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Executive Summary

Embodied artificial evolution (EAE) is an 'umbrella' term and vision to aid the development of a high potential research area. The essence of this vision, refined through the course of the Evobody project, can be briefly summarized as follows. Evolutionary computing as we know it today is 'disembodied', performed in an imaginary computer space. However, recent advances (e.g., 3D printing and molecular engineering) make it possible to move evolutionary computing outside traditional computers and make it 'embodied'.

There is a historical perspective that aligns biological evolution, computer simulated evolution and embodied artificial evolution:

- 19th century: "evolution" is a passive concept, a theory, that is used to explain a past process, e.g. the origin of species, etc. – **Biology**.
- 20th century: "evolution" is an active concept, a tool, that is used to start computational (digital) evolutionary processes that produce solutions to problems – **Evolutionary Computing**.
- 21st century: "evolution" is an active concept, a tool, that is used to start physical evolutionary processes that produce artifacts – **Embodied Artificial Evolution**.

The EvoBody project identifies this line and explores the next big step: Embodied Artificial Evolution (EAE), where human engineered (cf. "Artificial") evolutionary process take place in real time and real space (cf. "Embodied").

Independent of what the dominant future technology might be, we face the new problem of the integration of methodologies, paradigms and approaches from different areas of biology, chemistry and material science into classic robotics. This new integration will require a re-structuring of the current research landscape, which will not only essentially change the way we think about robotics, but also extend the scientific and technological boundaries for synthetic systems. Materials science, bottom-up chemistry and genetic engineering are especially relevant for open-ended evolution and unbounded self-development in autonomous systems.

We believe that EAE is a high potential research and application area, and by this report we wish to promote developments in this direction. This exploration includes a review of the state of the art (key people, projects, scientific journals, etc), a discussion of the most likely enabling disciplines and technologies for EAE, as well as an elaboration of the main scientific, technological, and societal challenges.

Chapter 1

Evolution of Things

There's no sense in being precise when you don't even know what you're talking about. (John von Neumann)

Embodied artificial evolution (EAE) is an 'umbrella' term and vision to aid the development of a high potential research area. The essence of our vision, refined through the course of the Evobody project, can be briefly summarized as follows.

Evolutionary computing as we know it today is 'disembodied', performed in an imaginary computer space. However, recent advances (e.g., 3D printing and molecular engineering) make it possible to move evolutionary computing outside traditional computers and make it 'embodied'. We believe that this is a high potential research and application area, and by this report we wish to promote developments in this direction.

We have identified that the two major EAE enablers, distinguished by the physical medium, are: mechatrono-robotic systems (hardware, inorganic) and bio-chemical systems (wetware, organic).

In this chapter we try to make a step forward and offer a joint identity represented by the name embodied artificial evolution. In the next section we give a definition of the notion of embodied artificial evolution and later, in Section 1.2, we discuss some of its basic aspects, such as feasibility, usefulness and desirability. And, in Section 1.3 we give an overview of the evolutionary systems of the future. Finally, Section 1.4 introduces the remaining chapters of this report.

1.1 Definition of EAE

In general, the concept of embodied artificial evolution assumed here differs from the standard evolutionary computing algorithms in some important ways:

1. It involves physical units instead of a just group of digital individuals in a computer.
2. It has real 'birth' and 'death', where reproduction creates new (physical) objects, and survivor selection effectively eliminates them.

3. Reproduction and selection are not executed through a centrally orchestrated main loop, but in a fully asynchronous and autonomous manner by the individuals themselves. Consequently, the population size may increase or decrease 'by itself'.
4. Evolution can be driven by a combination of task-based and open-ended fitness.

Ironically, the term embodied evolution has been introduced in evolutionary computing for systems that do not have all four properties as listed above. Watson *et al.*[1], use evolutionary computing for online optimization of robot controllers. In their system, the robot controllers are deployed on actually working robots. Furthermore, the evolutionary operators are also implemented inside the robots and are executed on-the-fly, as the robots are going about their tasks. Birth and death, i.e., reproduction and survivor selection, is restricted to the digital space of all possible controllers, on the robot's processors. However, fitness evaluation happens *in vivo* here as the reproductive probabilities of any given controller are determined by the real-world performance of the robot driven by that controller. In the present literature the name online, on-board evolution is also used for such robotic systems.

The main difference between such systems and embodied artificial evolution as perceived by us is the notion of embodiment. To be specific, in the systems mentioned previously the objects to be evolved are digital, hosted by a physical robot that has an inner computer running an evolutionary algorithm. In 'real' EAE, the objects to be evolved are physical – but they may include digital components, like controllers and parameters. If needed, these two cases could be distinguished by calling these two types of systems 'weakly embodied' and 'strongly embodied', respectively.

The fitness function driving an EAE process can be task-based, open-ended or both. Evolutionary computing almost exclusively works with task-based fitness that represents the optimization or design objectives of the given application. However, natural evolution is not optimizing towards a specific objective: fitness is open-ended, geared towards a better adaptation to a given environment. Task-based fitness represents performance w.r.t. solving an specific problem, while open-ended fitness drive the population towards better computational capabilities in general.

With respect to the enablers, it is interesting to note, that in case of a robotic application it is possible to separate the body, i.e., the physical robot (with its wheels, sensors and etc.), and the mind, i.e., the controller regulating the behaviour of the robot. Consequently, the task of designing them also can be split into two and also combined, if needed. For the task of designing bacteria, this is not possible, because the regulatory mechanisms in bio-chemical organisms are not separated so clearly from the bodies to be regulated.

Yet another difference between a robotic application and a bio-chemical one is the fact that a robotic object is more controllable. Robot bodies are built and robot controllers are programmed by the human experimenters. Even if we consider evolutionary – thus autonomous – development of robot bodies and controllers, the process is driven by human designed operators. These operators are usually simple: complexity emerges by their interactions. This is not the case for bio-chemical organisms, where the operators are those invented by nature. These are often very complex to understand and to steer. Replacing one mutation operator by another one can be easy in an evolutionary robotics application, but switching off one molecular interaction and switching on another one can be (nearly) impossible.

1.2 Basic Aspects of Embodied Evolution

1.2.1 Feasibility

On analysing the feasibility of EAE systems, it is expected that such systems will happen in the near future – specially if EAE development is tied to the engineering of biological systems. However, as a multi-disciplinary effort, the steps toward it are not straightforward. On the one hand, some necessary elements to realise EAE systems already exist, but there are still a number of crucial elements missing.

For instance, (self-)replication is an essential element for EAE systems to be obtained. At the moment, there is no non-biological system that can (self-)replicate[1]. In this case, to obtain self-replicating non-biological systems, smart material engineering is required. Note that this is differs significantly from self-assembling approaches from available building blocks, as seen in Zykov *et al.* [3].

On the other hand, there is still room for studying 'disembodied evolutionary' processes. Existing methods, such as simulation and evolutionary computing, remain relevant as they help understanding general properties of evolutionary systems and can be seen as a design toolbox. However, the level in which systems are described might need to suffer considerable changes.

With EAE, we could easily end up with a system that we cannot fully understand or, perhaps, cannot control. In order to prevent this from happening, we need a method(ology) capable of controlling evolution. In particular, we need a methodology (or, methodologies) that is all-inclusive (e.g., adaptivity). In this context, top-down and bottom-up engineering can be distinguished. Bottom-up engineering assumes that we have complete understanding of the effects of our manipulations, and this does not hold for complex adaptive systems. But, is bottom-up engineering more likely to generate unexpected indirect effects? Or is top-down control (e.g., manipulation of selection or selective process) less likely to have some unexpected effects and, as a consequence, deliver more robust systems?

Furthermore, some smart dialogue/interface mechanism should be provided in order to obtain the best interaction between system and designer.

1.2.2 Usefulness

In terms of potential fields of application of EAE, the following could be identified: biomedical (already used for drug design), adaptive materials; and, adaptive robots. In fact, one of the largest current application domains is the bio-medical research and drug discovery. One example of a potential market is enhancing immune system with EAE technology, being a means of providing better resistance to infections. Another possiblity is the development of the personal companion, integrated into the body and enchanting mental and physical capabilities of humans.

[1]Here, non-biological is understood as systems that are primarily non-molecular. However, the concept can have a wide range of interpretation, see more in [2].

In general, the tasks performed by EAE systems should have a high level of difficulty, including (but not restricted to): (i) changing environments; (ii) multitasking and multi-objectives applications; (iii) problems where robust and/or distributed solutions are required; (iv) on designing emergent capabilities; and, (v) where simulation is not enough to make use of numerical artifacts. Furthermore, systems might present other interesting characteristics such as the capability of learning properties from the environment, empowered by evolution and social networks, as well as personalisation of its components, where the machinery is adequate to specific (personal) needs and requirements.

EAE systems exploit the features of the body: you need a body to be able to do something in the environment, to interact with the real world, but you get for free the properties of the material used, physical-chemistry and self-organisation. Finally, EAE can represent a tool for studying properties of pre-Darwinian evolution.

1.2.3 Desirability

In general, designing and implementing different EAE scenarios seem to be necessary before all aspects of such systems can be coherently analysed and evaluated.

With respect to commercialisation, the overall feeling is that technologies and ideas should be of public domain. In this context, evolutionary technologies should be developed to make processes more efficient and/or provide social benefits, rather than just being developed for the benefit of commercial interests.

However, commercialisation may 'prove' relevance and it might be necessary in order to stimulate research funding. Examples of possible commercial applications of EAE systems are:

- Adaptive/evolutionary packaging in supermarkets. That is, physical packages (color, shape, images) that are produced on-the-fly adapting to the customers' preferences.
- Adaptive/evolutionary recreational animals (artificial pets).
- Co-evolutionary vaccine development.

In any case, systems should be robust. Fault tolerance is, therefore, imperative.

There are, however, a number of points that can constitute reasons on why we might not want embodied evolution systems to be accomplished. For instance, as mentioned previously, those systems might be useful for the creation of personalised items, products and services that can fit one's needs and requirements. But this, of course, opposes the concept of general applicability of systems. As a consequence, EAE systems might become very much dependable on the applications that they were designed to. Considering that EAE systems are expected to be of high complexity, each product might become a research project in itself. The key aspect is the balance between general applicability and personalised functionality.

Because we might not be able to predict all the properties and envision the true power of EAE systems, we might run the risk of dealing with uncontrollable technology. And we might not want to simply accept this risk. So, once an evolving technology is in place, a mechanism that allows us to stop the system from running out of control might be required. Besides, evolution may not be fast enough when used as means of adaptation. Moreover, the issues of stability, trust and controllability can be hardly ensured. Open-ended evolution and controllability are in opposition. Furthermore, EAE might produce things that we do not fully understand, bringing up other issues such as reliability, safety, and responsibility in case of failure.

Finally, EAE is time and material consuming, and it will (most probably) produce solutions that are not optimal as well as many individuals that fail. It might become trapped in history: once a path is chosen it is very difficult to reconsider and turn around. That is, EAE needs a fast turn around time to be useful. And, recycling of materials is essential.

1.2.4 Concerns

The major **challenges** of EAE identified so far:

Embodiment The realisation of hardware components that can effectively carry out evolution.

Multi-disciplinary Collaboration The interaction and cross-fertilisation between ICT, bio-technology and materials science. Putting those relevant areas together is imperative to realise EAE. Incentive of basic, fundamental research is needed.

Role of Disciplines How to feed information into such a system? Or, more generally, what is the role of ICT in bio-chemical EAE? And of bio-chemical developments in ICT?

Materials and Energy How to design an evolvable system, which uses properties of free environmental materials and energy? What elements can be evolved and which principle(s) can underlie such EAE systems? Are these Darwinian principles?

Evolutionary Design Being able to design systems based on evolution principles, a concept that we do not fully understand.

Mind & Body body and controller (i.e., mind) should evolve together. In other words, there is a need to consider a parallel embodied evolution of body and mind.

A number of **obstacles** could also be foreseen:

Objectives Biological populations evolve to survive and reproduce, not to solve specific problems. But, here, it appears that we might want to develop systems with specific goals and that have a number of particular properties and characteristics. Open-endedness versus user-defined purposes.

Complexity The complexity of engineered systems can become intractable, unless the right design tools and methodologies are used.

Guaranteed Results How can we accomplish what we want without an external evaluation loop and human intervention?

Finally, that are some **dangers** associated to the achievement of EAE:

Runaway Evolution We should not run the risk of loosing control over the system. We may need 3 laws for embodied evolutionary systems (a la Asimov's 3 rules of robotics).

We will probably need a stop button that can allow us to cease system execution at any point.

Unprecedented Legal Issues It is necessary to distinguish the method and the end product. But what happens then? Could method(s) be of public domain, and the end product be owned? And, who owns the 'evolving stuff'? Can you, in fact, patent the evolutionary process?

Other Unprecedented Issues Other issues regard trust, verification and liability of the EAE systems. For instance, what can we expect in terms of costs of test and evaluation before we can gain enough confidence that the system does what it was designed for?

1.3 The Future of Evolutionary Systems

In this chapter we introduced the concept of embodied artificial evolution, i.e., evolutionary systems that are (i) embodied because operators (reproduction, selection, fitness evaluation) are implemented in/by the individuals that undergo evolution, and (ii) artificial because the individuals and the population as a whole were designed (or, programmed) to fulfil a certain purpose, executing a certain task, besides allowing open-ended evolution to take place.

Even though some elements of EAE already exist, considerable advances, both scientific and technological, are necessary in order to achieve the embodied evolutionary systems envisioned here.'Real' (self-)replication, in which basic elements are reproduced and used in the creation of new entities, is still far from being realisable. Existing methods and algorithms for simulation and evolutionary computing will remain relevant as part of the designing toolbox. However, the level at which systems are described might need to undergo considerable changes.

Because we are unable to predict all the properties and true power of EAE systems at this moment, we might run the risk of dealing with an uncontrollable technology. Or, in the worst case, a *runaway evolution* scenario. The developed systems should be autonomous and evolutionary, but we might still want to be 'in charge'. Finally, as developments happen towards EAE systems, other issues should also be considered such as robustness, reliability and safety.

1.4 Structure of this Report

This resport is a result of the EvoBody project, during which a number of interviews with various researchers regarding their views on EAE where conducted. Even though no individual interview description will be provided here, the views of interviewed experts are coherently incorporated in the upcoming chapters. In the same way, the topics discussed during both EvoBody workshops are extensively described throughout this report. Embodied evolution definition, strengths and weaknesses were introduced in the current chapter, while EAE disciplines and challenges are covered in Chapters 2 and 3, respectively.

The avalanche protocol performed during the interviews and workshops, where experts were required to name relevant researchers, projects, and literature items, helped us to map the area of embodied artificial evolution. As a result, an extensive list of researchers, projects, institutes and organizations associated (somewhat) to EAE is given in Chapter 4. A literature overview, covering relevant books, journals and articles, is provided in Chapter 5.

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[3] V. Zykov, E. Mytilinaios, M. Desnoyer, and H. Lipson. Evolved and designed self-reproducing modular robotics. *IEEE Transactions on Robotics*, 23(2):308–319, 2007.

Chapter 2

Disciplines

> *It makes sense that whatever the topic is, it's more compelling if you can provide the audience with a range of perspectives, and you can cross disciplines. And you don't have to control what people take out of it.* (Bernice Johnson Reagon)

One of the main dissemination instruments of the EvoBody project was the site visits at universities, institutes and labs to conduct interviews with experts about their expertise and knowledge within the context of the project. We have incorporated the gained knowledge from these interviews throughout this report, and specially in this chapter.

In short, the chapter is divided in 5 sections: Biology, Chemistry, Computer Science, Robotics and Materials Science. Each section has the purpose of describing the related subject and also include the main issues discussed during the conducted interviews.

2.1 Biology

2.1.1 Genetics

Life evolves from common ancestors, and by means of natural selection and adaptation. Genes are the blueprint of all living organisms, and genetics studies them and attempts to explain what they are and how they work. The role of genetics in EAE lies, therefore, in the understanding of evolution: the inheritance of features through organisms' generations and the complex mapping genotype-phenotype.

As Keith Bennet states in [3], "... the true source of macroevolutionary change lies in the non-linear, or chaotic, dynamics of the relationship between genotype and phenotype – the actual organism and all its traits. The relationship is non-linear because phenotype, or set of observable characteristics, is determined by a complex interplay between an organism's genes – tens of thousands of them, all influencing one another's behaviour – and its environment."

Besides the relationship between genotype and phenotype (and proteine), there are also complex dynamics between the micro- and macro-levels in biological systems. Many researchers only look at the uni-directional relationship from micro to macro-level. But it is good to consider the other direction as well (from macro to micro), of which there are many examples in nature, e.g., when the environment is made by an agent. All these different inter-relationships are collectively called *multi-level interaction*[1], i.e., looking at biological systems as dynamic information processing systems at interconnected levels.

When defining evolution while keeping multi-level interactions in mind, we actually see that *evolvability evolves*: in biological systems, the genotype mapping is an evolved property. A consequence of this is that we should not always simplify parts of biological systems as much as possible. For example, genotype mappings should not be as compact as possible – landscapes of high-dimensional (e.g. 400) problems are very different from simple/simplified problems. In nature, we have high-dimensional systems, thus we should also model these as such.

By understanding the characteristics of evolutionary systems, the intricate nature of its components and their relationships, one may be able to apply this knowledge – in some extent – to artificial designed systems, developing – in the end – systems that not only resembles natural systems, but are in fact capable of carrying out evolution. In other words, true evolutionary systems. The feature of an organism, or a *trait*, comes from the genes in a cell. By putting a new piece of DNA in a cell, a new trait can be produced, and that is how synthetic engineering manipulates an organisms' genome.

Synthetic biology takes genetic engineering a step further by introducing artificially synthesized genetic material from raw materials into an organism.

2.1.2 Synthetic Biology

Biological systems are naturally equipped to fulfill evolutionary processes. Not only reproduction and self-preservation, but also selection and adaptation capabilities are inherent to those systems. A great challenge, however, is how one can manipulate such a system in order to obtain exactly what one is looking for. Or, in other words, how to *program* a bio-synthetic system. This task requires not only the attainment of certain properties and capabilities of the developed systems, but also other issues such as sustenability, safety and bioethics.

Examples of such bio-synthetic systems are the optimisation of the E.coli chemotaxis network, design of the cyanobacterial KaiABC circadian clock, and synthetic post-transcriptional networks[2]. In these examples, an evolutionary approach can be used by (i) calculating model parameters in the computer, e.g., the growth rate cost, to find out at which the selection pressure is highest; (ii) to give these parameters to the specialist micro-biologists; (iii) who can let the bacteria evolve for a significant period of time (typically, 1 year) under same conditions. This approach is then interdisciplinary endeavour between biologists and computer scientists. The latter have models about optimality/low-cost/information processing (e.g., disturbance decoupling in noise) that are applicable in biological systems. Although biology and computer science may seem worlds apart, information is a pivotal concept: in biological world this is concentration of molecules; in living systems information is transported by phosphor groups. This makes the bio-synthetic approach much like engineering, but with many energy constraints.

[1] http://www-binf.bio.uu.nl/ph/

[2] http://www.biologie.uni-duesseldorf.de/Institute/Mathematische_Modellierung

Such constraints also come into play when trying to affect the behaviour of living bacteria. We can take living bacteria (tens of millions), put them under a microscope, ask each of them how they are behaving (with fluorescent material) and punish them if they do not behave appropriately. It turns out that this (bacterial behaviour modification) is very hard. It basically boils down to how to get the selection pressure such that the bacteria evolve in a certain direction, for which currently apparata need to be designed to get this working. When this selection pressure can be controlled, this frees the way to create big organisms of living systems of bacteria. Still, biologists are sceptic about the success of such work and consider the control of selection pressure impossible. A feasible approach might be to let part of the information processing be done by a computer, not only by the cell, and feed output of the computer back into the bacteria (e.g., laser beam destroys part of the bacteria that don't do well enough).

Synthetic biology holds a great potential in terms of design of 'new forms' (e.g., engineered tissues and materials) that are able to respond to environmental changes and that incorporate the properties of living systems, as mentioned above. Synthetic biology is inspired by the convergence of nanoscale biology, computing and engineering. "Using a laptop computer, published gene sequence information and mail-order synthetic DNA, just about anyone has the potential to construct genes or entire genomes from scratch (including those of lethal pathogens). Scientists predict that within 2-5 years it will be possible to synthesise any virus; the first de novo bacterium will make its debut in 2007; in 5-10 years simple bacterial genomes will be synthesised routinely and it will become no big deal to cobble together a designer genome, insert it into an empty bacterial cell and voilá give birth to a living, self-replicating organism."[6].

Another application of synthetic biology is the re-programming of the genetic pathways of existing organisms in order to modify performed functions, or to create whole new functions. This is, for instance, relevant in the manufacture of new drugs. Synthetic biology also holds the key to the production of cheap (alternative) biofuels, the means of mediating natural disasters, and even the cure to some diseases. But it also holds the risks of creating life-theratening artificial organisms and bioweapons.

"The application of synthetic biology to architecture holds promise for solving major environmental problems. Further collaborations between biologists, chemists, architects and industry are needed to expand the range of tools, methods and materials available. As with any new technology, engagement with the public and with policy-makers is vital to direct future regulation that will protect public safety and address perceived risks." [2].

2.1.3 Summary of Interviews

Table 2.1: Summary of interviews: biology

Expert	**Main thing(s) we have learned**
Paulien Hogeweg	Developers of applications that use evolution (as EvoBody does) for any purpose should get a better idea of what evolution is, i.e., what it encompasses and what the related dynamic aspects are – in other words, should get a better bigger picture of evolution.

Table 2.1: (continued)

Expert	**Main thing(s) we have learned**
Markus Kollmann	Regarding the fear that artificial mutants may escape from the lab, the current state-of-the-art is such that the wild-type that evolved out there in the real world will win from the mutant developed in a lab.
Francesco Gervasio	One can approach the self-replication problem through chemistry as well as through biology. The first one seems much harder, though. Biologist can start with self-replicating units (cells) and "only" need to simplify them.
Eors Szathmary	Computer simulations can never approach the richness and complexity of the real world. However, these are necessary for genuine evolution. Embodied Artificial Evolution can teach us much more about real evolution than Evolutionary Computing has.

2.2 Chemistry

Chemistry is the science of matter and the changes it undergoes during chemical reactions. From the analysis of different materials, a better understanding of their composition and structure can be obtained, which is relevant for the study of organic and inorganic compounds and the development of new (alternative) materials, as well as the study of chemical reactions (and interactions) in living organisms.

An abstract model presented by Gánti in his book *Principles of Life*[5], so-called chemoton model, shows that three chemicalsystems can be combined in order to create the simplest living organisms: (i) a chemical motor, which is a self-reproducing system capable of synthesising chemical substances for itself as well as for the other two systems; (ii) a chemical boundary system, which is capable of spatial separation, of being selectively permeable to chemical substances, and of growth; and (iii) a chemical information system, which is capable of self-reproduction. Those systems could originate independently from non-living matter and then added together in order to form a living system. In other words, life is basically a chemical phenomenon and creating life in a lab is achievable. Enzymes and genetic code can be included later.

In fact, differently than (top-down) genome engineering that utilizes existing biological cellular systems and their very complex metabolism, the approach of (bottom-up) chemistry creates elementary basic cellular and multi-cellular structures 'from scratch'. Clear advantages of this approach are multiple degrees of freedom in designing metabolic networks – in simple cases, autocatalytic reactions – and different internal and external interaction mechanisms.

Moreover, chemistry concepts can be applied in molecular self-assembly in order to cause single-molecule components to automatically arrange themselves into large-scale patterns, what can be useful for different purposes, such as the topic of programmable matter discussed below.

There exists a close connection between artificial chemistry, synthetic biology and material science[3] in research on creating artificial DNA to evolve (new) functionalities. The current state-of-the-art of this research is that libraries of DNA are constructed, creating a function space which can then be searched for desired purposes. The future is that these functions are actually evolved. An important example application of it is a drug delivery system, where nano-particles are designed with particular functionalities. However, what is also seen here as a major obstacle is to interface the chemistry and the computer: in other words, to bring coherence in the chemical and electronic world. Careful speculation says that in this research, development of mechatronical/sillicon-based materials will go down over the next 50 years, and the future thereafter is in bio-organic materials.

Current work in artifical DNA chemistry involves molecular cloning and protein expression, according to the following process: synthesis, self-assemble materials, develop physical methods, test biological activities, cell culture experiments and then move to animals. The current state-of-the-art is that they are halfway this process and it is expected that in few years they can start using evolution. The main obstacles before accomplishing this are to use DNA as a scaffold in the energy field; and that biologists and computer scientists need to come closer (biologists hardly use what they do out-of-biological-context). We already mentioned drug delivery as an application, another example is the creation of LEDs that are based on organic molecules (same exists for solar cells).

2.2.1 Programmable Matter

Programmable matter, or *infochemistry*, is a new field of study that combines different sciences such as chemistry, information theory and control engineering to build information directly into materials. It refers to matter that have ability to perform information processing and change their properties in order to adapt to changes in the environment. It refer thus to materials that self-assemble or alter their shape, perform a certain function and then disassemble themselves.

"In the future a soldier will have something that looks like a paint can in the back of his vehicle. The can is filled with particles of varying sizes, shapes and capabilities. These individual bits can be small computers, ceramics, biological systemspotentially anything the user wants them to be. The soldier needs a wrench of a specific size. He broadcasts a message to the container, which causes the particles to automatically form the wrench. After the wrench has been used, the soldier realizes that he needs a hammer. He puts the wrench back into the can where it disassembles itself back into its components and re-forms into a hammer.", according to Dr. Mitchell R. Zakin, manager of the DARPAs Programmable Matter program in [7].

Metamaterials, shape-changing molecules, synthetic biology, self-configuring modular robotics and claytronics can be seen as examples of what programmable matter encompasses.

2.2.2 Summary of Interviews

[3] http://www.rug.nl/zernike/research/groups/PCBE/index

Table 2.2: Summary of interview: chemistry

Expert	**Main thing(s) we have learned**
Andreas Herrmann	Although the materials for experimenting with evolution can be prepared, we cannot yet perform evolution itself.

2.3 Computer Science

Considering the position of computer science there are two main perspectives to be mentioned. First, the historical perspective that aligns biological evolution, computer simulated evolution and embodied artificial evolution as follows:

- 19th century: "evolution" is a passive concept, a theory, that is used to explain past process, e.g. the origin of species, etc. – Biology.
- 20th century: "evolution" is an active concept, a tool, that is used to start new processes that produce solutions to problems – Evolutionary Computing.
- 21st century: "evolution" is an active concept, a tool, that is used to start new processes that produce artifacts – Embodied Artificial Evolution.

The interesting issue here is the essential role of Computer Science: with the invention of computers it became possible to create artificial worlds where we could engineer evolutionary processes in ways that are not possible in biology. This taught us a lot about various evolvable objects, reproduction operators and selection mechanisms in digital spaces. In other words, we have gained much expertise and know-how on how to set up and manage evolutionary processes that do something useful for the user. In this respect, Computer Science, in particular Evolutionary Computing therein, is a key enabler of Embodied Artificial Evolution as it provided the "playground" to gain all that experience. EAE is the logical next step, where we leverage on this know-how and (try to) utilize it in physical spaces.

The second perspective is that of the future. EAE technology can radically change Computer Science as we know it. This change seems almost obvious, if we distinguish passive artifacts (e.g., T-shirts, jewelry) and active artifacts with a degree of autonomy (e.g., robots in the broadest possible sense). Active artifacts inherently need a kind of controller that regulates their activities. Such a controller is an information processing system connecting sensors and actuators or, more generally, a computing system linking inputs to outputs. The physical embedding of this system can be naturally positioned in the body – brain – mind trichotomy. Thinking within this scheme it is straightforward that for active artifacts the Embodied Artificial Evolution technology will:

- lead to *new types of bodies*. Hence it will
- lead to *new types of brains*. Hence it will
- require *new types of minds*.

In essence, this means that we will obtain radically new computing hardware (brains) that will require radically new computing software (minds). It is obvious that the new hardware can be very very different from the traditional van Neumann architecture. It can be something we have seen before, e.g., some network architecture like neural nets, some fluid dynamics system not unlike hormones, or it can be something completely new. Either way, such new types of brains –or in general computing devices– cannot be filled with content the way we do today. Therefore, the current notions of “program”, “programming”, “software”, “software engineering” etc. will become pretty much inappropriate, if not useless. Similarly, the validation protocols, e.g., debugging and testing, will have to be changed too. All in all, the fundamental notions of computers, computer science, etc. will be drastically redefined by EAE technology.

2.3.1 Evolutionary Computing

As mentioned above, Evolutionary Computing is a key enabler of Embodied Artificial Evolution as it provided the “playground” to gain know-how regarding human engineered evolutionary processes. Meanwhile, EAE will greatly extend the present range of knowledge - revitalize Evolutionary Computing if you wish. For example, the user (algorithm designer) will have to take physical constraints and feasibility into account when designing reproduction operators. This is different from current practice, where practically any conceivable mutation and crossover operator can be implemented in the computer. Furthermore, the fact that individuals of a given population reproduce autonomously and asynchronously without any central control, implies that acts of birth and death are not synchronized. Therefore, the population size will be inherently changing and the whole system will require some mechanism to keep it from extinction as well as from explosion. In Evolutionary Computing there are no recipes for this, because the population size is almost always constant and even in the few exceptions it is regulated in a centralized way. The few studies into a decentralized and desynchronized reproduction-selection system show that this challenge is very hard to solve [14].

Applying evolution principles directly in the real world can provide interesting insights with respect to developing systems, because simulation is not always the most appropriate tool. For instance, when working on making real 3D structures, the actual result produced by the printer can differ – quite significantly – from results produced through simulation. “Evolutionary algorithms have been used to design a wide number of virtual objects, ranging from virtual creatures to telescope lenses. Recently, with the advent of rapid prototyping 3-D printers, an increasing number of evolved designs have been fabricated in the real world as well.” [8].

Online in-vivo design and manufacturing of dynamic structures is what EAE requires. This means that design and manufacturing are continuous activities. In this context, two forces (processes) need to be balanced: (i) blind evolutionary adaptation, and (ii) goal-oriented, directed search towards user objectives. In other words, the system that has its own, quasi-autonomous dynamics, has to also take into account defined user objectives.

Technically this means directed evolution that could be realised by directed selection (akin to breeding) and/or directed reproduction (as in genetic manipulation). On a conceptual level, this requires a new kind of methodology that must contain traditional elements, such as specifications and validation, as well as address previously unforeseen aspects, e.g., mixing (the dynamics of) “free” evolution with specific design objectives on-the-fly.

2.3.2 Simulation

An abstract model (of a given system) can be simulated by means of a computational model. Simulation is a useful tool on studying natural systems, systems that are too complex to be analysed some other way – as such systems could hardly have, for instance, a deterministic solution. Besides, simulation is also suitable for the exploration of new technologies.

Simulation can be used, for instance, to show the mechanical properties of prosthetic devices and how these match with the body's natural mechanics. Additionally, considering that systems should carry out evolution, simulation will probably be an important evolutionary design tool.

2.3.3 Summary of Interviews

Table 2.3: Summary of interviews: computer science

Expert	**Main thing(s) we have learned**
George Kampis	EAE will be probably most welcome in ICT (as opposed to bio), because ICT has a "paradigm-deficiency" – it needs some new stuff to be revitalized. Also, ICT has shorter loops than bio-research, hence results are visible sooner.
Mark Jelasity	EAE would induce a new type of synergy between computer science, biology and chemistry. It will lead to a new kind of evolutionary computing too.
Jim Smith	We do not want to waste resources and leave a lot of mechatronic trash. We should go towards more sustainable artifacts, just like all life on Earth is part of the recycle chain.
Larry Bull	The most intriguing aspect here is the evolved intelligence. This is strongly related to and grounded in the bodies. EAE will provide a good tool to study this interplay.
Kenneth De Jong	In Evolutionary Computing, the hardest part is always the right representation. This should be the same in EAE, that is, the type of bodies and the corresponding "genetic" encoding.
Zbyszek Michalewicz	It is a question whether the knowledge and expertise acquired through Evolutionary Computing can be used in an embodied evolutionary system.
Rineke Verbrugge	EvoBody should give more attention to cognition.

2.4 Robotics

Applications of mechatronic systems, primarily in robotics, involve the concept of embodiment, i.e., using specific properties of materials to achieve a desired functionality. Generally, modern robotics utilizes different fields of materials science, which vary from modifications of surface properties up to composite materials with specific mechanical features.

It is interesting to notice that in a robotic application mind and body can be considered separately. This facilitate the designing task, which can be split into two and recombined whenever necessary. Besides, a robotic object is controllable, programmable and modular.

Hybrid systems, a mix of simple organic material and robots, such as a Phi-Bot[4] – whose electronics is controlled by a slime mould – are also been investigated. The behaviour of such systems are quite complex and traditional computing methods are no longer applicable, pushing the boundaries of technological and scientific developments.

Due to workshops, it became clear that new fields – molecular, colloidal and multi-particle phenomena – should be included into robotic areas. Here the size of the agents varies between hundreds of μm and hundreds of nm. This new domain is also characterized by the appearance of several new challenges: new physical laws must be taken into account (for example electrostatic or capillary forces instead of gravitational forces) – the so-called "small world laws" – including the very limited capabilities of tuning individual interactions, the wide utilization of microscopic collective phenomena (for example self-assembly) for creating collective behavior, the very large number of elements, and others. The variation of size in this class of collective systems is about four orders of magnitude; a huge research field. Currently there is no commonly accepted name for the field. Although several authors try to introduce the notion of "nanorobotics", we will refer them to as "small world" systems.

Collective systems in the micro-, meso- and nano- domains are approached from three different directions. First is the further miniaturization of micro-systems and structuring of material by micro-/nano- manipulation. The appellation of "nanorobotics" is mostly applied to this research branch. The second approach considers meso- and nano-objects, such as particles with functionalized surfaces, colloidal systems, or molecular networks; a system of elementary autonomous agents, which possess rudimentary capabilities of sensing and actuation. Information processing and collective actuation is performed collectively as, for example, stochastic behavioral rules. Several phenomena, such as meso-scale self-assembling or diverse self-organizing processes, make these type of systems attractive in applications. The third approach utilizes modified biological objects, such as bacteria or fungi to create collective robot systems with dedicated properties of self-maintaining and self-reproduction.

Molecular, colloidal and particle systems also use local interactions and horizontal mechanisms, similarly to 2D and 3D ecological swarms, however we can observe another approach for designing collective phenomena, using the same very simple but large-scale interaction patterns for whole systems.

2.4.1 Summary of Interviews

Table 2.4: Summary of interviews: robotics

Expert	**Main thing(s) we have learned**
Ricardo Chavarriaga	Neuronal plasticity is important for EAE application in neuro-hybrid robotics.

[4] Andy Adamatzky's Unconventional Computing group, The University of West England Bristol, UK.

Table 2.4: (continued)

Expert	**Main thing(s) we have learned**
Alan Winfield	Our solution to the problem of self-replication could be biologically implausible. This will be OK; the only thing that counts is that we can evolve new features for the artifacts. The technology can be here in a few years, but we are missing the know-how.
Justin Werfel	For the EvoBody application scenarios, keep in mind that it is easier to get them under water than in outer space.
Dario Floreano	The classical robotics approach seems too limited to solve the self-replication problem. The most likely candidate for a new future breakthrough is the biological approach.
Claudio Rossi	Robotics is rapidly changing by the advances in material science. New types of (soft) bodies are becoming available and 3D printers are maturing quickly. This is a very promising way to achieve EAE.
Manuel Ferre	There could be a small niche for robotics based on the EAE approach. However, the majority of robots will be engineered in the traditional way also in the future.
Kirsty Grant, Angel A. Caputi, Konstantin Anokhin, Vladimir Red'ko	EAE systems should look more for neuro-hybrid approaches.
Rolf Pfeifer	Fundamental question for new areas such as molecular or colloidal systems is the programmability of interactions.
Steen Rasmussen, Oliver Scholz, Joahim Spatz	Involving of chemo-hybrid systems into EAE.
Peter Lewis, Martin Wirsing	It needs to consider mechanisms of creating global awareness and self-awareness into EAE systems.
Haruhisa Kurokawa, Kasper Stoy	Using reconfigurable systems for studying EAE

2.5 Material Science

Materials science can be briefly defined[5] as the "science of stuff". In the field, the relationship between the structure of materials (at atomic or molecular scales) and their macroscopic properties is investigated. The area is recently gaining much interest. We observe trends and directions in materials science that must be considered within the context of this document, since there is considerable overlap between the area of embodied evolution and a subfield of materials science called *smart materials*.

What do materials scientists do and why is it interesting to look at materials science from within EvoBody? To answer the first question, we now give an overview of what the field

[5] *Introduction to Materials Science and Technology*, U.S. Department of Energy, Pacific Northwest National Laboratory, 2002

encompasses. To answer the second question, we look at a number of applications that are somewhat on the (overlapping) borders of materials science and embodied evolution.

Materials science[10] starts with the categorisation of *materials*: this can be done by state (e.g., solid, liquid, organic), by morphological structure (crystalline, amporphous), and by atomic structure. The materials that can then be placed in specific categories are, among others, metals, polymers (plastics), ceramics, glass and wood. The major classes of materials are metals, ceramics and polymers, and additionally we know composites (material combinations). Also, a very important type is electronic materials (although not major by volume) – examples are silicon chips and transistors. Although it might be superfluous to mention, all materials are obtained from the earth crust and atmosphere.

A technological approach to materials science involves designing, choosing and using materials within the disciplines of engineering, chemistry and physics. There has always been a large interest in studying materials, since their production and processing constitute a large part of the economy, new applications ask for new materials, and for some applications the material properties might be needed to modified. A distinction can be made between materials *science* and materials *engineering*. The former concerns obtaining the basic knowledge about the internal structure, properties and processing of materials; the latter is then the application of the former to convert materials into products.

Recent advances and future trends in material sciences are: smart materials – which react to environment stimuli and change properties by sensing external stimuli; and nano-materials – smaller than 100 nm particle size. Also, novel materials will be synthesized by the atom – there are infinite numbers of combination of *atomic assemblies*. In general, innovations in materials science happen throughout the (European) research and industrial landscape – including the areas of environment, energy, agriculture, health, ICT, infrastructure and construction, and transportation. A 2001 study from the Max-Planck-Institut study[6] aimed to assess the state-of-the-art, scientific opportunities, impace of materials science on society, and provide guidelines for European policy makers. The study focused on materials that are the basis of modern, futuristic high technology, for instance, polymers, carbon materials, and biomaterials.

Although we want to point out the existence of this white book, we do not consider it necessary to repeat all that is there. It is, though, important to mention it here for two important reasons. Firstly, it maps out the state of the (European) research and industry landscape for materials science, which is important to incorporate within our project (albeit for embodied evolution). This is discussed in terms of social acceptance of the area, political support, basic research and industry, educational programmes, facilities and research networks. Secondly, it shows that, already then (10 years ago), there is considerable overlap between the foreseen future directions for research and development in materials sciences and the possible directions that EAE could lead us. Some examples of this overlap is given in Section 2.5.3. The study gives four general recommendations to advance materials science research in Europe that are based on the following themes: importance of the field to the prosperity of humankind; need for better theoretical understanding and necessary fundamental research to obtain this; highly interdisciplinary nature of the field, need for continued, long-term investment.

[6]European White Book on Fundamental Research in Material Science, Max-Planck-Institut fur Metallforschung Stuttgart, 2001.

In the remainder of this section, we first look at the area of smart materials. After consulting with field experts as well as reading and exploring relevant literature, we consider this the most important area to watch within the context of EvoBody. After that, we zoom in on work combining neural and artificial materials, which is also a very relevant area. Following this, we describe a number of selected applications that have been featured recently in the media (also published on the EvoBody website) – all of which are on the forefront of academic and industrial research.

2.5.1 Smart Materials

Smart materials are materials that react to environment stimuli (e.g., stress, temperature, and magnetic field) by changing their properties, such as shape or colour. In other words, materials that can sense and respond to the world around them in a predictable and useful manner. Smart materials arise from research in many different areas and there is a great overlap with nanotechnology.

"Smart materials open up new possibilities, such as clothes that can interact with a mobile phone or structures that can repair themselves. They also allow existing technology to be improved. Using a smart material instead of conventional mechanisms to sense and respond, can simplify devices, reducing weight and the chance of failure.", as stated in the UK Pariliamentary Office publication [1].

Some types of such materials are:

Chromogenic systems: change colour in response to environmental changes. These include electrochromic materials, which change their colour or opacity on the application of a voltage (e.g., liquid crystal displays); thermochromic materials: change in colour depending on their temperature (e.g., bath plugs that change colour when the water is too hot); and photochromic materials, which change colour in response to light (e.g., spectacle lenses that darken when exposed to sunlight).

Shape memory alloys and **shape memory polymers:** materials in which large deformation can be induced and recovered through temperature changes or stress changes (pseudoelasticity). They are, for example, used in artery stents – tubes threaded into arteries that expand on heating to body temperature to allow an increase of blood flow.

Magnetorheological: fluids become solid when placed in a magnetic field. These can, for instance, be fitted to buildings and bridges to suppress the damaging effects of high winds or earthquakes.

Self-healing materials: materials that have the intrinsic ability to repair damage caused by mechanical usage over time. The inspiration comes from biological systems, which have the ability to heal after being wounded. Biocompatible self-healing composite materials can be used, for instance, in artificial bone replacement, extending its lifetime beyond the usual 10-15 years.

Smart materials have a wide range of applications. In engineering, for instance, smart materials can be incorporated in the structure of buildings, bridges, aircrafts and ships in order to continuously monitor their integritry and avoid damages that may cause failures. Embedded sensors can kept track of stress and damage, while healing materials can help to self-repair damages, what is of special importance in places of difficult access, such as under water or in space.

Smart materials can also be used in health applications. Existing devices are capable of, for example, measuring body movements and wirelessly send information directly to a computer. Other can inform whether a joint replacement is loose or if there is an infection. However, more that only sensing and communicating data, future devices are expected to respond directly to the observed changes – for instance, by releasing the necessary amount of antibiotics to treat an infection.

Finally, one of the main concerns of the use od embodied artificial evolutionary systems is the production of waste and how this should be recycled in order to avoid irreversible disturbance of the environment, following an environment-friendly policy. In this context, the use of smart materials has the potential to reduce waste and even to simplify recycling methods.

2.5.2 Neuron Modeling

One of the most advanced 'materials' that we know are human cells, tissues and neurons. Cells, in particular, have the ability to not only react to stimuli, but can also change their on structure depending on the types of stimuli they receive. This makes them nature's smart materials and, therefore, extremely relevant area for EAE.

We have to understand the behaviour of these cells (and neurons) in order to make them fit for combining with artificial materials. Anecdotal, the first artificial hips caused strange and surprising reactions from the tissue surrounding the "invasive materials": these cells did not receive the necessary feedback from their neighbourhood to stay activated and, as a consequence, died. Researchers Jerusalem and Peña do research (http://jerugroup.materials.imdea.org/) on the simulation of neuron growth. Currently, the research looks at investigating the behaviour of cell, but not to (re)build these.

Future research directions include the visualisation of these growth models (already done in a CAVE environment for interactive (drug) design) and combining the metabolic network dynamics with evolutionary dynamics. The latter relates to the evolution of protein networks (within a cell) where the actual cell structure evolves. Current models employ a deterministic way that this network grows, but in reality this is more trial-and-error. Generalising this to the level of development of material science related to EAE creates an interesting tension: whereas trial-and-error is the much used method for growth and development in nature, material science in general does not believe in chance (i.e., evolution). This issues has to be addressed for future cooperation with material science to be successful.

2.5.3 State-of-the-art Applications

In order to make it clear what could be potential combinations of materials science and embodied evolution, we include here a number of state-of-the-art applications that have been featured recently in the media. We expect that possible cooperations between the fields are in the realm of similar applications.

Stretchable microfluidic electronics The latest advances in the field of microfluidic stretchable radio-frequency electronics show the possibility of components that can be bend and stretched. Here, eletronics components can be combined with channels of elastomers filled with fluid metal. This allows systems that can undergo servere mechanical deformation and regain their original form. They can, therefore, adapt to (nearly) any bent and moving surfaces on a human being or a robot and can, thus, serve as a second layer of smart e-skin for health monitoring or remote control. [4]

Self-Assembling Electronic In order to be able to fabricate an electronic device out of nano-components, one possible approach is to “provoke” individual components to assemble the desired form, in a self-organising fashion. It is following such a paradigma that a group of researchers were able to apply synthetic adhesives to magnetic molecules make them to properly position themselves on a nanotube – without any intervention. [13]

Smart materials for new drugs Advances in the field of smart materials can have an important role in the development of new drugs. One example is the new method that induce proteins to form crystals using ‘smart materials’ that remember the shape and characteristics of the molecule. This is an important step into determining the structure of drug targets, which is crucial for the development of new medicines. [9]

Self-healing sensor In order to address structural safety in the face of natural disasters or unexpected events, the analysis of stress in (existing) structures (e.g., bridges, buildings, aircraft wings) is of special relevance. In this context, researchers have given an important step on collecting data regarding the strain found in structural materials. A new designed sensor to be used for such measurements can not only inform how a structure performs under stress, but it is also capable of healing itself – what extends the sensors’ lifetime and allows its deployment in ‘inaccessible’ locations. [11]

Prosthetic limbs This refers to the use of alternative materials for the creation of artificial bones, important for the replacement of real bones when those are beyond repair due to diseases or accidents. An example is shown in the innovative use of wood as source material. After its undergone transformations, the rattan wood was strong enough to stand for a bone and being, therefore, suitable for bone engineering applications. [12]

2.5.4 Summary of Interviews

Table 2.5: Summary of interviews: materials science

Expert	**Main thing(s) we have learned**
Lee Cronin	We are much closer to creating artificial evolutionary systems than many people think. These will represent a huge breakthrough helping us understand deep scientific issues, for instance the minimal requirements for life and evolution.

Table 2.5: (continued)

Expert	**Main thing(s) we have learned**
Antoine Jerusalem	When you put artificial and natural tissues together, the natural tissues can react surprisingly. With the first artificial hips, the human cells surrounding the artificial tissue died, because they did not receive the necessary feedback they expected to stay activated.
Zoran Konkoli	I believe that [EAE] is grossly futuristic and that we are far away from it. [. . .] Though, recent advancements in Synthetic Biology will certainly prove me wrong.
José M. Peña	The best way for computer and material scientists (and biologists) to cooperate is in a so-called "equipment relationship", such that we supply the means to investigate their ends.
Goöran Wendin	To evolve complex systems in hardware remains a dream. If we define Embodied Evolution by "artificial physical systems self-organising and evolving increasingly complex system", then I don't even see the beginning of it in real terms mimicking living biological systems.

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Chapter 3

Some Grand Challenges

> *Any sufficiently advanced technology is indistinguishable from magic.* (Arthur C. Clarke)

Future development of EAE could take place along different lines: development of mechatronic systems, the growth of bio- and chemo- synthetic systems, the hybridization of robotics, and the appearance of 'soft-' systems. Each of these developments has its own challenges, promises and risks. However, independent of what the dominant future technology might be, we face the new problem of the integration of methodologies, paradigms and approaches from different areas of biology, chemistry and material science into classic robotics. This new integration will require a re-structuring of the current research landscape, which will not only essentially change the way we think about robotics, but also extend the scientific and technological boundaries for synthetic systems. Materials science, bottom-up chemistry and genetic engineering are especially relevant for open-ended evolution and unbounded self-development in autonomous systems.

In the following we discuss some of the grand challenges of embodied artificial evolution. Our treatment is inevitably incomplete, but can serve to inspire further discussions and stimulate research initiatives.

3.1 Robot Reproduction

As mentioned in Chapter 1, one critical step in the context of EAE is how to implement birth and death (reproduction and survivor selection) to physical mechatronic devices, in particular, robots.

Replication is a life-cycle process. Rather than considering only the moment of birth, the process starts much earlier with an embryo or seed, which developed in an appropriate environment. The growth process is associated to the object produced. Developmental robotics (ontogenic robots) is a field which includes learning and change over a long time scale, potentially including growth, which indicates that developmental processes need to be considered as part of evolutionary robotics.

However, we are used to thinking in terms of replication via polymerisations and folding to get functioning. What about alternatives? Other replication paradigms may include: (i) going back to von Neumann's considerations of self-reproducing automata, and consider blindly copying instructions and execution of these in order to make things (like polymers RNA/DNA/protein folding); but also (ii) consider replication by self-examination: at no time does there exist a full description, one has to examine and reproduce bit-by-bit – which may be applicable for scanning and printing of 3D models.

An important thing to consider is that, in the context of embodied artificial evolution, we need not restrict to 'self-' (self-reproduction, self-assembly, self-preservation) and events (such as birth). The important concept is the production of a new object of the same type, with inheritance methods, where (following von Neumann) new individuals should potentially have increasing functional complexity and heritable genetic material. Here we reproduce copier mechanisms not just an object.

It becomes, therefore, relevant to differentiate between two crucial concepts in mechatrono-robotic systems: self-assembling and self-replication. Self-assembling is a process which creates complex systems from basic elements, whereas self-replication means a reproduction of these basic elements. The self-assembling has already been targeted several times in robotics. The field of modular (reconfigurable) robotics aims at self-assembling of robot modules into complex structures, so called artificial organisms. Robots are able to make functional copies of artificial organisms from basic building blocks provided that an essential reserve of such basic modules already exists.

The self-replication (or, simply replication) of basic elements remains so far unsolved, even in principle. The problem lies in a high technological complexity of functional units, such as motors, gears or microelectronics. There are several attempts to address self-reproduction in modular robotics by additive plastic molding[1], or by using 3D prototyping technology. No one of these technologies apply reproduction as introduced above. For that, further developments are still necessary. This relates not only to the creation of physical units, but also to the computing capabilities, as well as inheritance mechanisms.

3.2 Kill Switch Mechanism

A serious concern related to EAE is the possibility of runaway evolution. By this term we do not mean the Fisherian notion of sexual selection reinforcing useless traits. Runaway evolution as we see stands for the process of uncontrolled population growth, which might result in the emergence of new, unwanted features in the population. In principle, we can create technologies that could get out of control and make their own rules.

Obviously, it would be highly irresponsible to expose ourselves to such a risk. To reduce this risk, all EAE-related experiments could be carried out in highly secured isolated environments, not unlike current research into certain germs, bacteria, viruses, etc. However, this might disable the whole application in cases where the evolving population is inherently free, where the individuals are part of our everyday life (robot companions, waste-eating organisms, medical nano-robots in the human body, etc.). In such cases a kill switch is required to

[1] See RepRap.org

guarantee that human supervisors are able to shut down the system, if and when they deem necessary.

The overall agreement is that no real danger is imminent. However, one another way to deal with the possibility of runaway evolution is to stablish a set of milestones that need to be achieved[2] before any real concern rises. Once a red flag milestone is reached, new constraints are introduced. This way, the development of systems can be kept between certain boundaries, which prevent that a *grey goo* scenario becomes a reality.

In general, the process of developing EAE systems (i) needs to be transparent, and (ii) compare with validation of complex engineered systems. We will be dealing with designed systems that need to be approved for safety, correct functionality, and so on. In this context, we cannot rely on references to what happens in the nature. The conclusion is that we need to co-invent a new validation methodology for EAE systems.

And, after all, in nature things do go wrong, e.g., cells lose their kill switch resulting in cancers. And that is where the death of lower level replicators becomes useful. Apart from being used to stop runaway evolution from taking place, a kill switch can also be seen as a way of getting back used resources.

3.3 Body Types

One should note that on making a minimal living molecular machine (a protocell) three embodied components must cooperate: an informational system, a metabolism and a container. Also in a modern living cell these three key components (information, metabolism and container) are clearly embodied as different molecular aggregates. Embedded and integrated information, containment and energetics, are also necessary when making molecular devices for drug delivery systems or artificial molecular photosynthesis systems.

In mechatronic level we miss the properties of living organisms, but we gain crucial advantages such as programmability, modularity and portability. The regulatory mechanisms in bio-chemical organisms are not separated so clearly from the bodies to be regulated. In robotics, the metabolism is not usually viewed as also being an integrated part of the embedded information. There is a grand challenge in understanding how to implement micro-level advantages at the macro-level and macro-level advantages at the micro-level. One way of identifying the boundary between the macro- and the micro-level is the scale at which an ICT microcontroller can no longer be produced, which defines the smallest scale reach by the top-down ICT technology. Therefore, an important research frontier for EAE is defined by this interface between the ICT and the biochemical levels by exploring and implementing hybrids with information processing, energy harvesting, production, mobility and cognitive properties.

In this context, two properties are critical: (i) programmability of, and granting of a function to, organisms, and (ii) (self-)replication. These are hard vs. easily achievable at higher vs. lower level scales. A trade-off decision is, therefore, necessary. Embodied robotics replication

[2] Such an approach is described in the ethical section of PACE project regarding protocells.

of the type we see for molecular systems is very difficult to imagine in a short-term (e.g., pregnant robots). However, replication seeing in modular robotics, is within reach. Developing a replicating system defines another EAE research frontier.

The hybrid scenario (bio + mechatronic) can be considered as the most probable basis for future EAE systems. This line of development implies the extension of the notion of robots and robotics. Compared to the current situation, this extended concept will include a much larger class of human engineered artifacts with specific functionalities. Here we can identify several open research questions, the most important of those being: *How can the current ICT be combined with biochemical developments?* This question can also be formulated as "programmability of synthetic systems", or "open-ended embodied evolution", and it is the key point in several scientific and technological challenges and, to some extent, even in understanding principles of synthetic life.

The integration of bio-chemistry, micro-biology, synthetic biology, and robotics will be a vital challenge in coming years and promises several radical breakthroughs regarding the adaptive, developmental and evolutionary properties of EAE systems.

3.4 Design Methodologies

In the same way that we miss the properties of biological organisms in mechatronic systems, we miss the programmable and controllable aspects of mechatronic devices in the bio-chemical systems. Perhaps, as mentioned above, the answer lies in the hybrid of the two: bio-chemical and mechatronic streams, trying to combine the best qualities of each. In any case, the complexity of the systems that we will be dealing with seems greater than anything that has been produced so far. And, therefore, design methodologies become crucial.

EAE design and manufacturing become is an online, continuous, intertwined activity. This empowers individuals to develop their own designs and products. Besides, its autonomous aspect empowers a product to improve itself. The analogies between the cycles of biological reproduction and the in-vivo evolutionary design are shown in Figure 3.1.

In short, systems are autonomous and self-improving. In this case, there are 3 points of influence on such a process:

- Selection: in 2 variants, direct and indirect influence (adjust fitness function)
- Design: genetic manipulation
- Manufacturing: interpreting blueprint during delivery

Coevolution of physical morphology and controllers of robotic systems can be achieved as well as directed mutation (done by the user), and embodiment has the advantage of allowing implementation of open-endedness. However, unbound evolution makes it impossible to guarantee that system's outcome is safe. On the one hand, the requirement might be that search space of all possible designs, operators, and verification proves that any point that you can get to is safe. On the other hand, this compromises the open-endedness iam. A solution might then lie on subspaces that may restrict certain types of danger.

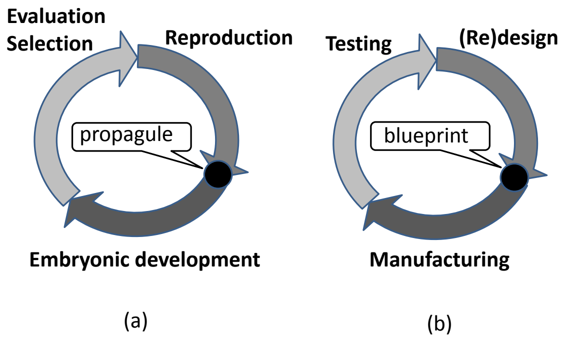

Figure 3.1: Two circles showing the analogies between the biological circle of reproduction (a) and the new kind of *in vivo* evolutionary design (b).

To consider an online methodology means that real time requirements need to be addressed. One cannot afford to stop design and then manufacture, if continued function is needed. In this context, offline precalculation of genotype should be within scope, to allow real time rapid reactions online.

3.5 Evolution Rate

It is well-known in biology as well as in evolutionary computing that evolution takes time. One might even say that evolution is slow. Although this statement obviously lean on the context dependent notion of time, it is safe to say that, in general, it takes many generations to achieve a 'decent' level of development.

For future EAE systems this means that the reproduction cycles must be sufficiently short and/or the improvement from generation to generation must be sufficiently large. This is a non-trivial challenge on its own. Failing to meet this challenge would imply that the real time performance of EAE systems is too low. Ultimately, this could even disqualify the whole approach – at least, for certain applications.

In general, the speed of evolution should be used as one of the essential assessment criteria for judging the feasibility of any given application. In particular cases, this assessment will be comparative. On the one hand, we will have the application-dependent time requirements – e.g., a group of medical nano-robots should adapt to a changing environment within 8 hours, or a group of Mars explorers with a rough pre-design should adapt to Mars within 2 weeks. On the other hand, we will have the speed of possible progress, determined by the evolutionary operators.

Chapter 4

Research Centres, Projects and People

The best way to predict the future is to invent it. (Alan Kay)

In this chapter we list institutes, organizations, projects and experts related - in some extent - to embodied artificial evolution.

4.1 List of Institutes and Organizations

Faculty of Environment and Technology
UWE, UK

- International Center of Unconventional Computing
- Intelligent Autonomous Systems Laboratory

School of Computing, Mathematics and Digital Technology
Manchester Metropolitan University, UK

- Novel Computation Group

Chemistry and Biochemistry Faculty
Ruhr University Bochum, Germany

- Biomolecular Information Processing Research Group

University of Southern Denmark, Denmark

- Center for Fundamental Living Technology
- The Mærsk Mc-Kinney Møller Institute

Weissman Institute of Science, Israel

- Faculty of Biochemistry: Department of Molecular Genetics and Department of Biological Chemistry
- Faculty of Mathematics and Computer Science: Laboratory for Biomolecular Computers

Laboratoire de Biochimie
École Polytechnique and the Centre National de la Recherche Scientifique

- Systems and Synthetic Biology Research

Madrid Institute for Advanced Studies of Materials

- IMDEA Materials Institute

Glasgow University - Department of Chemistry

- Cronin Group

Chalmers University of Technology

- Department of Microtechnology and Nanoscience

The European Center for Living Technology ECLT is an international Research Centre dedicated to the study and creation of a new generation of technologies which embody the essential properties of life, such as self-organization, adaptability, capacity to evolve and react to environmental stimula, etc. The research, focused mainly in the bio-nano-technology and synthetic biology sectors, is developed in collaboration with scientists belonging to the 15 European Universities and international Research Centres which are members of ECLT. Some of which were listed above.

The Initiative for Science, Society, and Policy ISSP aims to help make science and technology more effective components of societal planning and public discourse. The ISSP aims to be a leading platform for highlighting, expanding and rethinking the meaning of scientific social responsibility in universities across Denmark and abroad. ISSP working groups will serve as an open and independent platform for addressing critical contemporary issues that require productive interactions among science, society and policy. The ISSPs project on living technology aims to take stock of the state of the art in living technology and recommend priorities for the socially responsible scientific pursuit of living technology.

Interuniversity Microelectronics Centre Imec performs world-leading research in nanoelectronics. Imec leverages its scientific knowledge with the innovative power of its global partnerships in ICT, healthcare and energy. Imec delivers industry-relevant technology solutions. In a unique high-tech environment, its international top talent is committed to providing the building blocks for a better life in a sustainable society.

European Multifunctional Materials Institute EMMI was created in the framework of the European FP6 Network of Excellence FAME (Functional Advanced Materials and Engineering of Hybrids and Ceramics). FAME initiated a number of very successful research collaborations and educational projects, and EMMI is the main tool for durable integration of the FAME network.

4.2 List of Projects

4.2.1 BACTOCOM

BACTerial COMputing (2010-2013). Coordinator: Martyn Amos, Manchester Metropolitan University, UK. (7th FWP, 1.95 million euro)

The main objective of BACTOCOM is to build a simple computer, using bacteria rather than silicon. Microbes may be thought of as biological "micro-machines" that process information about their own state and the world around them. By sensing their environment, certain bacteria are able to move in response to chemical signals, allowing them to seek out food, for example. They can also communicate with other bacteria, by leaving chemical trails, or by directly exchanging genetic information. We focus on this latter mechanism.

Parts of the internal "program" of a bacterial cell (encoded by its genes, and the connections between them) may be "reprogrammed" in order to persuade it to perform human-defined tasks. By introducing artificial "circuits" made up of genetic components, we may add new behaviours or modify existing functionality within the cell. Existing examples of this include a bacterial oscillator, which causes the cells to periodically flash, and cell-based pollution detectors that can spot arsenic in drinking water. The potential for bio-engineering is huge, but the process itself is made difficult by the noisy, "messy" nature of the underlying material. Bacteria are hard to engineer, as they rarely conform to the traditional model of a computer or device, with well-defined components laid out in a fixed design.

We intend to use the inherent randomness of natural processes to our advantage, by harnessing it as a framework for biological engineering. We begin with a large number of simple DNA-based components, taken from a well-understood toolbox, which may be pieced together inside the cell to form new genetic programs. A population of bacteria then absorbs these components, which may (or may not) affect their behaviour. Crucially, the core of our bacterial computer is made up of engineered microbes that can detect how well they are performing, according to some external measure, such as how well they can flash in time with light pulses.

Project details

4.2.2 COBRA

Coordination of Biological and Chemical IT Research Activities (2011-2014). Coordinator: Martyn Amos, Manchester Metropolitan University, UK. (7FWP, 484.635,- euro)

The project acronym stands for Coordination of Biological and Chemical IT Research Activities, and our main objective is to act as a unifying focus for bio/chem IT, across a range of different research topics.

The project is firmly rooted in the four small and medium scale projects funded under the 7th Framework Programme, BACTOCOM, ECCell, MATCH-IT and NEU-NEU. Considered as a whole, these projects capture a significant proportion of European activity in bio/chem IT. This project will link these existing communities into a "network of networks". It will achieve this by capturing the current state-of-the-art in European research in this area, organizing small to medium-scale workshops, developing a strategic roadmap document, and working with international partners.

Goals and instruments

4.2.3 ECCell

Electronic Chemical Cell (2008-2011). Coordinator: John McCaskill - Ruhr University Bochum, Germany. (7FWP, 2 million euro)

The aim of the project is to establish a novel basis for future embedded information technology by constructing the first electronically programmable chemical cell. This will lay the foundation for immersed micro- and nanoscale molecular information processing with a paradigm shift to digitally programmable chemical systems.

Chemical cells must combine (i) self-replication, (ii) self-containment and (iii) self-regulation of resources (metabolism), enabling evolution to qualify as alive. Electronic chemical cells will do this in conjunction with a reconfigurable electronic system. ECCell will employ novel families of fully synthetic hybrid informational polyelectrolyte copolymers (not simply DNA), which simultaneously support all three cell functionalities. Their microscopic multiphase self-assembly under electric field control is the primary information processing mode of this technology.

The research will establish an effective IT interface between microelectronic and molecular information processing, by demonstrating its use to achieve a hard chemical synthetic systems objective (an artificial cell) opening a platform for programming a novel chemical Living Technology at the microscale.

Overall objectives

ECCell as ICT

4.2.4 e-Flux

Evolutionary Microfluidix(2009-2012). Coordinator: Parmenides Foundation. (7FWP, 2.3 million euro)

This project rests on the realization that forefront theoretical research, coupled to cutting-edge technologies, can produce the necessary knowledge and know-how to understand how complex system evolve. In particular, how evolvability in natural system can be used for engineering purposes. Thanks to the realisation of complex microfluidic systems, the team will study an unprecedented number of small cellular populations from which it will be possible to develop an evolvable machine to enable the monitoring of a evolutionary pathway for long periods of time.

Understanding evolvability could bring a step forward towards the comprehension of the fluid automata, with impact on drug discovery and biotechnology. Technological and theoretical sources amalgamate into a bottom-up research project.

Project summary

4.2.5 ETICA

Ethical Issues of Emerging ICT Applications. Coordinator: Bernd Stahl - De Montfort University, UK.

The ETICA project will identify emerging Information and Communication Technologies (ICTs) and their potential application areas in order to analyse and evaluate ethical issues arising from these. By including a variety of stakeholders and disciplinary perspectives, it will grade and rank foreseeable ethical risks. Based on the study governance arrangements currently used to address ICT ethics in Europe, ETICA will recommend concrete governance structures to address the most salient ethical issues identified. These recommendations will form the basis of more general policy recommendations aimed at addressing ethical issues in emerging ICTs before or as they arise.

The list of emerging technologies identified as having a significant potential impact on humans and society: affective computing, ambient intelligence, artificial intelligence, bioelectronics, cloud computing, future internet, human-machine symbiosis, neuroelectronics, quantum Computing, robotics, virtual/augmented reality.

Deliverables

4.2.6 MACHTIT

MATrix CHemical IT (2010-2013). Coordinator: Steen Rasmussen, University of Southern Denmark, Denmark. (7FWP, 2.77 million euro)

MATCHIT (MATrix for CHemical IT) will develop programmable information chemistry by introducing an addressable chemical container (chemtainer) production system and interfacing it with electronic computers via MEMS technology with regulatory feedback loops. As in the biological subcellular matrix, the chemical containers at the micro and nanoscales will be self-assembling, replicable and self-repairing.

At the nanoscale, DNA containers will provide a programmable and replicable chemistry in which positional information can be harnessed for a range of nanoscale utilities. At the microscale containers based on DNA labelled heterophase droplets and vesicles, will form microscopic labelled reaction vessels, which can themselves determine their next processing steps. Their DNA based addresses will be computable, enabling parallel chemical programming in a new multilevel architecture through autonomous address modification and resolution at the containercontainer, containersurface, and container molecule levels, providing a concrete embedded application for DNA computing. This generic programmable information chemistry will not only be an enabling technology for "immersed systems IT applications in the life sciences, chemistry, and nanotechnology, but also promote a deeper understanding of the computational power of coupled production and information processes, as in biology, and provide a platform for building the more organic computers of the future. MATCHIT will investigate the general use of self-assembling chemtainers for informationintensive ChemIT.

The project will develop and apply multiscale physical simulation tools and novel embedded IT architectures to process and integrates modular chemical and digital information. It will integrate and disseminate multidisciplinary European activities in ChemIT, supported by the European Center for Living Technology and provide an assessment of the likely long-term socio-technical impact of this powerful technology.

Objectives and progress (extra-information on work packages 3-6)

4.2.7 Mould Intelligence

Mould Intelligence: Designing Biological Amorphous Robots. Coordinator: Andrew Adamatzky. UWE, UK.

The aim of the project is to investigate methods to construct prototypes of amorphous robots - robotic devices which have distributed morphology, distributed control systems, and distributed motor behaviours. Conventional robotic devices have a fixed shape, within which are separate dedicated units to control - for example - sensory inputs, control systems, and motors or other actuators.

The aims of the Biological Amorphous Robots project are inspired by the behaviours of the true slime mould Physarum polycephalum an amorphous single-celled organism which exhibits extremely complex biological and computational behaviours. Physarum utilises a complex mechanism of internal oscillations to adapt both its morphology and behaviour to changing environmental conditions. We aim to use similar mechanisms to those used by Physarum to effect sensory, control and motor behaviours in amorphous robotic devices. The distributed and amorphous nature of the devices should ensure that they can adapt to changing environmental conditions and are resilient to damage.

4.2.8 NeuNeu

Artificial Wet Neuronal Networks from Compartmentalised Excitable Chemical Media (2010-2013). Coordinator: Peter Dittrich, Friedrich Schiller University, Germany. (7FWP, 1.78 million euro)

The NEUNEU research programme is concerned with the development of mass-producible chemical information processing components and their interconnection into functional architectures. The individual supramolecular components will crudely resemble biological neurons and will be capable of excitation and self-repair. Self-organisation of organic compounds and proteins will be complemented with dielectrophoretic manipulation to fabricate small devices from interconnected supramolecular components.

State-of-the-art micro- and nano-scale technologies will be exploited to take well established physico-chemical phenomena into the new context of forming a exible and efficient substrate for a chemistry-based information technology. Through integrated modelling from component to architecture level a broad understanding of the capabilities and limitations of the implemented as well as related technologies will be established.

This ambitious collaboration among computer-scientists, biophysicists, chemical-physcists, biochemists, chemical-biologists, and electrical engineers will develop the core science needed to build a future massively parallel computing infrastructure, will deliver prototype devices, and will pave the ground to harnessing bio- and nano-materials for a novel approach to cognitive computing.

Deliverables & publications

4.2.9 PACE

Programmable Artificial Cell Evolution (2004-2008). Coordinator: John McCaskill - Ruhr University Bochum, Germany. (6FWP, 6.6 million euro)

PACE has created the foundation for a new generation of embedded IT using programmable chemical systems that approach artificial cells in their properties of self-repair, self-assembly, self-reproduction and evolvability.

PACE has investigated a novel basis for evolvable IT using complex chemical systems that self-organize and self-reproduce: artificial chemical cells. While it would have been premature for PACE to have aimed to deliver the first novel chemical cell, novel IT technology for programming semi-autonomous chemical systems has been established and effective architectures for artificial cells established, so that now this objective should be achievable in the near future.

PACE has integrated and extended a suite of physical and chemical simulation tools and multiple scales to promote the design of information-intensive autonomous chemical systems. The project has evaluated the adaptive and evolutionary potential of chemical artificial cells and how they can be programmed to perform useful tasks for a chemically-active, “immersed” rather than embedded, IT. The project has constructed novel chemical systems, that can serve as an effective basis for reducing the complexity of artificial cells.

PACE has developed and tested a novel digital electronic-chemical microprocessor technology in connection with a new machine architecture based on a real-time microscale feedback loop - the “omega machine” - on the hard task of bootstrapping chemistry towards artificial cell autonomous operation. PACE has also developed algorithms and the technology to optimize rather general experimental protocols, going well beyond evolutionary optimization techniques. The project has also constructed a platform for controlling and monitoring the self-assembly of multiple artificial cells, that have been functionalised by specific surface structures.

Scientific progress and results

Ethical guidelines concerning artificial cells

4.3 List of Events

CEC 2011 2011 IEEE Congress on Evolutionary Computation

DECIE 1st International Workshop on Distributed Evolutionary Computation in Informal Environments

EA 2011 10th International Conference on Artificial Evolution

IB 2011 International Symposium on Integrative Bioinformatics

BIOINFORMATICS 2011 International Conference on Bioinformatics Models, Methods and Algorithms

EVOBIO 2011 9th European Conference on Evolutionary Computation, Machine Learning and Data Mining in Bioinformatics

ECAL 11 20th European Conference on Artificial Life

GECCO 2011 Genetic and Evolutionary Computation Conference

ALIFE XII 12th International Conference on the Synthesis and Simulation of Living Systems

AHS-2010 NASA/ESA Conference on Adaptive Hardware and Systems

ICES 2010 9th International Conference on Evolvable Systems - From Biology to Hardware

4.4 List of Experts

Experts are listed in alphabetical order. Note that an expert's affiliation might have changed after completion of this report. We can therefore give no guarantees regarding the trustworthiness of the references given below.

We list experts according to the four major clusters of interest, namely i) robotics, ii) computer science, iii) biology, chemistry & materials science, and iv) ethics and philosophy.

4.4.1 Robotics

Covering the areas of (evolutionary) robotics, evolvable and bio-inspired hardware:

Table 4.1: List of experts. Major area: robotics

Name	Current Affiliation	Country
Antonio **Bicchi**	University of Pisa	Italy
Mikhail **Burtsev**	Russian Academy of Sciences	Russia
Angelo **Cangelosi**	University of Plymouth	UK

Table 4.1: (continued)

Name	**Current Affiliation**	**Country**
Ricardo **Chavarriaga**	EPFL	Switzerland
Karl **Crailsheim**	University of Graz	Austria
Kerstin **Dautenhahn**	University of Hertfordshire	UK
Ralf **Der**	Max Planck Institute	Germany
Marco **Dorigo**	ULB	Belgium
Dario **Floreano**	EPFL	Switzerland
Toshio **Fukuda**	Nagoya University	Japan
José **Halloy**	Université Libre de Bruxelles (ULB)	Belgium
Inman **Harvey**	University of Sussex	UK
Phil **Husbands**	University of Sussex	UK
Hod **Lipson**	Cornell University	USA
Julian **Miller**	University of York	UK
Juan Manuel **Moreno**	Technical University of Catalunya	Spain
Mark **Neal**	University of Wales	UK
Valentin **Nepomnyashchikh**	Russian Academy of Sciences	Russia
Stefano **Nolfi**	Inst. of Cognitive Sciences and Technologies	Italy
Rolf **Pfeifer**	University of Zurich	Switzerland
Thomas **Schmickl**	University of Graz	Austria
Michele **Sebag**	INRIA	France
Wei-Min **Shen**	University of Southern California	USA
Luc **Steels**	ULB	Belgium
Kasper **Stoy**	University of Southern Denmark	Denmark
Adrian **Thompson**	University of Sussex	UK
Andy **Tyrrell**	University of York	UK
Alan **Winfield**	University of the West of England	UK

4.4.2 Computer Science

Covering the areas of evolutionary computing and simulation:

Table 4.2: List of experts. Major area: computer science

NAME	CURRENT AFFILIATION	COUNTRY
Andy **Adamatzky**	University of the West of England (UWE) Bristol	UK
Thomas **Bäck**	Leiden University	The Netherlands
Wolfgang **Banzhaf**	Memorial University of Newfoundland	Canada
Josh **Bongard**	University of Vermont	USA
Larry **Bull**	UWE	UK
Ernesto **Costa**	Universidade de Coimbra	Portugal

Table 4.2: (continued)

Name	**Current Affiliation**	**Country**
Peter **Dittrich**	Friedrich-Schiller-University Jena	Germany
Bruce **Edmonds**	Manchester Metropolitan University	UK
Andries **Engelbrecht**	University of Pretoria	South Africa
Emma **Hart**	Napier University	UK
Christian **Igel**	Ruhr University Bochum	Germany
Márk **Jelasity**	University of Szeged	Hungary
Yaochu **Jin**	University of Sussex	UK
Kenneth **De Jong**	George Mason University	USA
Jozef **Kelemen**	Silesian University	Czech Republic
John **Koza**	Stanford University	USA
Natalio **Krasnogor**	University of Nottingham	UK
Jose A. **Lozano**	University of the Basque Country	Spain
Alcherio **Martinoli**	EPFL	Switzerland
Zbigniew **Michalewicz**	University of Adelaide	Australia
Chrystopher **Nehaniv**	University of Hertfordshire	UK
Norman **Packard**	University Ca'Foscari	Italy
Ben **Paechter**	Napier University	UK
Gheorge **Pãun**	Romanian Academy	Romania
Daniel **Polani**	University of Hertfordshire	UK
Riccardo **Poli**	University of Essex	UK
Jordan B. **Pollack**	Brandeis University	USA
Steen **Rasmussen**	University of Southern Denmark	Denmark
Vladimir **Red'ko**	Russian Academy of Sciences	Russia
Grzegorz **Rozenberg**	Leiden University	The Netherlands
Arto **Salomaa**	University of Turku	Finland
Marc **Schoenauer**	INRIA	France
Jim **Smith**	UWE Bristol	UK
Susan **Stepney**	University of York	UK
Jon **Timmis**	University of York	UK
Gunnar **Tufte**	Norwegian Univ. of Sci and Techn	Norway
Mihaela **Ulieru**	University of New Brunswick	Canada
Rineke **Verbrugge**	University of Groningen	The Netherlands
Justin **Werfel**	Harvard University	USA
Klaus-Peter **Zauner**	University of Southampton	UK

4.4.3 Biology, Chemistry & Materials Science

Covering the areas of (evolutionary) synthetic biology, bio-molecular science, chemistry and materials science:

Table 4.3: List of experts. Major areas: biology, chemistry & materials science

Name	Current Affiliation	Country
Martyn **Amos**	Manchester Metropolitan University	UK
Mark **Bedau**	Reed College	USA
Nils **Blüthgen**	Charite - Universittsmedizin Berlin	Germany
Lee **Cronin**	University of Glasgow	UK
Jean-Louis **Deneubourg**	ULB	Belgium
Chris **Fernando**	University of Sussex	UK
Kirsty **Grant**	UNIC - CNRS	France
Masami **Hagiya**	University of Tokyo	Japan
Sinan **Haliyo**	Université Pierre et Marie Curie	France
Simon **Harding**	Memorial University of Newfoundland	Canada
Piet **Herdewijn**	Catholic Univ. Leuven	Belgium
Andreas **Herrmann**	University of Groningen	The Netherlands
Pauline **Hogeweg**	Utrecht University	The Netherlands
Alfonso **Jaramillo**	Universite d'Evry Val d'Essonne-Genopole	France
Antonie **Jerusalem**	IMDEA	Spain
Colin **Johnson**	University of Kent	UK
Richard **Jones**	University of Sheffield	UK
George **Kampis**	Eötvös Loránd University	Hungary
François **Képès**	CNRS	France
Markus **Kollmann**	Humboldt University	Germany
Zoran **Konkoli**	Chalmers University of Technology	Sweden
Kornél L. **Kovács**	University of Szeged	Hungary
Sylvain **Martel**	Polytechnique Montréal	Canada
John **McCaskill**	Ruhr-University Bochum	Germany
Beáta **Oborny**	Eötvös Loránd University	Hungary
José Maria **Peña**	UPM	Spain
Alexandra **Penn**	University of Southampton	UK
Steve **Potter**	Georgia Inst. of Technology	USA
Markus **Schmidt**	Org. Intl. Dialog and Conflict Manag. (IDC)	Austria
Ehud **Shapiro**	Weizmann Institute of Science	Israel
František **Štěpánek**	Institute of Chemical Technology	Czech Republic
Eörs **Szathmáry**	Eötvös Loránd University	Hungary
Guy **Theraulaz**	Universit Paul Sabatier	France
Harris **Wang**	Harvard University	USA
Kevin **Warwick**	University of Reading	UK
Göran **Wendin**	Chalmers University of Technology	Sweden

4.4.4 Ethics & Philosophy

Table 4.4: List of experts. Major area: ethics & philosophy

Name	Current Affiliation	Country
Ronald **Arkin**	Georgia Institute of Technology	USA
Daniel **Dennett**	Tufts University	USA
Patrick **Lin**	California Polytechnic State University	USA
Noel **Sharkey**	University of Sheffield	UK

Chapter 5

Literature Overview

> *Knowledge is of two kinds. We know a subject ourselves, or we know where we can find information on it.* (Samuel Johnson)

In this chapter we include all the references collected in the course of the past year, through the literature review performed by project members as well as suggestions obtained from experts during workshops and site visits.

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