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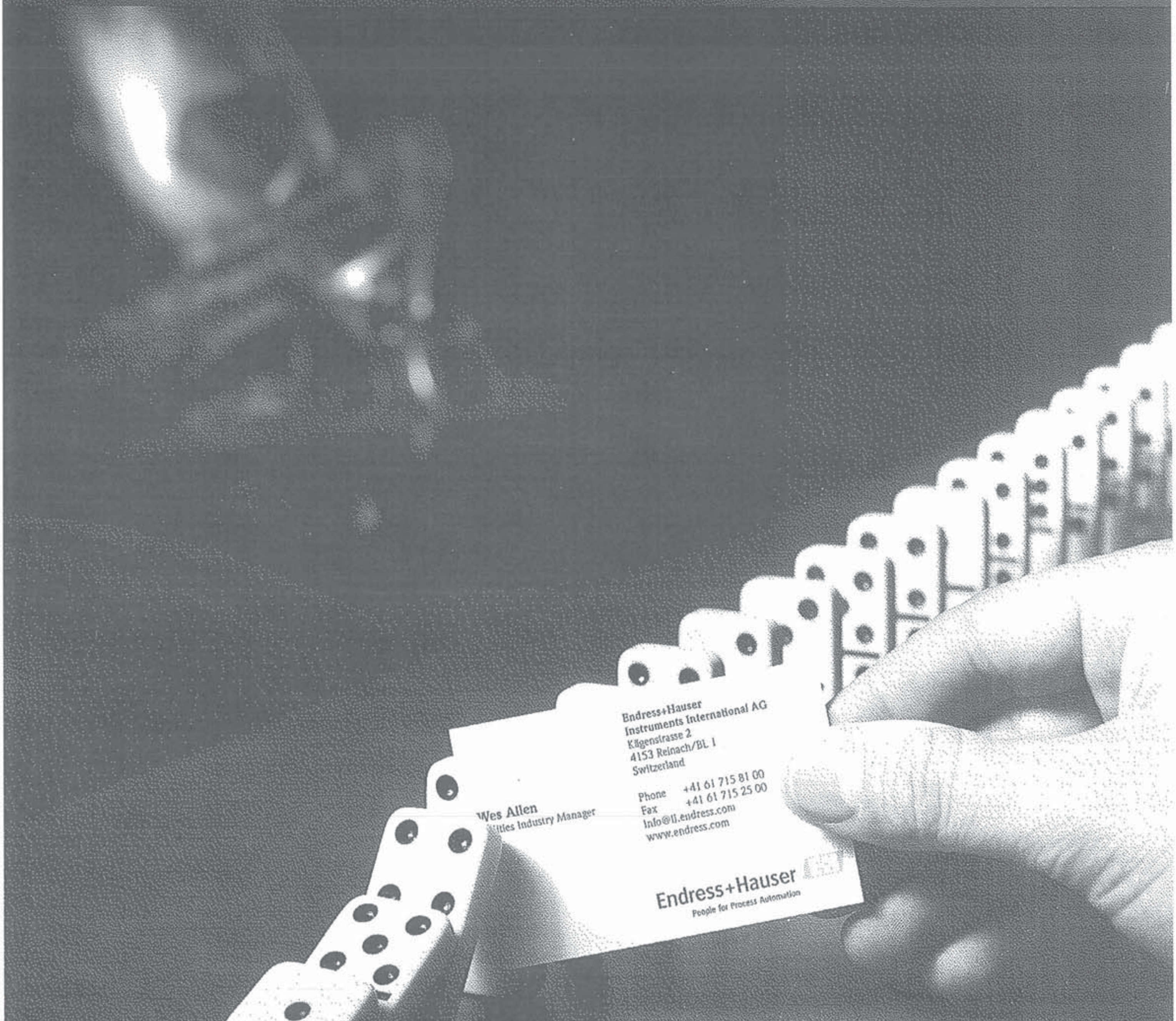

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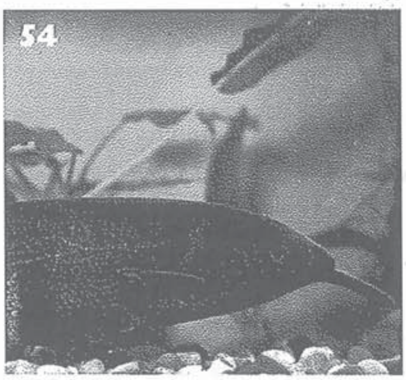

Sensing in nature: using biomimetics for design of sensors

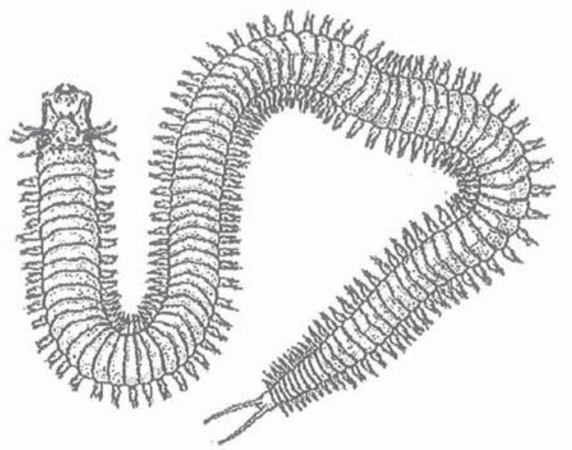

Figure 1: A ragworm inspires new ways to move in slippery substrates (based on Hesselberg 2007).

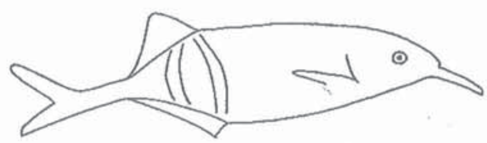

Figure 2: The nocturnal fish Gnathonemus petersii navigates by sensing changes in an electric field produced by itself (based on Bleckmann et. al 2004).

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Abstract

The paper illustrates how biomimetics can be applied in sensor design. Biomimetics is an engineering discipline that uses nature as an inspiration source for generating ideas for how to solve engineering problems. Using biomimetics involves a search for relevant cases, a proper analysis of the biological solutions, identification of design principles and design of the desired artefact. We use a search method developed at University of Toronto. It is based on formulation of relevant keywords and search for occurrences in a standard university biology textbook. Most often a simple formulation of keywords and a following search is not enough to generate a sufficient amount of useful ideas or the search gives to many results. This is handled by a more advanced search strategy where the search is either widened or it is focused further mainly using biological synonyms. The paper also reviews a number of biomimetic studies of sense organs in animals.

Biomimetics

Man has always been fascinated by nature and intrigued by the many genius ways that everyday problems are handled and solved. Functionality in many of the tools and artefacts that we use in our daily life can be traced back to origins in nature. The terms bionics, bionik (German) and biomimetics, however, are of a much more recent date. They all designate a study involving copying, imitating and learning from nature. The terms are constructed from Greek "bios" meaning life, the suffix "in" meaning like and "mimeistai" meaning imitate. Some dictionaries describe the term bionics as constructed from "biology" and "electronics". There are excellent books on biomimetics highlighting both its history and many interesting examples (Bar-Cohen 2006).

There is only a very limited correlation between the principles used to solve problems in technical artefacts and in biological systems. (Vincent et al 2006) have used the Russian TRIZ-method to show that there is only 12% similarity between biology and technology domains in the principles that bind solutions to problems. This indicates a wealth of inspiration in nature for how to solve technical problems.

(Bonser and Vincent 2007) has counted the number of 'biology-inspired' patents and found that it has gone from 0 to 1200 in the last 20 years.

It is possible to directly copy solutions from nature, but for engineering purposes it is often more useful to use nature as inspiration source. This can be done to various degrees of sophistication from the study of a single function as for example the self cleaning lotus flower to the study of more complex organisms involving several functions. An example of this is the ragworm – a marine creature that gives inspiration for how to move in slippery substrates and the design of novel endoscopes (*Figure 1*).

(Bleckmann et al 2004) looks at infrared organs in Bupestrid beetles and snakes and on electrolocation used by nocturnal fish. The beetles have infrared organs that can detect forest fires on a distance of many kilometres. The infrared light has a wavelength between 2.2 and 4 micrometer which travels well through the atmosphere. The reason for seeking the burned areas is that the larvae feed on wood but cannot cope with defence reactions of living trees. In addition the beetles eat other insects that has been injured or killed by the flames. The snakes use infrared organs on the head to detect prey.

The nocturnal fish Gnathonemus petersii shown in *Figure 2* has an electric organ in the tail that produces a weak electric field. A number of electro-receptors on the rest of the body can detect a change in the electric field caused by nearby objects.

Diverse vertebrate animals can sense the earth's magnetic field but primary magneto-receptors have not been identified. There are three hypotheses of magnetic field detection: electromagnetic induction in electro-sensitive fish, biogentic magnetite and chemical reactions that are modulated by earth-strength magnetic fields. For birds and turtles it is proposed that there are two types of magneto-reception in order to guide a long-distance migrant. The one is a compass that tells the direction and the other a "map-sense" that could measure field intensity or the inclination of field lines. However much empirical evidence is still missing.

There are many different ways of seeing light in nature. There are as many as 10 generalized optical mechanisms

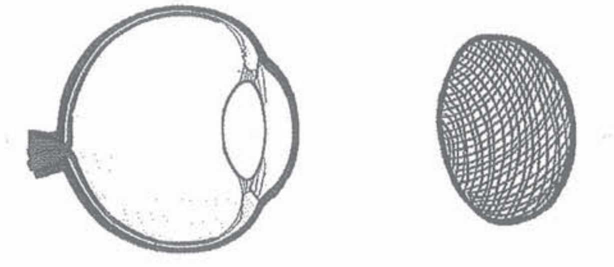

Figure 3: The human camera-type eye and the insect compound eye.

where two of the most prevalent are the camera-type eye and the compound eye as seen in figure 3. The human eye is a camera-type eye using muscles to change the focal length. Whales have a remarkable hydraulic system for the same purpose. It allows for good vision in and out of the water and compensates for increased pressure at the sea floor. Insects have compound eyes which allow parallel processing of signals and therefore faster motion detection and image recognition. The trade off is a reduced brightness.

The knobcone pine growing in the northwest USA has a fire dependent behaviour that can be used for fireproofing applications. The cones will remain closed for as long as 30 years and only open and throw its content of seeds when exposed to the high temperatures in a forest fire. In this way the seeds can start to grow on fresh land with only very few competing plants.

Light owls possess highly developed hearing. Owls are able to hear living prey moving under the leaves at the ground while flying. The hearing is particularly efficient in the range of 1-10 kHz. Some of the strictly nocturnal species have facial disks that collect sound from a larger area. The shape of the disk can be altered using facial muscles.

Metallic look and bright colours are achieved in beetles. Basically the spectacular appearances results from light interference in thin layer structures – see *Figure 4*. The reflectors can reflect broadband light which gives the metallic look. This only requires a single birefringent substance organised in many thin layers with varying thicknesses.

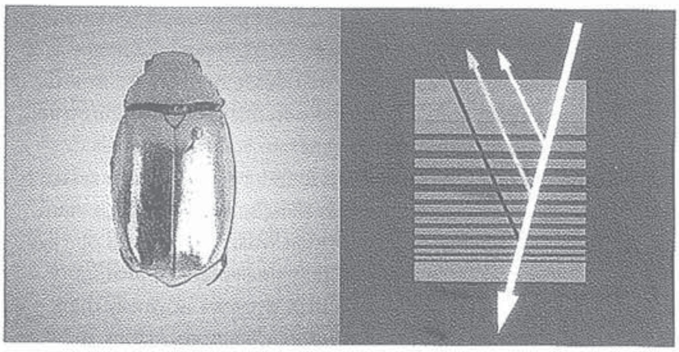

Figure 4: The beetle Plusiotis resplendens has a bright golden metallic appearance. The multilayer nanostructure in the beetle shell gives inspiration to polymer coatings looking like metal (Lenau and Barfoed 2008).

(Waters 2007) reports on echolocation in air and water where bats and tooth whales use sonar to locate prey. He makes a distinction between a biomimetic approach and a biologically inspired one. The point is that the sonar systems used in nature are highly specialised and copying these solutions would only have limited value. But studying the principles in natural sonar can be very fruitful when designing artificial systems.

Despite the many good examples of biomimetics design that can be found in the literature, engineers face a challenge when using nature as an inspiration source namely how to find the relevant cases. (Vincent 2006) point out that a technical abstraction of the biological phenomena is required and this is often done by biologists that draw attention to interesting or unusual biological topics and uncover the general principles.

Biomimetic design involves a number of steps as illustrated in *Figure 5*. They include 1) a search for relevant cases, 2) a proper analysis of the biological solutions, 3) identification of design principles and 4) design of the desired artefact (Shu et al 2003). Furthermore the search most often requires refinement activities where the search area is widened as well as focused.

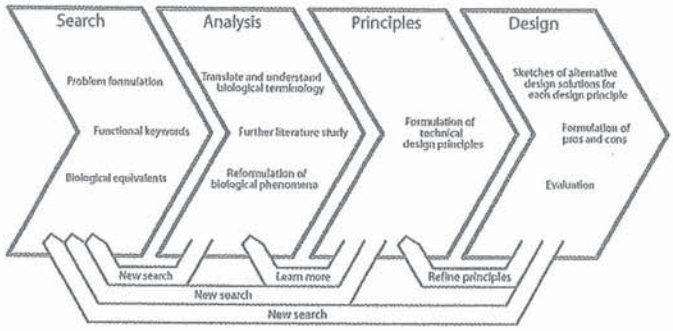

Figure 5: Steps in biomimetic design

Design in product development

Product development involves a number of tasks and people from the initial identification of a market need, formulation of requirements to the conceptual and detailed design. Biomimetic design will typically be one of several activities required to make a good product and it will be targeted towards a well defined sub-problem. For example will the design of a sensor probably be part of a larger task to make an artefact that can register its surroundings and take some action on the findings. A sensor like an artificial nose for food testing could be part of a system that brings the food close to the "nose", transmits signals from the "nose", remove the food again and maybe clean the "nose" before the next test. The other elements in the system can have a large impact on the sensor and how it should be designed. It is therefore important both to make a good formulation of the sub-problem to be solved but also to remember the system context in order to ensure a good product.

Biomimetic search

The design object treated in this paper is very broad and not typical for a design situation where a solution for a given problem is sought. Simple sensors detect whether a condition is present or not, while more advanced sensors can measure the strength or amplitude of the signal. Some sensors can determine a variation of a signal like the frequency of sounds or the wavelength of light. However, even though the topic is broad it can be used to illustrate how biomimetic design can be applied. We have chosen to make a biomimetic search starting very broadly looking at the 5 human senses: feeling, sight, hearing, smell, taste.

Basically a biomimetic search can be done using different sources of biological information. One that is obvious to researchers is the scientific literature in the form of books and journal papers. Within the last years this has become even easier since on-line searches can be accessed through most University libraries. This is a good and valuable source but it is limited to the specific topics that have been studied.

The Toronto method for biomimetic design (Shu et al. 2003) illustrated in this paper uses a digital version of the standard university biological textbook "Life, The Science of Biology" (Purves et al 2001).

In engineering it is common to use keywords that relate to the desired function. These words will typically not find all the relevant matches in a biological text, and the first step is therefore to determine which biological keywords that would be equivalent to the engineering functional keywords. For example, instead of searching with "sense," which is a functional basis word, we searched with "receive" and "receptor" which we expected to be more likely to return helpful matches.

We got 164 matches with "receive" and 503 with "receptor." Even though this is a large number of matches it was possible to find the results on how sensory cells and chemoreceptors work (see below). This search also resulted in the finding that the sensing sensitivity is dependent on the number of receptors an animals have.

In order to limit the search the topic can be narrowed. For example does the sensing activity involve 'recognition'. This is a functional keyword that is not typically used in the biology text. From reading the text sections on receptors it turned out that "bind" was the corresponding biological keyword. Once we saw that chemoreceptors used the technique of binding, we were intrigued to see what other results the search keyword "bind" could lead to. Since, "bind" alone would generate all different types of results it was combined with "recognize" and "sense." This gave 17 and 14 matches, respectively.

Some artificial sensors have already mimicked the biology. For example, do photoreceptors and optical sensors both work by absorbing photons and eardrums and thin membranes in microphones both collect sound waves? For the development of new sensors it could therefore be interesting to focus on analogies from chemoreceptors. These are receptors that respond to specific molecules used in olfactory or gustative sensing. The sensory cells actually recognize the characteristics of molecules by specific binding between the molecules and receptor proteins. If they bind in a certain way, the process of generating action potentials is activated.

A specific example of animals using chemical signals, is arthropods that apply pheromones to attract mates. They sense these hormones released by the other sex by the work of chemoreceptors, similar to smelling or tasting.

A snakes' tongue samples the air and delivers it to olfactory receptors present in the roof of its mouth. This is why the snake continually darts its tongue in and out, and actually smells the environment in a much quicker way than is possible with its very slow speed respiration.

Biomimetic analysis

Having found a number of matches the next step is to understand the found biological analogies. This is not a trivial task for engineers since most engineers do not have a detailed biological insight and knowledge of the vocabulary (often in Latin) used.

A basic mechanism in biological sensing is the translation of physical input into electric signals in the nervous system. For animals, sensory cells are used in recognizing different sensory input. The phenomena associated with each sense is the same – only the

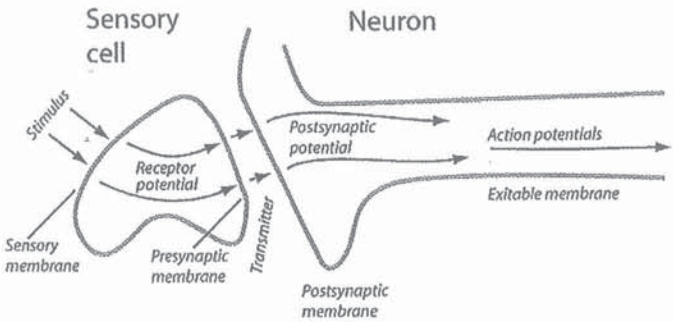

Figure 6: Sensory cell and neuron – based on descriptions in (Upsala Universitet 2008)

difference is the stimulus recognized by each sensory system.

The sensory system usually consists of a sensory cell and a neuron as shown in figure 6. The sensory cell has a few sensory membranes (receptor protein) that detect different types of "stimulus". For sensations such as touch, the membrane receptor protein would recognize pressure directly applied to the skin. In the case of smell or taste, odorants or food molecules "bind" to the receptor protein. When the receptor protein detects the "stimulus," it opens or closes ion channels and therefore changes the receptor potential (flow of ions) in the sensory cell. This causes transmitters to be released from the sensory cell (presynaptic membrane) to the neuron (postsynaptic membrane). The neuron then converts this potential (detected by postsynaptic membrane) into action potentials, so that they could travel in the nervous system. In essence, the sensory system upon recognizing stimulus creates chemical potential. This is converted into an electrical signal that can travel down the nervous system.

There are basically 5 different types of receptors that respond to changes in pressure, temperature, electric charge, chemistry and light as illustrated in *Figure* 7. The receptors in mechanoreceptors, thermoreceptors, and electroreceptors are themselves ion channels. The activated receptor proteins of chemoreceptors and photoreceptors initiate biochemical cascades that eventually open or close ion channels. The sensory cell itself may generate action potentials as a result of stimulation, or it may vary its release of neurotransmitter in response to changes in its membrane potential, and the neurotransmitter may induce another cell to generate action potentials.

One type of chemical receptors is found in the olfactory system. Compared to other mammals the smelling sense is less important for humans since we rely much more on what we see with our eyes. However, recent research indicates that smell plays a much more central role in our social behaviour than what we normally think – in particular odours that we register without being conscious about it.

Odours reach the nose as airborne molecules. In the top of the nasal cavity the molecules reach the olfactory epithelium where they are suspended in the mucus covering the epithelium – in other words they have to become liquid before being recognised. In the mucus the molecules reach the chemical receptors that send signals

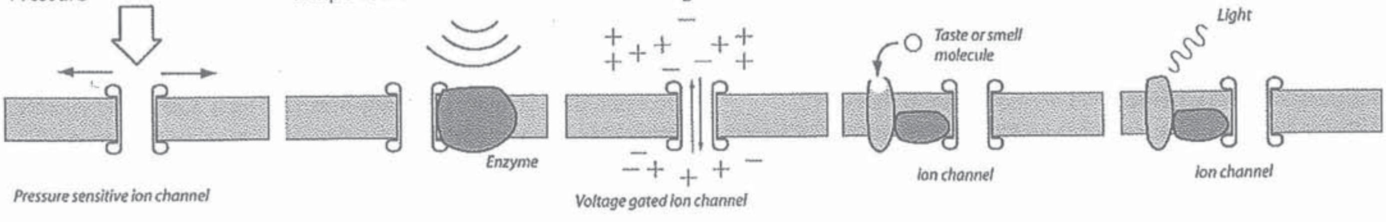

Figure 7: 5 types of sensors with ion channels in the sensory cell wall (based on Purves et al 2001)

to the part of the brain called the olfactory bulb.

The human nose has 400 different receptors but we are able to recognise about 10000 different smells (Bar-Cohen et al 2006). This is explained by a combinatorial recognition of odorants. A substance is not identified by only one receptor but by more than one. A single receptor is able to react on a range of different chemicals, and it is the combination of triggered receptors that identify an odour.

Besides the olfactory epithelium, mammals and other animals have a so-called vomeronasal organ placed at the floor of the nasal cavity and often connected to the mouth through a small channel (Halpern and Martinez-Marcos 2003). This organ registers pheromones which are odours "without smell" that shortcuts the conscious part of the brain and affect the animal similarly to hormones.

Identification of design principles

Based on the understanding achieved in the analysis the next step is to identify and formulate the design principles. The principles should be formulated in an abstract way in order to stimulate the generation of design concepts.

An interesting and relevant design principle in the odour recognition is the combinatorial identification of a large set of substances based on smaller set of sensors. This is relevant not only to odour recognition but to any situation where individual members of a large population should be identified.

A number of design principles are found in the way the ion-channel is activated. The simple principle is that the activating agent directly causes a changed condition in the sensor similar to mechanoreceptors, thermoreceptors, and electroreceptors. The more complex principle in the chemoreceptors and photoreceptors is an indirect activation where an extra link is inserted between the registrating part of the sensor and the part of the sensor that sends a signal further.

The formulation of design principles could also lead to a new search. For instance, are the signals described in this paper translated into electrical potentials that travel in the nervous system. A new search could explore how signals are transported and this could lead to results like hormones transported in the blood veins or hydraulic pressure as used in plants.

Design of artefacts

Having a number of different design principles the rest of the process is like normal designing. For each principle should alternative design concepts be formulated and drawn? In the following a few examples of design ideas inspired by the design principles are described.

The combinatorial principle from the nose is actually already used for the development of artificial noses, which are industrial sensors for odour detection (Bar-Cohen et al 2003). A major challenge here is to identify the basic types of odours that should be detected. A valuable input could be knowledge of the 400 basic chemoreceptors and the molecules they recognise.

The direct activation principle could be used to make a combined sensor and valve for the control of liquid flow as shown in figure 8. A thin membrane with holes will increase the diameter of the holes when the membrane is stretched. In this way a higher pressure would lead to an increased flow and by tuning the membrane thickness and the size of the holes a desired characteristic behaviour could be achieved. A foam membrane with holes could deliver the reverse relation between pressure and flow. As the foam membrane is expanded the holes become smaller.

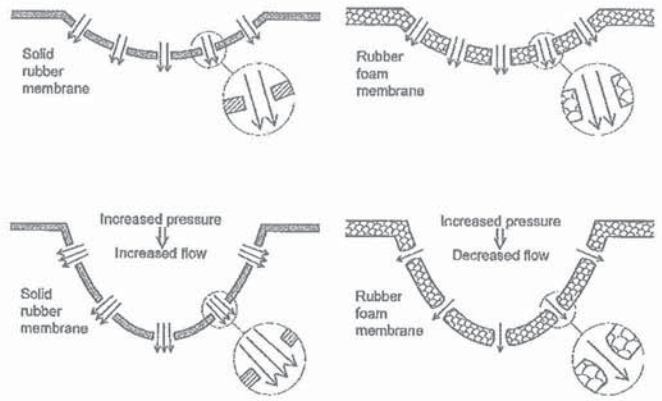

Figure 8: A solid rubber membrane with holes will give increased liquid flow for rising pressure while a foam membrane will behave in the opposite way. This way of combining a sensor and a valve is inspired by the direct activation principle in sensory cells.

Conclusion

Nature has had several billion years to develop and select a myriad of organisms that solve problems in many different ways. Biomimetic design is a way of using the experience in nature to develop new technical artefacts and refine their functionality. This can be done by directly copying solutions from nature like the Velcro fastener from the burr or it can be more indirectly by getting inspiration for the design process. A major problem in biomimetic design is finding the relevant analogies to actual design challenges in nature. We have in this paper described how a systematic method for searching a biology text using keywords can be used to generate new ideas for design work.

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