Edited by PETER WEINGART and NICO STEHR

# Practising Interdisciplinarity

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# The Interdisciplinary Nature of Science: Theoretical Framework and Bibliometric-Empirical Approach

ANTHONY F.J. VAN RAAN

## Contours of a Theoretical Framework of Interdisciplinarity

In this essay I discuss different aspects of the phenomenon called the 'interdisciplinarity' of science. Primarily I aim at an empirical investigation of interdisciplinarity in an *instrumental sense*: how to observe scientific activities in order to discover their interdisciplinary characteristics, and, next, to analyse these characteristics in more detail. Such observations are important as 'input knowledge' for other studies on interdisciplinarity, for instance, the more sociologically oriented work on the cooperation of researchers within interdisciplinary teams and the policy-oriented work on the stimulation of interdisciplinary research activities. But in this essay I also develop a theoretical framework. Thus, to present some basic ideas, or working hypotheses, concerning interdisciplinarity. Earlier empirical evidence is in line with these ideas, but more research is certainly necessary.

### PROBLEM-DRIVEN MOTIVATION AND REPUTATION-DRIVEN REGULATION

The first working hypothesis deals with *motivation* and *reputation*. On the basis of the most fundamental characteristic of science, curiosity, science has always been and still is a highly problem-oriented enterprise that is stimulated by societal problems in many ways – much more than policy-makers try to believe. Societal problems constitute, in fact, a very profound *external* motivation of scientists. Most probably, precisely this motivation was the main driving force of the great (and only) Scientific Revolution in sixteenth-century Western Europe. Given the crucial role of reputation in science (Merton 1973), it is obvious that problem-driven, externally motivated research, *if* carried out successfully, can contribute highly to reputation in science. So there are good sociological reasons for why science, which is after all a human activity, will have strong problem-driven features.

This first working hypothesis has several further consequences. It is not only reputation *in* science but, equally important, reputation *by* science that may stimulate scientists. Here we have interesting research objectives for social-psychologically oriented studies of science.

Next, as stated above, problem-driven, externally motivated research can contribute to reputation, *if* the research is carried out successfully. This seems a rather obvious remark, but it is not. It means implicitly a hard precondition: socioeconomic problems *must also* imply interesting *scientific problems* (some more basic, like research on diseases, some more applied or technological, like semiconductor devices), otherwise they cannot contribute to scientific reputation. Absence of this *internal* motivation, appealing scientific problems, will immediately block the interests of scientists.

Third, most socioeconomic problems are *interdisciplinary* in nature. On the other hand, both scientific appeal – if present – and scientific reputation work are predominantly *disciplinary*, simply because reputation is generally coupled with the more or less established categories in which scientists are educated. Therefore, a specific discipline will mostly play the first violin in interdisciplinary work. Furthermore, this leading part of a specific discipline will be strengthened very effectively by technology, as we discuss in the next section.

The conclusion from the above scheme of thought is that there is a very tight *sociocognitive triangle* of three interacting elements: socioeconomic problems, scientifically interesting problems, and interdisciplinarity. The interactions among these three elements are *driven* by motivations, *regulated* by the reputational system in science, and *dominated* by the knowledge, craftmanship, and habits of mostly one or just a few specific disciplines.

## TECHNOLOGY-DRIVEN REINFORCEMENT

The second working hypothesis concerns the role of *technology*. Apparently there is an unavoidable 'natural' and 'self-organizing' development of science towards more interdisciplinary activities, comparable with ecological systems (van Raan 1990; Noyons and Van Raan 1998). The reason is that technology – and more generally the 'extension of our human brain with relevant artifacts,' i.e., powerful instruments – acts as a bridge between the different scientific disciplines. *Without technology, domains of human knowledge would remain largely isolated.* As an example, recent developments in the neurosciences show the overwhelming role of instruments. Observations by advanced brain-scanning apparatus (based directly on fundamental physical processes) are influencing medicine and molecular biology tremendously, but also the behavioural sciences and even philosophy. Therefore we can conclude that technology continuously *reinforces* the sociocognitive triangle dramatically, mainly by the permanent creation of new instruments. And because instruments are mainly developed in specific disciplines – it is often not realized how typically disciplinary crucial instruments and apparatus are! – we have an extremely effective 'co-reinforcement' of the role of a specific discipline in the sociocognitive triangle of interdisciplinary work.

The capacity to combine brain and hands in making things we call instruments or apparatus is a unique property of the human species. Bluntly speaking, it is precisely this property that is responsible for the advancement of our human, objective knowledge, which is, given the above reasoning, increasingly interdisciplinary. Scerri (this volume) shows that eminent scientists strongly emphasize the crucial role of instruments for the progress of science, particularly the 'bridging' role between disciplines, by transferring instruments from one discipline to another.

## THE DECAY OF CHATTY SCIENCE

The above ideas have further interesting consequences. From these ideas we can infer that the typical non-instrumental scientific activities such as philosophy and parts of the social and behavioural sciences and the humanities are in danger of losing their connections with the natural, basically interdisciplinary advancement of science. As a consequence, they will then lose their objective, scientific character, because they will be less and less subject to the regulating rigour of the hard disciplines that provide instrumentation. These disciplines will become more and more unscientific, moving towards ideology-based, nonsensical, *chatty* activities dominated by current fashions. These fashions are, in turn, often dictated by current politically correct opinions, thus undermining the typical scientific critical attitude.

In summary, scientific interdisciplinarity is a result of one of the main aspects of science itself, its socioeconomic, problem-driven character preconditioned by scientific motivation, regulated by the reputational system in science, and reinforced continuously – and very effectively – by technological developments. Needless to say, these technological developments are in turn influenced by scientific developments. This feedback character of the science–technology interaction is an indisputable fact. But the point here is that this feedback is dominated by sudden changes that are *not* caused predominantly by new, typically scientific, 'cognitive' discoveries, but much more by the rather contingent, thus 'stepwise,' introduction of further new instrumentation.

## Bibliometric Methods of Studying Interdisciplinarity

### THREE ANALYTICAL APPROACHES

Above I sketched the outlines of a theoretical framework of science and its intrinsically interdisciplinary character. This framework indicates where interesting empirical work can be done. Now we arrive at the more empirical part of our work, based on advanced bibliometric work. First we develop analytical tools in order to observe and interpret the interdisciplinary aspects of scientific research. Beyond the scope of this essay, but certainly one of the major objectives, is to test this theoretical framework to see if the working hypotheses can find support in empirical evidence.

In this section I discuss three bibliometric methods of studying the phenomenon of interdisciplinarity in science:

1 the construction of a *research activity profile:* a breakdown of the scientific work published by a research group/institute into (sub)fields, on the basis of the field-specific characteristics of the institute's own publications
2 the construction of a *research influence profile:* a breakdown of the scientific work citing the work of a research group/institute into (sub)fields, on the basis of the field-specific characteristics of the institute's citing publications
3 the construction of *bibliometric maps* of scientific fields in order to identify as objectively as possible structural relations between various subfields, as well as the relations of these subfields with other disciplines outside the central map of the field

In this essay I sketch the main lines of these approaches. For a detailed and critical discussion of the potentials and limitations of bibliometric methods, refer to a recent overview paper (van Raan 1996).

## RESEARCH ACTIVITY PROFILE

For a first discussion of these three approaches, I present concrete examples.

In line with our first working hypothesis that socioeconomic problems constitute a major driving force in science, I analyse how the interaction triangle of socioeconomic problems and scientifically interesting problems and interdisciplinarity becomes visible in the scientific work of a research group/institute.

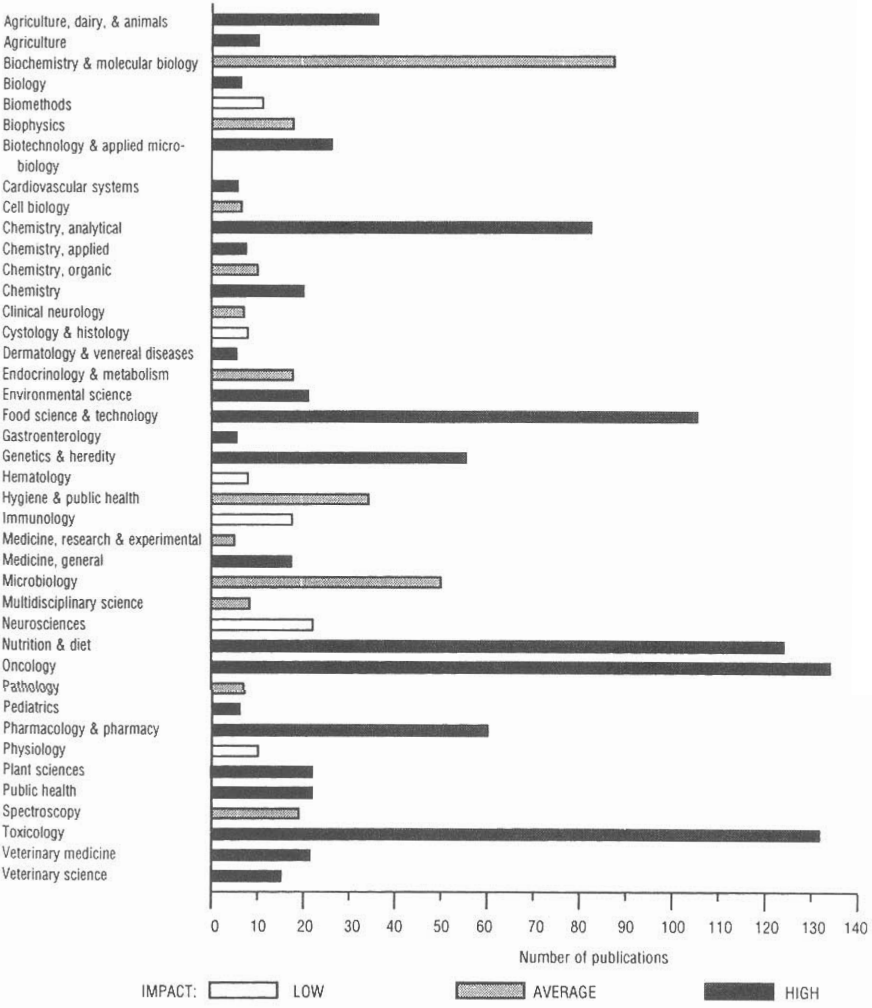
Here I focus on a typical socioeconomic problem: nutrition and food, showing that such a problem is immediately related to interdisciplinary research, and observing how this interdisciplinary research is valued by the scientific community (i.e., contributes to reputation). Such a valuation is a proof of being successfully engaged in scientifically interesting problems connected with more basics-oriented, disciplinary fields of research.

The target institute is the TNO Nutrition and Food Research Institute in The Netherlands, one of the major and most outstanding research institutes in its field in Europe. Recently, with Thed van Leeuwen, I performed an extensive bibliometric analysis of the research performance of this institute (van Raan and van Leeuwen 1999). An important part of the method consisted of breaking down the institute's publications in terms of fields defined by sets of journals. This *activity breakdown* gave a direct overview of all the (sub)fields involved in the research activities of the institute. As discussed above, this can be seen as an unambiguous indicator of interdisciplinarity. The rank-distribution function of the number of publications over (sub)fields can even be used as a measure of the degree of interdisciplinarity.

We constructed the institute's research activity profile for the period 1987–96 and for the two subperiods (1987–91, 1992–6) in order to visualize possible shifts in interdisciplinarity. In this paper I focus on the results of the entire period of 1987–96 (see Figure 4-1). The abscissa of the profile gives the size of the activity (number of publications) per (sub)field, and the colour of the bars represents the influence of the institute in the (sub)field concerned, normalized to an international standard (based on advanced citation analysis; see van Raan 1996 and legends to the figure). The institute's research relates to about forty fields

Figure 4.1
Research activity profile, TNO Nutrition and Food Research Institute, 1987–96, based on 1395 publications of the institute.

The length of the bars represents the number of publications in the (sub)field as specified on the vertical axis. The colour of the bars represents the impact level: low (white bars), average (grey bars), or high (black bars) as compared with an international standard for each (sub)field. Example: The TNO Institute published in the period 1987–96 about 130 publications (covered by the *Science Citation Index*) in the field of toxicology. These publications together (the work of the TNO Institute in toxicology) have an impact above the international (worldwide) average for the field of toxicology. For further explanation of bibliometric indicators see van Raan 1996.



of science. No doubt, the institute's scientists perform very well in their core fields, food science and technology, and nutrition and dietary research. But they also have substantial influence in oncology, analytical chemistry, toxicology, genetics and heredity, in biochemistry and molecular biology, microbiology, pharmacology, and many other fields of science.

My main objective is to demonstrate the potential of this approach for analysing interdisciplinarity in general. If we look at the above list of research fields, we can ask another question: What is a discipline? Most research fields are quite interdisciplinary, at least to a certain level of aggregation. Therefore, it is hardly possible to 'define' interdisciplinarity. Would science be 'truly interdisciplinary' if there were, say, a complete 'amalgam' of physics and biology? Or is there already substantial interdisciplinarity if many research fields are dominated by a main discipline (e.g., physics) but at the same time have important other-discipline-oriented aspects, such as are clearly visible in the 'science map' discussed in the section 'Bibliometric Maps' that follows in this chapter?

At least the latter type of interdisciplinarity is more a rule than an exception. Perhaps the current problematization of interdisciplinarity is more a matter of mystification cultivated by post-modern ideologies or related politically correct thinking, such as the 'invention' of mode-2 research by Gibbons et al. (1994). Often claims of interdisciplinarity or 'transdisciplinarity' are supported by 'moral enthusiasm,' as described by Weingart (this volume).

## RESEARCH INFLUENCE PROFILE

The measurement of the international influence of scientific work is operationalized by the concept of 'impact,' which is a bibliometrically defined measure based on citation analysis (van Raan 1996). The impact per (sub)field as indicated in the Figure 4.1 nutrition and food research activity profile concerns the impact of the institute's publications in these specific (sub)fields, regardless of the citing field. Thus, the next step is a further breakdown into (sub)fields of the scientific work citing the publications of a research group or institute (for earlier work on similar cross-disciplinary citations, see Porter and Chubin 1985).

Current work in our group is going on to design and elaborate an optimal representation of a scientific *influence profile* by a breakdown of an institute's impact on the basis of field-specific characteristics of the citing publications. Contrary to the earlier case, we are focusing on a typical mono-disciplinary institute: CERN (Geneva), the European Organization for High-Energy Research, one of the world's major high-energy physics institutes. I refer for details to Davidse and van Raan (1997). This CERN study aims at analysing the influence of basic high-energy physics research on fields other than physics, and particularly on application-oriented research. We found that about 10 per cent of the CERN physics publications were cited by publications outside physics. The most important outside-physics fields appeared to be astronomy and astrophysics, computer science, electrical and electronic engineering, and instruments and instrumentation. Similar analyses were made for two other large particle accelerator institutes, Deutsches Elektronen-Synchrotron (DESY, Hamburg) and Stanford Linear Accelerator Centre (SLAC, Stanford), for comparison. We found that accelerator institutes, particularly DESY, have developed a quite substantial interdisciplinary environment, mostly because of the application of photon and particle radiation in biological and medical fields. So I stress that our study focused on the *physics* of these institutes.

We found that the physics-to-nonphysics knowledge flow (an interdisciplinary flow), as measured by unravelling the 'citation traffic,' was about six times smaller than the physics-to-physics knowledge flow (the disciplinary flow). Nevertheless, this interdisciplinary flow is still considerable in size. Particularly, but not surprisingly, the strong relation between basic physics and engineering/instrumentation (the technological influence) plays an important role.

### BIBLIOMETRIC MAPS

The third major line of our quantitative methods is *bibliometric mapping,* or cartography of research fields. Here I limit myself to the main lines and refer for a more detailed discussion to Tijssen and van Raan (1994) and Noyons and van Raan (1998). The basic idea is as follows: each year about a million scientific articles are published. For just one research field, such as materials science, the number of papers is already about 30,000 per year. How do we keep track of all these developments, particularly relations with other fields? Are cognitive structures hidden in this mass of published knowledge at a meta-level? And what can these cognitive structures tell us about interdisciplinarity?

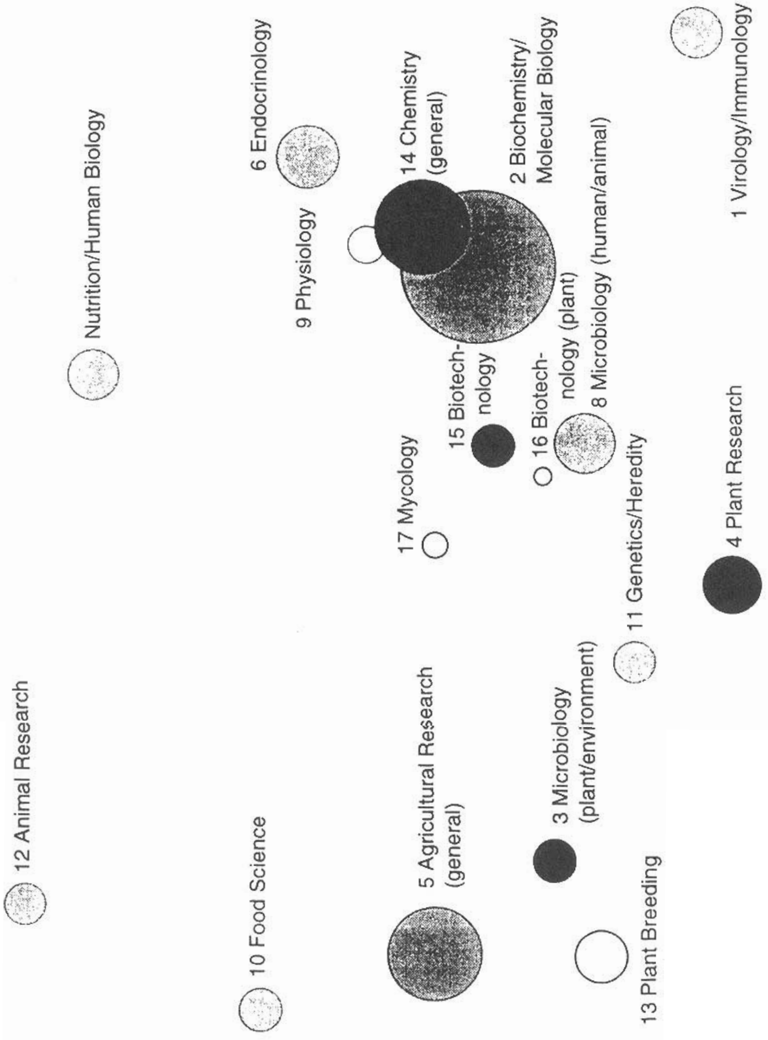
Suppose each research field can be characterized by a list of the most important, say 100, keywords. For materials science such a list will cover words like ceramics, polymers, semiconductors, high-temperature superconductivity, alloys, and so on. Each publication can be characterized by a subset from the total list of keywords. For all 30,000 publications we compare their keyword lists in pairs. In other words, these 30,000 publications constitute a gigantic network in which all publications are linked by one of more common keywords. The more keywords two publications have in common, the more these publications are related (keyword-similarity) and can be regarded as belonging to the same research field or specialty. In mathematical terms, publications are represented as vectors in a high-dimensional word-space. In this space they group together, or take very distant positions when they are not related to one another.

We developed mathematical techniques to unravel these publication networks and to successively cluster and map the underlying word-structures ('co-word maps'). What is fascinating is that these structures can be regarded as the cognitive or intellectual structure of science. As discussed above, this structure is entirely based on the total relations among all publications. Thus, the structures that are discovered are not the result of any pre-arranged classification system whatsoever. Nobody prescribes these structures – they emerge solely from the internal relations of the whole universe of publications. In other words, what we make visible by our mathematical methods is the *self-organized 'ecology' of science* (van Raan 1990, Noyons and van Raan 1998). Similar structures arise from the analysis of citation-relations ('co-citation maps').

Figure 4.2 shows the first results of our recent work: the 'freezing-out' of the underlying patterns in about 100,000 publications in agricultural research (based on a co-citation and co-word analysis combination). We performed a two-step procedure: First, we constructed one global overview map (shown in Figure 4.2) and, second, for each discovered cluster (which practically means field of research) we made detailed, fine-structure maps (for details of this work, and particularly for a presentation of the fine-structure maps, we refer to Noyons et al. 1996, as well as note 1.)[1] Figure 4.2 clearly shows the mutual relationships between agricultural research (a field undoubtedly devoted to a whole spectrum of socioeconomic problems) and many other fields of science. The closer the clusters (fields) are, the more related they are *in connection with agricultural research*. We observe, next to agricultural research (general), the dominating role of biochemistry and molecular biology as well as chemistry (general). Many other fields of science play a role, such as microbiology, endocrinology, virology and immunology, plant research, and biotechnology.

Figure 4.2
Bibliometric map of agricultural research, 1994, based on about 100,000 publications worldwide.

The map represents a relational structure of clusters of publications based on cluster-similarity measures. The clusters can be identified as research fields. The closer the clusters are, the more related the (sub)fields concerned. White clusters are characterized by decreasing publication activity worldwide; grey clusters by no significant decrease or increase in publication activity; black clusters by increasing activity. For further explanation see note 1.



Again we make the same observation discussed earlier: science is a fascinating amalgam of 'cognitive regions' that are part of more or less established disciplines. Often these disciplines are research fields that originated from earlier interdisciplinary developments. Above all, the whole is undoubtedly interdisciplinary. As in any complex, self-organizing system, the global characteristics of the whole – such as the typical power-law distribution of the sizes of parts of the system – are not so much a direct result of the constituting individual elements, but they represent a very specific property of the system as such.

This bibliometric cartography has interesting potentials. First, it visualizes the intrinsically interdisciplinary landscape of a scientific field embedded in its surroundings. These surroundings have both a cognitive as well as a semantic meaning: the word combinations on the map are always positioned in relation to other word combinations, i.e., representatives of research fields, specialty topics, or scientific concepts. Thus a field-specific context is generated automatically by the above-described self-organizing process. Therefore, problems of interpretation of words on the map are in our opinion much less severe than as discussed by others who consider these interpretation problems a serious drawback of bibliometric mapping (Maasen, this volume).

Second, by making these maps for a series of years, we are able to observe trends and changes in structure. So we gain insight into the dynamics of the scientific endeavour, particularly the interdisciplinary developments. Clearly we observe the phenomemon described by Weingart (this volume): 'Instead of assuming a disciplinary structure that has to be adapted to the structure of the real world by approximation, it has to be recognized that the structure of knowledge and the delineation of disciplines and their subject matters constitute perceptions of the world.'

Third, we are able to put the position of major actors on the map. Thus we are creating a strategic map: who is where in science, and, more precisely, what is the position of these actors in terms of the interdisciplinary relations of the different fields? (For recent examples of bibliometric mapping including 'dynamic' examples, see note 1).

## Concluding Remarks

In this paper I first presented a theoretical framework for the interdisciplinary nature of science. It can be described as a socio-cognitive triangle of three interacting elements: socio-economic problems, scientifically interesting problems, and interdisciplinarity. The dynamics of the relations between these elements of this triangular compound are driven by motivations, regulated by the reputational system in science, dominated by one or just a few disciplines, and continuously reinforced by instrumentation. As a consequence of this model, we can forecast the decay of what I call 'chatty' science.

The combination of the three bibliometric approaches – analysis of research activity, research influence, and mapping – appears to be a powerful instrument for further investigating the interdisciplinary nature of science. They form a coherent set of approaches for diagnosing important aspects of interdisciplinarity. In particular, the analysis of developments over time and of the role of major actors is important in testing the various working hypotheses that form the basis of our theoretical framework.

In this contribution I presented the main lines of our empirical 'instrumentation.' Further elaboration will address more specifically how the above empirical methods fit into the theoretical framework, that is, how the different empirical steps are related to the different parts of the theoretical framework.

This context involves further important problems. For example, the first two bibliometric methods focus on science as represented by its chief constituting elements, namely research groups or institutes. The third method addresses science – or at least major parts of it – as a whole. This dichotomy is typical for any complex system. On the one hand we have the elements with which the system is built; on the other we have the system as a whole, with its global characteristics, which are partly related to properties of the constituting elements, but partly also has its own properties.[2] This demonstrates a fundamental aspect in the empirical operationalization of a concept such as 'science,' and, in fact, of any complex system. We think that in science disciplinary fields are the constituting elements, and that interdisciplinarity is the general, large-scale property. We know that a general property of a system (e.g., the always limited amount of total space, energy, resources) can induce major effects in its constituting elements (e.g., in the way they have to interact).

## Notes

1 For recent examples refer to our institute's Internet home page at http://sahara.fsw.leidenuniv.nl/cwts/cwtshome.html

2 To further illustrate this problem I will make a comparison with a physical complex system: turbulence in boiling water. Certainly several aspects of this complex system are related to the properties of the constituting elements, the water molecules. Clearly the boiling point temperature is element-dependent: for the water molecules it is 100°C, for any other molecule it will be completely different. Nevertheless, the turbulence patterns resulting from boiling will be very general and will manifest themselves in any type of liquid, regardless of the specific properties of the constituting elements, in this case the water molecules.