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Materials as Machines

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Over the past decade the phrase 'molecular machine' became a buzz word in biology, chemistry and nanotechnology. Whereas twentieth-century physicists were provided with ample of funds and big machines for exploring the composition of the universe and the ultimate components of matter, in the past two decades public funds have been allocated to making tiny machines. The quest for structural units gave way to the quest for tiny machines performing basic tasks.¹

The major implication of this shifting goal is that it blurs the boundary between nature and artifact. Every material is characterized by what it does rather than by its molecular structure. Substances that used to be defined by their overall structure are redefined by their performance. In a sense, this is moving back to early modern times prior to the reform of chemical language in 1787, which gave up names referring to pharmaceutical virtues and replace them by systematic names based on their chemical composition.

How are we to understand this changing perspective on the molecular world? How came individual units of inorganic and organic matter, usually named and characterized by their structures to be viewed as machines? It is a complex process in which the main actors are instruments, concepts, military and economic competition. In my view, it is a three-step process i) first material structures have been functionalized: this is the emergence of materials approach in the 1960s; ii) from materials to systems approach in the 1980s; iii) then with the emergence of nanotechnology the functionalization of individual units tends to prevail over systems approach

I From Structures to Functions

How is it that physicists and chemists became more and more concerned with functions? Ironically, the access to microstructure allowed by x-ray diffraction was a prime mover. In the interwar period X ray diffraction of metal structures helped establish a relation between their microstructure and their metallic properties. The determination of microstructure became the prime concern of physical metallurgy and the notions of crystal lattices, of dislocation, of defect, provided a key for understanding the macroscopic behavior of metals. The connection between microstructure and mechanical properties was thus probed and the models and theories elaborated by physicists were put at work for designing new materials.

¹ See for instance ELI KINTISCH: Embracing Small Science in a Big Way, in: *Science*, 13, 29 September 2006, pp. 1872 – 73.

Once x-ray diffraction techniques had provided precise atomic pictures of solids, quantum mechanics provided the theoretical foundations for the description of solids. Solid state became an object of investigation in itself. Solid-state physicists discriminated between the properties depending on the idealized crystal pattern and the properties dependent on ‘accidents’ of the inner arrangement or of the surface of the solid. This focus on structure-sensitive-properties in the study of crystals can be seen as the main pathway which led to materials science.

Scientists who are inclined to view their research orientations as the outcome of the inner logic of autonomous knowledge describe the emergence of materials science as a natural process toward science-based technology. ROBERT CAHN, for instance, describes the emergence of MSE out of metallurgy via solid-state physics around 1960 when the departments of metallurgy of a number of academic institutions were renamed “metallurgy and materials science” and a few years later materials science emerged as an autonomous entity.

However, this storyline is an oversimplification, which occults two major aspects.

- First, the shift from traditional materials species such as metals, or ceramics to the generic notion of materials requires a generic notion of materials. A notion encompassing such diverse substances as wood, iron, paper, semiconductors, polymers or ceramics is a bizarre composite of many different disciplines. From an epistemological standpoint it is an oxymoron. Matter is a generic and abstract notion, whereas the notion of material refers to singular entities. Historically, the construction of an abstract and general concept of matter conditioned the science of nature in general. Otherwise physics would be a ‘zoology’ of materials, like stamp collection. Moving beyond the multiplicity and the variety of individual and phenomenological substances was the key to ‘modern science’. In other terms, materials were an obstacle that had to be overcome. This notion, associated to concrete sense qualities, and to human interests is a typical example of what GASTON BACHELARD called “epistemological obstacles”². It thus seems that western science had to give up the study of materials (or to leave it to chemists!) in order to become a rational and mathematical science.
- Solid State Science does not study materials. Certainly, solids can be materials but, on the one hand, not all materials are solid; on the other hand, the notion of materials refers to a substance of use or value for human purposes. Materials are commonly defined as “substances having properties which make them useful in machines, structures, devices, and products”³. Materials combine physical and chemical properties with social needs, industrial or military interests; they are composites or compromises between natural data and social constraints. Materials blur the boundary between society and nature. Significantly, the American official report on the state of the art in 1975 was entitled *Materials and Man’s Needs*. It insisted that the new discipline had to be called Materials Science & Engineering, that making new stuff useful for something was the main goal. The reference to the metaphysic notion of vital needs of *homo sapiens* covered more concrete needs for space and military programs.

Looking at what occurred at the institutional level, we see that interdisciplinarity was a state decree promulgated in a specific historical context, the cold war period in the US. In fact, the plural entity ‘materials’ first appeared in the language of science policy makers under the auspices of a bottleneck for advances in space and military technologies. Whereas during World War II the critical needs were still addressed in terms of one strategic material

² GASTON BACHELARD: *La formation de l’esprit scientifique*, Paris, Vrin, 1938.

³ National Academy of Science: *Materials and Man’s Needs. Supplementary Report of the Committee on the Survey of Materials Science and Engineering (COSMAT)*, Washington DC 1975, vol. 1.

(synthetic rubber, or plutonium for instance), in 1957 the US President Science Advisory Committee singled out materials in general as a priority. The advent of Sputnik in 1957 brought heavy investments in space research and prompted long-range programs without need of payoff. The idea that all materials were strategic emerged in the context of the cold war as a means for building up sufficient industrial capacity for future emergencies.

The Department of Defense (DoD) decided to sponsor many investigations into materials for special applications in weapons or aerospace. Through its Advanced Research Project Agency (ARPA), the DoD developed contracts with a number of universities. The ARPA program was twofold. Instead of a big unit like Los Alamos for the nuclear bomb program in wartime, the DoD generously funded university research with the intention of military exploitation, thus providing academic scientists with equipment that they could never afford. DoD strongly encouraged interdisciplinarity through interdisciplinary labs (IDLs), modelled after the Nuclear and Electronics Labs. Here is a distinctive feature of materials science: Laboratory equipment acted as a driving force in its emergence and consolidation. Not only did the sharing of instruments encourage interdisciplinarity, but innovation in instrumentation opened up new vistas for MSE. From x-ray diffraction to scanning probe microscopy, techniques have continued to drive and orientate research on materials.

The critical need for new materials prompted the era of materials by design. Given such-and-such functions performed by the wing of this airplane design the best material, combining the properties required for performing those functions. For instance silicon has been selected for semiconductors. Requirements list moved from function to properties and finally structure. Thus function became the priority in the design process. The material is no longer a constraint, it is designed for specific performances.

Thus the emergence of the generic concept of materials resulted from military and political pressures for embedding functionalities into material structures rather than from a 'natural' evolution towards increased abstraction in natural sciences.

II From Materials Approach to Systems Approach

The intermingling of science and industry had a strong impact on the discipline of MSE. While the first generation of materials scientists only focused on the relation between structure and properties, in the 1980s materials processing became a major concern. In the early 1980s, international competition prompted a radical change in US science policy, in order to foster industrial innovations and rival with Japan. In 1980, the Bayh-Dole University and Small Business Patent Act established a uniform patent policy for all federal agencies.⁴ The aim of this legislative measure was to encourage collaborations between industrial companies and universities, to have academic inventions developed for the market. It even imposed a duty for all researchers working under contracts with the government to pursue the commercialization of their government-funded inventions. Thus, after the blurring of disciplinary boundaries in the 1960s, the boundary between academia and business was also blurred in the 1980s.

This institutional change had an interesting epistemological impact on MSE. Academic material scientists repeatedly urged for a reorientation of research from the quest for new materials towards processing. MIT, with a long tradition in engineering and applied science, was at the forefront of the re-orientation. In the late 1970s, THOMAS EAGAR argued that it was

⁴ The Bayh-Dole University and Small Business Patent Act of Dec 12, 1980. JENNIFER A. HENDERSON, JOHN H. SMITH: Academia, Industry, and the Bay-Dole Act: An implied Duty to Commercialize, CIMIT, October 2002.

more important to improve processes than to invent new materials. He worked hard and successfully to create the Materials Processing Center, inaugurated on February 1, 1980.⁵ “Designing new materials with curious properties is fun for the materials scientists and engineer but it does not often yield results of major commercial or social benefit. American companies must spend their resources learning how to manufacture existing materials economically, not searching for exciting new materials. But if we spend our resources on processing selected new products of high reliability and low cost, we will all be winners.”⁶ At this stage, chemical industry played a leading role in shaping the identity of Materials Science comparable to the role played by metallurgy in the earlier period. Organic chemists pioneered the age of materials by design. In fact, materials are never meant to perform one function but for a set of functions. As conventional organic polymers did not present properties such as high-temperature stability, electrical or thermal conductivity that could expand their market, they developed composite materials with desirable properties. Those materials made of resin matrix and reinforcing fibers required a new specific approach to their design. On the one hand, emphasis was put on performance, since they are tailored to a specific task in a specific environment. In contrast to conventional materials having standard specifications and a global market, composites created for aerospace and military applications are developed according to the functional demands of the final product and the services expected from the manufactured product. Instead of supplying commodities to be finalized by the customers, they are the end-products of a cooperation between customers and suppliers. On the other hand, this cooperation required that the traditional linear approach (given a set of functions, let’s find the properties required and then design the structure combining them) give way to a systems approach. Any change made in any of the four parameters—structure, properties, performances and processes—can have significant effect on the performance of the whole system and may require a re-thinking of the whole device. Therefore, such materials call for a holistic way-of-thinking with continuous feed-back loops between the various specialists involved in design.

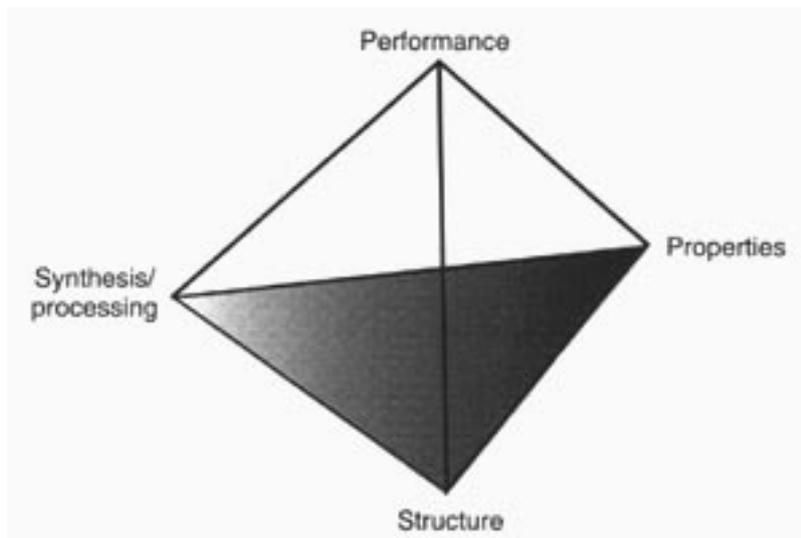
MERTON C. FLEMINGS, who served as the first Director of the Materials Processing Center at MIT, from 1980 – 1982, played a decisive part in building a conceptual basis for MSE. In the early 1990s, while he co-chaired the National Academy of Science Materials Study with PRAVEEN CHAUDHARI, FLEMINGS drew this figure—a tetrahedron with structure, properties, performance and process at each of the four vertices—to visualize continuous feedbacks⁷. Processing affects a material’s performance, but the required performance often determines the processing employed; processing affects structure, but structure determines what type of processing is chosen, etc. Being applicable to all kinds of materials, from cement to nanotubes, the tetrahedron brought home the materials generic perspective⁸. Since 1989 it has been deployed frequently in both research reports and textbooks.

⁵ MIT Office of the President Records 1943 – 1989, AC 12, Box 87. Interestingly four years after the opening of the Materials Processing Center another project was submitted to the National Academy of Science which was directly aimed at responding to the Japanese leadership. “This nation has been slow to respond to the materials processing/manufacturing challenge from abroad” stated the author of the memorandum submitted to the national Academy of Science. Memorandum to the National Academy of Sciences Committee on Materials Research, Toward an advanced materials processing and analysis center (AMPAC), MIT Office of the Associate Provost and Vice President for Research (1976 – 88), AC 149 BOX 6, p. 5.

⁶ THOMAS W. EAGAR: The real Challenge in Materials Engineering, in: FORESTER, TOM (ed): *Materials Revolution. Superconductors, New Materials and the Japanese Challenge*, op.cit. supra. pp. 241 – 253, quot. on p. 253.

⁷ MERTON FLEMINGS, personal communication May, 18, 2003.

⁸ See MERTON C. FLEMINGS and ROBERT W. CAHN: Organization and Trends in MSE Education in the US and in Europe, *Acta Materialia*, 48 (2000) 371 – 383. The first published occurrence of the tetrahedron that I have found was in National Research Council, *Materials Science and Engineering for the 1990s*. Report of the Committee on Materials Science and Engineering (Washington DC, National Academy Press, 1989).



More recently, some courses of MSE went further and included a fifth summit: end-users. Potential users or clients became partners in the design of new materials as a new parameter to be taken into account and interfering with structures and properties. Systems approach, assisted by all sorts of computer softwares thus became a standard practice in the design of new materials and the teaching of MSE. Materials are no longer viewed as functionalized structures but as hybrid products of natural, artificial and social requirements. However high-tech they can be, they result from a kind of bricolage based on pragmatic considerations. The end product of such designs is individualized by the continuous backs and frosts between structure, properties, performances, process and uses.

III From Systems to Machines

Four decades after the foundation of the earliest materials departments and despite the proliferation of materials centres and materials generic teaching programs, there is no evidence that Materials Science is reaching the stable state of a 'mature' discipline. In fact, its rapid expansion may be at the cost of its coherence.

Since the 1990s, nanoscience and -technology has emerged as a fulcrum of science policy. In a sense, nanoscale science could reinforce the coherence and vitality of MSE for a number of reasons: i) nanoscience is a generic concept that helps break with materials specificity; ii) virtually all sorts of materials can be nanostructured; iii) nanoscale research is as interdisciplinary as MSE and also develops across the border between science and technology; iv) nanoscience and MSE extensively use biomimetic strategies of synthesis; v) like MSE, nanoscience has been driven by instrumentation: Whereas in the 1980s chemists shifted their attention from atoms and molecules to condensed phases in order to design new materials,⁹ the 1990s brought about a move towards individual molecules. The crucial role of near-field microscopy STM and AFM has often been emphasized.¹⁰ Another instrument introduced in 1986, the year of BINNIG & ROHRER Noble Prize, allowed similar advances in biology. Optical tweezers using the forces exerted by a strongly focused beam of laser light allow trapping and moving objects ranging in size from tens of nanometers to tens of micrometers. They are used for atomic clocks but also for observing cells and batteries at

⁹ FLEMINGS, CAHN 2003

¹⁰ HESSENBRUCH + CYRUS MODY

ambient temperatures.¹¹ In the domain of electrophysiology, the method of patch clamps introduced in the 1970s allowed the study of ionic canals in membranes.¹² However, the current expansion toward the nanoscale brought about epistemic changes. A new paradigm seems to take over through the extensive use of the machine metaphor. Whereas in the late decades of the twentieth century, materials scientists were striving for designing smart materials or intelligent materials (systems responding to their environment) the machine metaphor reigns supreme. For lack of in-depth study of the rise of this metaphor, I just point to its possible niches. It seems to me that it emerged simultaneously in two different communities: among molecular biologists and among engineers who promoted nanotechnology.

III 1 The Engineering Milieu

The engineering milieu is in a sense close to the milieu that developed the systems approach. DREXLER was still at MIT in the 1986. But there is a variety of sub-cultures at MIT and the community DREXLER belonged to was quite different from the chemical engineering department. He was working in MARVIN MINSKY's Lab, in the AI culture which is quite different from that of chemical engineers. Although both laboratories were founded in the same period and equally claimed to be interdisciplinary,¹³ the AI Lab was mainly based on computer programmers while the MSE lab was headed by chemical engineers trained to work on materials processing. The AI Lab was interested principally in research on neuronal networks, vision, mechanical motion and manipulation, and language, which was viewed as the keys to more intelligent machines. In the 1970s, MINSKY developed with SEYMOUR PAPERT 'The Society of Mind Theory', based on the assumption that intelligence emerges from non-intelligent parts.

The contrast between the rhetorics surrounding MSE and AI is striking. Materials scientists already celebrated the coming of a new era of science-based engineering that would replace ages of empirical practices of design. They claimed that they were 'designing a new world' by combining the information pool generated by reductionist analysis with the component of design for which the systems approach was crucial.¹⁴ However, MSE was never presented as the exploration of a brave new world. The pragmatic turn dominates. Industrial competitiveness, energy and 'social needs' were the main legitimization of research investments. By contrast, in the Artificial Intelligence community science and science-fiction are closely associated and grandiose visions about a brave new world are ordinary language. MINSKY acted as an adviser for the movie *2001 A Space Odyssey*, later co-authored a science fiction thriller *The Turing Option* about a superintelligent robot. Just as AI scientists, nanoscientists are shaping 'a new world' through a convergence of disciplines, which is said to bring a new Renaissance.¹⁵

Finally, most of the machines designed in this context are conventional machines reduced to the nanoscale. DREXLER's molecular manufacture is like assembling a Lego. Each individual part is meant to perform a task and then connected to the others. Whether they perform

¹¹ Nobel prize CHU, see BENSIMON interview

¹² Nobel prize NEHER and SACKMANN (see BENSIMON interview)

¹³ Research at MIT in the field of artificial intelligence began in 1959. In 1963, the (then) "AI Group" was incorporated into the newly-formed Project MAC, only to split off again in 1970, as the MIT Artificial Intelligence Laboratory. In 2003, the AI Lab (as it is commonly abbreviated) was merged with the Laboratory for Computer Science, the descendant of Project MAC, to form CSAIL.

¹⁴ GREGORY B. OLSON: Designing a new world, *Science*, 288, 12 May 2000, pp. 993 – 998.

¹⁵ See MIHAIL ROCO and WILLIAM SIMS BAINBRIDGE (eds.): *Converging Technologies for Improving Human Performance. Nanotechnology, Biotechnology, Information Technology and Cognitive Science*, National Science Foundation, June 2002, Arlington, Virginia.

mechanical or logical functions, the machines currently designed follow conventional design principles with an outsider designer (like a clockmaker) planning and controlling the functioning of the components.¹⁶

III 2 Instrumentations Acted as a Driving Force

Visualizing individual molecules is one major resource. But in order to consider a molecule as a machine you need access to dynamics. Femto-second spectrometers and electron microscopes allowed seeing the move from non-equilibrium to equilibrium, identifying transient or intermediate structures and visualizing complex energy landscapes. AHMED ZEWAİL who was awarded the 1999 Chemistry Nobel Prize for his studies of the transition states of chemical reactions using femto-second spectroscopy, claims that it is a new era that opens up: whereas molecular biology rests on what he labels ‘Francis Crick’s dogma’ i.e. if you want to understand function you have to understand structure, now functions are directly accessible by integrating dynamics.¹⁷ Systems biology with mathematical simulations of the process should derive from this dynamical approach.

III 3 Molecular Biology

The Bioengineering Nanotechnology Initiative launched in 2002 by the US National Science Foundation prompted a reorganization of research with interdisciplinary teams aiming at identifying the molecular components of living systems and understanding the process of their synthesis *in situ* in order to take inspiration from them. Understanding the ways of nature and exploring new technological avenues merge into one single research program. In this program, it is more or less tacitly assumed that understanding one biological motor comes down to understanding a fundamental process because nature tends to use and re-use the same solution to a problem. And it is more or less expected that the access to the ‘fundamental’ level secured by molecular biology will provide us with *the* bottom-up method that nature and art can share. Nanotechnology and molecular biology rest on the same epistemological credo that each material unit, each molecule or macromolecule is or can be functionalized in order to perform a specific performance. It is designed as a tool for performing a specific task or operation: moving, rotating, computing in the case of logic machines. Enzymes and proteins are redefined as biological machines. More generally, the cell is viewed as a kind of factory or warehouse full of small machines. SHUGUANG ZHANG from MIT describes its components by analogy with current human technologies.¹⁸

¹⁶ See BERNADETTE BENSUAUDE-VINCENT and XAVIER GUCHET: Nanomachine: one word for three different paradigms, forthcoming in *Technê*, 2007.

¹⁷ See PHILIP BALL: Dynamic days, *Nature Materials*, 5, August 2006, p. 603.

¹⁸ ZHANG SHUGUANG: Fabrication of novel biomaterials through molecular self-assembly, *Nature Biotechnology*, 21, number 10, oct 2003, pp. 1171 – 78.

Table 1 What do they have in common? Machines and molecular machines

(from Zhang, 2003, p. 1174)

Machines	Molecular machines
Vehicles	Hemoglobin
Assembly lines	Ribosomes
Motors, generators	ATP synthases
Train tracks	Actin filament network
Train controlling center	Centrosome
Digital databases	Nucleosomes
Copy machines	Polymerases
Chain couplers	Ligases
Bulldozer, destroyer	Proteases, proteosomes
Mail sorting machines	Protein sorting mechanisms
Electric fences	Membranes
Gates, keys, passes	Ion channels
Internet nodes	Neuron synapses

The ideal for molecular computing is one molecule for electrodes, one for transistor, one switch. No synergy. It is a transparent automaton like VAUCANSON's flute player.

As long as such programs tend to capture an essential structural element and rely on it while neglecting all the messiness created by molecular agitation at the nanoscale, they are not really leading to a new technological paradigm. Whatever the promise of the sophisticated nanomedicines under study, from a philosophical perspective they look extremely conventional.

In conclusion, materials are not just 'epistemic things'. They are material agencies characterized by what they do or perform. Just as biological materials, synthetic materials are multifunctional and designed to work in a messy, noisy openworld. By contrast, the molecular machines or nanorobots so far designed by scientists and engineers are products of the mind, materialized principles or reified fictions. They perform only one task and only in highly protected laboratory conditions. I have argued that the contrast is less between science and engineering than it is a contrast between two engineering cultures, the culture of chemical engineers and that of information technology and Artificial Intelligence.

I have emphasized the contingent circumstances that presided over the emergence of MSE with a view of counteracting the determinist accounts told by most actors of the field. The same could be done for the accounts of the emergence of NST, based on MOORE's law and/or FEYNMAN's famous word "There is plenty of room at the bottom".

More importantly this too brief historical survey of the shift from materials to systems then to machines could be used to raise doubts about the future. Looking at how it works can tell us something about how it could work. For the Foresight Institute and for the propagandists of the NBIC convergence, there is no doubt that nanostructured materials are only the first generation of NST; the second generation will be nanomachines for drug delivery, computers etc. and the third generation hybrid nanomachines performing cognitive functions to enhance human performances. This determinist account is taken for granted in many reports as a natural trend. Against the magic spell of deterministic schemes it may be worth demonstrating that there are alternative possible futures. Considering the heterogeneity of cultures, of practices, and expectations that coexist under the umbrella of NT, one can make a plea for the divergence of future technologies. I am aware that this suggestion is a serious move from descriptive to normative. But this move becomes inevitable when one realizes that social studies of NT and NBIC are in a way reinforcing them by reifying unstable and heterogeneous interdisciplinary practices.

Zusammenfassung

Im Verlaufe des letzten Jahrzehnts ist es in Biologie, Chemie und Nanotechnologie in Mode gekommen, von ›molekularen Maschinen‹ zu sprechen. Im 20. Jahrhundert flossen große Summen in physikalische Projekte, die mit der Hilfe großer Apparate den Aufbau des Universums und die Struktur der Materie erforschen wollten. Diesem Vorhaben stehen nun winzige Maschinen gegenüber, die aber nicht die theoretische Struktur erhellen, sondern vielmehr bestimmte Aufgaben durchführen sollen.

Durch diese Verschiebung der Aufgabenstellung wird auch die Abgrenzung zwischen Natur und Artefakten unklar, denn die neuen Materialien und Substanzen sind dadurch bestimmt, was sie tun und wie sie funktionieren – kurz: molekulare Struktur wird durch Performanz in einem bestimmten Kontext ersetzt. Historisch gesehen wird damit die Reform der chemischen Sprache rückgängig gemacht, die im 18. Jahrhundert die pharmazeutischen Eigenschaften durch systematische, von der Struktur abgeleitete Namen ersetzte.

Wie sollte man diesen Perspektivwechsel von der Struktur zur Maschinenfunktion auffassen?

Es handelt sich um einen komplexen Prozess, der von Instrumenten, Konzepten und dem militärischen wie ökonomischen Wettbewerb gleichermaßen angetrieben wird. Man kann innerhalb dieses Prozesses historisch drei Stufen unterscheiden: (i) Materielle Strukturen werden funktionalisiert (Materialwissenschaften der 1960er), (ii) von Materialien zu Systemen (1980er), (iii) schließlich führt aktuell die Nanotechnologie zu einer Funktionalisierung individueller Einheiten.