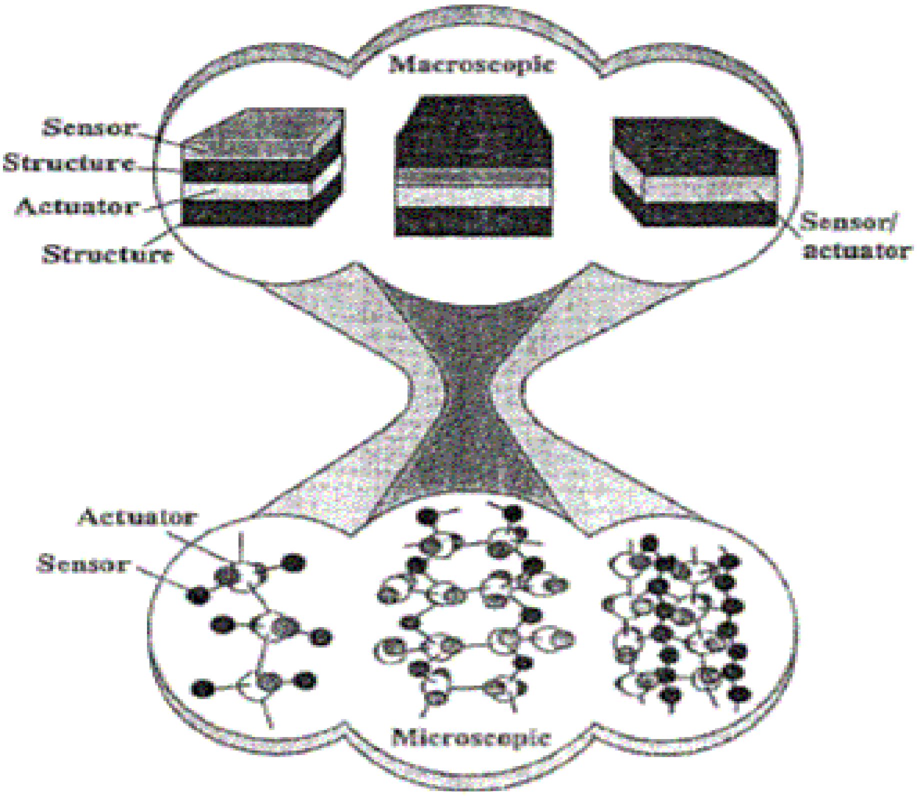

Figure 2.9 – the adoption of macro to micro, taken from [Thompson et al., 1992]

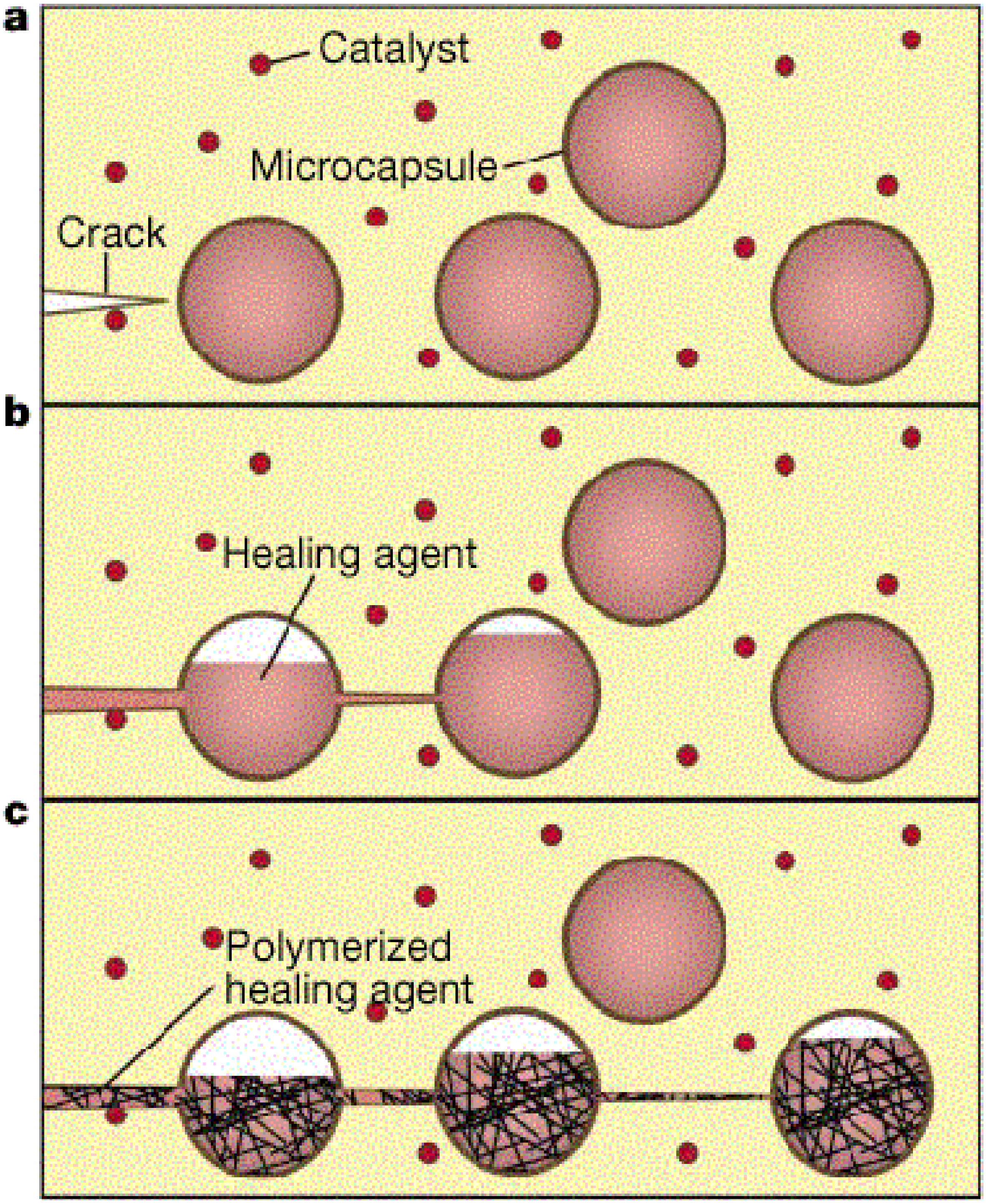

Figure 2.10 – simple illustration of the self-healing concept. The curing process upon rupture of a healing agent micro-sphere may or may not make use of a catalytic agent, itself distributed throughout the material (adapted from [White et al., 2001]).

3 MECHANICS AND PROCESSES (6200)

3.1 MECHANICS

The transformation of chemical energy into kinetic energy is the focus of this section. Mechanical mechanisms within the natural world are vital not only for animals which must locomote to hunt, mate, forage etc., but mechanical processes are also used by plants, in deployment of leaves and flowers etc. A variety of actuation mechanisms are present throughout the natural world, relying on direct conversion of chemical into kinetic energy through the use of muscle, as well as elastic energy storage mechanisms. These are used in a huge variety of modes of movement, the principle ones of interest from the biomimetic perspective being locomotive modes, such as walking, flying and swimming.

3.1.1 Muscles and Actuators

The mechanism for actuation in plants (*stomata* opening, leaf deployment etc.) is osmotic pressure within the cell, acting via the cellulose wall (in other words hydraulic actuation). The pressure is typically very low, and so plants have developed amplification mechanisms whereby elastic energy is stored within the structure. Insects employ a material called *resilin* in the cuticle in a similar fashion, by storing mechanical energy during the down stroke of the wing for subsequent release in the upstroke. *Resilin* is also used in the legs of small jumping insects such as fleas that cannot contract their muscles quickly enough to deliver all their energy to their legs before they lose contact with the ground [Bennet-Clark & Lucey, 1967].

Elastic storage of energy used for subsequent actuation (or as an aid to actuation) is present throughout the natural world. However, elastic actuation in animals should be considered as a secondary actuation form, storing energy generated originally by muscle. Hydraulic actuation in animals is also secondary to muscle actuation; spiders use hydraulic actuation, employing the pressure of their blood (substantially higher than those in other related animals) to drive the exquisite and often extremely fast movement of their legs. The mechanism by which the required hydraulic pressures are generated uses muscles to compress the forepart of their body, thereby causing an increase in blood pressure that is transferred to the legs; muscle is therefore indirectly involved.

Three fundamental mechanisms generate actuation in animals: amoeboid movement, ciliary and flagella bending (at the bacterial level), and muscle contraction. Within the animal kingdom muscle is the overwhelmingly common and direct means by which actuation occurs. Muscle converts chemical energy (produced through hydrolytic ATP > ADP synthesis) to mechanical energy (employing reversible hydrogen bonding between two contractile proteins, *myosin* and *actin*, that slide across each other during muscle contraction). This microscopic action is translated through a complicated hierarchical structure (figure 3.1) into macro-scale motion.

There are two basic types of muscle, *smooth* and *striated*. *Smooth* muscle is used for slow rhythmic movements, such as movement of food through the intestine, whilst *striated* muscle can be further divided into skeletal (*voluntary*) and *cardiac* muscle. Muscles always actuate contractually, so voluntary muscles always exist in antagonistic pairs so as to provide a full range of movement to the area of the body they actuate. They can therefore be divided into *flexor* or *extensor* muscles depending on their role within the pair (for example triceps are *extensors*, biceps are *flexors*).

In addition to their primary role as a generator of mechanical energy, muscles perform several other roles at a systemic level. These secondary functions include roles as shock absorbers and brakes; action as spring elements, rigid struts [Kornbluh et al., 2002] and heat generators. Observation of the animal kingdom shows the huge range of performance that muscle has (ranging from the 1000Hz flapping of an insects wing, jump-actuation in frogs to load-bearing and transport in the African elephant). The multi-functional nature of muscle (largely appreciated through the analytically tool of 'work loops' [Dickinson et al. 2000]) is in-keeping with the highly integrated nature of biological systems in general.

In order to try and emulate the muscle mechanism, it is first required that the metrics that define a typical muscle are defined. Unlike existing linear actuators that could be considered roughly analogous to muscle (such as hydraulics for example), the muscle is a highly non-linear, time variant and multivariate component of the animal system. These essential characteristics of non-linearity, time-variable, repeatable performance and exquisite level of control make the imitation of living muscle an incredible engineering challenge. However the engineering benefits of achieving a high-performance artificial muscle are obvious; the range of speed and precision of muscle actuation would revolutionise robotics for example.

How then to imitate muscle? The complex molecular structure of muscle obviously, for the moment and for the foreseeable future, precludes the direct imitation of muscle. The development of artificial muscle is therefore centred on the search for materials and mechanisms that could conceivably display muscle-like characteristics at a macro-level. There exist at present several candidate materials and mechanisms that are being considered as suitable for artificial muscles. These include:

- Shape Memory Alloys
- Electro active Polymers and Ceramics
- Micro/nanoscale actuators
- Other actuator types

3.1.1.1 Shape Memory Alloys (SMAs)

Shape Memory Alloys are a well-developed technology, and there already exist several commercial available products using SMAs. SMAs work in a cycle between heated and cooled conditions, adopting a specific geometry within each phase. Usually the heated condition is achieved by the Joule effect, but the material can also be heated by radiation or convection. The most common SMA is *Nitinol* (an alloy of Nickel and Titanium) and wires are commercial available in several diameters normally ranging from 50µm to 250µm.

Nitinol has an energy conversion efficiency of around 5%, and a work output of around 1 kJ/kg (compared to the typical and in fact generally constant work output of real muscle of around 100 W/kg). SMAs have been proposed as actuators for solar panels, adaptive structures such as wings for optimising shape at a given velocity, pressure and attitude, and Nitinol has already been proposed for use in a space application as a release and deployment mechanism [Fragnito & Vetrella, 2002]. SMA actuators have also been developed directly within a biomimetic system concept for the Robolobster project [Witting et al., 2002] (see section 3.1.2.1).

3.1.1.2 Electro Active Polymers and Ceramics

Electro active polymers and ceramics exhibit an electro-mechanical response (i.e. undergo deformation) when a voltage is applied across them, enabling their use as actuation devices (and also in reverse as piezoelectric sensors – see section 5.1.3). Since the beginning of the 1990s the development of a series of new EAP materials that can induce large strains has led to a review of their possible application as artificial muscles. EACs are more suited to smaller deformation applications such as ultrasonic motors; EAPs [Shahinpoor et al., 1998], [Horning & Johnson, 2002], [Bar-Cohen et al., 1999a], [Bar-Cohen et al., 1999b] are not restricted by the displacement restrictions of rigid ceramics, making them more suitable for applications requiring larger deformations. Furthermore, EAPs have demonstrated high strain (in excess of many muscles), high efficiency and energy density, fast response, good controllability and impedance-selection and modulation, and are superior to SMAs in spectral response, lower density and resilience. EAPs can be divided in two categories.

- Electronic EAPs - polymer that change shape or dimensions due to migration of electrons in response to electric field. They have the disadvantage of requiring very high voltages (in the order of thousands of volts) to work.

- Ionic EAPs - polymer that change shape or dimensions due to migration of ions in response to electric field requiring 1 to 3V and miliampere currents, but are slower than the electronic EAPs. Additionally, they must be kept wet and it is difficult to maintain DC-induced displacements (except for conductive polymers).

Electro-active polymers (EAPs) include ion-exchange membranes, gel polymers, perfluorinated sulfonic polymers, self-assembled mono-layered polymers, electrostrictives and piezoelectrics, see table 2.1.

Electronic EAPs	Ionic EAPs
Ferro electric Polymers	Ionic Polymer Gels
Dielectrics	Ionomeric Polymer-Metal Composites
Electrostrictive Graft Elastomers and Papers	Conductive Polymers
Electroviscoelastic Elastomers	Carbon Nanotubes
Liquid Crystal Elastomers	Electroheological Fluids

Table 3.1 – summary of electronically and ionically activated EAPs (compiled from [Bar-Cohen, 2002])

In addition to EAPs there exist non-electrically (mechanically) activated polymers that exhibit a volume or shape change in response to a perturbation of the balance between repulsive and attractive intermolecular forces. The competition between these forces can be controlled by small changes in parameters such as composition of a solvent or gel, temperature, pH etc. These types of polymers include chemically, magnetically and light-activated shape memory polymers, and inflatable structures, the most well known being the McKibben artificial muscle, originally developed in the 1950's as an orthotic appliance for polio patients [Klute et al., 1999]. It is powered by compressed gas, which is fed into an actuator composed of an inflatable bladder sheathed with a double helical weave. When the gas enters, the bladder increases in volume, expanding radially and contracting along its length. Figure 2.1.2 shows the basic actuation character of the McKibben artificial muscle and a generic electroactive polymer.

3.1.1.3 Micro and nano-scale actuation

Despite the majority of work into artificial muscles being concerned with the search for materials such as EAPs that exhibit muscle-like behaviour at a macro-scale, it is felt by some researchers that imitation of the sarcomere structure of the muscle may be necessary in order to achieve the desired performance. Although large-scale fabrication of the complex structure of muscle is not at present practical, the microscopic scale of individual actin filaments and myosin motor proteins does open up the possibility of using such elements to provide nanoscale actuation in biomimetic applications.

The action of a *myosin* head across an *actin* filament has been extensively studied (for a description of the individual mechanical events of force generation by *actomyosin*, see [Kitamura et al., 1999]), and their promise as microscopic actuating mechanisms for use in micro and nano-devices has been established. However, the difficulty in using actual muscular components (ATP-driven motor proteins such as *myosin*, *kinesin* and *dynein*) is their requirement for a specific chemical environment (principally containing ATP) in order to function. Recent research [Knoblauch et al., 2003] has identified another type of natural protein that could serve as the basis for a micro-scale actuation device – protein bodies in the sieve elements of legumes, which act as cellular valves through undergoing a Ca^{2+} dependent deformation that plugs the sieve element. Whilst in-situ the deformation is probably caused by ion transport across the cellular membrane, the deformation has been demonstrated in-vitro (figure 3.3); it is rapid (of the order of 0.05 seconds or less), reversible, anisotropic and most importantly (in the sense of application to engineered nanodevices) ATP independent. Importantly, the protein (termed a *forisome*) deformation, which is also inducible through changes in pH, has been demonstrated to be controllable through electrical means, through diffusional electrotitration (the induction of pH gradients in the vicinity of pulsed DC electrodes).

In addition to *forisomes*, which are a micro-scale actuation candidate, their have been several other non ATP-based micro scale devices that have been suggested, such as the Viral Protein Linear (VPL) Actuator, based upon a conformational change that occurs in a family of viral envelope proteins when they attempt membrane fusion with a target cell [Dubey et al., 2003] and a DNA-fuelled molecular machine (in the form of a pair of tweezers), which is constructed from DNA, and uses DNA as fuel [Yurke et al., 2000].

3.1.1.4 Other Actuator Types

There exist other types of actuator that have been considered as artificial muscle candidates, such as the Series Elastic Actuator, which uses a series arrangement of linear springs within the muscle between a motor and the actuator output [Robinson et al., 1999], and the reciprocating chemical muscle, which works by converting stored chemical energy directly into mechanical energy through a direct non-combustive chemical reaction, and is being developed as part of the Entomopter project (see section 3.1.2.2). However, the RCM should more correctly be considered a power source.

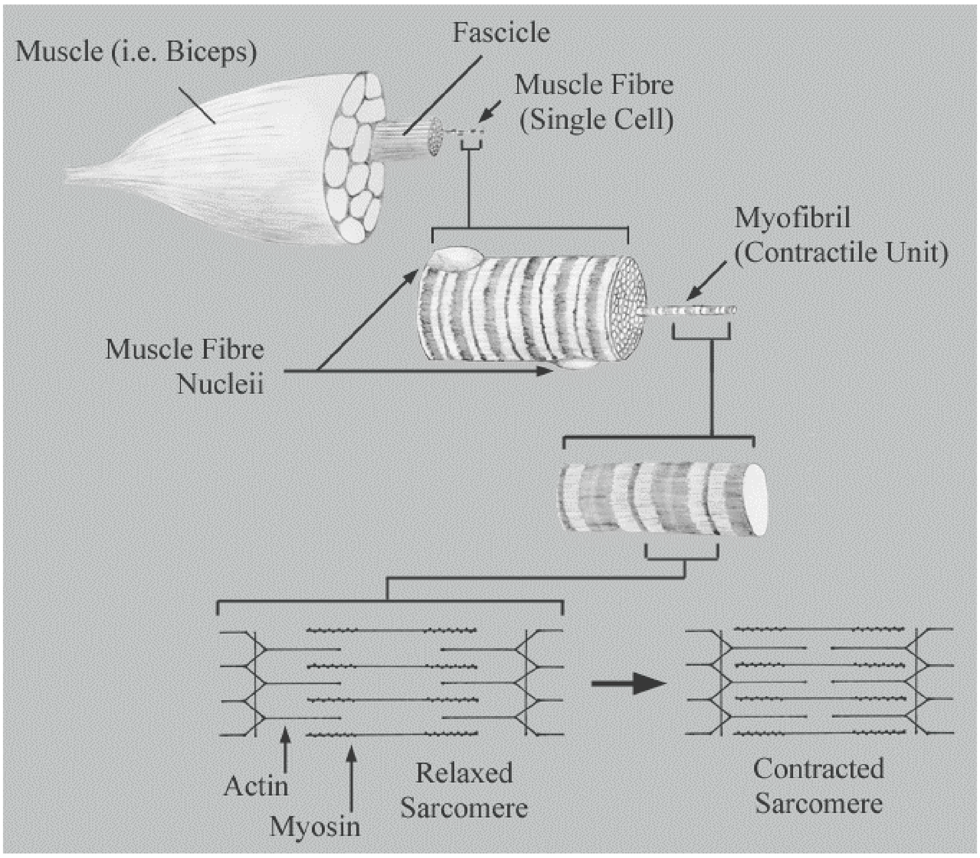

Figure 3.1 – a hierarchical view of striated muscle

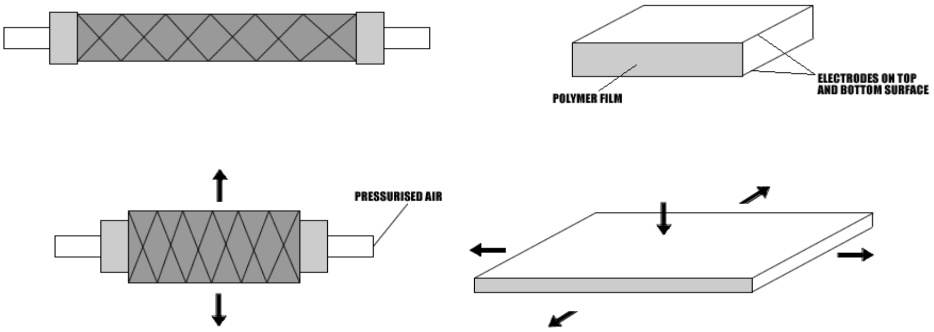

Figure 3.2 – McKibben artificial muscle (left) and electro-active polymer (right) under states of relaxation (top) and actuation (bottom)

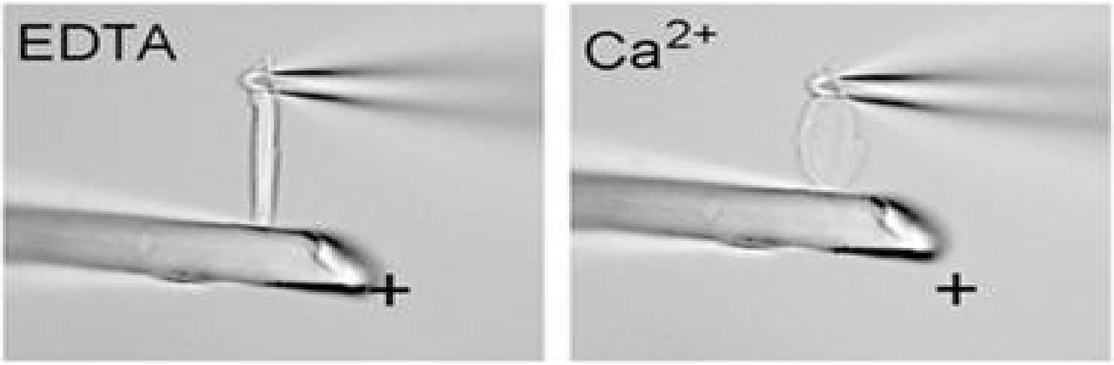

Figure 3.3 - Demonstration of pulling force in a forisome fixed in the expanded state between the tip of a rigid glass pipette (on the right) and a flexible glass fibre (9 μm diameter; on the left). On addition of Ca^{2+}, the forisome pulls the fibre towards the pipette (right image). Image adapted from [Knoblauch et al., 2003].

3.1.2 Locomotion

Locomotion is one of the most important types of routine activity undertaken by animals; its purpose is many fold - finding food, escaping predators and so forth. Of fundamental importance is the fact that locomotion enables the animal to increase the effective area that it can influence, thereby allowing the animal access to more food, more potential mates and more places to go where predators are not.

Locomotion in the animal world takes many forms and the characteristics of a particular species' locomotive capabilities (such as speed, acceleration, stability etc.) are an optimal compromise that supports the goal of genetic propagation (section 1.1). The ontology of the animal, it's chosen environment, food sources and ancestry all constrain locomotive capability. For example, high acceleration is a desirable trait for hunters such as the Lion (*Pantheras leo*) and consequently they have evolved to possess very high acceleration over short distances (higher than the acceleration of their prey), whilst the herbivorous Hermanns tortoise (*testudo hermanni*), which does not have to chase down it's food, and has evolved to resist predators attacks through armour rather than avoidance, speed is not important, but stability is. Thus the tortoise has evolved a mode of locomotion that is extremely stable and efficient. In both cases, the addition of two extra legs would have the potential to increase both the speed of the Lion and the stability of the Tortoise. However, the four-legged ancestry of both is also a constraint on their locomotive design [McNeill Alexander, 2002].

Because locomotion is typically one of the major metabolic sinks in the animal (for fish in general around 35% of metabolic energy production devoted to swimming [Alexander, 2002]), the least energy principle is highly applicable to the study of locomotion. From an energetic perspective, smaller animals incur higher costs in transporting their mass over a given distance; this is due to the higher rate of muscle shortening by smaller animals in order to attain a given velocity. In terms of locomotion type, terrestrial locomotion (running, walking, crawling etc.) is more expensive than swimming, flying or undulating due to the negative work employed in counteracting gravity (the CoM of a terrestrial locomotor typically oscillates in the vertical plane) – this work is done in decelerating the body of the animal as it falls towards the ground in between strides, and is necessary from a postural perspective but does not contribute towards the locomotion of the animal. When riding a bike, a person does not perform negative work, as the CoM is at a constant height, and posture on the bike can be maintained with no effort; this is why cycling is a much more efficient form of locomotion than running. Indeed the wheel can be considered a tactic for avoiding the negative work associated with walking. Both of these trends (increasing efficiency with stride and increasing energy use from swimming through flying to ambulation) can be seen in figure 3.4.

The two principle physical parameters that affect locomotion are inertia and drag. The Reynolds number of the fluid medium within which the locomotion occurs, and this value determines the type of locomotive strategy employed, encapsulating the interplay between these two forces. Fish for example move within a high density and therefore high drag and high buoyancy medium – hence the extreme emphasis on streamlined body shapes and smooth surfaces that encourage laminar flow; birds fly through a lower density, lower buoyancy medium and hence for them streamlining is not as important, but the production of lift is. Thus the body shape of birds is designed more towards lift generation. For terrestrial locomotors, the effects of viscosity and drag are not important, and so streamlining is not a driving factor. Figure 3.5 illustrates the transition from viscous to inertial effects as Reynolds number increases.

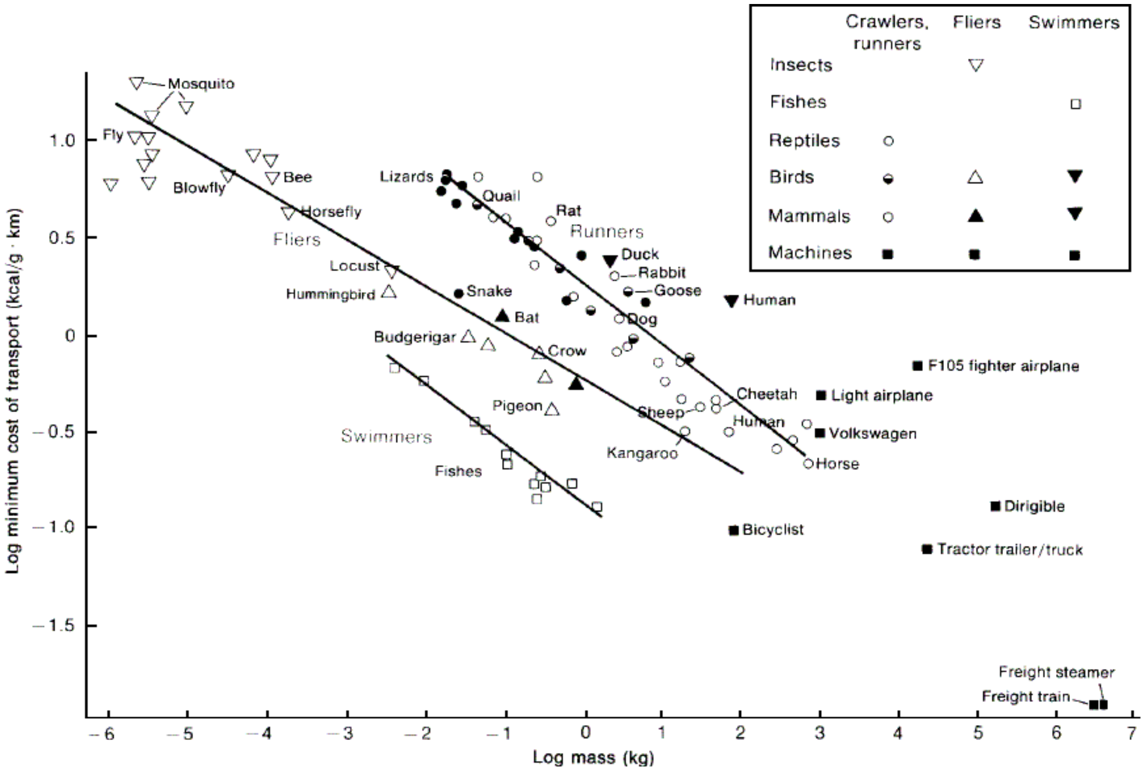

Figure 3.4 – cost of transport for different locomotion types: cost is primarily related to locomotion type rather than organism type. A general reduction in cost with increasing size is also clearly observed (adapted from [Eckert, 1988])

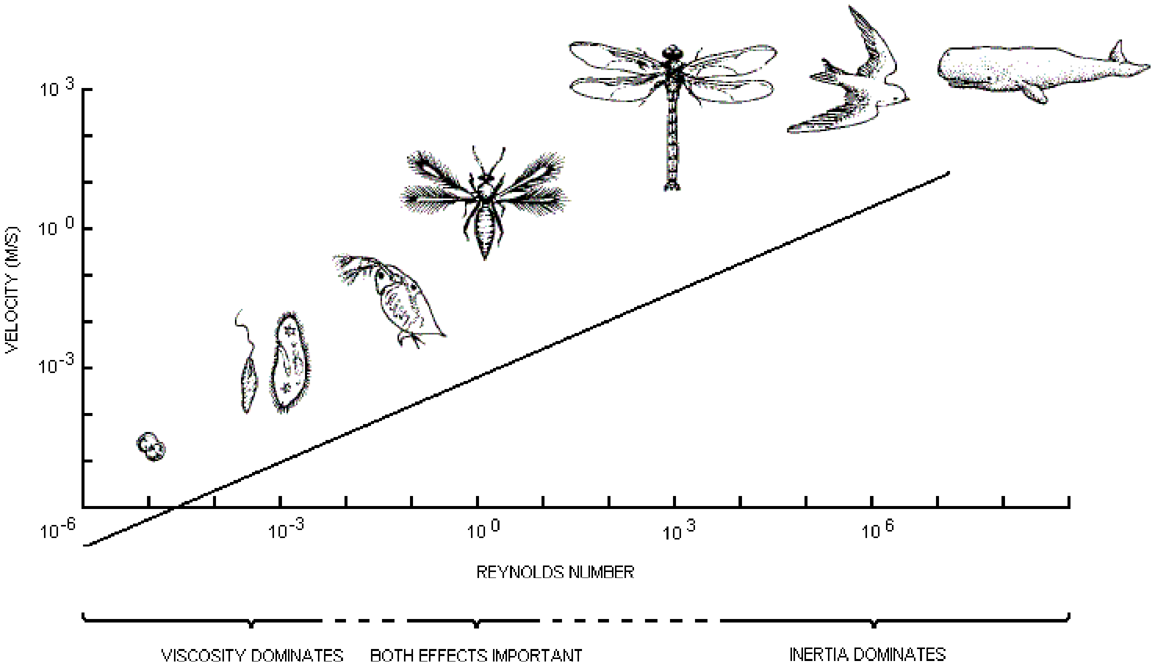

Figure 3.5 – Logarithmic scale of animal cruising velocity versus Reynolds Number; viscous forces dominate smaller animals, whilst larger animals are dominated by inertial forces (adapted from [Nachtigall, 1977])

In all instances, the locomotive form is optimised for efficiency; this extends to the use of different *gaits* (which exist for every class of locomotors, not just walkers) depending on the speed at which the animal is travelling. *Gaits* are different patterns of movement that have distinct features, and can be considered a bifurcative response to the problem of optimising (to minimum energy use) locomotion over a particular range of speeds. For a comprehensive introduction to the field of study concerning animal locomotion (biomechanics), see [McNeill Alexander, 2002].

3.1.2.1 Ambulation

The majority of work on biomimetic robotic locomotion has centred on replicating some form of walking be it with two legs or more. The possible advantages of ambulatory locomotion when compared to wheeled locomotion are a robust response to obstacles, the ability to position the body of the robot to a high degree of accuracy, and rapid movement over complex and unpredictable terrain. Wheeled vehicles are obviously superior when the terrain is relatively smooth (compared to the diameter of the wheel), but have difficulties when encountering naturally uneven terrains with many substrates. Legged animals can traverse such environments extremely rapidly (insect legs commonly have over eight degrees of freedom), an observation that encourages the development of legged vehicles for use in such environments.

Legged locomotion can be broadly divided into three interconnected subsystems: posture control, swing control and stance control. Posture control positions the CoM of the robot and reacts to external disturbances; swing control cycles the legs periodically, and stance control reinforces posture at a local level. In the case of insect ambulation control, the walking system is divided into six coupled relaxation oscillators, consisting of intraganglionic interneurons, motoneurons, muscles, tendons and mechanoreceptors situated on the leg itself at various points. For biomimetic imitation of insect-legged movement, it is not possible or desirable to try and replicate this complexity. However, a good muscle analogue (see section 3.1.1) is thought to be the most important component that must be emulated well [Wendler, 2002] in order to achieve the goal of a controllable leg and hence locomotion.

Examples of current ambulatory robot projects include the *cricket robot,* with the goals of full autonomy and a size of two inches in length. The cricket robot uses custom McKibben artificial muscles (see section 3.1.1.4) for leg extension, a custom built compressor and smoovy motor for on-board power, and MEM valves [Quinn et al., 2002]. Another ambulatory robot currently under development is the *Scorpion* project. This is the development of an eight-legged robot, with the goal of full locomotive autonomy within an unstructured environment [Klaasen et al., 2001]. Of similar form is the Lobster robot project [Ayers et al., 2000], an aquatic legged robot based on the physiology of the lobster, being designed to have superior shallow-water performance, intended to fulfil an autonomous mine-clearing function in shallow bodies of water such as rivers or harbours (figure 3.6).

3.1.2.2 Flight

Flight mechanisms of biological systems centre on the ubiquitous use of the wing. However, the widely differing scales at which biological flight occurs mean that the mechanisms used for flight vary widely. In a fluid medium of fixed viscosity dynamic phenomena have a particular size scale (dictated by the *Reynolds number*); therefore smaller flying animals such as insects have the ability to employ fluid dynamic phenomena that are not available to larger animals such as birds. For example, insects extensively employ vortices to generate control and lift, ignoring classical aerofoil aerodynamics – hence the commonly held notion that bumble bee flight is physically impossible. Insects are able to fly at a significantly higher coefficient of lift (C_L) than conventional airplanes (~C_L = 1), due to these unique mechanisms for vortex manipulation.

Insect wings are thin and have sharp leading edges that lead to separation of the airflow as it passes over the leading edge, and the construction of a leading edge vortex. This augments the circulation and hence the lift of the wing. Removal of the vortex without stalling is achieved by span-wise pressure gradients that cause the vortex to travel down the wing to the tip, and hence transform into a tip vortex that is then shed safely. The wings are moved by rhythmic deformation of the thorax (driven by a neuronal cluster termed a central pattern generator-see section 4.2.2). When the large dorso-longtitudinal muscles contract, the segment is shortened, and the tergum bends upwards. This causes a downward sweep of wing around the hinge. Dorsoventral muscle contraction moves the wing upwards (assisted by elastic energy release from *resilin* in the structure of the thorax).

Because aerofoil dynamics provide the basis for classical aeroplane flight, classical aviation can be thought of as biomimetic, with of course the crucial difference that the aerofoil of a plane is not flapping (although of course this did not deter early aviators from trying to replicate flapping flight – see figure 3.7). Birds are capable of stunning flight performance, but flying insects achieve great energy efficiency and agility by oscillating and rotating their wings and achieve fine control of wing shape by using sensors on their surfaces. Flying insects are also capable of vertical take off and landing with kinematic control of flight manoeuvres being provided by the tilt of the stroke plane, asymmetry in wing beats, timing of down strokes and other techniques. Insect flight therefore has the potential to provide a relatively undiscovered country of flight dynamics, control techniques and therefore possibilities for small autonomous systems with the abilities of insect fliers, including the ability to softly touch down, quickly lift off, rapidly alter direction, as well as hover.

Current research into biomimetic flight is therefore focused around the use of insect-flight characteristics to contribute to the goal of small, autonomous flying agents. This is typified by research projects such as the *robofly,* with the design goal of the blowfly (*Calliphora*), consisting of a two-winged system driven by three stepping motors [Fearning et al., 2002]. Also of interest is the Entomopter project [Michelson, 2002], with the goal of a fully autonomous insect-analogue with crawling, swimming and flight capability. The flight system of the entomoptor employs a novel flapping-wing design that actually attempts to avoid the complexities of insect flight to a large degree, through the use of a simple resonant autonomic wing beat with just one degree of freedom. Two wings are set along the fuselage, which then pivot like seesaws (see figure 3.8) with a motion that is 180° out of phase. Because the wings have only one degree of freedom, they cannot employ the tilting mechanism usually used by insects to allow lift generation on the upstroke. Nevertheless, the wings are designed to provide lift on the upstroke through the use of structural materials that react differently to opposing loads. Wing deformation on the upstroke will then yield an angle of attack and camber that produces lift for at least a portion of the upstroke.

Wing actuation for the entomoptor will be effected by the reciprocating chemical muscle (see section 3.1.1.4). The small amounts of gas vented by the reciprocating chemical muscle will be used for active flow control, and the fuselage will be made of a material with a torsional memory, that stores wing mechanical energy (in the form of elastic potential energy) for release on subsequent wing strokes, mimicking the use of *resilin* in insect flight to store mechanical potential energy during the wing stroke.

3.1.2.3 Swimming and Undulation

Possible inspiration for mechanisms for locomotion in a liquid medium can be taken from the wide variety of creatures that inhabit oceans, lakes and rivers. Observation of many of these reveals the use of progressive waves that travel along the length of the creature, inducing forward motion. For example the Lamprey (one of the most primitive invertebrates). The Lamprey swimming motion involves the propagation of flexion waves along the body length, such that the body axis form is typically s-shaped in appearance. The waves increase in amplitude as they propagate from nose to tail. A prototype system has been based on the Lamprey's swimming motion [Wilbur et al., 2002]. A central pattern generator is used to generate an alternating bilateral pattern that moves along the body axis, actuated by segmented Shape Memory Alloy muscles fabricated from *Nitinol* (see section 3.1.1.1).

More evolved swimmers have learned, like flying insects, to manipulate vortices, by passing them along the length of the body as they undulate. When the vortices reach the swimmer's tail it flicks them from one side of its body to the other so translating the energy contained in the vortex into propulsive power. Examples of biomimetic replication of the motion of fish, in particular the vortex shedding mechanism, include the Robodolphin [Nakashima & Ono, 2002] and the VCUUV (Vortex Control Unmanned Undersea Vehicle) otherwise known as Robotuna [Barrett, 2002], [Anderson & Kerrebrock, 2002] Projects. A dolphiform/thunniform basis for motion was selected in both of these cases because the tuna and dolphin have several advantages in replication by an artificial mechanical system. The tuna and dolphin are very streamlined, relatively rigid in the fore body (the propulsive movements are localised in the last 40% or so of the body length) and propulsive movements are moderate in amplitude.

Undulatory motion of course also exists on (and in) solid ground, typified by the motion of a snake. The snake robot project [Miller, 2002] has involved the construction of a number of prototypes that display some of the locomotive forms employed by snakes. These are inherently different strategies that are suited to particular situations, essentially involving the propagation of waves along the snake's body. The types of locomotion are side winding (horizontal and vertical waves of motion propagating down the length of the snake, out of phase by 90°), concertina progression (a non-travelling curve along the length of the snake with amplitude modulation imparting forward motion), undulatory progression (a travelling wave along the length of the snake attaining forward motion by friction with the ground) and rectilinear progression (the skin is pulled forward and backward over the ribs as downward pressure is modulated by bulging and releasing of muscles). Systems such as this one are hoped to one-day find application in search and rescue and other situations where access to small spaces and confined tunnels is required.

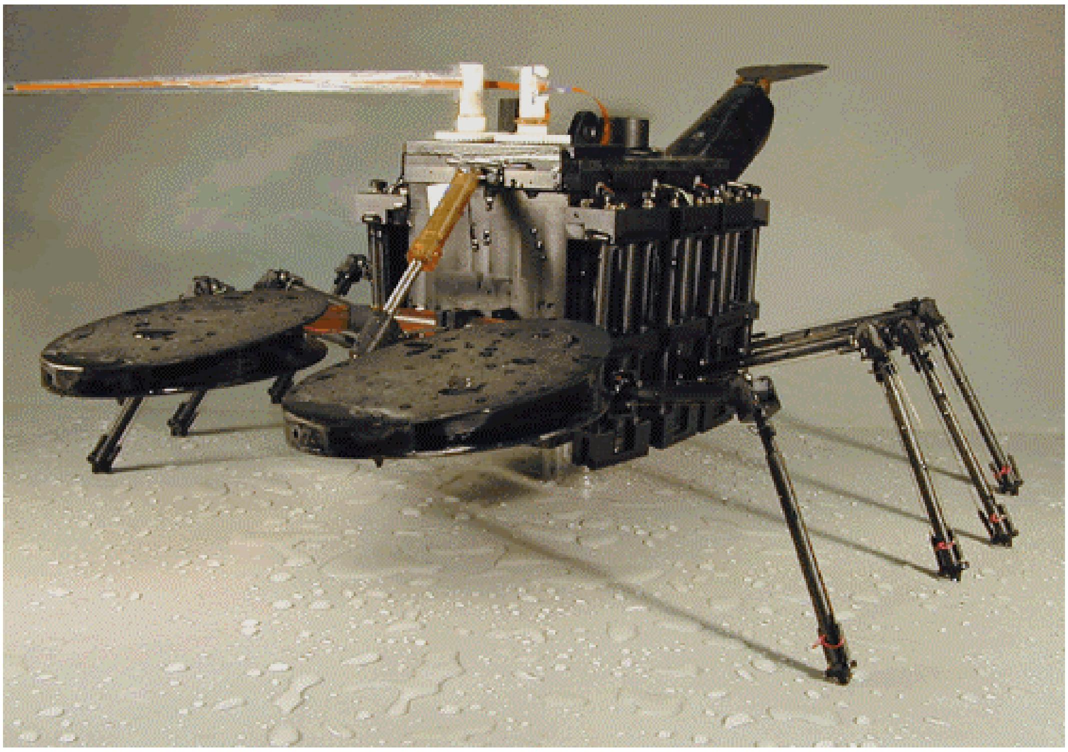

Figure 3.6 – Lobster robot intended for shallow water mine countermeasures [Ayers et al., 2000]

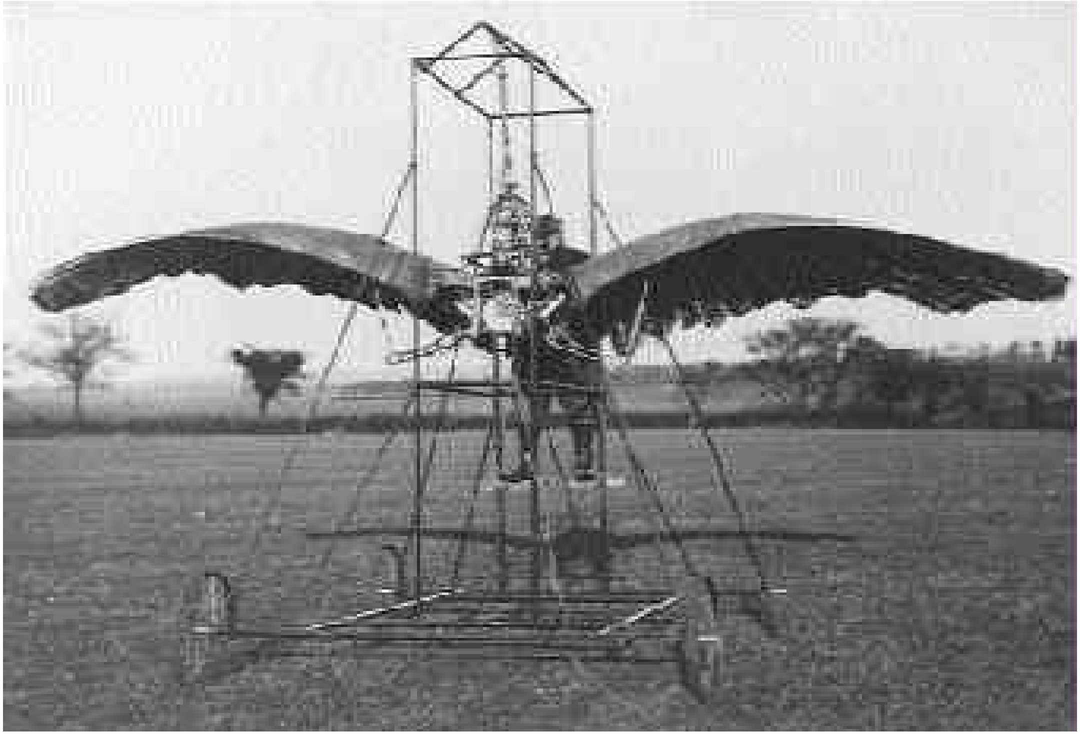

Figure 3.7 - the Frost Ornithoptor: every bit as impractical as it looks

Figure 3.8 – conceptual image of the entomoptor flying across the surface of Mars. Note the two seesaw wings operating out of phase.

Figure 3.9 –mock-up of the robotuna project

Figure 3.10 – a snake robot employing horizontal undulation to move

3.2 PROCESSES

‘Processes’ is a wide term in the context of this report, but can be taken to encapsulate those *mechanical* and *chemical* processes that are not directly related to any of the other categories. Examples include natural mechanisms for filtration (such as selective molecular transport across membranes), fluid circulation, power generation mechanisms such as photosynthesis, thermal management mechanisms, material fabrication, and many others. In this section, a brief introduction is given to two principle mechanisms – power generation in plants, and thermal management in animals. Additionally, a brief introduction to natural fabrication and construction processes is given.

3.2.1 Power Generation and Storage

The fundamental mechanism for energy generation in the natural world is photosynthesis. Photosynthesis occurs in many life forms, ranging from plants to bacteria. In chemical terms, photosynthesis is a light-energized oxidation–reduction process (oxidation refers to the removal of electrons from a molecule; reduction refers to the gain of electrons by a molecule.). In plant photosynthesis, the energy of light is used to drive the oxidation of water (H_2O), producing oxygen gas (O_2), hydrogen ions (H^+), and electrons. Most of the removed electrons and hydrogen ions ultimately are transferred to carbon dioxide (CO_2), which is reduced to organic products. Other electrons and hydrogen ions are used to reduce nitrate and sulphate to amino and sulfhydryl groups in amino acids, which are the building blocks of proteins. In most green cells, carbohydrates (especially starch and the sugar sucrose) are the major direct organic products of photosynthesis. The overall reaction in which carbohydrates (represented by the general formula CH_2O) are formed during plant photosynthesis can be indicated by the following equation:

$$CO_2 + 2H_2O \xrightarrow{light} CH_2O + O_2 + H_2O$$

This equation is merely a summary statement, for the process of photosynthesis actually involves numerous complex reactions. These reactions occur in two stages: the “light” stage, consisting of photochemical (i.e., light-dependent) reactions; and the “dark” stage, comprising chemical reactions controlled by enzymes (organic catalysts). During the first stage, the energy of light is absorbed by the photosynthetic pigments, resulting in excitation and a raised energy state in the pigment which is used to drive a series of electron transfers, resulting in the synthesis of the energy-rich compound adenosine triphosphate (*ATP*) and the electron donor reduced nicotine adenine dinucleotide phosphate (*NADPH*), both of which are crucial to the ‘dark’ stage reactions. During the dark stage, the *ATP* and *NADPH* formed in the light reactions are used to reduce carbon dioxide to organic carbon compounds. This assimilation of inorganic carbon into organic compounds is called carbon fixation. The light-dependent reactions in photosynthesis take place in specialised pigments, which come in a large variety of forms. There exist three major pigment types:

- Chlorophylls
- Caretonoids

- Phycobilins

These main pigment types each have a characteristic absorption spectrum. Chlorophylls and caretonoids (found in plants) absorb blue/red and blue/green light respectively; photosynthetic pigments in plants do not effectively absorb green and yellow light, which is why plants are green. *Phycobilins* are found (in addition to the first two pigments) in cyanobacteria (also termed 'blue-green' algae) that absorb the portions of the spectrum not effectively absorbed by plants. Cyanobacteria (which are *Prokaryotic* – i.e. do not possess sub cellular components) were probably the first photosynthetic organisms.

In plants (*Eukaryotic* organisms), photosynthesis is carried out in specialised organelles termed chloroplasts. The chloroplast has an intricate structure to mediate the number of complex reactions that comprise photosynthesis. The internal structure consists of a colourless matrix called the *stroma* (essentially an enzyme and molecular solution) within which are embedded the *lamellae*. *Lamellae* are where the photosynthetic pigments are located, and the 'light' stage photochemical reactions take place here; the *stroma* is the location where the enzyme-driven 'dark' reactions take place.

The maximum theoretical efficiency of photosynthesis (light energy stored per mole of oxygen evolved) has been estimated to be around 26%. However, the actual percentage is lower due to several reasons (photorespiration, incomplete light absorption, energy costs of maintenance of plant physiology etc.). This value can be compared to the efficiencies of current photovoltaic power generation systems. The maximum-recorded cell efficiency for crystalline silicon is 24,7%. Cell efficiencies greater than 25% have been recorded for cells made from III-V semiconductor material (for example gallium arsenide concentrator systems and for space applications because of their high cost). More normally, typical module efficiencies range from 11-15% for single crystalline silicon PVs, down to 5-7% for amorphous silicon.

The efficiency of photosynthetic power generation is therefore comparable to existing photovoltaic technology; as a consequence, the use of photosynthesis for a number of applications is currently being considered. In the future, photosynthetic organisms are likely to be involved in the production of enzymes and pharmaceuticals, in bioremediation (environmental clean-up of pollutants), and most importantly from an engineering perspective in the clean production of fuels [Vermaas, 1998]. Existing Algae can produce hydrogen under natural conditions, and the possibility of using photosynthetic processes to produce hydrogen is beginning to receive increasing attention, and the problem is being approached by exploring the use of existing biological photosynthetic cultures, and through the use of biomimetic mechanisms [AFOSR final report, 2003]. Recent work has involved the incorporation of $F_0F_1 - ATP$ synthase into liposomes containing the components of the proton pumping photo cycle. Irradiation of this artificial membrane with visible light results in the synthesis of ATP, mimicking the process by which photosynthetic bacteria convert light energy into chemical potential energy [Steinberg-Yfrach et al., 1998]. Photosynthetic mechanisms based on biomimetic technology have also been proposed as a means to enable oxygen recovery in next generation astronaut suits [Hodgson, 2003].

3.2.2 Energetics and Thermal Management

The sum total of chemical reactions that occur within an organism are collectively termed the metabolism. There are two types of metabolic activity, *anabolic* and *catabolic*. Anabolic reactions involve the construction of larger, more complex molecules from smaller, simpler ones, and are associated with growth and repair. Catabolic reactions are those that involve the breakdown of larger molecules into smaller, simpler ones, and are associated with digestion and energy generation (energy from catabolic reactions goes into the production of ATP). Metabolic processes of both types involve the release of heat energy, which contributes to the body temperature of the animal.

There are two principle thermal classifications of animal: *endotherms* and *ectotherms*. Endotherms maintain body temperature through internal heat production, whilst ectotherms rely on external heat sources to maintain body temperature. Between these two extremes lie *heterotherms*, which are typically largely ectothermic but employ physiological heat generation mechanisms when additional heating is required. Both endotherms and ectotherms (and heterotherms between them) utilise a variety of behavioural, autonomic and adaptive thermal management processes to regulate body temperature. Examples of these conservation and dissipation mechanisms are given in table 3.2.

Thermal Class	**Cold mitigation Mechanisms**		**Heat mitigation Mechanisms**	
Ectotherms	Extra cellular freezing Super cooling (prevention of nucleation) and presence of antifreeze Adaptive - Acclimatisation through physiological changes		Behavioural – e.g. Shade-seeking Autonomic – e.g. Regulation of blood flow to surface tissue Adaptive – Acclimatisation through physiological changes	
Heterotherms	Autonomic – e.g. heat generation through antagonistic thoracic muscle activation Behavioural – e.g. reduction in exposed body surface by snakes during brooding Adaptive – vascular organisation in warm-blooded fishes		Autonomic – e.g. regulation of blood flow to abdomen, drawing heat away from thorax Behavioural – e.g. bee muscle contractive thermogenesis coupled with alteration of swarm structure	
Endotherms	**Below LCT**	**Thermoneutral Zone**	**Thermoneutral Zone**	**Above UCT**
	Additional heat generation mechanisms, such as shivering and non-shivering thermogenesis	Autonomic – e.g. hair fluffing through pilomotor control Behavioural – e.g. postural changes to decrease exposed surface areas Adaptive – e.g. increased lipid deposition	Autonomic – e.g. limited heterothermy, radiative cooling, Behavioural – e.g. postural changes to increase exposed surface area Adaptive – e.g. large membranous and vascularised ears	Additional heat dissipation through evaporative cooling - sweating, panting

Table 3.2 – examples of thermal management mechanisms for Ectotherms, heterotherms and endotherms

Thermal management mechanisms in current engineered structures utilise similar mechanisms, such as the use of large surface areas through which hot fluids pass (radiators) mimicking the action of animals that use extensively vascularised large membranes such as the ears of the Desert fox. Insulation of areas where heat retention is required is achieved through the use of materials with a low thermal conductance, similar to fat deposition. These mechanisms, simple in concept, are well defined and used in many engineering fields.

In terms of biomimetic thermal management processes, the approach will be to mimic some of the more subtle aspects of thermal management in animals. Such examples of more complex thermal management concepts could include mimicry of counter current heat exchange, whereby heat exchange occurs between arteries transporting blood from the high temperature core of an animal to colder extremities, and veins transporting colder blood back towards the warmer central region from the extremity. The arteries and veins are positioned close to each other, thus allowing arterial blood to be cooled before reaching the extremity, thus minimising heat loss through the surface of the extremity.

3.2.3 Fabrication

A fundamental reason why nature is able to produce such complex composite materials is that it constructs them from the bottom-up. Growth and construction of natural materials occurs at a cellular level and can be divided into two types (both of which are driven by living cells) – **type 1.** Growth of living biological materials (cellular growth and division) and **type 2.** Construction of inert 'dead' biological materials (e.g. Abalone shell) whereby material is deposited. Growth of living cellular materials (for example muscle) occurs through a complicated process of cellular *morphogenesis*, which is effected through *hyperplasia*, *hypertrophy* and *apoptosis* (cellular division, enlargement and death respectively). In the case of construction of inert biological materials, deposition and absorption of the material is carried out by specialist cells (for example the osteoblast and osteoclast cells which deposit and absorb bone). The incredibly complexity of this 'manufacturing' process can be appreciated when considering the growth and transformation of a fully formed human, composed of muscle, tissues, organs, a nervous system and skeleton, from the initial single cell egg.

Traditionally, engineered materials are synthesised through a combination of approaches such as melting, solidification, heat treatment, mixing etc. These techniques are in contrast to the promise of nano-scale fabrication, where materials are constructed from the bottom up. Fabrication of such materials at a molecular level is possible using molecular engineering means - Such attempts at biomimetic fabrication at a molecular, nano and micro-scopic level have to date largely focused around biomineralization (type 2 deposition of material). Many microorganisms are capable of synthesising inorganic-based structures. For example, diatoms use amorphous silica as a structural material, bacteria synthesise magnetite particles and form silver nanoparticles, and yeast cells synthesise cadmium sulphide nanoparticles [Naik et al., 2002]. Generally, biomineralization occurs by the precipitation of inorganic crystalline or amorphous materials [Calvert, 1994a] (the specific mechanisms are different for different mineralised composites such as coral, shell and bone). In coral for example, the precipitation occurs outside the organism but with manipulation of solute concentrations near to the organism surface as well as possible provision of a nucleating site. By contrast, in bone the precipitation occurs into an organic matrix, which controls the form of the precipitate and can guide the structure of the mineralisation [Calvert, 1994b].

More fundamentally, proteins, and their specific interactions with inorganic materials affect this type of precipitation of inorganic materials. Proteins are fundamentally important in biological structures and systems; proteins are responsible for transport of raw materials, and are routinely capable of self and co-assembly of a hugely varied range of complex structures.

Under genetic control, living and inert biological materials as widely varying as muscle tissue, abalone shell, enamel etc. are constructed by biological macromolecules (principally proteins but also other types of macromolecule such as lipids) in a highly organised and hierarchical manner (see figure 3.1 for an example). The focus on research now is on the potential to use the recognition properties of proteins such that polypeptides could be used as binding agents to control the organisation and fabrication of desirable inorganic materials at a molecular level. This type of fabrication would require genetically engineered proteins, to ensure complete control over the molecular structure of the protein template. Because of the limitations of current knowledge with regards to protein folding characteristics, the approach suggested by [Sarikaya et al., 2003] is to use combinatorial biology protocols (such as those used in the screening for ligands – molecules that bind to other molecules – principally Phage Display and Cell-Surface Display technologies).

4 BEHAVIOUR AND CONTROL (6300)

4.1 BEHAVIOUR

With the appearance of *metazoa*, some means of coordinating the action of the many component cells of an organism became necessary. In the plant kingdom, the sole means of control and coordination that has developed is the *endocrine* system; hormones such as *auxin* direct growth, induce stomata opening and closure, and regulate seasonal mechanisms such as ripening. Within animals, the *endocrine* system is also vitally important in maintaining and regulating physiological function. The *endocrine* system regulates growth, sexual development, pregnancy, lactation, many other physiological mechanisms, and is vital in the maintenance of *homeostasis*. Hormones are a non-uniform group of chemicals that include *proteins*, *steroids*, *amino acid* derivatives and *peptides* that have specific actions on target organs and cell groups within the body.

However, in addition to the *endocrine* system, animals also possess another coordinating and controlling mechanism, the *central nervous system* (CNS). The CNS is responsible for the gathering, processing, and transmission of information within the body. The CNS gathers information from sensory organs, which are populated by specialised *receptor neurons* (see section 5.1). This information passes through the CNS in the form of electrical impulses, and a response is transmitted to specialised *effector neurons* that reside in muscle tissue.

The simplest type of *neural network* is the monosynaptic *reflex arc* (responsible for the stretch reflex in vertebrates). This is composed of a single *receptor cell* connected to a *single effector* cell. Increasing complexity during evolution has led to *interneurons* mediating between afferent *receptor* pathways and efferent *effector* pathways, increasing the ability of an animal to learn to form associations between different stimuli and form increasingly complex patterns of behaviour. The mediating body of neuronal clusters between receptor and effector cells are what have allowed complex behaviours to develop; initial evolution of nervous systems led to the formation of *ganglia* – clusters of neurons around a tangle of nerve fibres termed a *neurophil*, a mode of organisation that allows extensive connectivity between the neuron cluster. This in turn led to the development of series connection of segmental ganglia into ventral nerve cords of *annelids* and *arthropods*, and the formation of ‘*superganglia*’, which were formed from several ventral ganglia, and exert some degree of control over the rest of the segmental ganglia. These superganglia are more commonly known as brains.

Several types of neural circuitry have been identified within the CNS of various animals. There are a number of identified reflex responses (such as the stretch reflex – see above). Sensory filtering networks, and *Central Pattern Generators* (see section 4.2.2) for generating rhythmic movements. Much of the neural circuitry is fixed and innate, and termed *instinctive* (animals at all phylonetic levels are born with behavioural patterns that are expressed immediately, such as respiration). Whilst instinctive behaviour is present across all phylonetic levels, it is more prevalent in lower life forms. Generally, more complex higher order animals possess an increased ability to exhibit learning due to the increased complexity of the CNS that mediates between receptors and effectors. Learning is mediated by neuroplasticity (see section 4.1.1.2).

Whilst it is known that the physical substrate upon which behaviour is based is the central nervous system (and to a lesser extent the *endocrine* system), the enormous complexity of the CNS means that it is only poorly understood (refer to [Eckert, 1988] for a general introduction to CNS structure and function), and it is not currently possible to relate higher level behaviours to specific CNS events. Therefore the study of higher-level behaviour in animals (behavioural psychology) is a discipline, which does not concern itself with the neuronal substrate.

This is the application of biological principles of behaviour to the control of robotic systems, which may or may not contain biomimetic elements in their mechanical design (for example animal behaviour algorithms could be used to control simple wheeled robots with no biomimetic component in their physical design). Reproducing elements of the behaviour of biological systems has a long history, from the classic pursuit of artificial intelligence with reasoning and abstraction capabilities that mirror those of the human brain, through to the formulation and implementation of behavioural patterns of simple purely reactive animals such as ants. Artificial Intelligence can be broadly broken down into the following two main categories:

- Classical AI
- Behavioural AI

4.1.1 Classical Artificial Intelligence (‘top-down’ AI)

Classical AI aims to reproduce the thinking patterns and capabilities of abstract reasoning found in humans. This involves such abilities as abstraction, formal logical reasoning and other higher-order thinking processes that are traditionally associated with large brained animals such as us. The belief behind the classical AI approach is that intelligent, purposeful behaviour is the result of abstract thinking processes that are somewhat removed from the physical and biological substrate upon which they function (i.e. there is no consideration of the structure of the brain, just the logical thinking that sits on top). This essentially dualistic view of intelligence is also referred to as *Cognitivism*. In particular, the *Physical Symbol System Hypothesis* [Newell & Simon, 1974] posits that the essence of intelligence is rule-based manipulation of abstract symbolic representations. Thus classical AI systems are based around the manipulation of symbols according to the rules of formal logic, a process that occurs on a computational substrate, but with no consideration of the structure of the substrate.

The utilisation of high-level decision-making capability is still thought by many to be essential to the achievement of autonomy, particularly goal-directed autonomy [Antsaklis, 1991]. Use of some form of internal model of external reality is therefore thought to be required, in order to allow internal simulation and prediction of the environment and hence the formulation of decisions. This leads to the concept of *plan generation,* [Estlin et al., 2000], [Vendrell et al., 2001], whereby sequences of commands to the agent’s actuators are formulated based on the decided-upon actions. Plan generation can be regarded as a form of self-programming [Ellery, 2000] and can be considered a state space search for solutions to problems defined by the internal model (symbolically-based) of the environment. State-space searches of possible actions will thus involve manipulation of the world-defining symbol set according to formal rules, leading to the generation of decision trees of possible actions. This is the brute force ‘search and evaluation’ method used for example by chess playing algorithms, and quickly leads to large computational loads; thus the intelligence of the system quickly becomes a function of the computational speed and memory capacity of the agent (take for example the chess agent ‘Deep Blue’. During it’s match with Kasparov, which it won, Deep Blue was examining roughly 60 billion tree nodes per move; this is in comparison to the at most few dozen nodes examined by a human player [Biermann, 1978]). Indeed it has been argued that this type of approach to artificial intelligence, based around brute computational speed (obviously far faster than the speed of symbolic thought in the human brain as illustrated by the famous chess match mentioned above) was largely brought about by early successes themselves made possible by the rapid advances in processor and memory technology in the computer industry, rather than any sound basis in theory [Brooks, 1990]. Indeed, it has been freely admitted that the game-tree search techniques used by such systems work quite differently from how humans think about such games [Smith et al., 1998].

As a result of the exponentially increasing nature of the search-space involved with ‘brute-force’ intelligence, classical AI then experienced a shift from power-based computational inference to knowledge-rich strategies involving heuristics, in order to constrain the search space, and hence reduce the computational requirement. This is based upon the *Knowledge Principle*, which states that simple search, and reasoning ability is insufficient for intelligence; some measure of knowledge of the environment is also required, representing the agents learning history. For example human thought is predominantly knowledge rather than syllogism driven, and mental models are context dependent with knowledge providing the central utility in high-level cognition. Thus a system, which employs a few simple inferences, rules combined with a large body of conceptual knowledge can be very powerful due to the high number of ways the knowledge and rule can be combined.

An implementation of the *knowledge principle* is found in the expert system, an algorithm which mimics the decision making process of a human expert. This involves the use of a very large knowledge base (differing from a database in that the knowledge is stored in the higher form of symbolic data sets), which acts as the agent’s view of the world; this can be considered as the long-term memory of the agent. Information from the real world can be considered as the short-term memory of the agent. The agent matches the short-term memory against the long-term memory, and uses rules of inference and heuristic control procedures; the inference engine then interprets the state of the working memory and applies formal logic to formulate decisions. Expert systems have been demonstrated to perform at a similar level to human agents [Hayes-Roth, 1984], but only within very narrowly defined situations, where the expert system has a full appreciation of the nuances of any problem it may face. When a problem is positioned even slightly outside the expert system’s ‘area of expertise’, serious problems emerge.

4.1.2 Behavioural AI (‘bottom-up’ AI)

Whilst classical AI has been reasonably successful in areas such as theorem proving, AI systems based on logical inference have generally been unsuccessful in promoting the levels of decision-making, pattern recognition, robustness etc. exhibited throughout the animal kingdom. For a rigidly defined problem, subject to clear rules with no noise, such as a game of chess, a formal game-search method relying on brute force can be successful. However, in a constantly changing environment that is noisy and unpredictable, the symbolic reasoning approach to autonomy, planning techniques, internal models and so forth are largely inadequate; the situation can be thought of as an agent in the path of an oncoming car, who is so busy modelling the environment, formulating decision-trees and so forth, that the car has long since run him over before any action is taken. Because of this shortcoming, the incorporation of reflexive behaviour was adopted. This is the *Animat* approach to autonomous control of robots, which focuses on the complete system, and the fact that much adaptive behaviour in the animal world *does not* involve symbolic reasoning.

'Top-down' classical AI was attacked during the 1980s for these principal reasons. As a consequence of this rethink, intelligence has become increasingly viewed not as some internal abstraction, but as the capacity of an agent to directly interact with their environment through direct coupling between the agents sensors and their behaviours, leading to the situation where the agent becomes purely reactive, rather than using abstraction to decide on a response to a particular stimulus. Brooks suggests the *Physical Grounding Hypothesis* [Brooks, 1990], which states that the internal model should be discarded, and a direct link maintained between perception and action, without the intervening use of an inference engine and/or internal model of the environment. This leads to the principle of *situatedness*. This is also termed *statelessness or externalisation* [Brooks, 1991]. This is the design philosophy whereby the autonomous agent externalises as much information as possible – the environment is considered to be it's own best model, rather than constructing an internal model.

Behavioural 'bottom-up' AI is centred on autonomous agents, which exhibit animal-like behaviours, i.e. some degree of life-like behaviour. However, in addition to behaviour at the level of the individual animal, behavioural AI also includes intelligent behaviour as a result of adaptation at the group level. Behavioural AI can be broadly categorised into *Engineering Approaches* (section 4.1.2.1), which include basis behaviours and subsumption architectures and *Learning Approaches* (section 4.1.2.2) that include elements of agent-learning (the most important here are Connectionist/ANN learning and Evolutionary learning techniques).

4.1.2.1 Engineering approaches

In terms of implementation, an engineering approach to behavioural intelligence and autonomy involves pre-programming the behaviours of the agent, typically by decomposing a particular problem into less-complex sub-problems This leads to a modularisation of the internal control mechanism (termed by Brooks a '*subsumption*' architecture), down to the level of individual basis behaviours. The subsumption architecture involves placing control modules in parallel, in layers of increasing priority. All layers have access to the sensors and actuators (figure 4.2). Essentially a task-decomposition approach is taken rather than the function-decomposition of classical AI systems.

Basis behaviours can be defined as fundamental building block behaviours that form the basis of more complex emergent behavioural mechanisms. Selecting and evaluating basis behaviours is nevertheless still something of a black art, since agent behaviour is defined by interactions with the environment and not all possible situations that the agent may encounter can be known beforehand, and hence neither can agent response. Lack of care in behaviour definition can lead to problems such as stagnation and cyclic behaviour. Despite this, general criteria for basis behaviour selection at a qualitative level can be established, and include simplicity, locality, correctness, stability, repeatability, robustness and scalability [Parunak, 1997]. *Basis behaviours* can be defined as fundamental building block behaviours that form the basis of more complex *emergent* behavioural mechanisms. The simplest implementation of *basis behaviours* is direct mapping of one stimulus to one particular behaviour. However, in order to achieve more complex behaviour patterns, *basis behaviours* are normally hierarchically organised in a subsumption architecture using priorities and subsumption relations between the behaviours.

There exists a growing body of literature regarding the formulation of basis behaviours, attempting to apply a greater degree of formalism to their selection and combination. For example, [Iske & Ruckert, 2001] propose a methodology for behaviour design based around a tree structure that incorporates a method for estimating the resource requirements of component behaviours. [Martens & Paranjape, 2002] stress the importance of consideration of the environment when designing basis behaviours. [Mali & Mukerjee, 1998] formulate a system of metrics for evaluating basis behaviour effectiveness, through the use of the notational system employed in [Mali, 1998]. Novel metrics are introduced (power, flexibility etc.) which are then used to investigate the properties of behaviour spaces.

4.1.2.2 Learning Approaches

Acquiring new behaviours or adapting existing ones is obviously crucial for an organism in a dynamic environment. Genetically based and unalterable behaviours (for example Central Pattern Generators – see section 4.2.2) are present to a degree in all phyla, and can be viewed as a predictive ‘bet’ by the species about the nature of the neuronal mechanisms required for success in the environment. However, refining behaviour through learning ‘on the job’ is crucial to the success of higher order animals, which have consequently developed much more complex mediary neural structures between sensor and effector neurons. For example, the topology of the primate brain has been proven to be too complex to be fully described in the genome; it is established by synaptic firing in utero and the first decade of life [Vander et al., 1980].

At the level of behavioural psychology, learning can be broadly divided into two types: associative and non-associative learning. Associative learning is classically represented by Pavlov’s dogs [LeFrancois, 2000] and is characterised by formation of a relationship between two temporally related stimuli. Nonassociative learning involves a response increase (*sensitisation*) or decrease (*habituation*) to a repeated stimulus. More fundamentally, the biological mechanism by which learning is affected is at the neuronal level. N*europlasticity* allows an organism to learn by altering the connectivity between individual *neurons* and *ganglia*. According to Hebb’s rule, when two interconnected neurons fire together repeatedly, the strength of their connecting synapse is increased. Learning is therefore the result of repeated stimulus of patterns of neurons such that their interconnections increase in strength and durability.

Biomimetic learning can be considered a subset of the field of machine learning. Machine learning is concerned with imparting the ability to a machine to alter it’s own structure and programming in order to better fulfil it’s function, and as such is intimately coupled to efforts in artificial intelligence. Machine Learning as a discipline encompasses a large array of techniques based on statistics, adaptive control theory, decision trees and more. All of these can be considered biomimetic insofar that they all attempt to recreate the mechanism of learning; however, from the point of view of biomimetics, we are only concerned here with those that attempt to recreate some biological process in their actual design. Biomimetic learning paradigms can be defined as:

- ANN/Connectionist
- Evolutionary Algorithms
- Artificial Intelligence
- Psychological/Behavioural

ANN (*Artificial Neural Network*) learning (also called *connectionist* or *sub-symbolic processing*) is in the main based around a number of interconnected processing elements that are to a greater or lesser degree based in function on the *neuron* (see figure 4.3). The Neuron is composed of a *soma* (the body of the cell containing the nucleus) and projections from it – dendrites (inputs) radiating directly from the soma, and the *axon* (outputs), projecting from the soma at the *axon hillock*, which ends in one or more *terminal buttons* that are connected to other neurons. By comparison, the artificial neuron (figure 4.4) is a simple structure based around a number of weighted inputs (analogous to the dendrites) that are summed in the soma, which then produces an output that is passed along weighted connections to other neurons.

There are many different ways in which the neurons can be combined into a *neural net*. The simplest form of ANN topology is the single layer *Perceptron*. However, more complex levels of interaction between neurons are now well established such as multi-layer NNs, Elmann NNs, competitive NNs and others [Boutsinas & Vrahitas, 2001].

ANNs learn by changing the weighting functions associated with each individual neuronal element (w_1, w_2 and w_3 in figure 4.4) according to a learning algorithm such as backwards error propagation (a 'supervised' learning algorithm) or competitive learning (an 'unsupervised' algorithm). Learning mechanisms that rely on adjustment of connection weighting obviously have the disadvantage that the topology of the ANN is fixed, and may well be unsuitable for the particular behaviour or learning required. Therefore, topology-alteration has been adopted into ANN design to allow the actual structure of the ANN to be tailored to the specific problem. There are two existing strategies that have been employed in this regard: Evolutionary design of ANN topologies through evaluation and breeding, and *ontogenic* topology alteration (employing evolutionary algorithms – see section 6.2), whereby *growth* and *pruning* mechanisms are employed to modify the ANN topology.

Evolutionary Algorithms are a principle technique used in learning algorithms. They are used as a complementary tool within other learning techniques, for example as a means of generating new rules in learning classifier systems, and optimising ANN topologies.

Classical AI learning is based around using high-level symbolic constructs that humans employ whilst learning, rather than modelling any type of structural changes that may occur in the nervous system during learning, as is the case with ANN learning. Examples of Classical AI learning include the use of analogy in learning, basing future actions on previous exemplary cases, discovering rules for expert systems based on decision tree methods, and inductive logic programming [Nilsson, 1996].

4.1.3 Hierarchical Architectures

The principles behind basis behaviours have important consequences for the architecture of the autonomous system. Although reactive intelligence is a central tenet of the behavioural approach to AI, behavioural architectures do not preclude systems with internal states, and proactive behavioural elements can be placed within a *subsumption* architecture to endow purposeful behaviour. Despite this ability for goals to be integrated within a *subsumption* architecture, a long list of hybrid systems have been investigated, whereby a reactive behavioural layer of control is placed below a classical AI ‘planner’ layer that formulates decisions and instigates goal-driven behaviours (for a discussion of integrating high-level planning with lower-level reactive behaviours, see [Payton et al., 1990]). This hybridisation of control typically involves a trade-off between goal-directed and reactive behaviours, which can be considered, in implementation terms, as orthogonal to each other.

However [Mali, 1998] has shown, in keeping with [Brooks, 1991], that goal-achieving behaviour can be incorporated into a behavioural system, allowing reactive and goal-fulfilling behaviours to be encapsulated within the same architecture. Using a specially developed notation, he investigates the constraints involved, and concludes that incorporating increasingly complex goals increases the requirement for coupling between behaviours, and attempting to eliminate this coupling will increase the number of required behavioural modules. He does however optimistically conclude that despite these constraints, there exists a rich space of possible behaviour-based architectures that allow highly directed behaviour to emerge.

4.1.4 Multi-Agent Systems and Distributed Artificial Intelligence

For many years, group behaviour in robotic systems was centralised, with global planning and decision. This was a reflection of the belief that in order to obtain global level intelligence, the intelligence must be engineered at a global level. However, there are serious problems with centralised multi-agent control. For example, exponential growth of the state space with the addition of agents makes on-line global planning prohibitive and intractable, since the state of each agent needs to be modelled and tracked.

In the mid 1940s, Grey Walter and Wiener studied turtle-like robots equipped with light and touch sensors and very simple behaviours. When placed together, these robots exhibited complex social behaviour in response to each other’s movements [Cao et al., 1997]. Early examples like this suggested that complexity at a group level might be achievable with even very simple individual agents, with no need for central control. From this idea comes the concept of *Group* intelligence, or Distributed Artificial Intelligence. Distributed Artificial Intelligence can be defined thus [Weiss, 1999].

…DAI is the study, construction, and application of multiagent systems, that is, systems in which several interacting, intelligent agents pursue some set of goals or perform some set of tasks.

As a consequence of swarm intelligence, decentralisation is now the current dominant paradigm in group robotics and agent scenarios, and DAI is used not only in the construction of intelligence, distributed systems for a variety of applications, but also in the study of complex natural multiagent systems, including human societies [Axelrod, 1997]. The behaviour of a decentralised system is often described using terms such as *emergence* and *self-organisation*. Decentralised architectures have inherent advantages compared to centralised architectures, which include:

- Fault tolerance
- Natural parallelism
- Reliability
- Scalability
- Much larger possible behaviour space

Existing architectures based on the swarm concept include CEBOT, ACTRESS, SWARM, GOFER, and ALLIANCE [Cao et al., 1997].

Centralised Approaches		Decentralised Approaches
Optimisable globally		Optimise locally
Scale poorly		Scale well
Require global sensing and communications		Local sensing and no communications required
Computational bottlenecks		No computational bottlenecks
Hierarchical control		Use flat control
Not usually redundant		Redundant

Table 4.1 – summarised differences between centralised and decentralised approaches to group behaviour

4.1.4.1 Behavioural 'Swarm' Intelligence

Swarm intelligence can be defined as the exhibition of collective intelligence by groups of simple agents [Bonabeau et al., 1999]. The Swarm Intelligence approach argues that there may exist an alternative approach to problem solving that operates at a level above our traditional problem solving processes. That is, problem solving can occur at a level above a collection of idealized agents, without intentional "problem solving" on the part of the individual. In other words, the individual agents do not know they are solving a problem, but their collective interactions do solve the problem. This hypothesised emergent intelligence can be ascribed to ant colonies and other eusocial creatures, where individuals can be said to exist for the benefit of the group as a whole [Fong et al., 2003]. However, emergent intelligence obviously operates within what can be termed individualistic (society for the benefit of individual) human society, in the case of large scale and complex engineering projects for example, where no one person has the required intelligence or knowledge to realise the project.

Central to swarm intelligence is the concept of *stigmergy*, whereby two agents interact indirectly when one of them modifies the environment and the other responds to the new environment at a later time. In other words, agents have an effect on their environment through their simple behaviour, which acts as a behaviour-determining signal to other nearby agents. Swarm behaviour is characterised by:

- No centralised control
- No internal model of the environment
- Environmental perception
- Ability to change environment

Because of the absence of internal models, the application of swarm intelligence is closely related to *basis behaviours* and the paradigms introduced by Brooks and others of *situatedness* and *statelessness* (see section 4,1,2). Behaviour in social insects is thought to be a stored programme that is prompted by specific sensory stimuli, i.e. the coupling between sensors and stimuli is direct, with no mediation by an internal model of the world. Very simple basis behaviours of identical individuals, when combined into a group, can exhibit a very high degree of group-level complexity and problem solving ability. Examples of basis behaviours in group situations leading to global problem solving are shown in figure 4.6.

The cooperative behaviour between agents is not restricted to indirect communication through environmental change; direct communication can and does also take place (e.g. the waggle dance of the honeybee). However, the central concept of *stigmergy* is that, particularly in homogenous groups, a significant amount of information about an individual's goal can be inferred from observable state and behaviour, with no explicit communication required. In addition, homogeneity within the group means no requirement for designations (again encompassing *statelessness*), further simplifying the interactions between group members. However, there can be problems associated with swarm intelligence. The absence of an internal memory of individual agents can lead to stagnation and cyclic behaviour (a fundamental problem with behavioural AI-based systems). Honeybees (*Apis mellifera*) for example exhibit disarray when building honeycomb; workers, in search of pieces of wax for cell construction, often rip down walls their colleagues are building. This can not be considered to be optimal behaviour; nevertheless swarm intelligence leads to pragmatic, effective solutions that do work and which are, more importantly, very robust when faced with a dynamic environment.

4.1.4.2 Distributed Artificial Intelligence

Distributed Artificial Intelligence in the context of this study is the application of mulitagent systems where individual agents are driven by classical AI algorithms. As such, symbol manipulation, rather than simple reactive behavioural control, as is the case with Swarm intelligence.

Broadly speaking, both classical AI and DAI deal with computational, symbolic manipulation aspects of intelligence, but from different starting assumptions; Classical AI concentrates on stand alone agents, whereas DAI concentrates on agents within an intelligent and interconnected system; thus whereas classical AI focuses on cognitive processes within individual agents, DAI focuses not just cognition within an individual agent but also social processes that occur between agents. Because of this, DAI finds considerable application in social sciences and economics, where such branches as rational choice theory are developed to help explain economic behaviour of rational economic agents.

DAI shares many of the characteristics of swarm intelligence, such as emergent properties and so forth. However, whereas the focus in swarm intelligence is on minimal or no communication, and stigmergic interaction mechanisms, in DAI explicit communication between agents plays a much larger role. DAI involves all the classical AI paradigms such as planning etc.

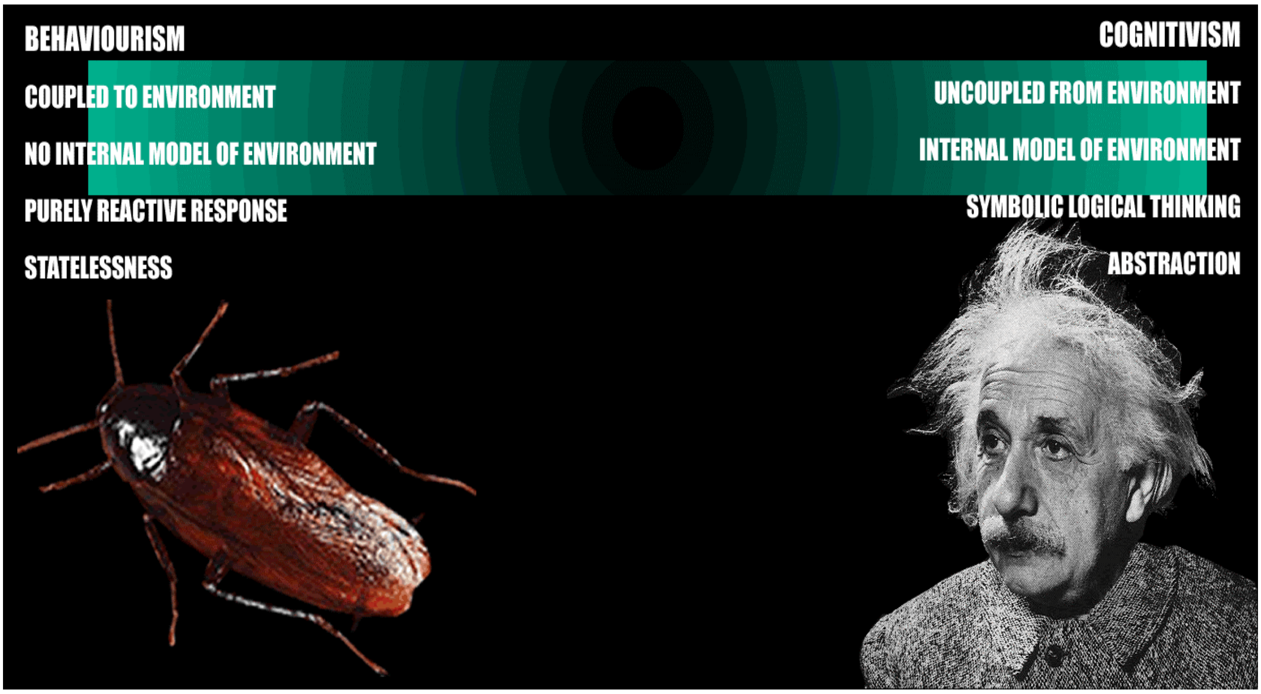

Figure 4.1 – Einstein versus the roach: the two extreme views of intelligence

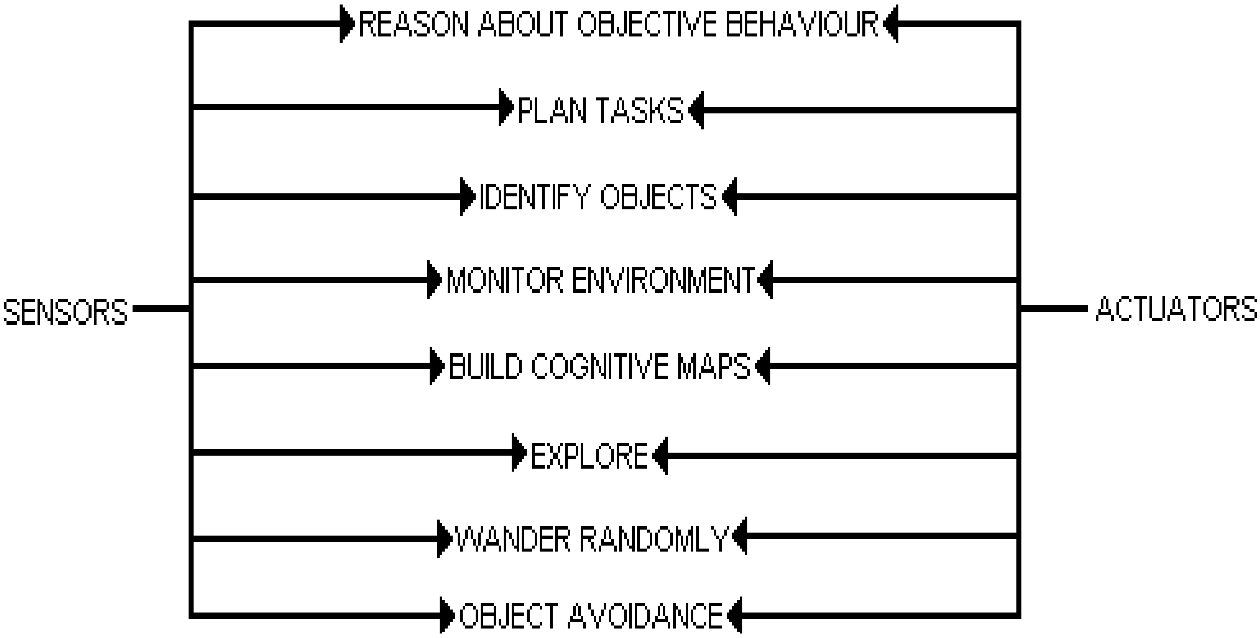

Figure 4.2 – subsumption architecture task decomposition (adapted from [Brooks, 1986])

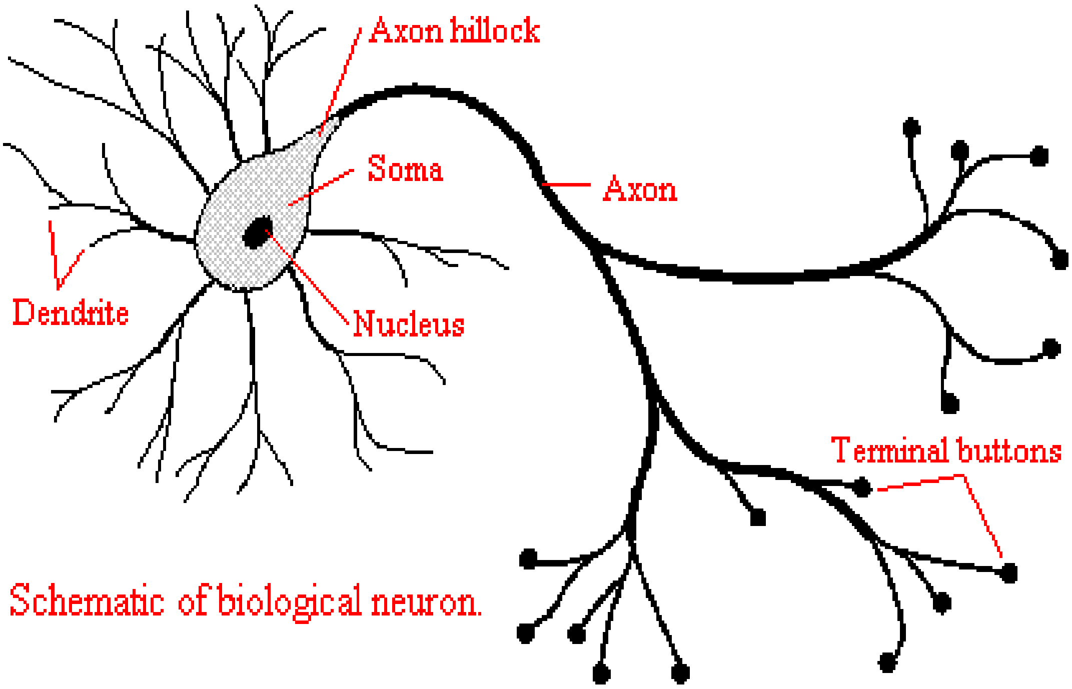

Figure 4.3 – the basic structure of a neuron

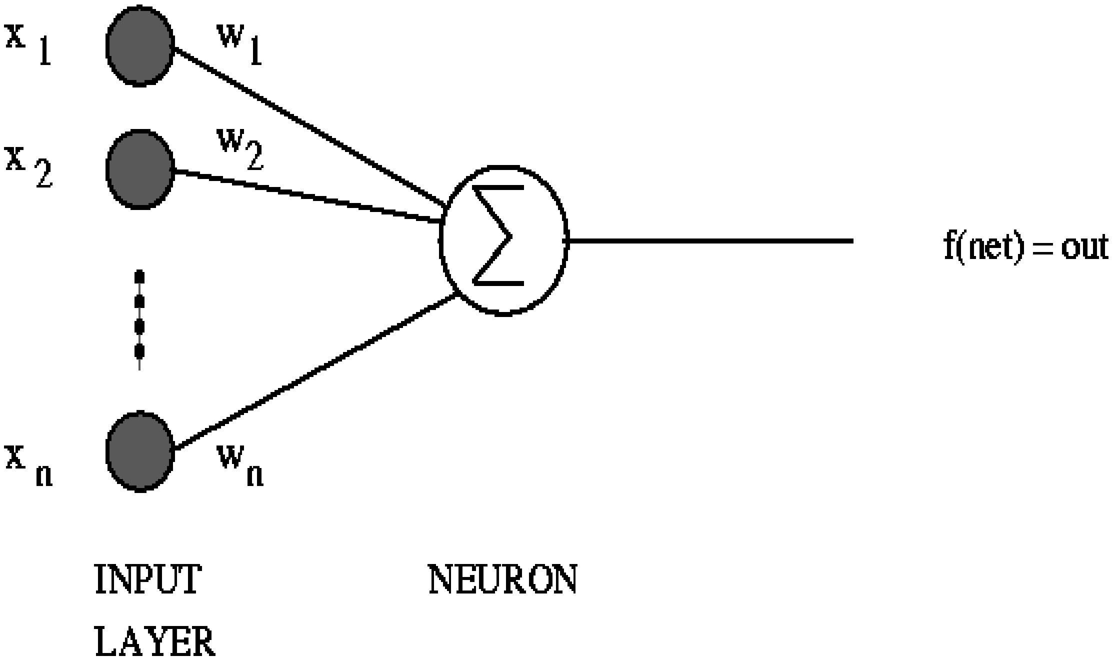

Figure 4.4 – the structure of an artificial Neuron

Figure 4.5 – a termite mound in Australia. The central pillar is over 3 metres in height.

Ants: Path planning

1. *Avoid obstacles*
2. *Wander randomly (with a weighting towards pheromone trails)*
3. *If holding food, drop a pheromone trail§*
4. *Find food (if not carrying) and pick it up*
5. *If find nest, drop food*

Termites: nest building

1. *Metabolise bodily waste*
2. *Wander randomly, with preference towards strongest local pheromone concentration§*
3. *At each time step, decide stochastically whether to drop the current load of waste (probability dependent on local pheromone density and amount of waste being carried)*

Birds and fish: flocking and shoaling

1. *Maintain specified minimum distance from nearest object or bird*
2. *Match velocity to nearby birds*
3. *Stay close to the centre of the flock*

Figure 4.6 – example lists of three simple sets of basis behaviours that lead to ant path planning and food collection, termite nest building and flocking [taken from Parunak, 1997] § pheromone trails are temporally degraded

4.2 CONTROL

Whilst a clear difference between behaviour and control is difficult to define (especially from a physiological perspective), behaviour can be simply defined as the decisions taken by an animal (such as which prey to chase, when to sleep etc.), whilst control can be defined as the actuation of behavioural decisions, such as the motion of the legs during an attempt to catch prey. The CNS, and physiological structures such as the reflex arc affect control in the natural world. Control within the context of this study can be taken to refer to the innate or learned mechanisms (based on lower-level neuronal structures) that directly underpin basic physiological functions of movement such as walking, running, flight and so forth. Two distinct schemes exist in animal control literature:

- Reflex driven control (environment-dependent)
- Central pattern generator (environment-independent).

Reflex-driven control includes all reflexive responses to stimuli. These range from simple myotatic reflexes, to more complex reflexive control systems such as taxis (homing) behaviours. Of particular interest is the neuronal processing of sensory information, and modelling of the intermediate neuronal structure between sensor and effector neurons that allows control mechanisms such as obstacle avoidance, phonotaxis and escape reflexes to occur. As such, investigation of environmentally driven control is closely linked to the study of biomimetic sensors (section 5.1). Environmentally independent neuronal control structures are those that produce rhythmic, patterned behaviour; for example, breathing in humans is a rhythmic behaviour that is largely controlled by central pattern generators located in the medullary respitory centres. Rhythmic control includes neuronal structures for walking, flapping etc.

These two concepts, from an engineering perspective, can be considered roughly analogous to feed forward (open-loop) control and feedback (closed-loop) control [Klavins, 2002]. Investigation of these control structures within the natural world is the field of neuroethology and neuroscience. In both cases, the fields of neuroscience/neuroethology and biomimetic robotics are highly complementary to each other. Neuroethological knowledge of the structure of neuronal control circuits provides templates as to the form of the neurophysiology of an animal. This then allows robotic representations of the animal to be built, and the relevant neural structure can be investigated in a real world environment, generating insights not only into neuroethology, but also into biomimetic robotic engineering [Webb, 2002].

In general, neural control circuits from invertebrates are chosen as models for replication in a robotic setting. There are a number of reasons why invertebrates are used: invertebrate control mechanisms and behaviours tend to be more stereotyped (i.e. more predictable – stereotyped behaviours can be considered highly instinctive) so the underlying neuronal substrate is consistent across multiple test subjects and thus easier to analyse; additionally, the number of (inter)neurons between sensor neurons and effector neurons is orders of magnitude less than for vertebrates, simplifying comprehension.

The incomplete nature of our knowledge concerning the function of biological systems is apparent here, and has consequences for the direction biomimetic design should take (for a good discussion of low-level motor control in legged vertebrates that nicely summarises the current thinking, see [Giszter, 2002]).

4.2.1 Reflexive and Environmentally driven Control

The simplest types of control movements are reflexes, which are involuntary. There are several defined types of reflex, of which the *Myotatic Reflex* is the simplest type in vertebrates, dependent upon two types of neuron – a sensory fibre and a motoneuron. A familiar example of the *Myotatic Reflex* exists in the form of the knee jerk evoked by tapping with a hammer. Reflexive control obviously is obviously important in fast-response actions such as withdrawing a limb from danger, but reflexive control also has the ability to coordinate limb motion in a fashion that produces directed, locomotive behaviour, by employing *proprioreceptors* (see section 5.1.3) in the limbs that trigger reactive movement upon certain a certain stimulation. For example, work on a locomotory control model for a stick insect (*Carausius morosus*) [Cruse, 1990] proposes a completely decentralised control architecture that utilises reactive control based on local sensing (with no communication between sensors at a global level) which results in (apparently) coordinated locomotion. Beyond simple reflexes, more complex control responses to environmental stimuli include such mechanisms as object avoidance, various types of taxis behaviours and so forth. Several of the neuronal circuits that underpin these types of control have been well investigated in several invertebrates, and this has provided the inspiration for the construction of biomimetic robots.

Lobster chemotaxis to guide orientation-related behaviour in the sea [Grasso, 2002]. Work into biomimetic reproduction of control using reflex driven methods also includes work on the Sahabot, which has copied the navigation capabilities of the Saharan desert ant (*Cataglyphis*), which detects polarised light. Cricket phonotaxis [Webb & Harrison, 2002]. Fly visual behaviour, in particular the optomotor response (the use of visual motion information to estimate self-rotation and actuate a compensatory torque response to maintain stability during flight [Harrison, 2002].

4.2.2 Rhythmic Movement and Central pattern generators

Rhythmic motor patterns comprise a large part of the suite of mechanisms that contribute towards the control of an animal. They are complex (unlike reflexes) and repetitive, and are caused by central pattern generators [Wilson, 1961]. Central pattern generators are neuronal groups that produce rhythmic patterned output without rhythmic sensory or central input, and are responsible for most instances of rhythmic movement found in nature, such as wing flapping, walking and breathing. Central to CPGs is the half-centre oscillator, a pair of neurons that are reciprocally coupled (firing one inhibits the other) to produce rhythmicity.

Looking to figure 4.7, which shows a very simple representation of a CPG. The reciprocally coupled neurons are labelled 1 and 2. Neuron 1 is excited by a sensory neuron, and this excitation causes neuron 1 to, after a delay, excite neuron 2 that produces an output, but also has an inhibitory effect on neuron 1, causing it to stop firing. Once the inhibition of neuron 1 has stopped, the sensory input refires neuron 1 and the process is repeated. This leads to a rhythmic output to the effector neuron.

CPGs exist in the spine in vertebrates, therefore allowing spinal trauma victims to regain motor function through intense treadmill exercise. Recently it was found that it is possible to regain some locomotor activity in patients suffering from an incomplete spinal cord injury (SCI) through intense training on a treadmill. The ideas behind this approach owe much to insights that humans may have a central pattern generator for locomotion located at spinal level [Duysens et al., 1999]. Biomimetic CPGs have been used in several research projects in order to provide repetitive actuation to control locomotion. Examples include the Robotuna project [Barrett, 2002], and autonomous control of hexapod walking [Cruse et al., 2002].

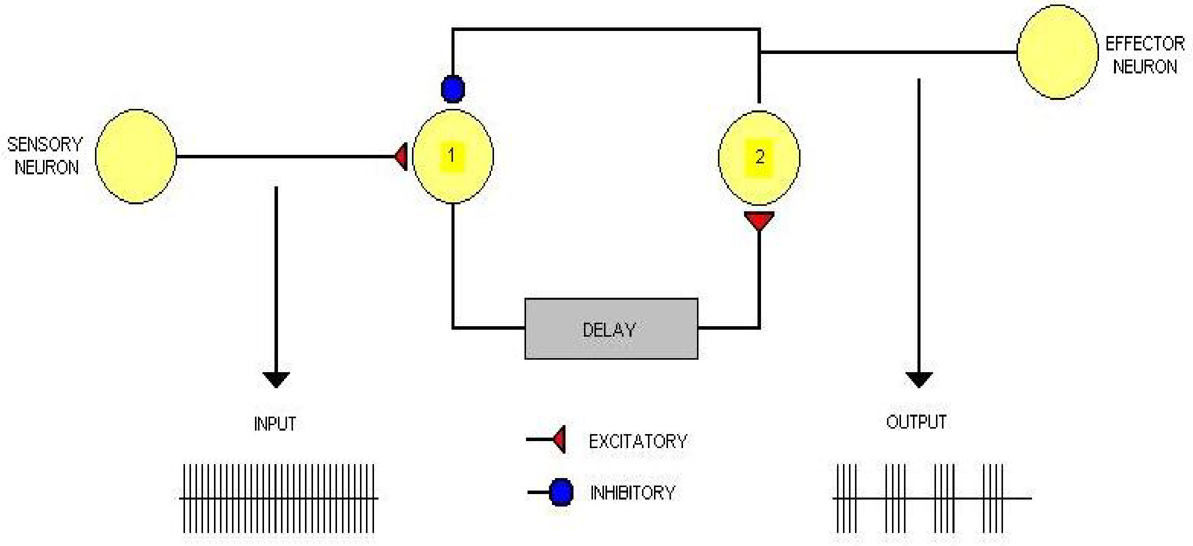

Figure 4.7 – schematic of a central pattern generator

5 SENSORS AND COMMUNICATION (6400)

5.1 SENSORS

In order to survive and function effectively, all life forms across all phyla employ sensory mechanisms to collect information about their environment. Plants employ a mechanism (*phototropism*), whereby photoreceptors are used to sense the direction of the sunlight, actuating a growth response through the release of the hormone *Auxin* that promotes cell elongation, turning the leaves of the plant towards the sun. A similar mechanism (*geotropism*) exists for the perception of gravity, and again leads to a hormone-mediated growth response.

In animals, sensory perception is mediated not by hormones, but by a mechanism unavailable to plants, the central nervous system. Animals typically have a number of sensory organs, all of which have certain common elements; all sense organs are positioned on the body to respond optimally to certain stimuli. Moreover, the receptor cells of each sense organ are specialised components of the nervous system, termed *receptor* neurons. Most receptor neurons contain specific *organelles* (cellular components), which are sensitive to certain stimuli. For example the light-sensitive *rhodospin* pigment layers in the outer segments of mammalian visual cells, and the *cilia* of the receptors in the auditory/vestibular organs. Stimulation of these specialised receptor neurons lead to an action potential that generates an afferent signal that is sent to processing centres in the brain by a series of synaptic relays. Response to a sensory input takes one of three forms:

- Flexor reflexes (also termed unconditioned reflexes) – these are innate behavioural responses based on a fixed chain of neurons from the receptor cells to the effector

- Conditioned reflexes – these are automatic reflexes, but are learnt by the animal through conditioning (Pavlov's dogs are the classic example of conditioned reflex response)

- Conscious response – this is a non-automatic response to a stimulus that is mediated by a process of conscious thought. This type of response involves a decoupling of the received input from a response and storage into memory, where a suitable response is formulated.

5.1.1 Sight

Biological vision involves the sensing of a species-specific part of the electromagnetic spectrum. In the human eye, receptor cells that contain the visual pigment rhodospin transduce insolating light. At a particulate level, a photon hits a molecule of *rhodospin*, which is excited to a higher energy level, and vibrates more strongly. This leads to the breakdown of rhodospin into *retinol* (from vitamin A1) and *opsin*, in turn leading to the closing of an ion channel and generation of an electrical signal, which is then sent down the optic nerve stem for processing in the brain. This process of chemical transduction of photonic to electrical energy is common across the animal kingdom.

The eye has evolved independently and in a wide range of forms across all phyla from humble origins. Even the lowest and most primitive forms of life exhibit some sensitivity to irradiance. For example, the planaria (a flatworm), *dugesia tigrina*, employs a curved row of photoreceptor cells (photospots) along each side of the anterior body, next to which is another row of cells, forming a barrier. These allow the planaria to sense the direction of the source of illumination by the way the photoreceptors are shadowed by the barrier. From simple photospots, more complex visual sensors have evolved, *ommatidum*, *ocellus*, through to the compound eye (composed of multiple *ommatidum*) and the complex eye (subdivided into those with direct and inverse retinas, used by the orders *mollusca* and *chordata* respectively).

It is difficult to explain the form of the eye structure adopted by an individual species. The evolution of the eye obviously occurs in tandem, and is influenced by, other physiological characteristics of the animal. The type of visual system employed is closely linked to the environment of the animal, and the mobility of the animal with respect to those above it in the food chain. Earthworms (phylum *Annelida*), which spend the majority of their life underground, require only limited visual capability; these extend to knowing when they are above ground and exposed to their primary predator, birds. Thus for the earthworm simple photospots are adequate as a visual system.

Alternatively, insects generally exist in a position continuously exposed to predators. Their requirement is for information concerning the approach of predators from any direction. The housefly (*Musca domestica*) for example, relies heavily on visual motion information to survive. Therefore, the compound eye on which the housefly's vision is based is capable of detecting frequencies up to 300Hz (as opposed to the human eye at 20-30Hz). Conversely a fly's visual resolution (the blowfly *Calliphora erythrocephela* has roughly an equivalent to a 77 by 77 pixel array covering one visual hemifield [Harrison, 2002]) is extremely poor compared to, for example, our own. The desirable characteristics of the visual system of a fly (in terms of motion sensing frequency limit, acuity, colour perception, focal range, field of vision, etc.) are markedly different from those of a human being. Despite the massive differences in structure and performance of eyes throughout the animal kingdom, certain gross classifications are possible. Within the animal kingdom, there are three primary ways the eye is integrated into the body:

- Body-part mounted, as in the case of *anthropoda*. There is no relative motion between the eye and the body part
- Body-part mounted with reduced optical cord width, leading to one degree of angular freedom
- The *chordate* eye, with a much-reduced optical bundle, giving two degrees of angular freedom.

There exist usually two eyes (binocular) vision in order to allow depth perception (spiders have eight, but in species where depth perception is important, such as jumping spiders (family *Salticidae*), two of the eyes are much more developed than the others, that are used for peripheral motion detection).

Because vision is the richest and most important sense for humans, our camera technology is well developed and advanced. Existing cameras can be considered highly biomimetic in that they utilise a similar lense/surface arrangement to the eye and image information is transduced chemically in the case of analogue cameras (using for example silver oxide), and electrically in the case of digital and video cameras (using some form of photodiode).

Attempts to more closely mimic natural vision systems include attempts to reproduce compound vision [Harrison, 2002] using VLSI and the fly eye to construct an optomotor system. Examples of other work include attempts to replicate certain aspects of oculomotion [Landolt, 2002]. The human eye for example actually uses microsaccades when focused on a particular subject in order to maintain visual acuity by avoiding image degradation. Work has also been conducted on biomimetic gaze stabilisation and visual tracking [Neumann & Bulthoff, 2002], [Shibita & Schaal, 2001].

5.1.2 Hearing

Hearing is a primary sense for many species. Hearing involves the sensing of vibrations within the medium surrounding the listener, involves the use of mechanotransducive receptor cells, and is therefore along with touch (section 5.1.3) a mechanical sense. Within the mammalian ear, the *mechanoreceptors* are sub microscopic hair cells termed *cilia*, which line the interior of a fluid-filled cavity called the *membranous labyrinth*, also termed the inner-ear.

The structure of the hearing apparatus is optimised and sized according to the requirement of the species. In mammals, the external ear (*pinna*) varies widely in shape and size, but are all structured so as to channel sound vibrations towards the *tympanic membrane* (ear-drum) that is situated at the end of the external auditory canal. Sound is transmitted from the *tympanic membrane* via a complex arrangement of three bones, the hammer (*malleus*), anvil (*incus*) and stirrup (*stapes*). The *malleus* is firmly connected to the *tympanic membrane* whilst the *stapes* is connected to the inner ear (*cochlea*), itself composed of the organs of equilibrium and hearing.

In other orders, hearing apparatus varies widely. In insects, the *tympanal* organs are analogous to the ear, and are found at many positions on the body (for example on the legs of the cricket). However, at the sensor cell level the transducive mechanism is the same; mechanoreceptors generate an action potential through ion-channel closure in the receptor cell upon deformation of the receptor structure. In the case of the *cilia*, deformation will cause opening or closure of ion-channels in the receptor cell that leads to depolarisation or hyper polarisation, in turn generating an electrical signal that is transmitted through afferent nerve fibres to the brain.

Whilst interpretation of a full range of sounds, frequencies, amplitudes and waveforms within a particular spectrum has not received much attention due to the complexity of recognition algorithms [Carmena et al., 2000], the use of sound information in the form of simple monotonal forms in order to provide spatial and orientation information has received substantial attention. Of particular interest to recent researchers has been the mimicry of echolocation. Echolocation involves the use of high-frequency emitted pulses that rebound from objects back to the ear of the emitter, providing positional, orientational, size and textural information about the environment. Echolocation is employed be two mammal groups, microchiroptera and cetaceans such as the dolphin, and by two bird genera.

Biomimetic work on echolocation includes reproduction of the pinna movements of the bat [Walker et al., 1998], Doppler-based motion control for mobile robots [Carmena & Hallam, 2001], and biomimetic sonar [Kuc, 1997].

5.1.3 Touch, Balance and Somatovisceral Sensibility

Touch, along with the senses of hearing (section 5.1.2) is a mechanotransductive sense. The sensory modality of touch is different from the other senses in that it is not localised into well-defined sensory structures such as the eye or ear, but distributed throughout the body. In the primate body for example, there exist three basic mechanoreceptor types that are located in the skin and mediate the sensation of touch - intensity, velocity and acceleration receptors.

Within other orders, different sensor types are present. Hair-shaped *sensilla* are the most common type found on insects, distributed all over the body, including the antennae. However, there also exist campaniform *sensilla* (that sense stresses placed upon the cuticle, primarily placed in regions where high cuticle stresses occur, for example at the base of the wings) and *chordotonal* organs, which sense vibrations, and include the *tympanal* organs. These are the true hearing organs of insects (although other chordotonal organs are involved in hearing) and can be considered analogous to the eardrum. In addition to *cutaneous* receptors that mediate the sense of touch, *extracutaneous* mechanoreceptors (termed *proprioreceptors*) exist that are the primary mediators of the sense of position and movement of the body itself. Organs of equilibrium (located in the inner ear of mammals) have evolved to allow sensing of position and acceleration. Insects however do not have these and rely on the other senses to provide positional and orientation information.

As with the transducive mechanism of hearing, mechanoreceptors generate an action potential through ion-channel closure in the receptor cell upon deformation of the receptor structure (piezoelectric). In the case of mechanoreceptors based upon hairs for example, deformation of the hair will cause opening or closure of ion-channels in the receptor cell that leads to depolarisation or hyper polarisation, in turn generating an electrical signal that is transmitted through afferent nerve fibres to the brain.

The Robotic Lobster Project [McGruer et al., 2002] has developed two types of sensor to mimic the lobsters contact/bending sense (for the antenna) and current/flow sense. The contact/bending sensors consist of a micro machined gold cantilever beam, which is placed on a very flexible and thin silicon substrate. Bending of the silicon substrate beyond a certain curvature activates a switch. The second sensor system consist of small hinged paddles which, when moved under the action of a current, switch digitally. Altering the dimensions of the paddle allow different flow speeds to be detected. Other work includes development of strain sensors based on insect campaniforms [Skordos et al., 2002], micro machined biomimetic sensor using modular artificial hair cells [Li et al., 2000], fluid-based haptic systems [Marvroidis et al., 2000] and position sensors for robotics [Jaax et al., 2000].

5.1.4 *Taste & Smell*

Taste and smell are termed the *chemical senses* (the other three senses can be legitimately termed the physical senses*)*, as they are characterised by sensitivity to a selection of certain chemicals, in the form of volatile and non-volatile organic and inorganic compounds. As with visual receptor cells, transduction is mediated by chemical interaction between the receptor cell and the activating molecule. The odorant molecules bind with protein receptors leading to a cascade of biochemical events that culminate in the opening of ion channels in the receptor cell membrane. This leads to depolarisation of the olfactory sensor neuron and generation of an electric potential, which is then transmitted synaptically to the brain via afferent nervous fibres. The pattern of electrical excitation corresponds to the type of exciting molecule, thereby allowing very subtle differentiation between different types of odour and taste.

Within vertebrates, including humans, smell is associated with a specific physiological structure that mediates conveyance of molecules to the receptor cells, through inspiration, muscle action, or some other mechanical process (e.g. a nose, antenna). The structural properties are very important in determining sensitivity – for example, in dogs and other mammals that possess superior sense of smell (called macrosmats) the nasal cavity is a highly convoluted structure, allowing a large surface area of the olfactory *epithelium*. In insects, the sense of smell is mediated by chemoreceptors usually located in the antennae, positioned away from the body. In insects, smelling behaviour is characterised by antenna waving, which can be considered analogous to sniffing in land-vertebrates. In all cases, the olfactory organs are positioned in order to be well exposed to the fluid medium within which the creature is situated.

By contrast, taste chemoreceptors are located within the mouthparts of most species – in mammals for example taste receptors are located on the surface of the tongue in groups (taste-buds). However, taste receptors are also sometimes located on other parts of the body. For example, the Housefly (*Musca domestica*) has taste receptors not only within the mouth but also on the *tarsi* (the *distal* part of the leg), allowing it to make a preliminary taste assessment of potential food sources just by alighting on them.

The sensation of smell is used for a variety of purposes. The atmosphere or ocean is capable of transporting information in the form of compounds over large distances, and this information is used in formulating every type of behaviour response. Smell is also of particular importance in regulating the behaviour of *eusocial* creatures such as ants and termites, creatures that organise their collective behaviour primarily through *pheromones* (see section 4.1.4.1).

Biomimetic reproduction of the senses of smell and taste presents a real challenge. Biological taste and smell organs are characterised by a high sensitivity to a very wide range of compounds, and the neuronal 'post-processing' of the electrical signal generated by the receptor cells is a vital part of this wide sensitivity. It is difficult to define which aspects of the physical stimuli neuronal circuits encode. Unlike light for the visual system, or sound for audition, the perceptual experience of smell and the odorants that cause it cannot be characterised easily along a well-defined spectrum. For example, odorant molecules that are structurally identical apart from their chirality (the structural characteristic of a molecule that makes it impossible to superimpose it on its mirror image) can invoke a completely different smell, whereas compounds that are structural very different can smell similar [Kauer, 2002].

In order to detect chemical compounds, biomimetic noses and tongues need to reproduce this sensitivity to chemicals that is present in natural *olfactory* and *gustatory* sensors. This requires a chemically sensitive (and therefore reactive) component, analogous to the receptor cells in the *olfactory epithelium*. Sensors of this type, which incorporate a chemically or biologically reactive component, are termed biosensors.

Biosensor development has focused around the mechanisms found in biological systems to recreate the chemical senses; these include parallel processing of multi-dimensional information, and the development of transducive interfaces capable of responding to a wide range of chemicals. As such, biosensors can be defined as analytical devices incorporating a biological material (e.g. tissue, micro organisms, organelles, cell receptors, enzymes, antibodies, nucleic acids, natural products etc.), a biologically derived material (e.g. recombinant antibodies, engineered proteins, aptamers etc.) or a biomimic (e.g. synthetic catalysts, combinatorial ligands, imprinted polymers) intimately associated with or integrated within a physicochemical transducer or transducing micro system, which may be optical, electrochemical, thermometric, piezoelectric, magnetic or micro mechanical. Biosensors usually yield a digital electronic signal, which is proportional to the concentration of a specific analyte or group of analytes [Gopel et al., 1998].

Biosensors are well established in fields such as food production and medicine, usually highly tuned to a specific or narrow range of chemical compounds (for example enzyme sensors that have a very high sensitivity to a particular compound). These cannot be considered equivalent to true taste or smell sensors. Taste for example is such as hugely complex process, involving the interaction of literally thousands of compounds, that attempts to quantify it have led to such fuzzy classifications as ‘factors of deliciousness’ [Toko, 2000]. To be able to reproduce the multidimensional nature of taste is a huge challenge. However, examples of biomimetic biosensors that attempt to replicate the action of smell and taste include the Tufts Medical School Nose [White et al., 2002] which employs an array of dyes, polymers and dye/polymer mixtures that change their fluorescence upon exposure to compounds; and the ‘electronic tongue’, based upon an active lipid membrane [Toko, 2000].

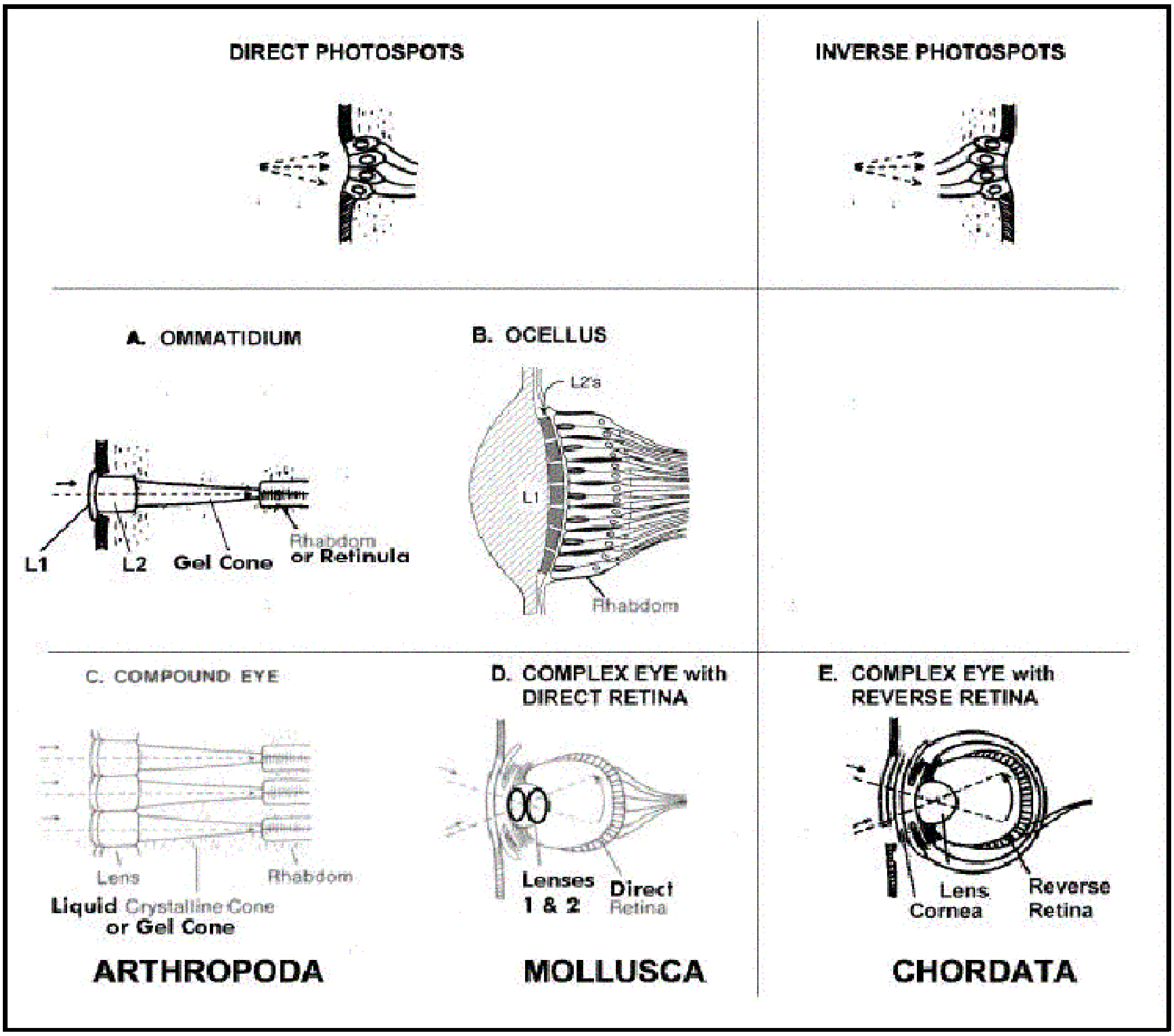

Figure 5.1 – the basic eye classifications.

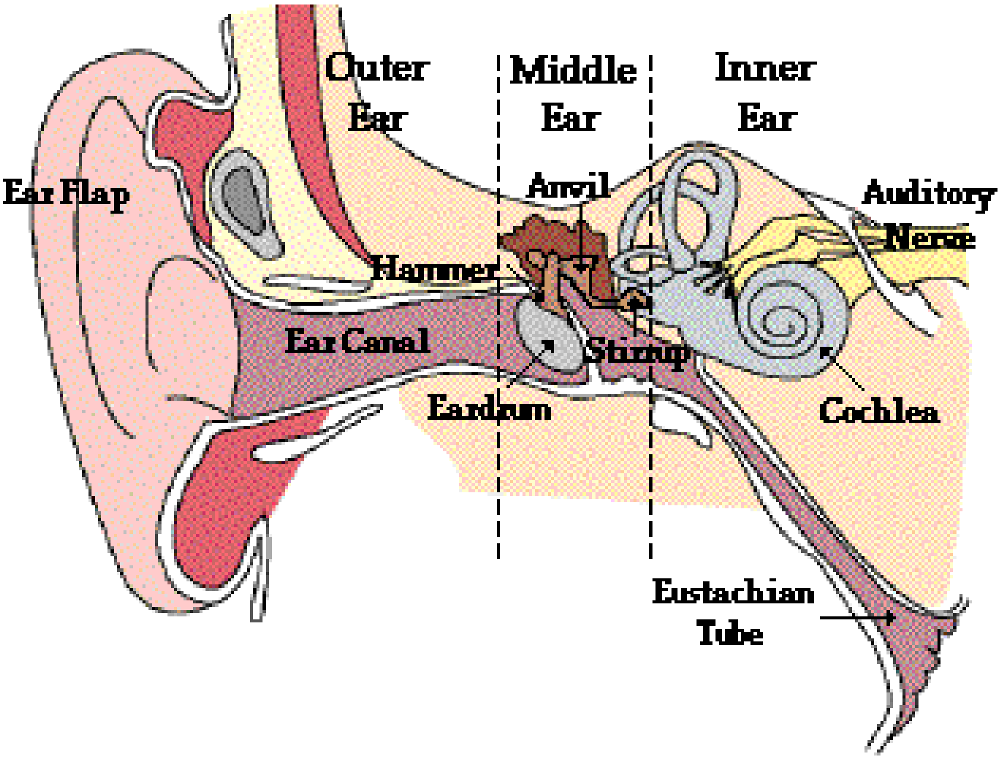

Figure 5.2 – the human ear

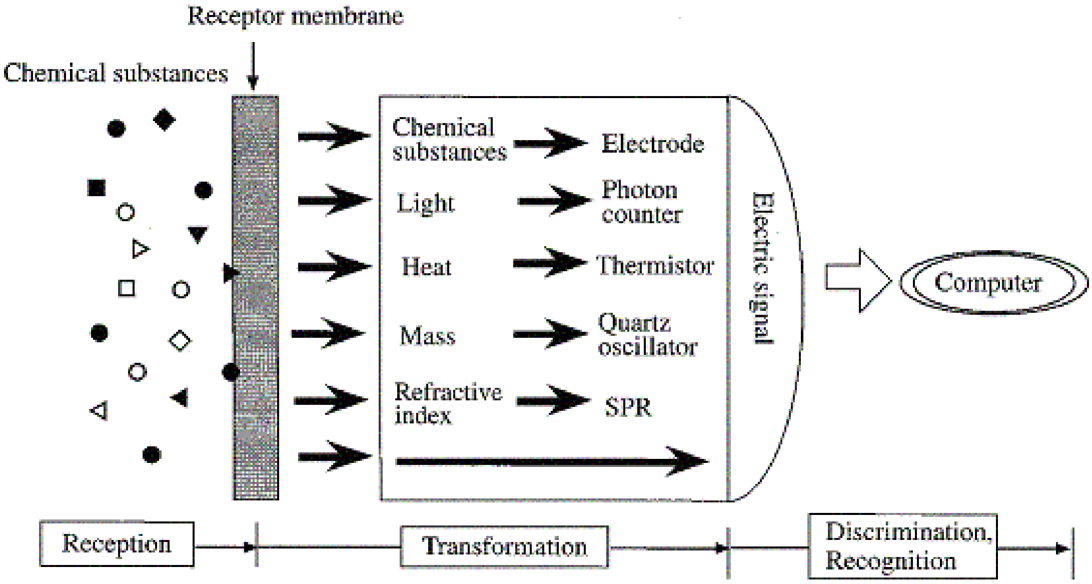

Figure 5.3 – the generic structure of a biosensor (taken from [Toko, 2000])

5.2 COMMUNICATION

Many life forms employ mechanisms to communicate information to other creatures, for a variety of reasons. The mechanism usually involves use of some physiological characteristic of the communicator. For example, within a particular species, much communication is involved in sexual behaviour: A female lion give off *pheromones* from anal glands to advertise that she is in estrus; male peacocks use an enormously expensive and ornate tail to signal reproductive fitness to females. Indirect communication involving using elements of the environment is also used. Weaverbirds construct a nest of green grass as an incentive to females; Bowerbirds construct a bower, composed of thick pads of plant material ringed with ornaments, in order to attract a mate. There are countless examples of ritualised dances, fights, scent production, calls and other communicative efforts (all of which in some way signal reproductive fitness) associated with sexual behaviour. Reproductive communication also exists between species (as in the case between flowers and bees), and this communication can sometimes be very deceptive. Many species of orchid produce flowers that resemble the female of specific species of insect. This deceptive appearance is part of a system for tricking male insects into pollinating the orchids and extends to the imitation of insect pheromones, luring in male insects with analogues to female scents.

There are of course many other reasons for communication between life forms than just mating behaviour, for example signals to other group members (critical in the construction and maintenance of culture – see section 6.3) and warning signals to other species, particularly predators. For example the moth *automeris io* uses fake eyes on its wings to deter birds – see figure 6.4). Camouflage can be considered a form of anti-communication in that it's objective is to minimise or eliminate the transmission of information to a hostile predator or potential prey.

Taking the dominant metric for determining success of gene-survival (see section 1.1), then all communicative actions such as those involved in mate attraction, predator avoidance or deterrence etc. are likely to be of limited or no use in a biomimetic system. For a biomimetic system with specific goals, only those communicative mechanisms involved with completion of mission-specific tasks are important. Whilst the form of future biomimetic missions cannot obviously be specified, the general communication requirements of space missions remain the same. The fundamental goal of communication is of coordination between agents in task-completion. To this end, the use of radio or some other portion of the electromagnetic spectrum to send and receive information between agents would appear better than any type of communication used in the natural world. However, the actual management of information transmission over networks between a large number of agents can and does benefit from ideas taken from the natural world. Here again the concept of swarm intelligence has provided inspiration. The foraging behaviour of ants (see figure 4.6), which involves pheromone-trail laying behaviour upon discovery of a food source, in turn leading to *recruitment* of other ants towards the food source. A principle advantage of swarm intelligence approaches is their robust response to time-varying situations. If new food sources become available, or existing food sources move, the swarm behaviour of a foraging ant colony will adapt (through the random element in the ants wandering behaviour and the temporal degradation of pheromone trails) to these changes. This has been applied to the design of routing algorithms, which direct routing traffic over a dynamic network through the use of virtual ants that deposit virtual pheromones on routing table entries [Schoonderwoerd, 1996].

Figure 5.4 – the moth automeris io sweeps forward it's frontal wings to reveal two fake eyes on the anterior wings

6 GENERATIONAL BIOMIMICRY (6500)

In the natural world there are many processes that occur at a species and generational, rather than individual or group level. Generational mechanisms can be defined as those that guide the evolution of a particular species or ecology over time. The characteristics of a particular species, down to the phenotype of an individual, can be considered a product of generational influences. There are two generational mechanisms whereby the phenotype of an individual within a species can be affected:

- Genetic transmission of information through breeding
- Cultural transmission of information through communication
- Transmission of Information within an ecology.

It is the action and interaction of these three mechanisms that define the phenotype of an individual, and their effect in tandem determines the reproductive success of the species as a whole.

6.1 ECOLOGICAL MECHANISMS

The significance of the ecology (i.e. an environment composed of other living organisms) in shaping the evolution of a particular species is of crucial importance; to a greater or lesser extent, every species within an ecology exerts selective pressures on every other species, through a variety of direct and indirect mechanisms (through competition for resources, predator-prey relationships etc.). Similarly, the evolutionary path of a particular species can be considered a product of the sum total of influences from every other species within the environment, as well as the physical parameters of the environment itself. The mechanisms that operate within an ecology have a tendency to promote, in general, the extension of the area in which life can exist. A simple example can be found in plant seed distribution by animals; as a wandering animal drops a seed in a region hitherto unpopulated by the plant, that seed will grow and the region covered by the plant will increase; this in turn will increase the habitable region of the animal (defined simply as the area where the plant exists), and encourage the existence of more seed-dropping animals. The tendency of ecosystems is therefore to expand until physical limits are reached (tree-lines in mountainous regions are a clear example of life expanding to physical limits). Self-regulation is a key component of this 'self-promotion'. Movement into areas with differing physical parameters leads to the emergence of differing species, with an ever-increasing tendency towards complexity and variety.

This tendency of ecosystems to construct, promote and maintain conditions for life has led to hypotheses that the ecosystem of the planet as a whole is self-regulating and self-promoting, and can legitimately be viewed as an organism in itself. This view of the Earth as super-organism has found adherents in Lamark, Goethe, Humbolt and Vladimir Vernadsky who introduced the concept of the biosphere. The most famous modern expression of this premise is found in the Gaia hypothesis [Lovelock, 1987]. Lovelock uses such evidence as the historically (and amenable to life) constant surface temperature of the Earth since life began despite a 25% increase in insolation from the sun over the same period, and the highly unstable mixture of reactive gases (79% nitrogen, 20.7% oxygen, 0.03% carbon dioxide with traces of methane and other gases) that constitute the atmosphere; these could not be maintained without constant replacement or removal by the biosphere.

6.2 GENETIC MECHANISMS

Within most metazoan species, sexual reproduction is the mechanism whereby progenitors are created. Sexual reproduction involves the partially random combination of *gametic* cells (sex cells that have undergone *meiosis* and have half the number of chromosomes found in *somatic* cells) from two parents. Asexual reproduction involves the separation of a cluster of cells (a *blastema*) from the parent, producing a genetically identical offspring (although minor genotype changes can occur due to mutation). Though asexual reproduction is advantageous in that, if the parent animal is well adapted to its environment and the latter is stable, then all offspring will benefit, it is disadvantageous in that the fixed genotype not only makes any change in offspring impossible, should the environment change, but also prevents the acquisition of new characteristics, as part of an evolutionary process. Sexual reproduction, on the other hand, provides possibilities for random variation among offspring and thus assists evolution by allowing new pairs of genes to combine in offspring.

Genetic transmission of information through sexual reproduction leads to evolution of the genotype in response to environmental pressures. If a particular gene is found to be advantageous within a certain ecology, that gene is more likely to be passed on to the next generation, whilst disadvantageous genes are more likely to be removed from the gene pool. This process (natural selection) will therefore lead to the breeding of optimal creatures over time. It is important to remember that this tendency towards optimality is with respect to the environment; in an environment that includes humans, domesticated animals have experienced loss or degradation of their phenotypic abilities (such a speed, sensory acuity etc.), but can be considered genetically successful because of the arrangement they have entered into with man (as sources of food, amusement etc.); in the ecology that includes humanity, being plump, tasty and docile (though not necessarily very fast) is a genetically successful strategy. It is therefore important to remember that evolution is not a directed, purposeful process, perhaps culminating in some end-goal such as mankind.

Because of the optimising effect of natural selection, the principals of genotype evolution have been formulated and used extensively in solving engineering and optimisation problems [Ng & Leng, 2002]. Evolutionary techniques are typically very effective in solving optimisation problems that possess a very large and complex solution space, and avoid the problems associated with more classical tools (gradient methods, etc.) when faced with such a problem (collapsing to local minima etc.). There are two main types of computational methodology that utilise some of the known mechanisms of evolution:

- Genetic Algorithms and Genetic Programming
- Evolutionary Programming.

6.2.1 Genetic Algorithms and Genetic Programming

The Genetic Algorithm (refer to [Goldberg, 1989] for a good introduction to the field) is used in a number of areas of application, such as incorporation into machine learning; however, the most common application is multi-variate optimisation. The GA is based around the creation of a population of individuals, which are represented by *chromosomes*. The chromosome is essentially a set of character strings that can be considered analogous to the base-4 chromosomes found in nature. Defining chromosomes as simple strings of characters enables evolutionary mechanisms such as *mutation* and *crossover* (breeding) to be modelled by simple bit manipulation. Implementation of a GA takes the following general steps:

1. Define a population of *n* individuals represented by character string chromosomes
2. Evaluate the fitness of each individual (quality of the solution represented by the individual)
3. Create a new population be performing operations such as random bit manipulation (mutation), fitness-proportionate reproduction etc.
4. Return to step 2 with the new population of *n* individuals.

One iteration of this loop is defined as a generation. Genetic Programming is simply the application of the genetic algorithm to the development of computer programs; here, instead of the individual chromosomes representing possible solutions to a problem, they represent programs that, when executed, are candidate solutions to a problem.

6.2.2 Evolutionary Programming

Evolutionary Programming (EP), like GAs, assumes a ‘fitness landscape’, characterisable by a certain number of variables, with possible solutions to the problem being definable by these variables. The basic EP methodology involves three steps:

1. Random generation of an initial population of *n* trial solutions, defined by chromosomes that contain random (but bounded to reasonable values) values of the solution variable
2. Replicate each solution into a new population. The new population is based upon a distribution of mutations based upon the original individual, ranging from minor to extreme changes
3. Each member of the new population is assessed by determining its fitness. Typically, some type of process with a stochastic element is employed to select *n* solutions to be retained for the next iteration
4. Return to step 2 with the new population.

EP methods differ from GAs in that they do not typically employ crossover, so there is no modelling of sexual reproduction, which is the case with genetic algorithms. For a good introduction to EP, refer to [Fogel et al., 1966], [Fogel, 1995]. Evolutionary programming techniques have also been used in the automatic design and manufacture of robotic life forms [Lipson & Pollack, 2000].

6.3 BEHAVIOURAL/CULTURAL MECHANISMS

Culture, a word more commonly applied just to *homo sapiens*, has received over 100 definitions, most of them anthropological. What is regarded as the classic definition of culture was provided by the 19th-century English anthropologist Edward Burnett Tylor [Tylor, 1871]:

…that complex whole which includes knowledge, belief, art, morals, law, custom, and any other capabilities and habits acquired by man as a member of society.

This definition of culture is founded upon the belief that symbolic communication (principally through language, spoken or written) is the basis of culture, and therefore that culture is exclusive to humanity. However, wider definitions of culture exist which reflect the belief that culture is something that intelligent animals can also possess. The definition given by Bonner [Bonner, 1980] provides an example of this:

…the transfer of information by behavioural means, most particularly by the process of teaching and learning. It is used in a sense that contrasts with the transfer of genetic information passed by the direct inheritance of genes from one generation to the next.

Such a definition allows intelligent animals also to possess culture. In addition to genetic transmission of information within a species across generations through breeding, transmission of information via communication between individuals also occurs. Examples of this type of information exchange exist both laterally (i.e. between members of the same generation) and generationally (across the generations – usually in a ‘downward’ direction).

Typically this transmission of information is undertaken in order to confer some benefit to the society. The transmission of information is undertaken through modifications to the environment: these modifications may be ephemeral (through mating calls, language etc.) or more permanent (burrow/nest construction, written language). Through these mechanisms, beneficial (i.e. fitness-enhancing) information may be transmitted to other members of the group, including offspring [Spector & Luke, 1996]. Thus intelligent creatures create and refine culture in order to perpetuate their society and by extension the species. Culture allows genetic parsimony, because fewer traits have to be innate, as more can be learned. Culture also allows for faster adaptation to an environmental change; forms of social interaction can be created and destroyed within a single generation. Culture also allows *Lamarckian* evolution, whereby *phenotypic* traits can be passed on to the next generation. An example of this is the adopted practise by Blue Tits in England of breaking into milk bottle tops in the 1940s [Hinde & Fisher, 1951]. This process obviously has its most extreme form in human society. Human infants are born with less innate behaviours than the infants of other species, and the amount of cultural information that we transmit across generations is very large (consider the time period involved in educating a modern child). Therefore cultural information transmission is at it’s most important and extensive in human societies.

Attempts to apply the formalisms associated with genetics to the propagation of culture began with the definition of the ‘meme’ by Dawkins [Dawkins, 1977]. The meme has been the subject of countless different meanings, but can be defined as a ‘cognitive or behavioural pattern that can be transmitted from one individual to another’. This definition is of course quite fuzzy, and strict definition of the meme, in a manner similar to that of the gene, still proves to be very difficult [Wilkins, 1998].

Figure 5.5 – A mother tiger teaching it's offspring hunting skills through play

6.4 GENETIC ENGINEERING AND HUMAN ALTERATION

Humanity has for centuries been guiding the evolution of a number of species around itself through selective breeding; witness for example the huge range of canine breeds, of hugely differing physiology and temperament that have fulfilled a number of roles within human society. From hunters (hounds such as the Afghan) to livestock herders (sheepdogs) to aesthetically pleasing and manageable pets (Pekingese). This process of guiding evolution (a cultural process) extends to the erection of cultural mechanisms that have guided the breeding of groups of humanity itself (for example class distinction and heavily regulated marriage protocols within ethnic and societal groups such as the European aristocracy).

Until relatively recently, alteration of the genotype of a species has been constrained to the normal mechanism of breeding; thus despite the obvious ability to guide the evolution of a particular species through the coupling of breeder pairs that possess desirable characteristics, the random component in the process could not be bypassed, and exact results could not be achieved. However, the development of genetic engineering opens up the *possibility* of direct manipulation of the genotype with a much greater degree of accuracy, as well as the ability to combine genes from species that would not in nature be able to do so. In the case of engineering the human genome, direct genetic self-alteration represents the most extreme case of a species using cultural transmission of information to affect the genotype, potentially bringing our genetic evolution under the direct control of culture; as such, genetic self-alteration can be viewed as a biomimetic discipline.

Various genetic engineering techniques exist, the oldest being *recombinant* DNA techniques, which use a biological vector, such as a plasmid or a virus, to carry foreign genes into a cell. Other techniques include electro and chemical *poration* (the creation of pores in the cell membrane through chemical or electrical means to allow the entry of new genes), *microinjection* (simple injection of genetic material into the recipient cell) and *bio ballistics* (bombardment of a cell with slivers of metal coated with genetic material).

Genetic engineering applied to humans for therapeutic ends is termed *Gene therapy.* Gene Therapy can be divided into two broad categories: *germ-line* therapy and *somatic cell* therapy. Germ-line therapy involves alteration of the reproductive cells (*gametes*), such that the genetic changes are passed on to the patient's offspring (i.e. will be present in the genotype of the offspring). Somatic cell therapy involves the alteration of *somatic* (i.e. non-reproductive cells) of the body, and will therefore only be expressed in the patient, not their offspring.

In gene therapy, the method of introducing new genes largely centres on using modified viral vectors. Viral vectors are suitable because viruses have evolved effective mechanisms for encapsulating and delivering their genes to human cells. The modification thus involves inactivation (usually by removal) of the virus genes that cause disease, and the introduction of therapeutic genes. There also exist non-viral gene delivery systems, including direct introduction of therapeutic genetic material into the target cells, the creation of an artificial lipid sphere containing genetic material, which is capable of passing the cell membrane, and chemical linking of the therapeutic DNA to a molecule that will bind to cell receptors [Kelley, 1998].

The accuracy and predictability of all the above genetic engineering techniques relies on *the central dogma* expounded by Crick [Crick, 1970]. The central dogma states that the organism's genome should entirely account for the characteristic assemblage of inherited traits. This is a consequence of the sequence hypothesis, stating that the sequence of nucleotides in a gene is a direct codified representation of the amino acid sequence of a particular protein. This premise relies on the assumption that once sequential information has been passed into a protein it cannot get out again.

The actual accuracy and predictability of the phenotypical outcome of placing a foreign gene into an organism are somewhat less than perhaps the impression given by proponents of the technology, and arises from serious challenges to the central dogma, which has come from many studies. The most famous result that contradicts the central dogma is from the Human Genome Project [Venter et al., 2003]. The predicted number of genes to codify a human being at the start of the project was 100,000 or more genes (estimated from the number of proteins in the human body). However, upon completion, the number of genes counted was around 30,000. This result is a consequence of additional processes that occur during transcription and translation.

The first of these is the role of the *spliceosome* in protein synthesis, termed *alternative splicing*. A group of specialised proteins, plus some RNA fragments (collectively termed the spliceosome), acts upon mRNA during transit through the cytoplasm to the ribosome. Spliceosomes selectively attach themselves to the mRNA at specific points, fragment it and then splice it to form new sequences of nucleotide information. This process allows the same original nucleotide sequence of the DNA to be rearranged into many different sequences before translation. The current record for the number of variant proteins produced through alternative splicing from a single gene is 38,016 [Schmucher et al., 2000].

The second process affects the formation of the expressed protein after translation during folding. All proteins need to be very precisely folded in order to function correctly. Some nascent proteins produced by the ribosome require interaction with *chaperone* proteins in order to fold correctly. Thus the structure of a completed (i.e. folded) protein is not solely determined genetically (a premise of the central dogma), but also by the protein environment into which it is translated.

These two processes mean that placement of a novel gene into an organism can have completely unforeseen effects that will be determined by the protein environment in which the mRNA and unfolded gene products find themselves. Such effects cannot be predicted at present and could be very damaging. Beyond these technical problems, genetic engineering of the human genotype faces moral objection from many fronts. The potential of genetic engineering is to allow the inclusion within the human genotype of certain desirable characteristics. Desirable characteristics is obviously a term that is open to interpretation, but includes the eradication of genetically based diseases such as haemophilia and the increase of resistance to diseases such as cancer (noble but still morally contentious), and the accentuation and promotion of socially desirable traits such as increased intelligence, height or beauty (morally very contentious). For an introduction to the ethical questions raised by genetic engineering of humans, see [Fukuyama, 2002].

Nevertheless, human genetic engineering does have an enormous potential field of application, and genetic engineering as a whole has been called ‘The ultimate technology’ [Kammermeyer & Clark, 1989]; all engineering to date is ultimately concerned with altering the environment in order to make it more amenable to humanity. With genetic engineering, the potential now exists to alter humanity to make us more effective within the environment. This opens up the possibility of engineering humans to thrive in different environments, or equipping humans with physiological characteristics and mechanisms such as the ability to hibernate, allowing for example a drastic reduction in resource requirements for manned deep space voyages.

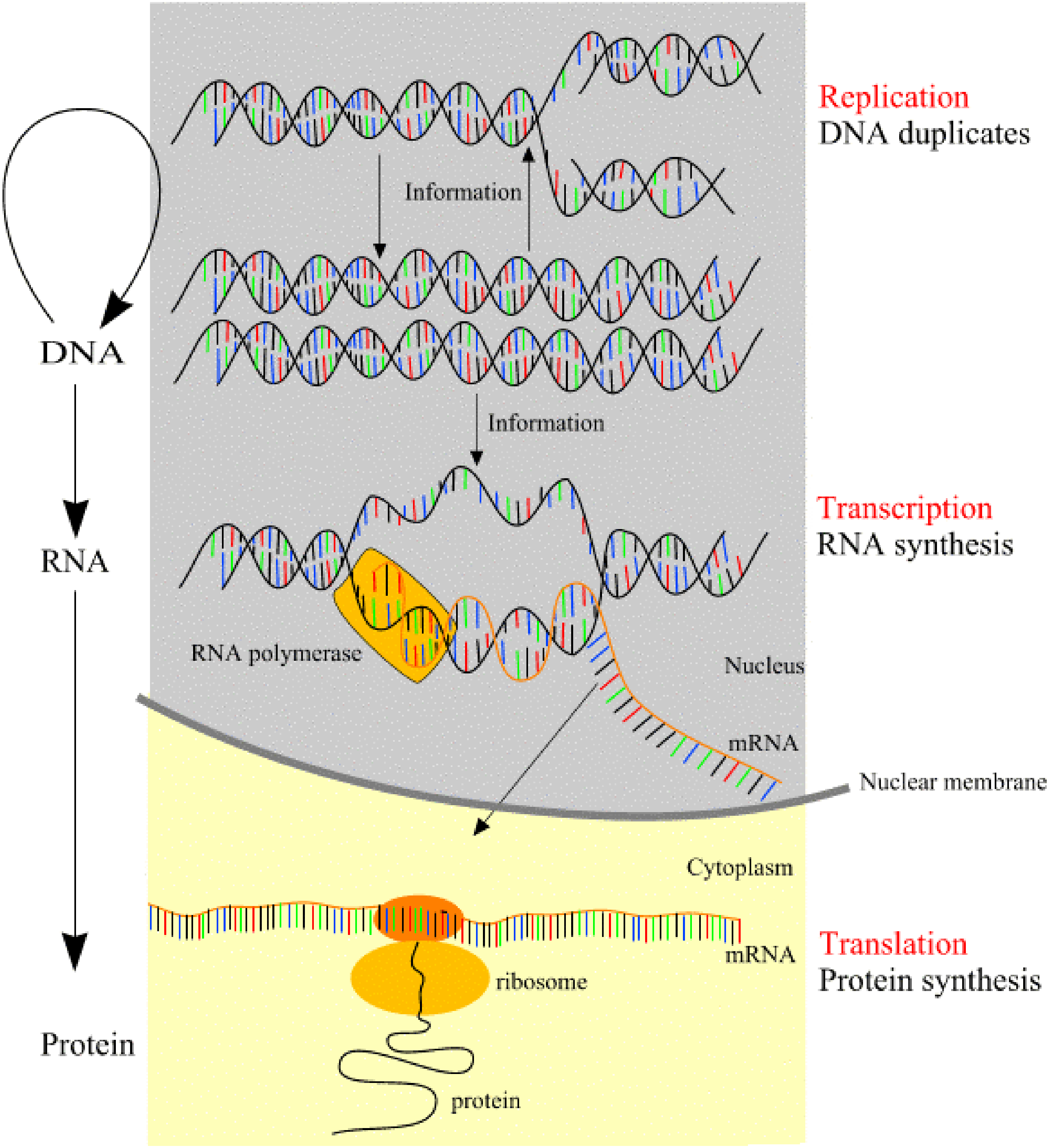

Figure 5.6 – the central dogma of molecular biology

7 SUMMARY

A very shallow and broad introduction into the main areas and current research of biomimicry has been presented. From the review of work done to date presented briefly and incompletely in this report, it is more than apparent that a huge and on-going body of work exists covering an enormously diverse range of scientific and engineering disciplines and applications. When the enormous range of processes, materials, behaviours etc. that are present in the natural world are considered, it is difficult to predict where new ideas and engineering applications will come from.

APPENDIX: BIOMIMICRY TECHNOLOGY TREE

This Appendix defines an abbreviated and unfinished version of the ESA Biomimicry Technology Tree, presenting the ESA structured classification of technological areas related to biomimicry.

6100 Structures and Materials

6100 (Structures)

6100 (Structures.1) Novel Structures	Structures that mimic novel forms found in natural structures. Examples include: Structures built by animals (for example honeycomb, webs) Load optimised structures Structures with novel topologies (for example water collection by stenocara beetle).
6100 (Structures.2) Dynamic/Adaptive Structures	Structures that exhibit an intelligent response to changing loads, either transient (dynamic response) or sustained (adaptive response).
6100 (Structures.3) Deployment, Folding and Packing	Novel bio-inspired deployment, folding and packing strategies. Examples include: Sunflower seed head packing Insect wing packing and deployment Leaf packing and deployment.

6100 (Materials)

6100 (Materials.1) Composites	Novel forms of composite materials that reproduce the composite nature of biological materials. Examples include: Fibrous composites that replicate lignin and polysaccharide phases of wood Plate and polymer composites that mimic the structure of shell.
6100 (Materials.2) Bio-Incorporated Composites	Composite materials that incorporate to some extent biological or engineered biological materials/molecules. An example is the use of genetically engineered spider silk proteins in high tensile materials.
6100 (Materials.3) Smart Materials	Materials that can exhibit an ‘intelligent’ response to stimulus. Such materials incorporate: Sensing technology Actuation/response technology Control mechanism. Examples include photo chromic glass, and self-healing/self-monitoring materials.

6200 Mechanisms and Processes

6200 (Mechanisms)

6200 (Mechanisms.1) Muscles and Actuators	Biomimetic reproduction of the actuation characteristics of living systems (plant hydraulic mechanisms etc.). The focus is on reproduction of the characteristics of muscle. Examples of candidate materials and mechanisms include: Electroactive polymers and ceramics Shape memory alloys McKibben artificial muscles.
6200 (Mechanisms.2) Locomotion	Reproduction of one or more aspects of locomotion in the animal kingdom. Examples include: Flight mechanisms (predominant focus is on reproduction of insect flight, particularly vortex control) Ambulation mechanisms mimicking natural walkers Undulation mechanisms. Within fluids (.e. swimming) the focus is again on vortex control. Also includes undulation on land (slivering) and within a solid material (burrowing).

6200 (Processes)

6200 (Processes.1) Novel Processes	Novel processes from natural systems, including: Cellular mechanisms (filtration, fluid and ion transport etc.)
6200 (Power.2) Thermal Management	Biologically inspired heat management and dissipation strategies. Includes both mechanisms for thermal energy retention and thermal energy dumping. Examples include: Use of capilliaried surfaces to dissipate heat (Desert fox ears) Differential temperature regulation within termite mounds.
6200 (Processes.3) Fabrication	Novel processes for the fabrication and manufacture of materials. Examples include: Deposition and mineralisation processes such as those involved in the growth of bone, shell and horn JIT manufacture, inspired by venom production in snakes.
6200 (Power.4) Power Generation and Storage	Power generation and storage technologies based upon mimicry of natural power production and storage (for example Pentads).

6300 Behaviour and Control

6300 (Behaviour)

6300 (Behaviour.1) Classical Artificial Intelligence	AI based upon the classical AI paradigm (physical symbol system hypothesis) of functional decomposition. Examples include: Dynamic programming Reverse topological sorting Expert systems.
6300 (Behaviour.2) Behavioural Artificial Intelligence	AI based upon the behavioural paradigm (situatedness) of task decomposition. Examples include: Study and application of animal behavioural mechanisms (animat approach). Development and design of basis behaviours and action selection mechanisms.
6300 (Behaviour.3) Learning Mechanisms	Biologically inspired behaviour in-situ mechanisms for behaviour modification. Examples include: Neural networks Learning classifier systems Reinforced learning.
6300 (Behaviour.4) Swarm Intelligence (DAI)	Distributed Artificial Intelligence control strategies based upon group and swarm mechanisms observed in nature. The central focus is on emergent properties and global problem solving behaviour. Examples include: Stigmergic behaviour Ant swarm mechanisms Shoaling and flocking behaviour Pack (small group) dynamics.

6300 (Control)

6300 (Control.1) Reflexive Control	Biologically inspired control mechanisms centred on reflexive (i.e. stimulus-response) control. The focus is on integration of sensor systems and actuation systems – of particular importance here is the field of neuroscience and animat control, where neuronal control structures of animals are reproduced in robotics.
6300 (Control.2) Rhythmic Control	Control using bio-inspired rythmic pattern generators. Current focus is on Central Pattern Generators.

6400 Sensors and Communication

6400 (Sensors)

6400 (Sensors.1) Vision	Bio-inspired vision systems. Examples include: Reproduction of oculomotor function. Reproduction of insect compound vision Image processing including image recognition, edge detection etc. Integration with behaviour and control systems.
6400 (Sensors.2) Hearing	Bio-inspired auditory systems. Examples include: Reproduction of Pinna movement to optimise sound reception. Bio-inspired mechanotranducive mechanisms (e.g. artificial hairs) Echolocation. Integration with behaviour and control systems.
6400 (Sensors.3) Touch	Bio-inspired touch systems. Examples include: Mechanotransducive mechanisms (EAP/SMA based etc.) – include touch sensors for temperature Haptics for telepresence. Integration with behaviour and control systems.
6400 (Sensors.4) Taste and Smell	Bio-inspired taste and smell systems. Examples include: Biochemical signal transduction. Narrow and broad range compound detection. Integration with behaviour and control systems.

6400 (Communication)

6400 (Communication.1) Passive Group Communication	Communication mechanisms based upon instances such as pheromone deposition by ants.

6500 Generational Biomimicry

6500 (Generational.1) Ecological Mechanisms	Ecology inspired mechanisms. Examples include: Recycling Life support and enclosed biospheres.
6500 (Generational.2) Genetic Mechanisms	Genetically inspired mechanisms. The focus is on optimisation techniques. Examples include: Evolutionary Programming Genetic Algorithms Genetic Programming.
6500 (Generational.3) Cultural Mechanisms	Culturally inspired mechanisms. Focus is on development of culture within agent teams to improve task performance, as well as combining cultural and genetic techniques in optimisation.
6500 (Generational.4) Geneering/Human Alteration	The use of genetic engineering and therapeutic measures. Focus is split between: Mimicry of desirable traits of other organisms by therapeutic means (e.g. pharmacological means, or incorporation of trait specific genes into human genotypes (for example the ability to hibernate) Engineering/alteration of other organisms to improve their utility (for example nutritionally improved foods).

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