Analyzing the Complexity of Nanotechnology

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The Complexity of Technology

In the past decades engineers have increasingly been confronted with the complexity of technological developments. In the 1950s and 1960s engineers could afford to focus very much on the scientific and technical aspects when developing new products, because they knew that it would not be difficult to be successful on the market. Customers could afford to explore all sorts of new gadgets, as there were no real economic barriers for them. Also there was not yet an organized resistance against technology in society. Issues such as environmental damage and ethical questions were not really urgent at that time. This changed in the late 1960s and early 1970s, and from then on engineers have learnt that it is nowadays not enough to come up with a nice technical idea. A great variation of conditions needs to be met. Not only should the new product fit with the current scientific and technological insights, but also economic, social, legal, aesthetical, environmental, psychological and numerous other conditions need to be taken into account when developing new products. This makes the work of engineers both complex and challenging. It also brings about the need to reflect on the nature of this complexity. The question emerges if it is possible to analyze this complexity in a more or less systematic way.

This question most certainly applies to the field of nanotechnology. Although still in its infancy, it clearly is a field in which quite a variety of aspects have to be taken into account. Not only are there gaps in our scientific knowledge, for which reason some people rather talk about nanosciences and wonder if one can use the term nanotechnology at all, but also there are great uncertainties about what will be feasible in the future, and what will appear to be mere ‘guru talk’ in the end. Already now institutes in a number of countries have started ethical debates about nanotechnology. Also the question has been raised how to set up new legislation for this emerging field, even though it is still uncertain what that legislation should exactly cover. Others worry about economic aspects of nanotechnology and in particular industrial companies are confronted with the difficult question if, and if so, how to invest in this still uncertain new type of technology. In other words: already now it is clear that the development of nanoscience and nanotechnology is a matter of great complexity, in which many different factors and issues are involved. For that reason, here too there is a need to analyze this complexity, in order to gain insights that can support decision making with respect to developments in nanoscience and nanotechnology.[1]

Analyzing Technological Complexity

Several options for analyzing the complexity of technological developments have been suggested. Perhaps the most basic one is the "Dual Nature of Technical Artifacts" approach, which is investigated at the Delft University of Technology.[2] In this approach, a technical artifact is analyzed according to the two natures it has: a physical nature and a functional nature. The physical nature comprises the non-relational (or non-intentional) aspects of the artifact, such as its size, shape, weight, structure, and so on. The knowledge about this nature of the artifact is, generally speaking, of a descriptive nature. On the other hand there is the functional nature of the artifact, which refers to what the artifact should enable us to accomplish. This nature involves relational (intentional) aspects, and the knowledge about this nature has a normative dimension. When an engineer says: "I know that this is a screwdriver", (s)he means to say: "I know that this is a device that *ought to* enable me to drive screws". The "ought to" nature of this knowledge shows its normative nature. What the engineer has to do is to find a physical nature for the artifact-in-design that fits the desired functional nature." One could say: the dual nature approach analyses in terms of a two-fold complexity. One could wonder if two natures only are sufficient to justify the term 'complexity' here. On the other hand, in practice finding the fit between these two natures can already be quite a challenge for engineers.

In a response to the Dual Nature approach, Carl Mitcham (2002) pointed out that analyzing the artifact in terms of just two natures may be too much of a reduction. Therefore other, more detailed analyses may be necessary. Such an alternative analysis was developed by Andries Sarlemijn at the Eindhoven University of Technology. The acronym he came up with for his approach was STeMPJE, which stands for a range of factors that need to be taken into account in technological developments, if ever they are to be successful: scientific, technological, market, political, juridical and (a)esthetical factors. By applying this analysis to different examples of technological developments, Sarlemijn (1993) was able to show the need for distinguishing between different types of technologies. His distinction was based on differences in the dynamics of these factors in the course of a technological development. Comparing his approach with the Dual Nature approach, one could say that his M, P, J and E factors are a further explications of the functional nature of an artifact, while the S factors and partially the Te factors relate to the physical nature of the artifact (Te factors partially, because those factors also can deal with functional aspects of the artifact, and thus relate to the functional nature of the artifact). One might say that Sarlemijn's approach splits up the two-fold nature of a technical artifact into a six-fold nature. His taxonomy of types of technologies indicates that it makes sense to apply this more detailed analysis.

In this article a third, even further detailed approach will be described. This approach was developed as early as in the 1930s by a Dutch Calvinist philosopher, named Herman Dooyeweerd (1969). Because his approach[3] was only applied to technology by Hendrik van Riessen, who hardly ever published in English, it has remained fairly unknown internationally throughout the years. Yet, it has some features that make it interesting as an analytical tool to investigate the complexity of technological developments. By applying this approach to nanotechnology, I will argue that it offers an analytical instrument for reflecting on the complexity of technological developments, while at the same time it offers analytical tools for creating order in the possible chaos that emerges when one explores this complexity. Dooyweerd himself saw his approach as a direct consequence of his Christian perspective on reality. It is interesting to note, however, that recently philosophers coming from different backgrounds have discovered the possibility to use some of his concepts separate from this Christian perspective. In particular in the field of systems methodology, the Dooyeweerd approach is now used to gain insights into the complexity of systems and the design of systems. Bergvall-Kåreborn (2000), for instance, has combined some of Dooyeweerd's concepts with the Soft Systems Methodology, which had been developed by Checkland (1981) and others. In the Proceedings of the annual conferences organized by the Centre for Philosophy of Technology and Systems (CPTS), other examples can be found. These examples show how the analytical instruments that Dooyeweerd developed can have a wider implication than only for a specific denomination of philosophers.

Aspect	Application to objects
1. Numerical	Object have a certain number of parts
2. Spatial	Objects occupy a certain space
3. Kinematical	Objects can move or be moved
4. Physical	Objects can interact by mechanical cause-effect relations
5. Biotic	Some objects live or are a part of other living beings' environment
6. Psychic/sensitive	People can observe objects
7. Logical/analytical	People can reason about objects
8. Cultural/developmental	People develop objects
9. Symbolic/linguistic	People represent objects by names or other symbolic representations
10. Social	People can share objects
11. Economic	People can sell objects
12. Aesthetic	People can appreciate objects for their beauty
13. Juridical	People can make laws in which objects feature
14. Ethical	People can assess objects from an ethical point of view
15. Pistic	People can believe in the positive effects of objects

Table 1. Aspects of reality according to Dooyeweerd

Before applying Dooyeweerd's concepts to the field of nanotechnology, it is useful first to give a more general description of those concepts. Basically what Dooyeweerd claims is that reality can be analyzed in terms of fifteen aspects or modes of existence (see his New Critique, Vol. II). Those aspects can be seen in Table 1. Any entity exists in all of these modes: it has a numerical existence, a spatial, a kinematical, etcetera. Furthermore, Dooyeweerd's claim is that these aspects or modes of existence show a certain order: each 'higher' aspect presupposes the existence of the 'lower' aspects. For example: the spatial aspect cannot exist without the numerical (because we have one, two, three, etcetera dimensions). Similarly, the biotic aspect cannot exist with all previous ones (life presupposes the possibility of energy conversion and movement, and movement can not exist without space). Up until the psychic aspect, Dooyeweerd explicitly argued for this particular hierarchy in the aspects, but for the later aspects he wrote more loosely about their order, and it is obvious that here it is much more problematic to set up a proper argumentation for this particular order of aspects. For that reason, his followers have had many debates about the proper order of the aspects, and nowadays several of them take a fairly pragmatic approach and leave the exact order of the higher aspects in the middle. This approach will be used in this article. The number of aspects also has often been debated. Dirk Vollenhove,[4] one of Dooyeweerd's colleagues, for instance, challenged the idea that the historical (or development) aspect should be regarded as a separate aspect. In his opinion the concept of time, which overarches all aspects, should be seen as the proper conceptualization of development. In this article I will keep the historical aspect but take it as an expression of the fact that every entity exists in a developmental way: it is able to bring forth or has been brought forth itself. One could use the term 'cultural' or 'developmental' aspect for this.

Another important feature of Dooyeweerd's approach is that entities can have subject and object functions in the various aspects (i.e. can exist as subject or as object in the various modes or aspects). For instance, a stone can exist as a subject in the kinematical aspect: it can move. It can also exist as an object in the same aspect: it can be moved. In the economic aspect, it can exist as an object (it can be bought), but not as a subject (it can not buy). Likewise, all entities have a 'highest' aspect in which they can still exist as a subject. Here his idea of a hierarchy in the aspects is used by Dooyeweerd and at first sight it may seem that the uncertainties about the order of the aspects may weaken this subject and object function concept; but it does not really, because there is a discontinuity in the transition from the psychic to the analytic aspect. Humans are the only entities that can function as subjects in the aspects from the analytic aspect and higher on. For that reason the exact order of the higher aspects does not matter for the analysis of subject and object functions. A third concept related to functions is the qualifying function. This function indicates what defines the entity's purpose or reason for existence. The qualifying function of a coin, for instance, is in the economic aspect, where it functions as an object. The functioning of entities in the various aspects is further analyzed by Dooyeweerd in terms of the ‘laws’ that hold for the various aspects. To continue the example of the coin: for its proper functioning we need to take into account a ‘law’ that holds in the economic aspect, which says that each coin can only be spent one at a time. That is why we have to calculate how much money we need to buy something before we commit ourselves to the transaction. One could see this as a sort of ‘law of conservation’ and similar conservation laws are found in other aspects (for example in the physical aspect where we find the law of conservation of energy). Dooyeweerd distinguished descriptive laws (such as natural laws) and prescriptive laws (of which examples can be found in the technological domain: technical norms and standards, good practice, etcetera). The different aspects have different laws, although the example of the conservation laws show that there may be analogies between the laws in the various aspects.

How does all that apply to technology? Technical artifacts can be analyzed in terms of their functioning in the various aspects. We can get to know their character by investigating which aspect they can serve as a subject or as an object, and which aspect we must seek their qualifying function. By reflecting on the possible laws in each of the aspects that should be taken into account when developing the artifact, engineers can develop a list of requirements for the artifact design. By taking into account the full list of aspects, one can get a fairly detailed impression of the complexity of the design problem. The Dooyeweerd approach can be seen as an extension of the Dual Nature approach. There is a split between the biotic and the psychic aspect. Functioning as a subject in the lower aspects does not require intentionality (a stone can move without having an intentional state of mind), while functioning as a subject in the higher aspects does require intentionality (one can not buy or sell without having an intentional state of mind). For this reason one can say that the lower aspects relate to the physical nature of a technical artifact, while the higher aspects relate to the functional nature of the artifact. In a similar way one can see Dooyeweerd’s approach as a further explication of Sarlemijn’s STeMPJE approach (in fact, some of Sarlemijn’s factors have the same name as some of Dooyeweerd’s aspects).

The Complexity of Nanotechnology

Non-intentional Aspects

Having seen the basic elements in Dooyeweerd's analysis we are now ready to explore how this approach can be instrumental in analyzing the complexity of nanaoscience and nanotechnology developments. I will confine myself here to indicate what issues are raised by the application of Dooyeweerd's approach to nanoscience and nanotechnology without discussing those issues in further detail. Let us now examine what each of the aspects means for the case of nanoscience and nanotechnology.[5] I will take nanotechnology to be the manipulation of individual atoms and molecules at the nanoscale, and nanoscience to be the development of scientific knowledge of the natural phenomena on nanoscale, in so far as they are relevant to nanotechnology.

(1) Dooyeweerd's first aspect (see Table 1) is the numerical. It belongs to their existence that nanoartifacts can be numbered. Already in this first and seemingly unproblematic aspect we start seeing the complexity of nanotechnological developments. As we are within the realm of quantum theory, numbering particles is not as we are used to in the macroscopic world. Furthermore, the most far-reaching claim of nanotechnology, as stated by some nanotechnology visionaries, such as Eric Drexler (1986), is the totally bottom-up construction of macroscale artifacts. For manipulating individual atoms extremely large numbers of assemblers will be necessary in order to get macroscopic results within a reasonable time scale. Drexler has suggested a scheme that would solve this problem by claiming that this can be done in the same way as nature does it: replicators continuously produce the assemblers that make the desired artifacts, and their self-reproduction will speed up this process. But there is a problem here when copying this procedure from nature. Drexler's replicators and assemblers need to be universal in order to be able to produce any desired artifacts, while their biological analogs, enzymes and ribosomes, are always specific (Burkhead 1999). So it may well be that the problem in the numerical aspect of the nanoartifacts cannot easily be solved (if at all this would be an easy solution, for it is yet unclear what the technological analog of the natural solution would look like).

(2) Next we have the aspect of space. This aspect seems to be what defines nanotechnology, given the fact that nanotechnology by definition has to do with manipulating matter at the level of nanometers. Indeed, most of the struggles that nanoscience and nanotechnology go through are related to the fact that it is difficult to observe and manipulate things at this level.

(3) (4) The next two aspects in Dooyeweerd's approach are the kinematical and the physical aspects. I will take them together here, as some of Dooyeweerd's followers have suggested. Motion and energy aspects of nanoartifacts both need to be described in terms of quantum phenomena. This description is, as yet, in development, and this is why nanoscience and nanotechnology are so closely related and often mentioned together. The fact that the phenomena at nanolevel are not yet fully known, while at the same time scientists try to build nanoartifacts, has as an interesting consequence that the functional and the physical nature of nanoartifacts (the two natures in the 'Dual Nature of Technical Artifacts' approach; see above) are not entirely known, while usually at least one of them is fairly well known in the beginning of the design process. Here the creation of a physical nature and the ascription of functions to the resulting artifact almost happen at the same time. Philosophically, this is perhaps one of the most significant issues in nanotechnology. In particular the process of defining a qualifying function (in Dooyeweerd's terms, i.e. not only telling what the emerging artifact can be used for, but also what it's most important function will be) to the artifact is a process that may well be different in the case of the creation of nanoartifacts compared to more traditional design processes.

(5) The fifth aspect is the biotic aspect. Here too, problems have already been identified. Nanoartifacts will interact with living creatures, and this may create problems that are similar to the asbestos problems that have caused quite some concern in the past. So far for the non-intentional aspects.

Intentional Aspects

(6) Now for the intentional aspects, starting from the psychic. This aspect has to do with consciousness. Here a concern for nanotechnological developments is the fact that our awareness of nanoartifacts is very indirect. We can only conceptualize them through pictures that have been produced by using

complicated processes that are far removed from direct observation. A commonly used way of picturing nanoartifacts is by using spheres to indicate individual atoms. This image, of course, is more symbolic than realistic, because of the quantum characteristics of atoms. A different way of picturing nanoartifacts is used when the outcomes of scanning tunneling microscopy are displayed. In such cases we see a surface with blobs emerging from it. The story that we are told is, that the raised blobs represent atoms. But this again is no more than a pictorial tool to help us conceptualize for ourselves what a nanoartifact looks like.

(7) A problem that is more interesting from a philosophical perspective, but may also have practical impact on the development of nanoartifacts can be identified when we consider the next of Dooyeweerd's aspects, which is the analytic or logic aspect. Analysis to Dooyeweerd is related to distinguishing. One of the perhaps most intriguing problems of nanotechnology is the question of how it could blur the boundaries between living and non-living matter. In terms of Dooyeweerd's concepts, the issue can be formulated as follows: is it still possible to identify a transition between the nanoartifact having its 'highest' subject function (i.e. the highest aspect in which it can function as a subject) in the physical or in the biotic sphere, and if yes, how? If indeed nanoartifacts can be built atom by atom, and this could also result in living tissue, then how do phenomena that indicate life emerge in this process? Self-reproduction, for instance, can be seen as a phenomenon that is typical for life. When such a phenomena would emerge in a process of building nanoartifacts, this may mean that we have to take that into account when taking safety precautions. From biology we know that self-reproduction can have as a consequence that the life system becomes autonomous in its growth, which may result in a threat for other life systems. A similar aspect can be asked with respect to the transition from the biotic to the psychic aspect. Is it possible that characteristics of consciousness would 'suddenly' start to appear in the process of building a (very complex) nanoartifact, and if yes, would consequences could that have for our attitude towards that nanoartifact.

(8) Now we come to the historic or development aspect. This is the aspect that we study when we consider the way in which the field of nanotechnology develops. As we noted before an interesting issue in this respect is the

development taking place based on only partial knowledge of the underlying natural phenomena.

(9) The study of these phenomena is what the next aspect, the linguistic or symbolic aspect, refers to. It seems that here we have an example in which the 'technology as applied science' paradigm fails to account for the relationship between science and technology. The relationship between nanoscience and nanotechnology is much more complicated.

(10) The issues that can be identified by considering the next five aspects are all related to the fact that nanoscience and nanotechnology are, as yet, in a state of infancy and much is unknown about the possible social effects of nanoartifacts and their use. In terms of the social aspect of nanoartifacts, it is yet unclear how the emergence of nanotechnology will affect social relationships (see e.g. Roco & Bainbridge 2002). Already now there are concerns about the possibility that nanotechnology will enhance the gap between those that have and those that do not have access to new technologies.

(11) As for the economical aspect, business corporations are faced with great uncertainties when making decisions about whether or not to invest in nanotechnological developments (at least, as far as the long-term future is concerned; at the short term there are fairly detailed expectations about possible industrial applications).

(12) Next in Dooyeweerd's ladder of aspects is the aesthetical aspect, which is the aspect in which the issue of harmony or disharmony is the key issue. Here too there are great uncertainties. Will nanoartifacts function in harmony with the artifacts that have been produced in more traditional ways? This point was raised by Langdon Winner in his testimony to the committee on Science of the US House of Representatives.[6] Perhaps that question presses even more when we consider the option that these nanoartifacts show characteristics of life, and yet are known to be the result of an artificial process.

(13) The juridical aspect raises questions with respect to developing legislation in a situation where the technology is not yet well known. What kind of laws should be defined in such a situation? Can laws be used to prevent undesired practices in

an early phase of a technological development? Usually legislation lags behind, and undesired practices have already had the chance of developing. It would be better to prevent such practices than trying to get rid of them once they have already emerged. Could nanotechnology be one of the first examples in which legislation is not just an effort to clean up the mess? But how can we determine what legislation would be appropriate?

(14) Also in the ethical aspect discussions are difficult because of the uncertainties about what nanotechnology will look like in the future. Several possible ethical issues have already been identified: the possibility of nanotechnology running out of hand and causing life-threatening situations (this in fact is the basis of Michel Crichton's (2002) novel *Prey*), and possible privacy problems when miniature equipment can be made and installed without being visible for the naked eye. But at this stage it is difficult to develop concrete ethical guidelines for nanotechnological developments.

(15) Finally we have the pistic aspect, which refers to beliefs and convictions that people may have with respect to technological developments. Nanotechnology offers a nice example of the important role such beliefs can have. Nanotechnological developments are often strongly pushed by strong beliefs in the far-reaching promises that are made by some nanotechnology visionaries. They suggest that nanotechnology in the end will offer us the means for the ultimate control over our world, because we can manipulate things at the most fundamental level. The pistic aspect raises the question which drives people to be involved in nanotechnology. Is it a matter of having control for the sake of exerting power over others or over nature? Or is it a matter of serving other people? Or is it a matter of responding to God's call to humans to serve Him by bringing into further deployment what He created? The answers to such questions can also be very determining for one's attitude towards the issues that have been raised by considering the previous aspects.

Integration of Aspects

An issue that is raised by the considerations above is the integration that is needed to make informed decisions about nanotechnological developments. According to Dooyeweerd integration of knowledge of the various aspects takes place when an engineer is involved in practical design and problem solving work. He/she takes notice of scientific knowledge referring to the various aspects and then tries to take all of that into account in one comprehensive decision. In order to gain that scientific knowledge people in the various scientific disciplines have each abstracted one aspect from the full complex reality and focus on a description of the regularities and particularities of that aspect. The engineer when using that knowledge then moves back to the 'level' of the full complex reality when making his/her design decisions. But there is also a second way of knowledge integration, which is still at the level of scientific, abstract considerations. It is what we usually call interdisciplinarity. At that level we seek abstract and general knowledge not with respect to one aspect (as in a specialized discipline) but with respect to more than one aspect. Interdisciplinarity is often mentioned as a characteristic feature of nanoscience and nanotechnology. A proper philosophical conceptualization of interdisciplinarity is not yet available (Margareth Boden's [1997] well-known taxonomy of levels of interdisciplinarity is more sociologically oriented than philosophically). Dooyeweerd has not systematically reflected on how knowledge about the various aspects can be brought together in true interdisciplinarity. He does have some notions that may be useful to explore for the purpose of conceptualizing interdisciplinarity. For example, he claims the possibility of analogies between the 'laws' in the various aspects. These emerge as a result of anticipations and retrocipations between the aspects. Anticipation means that a concept in a certain aspect contains a reference to a concept in a later aspect (for example, the concept of emotional value in the psychic aspect refers to the concept of value in the economic aspect). Retrocipation, likewise, means that a concept in a certain aspect contains a reference to a previous aspect (for example, the concept of profit margin in the economic aspect refers back to the concept of margin in the spatial aspect). Because of such relationships between concepts in different aspects, analogies between laws can emerge. For instance, we find conservation laws in several of the aspects. Such analogies could be the basis for finding regularities that would hold for more than one aspect and thus could contribute to interdisciplinary knowledge. But this needs much further explication in order to be fruitful for conceptualization of interdisciplinarity. One of the fields that can be drawn from here is that of systems sciences. In that field analogies between systems in various aspects (e.g. ecosystems in the biotic sphere and mechanical systems in the physical aspect, but also social systems in the social aspect) are studied and conceptualized.

Final Remarks

A survey of what the aspects may mean in the case of nanotechnology has shown how complex a non-reductionist description of nanotechnological developments will be. The survey raises more questions than it answers. One could also read the previous considerations as an agenda for further philosophical reflections on nanoscience and nanotechnology.[7] A challenge for further reflections is certainly to seek out the consequences of the different 'laws' that we can find in the different aspects, and—as stated above—the integration of knowledge of those 'laws.' Perhaps at this stage the identification of relevant philosophical questions is more important than providing the answers to such questions. Probably the content of this issue of Techné will reflect that at the moment we do not have that many answers yet. But in that situation setting up a proper research agenda is important and the Dooyeweerd approach that was described here can be a contribution to that, as well as to the later effort of seeking answers to the research questions.

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[1] In this paper the concept of complexity will be analysed differently from the way it is done in complexity research in the context of the theory of non-linear systems and computational theories of complexity. A more qualitative approach will be used here.

[2] More information on this project can be found at www.dualnature.tudelft.nl/

[3] Because of his Calvinist background, we speak of 'reformational philosophy'. More information can be found on www.isi.salford.ac.uk/dooy/ and home01.wxs.nl/~srw/

[4] Some information on his person and work can be found at: home.planet.nl/~srw/nwe/vollenhove/kok.html.

[5] I will assume that elsewhere in this special issue a global description of nanoscience and nanotechnology has been presented already.

[6] See www.rpi.edu/~winner/testimony.htm.

[7] Probably several of the issues that have been mentioned here will also feature in other articles in this Special Issue of Techné. Several of the issues also feature in the University of South Carolina research agenda on the philosophy of nanotechnology (see www.cla.sc.edu/cpes/nirt/nirt200112/nirt.html). It is also possible that some issues have not yet become the focus of philosophical reflections, and in such a case the reward for applying Dooyeweerd's approach is that we may start appreciating the relevance of such issues now.