Chapter 9
Structure–Property Relations Between Macro and Micro Representations: Relevant Meso-levels in Authentic Tasks

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Abstract In chemistry education, micro–macro thinking using structure–property relations is considered as a key conceptual area for students. However, it is difficult but challenging for students and teachers. In this chapter, we have redefined this domain in terms of a coherent set of philosophical, substantive and pedagogical substructures. Starting from the philosophy that chemistry should be considered as a human activity, scientific and technological developments are interrelated with issues in society and part of our cultures. In many communities of practice in society, knowledge is regarded as a tool necessary for performing the activities of those practices. Learning chemistry can be seen as participation in relevant social practices. Within this vision, we have selected tasks belonging to authentic chemical practices in which structure–property relations were explored in different subdomains (biochemistry, inorganic material science and organic polymeric material science). Within the substantive substructure, meso-structures are essential to iterate between the macro- and the sub-microscopic level. Interrelating structure–property relations connect student learning of these chemical concepts to the contexts of their everyday lives and to contemporary science and technological issues. Using this way of macro–micro thinking, two units for teaching structure–property relations were designed. These units focus on macro–micro thinking with steps in between: what we have termed 'meso-levels'. The results of the conceptual analysis of structure – property relations and how these relations are used in macro–micro thinking are discussed. We also present a first exploration of students' learning of authentic tasks, focusing on their conceptual development.

Reconsidering the Content of the Domain of Macro–Micro Thinking

Micro–macro thinking using structure–property relations is considered as a key conceptual area in the domain of chemistry. This area is concerned with the understanding of properties and transformations of materials, for which chemists

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construct models for investigating known and new substances and their transformations (Justi & Gilbert, 2002). For some tasks these models imply evident relations between macroscopic properties (boiling point, solubility) and sub-microscopic models like molecules or atoms. However, for many other tasks in contemporary science and technology, the relevant structures appear to be at other levels than the sub-microscopic level. In many contemporary authentic tasks, properties of materials are explained and predicted by 'models' that do not immediately relate to structures at a molecular or atomic level (e.g. nanotechnology, genomics and micro-structured materials). Empirical data on the functional relevance in chemical expertise for such tasks and the scales of these intermediate levels will be discussed in this paper.

Learning to relate macroscopic phenomena to sub-microscopic models is perceived as difficult. When trying to acquire knowledge about such models, students have difficulty understanding the relation between the phenomena and their representation. The step from the level of macroscopic phenomena to the lowest sub-microscopic representations is huge. Often it implies a number of relations and steps that are not described explicitly in textbooks (Han & Roth, 2006). Breaking up the macro–micro jump into smaller parts could make the cognitive load less demanding for students. Intermediate (meso) levels might be functional in the teaching and learning of macro–micro thinking. Within this respect, Millar (1990) states that

> 'we do not have to go straight from the observable to the atomic/molecular level; there are steps in between' and 'that learning necessarily proceeds via a series of intermediate steps, or 'models' . . .' (see also Besson & Viennot, 2004 for physics education).

We therefore focus on a system of intermediate 'meso' levels that manifest when studying structures and properties of macroscopic objects and materials, such as foods, designed everyday artefacts and cloths (cf. Aguilera, 2006; Cussler & Moggridge, 2001; Walstra, 2003). For example, weaving patterns of threads comprise fibres that have amorphous and crystalline filaments. These structures are examples of intermediate meso-structures that relate to properties, such as the strength of a thread, the flexibility of textile and the stiffness of cloths. Properties and structures can be attributed to the different scales of this system. Within such a conceptual schema, the meso levels should link macroscopic phenomena to microscopic models in a step-wise thinking process using the structure, properties and their interrelations at the different levels.

Although in the context of everyday life and in contemporary science and technology, new materials and structured foods have come into focus, the learning of how to relate the sub-microscopic world of chemistry to macroscopic phenomena of these (bio)materials has not become a substantial part of the chemistry curriculum in schools. Instead, many school chemistry curricula have a dominant focus on corpuscular theories that pretend to offer students a general perspective for interpreting macroscopic phenomena. Additionally, student learning is organised by textbooks-with-exemplars where dealing with the symbolic representations may lead to 'plugging in numbers' (see Van Berkel, Pilot, & Bulte, in press). Van Berkel et al. have analysed how a curriculum consists of three substructures: a substantive,

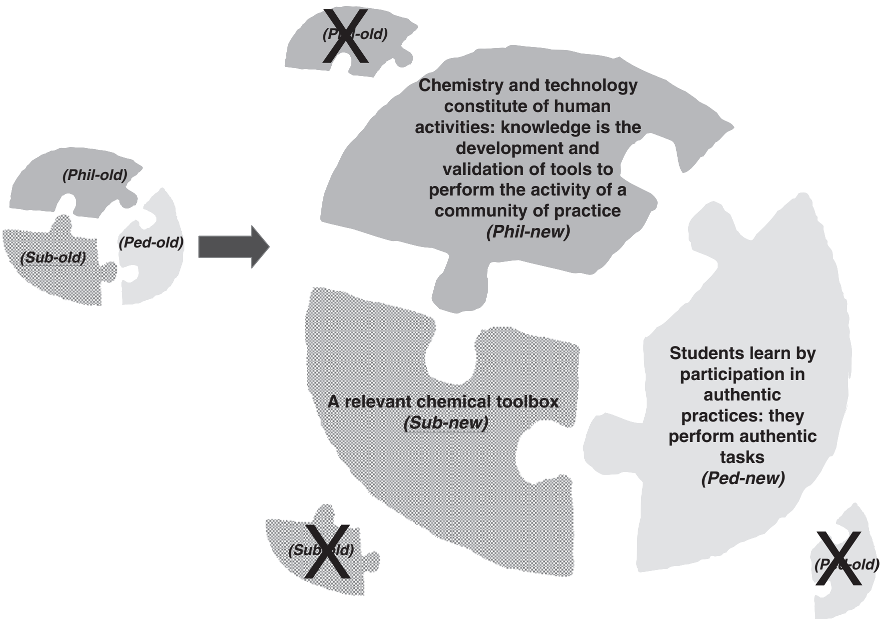


Fig. 9.1 For a new coherent relationship between philosophy, pedagogy and scientific content; the three conventional substructures should be simultaneously replaced by three new substructures in a coordinated way

a philosophical and a pedagogical substructure (Schwab, 1964, 1978; Fig. 9.1). Van Berkel et al. conclude that a coordinated replacement of all three substructures, including the reconceptualisation of the substantive substructure, is necessary if school chemistry is to address new scientific and technological developments and to deal with a better pedagogical approach than the dominant *micro–macro thinking* with its strong corpuscular basis. Students' thinking should start with macroscopic phenomena; it implies the search for those models that are applicable when manipulating and understanding properties of materials. We therefore identify this type of thinking as *macro–micro thinking* (in stead of micro–macro thinking). The meaningful learning of macro–micro thinking in a relevant context (Gilbert, 2006; Pilot & Bulte, 2006) thus implies a new coherent vision on the curriculum's philosophy; the curriculum content and its pedagogy (see also Fig. 9.1).

Towards a New Vision of Macro–Micro Thinking

Philosophical Substructure

A key starting point for learning chemistry is to consider chemistry as a human activity. Scientific and technological developments are interrelated with society and part of our cultures. In society, in many communities of practice (Wenger, 1998), knowledge is seen as a tool necessary for performing the activities of those practices. A chemical and technological perspective offers a view on the materials and substances we use, that we are made of and that constitute our material world. This enables us to understand certain macroscopic phenomena and offers us possibilities to technologically improve our environment, and reconsider their ethical implications. The way communities discover knowledge as tools and define these tools as valid and applicable constitutes the philosophical structure of the community. The process by means of which representative participants of relevant scientific and technological communities deal with material science, develop and validate knowledge, is related to the selection and analysis of authentic tasks.

Substantive Substructure (Sub)

The content of a curriculum must be functional when dealing with societal activities: necessary chemical concepts, skills and attitudes with respect to macro–micro thinking must be included. This can be derived from representative authentic tasks. The content of the curriculum should be considered as a *chemical toolbox*. The traditional content of the present chemistry curriculum, such as the structure of atoms, ionic theory, fundamental acid–base calculations, are not necessarily part of the chemical toolbox when addressing chemical and technological tasks. The validity of the toolbox (philosophical substructure) is determined by the representative practices and tasks related to chemistry (cf. 'need-to-know' principle in context-based approaches).

Pedagogical Design (Ped)

As Schwab explained (see Van Berkel et al., in press), the choice of a pedagogical approach is not independent of the chosen philosophical and substantive substructure of a curriculum. A philosophical and a substantive substructure together imply and determine a pedagogical substructure. The pedagogical substructure must be brought in agreement with appropriate principles of teaching and learning. Students should construct knowledge through their interactions with participants of relevant communities of practice in material science. Fundamental to this perspective are features of *active construction, situated cognition, community* and*discourse* (Anderson, Greeno, Reder, & Simon, 2000; Kelly, 2007; Rivet, Slinger, Schneider, Krajick, & Marx, 2000). Through discourse, students should become familiarised with the common language of chemistry as a perspective on the world. The design of learning tasks must stimulate students to realise that *they* come to *need* a chemical perspective. A new vision on chemistry education should explicitly aim at putting students in a position where they themselves *want* to extend their conceptual network (Lijnse & Klaassen, 2004). Novices learn by participation in a community where they learn the expert's personal knowledge, intellectual passion, faith, trust, tacit understanding, and methodological rules embodied in scientific and technological practices (Jacobs, 2000; Polanyi, 1958). It is by the expert's inspiration that students may enter their zone of proximal development (Vygotsky, 1986).

In sum, this new vision on the learning of macro–micro thinking consists of a coherent construct of the three following substructures (see also Fig. 9.1):

- *Philosophical substructure*: the argumentation about how content is defined as valid and applicable in chemically relevant social (communities of) practice;
- *Substantive substructure*: a chemical toolbox for the selected practices with macroscopic phenomena as relevant 'properties' as a starting point; the 'toolbox' consists of those representations identified as 'structures', relevant features of the structures and explicit relations between 'structures' and 'properties'.
- *Pedagogical substructure*: the way students may come to be participant of the selected practices.

In this vision, the conceptual analysis within the substantive substructure for macro–micro thinking is thus highly dependent on the selection of chemically relevant practices within which authentic tasks are situated. These tasks thus need to be selected on criteria consistent with the adopted vision on macro–micro thinking as described above. Firstly, tasks need to be situated in chemically representative practices (*Phil*). Secondly, a task should be selected such that it can bring students to within its zone of proximal development (*Ped*; Vgkotsky, 1986). In this way students can be expected to be willing to extend their conceptual network (cf. Prins et al., 2008). Thirdly, the exemplary tasks should cover a wide range of the domains of contemporary chemistry and technology in which macro–micro thinking plays a central role (*Sub*).

Consequently we have selected three tasks in three relevant domains of chemistry and (material or food) technology which are expected to be within the zone of proximal development for students:

- the development of gluten-free bread (domain of biochemistry);
- the design of unbreakable ceramic crockery (domain of inorganic material science); and
- the design of a flexible bullet-proof jacket (domain of polymeric organic material science).

With respect to the nature of the tasks, we chose a developmental or a design task because we expected that such a behavioural environment (Gilbert, 2006) is closer to the lives of students. Besides, these tasks may offer opportunities for experimentation and hands-on activities in classrooms, when such tasks are meant as contexts for learning macro–micro thinking.

We therefore started to explore the use of relations between representations of structure and properties of materials using these context-based authentic tasks as a starting point (cf. Bulte, Westbroek, de Jong, & Pilot, 2006). We aimed to reconceptualise the content of macro–micro thinking and structure–property relations, to make these structure–property relations explicit to connect macroscopic phenomena with microscopic representations in a new conceptual schema, which is appropriate for addressing contemporary chemical and technological tasks. Relevant documents (research articles, scientific textbooks, etc.) were analysed. Subsequently we selected experts for three tasks in representative authentic social chemical and technological practices. When consulting and interviewing the experts, they were asked to think aloud while addressing the tasks. By analysing the transcripts of interviews, we analysed the outcomes in terms of the substantive substructure of a curriculum, which should be in accordance with the chosen philosophy. This analysis forms the first part of this chapter.

In the second part of this chapter, we present to what extent students can learn to work with the new content of the activities closely related to the authentic practice. This is a further development of the pedagogical substructure that needs to be coherent with the curriculum's philosophy and its content. We therefore have used the same authentic tasks as were used for deriving the new content. By doing so, we maintained the coherency between the socio-scientific activity (*Phil*) and the content that was necessary to address the tasks (*Sub*). We investigated how students can be meaningfully involved in such authentic activities and come to see the relevance to explain and predict properties of materials (*Sub*). This should ensure an emerging coherency with the pedagogic substructure (*Ped*) of the curriculum. Therefore, the planning of an appropriate teaching and learning sequence should help students to *meaningfully* learn (*Ped*) to use structure–property relations as links between the different meso-levels. In this way, the students should see the point of why they should eventually use molecular and atomic structures at the sub-microscopic level. When students enter their zones of proximal development, the designed units should productively build on the belief system of prior knowledge and notions of students on how to handle this task and facilitate the expansion of their knowledge along their activities while descending from the macro to the micro level.

Substantive Substructure of Authentic Socio-scientific Activity

After a description of each task, we present the results of the document analysis and a summary of the experts' consultation. Interviews were mainly categorised on 'structure', 'property' and their interrelations (Meijer, Bulte, & Pilot, 2005). This section starts with a more extensive description for the task about crockery. The outcomes for the two other tasks are more briefly described. Subsequently, the outcomes of the analysis of the two other tasks are summarised and generalised.

The Analysis of the Design of Ceramic Crockery

Crockery preferably is made from ceramic materials, although it is brittle and can break rather easily. Properties of ceramics, such as resistance to absorb flavours and low heat conductivity, however, are superior compared to metals and plastics. Therefore, we defined a task to design crockery with improved mechanical strength.

Textbooks about inorganic material science report that the strength of porcelain cups is determined by the avoidance of crack growth. This can be achieved by using grain particles with very small diameter, by addition of grain-growth inhibitors, and by processing the material at high sinter temperatures. Changing these factors results in a densely compacted (low porosity) phase (with a low content of silica) which results in a limited crack growth. Such ceramic material will not break easily.

The expert tried to optimise the design of unbreakable crockery. First he wanted to find reasons for using ceramic as the main material in terms of desired properties. From this first step, he concluded that ceramic had some advantages over metals or composites. The expert made a sharp distinction between intrinsic and extrinsic properties. The choice of type of ceramics was not relevant because the desired properties are extrinsically determined. Thus relevant properties cannot be much influenced by the difference in bonding strength due to the different types of ions of the material. Consequently, the properties of ceramic crockery are not much influenced by the actual choice of ceramic material. Because of this, the expert did not include the ionic structure in his reasoning. When he was asked why he did not use this sub-microscopic level, he explained; 'it was not necessary because this [the desired property] is not undergoing influences at atomic level at all'.

Relevant information taken from the documents was combined with the expert's consultation. The verbal utterances combined with relevant representations of structures in textbooks, papers and journals could be combined into a system of structures, properties and their interrelation. The results are summarised in Fig. 9.2. Six meso levels were relevant to address the task. At a meso level of (10^{-3} m) the

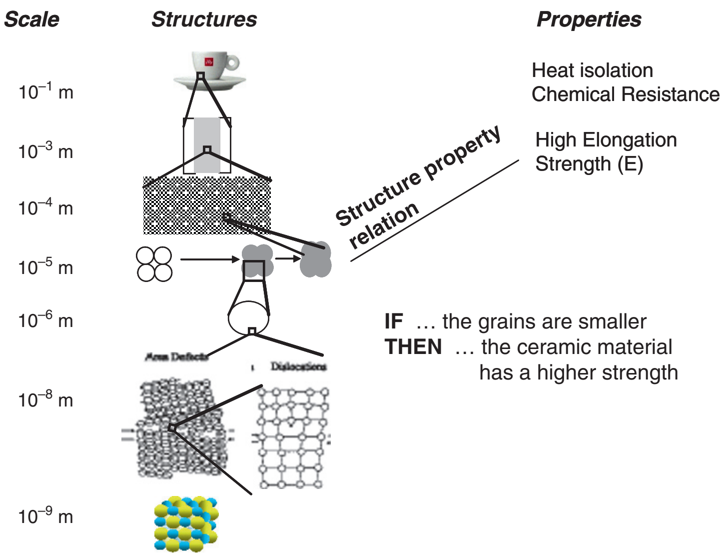


Fig. 9.2 Conceptual schema of the development of an unbreakable cup. Examples of structure–property relations are marked as *lines.*

ceramics is coated with a glaze. The ceramic is a porous material (10^{-4} m) which is a result of the sintering process (10^{-5} m). In this sintering process, grain particles (10^{-6} m) form necks. A particle is built up from amorphous and crystalline phases (10^{-7} m). Between these phases defects or regular parts (10^{-8} m) are found which are built up from ions (10^{-9} m).

The expert did not order his reasoning in a fixed manner between macro and micro level. This is expressed by reorientations (starting again at another level) and iterations (switched between levels) of the expert, when he was weighing two different alternative strategies (A and B). Examples of this type of reasoning are:

Re-orientation	– What must I do? I can do two things. Keep defects small, if I want to keep defects small I must start off with small particles. – Route A is to keep the defect small. Made small by impregnated. Two ways. Then you get route B that's the strain.
Iteration	– All right, then we get ceramics ... And ceramic is essentially brittle. – And I can think of impregnating the defects. If I make them large, yes exactly, that would be the alternative.

When comparing the document analysis with the expert's consultation, two important differences come to the fore: (1) the generalisation of the expert's thinking process, and (2) less focus on the micro-level by the expert. The expert started with a much broader set of materials (metals, polymers and ceramics). Then the expert wanted to find a clear argumentation for using ceramic as a main material. This makes the approach of the expert more general. Secondly, the expert had no reason to use detailed information about the chemical components. Most desired properties were only a result of microstructures (at meso level) and not of the (pure) ionic substances. This implies that the expert used his knowledge about general properties of this class of materials (ceramic). Documents, however, include the frequent use of chemical information about several types of ceramics, the influence of whiteners, grain growth inhibitors, and the amount of silica and mullite in porcelain. For the expert, these details were not necessary to address the task. The expert's reasoning is more generally applicable. Figure 9.2 represents the combined conceptual analysis of the design of unbreakable crockery taken from document analysis and the expert's reasoning.

The expert's use of structure property relations can be expressed in 'if ... then ...' clauses (Fig. 9.2) as 'rules' to connect properties to structures. In such relations structures are assigned to a 'smaller' scale compared to properties. Examples are: 'If you have particles with a small diameter (scale = 10^{-6} m), then the connection is less strong (scale = 10^{-3} m)', and 'If I observe a high value of shrinkage (scale = 10^{-5}), then it may have resulted in a low porosity (scale = 10^{-4} m)'. Ten structure – property relations were identified, but only one structure–structure relation was found: 'If I keep defects [structure] small then I must start with particles with a small diameter [structure]'. This sentence can be interpreted as a construction from two implicit structure–property relations between the diameter of the grains and strength and between defects and strength. For example, porosity [property] means less holes and pores between the sintered particles [structure], which results in a decrease of possible path ways for crack formation [structure]. A limitation of crack forming results in higher strength [property]. Connecting the properties with a scale leads to the conclusion that properties are connected to macro level or a meso level close to macro.

The Analysis of the Development of Gluten-Free Bread

This task involves the development of gluten-free food products for people that cannot digest gluten. Corn that does not contain gluten may be used as an alternative. However, gluten is a necessary component if dough is to rise, resulting in the desired texture of bread. For an address to the task, it is necessary to know more about the function of gluten. To capture the released gases (CO_2) during fermentation, the dough needs to be elastic though strong enough. The strength of the walls of the 'pores' that capture the gases is highly influenced by gluten. Gluten contains of a network of long intertwined chains absorbing water and capturing gases. Such a hydrophilic network structure can explain the strength and elasticity of the walls. Hydrocolloids have the ability to form such structures. The process of 'preparation of dough' and 'fermentation' mainly determines the final properties of the bread. The structures in the dough are fixed during baking.

Exemplary statements of the expert are:

- During mixing of dough larger aggregates arise from gluten (meso-structures)
- If gluten is too loosely distributed in the matrix, then the dough will collapse (structure–property relation)
- If the distribution is loose then the bread rises badly (structure–property relation).

In the documents, six different meso-levels are found. For example, dough contains gas cells (10^{-4} m), enclosed by walls made up of a matrix with embedded starch granules (10^{-5}m). Granules, degraded due to enzyme attack (10^{-6} m), are held together by gluten fibres made up of gluten particles (10^{-7} m). These particles form the long (protein) molecular chains (10^{-8} m), made up of a single unit (amino acids; 10^{-9} m). The elastic property of dough can be caused by the existence of a gluten network [structure] which is impermeable for gasses [property]. This gluten network is elastic [property] because chains of gluten particles [structure] can move with respect to each other.

The Analysis of the Design of a Flexible Bullet-Proof Vest

The task in this study focused on enhancing the flexibility and reducing the weight of a bullet proof vest (e.g. wearing it as a vest under tuxedos or evening dresses). Document analysis and expert consultation revealed that a number of specific structures at different levels are used. The vest is a combination of mats that are glued together with epoxy resin (Fig. 9.4). Each mat forms a densely woven pattern of strong polymeric fibres. The flexibility of the vest (property) can be enlarged in different ways. The expert was weighing alternative strategies, iterating between options, zooming in and out, checking consequences like: flexibility must not lead to divergence of fibres, because then the vest does not absorb enough energy and even the bullet will go through the vest. The balancing between flexibility and tightly woven fibres, leads to a new focus on the importance of the strength of separate fibres. The property 'strength' of the thread is related to the structure of the crystalline parts of the polymer: a shish-kebab structure[1] is strongly related to the strength of single fibres. Molecular ladder structures of polymer chains in the Kevlar fibres with regular patters of hydrogen bonds may result in a regular crystalline ordering. This will result in a higher strength of separate fibres.

The expert did not reason in a straightforward way from macro to micro, but alternated between different alternative solutions (mats glued together, a single mat, threads, fibres, other materials) and alternative reasoning for finding solutions by considering new relations between properties and structures.

Generalisation of the Outcomes on the Three Tasks

Three analogous but theme-specific conceptual schemas have been constructed, with systems which have several nested sub-systems (Meijer et al., 2005). Relevant microstructures at different meso-levels can be assigned to appropriate scales. In such conceptual schemas, 'structure' can be defined as the distribution over space of the components in a system. Physical building blocks of such a system are regions that are bounded by a closed surface (Walstra, 2003), where at least some of the properties within such regions are different from those in the rest of the system.

Intermediate meso-structures (and models of these structures) were necessary when addressing the specific theme-related task. Properties could be assigned to meso-levels as well, although properties usually are closer to the macro-level. There appeared to be no fixed number of meso-levels, and experts did not order their reasoning in a fixed manner of macro $\rightarrow$ $(\text{meso})_n$ $\rightarrow$ micro or micro $\rightarrow$ $(\text{meso})_n$ $\rightarrow$ macro; their reasoning is characterised by reorientation and iteration. Most structure–property relations bridge a gap of three or four orders of magnitude of ten, when descending from macroscopic phenomena to meso-structures, and they mostly do not directly relate to the macro- and micro-level. Such relations between the highest and lowest level are very rare: In total, three out of the 22 identified structure–property relations were identified in the experts' protocols. Usually textbooks, research journals and other relevant papers do not present a system of nested structures. The separate representations could be found, however, mostly presented

[1] Heterogeneous nucleation of polymer crystallization resembling a visualized metaphor: compare the way meat is prepared in an oriental way: shish – kebab.

in a non-systematic way and without a clear reference to sizes and scales. These documents did not systematically reveal different visualisations of (meso- and micro-) structures within a nested scaled system, and structure–property relations were seldom explicitly mentioned.

Structure–property relations usually have a qualitative character (words, causal relations) and can be expressed as if–then clauses by '*if* this is an existing property, *then* it is caused by this type of structure' or '*if* this is the existing structure, *then* probably this property can be expected'. Structure–property relations at the same scale (horizontally) were not found: all relations were links between two different (meso-) levels. Structure–property relations are different for the different tasks, and even within the same domain (e.g. ceramics) may well be different when the type of requirements is different (e.g. unbreakable versus resistant to certain chemicals). The relations will be specific for specific structures and specific properties, e.g. the strength of a jacket, a set of mats, one mat, a cluster of fibres, or one fibre.

To summarise: in authentic tasks, we have established that structure–property relations can be described by a dynamic system of structures, properties and their interrelations. Within the limits of our study we have derived a generalised conceptual schema, which we expect to be useful to teach macro–micro problems in which structure–property relations can be explicitly used (Figs. 9.2, 9.3 and 9.4). The system of nested structures, systematically assigned to appropriate scales, and the properties of the different structural components reveal a conceptual schema necessary for macro–micro thinking. The system of relevant nested structures and the explicit relations between structures and properties form the backbone of macro–micro reasoning. Depending on the task, a number of different meso-levels are relevant and

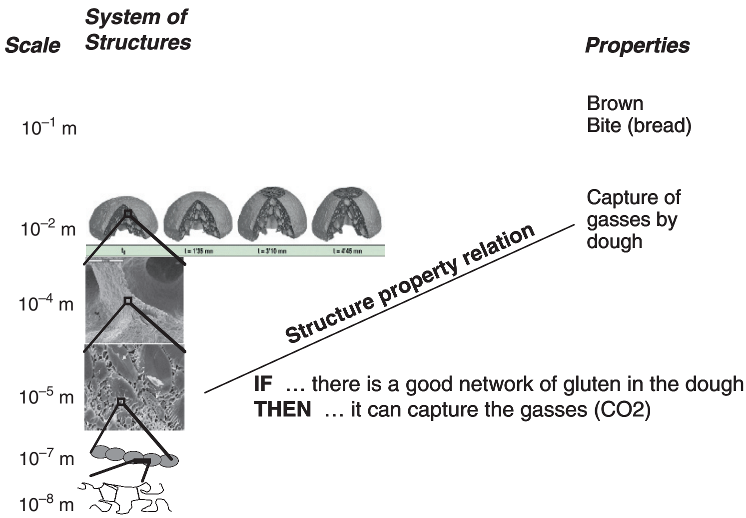


Fig. 9.3 The conceptual schema of micro–macro thinking for the task designing gluten-free corn bread, with the explicit use of structure–property relations

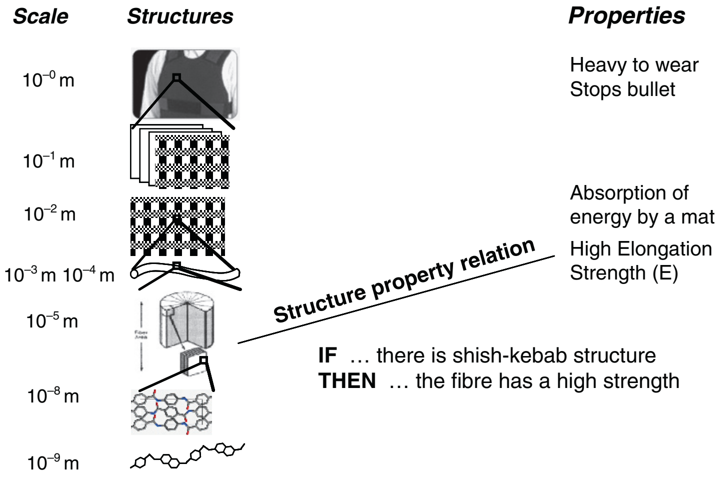


Fig. 9.4 Conceptual schema of the design of a bullet-proof jacket derived from the experts' consultation. An example of a structure–property relation is marked as a *line*

a certain set of explicit structure–property relations are necessary until sufficient structures, properties and their interrelations are available in the system to solve the tasks. Structuring of atoms and or ions at the micro level in a certain pattern should only be used when this is necessary to complete the task.

The conceptual schemas (Figs. 9.2, 9.3 and 9.4) represent macro to micro thinking in a systematic way (*Sub*). These have resulted from relevant socio-scientific tasks of social practices related to the chemical and technological domains (*Phil*). These conceptual schemas form the core of the substantive curriculum for macro–micro thinking; the authentic tasks from which these schemas originate define the type of community of practice in which the students' learning takes place (*Ped*). Both the authentic task as context and the bridging of the large step from macro to micro by several smaller steps should make the teaching and learning process meaningful for students. The learning process can start at a concrete, phenomenological (macro) level. At this level, phenomena or properties are observed and can be explained with intuitive notions of students. By introducing appropriate scientific concepts and relations, a more scientific explanation can be given for the observed phenomena or properties. Structures can be introduced by using visualisation of the structures at the macro level and the larger-scale meso-levels, and modelling of the 'invisible' structures to derive the necessary structure–property relations and experiments, using analogies (Treagust, Harrison, & Venville, 1998).

Towards Coherency with the Pedagogical Substructure of the Curriculum

The new conceptual schemas derived in the first part of this chapter could thus be used to design context-based units by a design research approach (Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006; Bulte et al., 2006). Two of the three tasks could be used to design such units, because related student experiments in this field could be developed within the limits of the school laboratory: one unit about development of gluten-free bread and a second unit about the design of unbreakable crockery (Meijer, 2007; Pavlin, 2007). In a small-scale enactment of (parts) of the units, 8–14 students (age 17, pre-university level) were involved. Classroom observations, students' materials, video and audio-taped discussions, interviews, and pre- and post-questionnaires were used as data sources. The outcomes were compared to the expected outcomes. With these data, the actual learning process was compared with the learning process that was expected in the theory-based design of the units.

The Design of a First Unit

The first unit, about the development of gluten-free corn bread (cf. Fig. 9.3), is to facilitate the learning of macro–micro thinking using structure – property relations in a meaningful teaching and learning sequence. For this, we have maintained the coherency between the defined (authentic) task (*Ped*) and the newly derived substantive content (*Sub)*. It is essential to create with students a community of practice that closely resembles the authentic (community of) practice the authentic task originates from.

The participation within a community (*Ped*) was planned as follows. After a short introduction to the problem, the students have to use their common sense knowledge to address this task. Students become involved in the task to develop gluten-free bread. It is anticipated that students became motivated by the socio-scientific issue that an increasing part of the population has become intolerant to gluten in their food. In this way, the students were expected to be willing to form a community in which they design (and thus analyse) a gluten-free bread with their teacher as a senior member and project leader of the practice. Different teams of students of this community subdivided the different tasks under supervision of their teacher (as a project leader). Several plenary sessions were planned to coordinate the work. Subsequently, the students should discover that they need more knowledge about the structure of dough prepared from corn to modify the ill-developed properties of corn-bread. Since the community resembles the authentic community of practice, this content could be expected to come to the fore, and should provide the relevant concepts for addressing the task. The students had to look more precisely into the function and the structure of the gluten, apparently necessary to bake high-quality bread. Their investigations were directed towards the selection of a replacement for the gluten. The texts they had to study were translated and modified versions of authentic research articles. It was expected that students wanted to know more about the molecular structure of gluten, to come with a well-informed selection of some hydrocolloids that can replace gluten when baking bread based on corn dough. The students were not a priori provided with the conceptual schema for the development of gluten-free bread (cf. Fig. 9.2). The pedagogical approach was that they had to gradually (re)construct such a schema during their design task, and that the complete schema was discussed in a reflection activity at the final phase of the teaching and learning process.

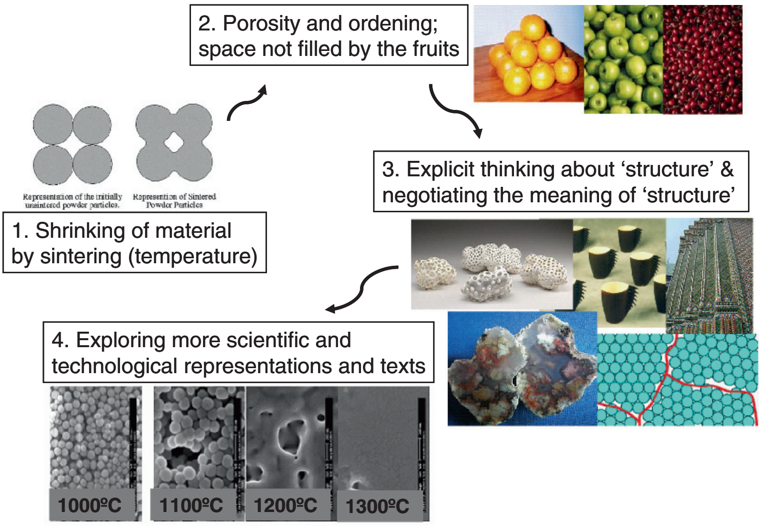
Evaluation of Implementation in the Classroom

Most of the expected learning and teaching activities proceeded as expected. As a result of the motivating task, students became involved in the planned social practice. The students identified that a well-developed dough is essential for baking bread with the desired texture. They related the rising of bread to the capability of a matrix of the dough to capture the CO_2 gasses. This can be achieved by absorption of water by the dough which leads to a flexible and strong matrix. The students could relate this to properties of the walls: these should capture gasses. Such a dough-matrix should not collapse. Some activities, however, delineated from the expected outcomes, and led to new questions about the pedagogy of the teaching and learning process. This particularly involved the concept of 'structure' at meso-levels below the scale of 10^{-5} m. When more abstract representations of structures were necessary for reasoning, the meaningful development of the system of structures came to a hold, and no further development of the structure–property relations took place.

Adjusting the Pedagogical Substructure of a Unit

An explanation for these findings can be found in the implicit use of and therefore poor development of the concept 'structure'. As long as 'structures' are related to visible and imaginable level, intuitive reasoning could take place. However, further concept development involving more abstract models needed attention. To start with that, we decided that we had to be more precise about the notion of 'concept'. As a starting point, we defined concepts as abstractions, representations of reality in our minds, not the realities themselves. We define concepts as *perceived regularities in events or objects*, *or records of events or objects designated by a label* (usually a word; Novak, 2002). The meaning of these perceived regularities is situated (Van Oers, 1998) and determined by their belief system of existing knowledge and notions (Vygotsky, 1986; Klaassen & Lijnse, 1996). This belief system should be viewed as 'explanatory frameworks' rather than fully specified theories (Nakhleh et al., 2005).

The main implication for designing a second unit involved the evoking of students' existing belief system of the concepts 'structure' and 'properties' by means of photographs of recognisable 'structures' (see for example the photographs of the packing of the fruit in Fig. 9.5). This step is essential for finding a common ground that forms a basis for understanding between the teacher and the students (Klaassen & Lijnse, 1996). For investigating this aspect of the pedagogical structure, we designed a second unit. The unit about unbreakable ceramics involved a less complicated task compared to the development of gluten-free bread, and ensured



1 *Assignment:* Try to describe the sintering process. Make a drawing of the step which has the largest influence on the strength.

Assignment: Can you relate the sintering process to the strength of the ceramics?

2 We can describe the system of fruit with the amount (percentage)of the space which is not filled with material. There are pores, canals and holes between the fruits. This is called porosity.

Assignment: Can you arrange the pictures from chaos to structured? Explain your order of the pictures.

Assignment: Can you find some similarities and differences between the fruit and clay particles?

3 Look at the different pictures.

Assignment: Can you describe what the structures are for each of the photographs?

Assignment: Can you describe what the properties are for each photograph?

Assignment: Define collectively what you consider as 'structure'and as 'property'

4 *Assignment:* What happens when the material is heated from 1000°C up to 1300°C? Write down in your own words.

Fig. 9.5 Sequence of activities to develop the conceptualisation of porosity and structure in the unit about unbreakable crockery (Example of expanding the meaning of the concepts by activities that are meaningful for students at every step of the teaching and learning process)

that evaluation outcomes were not too much situated and connected to one of the tasks. Similarly, as for the unit about gluten-free bread, we also maintained the coherency of the activity and its contents derived from the related authentic task (see text above and Fig. 9.2).

With the following example, we illustrate how in a sequence of activities the students' intuitive notions about the influence of particle size and the sintering temperature of the clay on the properties of ceramic materials have productively been used (Klaassen & Lijnse, 1996; Mortimer & Scott, 2003; Duit & Treagust, 2003;

Vygotsky, 1986; Fig. 9.5, assignment 1). More precisely the sequence of teaching and learning activities needed to start at what we describe as a concrete level (Davydov, 1975; Roth & Hwang, 2006). Before studying scientific and technological representations and texts about the influence of the sintering temperature on porosity, the photographs of the fruits were to be used to develop the conceptualisation of porosity and structure (assignment 2 in Fig. 9.5). Next, representations of recognizable photographs of different 'structures' are presented, and based on these photographs the meaning of the concept of 'structure' and also 'property' is to be negotiated with students (assignment 3 in Fig. 9.5). After collectively defining the concepts of structure and properties, these concepts can be expanded with representations like symbols, figures, words and relations to properties, much more in agreement with the scientific meaning of the concept of structure in this domain (assignment 4, Fig. 9.5).

This sequence of activities (Fig. 9.5) is justified from the perspective of learning (*Ped*) as follows. The activities in which the students expand the meaning of the concepts should be meaningful for them at every step. Students use their existing knowledge (including intuition), senses, sources of information and social aspects like values and norms when constructing new associations and relations to concepts. These relations and associations which influence their decisions about truth and meaningfulness (Vygotsky, 1986) are important because they are decisive whether the expansion of the knowledge is indeed accepted for further use or not (Bartsch, 1998). These considerations originating from rethinking our empirical findings are an extension of the pedagogical substructure (*Ped*).

Implementation and Evaluation of the Second Unit

It appeared possible to make intuitive notions about the concepts of 'structure' and 'property' productive for classifying structure–property relations in structures and properties. The intuitive notions for structure were: '*an ordering, arrangement*', '*how things are connected with each other*', '*how things are build*'. And for property the intuitive notion was: '*what something can or does*', '*a function*'. These notions appeared to be sufficient for these students to understand the information in the (authentic scientific) documentation. In the next activities, this way of defining these key concepts was good enough for the students to arrange the new scientific and technological terms in structure, property or process variable during sintering of the ceramic materials as were planned in the unit. Using this arrangement, the meanings of the concepts 'structure' and 'property' are expanded to respectively, '*a construction*', '*an ordering*', '*a pattern*' and '*a characteristic of a material*'. Subsequently, the group of students collaboratively ascertained these meanings, and constructed a conceptual schema for this authentic task (cf. Fig. 9.3) in a reflection activity in the final phase of the teaching and learning process. This learning activity within the adapted version of the authentic practice (*Phil* & *Ped*) consequently led to the students' own construction of the relevant content within this unit (*Sub* & *Ped*).

In Retrospect

On reflection, we proposed to use the analysis of authentic socio-scientific tasks as a route to formulate a new coherent vision on the domain of macro–micro reasoning in the chemistry curriculum. The proposed conceptual schema of macro–micro thinking can significantly address the problems in the learning of micro–macro thinking of students at secondary school for tasks in biochemistry and inorganic chemistry (Millar, 1990; De Vos & Verdonk, 1996; Harrison & Treagust, 2002). We think that the explicit use of structure–property relations as arguments may enhance the public understanding of science and technology. The use of meso-structures between the macro- and micro-level and structure–property relations as a tool to iterate between macro- and micro-level is essential to connect student learning of these chemical concepts to the contexts of their everyday lives and to contemporary science and technological issues. The presented conceptual analysis and its exploration with students have promising features to include contemporary science issues in the chemistry (science) curriculum, such as genomics and new innovative micro- and nano-structured materials.

To connect these outcomes to Van Berkel's analysis of the problematic nature of micro–macro thinking in chemistry, we have developed an alternative as a way to escape (Van Berkel, 2005). Using Van Berkel's framework, firstly, we understand what situation we had to escape from: the rigid combination of predominant substructures of main-stream chemistry curricula. Secondly, we expect to have found a route to escape by redefining a philosophy of chemistry based on social practices that at the same time determines the pedagogical and substantive substructure of learning to think in terms of *macro–micro thinking* using explicit structure–property relations. These levels include meso-levels with a scale ranging from metres to centimetres to millimetres to a nanometre level.

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