On the Stability and Robustness of Biological Systems

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Biological systems are often remarkably robust to changing environmental conditions. This property can, however, not be generalised simplistically. In fact, in all biological systems, certain parameters are subject to tight control, and even small deviations result in malfunction or even death of the system. Examples for such parameters include the temperature of the human brain, as well as that of bee hives and ant-hills, blood glucose levels, and more. In another perspective, biological systems are not entirely robust against failure of modules either. For example, certain failures in the brain result in mental failures such as neglect, and certain genetic failures result in cancer.

Biological systems are thus not robust in an unspecific, generic quantitative sense, according to which the total number of states in which a biological systems functions is greater (by orders of magnitude) than the number of states permissible to technical systems. Robustness in a completely general sense is precluded by the No Free Lunch theorem.

The key to the autonomy of biological systems is that such parameters are controlled by the system itself. Thus, while the cardinality of the set of permissible states may not be larger for biological systems than for technical ones, biological systems interact with their environment in a way that increases their chance of encountering favourable conditions in the future. Technical systems, on the other hand, tend to consume their resources, and to incorporate little or no anticipation of the effect that their actions or output may have on their environment, and how this may feed back on them.

The artificial plant from a LindEvol simulation [3], shown in Fig. 1 provides a simple illustration of this principle. The many genes in the genome form a discouragingly complicated network. However, only the "germ cell gene" is initially expressed, and only genes activated by this event are expressed subsequently. Thus, the system exploits the fact that it starts out with a single germ as a mechanism of controlling which of the pathways of the network become active.

In computer models such as LindEvol, the extent to which biological systems can gain control over their environment and their information processing is limited. In evolutionary algorithms, the interpretation of the genome is often prescribed externally by a fitness function that is entirely beyond the control of the evolving population.

Biological systems in nature represent the opposite extreme. They are genetically autonomous, i.e. all immediate processing of genetic information is carried out by components that are encoded, and hence controlled, by the genome. This principle of autonomy is a unifying theme for phenomena that would otherwise appear quite

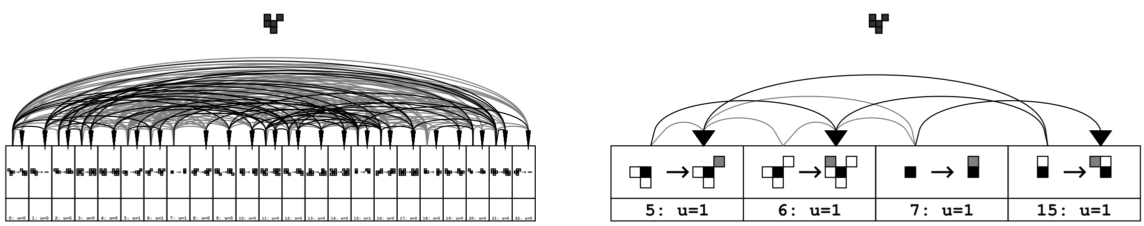

Figure 1: The 20 genes in the genome of an evolved, artificial plant form a confusingly complex regulatory network. Restricting the network to the genes that are activated during development reveals the biologically relevant pathways that control development.

unrelated:

Evolution of regulatory information is shaped by the principle of genetic autonomy. Specifically, genetic autonomy induces a link between the information content of transcription factor binding sites and the information content of binding sequences [4].

Active Perception is a paradigm that currently emerges as an approach to improve presentation of information (e.g. [2]). With devices that convert visual information to aural or olfactory signals, it has been found that these are much more useful to blind people if the user can control the direction from which the device samples information. It thus seems that humans have a rather generic capability to focus on information that they can meaningfully decode and learn from.

Revealing the principles underlying this capability may lead to new techniques for "programming" complex systems in order to exploit their potential of non-classical computation.

Sustainability is achieved by biological systems if they successfully create and re-produce the environmental conditions which they require for robust existence. Stability through sustainability is an important property of ecological systems at multiple scales, including the global scale, where it is discussed as the Gaia principle [5].

Organic Computing [1] is an emerging interdisciplinary field of science and engineering focusing on using the organisational principles underlying biological systems to design complex, autonomous technical systems that are self-configuring, self-protecting, self-healing, self-organising. An important objective in this field is the reduction of effort for developing and maintaining technical systems by equipping the systems with capabilities to evolve autonomously and "delegating" tasks of design, implementation and maintenance (often optimisation tasks) to the system itself.

Evolutionary epistemology has pointed out that ontogenetic *a priori* knowledge (i.e. knowledge not derived from the individual's own experience) may be phylogenetic *a posteriori*, i.e. it may be "genetically built into the organism" because its ancestors have been exposed to the condition in question sufficiently frequently for some behavioural adaptation to evolve. This perspective underlines once more that the capability of biological systems to adequately react to (ontogenetically) unknown conditions are inextricably linked to the individual system's evolutionary history, in which the condition in question may have been encountered.

In conclusion, autonomous computing, as sketched here, can be seen as a non-classical approach to computing that contrasts the classical, top-down, allopoietic approach by introducing autopoieteic elements. Advances in this field may, on the one hand, facilitate the development of novel complex technical systems, and on the other hand, they may provide insight into biological systems and enable us in the long run to design and use biological systems and our living environment in a rational and sustainable way.

References

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