Chapter 2
Being Bioinspired

As outlined in the introduction, an important part of the work in this thesis deals with the integration of biological systems and processes in technology. In order to understand what the implications of this are, and what it means on a practical level, it is of interest to discuss what the intermingling of biology and technology consists of. In this chapter, I will try to present some aspects of how nanotechnology brings biology into the realm of technology, in ways that to a certain extent are different from the bioscience of the late 20th century. I will also discuss how this interrelation disrupts the dualistic relationship between nature and technology, creating a world of hybrid entities. The purpose of this is to provide a better understanding of the ontological status of the different systems and assembly processes presented in this thesis. An important aspect of this is the notion that technological research is not descriptive, but performative. We, as researchers are not just studying the world, we are also creating it.

To illustrate the merging of nature and technology, I will discuss two different examples approaching each other from opposite directions. In 2010 Craig J. Venter and co-workers presented a bacterial cell controlled entirely by a synthesized genome [1]. Aside from the aspect of wanting to study e.g., gene function in a controlled way, an important goal within synthetic biology is the creation of minimal cells for engineering purposes. This would then constitute a purely technological entity with a designed constitution in the form of a living cell. The other perspective is represented by protocells, constructed membrane compartments having cell-like properties. Protocells are technological entities designed to perform certain functions where their life-likeness is part of the function [2]. Here, we see transitions were biological objects are designed to become more like technical devices, and vice versa.

Both these phenomena are clearly effects of the development of molecular biology, which offers access to biological system on the level of individual molecules. This access is associated with a certain merging of biology and technology. In "Modest_ Witness@Second_Millennium." Donna J. Haraway argues that biotechnology replaces the previously dominating conception of "Nature", characterized

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by whole organisms, with the conception of “Life”, materialized as information in the form of genes [3]. While whole organisms encompass life, genes are inanimate objects acting as a constituent for life. Genes also have transferable properties at a completely different scale than a complete organism has. These things together allow genes, and the living organism that host them, to become a technological entity. Of course, living organisms have been part of the technological domain before the advent of bioscience (breeding of livestock and crops in agriculture is perhaps the most striking example). However, this relation has been an external relation between living and non-living objects rather than a relation that transgresses the boundaries of the individual organism. The genetic material of an organism is both an internal and an external materiality (see schematic is Fig. 2.1).

Haraway writes:

> Transgressive border-crossing pollutes lineages-in a transgenic organism’s case, the lineages of nature itself-transforming nature into its binary opposite, culture. […] The revolutionary continuities between natural kinds instaurated by the theory of biological evolution seem flaccid compared to the rigorous couplings across taxonomic kingdoms. (p. 60)

The transitory process when an object becomes a technological entity has close ties to the question of patentability. Haraway writes that, as late as 1980, is was possible to patent biotechnical processes but not the microorganisms themselves. In 1980 however, a patent was approved for a bacterium that breaks down petroleum. The bacterium was ruled to be a patentable composition of matter and a product of human ingenuity.

Although much of this development occurs in the latter part of the 20th century, it should be noted however, that the conception of living organisms as machines is older than contemporary bioscience. The poster “Der Mensch als Industriepalast” by Fritz Kahn from 1929 depicts a cross-section of a human being (Fig. 2.2). Instead of having internal organs, the body is filled with connected industrial facilities performing all bodily functions. The poster works only on the level of metaphors but is still a striking representation of how the human bodily processes are incorporated into industrial logic and structure. Further, it is worth noting that the poster is produced during a period of great expansion of the German chemical industry.

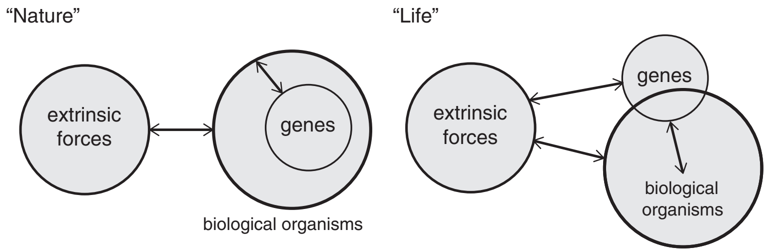

Fig. 2.1 Interrelation patterns for the organism-centered “nature” and the gene-centered “life” ontologies. The extrinsic forces can be any living or non-living entity acting upon the specified organism and its genome

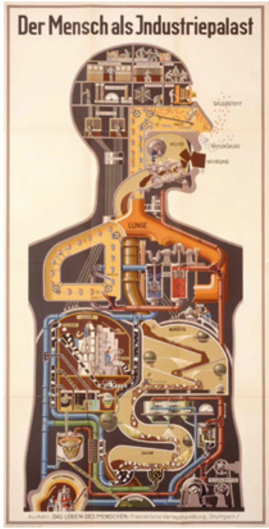

Fig. 2.2 "Der Mensch als Industriepalast" Fritz Kahn 1929. Courtesy of the National Library of Medicine

How does this all fit in with nanotechnology? While biotechnology more or less hijacks biological organisms to serve a specific purpose, nanotechnology completely removes systems and processes from their biological context. Nanotechnology has been defined as structures with dimension in the size range of 1–100 nm. This size range contain both the upper limit for synthetic structures and the lower limit for lithographic structures, as shown e.g., by Whitesides et al. in 1991 [4]. Moreover, this size range encompasses a wide variety of molecular structures, making them ideal candidates as bridging units between the molecular and lithographic domains. Sarikaya et al. describe techniques based on proteins with affinity to inorganic surfaces which could function as a biomimetic bridge between the macroscopic-technological realm and the molecular one [5].

2.1 Self-Assembly

For many bio-inspired technological systems, there is one process that is continuously reoccurring: self-assembly. Self-assembly is the process where a number of disordered entities spontaneously come together to form a system with higher order, often with emergent properties. This process is driven by the interaction of the constituting objects, and not by any external force acting on the system. The concept of self-assembly can be applied to a wide range of systems, acting on different levels. Self-assembly is not only a process found on the molecular scale, several macroscopic physical phenomena such as galaxies, weather patterns and schools of fish are characterized by self-assembly [6]. Even human societies carry aspects of self-assembly. How is self-assembly within these different domains related? Here, it can be useful to turn to Alfred N. Whitehead's conception of society. Michael Halewood writes in "A. N. Whitehead and Social Theory" [7].

> for Whitehead, societies refer to the achievement of groups of entities, of any kind, in managing to cohere and endure and thus to constitute some kind of unity. The term social refers to the manner and milieu in which such endurance is gained. Rocks, stones, amoeba, books can, thus, be considered to be societies. (p. 85)

According to Whitehead, societies are systems of interrelation between entities of any kind. Since self-assembly as a process is based solely on the interaction between the comprising entities, self-assembled systems are societies in themselves. This does not mean that all self-assembled systems are identical or that something which applies within one system necessarily holds for all. However, many of the fundamental aspects are transferable and it is reasonable to analyze different self-assembled systems using similar theoretical frameworks.

In this text, I will discuss self-assembly from a molecular and supramolecular perspective, outlining some of the key features of self-assembled systems. Where applicable, I will try to draw parallels to other, non-molecular systems, highlighting similarities and differences. Self-assembly within chemistry has been studied extensively by Whitesides [4, 5, 8]. He has also made a great effort to try to define what self-assembly in chemistry actually is. In order to distinguish self-assembly from other formation processes, he has put up five criteria that is defining for systems characterized by self-assembly [8]. The first criterion (1) deals with the self-assembling components. As previously stated, objects that undergo self-assembly are initially in a state of disorder. This disordered state can be e.g., molecules freely moving in solution or polymer subunits in random coil conformation. Nomadic populations of early human history can be seen as a type of disordered state since they lack physical structure, e.g., in the form of a localized settlement. Entities that undergo self-assembly need to have properties that facilitate interactions that lead to a more high-ordered state. Further, (2) interactions between components consist of a balance between attractive and repulsive forces and are generally of weak nature, e.g., hydrogen bonds and van der Waal forces. The dependence of weak interactions is associated with another important characteristics of self-assembled systems: reversibility (3). Since molecules move randomly by diffusion, they probe all reaction pathways available to them. For complex assemblies to spontaneously form, the process needs to be guided through a series of states of increasing stability allowing continuous rearrangements. For this to be possible, the strength of the bonds has to be of the same order as the thermal fluctuations of the system, hence the requirement for weak interactions.

Arranging large numbers of individual components into complex assemblies equals a large decrease in system disorder. Following the second law of thermodynamics, this decrease in disorder comes with an energetic cost. The driving force for self-assembly is provided through the change in interaction between the self-assembling components and their environment (4). If the components have properties that force the molecules in the environment to assume a highly ordered conformation, the formation of the assembled structure can lead to an overall decrease in order if it leads to a release of the environment molecules from this unfavorable conformation. The final point is perhaps obvious: the components must be mobile (5). This is a natural consequence of the dependence on diffusion for formation. The combination of weak and reversible interactions and mobile interacting objects is akin to the rise of cities. Following the reasoning of Manuel De Landa, cities are intensification of material flows in crystallized form [9]. One of the earliest processes leading to formation of cities was the cultivation of plants. Plants, in turn, are essentially stored energy from sunlight. Thus, cultivation of plants represents intensification of energy. Through the interaction of the many individuals in a city, material flows can change and transform.

It is of interest to take a closer look at how the interaction between individual subunits can lead to the self-assembly of complex, defined systems. Self-assembly is different from aggregation in the sense that in an aggregated system, the interaction between components is unspecific and the formed structure is disordered. In a self-assembled system, a defined structure is formed through specific interactions between the comprising entities. This specific interaction is called molecular recognition and consists of patterns of non-covalent bonds. Examples of molecular recognition are duplex formation between two complementary DNA strands or folding of proteins through the creation of specific patterns of hydrogen bonds. By design of patterns of molecular recognition, the structure of self-assembled systems can be controlled. This controlled formation is called supramolecular chemistry, a term coined by Jean-Marie Lehn. Supramolecular chemistry is a wide field ranging from biology to physics, where the focus is not on the formation of covalent bonds, but on non-covalent bonds [10–12]. Lehn writes [11]:

> Supramolecular chemistry, the chemistry beyond the molecule, is the designed chemistry of the intermolecular bond, just as molecular chemistry is that of the covalent bond. (p. 1304)

Supramolecular chemistry takes processes that are ubiquitous in biology, where components assemble from the bottom up rather than top down, and applies them in chemistry. The benefit of supramolecular chemistry is that it facilitates the creation of structures that are very difficult, or even impossible, to synthesize using conventional chemistry. This is particularly true for DNA nanotechnology, where molecular recognition patterns are designed to create a plethora of structures on the nanometer scale. In the combination of supramolecular chemistry and self-assembly, we find perhaps the most obvious example of how bio-inspired nanotechnology is qualitatively different from conventional technology. It is also through processes such as self-assembly which nanotechnology can widen our conception of what technology can be.

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