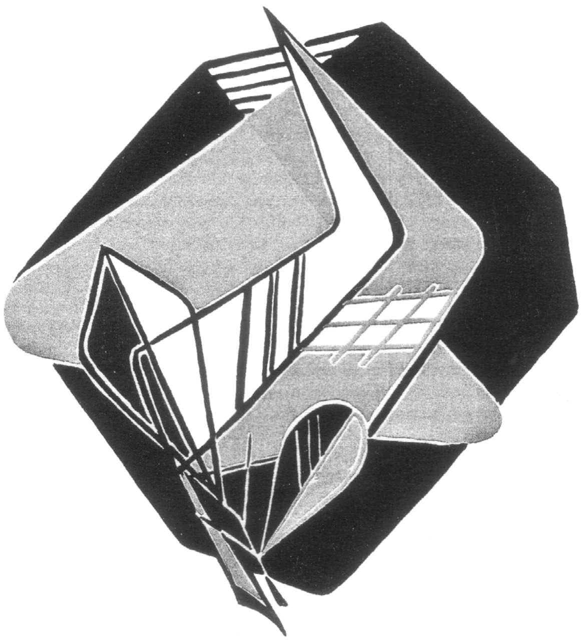
Towards systems thinking in cell biology education



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Towards systems thinking in cell biology education

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Roald Pieter Verhoeff
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Dit sal veele vreemt voorkomen, maar laten wij gedencken aande dierkens die waaragtigh in gemene Wateren, en in onse excrementen sijn en die geen 1/1000000000 deel van een groff sant groot sijn, dat sodanige kleijne dierkens een huijt hebben, en wie weet off sodanige huijtge niet versien is met schobbens, als ook met deselve pooten off vinnen moet hebben, waarmede dat het swemt. Item Mond, Darmen, Aderen, Musculen, Senuwen, jaa alle ingewanden die een groot dier heeft…

Antonie van Leeuwenhoek, 5 januari 1685

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Chapter 1

Introduction

1.1 Getting involved in cell biology

From my own secondary school experience I cannot remember having been very enthusiastic or astonished during lessons about cell biology. At the beginning of secondary school I was satisfied with the knowledge of cells being ‘the bricks in an organism’. The moment I realised that cells contained more than just a nucleus was a disappointing one because all those new facts coming out of nowhere had to be memorised somehow. I remember a specific schoolbook picture of a typical animal cell that was introduced in one of the final lessons of my secondary school period. It showed the process of RNA translation in more detail: strands of mRNA were floating in the cytoplasm and got attached to some ribosomes that were also floating in the cytoplasm along with all kinds of other stuff. Eventually proteins were formed in the cell in order to float around too. The fact that ribosomes both consisted of RNA and used RNA to produce proteins seemed a mystery. To me, the story that could be written with the words in that cell picture was still vague and the cell remained an unsolved cryptogram. To pass the national exam I paid some extra attention to the other biology topics at higher biological levels of organisation.

In the third year of my study biology at the University of Utrecht I happened to choose ‘molecular cell biology’ as a first specialisation, simply for the reason that ‘molecular cell biology’ was supposed to be at the ‘hard side’ of biology and offered the highest chance at a well-paid job. During this first specialisation I focused on one very small area of molecular cell biology: ‘The effect of ischemia (depletion of oxygen) on the transcriptional and posttranscriptional regulation of glucose transport in isolated rat cardiomyocytes’. Although this time I could explain the process of DNA-transcription and RNA-translation within the context of the production and translocation of glucose transporters in the cell membrane, the complete picture of the cell still remained rather blurred to me. The theoretical component of the specialisation comprised one oral exam on prokaryotes and one on eukaryotic cells and required studying more than hundred selected scientific articles. I studied hard on various cell biological topics, ranging from all kinds of signal transduction pathways after binding of hormones to cell-surface receptors in animal cells, to several chemiosmotic mechanisms of bacteria to harness energy. In order to transform the extensive knowledge of cells from just a list of structures and processes to ‘understanding’, all that knowledge had to be related and organised in some efficient way. From my current point of view I would say that at that moment I started to develop some kind of ‘expert knowledge’ in which meaningful concepts are connected and organised around some core concepts or ‘big ideas’ within the domain of cell biology. As a result, the enormous complexity of the cell as a functioning whole in which everything is connected with everything, struck me for the first time. At last, most pieces of the puzzle were combined into a picture of the cell as a coherent living system.

At the beginning of this research project, thinking about my own learning process only generated more questions instead of supplying any answers: Why did I not grasp the idea of the cell as a complex functioning whole earlier? Was all that detailed knowledge (at the molecular level), gathered during my university study, necessary to get amazed by the complex order of the living cell? If not, what knowledge is essential to grasp the idea of the cell as a complex function whole? In other words, is there a way to get secondary school students involved in and acquiring a coherent understanding of the cell as a living whole? And what exactly does coherent understanding of the cell as a living whole include? This thesis describes the search for answers through transforming own questions into research questions to be explored from a systems perspective.

1.2 Scope of the research project

In biology courses at secondary school students are expected to gain knowledge about a large variety of life structures and processes in a relatively short time. The biology curriculum comprises several themes such as genetics, metabolism and evolution, and every theme brings along a large amount of new concepts. In addition, most themes cross several levels of biological organisation, i.e. the molecular, cellular, organismic and/ or community level. The concepts used to describe the processes and structures at a certain level of organisation are mostly specific for that level. However, when a certain theme is dealt with, the concepts are hardly explicitly related to a specific level of organisation. So, students could have difficulties in acquiring a coherent understanding and an overall picture of life phenomena.

A lack of coherence in students' understanding is reported as a cause for conceptual problems in several subjects at the organism level, e.g. human nutrition (Núñez & Banet, 1997), digestion (Ramadas & Nair, 1996) and the body's defence against toxicants (Roebertsen, 1996). For instance, Roebertsen showed that upper secondary students had hardly integrated their knowledge of bodily processes, i.e. uptake, transport, breakdown, storage and excretion of substances, with the organs involved.

Biological education research literature reveals that many conceptual problems both at the organismic and at the cellular level are associated with a lack of interrelating these levels of biological organisation. A basic understanding of the functioning of the cell is assumed to be essential for sound understanding of the functioning of the multicellular organism. However, students are taught a large variety of life structures and processes at the cellular level. The concepts used to describe them are mainly drawn from the sub-cellular level, but this knowledge seems to be fragmentary if its integration at the cellular and organismic level remains undone. As a consequence, many students fail to acquire coherent conceptual understanding of the cell as a basic unit of the organism (Dreyfus & Jungwirth, 1989). In addition, conceptual problems associated with a lack of interrelating these levels of biological organisation arise when studying other biological topics as well (Núñez & Banet, 1997; Roebertsen, 1996; Songer & Mintzes, 1994). For example, Songer & Mintzes (1994) refer to problematic understanding of the relations between events of cellular respiration and various biological phenomena such as breathing, circulation and energy flow in natural ecosystems.

Douvdevany *et al.* (1997) showed in their study that even the knowledge of junior high school teachers about cellular processes lacked coherence, although they had enough specific declarative knowledge.[1] Interviews with Dutch upper-secondary biology teachers and explorative content analysis of schoolbooks showed difficulties similar to those identified in the research papers mentioned. In Dutch schoolbooks the cell takes an important but very isolated place and is one of the first subjects dealt with in upper-secondary education. In addition, cell biology, as it is introduced by the school curriculum, is explained mainly within the category of structures rather than of processes while understanding of biological processes has been recognised essential for comprehensive understanding of biological systems (Chi *et al*, 1994; Songer & Mintzes, 1994; Barak, 1999).

In this PhD project the focus is on a synthetic approach to cell biology in upper-secondary biology education. To enhance the coherence in learning and teaching (cell) biology we introduce systems thinking as a key competence. A competence is the combined action of attitude, knowledge and skills that enable to perform a task adequately and must be meaningful and functional in one or more real life activities or settings (Boersma & Kamp, 2001; Boersma & Schermer, 2001). So systems thinking competence is the ability and willingness to link different levels of biological organisation from the perspective that natural wholes, such as organisms, are complex and composite, consisting of many interacting parts, which may be themselves lesser wholes, such as cells in an organism (Mayr, 1997). Our assumption is that purposeful application of a systems perspective leads up to more coherence in learning and teaching of cell biology. Research biologists also state that studying biological problems can be seen as studying biological systems independent of the level of biological organisation on which the problem is studied. This has resulted in a strong integration of biological knowledge by now (Royal Netherlands Academy of Arts and Science, 1997). Although the Dutch examination syllabus underlines the importance of systems thinking in biology education, the implementation of systems thinking in classroom practice falls short of expectations.

Based on the preceding considerations this study aims at answering the following overall research question:

What learning and teaching strategy based on systems thinking results in an adequate and coherent understanding of the cell as a basic and functional unit of the organism?

This problem statement gives rise to a more specific description of my own initial questions that I posed at the end of section 1.1:

- What are the main difficulties in learning and teaching cell biology?
- What does a systems theoretical perspective on cell biology include?
- What design criteria for an adequate learning and teaching strategy could be derived from a systems perspective on cell biology?
- In what way could the intended learning and teaching strategy be shaped?

These four questions form the starting point of the explorative phase of our developmental research project during which we should identify the main criteria for

[1] The results of Douvdevany *et al*. imply that although biology teachers may have a meaningful understanding of specific functional relationships in the cell (i.e. declarative knowledge) they do not combine or connect the concepts and principles to understand certain cell biological phenomena.

designing an adequate learning and teaching strategy. In this initial phase a problem diagnosis and inventory of suggested or tested solutions was made by studying relevant literature and testing some first theory-based ideas in the context of a classroom setting. During this 'theory-guided bricolage' as Gravemeijer (1994) names it, a promising sequence of learning activities gradually emerged. At the same time, this phase gave me, being 'a junior researcher', the opportunity to develop a more articulated view on the field in between general educational theories and educational practice and taking into account the disciplinary knowledge: content specific methodology (Dutch: didactiek).

In the next phase of our research the supposedly adequate learning and teaching strategy is tested in a classroom setting in two successive cycles. This cyclic research phase is guided by the two questions below:

- What learning outcomes arise from the executed learning and teaching strategy and what learning processes constituted these learning outcomes?
- What indications can be derived from the observed learning outcomes and processes for revising the learning and teaching strategy?

Answering the two questions above contributes to answering the overall research question. The latter should be accomplished by presenting an adequate learning and teaching strategy for 'the cell as a system', which has a solid empirical base. In addition, a domain specific philosophy should be developed in which systems thinking is integrated with cell biology education.

1.3 Context of the research project

This PhD study is part of a research programme of the Department of Biology Education aimed at promoting systems thinking in biology education. Ultimately, this study will give more insight into dealing effectively with the problems in cell biology education and could also provide some indications about how to proceed in designing biology education from a systems perspective. Starting point of our research is that biology education must be founded in biological science. This means that major views and recent developments in biological science are important points of reference in our thinking about the contents and form of biology education. Therefore, we will first outline some aspects of biological science that have or should have implications for biology education. Furthermore, we will describe the educational context in the Netherlands with respect to biology education in secondary schools in the Netherlands. All together, this will help us to determine our position in the field of biology education and yield relevant elements for a philosophy for learning and teaching the cell as a system.

From mechanicism towards organicism

In section 1.2 we argued that conceptual problems are related to a lack of attention to coherence in biology education. The origin of the compartmentalised approach to dealing with life phenomena can be found in the development of biology itself.

The division of the domain in many subjects and the focus on detailed knowledge within each subject is typical for biology. These two characteristics are deeply rooted in the history and research practice of biological science and related to the emphasis on reductionist approaches within biology (Boersma, 2000). Biology is one of the youngest branches of modern natural sciences. Although the philosopher and naturalist Aristotle (384-322 BC) is generally accepted to be the first one who systematically studied the phenomenon of life, only just in the nineteenth century biology matured to be an independent science. During this development of 'modern' biology mechanicism (or reductionism) became the dominant view among biologists (Theunissen & Visser, 1996). The research approach of mechanicists was characterised by analysis: biological phenomena could be explained by the properties of its isolated components. Consequently, a mechanistic view stimulates division of disciplines into sub-disciplines. Until the 1970s biological research at universities was carried out in many separate sub-disciplines, like zoology, botany and microbiology. Moreover, biological phenomena at the different levels of organisation were also separately investigated in different sub-disciplines. We might say that with regard to those aspects, current biology education reflects very much the field of biology research in the 1970s and we suppose that this has negative influences on the conceptual understanding of upper-secondary school students.

Similar to the division of biological research into many sub-disciplines the content of biology curricula consists of many different subjects, e.g. cell biology, genetics, ecology and evolutionary biology. It is beyond dispute that the living world is complex, and, as a pragmatic necessity, we need division of work between various disciplines. As a consequence however, processes, which normally take place in mutual coherence, are treated separately in curricula and spread out over the whole year. When there is little explicit attention to the relations between the different subjects students will fail to acquire an integrated picture of life phenomena. For example, Nunez & Banet (1997) argued that many students finish their secondary education without developing an integrated and global notion about human nutrition. Instead, most students in their study hardly interrelated the different processes involved in nutrition, i.e. digestion, breathing, circulation and excretion.

Perhaps an even more influential characteristic of reductionism is the emphasis put on biochemical explanations. In the reductionist view biological phenomena are explained solely on the basis of the interactions between increasingly minute particles of matter, believing that the physical and chemical laws that govern matter are sufficient to account for the phenomena of life. Eventually this means that biological processes can only be explained by analysing them at the molecular level. In the 19th century analytical methods became established in biology research and due to the development of new research techniques, reductionism reached its top in the 20th century. Consequently, and because of the successful discoveries they covered, genetics and cell biology became important disciplines in the field of biology research. Biology had shifted from being primarily a descriptive science to being an experimental one at the molecular level.

The influence of these developments on biology education seems quite obvious. The Dutch examination requirements are a reflection of the dominant reductionist approach in the field of research. A lot of attention goes out to molecular processes and structures and students are hardly brought into contact with the more general and holistic side of biology. As a consequence students learn that explanations ought to be given predominantly at the molecular level. The concepts used in those explanations are usually drawn from the domain of biochemistry, which is quite esoteric to students and therefore can hardly function as a basis to develop a meaningful understanding of biological phenomena. So while for experts in the reductionist tradition the molecular level serves as an explanatory basis for macroscopic phenomena this is not just the same for students.

In contrast to the reductionist perspective there is another scientific perspective called organicism, which emphasises the necessity of understanding organisms in holistic, dynamic and interactive terms. Although, taken strictly, mechanistic and organismic views do not per definition exclude each other (see also section 3.3.2). The main focus of organiscists lies on self-organised systems and the concept of emergence, the idea that phenomena arising out of the interaction of parts are more complex than the parts themselves and cannot be explained on the basis of the parts alone. Organismic biologists recognise organisation as an essential factor in facilitating the complex physical and chemical phenomena that life comprises and those patterns of organisation could be studied scientifically. In the beginning of the 20th century the organismic perspective became increasingly influential in biology and the introduction of new concepts as interaction, coordination, integration and homeostasis caused a reorientation of biological research (Theunissen & Visser, 1996). In fact, concepts as emergence and level of organisation have become part of the standard language of biologists (Beckner, 1968). Organicism is nowadays accepted by many biologists and related to ‘systems thinking’ (see section 3.3). Von Bertalanffy, a theoretical biologist, was amongst the first to articulate a systems approach to the study of life in the 1930s with his General System Theory. He envisioned it as an interdisciplinary approach to the study of complex systems that would overcome some of the fragmentation between the various disciplines and help to develop a common vocabulary allowing experts in different fields to communicate with and learn from each other (Von Bertalanffy, 1950).

Over the last decades, the strong development of biological sciences has resulted in more emphasis put on systems thinking. Research biologists state that studying biological problems can be seen as studying biological systems and that this approach does not depend on the level of biological organisation on which the problem is studied. Enabled by technical innovations, i.e. molecular biological techniques, electron microscopy or the availability of powerful computers, important new insights of fundamental biological processes were gained within the field of genetics and molecular biology (Royal Netherlands Academy of Arts and Science, 1997). These insights at the molecular level are gradually connected to higher levels of organisation and reversibly much research at the molecular or cellular level derives its questions from new insights at the level of the organism or ecosystem. As the Biological Council (Royal Netherlands Academy of Arts and Science, 1997) stated, this has resulted in a strong integration of biological research methods and knowledge by now and it is expected that in the future this integration will only increase. The last decades, biology research is divided into broad-problem-oriented cooperations of scientists from different sub-disciplines (Bergman & Schoo, 1982; DeHart Hurd, 1997). Moreover, there is more focus on interdisciplinary research where different natural sciences are combined in upcoming sciences as biophysics, life sciences, molecular sciences, biomedicine, bio-informatics, behavioural neuroscience, etcetera.

In addition to the great transformations in the field of biological science, biology has increasing implications for our society. Biology is more and more integrated in our whole society and is related to big social issues as well as our everyday life. It has impact on our food (e.g. genetic modification, bio industry), health (development of medicines, defence against biological weapons), reproduction (in vitro fertilisation, genetic testing) and our environment (preserving biodiversity). Also many recent developments in biology demand social and political discussions about ethical, moral and risk aspects (e.g. research into genetic susceptibility to disease, cloning, using human embryonic stem cells in medical research). As a consequence, biological knowledge at all levels of organisation, from the molecular level up to the community level is linked inextricably.

As described earlier in this section, the developments in biological science have had its implications for biology education. Up to the 1970s biological subject matter on secondary school was mostly determined by the traditional academic knowledge and structure and little attention was paid to coherence, unifying themes or different biological perspectives (Buter, 1971; Buddingh', 1997). A more coherent and integrative approach to biology education was developed in the American Biological Sciences Curriculum Study-project (BSCS) that had major influence on biology education in the United States of America. Selection and structuring the content matter of the biology curriculum was guided by identification of unifying themes and different levels of organisation in biology. Moreover the emphasis was on principles of enquiry that could serve as a basis to construct learning strategies in order to acquire domain-specific knowledge (Janssen, 1999). Within the context of the BSCS project Schwab (1963) distinguished four principles: taxonomy, causality, structure-function relationship and regulation. He elaborated on these principles of inquiry by specifying the kind of questions to ask and information to gather about biological phenomena. Hereby, Schwab demonstrated that general ideas in biology are essential in shaping biology education.

In the footsteps of the BSCS, a more thematic approach to biology education was articulated in the Netherlands in the 1960s in the so-called 'Programmabasis' (Royal Netherlands Academy of Arts and Science, 1967). The Programmabasis introduced seven themes, i.e. life, unity and diversity, organism and environment, maintenance of the living organism, reproduction and development, behaviour and human biology, and forms the basis of the examination requirements today.

In the 1970s the thematical approach in biology education was integrated into a teaching approach that reflected 'the scientific method (enquiry skills)' (Treffers & Waarlo, 1989). As a result, biology education paid little attention to social and ethical aspects of biology as well as students everyday life experiences. In the 1980s, discontent about the limited objectives of biology education brought about new reforms. Biology education should not only be focused on the domain itself but also on the personal development of students in society, and their preparation for future education and careers. The national examination syllabus was extended with domain specific skills that would contribute to a more coherent learning approach. Systems thinking was now, at least on paper, explicitly added as attainment target into the examination syllabus: *'students should be able to indicate that in biology relations are complex by nature and many phenomena cannot be explained in a monocausal way, while research mostly concentrates on one aspect. The whole is more than the sum of its parts: 'systems thinking'* and *'students should be able to relate biological phenomena on various levels of biological organisation – cell, organism and ecosystem – with each other* (Attainment target in the National Examination Syllabus, 1998).

Current state of affairs in biology education in The Netherlands

In the most recent Dutch national educational reform more emphasis has been put on general and domain-specific skills and on tuning of the different science subjects, which mainly comprises new combinations of examination subjects in upper secondary education. The last decade a shift has taken place in science education in the Netherlands from a transmission model of learning, towards constructivist notions about learning that focuses on the learner who constructs his own knowledge. Kamp (2000) has shown that constructivist points of view are not only held by educational researchers and developers, but also by biology teachers. The dominant constructivist view also inspired the educational reform that focused on general skills that support students in 'learning to learn' and promote students' scientific literacy (De Jong *et al*., 2001).

The Biological Council recently formulated four aims that coherent biology education should accomplish (Royal Netherlands Academy of Arts and Science, 2003). It should help students to be able to a) engage in scientific thinking that is used to solve biological problems and to acquire knowledge at all levels of biological organisation that are needed to do so b) connect the foregoing to relevant social issues including c) personal and societal judgement and decision-making processes. In addition, it should help students to d) acquire understanding of the way biological knowledge is developed and the methods and techniques that are used. These aims are not just characteristic for biology education in the Netherlands but are very similar to the aims of the science curriculum as formulated in the report *Beyond 2000: science for the future* in the United Kingdom (Millar & Osborne, 1998).

In current educational practice however, the Dutch curriculum is overcrowded, again not different from the situation in the United States of America (described by Freedman, 1998) and the United Kingdom (Lock, 1997). The description of Lock well typifies the current curriculum in the Netherlands: 'heavy on content and light in process, combined with an assessment system that reinforces such a pattern' (p. 83). An evaluation of the implementation of the new educational reform confirmed the cognitive overload of the current biology curriculum in secondary education (Boersma, 2001; Tweede Fase Adviespunt, 2001).

The attainment targets still include detailed descriptions of the biological content that students should know. During the most recent reform general skills have been added to the extensive list, instead of being used to structure the content of the curriculum. Therefore it is not surprising that schoolbook authors stick to the traditional subject matter and pay little attention to domain-specific skills, e.g. systems thinking, when developing new methods. As Knippels (2002) has stated earlier, most schoolbook chapters have still been designed as separate units and most books lack integrating activities and explicit cross-references among chapters.

Most teachers comply with the structure and contents of the textbooks (Kuiper, 1993; Boersma, 2002) although their beliefs seem to be constructivist (Kamp, 2000). So, what do they think of the cognitive overload in the current curriculum? Approximately one third of the biology teachers think that the amount of face-to-face instruction is not sufficient in pre-university education (Morélis *et al*., 2001). Because their priority is to cover all examination requirements, many teachers feel as if their educational practice does not meet their own professional standards. For example, two third of the teachers state that they spend less time on practical work than before the educational reform and as a consequence their students are less competent in practical skills. In addition, 45% of the teachers state that their students work more independently as intended by the educational reform, but at the same time they find this undesirable for many topics such as genetics, DNA, transport, immunology and metabolism. All those topics are somehow related to the cellular level!

Summarising, we conclude that the present biology programme for secondary education shows three bottlenecks: overload, a shortage of coherence and a shortage of relevance to the students. To overcome these bottlenecks, Boersma & Schermer (2001) have proposed a programme, which aims at competencies, which have relevance in student's daily life and further education. A competence is defined as a repertoire of specific knowledge, skills and attitudes that is meaningful in one or more real life or professional practices. Biology education should focus on these competencies, to which biology can have a substantial contribution. Taking into account the four aims that coherent biology education should accomplish according to the Biological Council, systems thinking competence could contribute to the first aim, which underlines the importance of conceptual understanding at all different biological levels of organisation.

The biological component of the competencies can be defined in terms of a limited number of key concepts. As stated in the previous section the idea of a limited number of key themes in the Programmabasis (Royal Netherlands Academy of Arts and Science, 1967) already formed the basis for the present examination requirements. However, these seven themes reflect biology according to scientists and not so much the relevance and meaning that biology can have for students.

Our view on biology education underlines the importance of domain-specific competences in which the required biological knowledge is connected to practices that are relevant and meaningful to students. As stated in paragraph 1.2 we introduce systems thinking as a key competence in cell biology education. This means that in order to be able to develop a learning and teaching strategy for 'the cell as a system', we should articulate the key concepts in cell biology from a systems perspective.

1.4 View on learning and teaching

In section 1.3 we mentioned that in the last decade a shift has taken place in Dutch biology education practice from a mere cognitivist point of view to a constructivist point of view. Not only educational researchers and developers adhere constructivist notions on learning and teaching, but most biology teachers too (Kamp, 2000). Nowadays constructivism is seen as the dominant paradigm in theory on learning and teaching in science education (Mintzes e*t al*., 1998). In this section we will elaborate on the so-called problem posing approach. This approach is placed in the situated cognition perspective, one of the movements in constructivism. Consequently, we start with a general description of constructivism.

Constructivism

Constructivism can be seen as a reaction to traditional passing on knowledge on the one side and on discovery learning in the 1960s on the other side (Millar & Driver, 1987; Matthews, 1994). In the transmission paradigm, learners are more or less seen as passive receivers of knowledge or information (reception learning). The teacher provides information and the students presumably receive and 'absorb' the knowledge unaffectedly. According to constructivists, learning is a process of active reconstruction or 'meaning making' of the information that has been presented to the learner and his prior knowledge is essential to this process. Merely conveying knowledge induces 'misconceptions', i.e. conceptions that differ from the scientifically acceptable conceptions, and fragmentary knowledge (Duit, 1994; Eylon & Lynn, 1988; Núñez & Banet, 1997) because it does not actively involve students in integrating new information into what they already know. In the 1960s, Ausubel (1968) already stated that the most important single factor that influences learning, is what the learner already knows. He made a distinction between meaningful learning, in which new knowledge was related to students' prior knowledge and rote learning without relating new knowledge to prior knowledge.

Constructivism can also be seen as a reaction to self-discovery learning that took an important place in major curriculum projects in the United States in the 1960s (Bruner, 1960; Janssen, 1999). The rationale behind it was that formulating and testing their own hypotheses should enable students to get insight into the development and adequateness of (scientific) knowledge. In addition, discovery learning was expected to increase students' motivation as each discovery could be seen as a reward for the foregoing learning activity. However, the results of discovery learning were disappointing. Students did not discover the desired 'theories' and were less motivated than expected (Ausubel, 1968; Matthews, 1994; Tamir 1996). Ausubel stated that discovery learning did not take into account the prior knowledge of students, which directs students' observation. Students see or interpret things differently than the teacher and as a consequence they do not develop the scientifically acceptable conceptions. In contrast to the constructivist view, Ausubel preferred the transmission model of learning and teaching. In his view it was a more efficient and effective than discovery learning.

Nowadays, the common ground for all constructivists is the premise that cognition (learning) is the result of "mental construction". In other words, students learn by actively constructing new knowledge through interpreting new experiences and information on the basis of what they already know (Driver *et al.*, 1994; Duit, 1994). Learning is affected by the educational context in which the idea is learned as well as by students' beliefs and attitudes. However, this raises questions about how this construction process actually works and about what the consequences are for educational practice. In this respect, different movements of constructivism can be distinguished.

Review of research literature on science education shows that a distinction can be made between radical and trivial constructivism on the one hand, and between individual constructivism and social constructivism on the other hand (Boersma, 1995). Radical constructivism, as defended by Von Glasersfeld (1989) rejects the idea that reality can be known objectively and states that everybody at least perceives it differently. Trivial constructivism avoids the discussion about the a priori existence of an objective reality by stating that knowledge 'whether personal or public is a human construction' (Driver, 1988: p.163). It seems questionable however if both points of view have different implications for educational practice. Both radical and trivial constructivism state that construction of new knowledge is a personal process and therefore is more or less unpredictable. In order to guide the learning process into the intended direction, education must address the usefulness of knowledge within a certain culture or context. Eventually, students' knowledge will be judged on the extent that it is accepted within that culture. It seems to be the task of the teacher, as a representative of that culture, to help students to give meaning to their own experiences. Hereby he should take into account students' preconceptions that originate from society, personal experiences, upbringing, media, etc. on one side and the accepted, the intended scientific concepts on the other side and the construction process in between.

Problem posing approach

The question remains *how* to address the learning of science concepts and skills from a constructivist viewpoint within the design of a module. At the Centre for Science and Mathematics Education at Utrecht University learning and teaching strategies have been developed for various science subjects in which students' involvement is central. Klaassen (1995) has proposed a so-called *problem posing approach* that aims to actively involve students in their learning process on a content related basis.

In this general learning approach, the learning activities are sequenced in such a way that students themselves experience the need to expand their knowledge into the direction of the desired scientific knowledge. To start on common ground, students should be invited to activate and share their prior knowledge by discussing a content-related problem with other students. They need to experience a shortage of content knowledge when sharing and clarifying their prior knowledge, which provides them a motive for extending their knowledge into the, from the educators viewpoint, intended direction. Furthermore, the sequence of activities seems worthwhile to achieve this objective. The questions that rise during each following activity provide students with motives to engage in each subsequent activity and to gradually obtain more knowledge and insight into the domain-specific concepts and skills, i.e. the domain of cell biology.

Klaassen (1995) firstly articulated the problem posing approach for the topic of radioactivity. Since then, the approach has been further elaborated by Vollebregt (1998) and Kortland (2001) concerning the particle model and decision making about the waste issue respectively.

Within the domain of biology, Janssen (1999) used the problem posing approach in his strategy of *learning by designing*, in which students learn to generate knowledge about biological systems by 'redesigning' them. Knippels (2002) used the approach to engage students in thinking backward and forward between the different biological levels of organisation in her so-called *yo-yo strategy*. Both strategies were developed for biological subjects that cross various levels of organisation, i.e. immunology and genetics, and formed a bridge between a constructivist view on science education and content-specific notions about biology as a science. Taken together, the studies mentioned have shown the problem posing approach to be productive in tackling educational problems on the level of content-specific methodology.

The problem posing approach is based on the idea that students should realise what they are doing at any time during the process of learning and teaching and why they are doing it. An essential element of such a process is to provide students with content related motives for starting and continuing their learning process. In the approach a distinction is made between global and local motives. The global motive provides a starting point on common ground and gives students a sense of direction as to where the whole learning and teaching strategy will eventually take them (Klaassen, 1995). A local motive provides students with a reason for being involved in a particular learning or teaching activity induced by preceding activities. The local motives should be evoked by content related learning and teaching activities that have been designed in such a way that they raise questions that will be answered in the subsequent activity. Each learning or teaching activity results in the solution to a partial problem and gives rise to the next partial problem that is addressed in the next activity. Subsequently solving the partial problems in a series of well-chosen learning and teaching activities eventually helps students to solve the main problem and to acquire the desired scientific knowledge.

As Vollebregt (1998) emphasises, the account of a problem posing approach is rather idealistic as not all students will be able to raise the intended and adequate answers at every point in the learning and teaching sequence. Instead, 'a problem posing approach aims for a situation in which each problem is framed by at least some pupils and considered worthwhile to solve by all pupils' (Vollebregt, 1998: p.33).

Connecting the scientific knowledge to students' prior ideas requires a thorough analysis of the common sense knowledge of students, the scientific knowledge, and their interrelationship. Concerning students' previously developed knowledge before a specific topic in science education is dealt with, Klaassen (1995) has argued that students prior knowledge is largely correct or, for instance in the case of cell biology, developed rather superficially. Hereby, we reject a 'conceptual change strategy' as a means to change students' incorrect knowledge into the scientific acceptable knowledge. Instead, students' prior knowledge and everyday life experiences form the common ground from which students can extend their knowledge in a way that is meaningful to them. Moreover, answering the questions that students ask should demand the development of the very concepts and skills that we want students to learn. This way, the conceptual development as accomplished by a problem posing approach parallels the 'professional process of conceptual development in science itself' (Lijnse, 2002) and could be described as 'guided reinvention' (Freudenthal, 1991). The teacher and the learning materials are supposed to guide the course of the learning process and, if necessary introduce new concepts or information.

Positioning the problem posing approach

In our view, the problem posing approach is compatible with the situated cognition perspective, i.e. a socioconstructivist view on learning emphasising the sociocultural nature of a learning community (Rogoff & Lave, 1984; Henessy, 1993). The individual learning processes of the students that should take place are considered to be the result of interactions within the educational practice in the classroom. The emphasis in the approach is, to our opinion, on learning and teaching activities that take place within that educational practice. Moreover, a learning and teaching strategy should be designed by which students become increasingly involved in the educational practice and in order to become effective practitioners themselves, students will have to give meaning to the required concepts and skills.

Our view on learning and teaching that could be labelled as a 'situated cognition perspective' is in strong contrast with the current educational practice in the Netherlands. The most recent Dutch innovation, the so-called 'studiehuis' method, strongly focuses on students ability to learn independently and could be placed within individual or 'cognitive constructivism'. We will give a more articulated view on the contrast between our approach and the current Dutch educational reform by elaborating shortly on individual and situated learning below.

Individual constructivism and social constructivism differ by either focussing on individual or social aspects of the process of construction (Driver *et al.*, 1994, Cobb *et al.*, 1992). Individual constructivism or 'cognitive constructivism' focuses on individual constructions of the world in relation to students' cognitive development. According to this view, education should provide opportunities for experience with the world and should stimulate students to come to the right interpretation of the world. It is acknowledged that learning is embedded in a social context, but social interaction plays just a supporting role to understand and interpret phenomena (Driver *et al.*, 1994). Current cognitive constructivism combines these ideas with the development of metacognition. Instead of building a 'correct worldview', education should focus on the skill of (re) building a cognitive map (schema) which requires a combination of cognitive skills, such as reading and interpreting, and metacognitive skills, i.e. monitoring your own work. This 'self regulation' or 'self-directed learning skill' is an important aim in the most recent reform in secondary education in the Netherlands. Boekaerts (1995) suggests that monitoring one's own motivation to carry out an assigned learning task is one of the most important learning skills. Students are made responsible for their own efforts and have to motivate themselves to keep working on the task as formulated by the curriculum. This gives curriculum developers opportunity to shape the curriculum around scientific concepts that have to be learned as in traditional education. In this respect it is noteworthy that the current examination requirements still reflect the educational approach articulated in the Programmabasis in the Netherlands (Royal Netherlands Academy of Arts and Science, 1967) discussed in the previous section. A clear difference with traditional education is the role of the teacher who guides the students and encourages reflection (Simons, 1992).

Despite the fact that nowadays there is consensus about the desirability of students 'learning to learn' in society, in the government and among educational researchers, implementation of self-directed learning meets substantial problems (Van Hout-Wolters *et al*., 2000). Students are not always willing to acquire new learning skills and teachers do not always see the benefits of self-directed learning. Instead teachers may find it too time-consuming, hard to coordinate, and resulting in a loss of their autonomy in the classroom. Moreover, as already mentioned in section 1.3, teachers often state that self-directed learning is not appropriate for all subject matter.

Although individual constructivism acknowledges that learning does not take place in isolation, in our view it underexposes the social context of learning. In the situated cognition perspective, on the other hand, learning is seen as a process of enculturation within social communities. In other words, learning is a process that is part of a culturally organised activity, which is carried out within a specific sociocultural community of practitioners. The educational practice should help students give meaning to their own experiences within a certain socio-cultural community and enable them to become participants of that community. In section 1.3 we defined the overall learning goal of our learning and teaching strategy as a systems thinking competence, because it is functional within the context of biological science. So, in our case we have to actively involve students in an educational practice that forms an appropriate context for which the new the concepts, skills and attitudes that constitute systems thinking are functional.

The teacher plays an important role in the process of 'enculturation'. As emphasised by Vygotsky (Van Oers, 1988) students' development can be stimulated by engaging them in activities that they are not able to carry out by themselves yet, but only with help of the teacher. The more difficult activities are performed under guidance of the teacher until they can carry them out on their own. As learning takes place in a social environment, including other students, the teacher should also mediate and stimulate communication between students. Interaction between students is important to share prior knowledge and to become motivated to extend one's knowledge (Van der Linden *et al*, 2000). Moreover, this interaction between students and teacher creates the possibility to arrive at a collective process of construction. The learning activity becomes an activity that can be attributed to the community of learners and is the result of social interaction. In our research, which aims at developing a problem posing learning and teaching strategy, focus is on this collective process of construction. This process should reflect a careful balance between 'guidance from above' and 'freedom from below' (Lijnse, 1995, 2002). The teacher and the sequence of learning activities provide guidance from above while the learning activities should also provide enough freedom from below. Finding the balance between these two aspects of learning and teaching forms the core of our research as Lijnse (1995) already argued that this balance could only be carefully regulated empirically. In addition, in our research we should be aware of the differences between the problem posing approach and the current educational practice in the Netherlands.

1.5 Outline of this thesis

Chapter 2 will discuss the developmental research approach of this study. The cyclic research process featuring designing, testing and revising will be explained along with the explorative phase, which preceded the cyclic research phase. Chapter 3 elaborates the explorative phase and addresses the integration of cell biology and systems thinking in an initial learning and teaching strategy to be tested in classroom practice. During this phase the main difficulties in cell biology were identified and a systems thinking competence for biology education was formulated. Furthermore, chapter 3 presents a description of the cell biology content from a systems perspective and discusses two explorative case studies that tested some first notions about how systems thinking could be useful in shaping coherent (cell) biology education. Based on some design criteria formulated in the explorative phase, chapter 3 concludes with the presentation of an initial learning and teaching strategy for the cell as a system.

Chapter 4 describes the empirical research phase of this study, which probed the adequacy of the learning and teaching strategy. To this aim, the strategy was converted in a context-specific scenario that was field-tested in a first case study. To reflect on the expectations and objectives described in the scenario and on the internal consistency of the actual learning and teaching processes, data were obtained from various data sources and analysed subsequently. Based on the outcomes of the first case study the learning and teaching strategy was revised and tested in a second case study. Describing the results of this second case study forms the main issue of chapter 4 and leads to the presentation of the final learning and teaching strategy for the cell as a system at the beginning of chapter 5. Subsequently, chapter 5 will reflect on this final strategy and present theoretical implications that target domain-specific learning and teaching processes concerning cell biology and systems thinking. This finally enables us to answer the central research question of this thesis that was presented in the preceding part of chapter 1. Furthermore chapter 5 will go into the wider applications of systems thinking to biology education and outline further research to be done.

Chapter 2

Design of the study

2.1 Introduction

Chapter 1 described the context of the central problem that will be addressed in this thesis. The developments in biological science and biology education, as well as notions on learning and teaching served as a basis for a domain-specific philosophy of learning and teaching. The aim of this study is to develop an adequate and research-based learning and teaching (LT) strategy for the cell as a system in upper secondary biology education. The interpretative research approach applied to accomplish this aim can be characterised as 'developmental research' (Lijnse, 1995).

A general description of developmental research approach will be given in section 2.2. The various phases, products and activities that are part of this approach will be discussed. Section 2.3 focuses on how *this* study has been designed according to the developmental research approach.

2.2 Developmental research

The *developmental research approach* that is used in this thesis has been adopted and adapted in the last two decades by curriculum developers and researchers of the Centre for Science and Mathematics Education in Universiteit Utrecht. The approach strongly resembles what Cobb *et al.* have described as ‘design experiments’ (Cobb *et al.*, 2003) conducted in a classroom setting. In developmental research theory driven, creative and practicable solutions to learning and teaching problems are designed. In addition, iterative consultation with a limited number of experienced biology teachers takes place and researchers and teachers also co-operate in testing and reflecting on the developed learning activities in classroom settings (Lijnse, 1995). Several cycles of empirical testing are necessary to optimise the LT strategy.

‘Traditional’ research approaches such as experiments, surveys or correlation analyses hardly provide useful solutions to problems in science education and curriculum development, as they focus mainly on descriptive knowledge (Van den Akker, 1999). A considerable amount of educational research tries to identify and explore learning and teaching problems in classroom practice, e.g. students’ perceived or expected difficulties in understanding scientific concepts and theories. For example Bahar *et al.* (1999) show an extensive list of 36 biological topics with an index of relative difficulty as perceived by students and Dreyfus & Jungwirth (1989) present a ‘taxonomy of dysfunctional ideas’ about the living cell. Although we acknowledge that this kind of knowledge has important potential relevance for educational practice, the question *how* to effectively deal with the reported difficulties often remains unanswered. Therefore *exploratory* research has to be followed by research that contributes to a considerable and transparent *improvement* of science education.

Developmental research aims to improve science education practice and to yield scientific output, i.e. a domain-specific learning and teaching theory (cf. Cobb *et al.*, 2003). Such a domain specific theory prescribes teachers and curriculum developers which learning and teaching activities should be placed in what sequence for students to attain the desired learning outcomes. Since the relation between these activities and outcomes are studied in detail, a domain specific theory also explains why the intended learning outcomes are attained.

With regard to our study on the cell as a system the developmental research approach was chosen because within the domain of cell biology relatively much progress has been made and uncertainty exists on the question which learning outcomes are desirable and attainable for students in secondary education. As we described in chapter 1, biological science and biology education have been changing rapidly, especially with respect to the domain of cell biology. According to Freudenthal, the purpose of developmental research is to adapt education to a changing society or to try to anticipate the change (Freudenthal, 1991). However, as Lijnse (2002) remarks, developmental research also has to focus on more constant elements of science education, i.e. the scientific content and skills. With regard to the domain of biology, systems thinking is acknowledged as an important domain specific skill[1] and this study aims to contribute to the development of a learning and teaching theory for systems thinking in biology education.

Developmental research is not primarily aimed at explaining and understanding, but at enabling *action and change* (Freudenthal, 1991). The focus is on the interconnectedness of learning and teaching (Lijnse, 1995). The objects of study are the domain specific learning processes and outcomes of students, and the impact of teaching on these learning processes and outcomes (Boersma, 1998).

Two basic questions are addressed for a specific domain (Boersma, 1998): 1) How can students attain a priori formulated objectives and how can teachers help students to attain those objectives? and 2) How can learning problems be prevented or solved and how can teachers help students to prevent or solve their learning problems? The answer is provided by a theory-based and empirically validated design of a domain-specific effective learning and teaching strategy. Designing such an effective strategy can only be done on the basis of a proper interpretation of students' prior knowledge and skills (Klaassen & Lijnse, 1996). During an explorative phase, that could be described as 'theory guided bricolage' (Gravemeijer, 1994), a supposedly effective learning and teaching strategy (LT-strategy) that extends students' prior knowledge and skills into the intended direction emerges. Subsequently, it is checked to what extent the intended and expected learning and teaching processes take place and why (or why not). This feedback of practical experience into the improvement of the strategy induces a cyclic process of development and research, which is the heart of developmental research (Gravemeijer, 1994).

[1] In line with the literature that is referred to in this section, we make a distinction between knowledge and skills. In this context (and conform the Dutch examination syllabus), systems thinking is described as a domain specific skill. However, in our research systems thinking is defined as a competence in which attitude, knowledge and skills are combined (see section 1.2 and 3.3.2).

2.3 Research design

The process of developmental research is cyclic in nature and comprises the following stages:

- Theoretical reflections and empirical explorations, resulting in design criteria and a prototype of the learning and teaching strategy
- First test cycle of the designed learning and teaching strategy
- Revision of the strategy
- Second test cycle and further extraction of theoretical implications

The different stages can be categorised in an explorative phase and a cyclic research phase as depicted in figure 2.1 (Boersma *et al.*, 2002). In the explorative phase, the general characteristics and structure of the (supposedly effective) teaching and learning process for cell biology from a systems theoretical perspective are identified. During the cyclic research phase, a specific sequence of interrelated learning activities and guidelines for teaching these activities gradually emerges by a cyclic process of testing and reflecting. Eventually, this results in a theoretically founded and empirically tested LT strategy. Each phase can be characterised by its specific objectives, products and activities, as we will describe below.

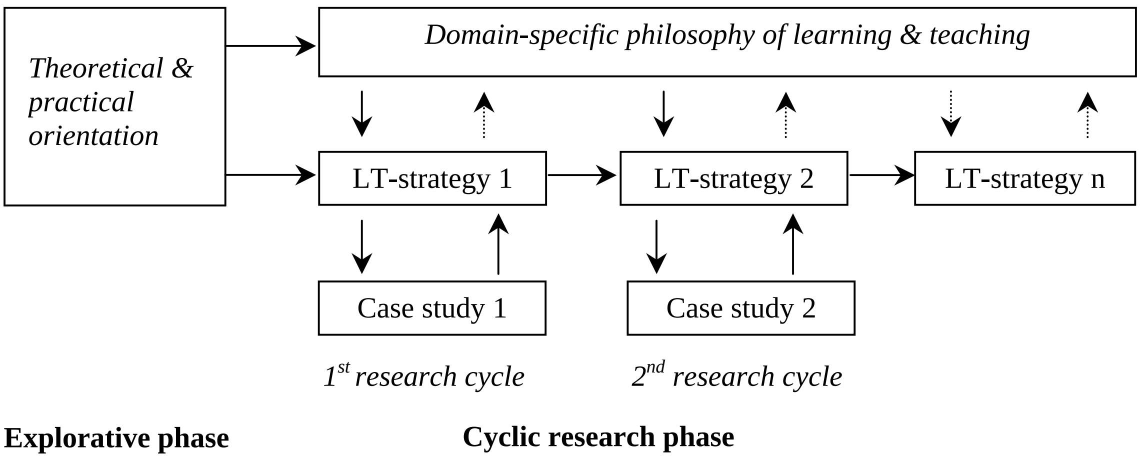


Figure 2.1 ***Design of developmental research*** *(Boersma et al., 2002), consisting of an explorative phase and a research phase in which a learning and teaching (LT) strategy is tested in successive cycles resulting in a domain-specific educational theory (n).*

Explorative phase

In this initial orientation phase studying relevant literature and testing some first theory-based ideas in the context of a classroom setting result in a problem diagnosis and inventory of solutions. At the same time, this phase enables the researcher to develop a more articulated view on the field in between general educational theories and educational practice and taking into account the disciplinary knowledge: content specific methodology. A significant part of theoretical foundation of the study should be articulated during this phase. This foundation includes the domain specific subject matter, i.e. its contents and conceptual structure (Knippels, 2002), and reported solutions to learning problems within the domain.

First orienting activities should focus on picturing the educational practice through observations and interviews with teachers and students. Furthermore, the process of 'theory-guided bricolage' enables small-scale case studies to explore some first theory-based ideas in classroom practice. Also, it enables the researcher to check his expectations concerning students' prior knowledge and skills and their behaviour. Combined, the theoretical and practical exploration should result in a domain-specific philosophy of learning and teaching and in the definition of design criteria for a preliminary LT strategy that will be tested subsequently.

Explorative research in this study

In the explorative stage of our study, we re-analysed the research literature on cell biology education and interviewed teachers and students. Furthermore, an explorative case study concerning two lessons on endocrine regulation was carried out. Emphasis was on relating students' prior cell biology knowledge to higher levels of organisation (Verhoeff *et al.*, 2002). Another exploration focused on computer-assisted development of a systems model of digestion in humans and applying this model to different levels of biological organisation (Schuring, 2000); Verhoeff *et al.*, 2002).

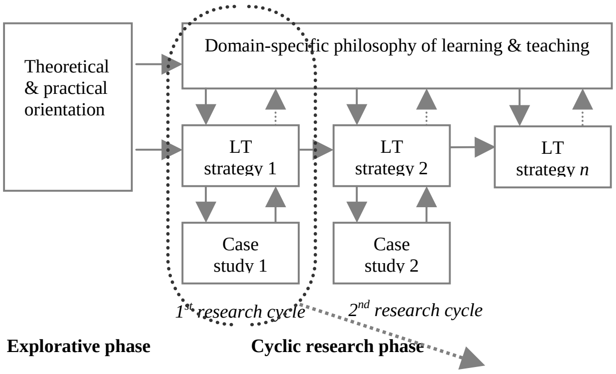
With these activities we identified the main problems in cell biology education and acquired more in-depth understanding of these learning and teaching difficulties and potential difficulties concerning systems thinking. In addition, we built some ideas of how cell biology education could be shaped from a systems theoretical perspective, in order to deal adequately with the difficulties that were identified. This included some promising learning activities and a definition of criteria for an adequate LT-strategy for cell biology from a systems theoretical perspective. So, in other words the exploration phase resulted in a preliminary domain specific philosophy that integrated systems thinking with cell biology education. The explorative phase is described in more detail in chapter 3.

Cyclic research phase

In the cyclic research phase, the domain-specific philosophy is being operationalised in a cyclic process of constructing the design, field-testing it, reflecting on the design and adjusting it, field-testing the revised design, and so on.

First a preliminary strategy is developed, based on the explorative phase and our view on learning. Developing such a strategy initially involves selecting and justifying appropriate subsequent steps in the process of learning and teaching the domain-specific content and choosing and designing specific activities that may lead students to understand what they are doing and why they are doing it. The structure of the domain-specific content is reflected by the sequence of the successive questions (problems) that will be addressed in a sequence of well-chosen activities. The sequence of questions is at first a top down construction that is supposedly effective in activating students' prior knowledge and skills. In addition, designing such a sequence requires not only being

Figure 2.1 ***Design of developmental research.***



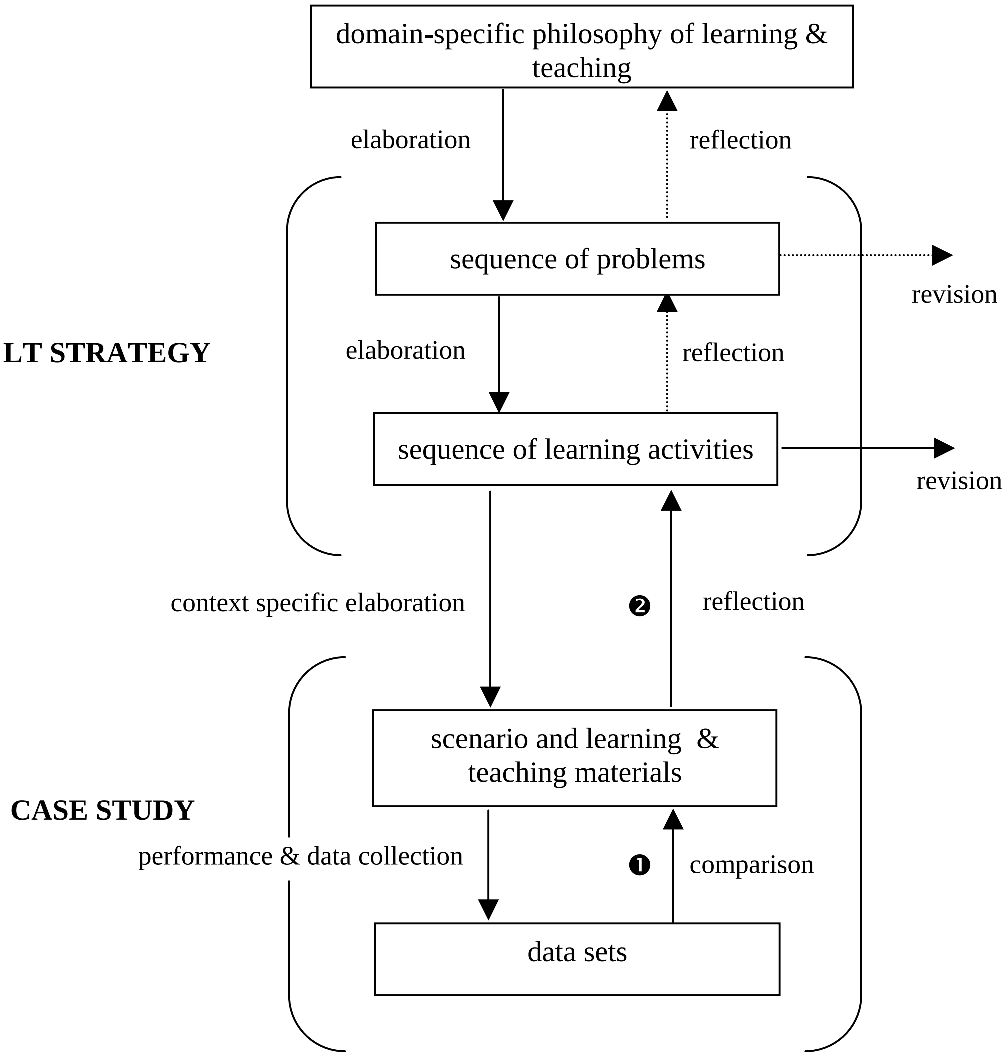


Figure 2.2 ***Research cycle of developmental research,*** *including the products (boxes) at different levels and activities (arrows) involved in one research cycle (Boersma et al., 2001; Knippels, 2002). The arrows show the sequence in which the LT strategy and its scenario are designed and subsequently reflected on. The numbers* ❶ and ❷ *refer to the research questions. A further explanation is given in the text.*

aware of students' prior knowledge and skills, but also needs an extensive consideration of how students will interpret the activities in which the problems are addressed. Students' subsequent experiences and the information that is presented to them should be meaningful within the context of the educational practice.

Next, the LT-strategy strategy will be empirically validated in two or more consecutive case studies (see figure 2.2). Hereby, it is investigated whether the learning and teaching activities promote students to raise the expected questions, whether students find the activities worthwhile in the light of these questions and whether they arrive at the intended outcomes. To conduct such an investigation it is necessary to elaborate the more general ideas in the LT-strategy into a more precise description of our expectations of what will happen during the process of learning and teaching in a *scenario*. A scenario is a more explicit, context-specific description and justification of the intended learning and teaching activities, including their elicited learning and teaching processes and their outcome. In testing the adequacy of the LT strategy the scenario guides the analysis of the actual learning and teaching process in the classroom practice. (For a more detailed description of the role of the scenario see section 4.2.3). As Lijnse has stated, 'the scenario describes and justifies in considerable detail the learning tasks and their interrelations, and what actions the students and teacher are supposed and expect to perform: it can be seen as the description and theoretical justification of a hypothetical interrelated learning and teaching process' (Lijnse, 1995, p.196). Hereby, the scenario is not only a research instrument that enables the researcher to observe precisely where the actual learning and teaching processes deviate from what he would expect. Also, the scenario facilitates the intended learning and teaching processes, as it serves as a means for the teacher to prepare the actual lessons. Although the scenario takes into account the specific situation, wishes and abilities of the teacher because he has been involved in the development of the teaching sequence, it clarifies to him what he is expected to do and, more particularly, why he is expected to do so.

Eventually, the overall research question is answered with an adequate domain-specific LT strategy with a solid empirical base. Arriving at this strategy demands in-depth, small-scale qualitative research. Two successive case studies are considered to be a minimum to provide the empirical basis for the LT-strategy. If, on the other hand the results are not yet satisfying after the second case study, a further cycle of revision and testing can be performed. When the strategy appears to be adequate under the circumstances of the two case studies, it may become worthwhile to extend the research into large-scale, quantitative research. However, this is beyond the scope of this study.

In the developmental research approach, the LT strategy (theory) evolves in a process of cyclical empirical testing of scenarios, i.e. successive case studies (fig. 2.1 and 2.2). The successive research cycles constitute a kind of learning and optimisation process itself, rather than a multiple case study (Yin, 1988). In a *case study*, a field-test is performed in a naturalistic setting, i.e. one form of one school. It includes a rich, detailed and in-depth description of the observed phenomena in the case. Multiple sources corresponding with different points of view (triangulation) are used for providing evidence (Ghesquière *et al.*, 1999), e.g. classroom observations, audiotaped classroom and group discussions, completed worksheets, written tests and interviews with students and teachers. As we described in section 1.3, two questions guide data collection and analysis during the cyclic research phase in order of appearance: ❶*What learning outcomes arise from the executed learning and teaching strategy and what learning processes constituted these learning outcomes?* and ❷*What indications can be derived from the observed learning processes and outcomes for revising the learning and teaching strategy?* Answering these questions leads to a revision and further elaboration of the scenario, to be tested in the next case study. Therefore, the second case study again addressed the above two questions.

Reflection on the outcomes of both case studies contributes to the development of theoretical notions concerning the learning and teaching of the specific subject. Reflection activities do not only occur afterwards, but already start during the development and testing of the learning activities, e.g. reflection on learning and teaching activities, experiences in the classroom, and the developmental process itself (Gravemeijer, 1999). In developmental research the *process* by which the *products* of the activities are created, is reported in such a detailed and comprehensible way that it justifies itself (Freudenthal, 1991). The reflection activities that are needed to accomplish this aim comprehend a careful process of thinking backward and forward between the observed learning and teaching processes and outcomes in each case study, the expectations as explicated in the scenario and the domain-specific philosophy of learning and teaching cell biology from a systems theoretical perspective. Discriminating between coincidental, crucial and context specific findings is a prerequisite to define LT strategy for this specific topic.

The cyclic research phase in this study

In this PhD-study, two case studies were planned in order to provide a solid empirical basis for a supposedly adequate LT-strategy that integrates systems thinking with cell biology. In this section, we will only roughly describe the case studies; more specific characteristics will be described in section 4.2.1. The results of the first and second case study will be described in section 4.4 and 4.5 respectively.

The topic of cell biology is usually taught in upper-secondary school at the beginning of the school year in September and October. Therefore the first case study was planned somewhere in this period. To be able to put enough effort in the explorative phase of our study, the first actual case study was performed in October and November 2001 (from 1 October to 8 November). The second case study was performed from 6 March to 19 April 2002. This was possible because our selected teacher followed the structure of a textbook that is not commonly used. The time in between both case studies gave us enough opportunity to analyse the data of the first case study, to evaluate the first LT-strategy, which provided guidelines for adjustment of the strategy. Moreover, the residual time from April 2002 till June 2003 provided enough space to analyse the second LT-strategy, to develop a domain-specific educational theory and to report the whole process of our developmental research in this thesis.

Of course, each case study is a one-time event and it can never be reproduced in exactly the same way. One way to increase the validity of the LT strategy and reduce its dependence on the specific context in which it was tested, is to perform the two case studies in different contexts. Therefore we selected two different teachers from two different schools to participate in our research. Hereby, both case studies differed in three aspects: teacher, school and students. It was expected that after two successive research cycles, including data analysis, evaluation and reflection, the core of the LT strategy that consists of the most crucial elements in the scenario, should have emerged.

Furthermore, we decided to include two classes per teacher in a specific case study. This way, small adjustments could be made before each lesson was carried out for the second time and the case study became less vulnerable for disturbing events like non-attendance of cancellation of lessons. More importantly, it enabled the teacher to familiarise himself with the scenario, resulting in an increased self-confidence and higher scenario-fidelity. At the same time, the teacher could anticipate on students' unforeseen reactions in the second lesson and apply minor deviations in the scenario to improve the fluency and coherence of the lessons. It must be noted that in our first case study it appeared that the selected teacher had only one class in which cell biology was introduced that year. Therefore it was decided to select another teacher at the same school who taught cell biology in another class of the same level during the same period of time. For further details see section 4.2.1.

Chapter 3

Exploration of cell biology and systems thinking

3.1 Introduction

In the explorative phase of our study (see figure 2.2), various research activities were performed to gather more insight into the two important piles that form the foundation of our initial learning and teaching strategy: cell biology and systems thinking. Integration of the outcomes of these research activities resulted in the formulation of the criteria for the development of the initial learning and teaching (LT) strategy, which will be presented in section 3.4.5.

Section 3.2 describes the educational difficulties regarding cell biology and some suggested solutions for dealing with these difficulties that were identified in the international literature. Subsequently, the Dutch situation will be elaborated by reporting on a schoolbook analysis. In section 1.2 we described systems thinking as a key competence for cell biology education. To gather more insight into what systems thinking actually implies, section 3.3 distinguishes and elaborates on three major systems theories resulting in a formulation of systems thinking as a domain specific competence for (cell) biology education. Section 3.4 seeks to integrate cell biology and systems thinking. First, we present a description of the cell biological content from a systems perspective (3.4.1). Next we try to theoretically underpin a supposedly adequate LT-strategy in which cell biology education is integrated with systems thinking (3.4.2). To gather more in-depth understanding of the educational problems concerning cell biology and how systems thinking could be helpful in dealing with those problems, we conducted two small-scale explorative case studies that are reported in section 3.4.3 and 3.4.4. All together, the sections in this chapter lay the foundation for the initial LT-strategy that is presented in section 3.4.5.

3.2 Cell biology

3.2.1 Reviewing the literature on cell biology education

As we stated in section 1.2, a basic understanding of the functioning of the cell is assumed to be essential for sound understanding of the functioning of the multicellular organism. Students are being taught a large variety of life structures and processes at the cellular level. The concepts used to describe these are mainly drawn from the sub-cellular level, but this knowledge seems to be fragmentary if its integration at the cellular and organismic level remains undone. As a consequence, many students fail to acquire coherent conceptual understanding of the cell as a basic unit of the organism. In addition, science education research on biological processes has revealed that many conceptual problems both at the organismic and the cellular level are associated with a lack of interrelating these levels of biological organisation. The poor understanding of the cell as a basic unit of life and the incoherent knowledge of cellular processes will be described first in this section. Next, we will describe some studies that offer empirically based solutions to learning and teaching cell biology.

Although the available studies on cell biology education show substantial problems in acquiring coherent understanding of the cell, the number of studies is limited. The number of studies that offer empirically based suggestions for improvement is even smaller. Nevertheless, reviewing the relevant literature offered more insight into the problems in cell biology education and gave us some indications about how these problems could be tackled.

Understanding the cell as a basic unit of life

Dreyfus & Jungwirth (1988, 1989, 1990) investigated the cell concept of 10th graders in Israel who had been taught about 'the living cell' the previous year as one of the main topics. The main principles and topics reflecting the 'idea' of 'living cell', on which university scientists, curriculum specialists, inspectors and practising teachers had agreed on, were condensed in a 12-point list of 'curricular demands'. Based on this list, an open-ended questionnaire was constructed and administered to 219 grade 10 students from different schools. A representative sample of respondents, about 20 percent of the total, was then selected for interviewing.

Although the students had been routinely examined on completion of the topic with satisfactory outcomes, the questionnaire results backed up by in-depth probing during the interviews show that very few students grasped the idea of the cell as a basic unit of life. For instance, students drew conclusions or invented principles, which were contradictory to the knowledge they had shown correctly before, e.g. 'The cell is the basic unit of every living thing' but …'only some parts of the body are made of cells, others are not' (Dreyfus & Jungwirth, 1988, p.228). The same study shows that students' lack of knowledge mainly concerned the physico-chemical aspects, which accounted for the idea of the living cell to be an empty shell. The authors stated that teaching the cell is faced with great difficulties that stem from the very nature of the idea of the living cell as a basic unit of life. This idea 'is and will remain an abstract idea' because the basic metabolic, i.e. biochemical or biophysical, processes of life cannot be directly perceived by means of the students senses nor described in terms of the scientific knowledge of 9^{th} grade students (Dreyfus & Jungwirth, 1988). The results implicate the necessity to rethink the curriculum in terms of intended learning outcomes and in terms of designing a specific context in which the concept of the living cell can be described by means of meaningful attributes and linked meaningfully to other relevant concepts. According to Dreyfus 'intracellular biochemical processes *are* the basic processes of life' (Dreyfus & Jungwirth, 1990, p.110), but from this statement it does not necessarily follow that they can serve as a basis to learn about the cell as a basic unit of life.

Douvdevany *et al.* (1997) probed junior high-school biology teachers' understanding of some essential biological concepts, which they were expected to teach meaningfully. The authors designed two game-like diagnostic instruments that were based on three concept maps of three subtopics of the 'living cell': DNA and proteins, energy in the cell, and water and membranes. The results of their study show that the knowledge of many teachers about cellular processes lacked coherence, although their specific declarative knowledge was satisfactory. The teachers did not spontaneously connect and interrelate specific concepts and principles, especially concerning the subtopic 'water and membranes' and to a less extent the sub-topic 'energy in the cell'.

So, teachers who are supposed to guide students in actively constructing the relationships between cell biological concepts lack coherent understanding as well.

Interrelating cellular processes

Interrelating cell structures and their functions and integrating them into an overall picture is considered to be crucial in acquiring meaningful understanding of the cell and its processes. A lack of such relationships impedes understanding of cellular processes such as respiration and photosynthesis (Lazarowitz, 1992; Songer & Mintzes, 1994) or genetic mechanisms (Lewis & Wood-Robinson, 2000; Marbach-Ad & Stavy, 2000).

Lewis investigated the knowledge and understanding of genetics amongst 482 16-year old students nearing the end of compulsory education. The students showed limited understanding of the nature of genetic information and a high level of confusion about basic biological structures such as cell, chromosome and gene and their relationships to each other. For a more detailed overview of the learning and teaching difficulties regarding cellular processes within the context of genetics we refer to Knippels (2002).

Songer & Mintzes (1994) explored both novice and experienced college-level students' understandings about cellular respiration, which is presented as being central for meaningful understanding of life at the organismic level. Students' understanding was explored by means of clinical interviews based on students' concept maps. Using the concept maps on cellular respiration as a point of departure, each student was interviewed to explore his or her understanding of the intracellular events of respiration first. Next cell-organism relationships were explored within the context of familiar organismic phenomena, including digestion, respiration and circulation. The results show that both novice and experienced students have conceptual problems that impede understanding of cellular respiration. For example photosynthesis and respiration are considered as equivalent processes. In addition Songer & Mintzes reported problems related to a lack of experience with 'thinking at the cellular level', i.e. seeking cellular explanations of biological phenomena that manifest themselves at the organismic level. The fact that the problems of more experienced 'second year' college students do not differ substantially from those of introductory students means that the curriculum needs rethinking. Instead of introducing cellular phenomena as a basis for understanding organismic phenomena, Songer & Mintzes suggest that topics at the cellular level should be preceded by important physiological topics such as gas exchange, digestion and transport mechanisms.

Songer & Mintzes (1994) addressed problematic understanding of the relations between cellular events and various biological phenomena at higher levels of organisation. Science education research has revealed many conceptual problems both at the organismic and the cellular level that are associated with a lack of interrelating these levels of biological organisation. Núñez & Banet (1997) investigated students' conceptual patterns of human nutrition and stated that their results indicate that many students in Spain finish their primary and secondary education without having developed an integrated and overall picture of nutritional processes. Analysis of students' difficulties revealed a lack of interrelating different processes involved in nutrition such as digestion and breathing, due to not understanding the cellular organisation of the human body and a lack of understanding the processes that take place at the cellular level. Núñez & Banet suggest that effective pedagogic strategies should put more emphasis on interconnecting the nutrition processes, clarifying the cellular structure of the human body, and clearly explaining the exchange of substances between cells and blood and their use in obtaining energy and building materials. Similar suggestions are made by Ramadas & Nair (1996) who investigated the conceptions of 6 to 13 years old students about the digestive system. They showed that although the basic information could be handled at an early age, a lack of integrating their ideas about digestion with related concepts of respiration, metabolism and growth persisted. Students had no idea of the chemical transformation of food. In line with the suggestions of Núñez & Banet, Ramadas & Nair stress the importance of treating the body as a system of interrelated structures and processes that, as they state, may come more naturally to children than treating the body as a compilation of quite isolated mechanisms.

In addition to a lack of relating macroscopic phenomena to microscopic phenomena as described above, conceptual problems about the cell and its processes have been attributed to students' lack of differentiation between some processes at the organismic and cellular level of organisation (Dreyfus & Jungwirth, 1990; Flores *et al.*, 2003). The results of the study of Flores *et al.*, based on data from 1200 high school students in Mexico show that, as a consequence of analogising, students' representation of the functioning of multicellular organisms and cell processes is isomorphic. For example, students consider nutrition in the cell to be similar to the digestive system where food is ground and processed. This corresponds with the findings of Dreyfus & Jungwirth (1990) who reported that students, when explaining unknown microscopic phenomena, tend to use analogies with systems they are familiar with but do not always understand better. These analogies are often based on complete ignorance, or on oversimplified knowledge of the micro-level: 'since cells do specialise (a system, which is familiar but seems to be only superficially understood), then, in some students' opinions, some of them certainly specialise in the production of energy, and this energy is later transported to the other cells of the body (superficial information leading to misconceived analogy)' (Dreyfus & Jungwirth, 1990, p.112).

Although the use of analogies is considered to be important in learning and teaching microscopic phenomena, it is recommended that special attention should be given to the organism-cell relationship where analogies may introduce incorrect interpretations.

Reflection on suggested/tested solutions

From reviewing the literature on cell biology education as described above, two categories of conceptual difficulties emerged. The first category refers to specific problems regarding a coherent understanding of the structures and processes that constitute the cell as a living whole, i.e. horizontal coherence. The second category refers to a problematic understanding of the functional relation between cellular processes and the functioning of multicellular organisms at higher levels of biological organisation, i.e. vertical coherence. The problems in both categories are associated with the absence of a meaningful context in learning the 'abstract' cellular structures and processes that cannot be directly perceived by the students. So, the domain of biochemistry does not provide a meaningful context for students to learn cell biology, but starting with students' knowledge and experiences with macroscopic phenomena seems promising. Although so far we have described various studies that show difficulties in relating concepts on the macro and (sub) micro level, some studies have suggested strategies to tackle these problems.

Dreyfus & Jungwirth (1990) proposed to use the more familiar macro level to introduce the nature of cellular problems by using carefully selected analogies with systems that 15-year-old students really understand better. For example the possibility of building different proteins from some basic amino acids was introduced as a set of answers to questions, which had been asked by students from the analogy of building different cars with Lego parts. As Dreyfus & Jungwirth state, the analogies in the strategy were not intended to serve as explanations of the microscopic phenomena, but as guides for exploring them. So, acquiring conceptual understanding about the different structures and processes at the cellular level was not addressed in this study.

Marbach-Ad & Stavy (2000) investigated students' cellular and molecular explanations of genetic phenomena. From their study, based on three relatively large populations of 9th graders, 12th graders and pre-service biology teachers, they suggest that students should first be introduced to various phenomena in human beings or higher organisms that are close to human beings, in macroscopic terms only. Then, when dealing with the cellular and molecular levels, it would be better to deal with lower organisms such as bacteria. Hereby, they state, it is important to allow students to find out the differences and similarities between the basic processes and concepts in the simpler systems, i.e. lower organisms, and those in the more complex systems, i.e. higher organisms. This seems to be in line with Flores *et al.* (2003) who suggest that treatment of the levels of organisation, including the cellular, should start with the most general aspects that are closest to students' experience.

Another approach to teaching 9th grade students about intra-cellular biological processes is the 'ostension' approach (Olsher *et al.*, 1999), i.e. teaching scientific principles by ostension', which means, literally, by showing (Millar, 1990). Millar claims that this approach shows the 'theory in action', instead of dealing with proofs for the existence of any abstract theory based on the micro level. Showing the 'theory in action' in the context of intra-cellular processes means putting emphasis on methods of intervention, e.g. biotechnologies, in such processes and on the outcomes of such processes. Both interventions and outcomes may be presented in concrete macroscopic terms and could be directly observed or perceived by the students. The micro-level still remains a 'black box' but showing the interventions and their results incites students to ask questions, which are both meaningful to them and relevant to the processes that take place in the 'black box'. According to this view, students' questioning is therefore central in acquiring insight into the nature, and not the details of intra-cellular processes. However, the study shows that this may not easily be reached, mainly because the structures and activities at the micro level involved in the processes are unknown to the students. As a result students did not spontaneously ask questions about the nature of the biological processes and consequently, as the researchers suggest, should be oriented into the desired direction by the teacher.

Knippels (2002) developed a learning and teaching strategy by means of a developmental research approach, in which the concept of 'levels of biological organisation' was used to cope with the abstract and complex nature of genetic phenomena. The strategy emphasises the genetics key concepts per level of biological organisation and their interrelationships, in particular reproduction, meiosis, and inheritance on the organismic and cellular level. Students descend gradually from the organismic to the cellular and molecular level and at each level the concepts of these levels are related to concepts at the level of the organism (ascending). The strategy has a problem posing structure (see section 1.4) of content related questions and reflection activities, which provides students with motives to engage in learning activities in which certain key concepts on a specific level of biological organisation are explored. Knippels argues that her so-called ‘yo-yo strategy’ enables students to acquire the competence of thinking backward and forward between the organismic, cellular and molecular levels of organisation and to relate the genetics concepts on these levels. This competence accounts for the effectiveness of the strategy in terms of coherent conceptual understanding of genetic phenomena, including molecular and cellular processes. Since the levels of organisation play an important role in most biological topics, it is argued that the yo-yo LT strategy is suitable for all biological topics that transect different levels of organisation, e.g. evolution, reproduction and behaviour.

So far, the suggested approaches for learning cell biology are mainly focused on understanding cellular processes. Flores *et al.* (2003) show in their study, which investigated 1200 high school students and their representations of the cell, problematic understandings of the structural relationship between the cellular and organismic level. For example, a large number of students thought that the shape of the cell is determined by the shape and size of the organ to which it belongs. In this respect Tregidgo & Ratcliffe (2000) have proposed the use of modelling. They state that engaging students in making 3-D models enables students to visualise cells in three dimensions and to relate them to macroscopic organisations such as tissues and body parts. For modelling cells Tregidgo & Ratcliffe recommend an educational strategy in which discussion about the scope and limitations of the model in interpreting real cells is an important element. The activity of modelling cells followed the introduction of cells from the context of ‘a prior study on classification and the processes of life’. *How* the cell and its processes were introduced, has not been elaborated.

Summarising, the reviewed science education research literature shows relatively few studies that offer empirically based solutions to learning and teaching problems within the domain of cell biology. Despite some efforts to provide meaningful contexts for students to learn cell biology through starting from the macroscopic level, acquiring a coherent understanding of the cell and its processes and relating them to higher levels of biological organisation remains problematic. This is illustrated by the study of Olsher *et al.* (1999) and very recently by the study of Flores *et al.* (2003). The latter shows an extensive list of problems of high school students with representing the cell and its processes.

Most studies discussed above recommend approaching the cell and its processes from the concrete macro-level, whereby the organismic level is mostly mentioned as closest to students’ prior experiences. The life processes fundamental to all organisms could be used as starting points to explore the cell. In this respect, the suggestion of Marbach-Ad & Stavy (2000), to use lower organisms as simpler living systems seems helpful.

3.2.2 Content analysis of school cell biology

Some explorative interviews with Dutch upper-secondary biology teachers and tentative content analysis of schoolbooks showed difficulties similar to those identified in the research papers mentioned. In section 1.2 we elaborated on contemporary biology education in the Netherlands and mentioned that many secondary education biology teachers are of opinion that the amount of face-to-face instruction is insufficient. Additionally, a survey under the same group of teachers revealed that a shortage in face-to-face instruction time impedes sufficient guidance of students (Morélis, 2001). The topics that were mentioned as least suitable for self-study reflect the problems in learning and teaching cell biology as described above. As a matter of fact, the topics mentioned most were those that are related to the cellular or molecular level, i.e. DNA, genetics, transport, immune system and metabolism.

With a shortage of face-to-face instruction, teachers are more reliant on the textbooks that are used. Because most teachers comply with the structure and content of their textbooks (see section 1.3) it is to be expected that the schoolbooks contribute to the problems that exist in cell biology education.

A tentative content analysis of three schoolbooks, performed within the context of our research, showed that the cell takes an important but isolated place and is one of the first topics dealt with in upper-secondary education. This reflects the idea that a profound cellular basis is needed to be able to understand the biological processes in multicellular organisms. However, the introduction of the cell mainly consists of an enumeration of the most important organelles and their function. As a consequence, the focus is on structural characteristics of the cell and less attention is being paid to the dynamic aspects of cellular processes and movement of substances through the cell. In addition, the concepts used in cell biology are mainly drawn from the sub-cellular level, and the cellular level itself is often neglected (Van der Ham, 1999). Moreover the cell is not connected to phenomena at higher levels of organisation and therefore it is quite hard for students to grasp the idea of the cell as functional unit of the organism. Or as a teacher mentioned:

> ‘Students can learn the different organelles very well but they are not aware that all kinds of processes take place in the cell which are necessary for the organism to function. Their knowledge about cellular structures and processes is bound to the context of an ideal cell and they are not aware of the continuous exchange between cells and their environment.’

While the relation between the cellular and organismic levels of biological organisation seems to get little attention, the (sub-) cellular level is worked out in great detail. Recently Morélis (2003) analysed four Dutch schoolbooks on the number of concepts that were used in connection to the theme ‘the cell’. It was found that all four books offer much more than is prescribed by the examination requirements, thus contributing to the cognitive overload of the curriculum.

To gain more insight into how cell biology is dealt with in Dutch biology methods, we performed an analysis of the two textbooks of the method ‘Biologie voor jou’ (translated: Biology for you) for pre-university education (Hund, 2003). This method is used by approximately 70 percent of all biology teachers in general secondary education and by approximately 40 percent of the biology teachers in pre-university education (R. van Soest, publisher Malmberg, personal communication) including the biology teachers who participated in the first case study of our research. Because of its market share it was supposed to give a representative picture of cell biology in Dutch biology schoolbooks.

Table 3.1 presents a confined overview of the results of the schoolbook analysis. As the table shows, the cell biological concepts, i.e. concepts connected to the theme 'the cell' were classified according to three main categories that represent the molecular, cellular and organismic level. A preliminary analysis gave rise to a further division of these main categories into a total of thirteen categories. At the molecular level, a distinction was made between concepts that indicate chemical compounds (e.g. oxygen, O_2, ATP, nucleotide), chemical reactions (e.g. fosforylation, polymerisation) and molecule characteristics (fat-soluble, oxidised). At the cellular level, the categories ranged from substances (e.g. hormones, nutrient), processes (e.g. diffusion, active transport) and cellular structures, e.g. organelles, and their functions to the concepts defining the different cell types and their characteristics (e.g. size, location, division rate). At the organismic level the concepts that were scored could be described as concepts that were used within the context of a theme transecting the cellular up to and

Table 3.1 ***The number of cell biological concepts used after implicit or explicit introduction in the method 'Biology voor jou' (n = 544)***. *The first three columns refer to the concepts used in all chapters; the last two columns refer to the concepts used in the first chapter, which introduces cell biology (see text for further explanation).*

Main categories of cell biology concepts	Number of concepts used	% of concepts explicitly introduced	% of concepts used after explicit introduction	% of concepts explicitly introduced in chapter 1	% of concepts implicitly introduced in chapter 1
Molecular level					
Compounds (symbols)	101	70	15	6	18
Chemical reactions (symbols)	23	83	9	0	9
Characteristics	17	47	6	6	47
Total	141				
Cellular level					
Substances	76	80	13	5	9
Processes	70	70	24	11	10
Structures	82	96	35	37	0
Functions of cellular Structures	23	83	39	74	4
Taxonomic groups	9	44	33	33	11
Cell types	67	76	16	1	3
Characteristics	30	40	17	17	33
Total	357				
Organismic level					
Processes	22	68	14	0	0
Structures	28	86	14	7	0
Characteristics	29	76	24	0	0
Total	79				

including the organismic level like genetics or reproduction. We made a distinction between processes (e.g. fertilisation, independent inheritance), structures (e.g. pacemaker, nerves) and concepts that specify organism characteristics and are related to the cellular level (e.g. phenotype, homozygote, autotrophic).

The schoolbooks were analysed per sentence and every cell biological concept mentioned, was scored. It was also checked if these concepts are just mentioned or if they are being introduced explicitly, i.e. explained in terms of prior conceptual knowledge. Next, it was checked if the concepts being introduced are subsequently used. This gives an indication whether the introduction of the concept is functional to deal with biology topics later in the curriculum. Finally, to gather more information about the coherence of cell biology in the schoolbooks, it was checked whether cross-references are made (both implicit and explicit) between the first and subsequent chapters.

The total number of cell biology concepts used in the two schoolbooks that constitute the method ‘Biology for you’ was 577. This underlines the fact that cell biology is a topic that is heavy on content and requires acquisition of a large number of new concepts.

As cell biology is not a part of students’ everyday life, it is remarkable that a significant percentage of the cell biological concepts that are used in the schoolbook are not introduced in terms of students’ prior knowledge. If we look at three categories of concepts at the molecular level together, approximately one third of the concepts are used without further explanation (from table 3.1 it can be extracted that the average percentage of molecular concepts that are explicitly introduced/ explained is 70%). The last column shows, that this problem is also apparent in the first chapter that introduces cell biology. For instance, the majority of the molecular concepts in the first chapter are used without any introduction.

Another striking feature shown in table 3.1 is that a significant percentage of the cell biological concepts that have been introduced, are not further elaborated. This is most prominent for the concepts at the cellular level. The fact that apparently many concepts are not required to deal with subsequent topics in the curriculum, questions the need of introducing them at all. Apparently, the number of concepts that is introduced exceeds the number that is needed as a profound cellular basis for subsequent biological topics like genetics or metabolism. Rethinking of what cell biological concepts are essential might reduce the cognitive overload of the curriculum as reflected by the schoolbook.

When we focus on the first chapter, the last two columns indicate that the chapter manifests itself as a chapter in which many new concepts at the cellular level are introduced. These concepts mainly refer to the different organelles and their cellular functions. There is less attention to the coherence at the cellular level in terms of the relations between the different organelles. In contrast to the number of molecular concepts that are used, only a small number of concepts at the organismic level are mentioned. This indicates that little attention is being paid to the relation between the cellular and organismic level of organisation. In addition, very few cell types are mentioned that fulfil specific functions in the human body. It underlines the fact that cell biology is a rather isolated topic with little thought for the fact that the cell is a functional unit for all processes in multicellular organisms. This is also supported by the observation that hardly any cross-references are made between the first chapter on cell biology and subsequent chapters.

Summarising, cell biology as it comes forward in the most prominent textbook in Dutch secondary biology education, reflects some of the main problems reported in the international research literature. An important characteristic of school cell biology is its detailed description at the molecular and cellular level. In addition, cell biology is fragmented over the different chapters and little cross-references are made.

To promote coherent understanding of the cell as a basic and functional unit of the organism more emphasis must be on the interrelation of the different concepts at the cellular level and on integration of these concepts at higher levels of organisation. In addition, selecting relevant cell biological concepts could reduce the cognitive overload. All together, it could be concluded that although systems thinking is included in the Dutch examination requirements (see section 1.3), it does not apply to cell biology.

3.3 Systems thinking

3.3.1 Systems Theory in general

In section 1.3 we presented systems thinking as a key competence to enhance the coherence in learning and teaching cell biology in secondary education. In this section we will give an historical outline on the development of systems thinking. Subsequently, three major systems theories and their central ideas are presented and elaborated to provide a basis for a more precise description of a systems thinking competence in section 3.3.2.

Some historical perspectives

In section 1.3 we stated that 'systems thinking' has its roots in the organismic perspective of biologists at the beginning of the 20th century. Organicists such as the physiologist Walter Cannon who introduced the concept of homeostasis in 1926, recognised organisation as an essential factor in facilitating the complex physical and chemical phenomena that life comprises, and argued that those patterns of organisation could be studied scientifically. For Ludwig von Bertalanffy, a theoretical biologist, this was the motivation behind the development of what he called the General System Theory (GST). He was among the first to articulate an organismic approach to the study of life that formed the basis for the development of 'systems thinking' in the 20th century.

In the development of systems thinking three phases can be distinguished (Strijbos, 1988). The first phase is closely connected to the developments within technical sciences such as computer science and Cybernetics in the 1940s. One of the leading figures in this phase was Norbert Wiener who applied theoretical concepts used within the technical sciences to biology as well. This is illustrated by the title of his first book, published in 1948: 'Cybernetics, or Control and Communication in the Animal and the Machine'. The central focus of Cybernetics is on communication patterns in closed networks and the central concept within Cybernetics is information. The idea of feedback introduced an appreciation for non-linear patterns of causality and brought about an emphasis on interrelationships and dynamic system properties instead of the more static conceptions of structural order. Feedback mechanisms could facilitate the development of self-reinforcing patterns of organisation in both living and nonliving systems.

The second phase in the development of systems thinking can be related to the work of Von Bertalanffy that gained acquaintance in the 1950's. Von Bertalanffy's GST and Cybernetics originated independently and there has been dispute which Systems Theory was developed first (Strijbos, 1988). As mentioned in section 1.3 Von Bertalanffy already formulated some of his ideas in the 1930's. The idea of a GST was first presented in 1937 at a philosophy seminar at the University of Chicago (Von Bertalanffy, 1968). However, the first official publication dated from 1949, one year after Wieners first publication about Cybernetics (Von Bertalanffy, 1949).

In the GST the focus is on a systems concept instead of the concept information as in Cybernetics. Von Bertalanffy did not reject Cybernetics but restricted its application to the machinelike structures in organisms. He was critical on the emphasis on equilibrium models and argued that typical phenomena of life cannot be explained on the basis of Cybernetics because equilibrium states were characteristic of closed systems. In contrast, living systems are by nature open systems and are characterised by dynamic steady states that maintain themselves in conditions that are far from equilibrium, e.g. a body temperature that is much higher than the external temperature. Therefore Von Bertalanffy proposed a systems approach that introduced the idea of the open system. This idea is regarded as his most important contribution to the study of complex systems because it meant a solution for the seeming contradiction in his time between the laws of thermodynamics and Darwin's theory of evolution (Hammond, 1997). According to the second law of thermodynamics the disorder of a system tends to increase over time while Darwin implied, on the contrary, that the complexity (organisation) of systems had been steadily increasing over time. Von Bertalanffy argued that living systems were not completely bound by the second law of thermodynamics because they were capable of importing matter and energy from the external environment and of exporting their wastes, i.e. reducing their entropy.

A third phase in the development of systems thinking that can be distinguished, started in the late 1970s. Although Von Bertalanffy already recognised the relevance of non-linear dynamics to the study of biological systems, in this phase it has been rigorously and formally applied in a so-called 'Dynamic Systems' approach (Thelen & Smith, 1994). Dynamic Systems Theory is strongly rooted in non-linear mathematics and thermodynamics and aims at acquiring insight into general modes of behaviour and development of complex systems. Studies on complex dynamic systems concern problems of emergent order and complexity: *how* structures and patterns arise from the cooperation of many individual parts, and in the case of biological systems, of enormous heterogeneity. In the 1980s a new vision on living systems emerged, with the central focus on their self-organising capacity (Maturana & Varela, 1980; Prigogine & Stengers, 1984). Living systems are described as being structurally and energetically open but organisationally closed. The *dissipative* structure of living systems is the result of continuous exchange of energy and materials with the surroundings. Despite this continuous exchange of substances, the system maintains its stable form or structural pattern that is far from equilibrium through a process of self-organisation or autopoiesis, which is a basic property of life. Prigogine and Stengers (1984) demonstrated that as a system (living or nonliving) moves further from equilibrium there is an increasing potential for the spontaneous emergence of more complex forms of organisation. As a result, spontaneity and self-organisation are inherent in open systems.

From a historical perspective, we have argued that three systems theories can be distinguished: General Systems Theory (GST), Cybernetics and Dynamic Systems Theory. Together the three systems theories cover the whole scope of biology but each systems theory also offers a certain perspective to look at biological phenomena. The GST covers mostly the structural organisation of living systems. Cybernetics addresses the regulatory aspects of life, while Dynamic Systems Theory is about the developmental and evolutionary side. So with each of the three systems theories we can look either at the structural, regulatory or historical aspects of living systems. We will now shortly elaborate on each of the three systems theories and their key concepts.

General Systems Theory

The contest between mechanists on one side and vitalists, who assumed a 'vital force' being responsible for life phenomena on the other side, confronted Von Bertalanffy with the problem of the differences between organisms and man-made machines and with the problem of how the essential character of life phenomena can be respected in a scientific model. Moreover, Von Bertalanffy sought the answer concerning the classical question in biology between fixed or static morphological structures and the dynamic processes of life. To this end he launched his conception of the organism as 'open system' on which his GST was based.

When we are interested in the structural organisation of organisms we can refer to the General Systems Theory of Von Bertalanffy (Von Bertalanffy, 1968; Koestler, 1978). Von Bertalanffy was among the first to articulate a systems approach to the study of life and was interested to overcome fragmentation between the various disciplines within biology. According to Von Bertalanffy it was necessary to study not only parts and processes in isolation, but also to solve the decisive problems found in organisation and order unifying them, resulting from dynamic interaction of parts. As a matter of fact, the behaviour of the parts differs dependent on whether they are studied in isolation or within the whole (Von Bertalanffy, 1968).

The most important contribution of his theory is the idea of the open system, which highlights the relationship between organisms and their environment. According to the GST living forms are not in being, they are happening. They are the expression of a perpetual stream of matter and energy, which passes through the organism and at the same time, constitutes it (Von Bertalanffy, 1968). The concept of open system means to think of interaction in every aspect of life and requires a definition of specific structural system boundaries. The system boundary enables the system to exchange materials, energy and information with its external environment and with other systems. Another main feature of the GST is the model of hierarchical order. Within living systems several levels of biological organisation can be distinguished. At each level of biological organisation different systems can be distinguished that mutually interact. Any particular system is a complex entity that maintains its wholeness by the mutual interaction of its parts, which can be a subsystem (part) of another system, depending on the observer's focus of interest. In other words:

> "…They (systems) are Janus-faced. The face turned upward, toward the higher levels, is that of a dependent part; the face turned downward, towards its own constituents, is that of a whole of remarkable self-sufficiency." (Koestler, 1978, p.27).

As life ascends the ladder of complexity, there is progressive integration, in which the parts become more dependent on the whole, and progressive differentiation, in which the parts become more specialised. Then the organism exhibits a wider repertoire of behaviour. Also, it causes progressive centralisation, which causes the emergence of leading parts (the brain), which may dominate the behaviour of the whole system.

To Bertalanffy the GST was a general science of wholeness: the characteristics of complexity appear as 'new' or 'emergent' (Von Bertalanffy, 1968). At each level of organisation emergent properties of the systems behaviour appear that were not present at the lower level of organisation. For example 'life', defined by being able to fulfil the fundamental life processes (see section 3.4.1), emerges at the cellular level or 'intelligence' emerges at the organismic level out of the complex neural networks within the organism. In biology there is a general agreement about the sequence of organisational levels that can be distinguished (Boersma, 1999; Koestler, 1978), i.e. the cell, the organism and the biosphere have unambiguous system boundaries. The biological levels in between those levels, e.g. organelles, tissues, organs or ecosystems cannot always be clearly separated. The choice of which levels of biological organisation are being distinguished therefore depends on the possibilities concerning a specific biological system and the need for distinguishing the levels of organisation.

The for biology relevant contents of the GST can be summarised by the following points:

- Biological objects can be seen as systems with an internal and external environment separated by a systems boundary.
- Living systems are open systems with a continuous exchange of material, energy and information with the external environment.
- Living systems are characterised by their form, function and behaviour.
- Living systems are hierarchical; several levels of organisation can be distinguished.
- At each level of organisation, living systems can be distinguished that are functional subsystems of the system at a higher level of organisation.

Cybernetics

In 1948 Norbert Wiener introduced Cybernetics as the science of control and communication in the animal and the machine. Addressing the organisational patterns that was done implicitly in organicist biology and Gestalt psychology became of explicit focus in Cybernetics (Capra, 1996). The central focus of Cybernetics is on communication patterns in closed networks and Cybernetics emphasises the (self-) regulation of living systems by means of non-linear causality. As Wiener already realised, the concepts 'control' and 'feedback' referred to patterns of organisation instead of 'fixed' structures of living systems.

For biology, homeostasis and feedback are central concepts from the domain of Cybernetics. Homeostasis or self-regulation is the process by which certain critical variables (e.g. body temperature, blood sugar level) are maintained within a very small range of variation. Hereby, living systems are able to maintain their internal conditions in a dynamic equilibrium despite of fluctuations in the external conditions. For a more extensive elaboration of the concept of homeostasis we refer to Buddingh' (1997). This state of dynamical equilibrium is maintained by a feedback cycle or a circular chain of causal events that eventually influence the begin conditions that caused the first event. Two different forms of feedback can be distinguished: positive or self-reinforcing feedback and negative feedback, the latter being responsible for homeostasis. The concept of feedback was derived from a technical approach to living systems and was supposed to facilitate the development of self-regulating patterns in both living and nonliving systems. When the critical value 'set point' of a certain systems variable exceeds a certain range, a negative feedback mechanism recovers the original value of the variable. This type of control circuit is called negative feedback because the change in the variable being monitored triggers a response that counteracts the initial fluctuation. Because of the lag time between sensation and response the variable drifts slightly above and below the set point, but the fluctuations are moderate. Negative feedback mechanisms prevent small changes from becoming too large.

The main characteristics of living systems from a cybernetic perspective could be summarised as follows:

- Living systems can maintain a dynamic equilibrium by self-regulation through feedback mechanisms.
- Living systems can be part of an organised pattern that constitutes a control circuit maintaining a dynamic equilibrium.

Figure 3.1 shows the two systems models representing the basic system characteristics according to the GST and Cybernetics.

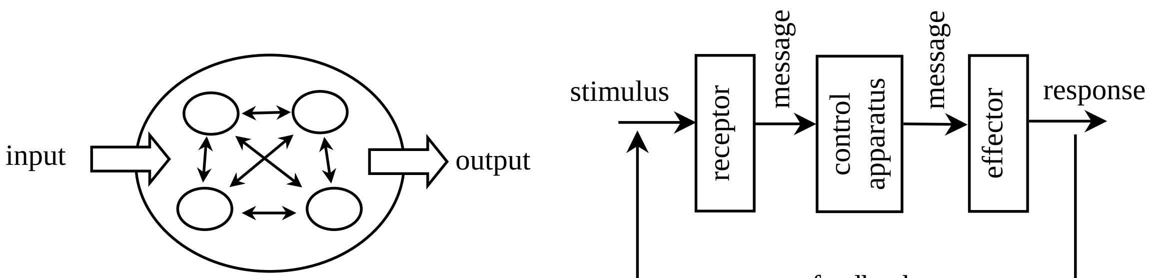


Figure 3.1 ***Two systems representations according to the GST (left) and cybernetics (right).*** *The GST model depicts the openness of the system (thermodynamically and kinetically) and the dynamical interaction of components. The cybernetic model stresses communication between sub-systems in a feedback cycle.*

Dynamic Systems Theory

The orientation towards non-linear processes goes further in the Dynamic Systems Theory or 'chaos theory' (Prigogine & Stengers, 1984). This theory deals with the self-organisation of open systems, which maintain conditions that are far from equilibrium. The GST already acknowledged the emergence of complex behaviour and organisation in living systems. However, within the domain of Dynamic systems thinking non-linear mathematics and thermodynamics were used to describe the process of spontaneous emergence of more complex forms of organisation. In other words, it characterises developing organisms in a dynamic framework and describes the principles of patterns formation in complex systems.

Living systems can be viewed as self-organising or autopoietic systems (Maturana & Varela, 1980). They are organised as a closed causal cycle of processes that only allows ontological or evolutionary changes that maintain the circularity and prohibit the loss of it. Because all changes take place within this basic circularity each constituting component of the cycle is being produced and maintained by this cycle. This pattern, in which each component is functional in helping to produce, maintain and transform other components and maintain the organisational pattern as a whole is considered as the basic organisation of all living systems. Maturana & Varela present the cell as the most simple autopoietic system (see also section 3.4.1).

In the description of dynamic systems as autopoietic systems, the focus is on living systems being organisationally closed. On the other hand, self-organising systems maintain themselves stable yet far from equilibrium by continuously exchanging energy and materials with their external environment. Over time, their order and complexity are not only maintained but may actually increase, as in ontogeny or evolution. As Prigogine & Stengers pointed out, such systems maintain their organisational complexity only by draining the order from their external environment and cycling high-entropy energy back. Such organised structures can be viewed as 'dissipative structures' because they maintain equilibrium by drawing energy from high-energy sources, doing work, and dissipating some of this energy, in turn, back to the environment. In this sense, living systems are considered as local concentrations of order maintained by a continual flux of energy and matter. When sufficient energy goes into these systems, new, ordered structures may spontaneously emerge that were not formerly apparent. The 'developed' structure may behave in highly complex, although ordered ways, shifting from one pattern to another over time resisting disturbance and generating elaborate structures (Thelen & Smith, 1994). The emergent organisation is totally different from the individual parts that constitute the system, and the pattern cannot be predicted solely from the characteristics of these parts. Instead the emergent properties of the system are the result of the interactions of the individual parts, the constraints of the system and the energy flux, the so-called order-parameters. When systems self-organise under the influence of an order parameter, they 'settle into' one or a few modes of behaviour that the system prefers over all the possible modes (Thelen & Smith, 1994). This behavioural mode is called an *attractor* state.

Complex, dynamic systems seek attractor states as a function of the interactions of their internal components and their sensitivity to external conditions. Attractor states can range from very stable to highly unstable. For instance, walking, as a mental construct or movement configuration, is a stable attractor (Thelen & Smith, 1994). All normal human infants learn to walk upright because of anatomical and neural elements that have an evolutionary history and a 'handy' environment such as support surfaces, gravity and helping parents. On the other hand, many sport skills have attractors whose stability is easily upset by contextual disturbances, lack of practice or by not paying attention.

In Dynamic Systems Theory, ontogenetic or evolutionary change is defined as the transition from one attractor state to another attractor state. During such a state-transition, the system loses stability and fluctuates around possible stable states. At critical points the system loses its ability to maintain its organisational pattern and the fluctuations become enhanced. During this phase the systems behaviour is instable or chaotic. At these points the system can evolve into a new and unpredictable attractor state, meaning that existing structures or behavioural patterns can disappear in favour of new ones. This way (minor) fluctuations arising out of the dynamic nature of the assembly from the individual subunits of the system are the source of new patterns in behaviour and development and account for the non-linearity of life (Thelen & Smith, 1994). Because of the chaotic phases in the ontogenetic or phylogenetic development of complex systems, Dynamic Systems Theory is also called ‘chaos theory’.

The main points of Dynamic Systems Theory as described above could be summarised as follows:

- Living systems are self-organising and maintain themselves in a state far from equilibrium by continuous exchange of materials and energy with the external environment.
- During ontogenetic and evolutionary change, living systems transit from one attractor state to another whereby new, complex forms of organisation can emerge spontaneously.

The above description of the three systems theories provides insight into the different perspectives they offer on living systems. As we have stated, with each of the three systems theories we can look either at the structural, regulatory or historical aspects of living systems. This ability of having different perspectives on life could be viewed as an important characteristic of systems thinking. Based on the theoretical exploration of the three systems theories described in this section, a systems thinking competence could be described that enables students to develop a coherent understanding of (cell) biological phenomena.

3.3.2 Systems thinking as a domain specific competence

Throughout the history of biological science, the method by which biological phenomena should be studied, i.e. analysis or synthesis, has been an important topic for debate. An important contribution to this debate has been given by the development of systems thinking, in which analysis and synthesis are considered as two complementary thinking processes (Hofstadter, 1980; Strijbos, 1988).

As opposed to mechanistic thinking, in systems thinking the accent is on synthesis instead of analysis. This means that the whole does not appear through reconstruction from the constituting parts: analysis followed by synthesis, but the process of thought is precisely the reverse. First, the containing whole (system) is identified, including its properties and behaviour. Next, the behaviour and properties of the constituting parts are explained in terms of their function within the containing whole. As a result, the focus of a synthetic approach to biological phenomena is on understanding the function of the system as a whole. On the other hand, analysis focuses on describing structures that constitute the system (Strijbos, 1988). So, analysis and synthesis do not exclude each other but can be considered as two complementing approaches (Hofstadter, 1980).

The yo-yo strategy of Knippels (2002) could be viewed as a strategy that combines an analytic with a synthetic approach, with the main focus on the latter. The yo-yo strategy copes with the complexity of biological phenomena by explicitly distinguishing the levels of biological organisation, and by descending and ascending these levels, starting from the concrete organismic level. The strategy emphasises the key concepts of the biological phenomenon to be studied per level of organisation and their interrelationships. The intended learning outcome to be attained has been defined as the competence of thinking backward and forward between the levels of biological organisation and relating the relevant key concepts on these different levels of each other. In line with her suggestion (see Knippels, 2002, p. 159) our research explores the possibility of introducing 'thinking in levels of biological organisation' or systems thinking as a meta-cognitive tool. So explicating a systems theoretical perspective should help students in acquiring a coherent understanding of cell biology. Systems thinking competence could then be described as being able to study biological phenomena from a systems perspective.

As we have shown in section 3.3.1 each systems theory comprehends different systems concepts and offers a different perspective on living systems. So the question rises which systems theory is most functional for biology education. As Boersma (1997) has stated all three theories should be considered worthwhile as long as biology education deals with the structure, regulation and development of living systems. The choice which systems theory is most functional depends on which of these aspects of biological systems are studied. This ability of having different perspectives on life could be viewed as a central characteristic of systems thinking. A systems thinking competence could then be articulated as being able to choose a certain systems perspective and use the subsequent descriptions of the system characteristics as a guideline to understand biological phenomena. This way systems thinking can be seen as a framework to order relevant questions (Boersma, 1997), for example: Which levels of organisation can we distinguish in the system? How does the system interact with its environment? How do matter, energy and information flow through it? How is the system regulated? How has the system evolved during evolutionary history? How has it developed during its lifetime?

Another important aspect of a systems thinking competence is thinking backward and forward between abstract systems models and concrete biological phenomena. As the previous section shows, systems thinking enables us to speak about biological objects and processes in general terms. The models that are being used (for example figure 3.1) can be applied to all concrete biological systems. When we ask students to engage in systems thinking we actually ask them to think backward and forward between general systems models and concrete biological objects and processes (Schaefer, 1989). At the same time, students will realise that in many cases a systems model should be altered in order to provide more insight into a specific object or process. For example, students should be able to view the cell models that are depicted in the students' biology textbooks as more specific and structural representation of a typical cell. On the other hand, these representations should not be interpreted as being *real* cells.

So far we have presented three central aspects of a systems thinking competence that biology education should aim for: thinking in levels of organisation, thinking backward and forward between concrete biological phenomena and abstract systems models, and being able to choose between certain systems perspectives. The three system theories, their concepts and the questions that could be derived from the different system perspectives as described above are quite abstract and are hardly meaningful from the student's point of view. They don't provide a guiding framework for designing a series of lessons. Also, despite the description of systems thinking as a domain specific skill in the Dutch examination syllabus, it has not been integrated into the biology curriculum. So, we can expect that students have little prior knowledge and experiences concerning systems thinking. Therefore, we have to determine how and what systems concept could be introduced in a biology curriculum that is both meaningful to students and functional within the context of a series of lessons on cell biology.

As the historical development of systems thinking indicates, the focus of systems thinking on biological systems started with the development of the GST. The GST describes the most basic systems concept for biology: the open system. Cybernetics on the other hand was originally developed for technical systems that are closed. For biology, Cybernetics is only useful when it is integrated with the idea of the open system. It becomes useful when dealing with the question how open systems can maintain themselves and how they regulate their internal environment. As described in section 3.3.1, the Dynamic Systems Theory elaborates on the idea of the open system in describing their self-organisation. For biology it becomes useful when dealing with the question how living systems develop both ontogenetically and phylogenetically.

So, introduction of a first systems concept based on the GST offers a starting point from which both cybernetic and dynamic systems approaches could be developed. Therefore, our LT-strategy for the cell as a system focuses on the explication of a systems perspective according to the GST that is functional for students when learning cell biology.

The GST offers a meaningful systems concept that could be introduced at the organismic and concrete level. The systems characteristics of the GST can be seen as abstractions of the fundamental processes of life (Dutch: levensfuncties), i.e. metabolism, growth and development, and responding to environmental stimuli (Von Bertalanffy, 1965). Hereby, we come up to the suggestions made in the literature on cell biology education to approach the cell from the macro-level and using 'general or basic' processes to start exploring the cell (see section 3.2.1).

Within the context of multicellular organisms we could also interrelate the organismic level with the cellular level. When we focus on a certain life function and how it is structurally organised we focus on a functional system in the organism, e.g. the digestive system. In reality this system could not be separated easily from its surroundings because it is cross-linked with many other structures and processes in the human body. However, this separation of functional systems offers us a way of interrelating the different levels of biological organisation, i.e. cells, organs and organisms. At each level of organisation we can distinguish a system that is part of a super-ordinate system and each system has a certain function in the super-ordinate system. In other words, the structural and functional perspective is what binds the different levels.

So, focusing on the functions of life and how they are accomplished by its different interrelated components can be a guideline to descend from the organismic to the cellular level. Going back to the level of the organism can be guided by the idea that every cell is dependent on organisational structures that emerge at the organismic level. For instance, each cell depends on the blood circulation system to obtain its food and oxygen.

In section 1.2 we described a first and rather general systems thinking competence as the ability and willingness to link different levels of biological organisation from the perspective that natural wholes, such as organisms, are complex and composite, consisting of many interacting parts, which may be themselves lesser wholes. In this section we presented three aspects of systems thinking making it more operational as a competence:

- Being able to 'think in levels of biological organisation'
- Being able to choose a certain systems perspective and use the subsequent descriptions of the system characteristics as a guideline to understand biological phenomena.
- Being able to think backward and forward between general systems models and concrete biological objects and processes

Because we focus on the integrating cell biology education with the introduction of a first systems concept derived from the GST, we will specify the systems thinking competence in relation to the key concepts of the GST. As we stated earlier this perspective connects with the structural organisation of living systems and thus to the first aspect of systems thinking: 'thinking in levels of biological organisation'. Obviously, in our study the cellular level is central:

- Being able to distinguish different levels of organisation, i.e. cell, organ and organisms, and matching biological concepts with a specific level of biological organisation
- Being able to identify different systems at each level of organisation, including their input and output
- Being able to relate the (cell) biology concepts at each level of organisation (horizontal coherence)
- Being able to relate the (cell) biology concepts on the different levels of organisation to each other (vertical coherence)
- Being able to think backward and forward between the general systems model and more concrete representations of cells, i.e. ranging from cell models to *real* cells seen under a microscope.

The above list constitutes the elements of a systems thinking competence that is addressed in this study. Hereby the main focus is on the GST. A theoretical foundation for a LT-strategy 'the cell as a system' that is based on systems thinking as described above, we refer to section 3.5. Section 3.4 offers a coherent description of the cell biology content from a systems perspective.

3.4 Towards a synthesis: the cell as a system

3.4.1 Cell biology from a systems perspective

In the explorative phase of our research we could not find a coherent and concise description of the cell as a basic unit of life that could form a basis for developing a LT-strategy that provides secondary students a coherent view on the cell. As we described in section 3.2.2, the cell biology content as it comes forward in the most prominent Dutch biology method ‘Biologie voor jou’, is heavy on details and does not provide an integrated picture of the cell in terms of horizontal and vertical coherence. Furthermore, tertiary schoolbooks (e.g. Campbell *et al.*, 1997; 1999; Alberts *et al.*, 1994) offer very extensive elaborations on cell biology and are not readily accessible for secondary students.

This section attempts to provide a concise and coherent description of the cell as a basic and functional unit of the organism. It is a first step towards integration of cell biology education and systems thinking and in acquiring more insight into what a systems perspective actually means for selecting and presenting the relevant cell biological content. The leitmotiv is the evolutionary development from the first prokaryote cell to the highly specialised cells in multicellular organisms like human beings. The focus is on the autonomy, complexity and functionality of the cell as basic unit of life respectively. This section has been published in two consecutive articles in the Dutch journal for biology teachers ‘Niche’ (Verhoeff *et al.*, 2001*; 2001**).

The cell as an autonomous system

In biology, the cell is the lowest structural level that can maintain itself autonomously, as the existence of unicellular organisms demonstrates. For self-maintenance, repair and growth, cells have to be capable of taking up materials from the external environment and of disposing their waste material. Besides performing these functions in order to preserve the individual cell, cells are able to reproduce. The simplest autonomous cells that exist are prokaryotes: cells lacking a nucleus. To us the intriguing question is: What exactly are the *essential* characteristics of an autonomous functioning cell?

A first evolutionary step towards an autonomous cell has been formulated by Hoffmeyer (1998) who describes living systems as consisting essentially of ‘surfaces inside other surfaces’. According to Hoffmeyer the origination of a living system, i.e. the cell basically comes down to ‘The closure of a membrane around some autocatalytic chemical reaction system’. In addition, the surface and its internal autocatalytic system would have to produce a written record of its own components, and the surface would have to devise means for controlling the translational process whereby components are produced. Hereby, maintenance, repair and cell division become possible. The autocatalytic nature of the processes means that the products of the (production) processes act as catalysts: they stimulate their own production without being used up. So, the reaction system as a whole is able to maintain itself.

An enclosing membrane is important for two reasons. On the one hand it protects the internal environment with optimal conditions for the autocatalytic processes from external disturbing influences. On the other hand, the selective permeability of the membrane enables an accurate selection of the cell's input and output. Hereby, the exchange of substances and information between the cell and its environment is carefully regulated. The exchange of materials is necessary to build and maintain the cell's structural organisation, which is mainly composed of macromolecules such as nucleic acids, proteins and lipids. Since macromolecules cannot pass the membrane, the cell must synthesise these molecules by itself. Synthesising macromolecules and active regulation of membrane transport requires energy, so another essential requirement of the cell is a well-ordered energy supply through energy transformations.

To uphold the cell's (structural) organisation and to regulate all metabolic processes, the cell needs information as well. This information is fixed in the relatively stable structure of the genetic material: DNA. DNA regulates intracellular processes by managing its own expression and protein synthesis, as the course of all intracellular processes is dependent on the presence of specific proteins (enzymes). Reversibly, the circumstances in the cell control gene expression. This interaction gives rise to a cyclic pattern of self-organisation, which is considered as one of the most fundamental properties of life: autopoiesis (Maturana & Varela, 1988). For the cell it means that its structural organisation is both the cause and result of its own activity.

The selective permeability of the cell membrane and the specific structure of DNA enable the cell to react to the circumstances outside the cell. Specific chemical signals are allowed to pass the membrane and subsequently influence protein synthesis by binding either directly or indirectly at specific sites of the genetic material. External stimuli can also alter DNA expression indirectly. In this case mechanical stimulation or interaction between certain chemical bonds and the plasma membrane induces an intracellular signal that is relayed to the nucleus via 'second messengers'. In both direct and indirect way, the cell can produce the required proteins to adapt to external circumstances.

In current biological research, much attention is being paid to the genetic basis of life. This has resulted, among other things, in the deciphering of the human genome. The fascination for DNA being 'the code of life' stimulated a group of researchers to reformulate the question 'What is life?' in genomic terms: 'How many genes are essential for cellular life?' (Hutchinson *et al.*, 1999). Answering this question started by tracking down the smallest independently replicating organism so far identified: *Mycoplasma genitalium.* Mycoplasmas are the only prokaryotes without a cell wall. They grow extracellularly in plants or animals, including humans. *M. genitalium* is a species that lives in our lungs and genitals without harmful consequences. The genome of this species has been completely sequenced and two third of the genes could be linked with cellular functions. By eliminating all genes of the organism one by one, the researchers investigated which genes are indispensable for the *M. genitalium* to stay alive and to reproduce. Eventually, they defined a minimal set of genes for cellular life, consisting of approximately 340 genes.

The results of the study by Hutchinson *et al*. support our description of the autonomous cell as an autopoietic unit. For example, the study underlines the importance of the cell membrane as a high amount of the genes present in the minimal genome were coding for membrane proteins, in particular those that are responsible for a selective input of nutrients. Also, a large proportion of the genome was coding for proteins that are involved in the nuclear regulation of intracellular processes, i.e. transcription, translation and DNA metabolism. Relatively few genes appeared to be coding for proteins involved in biosynthesis and energy supply. This could be explained by the fact that the minimal cell was equipped to survive under laboratory growth conditions with all required nutrients freely accessible. This had consequences for the cell's biosynthetic capacity, because there was no need to produce materials that can be taken up from the external environment. The data showed that glycolysis is the major energy source for M. genitalium.

The cell as a complex system

One third of the genes that constitute the essential genome of *M. genitalium* could not be linked to a specific cellular function. So even in the simplest known cell not all the important molecular processes have been tracked down yet. Apparently, even prokaryotic cells exhibit a high degree of complexity. When we turn from prokaryotic to eukaryotic cells, i.e. cells containing a nucleus, the increase in complexity strikes immediately: in eukaryotic cells all cellular functions are connected to complex structural components: the organelles.

The origin of the cellular complexity can be understood from an evolutionary perspective. In the genesis of the first prokaryotes some 3.5 billion years ago, the enclosure around a self-regulation process of RNA-replication by a membrane was probably a crucial step (Alberts *et al.*, 1994; Morowitz, 1992). In some subsequent steps these primitive cells evolved into the prokaryotes that were very similar to the present prokaryotes. The development of enzymes gave rise to more complex and efficient cells in which RNA was substituted by the more stable structure of DNA containing genetic information. Approximately 1.5 billion years ago the first eukaryotic cells originated. So, since then two fundamentally distinctive life forms exist: cells with and cells without a nucleus. The question how eukaryotic cells could evolve from much simpler prokaryotic cells has been addressed by Margulis, a microbiologist who got intrigued by the fact that not all genetic material of a eukaryotic cell is located in the nucleus (Capra, 1996). She discovered that most genetic material outside the nucleus originated from bacteria. There upon she developed a model of endosymbiosis. According to this model the eukaryotic cell evolved as an association of prokaryotes that established symbiotic relationships. Nowadays, it is accepted that mitochondria and chloroplasts are the descendants of early prokaryotes that infected or were engulfed by a larger host cell.

The origin of the organelles that constitute the endomembrane system, i.e. the nucleus, endoplasmic reticulum and the Golgi apparatus is explained by a more speculative model of invagination and specialisation of the plasma membrane (Campbell *et al.*, 1999). The supposed ancestors of chloroplasts and mitochondria are photosynthetic prokaryotes and aerobic heterotrophic prokaryotes respectively. Their symbiosis became mutually beneficial. So, instead of competition as a driving force of evolution, the endosymbiotic model introduces cooperation as a process of self-organisation resulting in more complex forms of life. The autonomy of the prokaryotic ancestor was given up in favour of the protective environment within the larger cell.

At the subcellular level, we cannot speak about autonomous functioning systems anymore. Each organelle fulfils a specific function for the cell and as such it is dependent on its cooperation with other organelles. For example, the processes in each organelle require energy that is harvested by the mitochondria, and to enable the processes in the mitochondria, enzymes are needed that are produced by the endoplasmic reticulum and Golgi apparatus. Similar to the cell, all organelles are enclosed by a selectively permeable membrane that controls their input and output. Due to this, each organelle is able to maintain an optimal internal environment for its processes that constitute the organelle's function. In addition, the possibility of efficient communication between the organelles arises. Analogous to the term 'organ system' we could use the term 'organelle system'. To maintain such a system, regulation by the nucleus is essential.

The complex system of cellular processes requires an optimal and rather constant condition of the cytoplasm. Cells can only tolerate deviations in the internal conditions within certain ranges, and control systems in the plasma membrane cushion the impact of fluctuations in the external environment. These *homeostatic* mechanisms concerning osmotic pressure, oxygen pressure, carbon dioxide pressure, pH, etc. usually involve negative feedback. An example of a homeostatic mechanism is the osmoregulation in *Paramecium*, a genus of freshwater protists. Unicellular organisms like *Paramecium* can only survive in water, from which nutrients can be taken up through the membrane. However, pond water is hypo-osmotic and consequently water will enter the cell by osmosis. To prevent the cell, which lacks a cell wall, from bursting, *Paramecium* contains a contractile vacuole that counteracts osmosis by bailing water out of the cell. The vacuole has an osmoregulatory capacity, which means that its contractile activity depends directly on the difference in concentration between the internal and external environment of the cell.

Eukaryotic cells are complex and highly organised systems of cooperating parts. Similar to prokaryotes, a system emerges at the cellular level that can fulfil all life functions autonomously. The difference is that eukaryotic cells display a substantial higher degree of complexity than prokaryotes. This higher degree of complexity is also reflected by the eukaryotic genome. While prokaryotic DNA floats freely in the cytoplasm, eukaryotic DNA is wrapped in the complex structure of a chromosome in the nucleus. Moreover, while the genome of *Mycoplasma genitalium* is composed of 580,000 nucleotide pairs, to arrive at the number of *Paramecium caudatum* this number must be multiplied by 15,000. It must be noted that the number of nucleotide pairs in itself does not account for the complexity of the genome.

The complex eukaryotic genome offers many possibilities to control the gene expression. Similar to prokaryotes, gene transcription is controlled by binding sites at the DNA nearby these genes. In prokaryotes transcription of a specific gene is usually 'turned on' by a single signal. In eukaryotic cells on the other hand, the binding sites are part of complex regulatory DNA-regions which integrate multiple signals that together determine whether or not the concerning gene will be transcribed. Because of this, gene expression can respond to much more complex situations within the cell.

The cell as a functional system

Unicellular organisms are being able to adapt to a large diversity of ecological niches, which explains the fact that they constitute more than half of the total biomass on earth. Most unicellular organisms show a highly efficient self-organisation, which only requires the uptake of few materials and some of them can reproduce in less than a minute. Nevertheless, multicellular organisms have been evolved and preserved since. But what adaptive benefits could be gained from multicellularity? The latter enabled organisms to explore and inhabit new terrestrial niches providing new food sources. The evolution of multicellularity involved increasing cellular specialisation and division of labour between cells. A primitive example of intercellular cooperation is *Dictiostelium*, a plasmodial slime mold that has both unicellular and multicellular life stages. Most of the time this organism exists as solitary amoeboid cells, creeping about by pseudopodial movement and engulfing bacteria as they go. In case of shortage of bacteria, the amoeboid cells swarm together in response to a chemical attractant they secrete and form a slug like colony. Subsequently, the multicellular colony migrates as a unit to a new food source in a way that cannot be achieved by solitary amoeboid cells and finally the colony develops into a multicellular reproductive structure.

Dictiostelium is easily cultured in the laboratory, and its relatively simple structure makes it an attractive research organism. Because the amoeboid cells in the slug like colony develop into specialised cells when they form the reproductive structure, *Dictiostelium* is a useful model for researchers studying the genetic mechanisms and chemical changes underlying cellular differentiation.

Multicellularity has given rise to organisms that consist of a large number of highly specialised cells. The human body, for example comprises 284 different cell types. The structural organisation of each cell is completely adapted to the function that it fulfils for the organism that it is part of. A muscle cell contains relatively many mitochondria to provide the required energy, a red blood cell lacks a nucleus and is pounded with haemoglobin to efficiently bind oxygen, and the epithelial cells of the intestine have a highly folded membrane at the interior side of the intestine to adequately absorb nutrients or secrete digestive enzymes. As a result of this functional differentiation, these cells are highly interdependent and cannot survive outside the organism by themselves. From an evolutionary perspective we can make the analogy with the origination of organelles by endosymbiosis. In both cases the autonomy of the constituting parts has been given up in favour of the benefits offered by an efficient cooperation.

In contrast to organelles, cells that are part of animals or plants still have some autonomy in carrying out the fundamental life processes. Similar to unicellular organisms, animal and plant cells actively take up nutrients from their environment and they dispose their waste material. The nutrients are used for maintenance, repair and growth. Each of these cells perform some general metabolic functions, such as respiration, replication and biosynthesis, and have a similar need for all kinds of substances, including oxygen, to harvest energy. In addition, each cell carries out specific functions and has specific needs that should be present in the cell’s vicinity, e.g. muscle cells need calcium, red blood cells need iron and thyroid cells need iodine.

For most cells to survive it is sufficient when the required substances are freely available in their external environment. This quality offers researchers the possibility to culture cells in a ‘growth medium’ and to preserve a certain cell line for a few generations. At present, researchers are able to grow and culture heart muscle cells that contract simultaneously, starting with some undifferentiated embryonic stem cells and a bottle of specific growth hormones. The cultured cells constitute a small communicative network that enables them to contract and relax all at the same time. However, such a system is far from being a functioning heart. For example, pacemaker cells are needed to accurately coordinate the contraction of the heart as a whole and enable it to alter its beat in reaction to different physical conditions of the body. In addition, the laboratory heart cells lack the complex structural organisation of the in situ heart and as a result each cell contracts in different directions.

Cell specialisation is strongly dependent on signals from the tissue surrounding the cell. When embryonic stem cells are cultured together with tissue that is taken from the area around the heart, the stem cells specialise into mature heart cells. Full-grown animals still contain stem cells at various regions in the body, but it is largely unknown where exactly these cells are located and if they are located in each organ. Presumably, they are located at isolated places throughout the body, waiting for some signal that causes them to migrate to the intended tissue, specialise into the required cell type and integrate into the tissues’ structural organisation. For instance, stem cells located within the adult human brain specialise into functional blood cells when they are brought into bone marrow. In the United States, cultured stem cells have been injected into the brains of patients recovering from a stroke. Within some patients the injected cells could indeed take over the functions of the lost brain cells.

From cell to organism

The functioning cell can at least be studied at the cellular level and the organismic level comparable to studying the organisation of a company. Each individual employee is the basic unity of the company. All activities in the company are carried out by individual employees, but the behaviour of the single employee derives its meaning from participation in the social organisation to which he belongs. The functioning of employees can therefore be observed and analysed at two levels of organisation at least: the individual and the social systems or community level.

However, the functional units of the single employee are his cells. All emergent phenomena at the organismic level, like muscle contraction, observation or digestion are the result of cellular activity. Vice versa, at the organismic level the optimum conditions are shaped that enable cells to perform efficiently. In this respect, the size of the multicellular organism provides some problems when it comes to transporting nutrients to each cell and carrying off its waste material. The huge number of cells in the human body makes it impossible for each cell to take up oxygen directly from the external environment by means of simple diffusion. Instead, a physical transport system is required to transport the oxygen to all tissues: the circulatory system. To answer the large oxygen demand of all cells, complex animals contain internal surfaces specialised for gas exchange. Across this surface a highly efficient exchange of oxygen and carbon dioxide is possible between the organism and its external environment. Besides this respiratory system, animals have a similar system for the uptake and transport of nutrients: the digestive system.

Similar to single cells multicellular organisms can be considered as autopoietic systems: they generate and specify their own structural organisation by producing their constituting units, the cells. The organisation of animals and plants emerges from the grouping of specialised cells into tissues, tissues into organs and organs into organ systems. Maintaining the, seemingly static, structural organisation at the organism level goes together with enormous dynamics at lower levels of organisation. Cells are being continuously replaced. Each day, approximately one kilogram of cells is replaced and at every moment 25 million cell divisions take place in our body to accomplish this aim. Most cell divisions within the human body take place in the red bone marrow, the epithelia of the intestines and in the skin. These cells have a relatively short life span of several days. So, although after a year's period we might still recognise a person immediately by his facial structure, all cells in his face have been replaced since. On the other hand, muscle and nerve cells normally last as long as their owner.

Division of eukaryotic cells involves a process called mitosis during which the nucleus and its genetic contents is duplicated and evenly distributed into two daughter nuclei. Subsequently, the cytoplasm divides in two. Mitosis is a remarkably accurate mechanism. Experiments with yeast indicate that an error in chromosome distribution occurs only once in about 100,000 cell divisions (Campbell *et al.*, 1997). Although the course of mitosis is carefully regulated at the molecular level by the cell's DNA, the 'decision' to stay in the mitotic phase or to specialise into a certain cell type is dependent on signals from outside the cell. As mentioned earlier, the surrounding tissue plays an important role. Consider the regeneration of a wound: damaged cells inform stem cells, which are located in the dermis and start to divide and specialise at a faster rate. The endocrine system also plays an important role in regulating cell division. Oestrogen for example, stimulates cell multiplication in the female skin, uterus and breasts.

The above description is the result of an exploration of the cell biological content that was mainly based on some prominent textbooks used in tertiary education. It can be viewed as a conceptual background for developing a LT-strategy for the cell as a system and is a first step in integrating cell biology with systems thinking.

The subsequent section provides a further theoretical underpinning of integrating cell biology with systems thinking in a LT-strategy for secondary education.

3.4.2 Theoretical foundation for the learning and teaching strategy 'the cell as a system'

As we have seen in section 3.3, three systems theories can be distinguished that offer different perspectives on living systems. From these three systems perspectives, the General Systems Theory (GST) has been selected to introduce a first meaningful systems concept into secondary education.

Understanding a systems concept, derived from the GST (see section 3.3) requires, among other things, understanding of the concept 'level of organisation'. The latter requires some knowledge about the different levels including structures and processes at these specific levels of biological organisation. So, acquiring a meaningful systems concept should start with (implicitly) exploring some levels of organisation.

In this study, the central problem is to integrate the development of the essential cell biological knowledge along with the basic concepts of the GST. In designing a LT-strategy that addresses this problem, we started with some assumptions that will be described in this section. Firstly, as literature review on cell biology education (section 3.2.1) made clear, a LT-strategy should start on the organismic level and subsequently descend to lower levels of organisation because students' prior knowledge mainly relates to the level of the organism. Moreover, research shows that when students are asked to order biological objects they mainly focus on the object as a whole instead of its constituting parts. This so-called 'whole object assumption' (Markman, 1990) indicates that students, when categorising, are inclined to focus on the object with the most notable system boundaries: the organism.

The assumption to approach the cellular and molecular level by descending from the level of the organism is supported by Knippels (2002) who designed a problem posing LT-strategy for genetics. Her so-called yo-yo strategy shows that students can develop coherent and meaningful insight into when (a) concepts of reproduction and genetics are classified by the levels of biological organisation, (b) students descend gradually from the organismic to the cellular and molecular level and (c) the concepts of these levels are related to concepts at the level of the organism (ascending). Knippels emphasises that in descending the levels of biological organisation none of the levels should be skipped. The same applies to the subsequent steps in the conceptual structure that is built from the selected key concepts for genetics. Since the levels of organisation play an important role in most biological topics, it is argued that the yo-yo LT strategy is suitable for all biological topics that transect the different levels of organisation, e.g. evolution, reproduction and behaviour. This leaves the problem of developing a domain-specific LT-strategy, besides designing a problem posing structure, with identifying the key-concepts of the topic and arranging them according the different levels of biological organisation.

The second assumption founding the development of our LT-strategy, is that insight into the nature of (scientific) knowledge enables us to indicate more accurately which learning problems students will have when acquiring that knowledge. In our study the focus is on developing a LT-strategy that focuses on one particular level of organisation: the cellular level. The central problem then is to integrate the development of the essential cell biological knowledge along with the basic concepts of the GST. In this respect, our assumption is that the nature of the cell biology or systems theory knowledge determines its 'learnability' and has implications for developing a LT-strategy for the cell as a system.

An important distinction can be made between theoretical knowledge and empirical knowledge. Theoretical knowledge consists of statements about empirical data or observations that try to explain certain phenomena or patterns. However, theoretical knowledge cannot be derived from empirical knowledge (Walgenbach, 1996). Instead theoretical knowledge concerns a new way of looking at familiar cause-effect relationships and as a consequence needs input of new ideas. Often, at first sight these new ideas seem to have no relation with the empirical data to be explained. Examples of theoretical concepts are 'set point' and 'positive feedback', which originate from the field of Cybernetics and are used to explain (amongst other things) the steady body temperature in mammals. On the other hand, empirical knowledge is developed by generalisation and induction based on observations and categorisations using already available knowledge (Van Aalsvoort 2000; Goldstone & Barsalou, 1998; Hempel, 1973).

What implications can be derived from this distinction between theoretical and empirical knowledge for developing a LT-strategy? When theoretical knowledge cannot be developed by generalisation and induction, the teacher should introduce it in the LT-process. Therefore it should be determined beforehand what concepts addressed in the LT-strategy are theoretical and what concepts are empirical.

Boersma (1999) has argued that the ‘cell theory’, formulated by Schleiden & Schwann, should not be considered as being theoretical because its statement that ‘all organisms are composed of cells’ originates from generalisation on the basis of microscopic observations. Understanding of structures and processes at the molecular level on the other hand is theoretical because it assumes understanding of a new theoretical concept of ‘molecule’, which cannot be developed by mere generalisation. Therefore it is preferable to make the step towards the molecular level only after the concept of molecule has been introduced in physics or chemistry classes (Vollebregt, 1998).

As mentioned above, Cybernetics involves theoretical concepts as ‘set point’ and ‘feedback’, which have been developed for technical systems. These terms cannot be developed by generalisation and induction based on biological phenomena and therefore Cybernetics must be considered as being theoretical. Although the denomination of ‘General Systems Theory’ suggests that it involves theoretical knowledge, a closer consideration shows that a systems concept according to the GST can be interpreted as the highest possible generalisation of concrete biological objects (Boersma, 1999). Hereby, we have the view that abstraction and generalisation are closely related processes so that *abstract* knowledge is not the same as *theoretical* knowledge. For example, the concept of organism has a high degree of abstraction, but is far from being theoretical. The same accounts for the concept ecosystem according to the GST, which can be developed on the basis of a worked out food chain in a biotope with clear system boundaries. Because the development of empirical concepts is based on observations, the presence of perceptible and well-defined system boundaries is essential.

Within a LT-strategy for cell biology we should pay attention to the introduction of the systems on different levels of organisation from organelle up to organism. For example, the concept system could be developed at the level of the organelle based on the observations of different organelles, which are visible in unicellular *Paramecium* through a light microscope.

So it can be concluded that the system characteristics as described in the GST, e.g. the distinction between different levels of biological organisation, the openness and interrelations with the external environment are not to be perceived as theoretical concepts. Therefore the insight that different levels of organisation can be distinguished in organisms can be developed by generalisation and abstraction of observations of the internal structure of organisms, as long as we confine this to the level of the organism, organ and cell with its organelles. When descending to the molecular level, it should be clear to students that the representations of molecules must be interpreted as theoretical models and not as further magnifications of organelles.

Thus far, we have stated that a LT-strategy for cell biology from a GST perspective should start at the organismic level and develop a systems concept by a process of generalisation and abstraction of concrete biological structures or processes. Within the context of our study, the assumption that a LT-strategy should start at a concrete and organismic level is investigated by Van Maanen (2001). She tested four different learning sequences, consisting of four subsequent questions regarding four different representations, in interviews with students from lower secondary biology education. The four learning sequences started respectively at a) the concrete and organismic level, b) concrete and cellular level, c) abstract and organismic level and d) abstract and cellular level. The investigation demonstrated that the first two learning sequences were most adequate in accomplishing the intended outcome: understanding that a cell can be seen both as an autonomous and functional unit. The fact that no difference could be demonstrated between the first learning sequence that started at the organismic level and the second that started at the cellular level is comprehensible because the latter started with a representation of a unicellular organism. After all, a unicellular organism can be seen both as a cell and as an organism.

The assumptions that have been argued above provide some initial general indications for developing a LT-strategy for the cell as a system but at the same time leave many questions unanswered. The problem posing approach implies that learning activities should be inherently motivating. This can be established through eliciting meaningful content-related questions and answers in a well thought out sequence. Starting from this perspective, the central question is when and how cell biology and systems theory could become meaningful and worthwhile for students to engage in. Developing a motive for learning cell biology doesn't seem to be problematic. By presenting a problem at the level of the organism and by asking for an explanation, students will try to find answers by descending to lower levels of organisation. However, developing motives for systems thinking will likely take some effort. Why making use of abstract concepts like system and level of organisation when more familiar concepts like organism and cell are satisfactory? The GST distinguishes some general characteristics that apply to all living systems at different levels of organisation. So what? The added value is not self-explaining. The systems concept can be functional only when it is recognized that structures and processes on different levels of organisation can be abstracted similarly. So the question rises when it could be relevant for students to find out some general characteristics of organisms, organs and cells.

A second problem that needs to be addressed is in what order cell biology and systems theory should appear in the LT-strategy. Should we start with cell biology and subsequently introduce the idea of a system in which different levels of organisation can be distinguished? Or should it be the other way around? When cell biology is dealt with firstly and serves as a basis to develop systems theory, the problem rises for students that they have to change their view on cell biology. It seems questionable if they will still be motivated sufficiently to do so. Moreover, it seems questionable if they will be able to develop a coherent understanding of cell biology.

When systems theory is introduced first, students should be able to use it in order to develop a coherent understanding of cell biology. The problem of this sequence however is that it does not come up to students expectations, because they expect the lessons to deal with cell biology. In fact, the choice to be made is between two approaches:

1) Systems theory is introduced and used as a framework to develop a coherent understanding of cell biology
2) Systems theory is developed as a second outcome of a series of lessons about cell biology and applied within another biological topic.

To be able to choose between the two approaches mentioned above and to articulate a more precise picture of a supposedly adequate LT-strategy for the cell as a system we conducted two pilot studies:

1) Developing and field testing a LT-strategy for endocrine regulation
2) Developing and testing a computer-learning tool that addresses the different levels of biological organisation.

In section 3.4.3 and 3.4.4 respectively we elaborate on the first and second pilot study. Section 3.5 presents some conclusions of the explorative phase of our research, including the exploration on cell biology and systems thinking and the two pilot studies with their implications for developing a preliminary LT-strategy for the cell as a system.

3.4.3 Explorative case study: endocrine regulation

In section 3.2.1 we described the lack of vertical coherence in students' understanding of biological phenomena. Within various topics that transect different levels of biological organisation conceptual problems have been related to a lack of interrelating structures and processes at the cellular level and higher levels of biological organisation. Moreover, in Dutch biology schoolbooks the cell biological content is rather isolated from other topics and cross-references with subsequent chapters are hardly made.

To get a better view on the learning problems related to a lack of vertical coherence and to design and test a initial systems approach to biology education that addresses these problems, we developed a LT-strategy for endocrine regulation that consisted of two lessons in the fourth form of pre-university education. Cell biology had already been dealt with at the beginning of the school year. The topic was chosen because for a good understanding of endocrine regulation, interrelating the (sub) cellular level and higher levels of organisation is essential. For instance, to understand the functioning of hormones in 'target cells', students should activate their prior knowledge about cells and relate it to the endocrine physiology at the level of the organ and the organism. In most schoolbooks, endocrine regulation is placed within the topic of homeostasis and is elaborated into great detail. Students are expected to know a large number of hormones including the functions they have in the human body. In addition, the functioning of hormones at the molecular level is extensively dealt with, without paying attention to the cell as a functioning whole.

Following the above, the research question for the explorative case study was formulated as follows:

In what way could systems thinking be introduced to provide a solution to the lack of coherence in learning and teaching endocrine regulation?

Data collection and analysis was aimed at providing indications for developing an initial LT-strategy for cell biology from a systems perspective.

The strategy: 'Temperature regulation: from body to cell'.

A first concrete consequence of applying a systems perspective to biology education is the classification of the content matter according to the levels of biological organisation (Boersma, 2000). In line with the findings of Knippels (2002), the LT-strategy started at the organismic level and subsequently descended to the cellular (and molecular) level of organisation. Table 3.2 provides an overview of the LT-strategy that was tested in classroom practice.

Table 3.2 ***Overview of the LT-strategy 'Temperature regulation: from body to cell'.***

Sequence of problems	Learning and teaching activities (LTA's)
<u>Lesson 1</u> How does your body accomplish a constant temperature of 37°C?	**LTA 1: Plenary introduction of the central question and orientating on the way it could be answered.** – Discussing the fact that phenomena at different levels of biological organisation, i.e. organism, organ and cell, are involved – Explicating the arrangement of the content matter in the lessons to come according to the levels of biological organisation
How does the body react to: – change of temperature in the external environment? – physical exercise? Which organs are involved and what functions do they fulfil? How are the organs interrelated?	**LTA 2: Orientation at the organismic level in groups of three students.** Discussing perceptible phenomena related to body temperature regulation and subsequently working on a written assignment concerning the physiological phenomena related to the temperature regulation, mainly focusing on the control circuit.
<u>Lesson 2</u> To what extent has the central question been answered?	**LTA 3: Plenary reflection on answering the central question.** – Explication of the process of descending the levels of biological organisation – Introduction of the cellular level and the process of energy transformation generating heat
Which organelles are involved in energy transformation and what function do they fulfil?	**LTA 4: Individual assignment to activate relevant knowledge regarding cell biology** that requires making a cross-reference to the chapter about cell biology.
What are the consequences of a malfunctioning thyroid gland? – For the athlete? (behavioural phenomena) – For the endocrine control circuit? (internal/ physical phenomena) – How can the disorder be treated? (cellular phenomena)	**LTA 5: Group assignment integrating the organismic and cellular level of organisation**, focussing on an Olympic athlete who suffered a metabolic disease. – Reading a text and discussing perceptible and physical phenomena – Descending to the cellular level and discussing the working of a medicine to overcome the disorder.

Developing a systems concept and understanding its relevance should precede developing systems thinking competence. It is easier to grasp an abstract concept when it is being related to perceptible structures instead of being related to processes, which can only be perceived indirectly. Consequently, an initial systems concept should be developed by explicating the hierarchy of levels of organisation as a structural characteristic of living systems.

In the LT-strategy an initial systems model is introduced at the beginning of the first lesson on a transparency. It illustrated to students the classification of the content matter according to the levels of biological organisation (see figure 3.2). This way, students could see beforehand in what steps of increasing detail the main problem will be solved: starting with perceptible phenomena at the organismic level and ending with the cellular processes. Subsequently, in the first lesson the central question is answered on the organismic level in terms of interrelating the different organs and their relations. Afterwards, the subsequent shifts between the different levels of organisation will be reflected on in LTA 3. Also, an initial outlook at the remaining part of the LT-strategy was provided, in which the cellular level would be addressed. So, reflection on the classification of the content matter provided a means to explicate the levels of organisation. Note from table 3.2, that the first lesson mainly dealt with phenomena at the organismic level while in the second lesson students descended to the cellular level.

Integrating a systems approach with the problem posing approach[1] requires developing a motive for students to descend from the organismic level to lower levels of organisation. It was aimed to provide this motive by posing the central problem how the

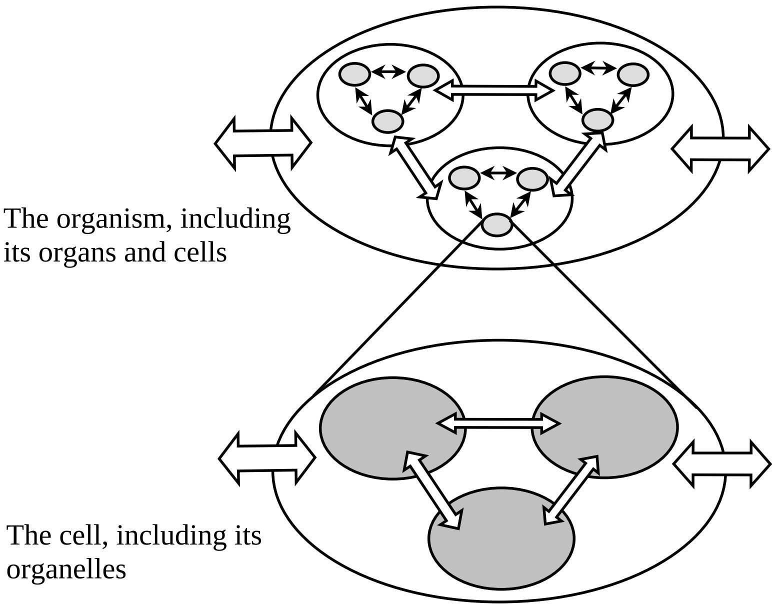


Figure 3.2 ***Systems model of a multicellular organism***

[1] This explorative case study also contributed to an improved insight of the researcher into the problem posing approach. Therefore, the LT-strategy described here cannot be considered to be an adequate problem posing approach as elaborated in section 1.4.

human body accomplishes a constant temperature of approximately 37°C. Next, answering a sequence of problems was supposed to guide students from the organismic level to the cellular level via the level of the organ.

Results

The intended LT-activities as outlined in table 3.2, including elicited learning and teaching processes and their outcomes, were elaborated in a scenario (for a more detailed description of a scenario, see section 2.3.). The scenario was used to prepare the teachers and to analyse the actual learning and teaching processes in the classroom. The strategy for endocrine regulation was tested in two classes at the ‘Oosterlicht College’ in Nieuwegein and the ‘Heerenlanden College’ in Leerdam respectively. The first class consisted of 21 students and the latter consisted of 23 students. During the lessons, qualitative data were collected through classroom observations, audio taped classroom and group discussions, completed worksheets and interviews with the teacher and students. In this section the main results of the analysis of the learning and teaching processes are described. The central focus in the explorative phase of our study was to gather more insight into the way a LT-strategy for the cell as a system could be built. Consequently, the empirical data that are brought up here aim to support the reconstruction of this explorative process.

In LTA 2 students were asked to mention physical phenomena that occur during physical activity, e.g. sports, and are related to keeping a steady body temperature. As expected, students mentioned many phenomena from their everyday experience, i.e. sweating, the skin turning red, an increased breathing and heartbeat frequency. Subsequently, in the same discussion students spontaneously posed the question for a physiological explanation of the perceptible phenomena: …’but what actually happens *in* your body?’… Several students soon related the increase in body temperature to combustion that takes place in the muscles. This description at the organ level provided a sufficient explanation for heat production and none of the students was urged to search for a more detailed explanation at the cellular level. As a result students did not acquire a total and coherent picture of the body temperature regulation. In a group discussion involving four students, the increased heartbeat frequency was not related to cellular combustion. Instead it was supposed to cool off the body: …’if your heart beats faster your oxygen is carried off so that it gets less warm’… Apparently, students were lacking a motive in LTA 4 to go deeper into temperature regulation at the cellular level and address the process of combustion. In this respect it was striking that at the beginning of LTA 3, when students were descending to the cellular level, one student cried out that cell biology did not belong within this topic because it had already been dealt with in the first chapter. Therefore she assumed that she did not have to learn it for the coming examination.

The systems model that was presented at the start of the LT-strategy apparently did not motivate students to descend to the cellular level. During the plenary introduction, the students were observed and showed little interest in, or did not feel a need for, the abstract representation of the body; they were rather passive. In an interview afterwards, students said that the model was complicated and they could not see a direct benefit of it. In this respect, one student criticised the general character of the model: ‘When you’re speaking about organs or cells you know better what you’re exactly talking about'. In addition, the teacher soon turned the attention to a more concrete description of the subsequent steps with respect to the content. Consequently, the systems model disappeared to the background and was neither appealed to afterwards nor did it help students to descend to the cellular level.

Making an explicit cross-reference to the cellular level in LTA 4 provided a useful starting point to come to a more detailed explanation of the body temperature regulation. Introducing the process of cellular combustion, provided students with a motive to descend to the cellular level and in the following plenary discussion students brought up the need for a supply of glucose and oxygen. An increasing respiratory activity during practising a sport asks for an increase in the glucose and oxygen supply. Next, the teacher questioned in a plenary discussion how an increasing supply could be accomplished. Answering this question, stimulated students back to the function of an increased breathing and heart beat frequency at the organismic level.

Although we could claim that understanding of cellular processes contributes to a more coherent understanding of body processes, LTA 4 showed that to students cell biology remains a rather isolated topic. LTA 4 activated students' prior knowledge concerning cell biology by focusing on the role of cellular combustion in regulating the body temperature and the way hormones influence the combustion rate in a 'target cell'. During this activity, the group discussions were soon focused on the meaning of the different cellular structures and processes, e.g. DNA, ribosome or translation, without relating them to higher levels of organisation. Apart from the fact that 'combustion in mitochondria provides ATP for cellular processes' it was not raised that the process of combustion also contributes to the production of heat and thereby influences the body temperature. On the other hand, posing a sequence of content related questions during LTA 5 guided students from the organismic level to the cellular level and resulted in more students being able to see the relevance of relating the different the levels of organisation. Two students who were interviewed afterwards could reconstruct the different steps they had made during LTA 5 by explicating the different levels of organisation and they could indicate how each step was functional in acquiring a deeper understanding of the perceptible phenomena at the organismic level.

Summing up, descending from the organismic level to lower levels of organisation seems to be consistent with students' intuition. However, if we want students to develop a more coherent understanding of biological phenomena that transect different levels of organisation, we should pay explicit attention to the involvement of the cellular level. Moreover, descending from the organismic level to the cellular level should be guided by a sequence of content related questions. In developing such a sequence, more effort should be paid to a thorough analysis of students' common sense knowledge in order to design a 'bottom-up' sequence of activities that alternately raises and answers questions in order to provide students with motives for learning, i.e. a problem posing approach.

As our pilot study indicates, students hardly relate their prior knowledge concerning cell biology spontaneously to other topics that are dealt with later in the curriculum. This seems to be the result of the specific concepts that are introduced in the cell biology chapter, which are only meaningful to students within the specific context of the topic cell biology. The explication of systems thinking could help students to relate cell biology to phenomena at higher levels of organisation. However, the experience with the systems model in the pilot study indicate that introducing a systems model should take more time and requires an active participation of students. Besides thinking backward and forward between the different levels of organisation, systems thinking implies thinking backward and forward between concrete biological objects and abstract representations of the objects. Combining these two competences seems to be an important issue in developing a LT-strategy for the cell as a system.

3.4.4 Development of a computer-aided learning programme

The onset of integrating the processes of thinking backward and forward both between different levels of biological organisation and between representations of biological objects, which differ in abstraction, have been addressed in a computer-aided programme (Schuring, 2000).

The aim of the interactive learning material was to involve students actively in the development of a hierarchical systems model. To accomplish this aim, students went through a series of steps during which they gradually got acquainted with the systems model and at the same time descended to the cellular level. An important focus in designing the programme was that students should be able to indicate what they are doing on a content related basis, viz. exploring the process of digestion at different levels of organisation. When students are able to do so, it is expected that they will be better able to get a more coherent understanding of the organisation of the body, i.e. they will be able to interrelate the different concepts at the level of the organism and integrate the required cell biology concepts.

The organisation of the human body was explored within the context of nutrition. Similar to endocrine regulation, the topic of digestion covers all levels of biological organisation from the organism up to and including the cellular level. The programme deals with the digestion process that starts with the food taken up by the organism and digested by the digestive system. Subsequently the digested nutrients are transported to all cells via the circulation system. There they are used to obtain energy for the cells' metabolic activity and to obtain materials to maintain the cells structural organisation.

Literature research indicates that digestion is a problematic subject for students in terms of developing a coherent understanding (Núñez & Banet, 1997; Ramadas & Nair, 1996) even after finishing their secondary education. To solve this problem Núñez & Banet argue that biology education should emphasise 1) the functional relationships between the different processes such as respiration, digestion and blood circulation, 2) the cellular structure of the human body and 3) the exchange of substances between cells and blood and their use in obtaining energy and materials.

Guided by the computer-aided programme we expect students to extend their knowledge to the cellular level. If successful, the learning material could be integrated into the LT-strategy for the cell as a system. The research question for the explorative case study was formulated as follows:

> *In what way could a systems model, which focuses on distinguishing different levels of organisation and part-whole relationships, be introduced and to what extent does the approach contribute to the development of a coherent understanding of digestion?*

Structure of the programme

Figure 3.3 provides an overview of the content structure of the computer-aided learning programme. It starts with an orientation on the process of digestion at the organismic level on the basis of a concrete representation. Subsequently, the concrete representation is gradually transformed into an abstract systems model. Next, the programme descends to the level of the organ and cell respectively, and at each level of organisation the concrete representation of the process of digestion is gradually transformed into the same abstract systems model. This way, the student realises that at each level of organisation similar characteristics can be distinguished and how these characteristics can be depicted in a model. The general characteristics that were distinguished have been derived from the GST of Von Bertalanffy (1968) who described organisms as hierarchical and open systems (see section 3.3.1).

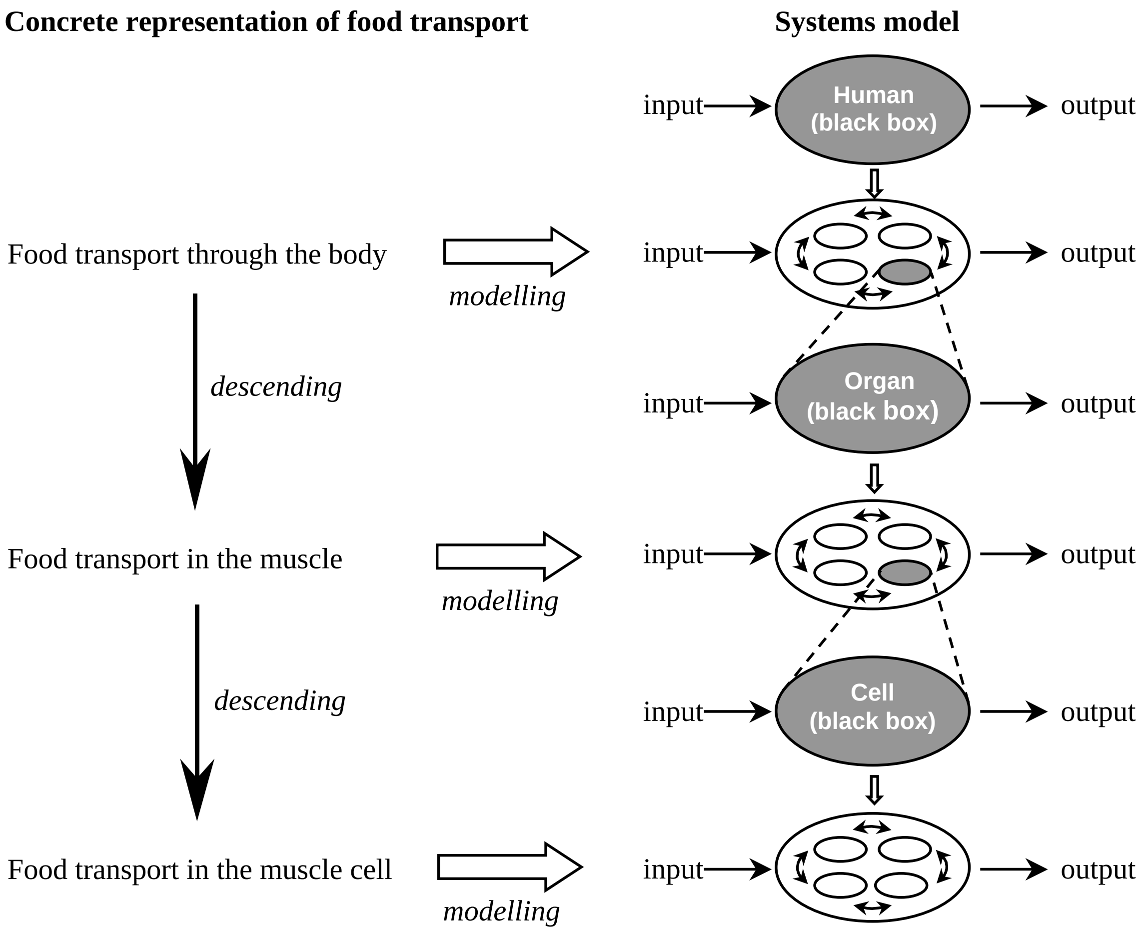


Figure 3.3 ***Content structure of the computer-aided learning programme.*** *For a further explanation: see text.*

At each level of organisation the student has to do a task, such as dragging the organs to the right place in the body or drawing arrows to interrelate the different organs and organelles. After each task, the step from a realistic representation towards the systems model is visualised in an animation. At the end, students are asked to integrate the systems models at different levels of organisation so that a hierarchical model of the organism emerges.

Results

The interactive learning material is tested by four student couples from the fourth form of pre-university education (4 vwo) and five student couples from the fourth form of the highest level in general secondary education (4 havo). Data were collected through observing and audio taping the couples during the activity and through interviewing them afterwards.

Observation of the students showed them to be fairly motivated during the whole activity. Also, in the interviews afterwards students' appreciated the computer-aided programme, whereby they mainly referred to the animations, the design and the interactive character of the programme as being positive qualities. According to the students the process of abstracting had not resulted in any problems. In this respect it was striking that many students valued the systems model as being useful in providing an orderly picture of the human body. Students did not mention this insight at first but mostly after having been descended to the organ or cellular level. Students also noticed the model of the organ or the cell 'being the same as the model for the body'. This motivated them to take a closer look at what characteristics were precisely distinguished. Some students mentioned a disadvantage of the model: 'you cannot see anymore what it actually represents'. These students preferred the realistic representation of the body in which the different parts could still be distinguished and named.

To the question what they thought was interesting about the computer-aided programme, students answered that in both organisms and organs, closely cooperating units can be distinguished. Students also indicated that they would like to know more about the exact nature of that cooperation: 'I do know now which organs cooperate, but not exactly how.' Suchlike questions concerning the nature of the coherence within the human body, is an important outcome of the computer-aided programme and provides an important reason to hold on to the process of developing a systems model. After all, the systems model guides students when searching *how* different biological objects are interrelated as well.

Although students could point out the main characteristics of the systems model, they had difficulties in taking the step back from the model to the realistic process of digestion. Thinking backward and forward between concrete phenomena and abstract systems models is not easy for students and in a LT-strategy that implies this process, so it should be practiced actively.

Summarising, we could state that the computer-aided programme enables students to engage in the development of the systems model. However, systems thinking competence implies thinking backward and forward between concrete and abstract representations of biological phenomena, i.e. digestion and the computer-aided programme seem to stimulate students insufficiently to do so. The programme raises content related questions concerning the nature of the coherence within the human body. So, the programme could be embedded in a series of other learning and teaching activities. It could engage students actively in the process of abstracting the hierarchical structure of the human body before introducing the concept 'level of biological organisation'. The programme should then be succeeded by a learning activity that focuses on the nature of the coherence at and between the different levels of organisation in organisms, i.e. horizontal and vertical coherence. Within a LT-strategy for the cell as a system the coherence at the cellular level and the coherence between the cellular level and higher levels of organisation should be addressed.

3.4.5 Designing the initial learning and teaching strategy for the cell as a system

Formulating the criteria

The explorative phase of our research has resulted in some implications for developing the LT-strategy for the cell as a system, which will be elaborated in this section. The first explorative case study concerning endocrine regulation revealed that students do not use their knowledge about cells spontaneously when other topics are dealt with later in the biology curriculum, i.e. transfer is lacking. If our objective is to enable students to do so, a cell biology course should pay explicit attention to the cell and its relation with higher levels of organisation. The interactive learning material concerning digestion, showed that developing a systems model can go hand in hand with descending from the organismic level down to the cellular level of organisation, whereby the cell can be introduced as a functional unit of the organism. By generalisation and abstraction of the hierarchical structure of organisms we can introduce the idea that different organisational levels can be distinguished in living systems. At this point we have solved the problem whether the LT-strategy for the cell as a system should start with either cell biology or systems thinking (section 3.4.2). Instead of choosing between the two approaches, a synthesis seems possible in which the development of cell biological knowledge parallels the development of systems thinking competence.

Based on the preceding sections the following content related criteria have been formulated to develop the LT-strategy for the cell as a system. In between brackets the specific sections are mentioned from which the criteria have been derived:

1) The cell as a basic unit of life should be introduced as a free living organism (the cell as an autonomous system; sections 3.2.1, 3.4.1 & 3.4.2)
2) The cell should be described as both an autonomous system and as a functional system within the organism (sections 3.3.2 & 3.4.1)
3) The content matter should be ordered according to the levels of biological organisation and this should be made explicit to students (sections 3.3.2 & 3.4.4)
4) The development of a systems concept, derived from the GST, should start at the organismic level[2] (sections 3.2.1, 3.4.2 & 3.4.4)
5) The systems characteristics as formulated by the GST should be developed by abstracting concrete biological objects or phenomena (sections 3.4.2 & 3.4.4)

[2] Structuring the LT-strategy according the levels of biological organisation has been further elaborated by Knippels (2002) in her so-called yo-yo strategy. However, this strategy was not yet fully cut-and-dried at the moment of formulating the criteria for a initial LT-strategy in our study.

6) Students should actively think backward and forward between concrete objects and abstract (systems) representations of those objects multiple times (sections 3.3.3 & 3.4.4)
7) To develop a coherent understanding of the cell as a system, the LT-strategy should address both horizontal and vertical coherence, i.e. the interrelations at the cellular level and the interrelations between the cellular level and the organismic level (sections 3.2.1, 3.3.2, 3.4.3 & 3.4.4)
8) To actively engage students in the subsequent LT-activities the LT-strategy should be structured according to the problem posing approach (section 1.4).

Description of the initial LT-strategy

Table 3.3 outlines the sequence of LT-activities encompassing a total of eight lessons of 45 minutes (see also table 4.3). The sequence of LT-activities should pave the way for developing a coherent understanding of cell biology and acquiring systems thinking competence in a for students reasonable way. The strategy can be divided into five phases, i.e. I) general orientation on cell biology, II) Introduction of the cell as an organism, III) explication of systems thinking, IV) application of the systems model to the cell as a functional unit and V) interrelating the different levels of organisation. In this section we will shortly describe the subsequent phases that constitute the LT-strategy and were designed in accordance with the criteria mentioned above. While some criteria in fact apply to all phases, e.g. criterion 3 and 8, most criteria will only be mentioned when they are central to the specific phase. First, we will start with a short elaboration of the strategy as a whole in the light of the eighth criterion.

Phase I to V, criterion 8 – The problem posing approach implies that learning activities should elicit meaningful content related questions and provide answers in a well thought out sequence. As the left column in table 3.3 shows, a content related sequence of problems guides the subsequent LT-activities. These problems or questions emerged from selecting the main cell biological content from a systems perspective (see section in 3.4.1). The phrasing and sequencing of the questions as shown in table 3.3 cannot yet be regarded as an empirically founded, bottom-up sequence of questions and answers as intended in a problem posing approach. An important aim of the first explorative case study was to investigate whether the questions will correspond with both global and local motives as formulated in section 1.4. In other words, analysis of the actual LT-processes will provide more insight into how a LT-strategy for the cell as a system could be shaped from a problem posing perspective.

Phase 1, criterion 3, 4 – To provide a general motive for learning cell biology the initial LT-activity focuses on how biological phenomena can be explained by describing them in terms of structures and processes at the cellular level (criterion 3). To this aim, we selected regeneration of a salamander limb, which could be well described in terms of students' prior knowledge of growth and development at the organismic level (criterion 4). Questioning how a salamander limb regenerates after having been cut off, was supposed to stimulate students to ask for an explanation at the organ and cellular level. Moreover, an initial description at the cellular level could provide students more insight into the phenomenon and into the fact that cell biological knowledge is an important prerequisite for this understanding.

Phase II, criterion 1, 2, 4, 6 and 7 – After raising a global interest in cell biology in phase I of the LT-strategy, phase II prepares students for the introduction of an initial organismic model in LTA 6, based on both unicellular organisms and multicellular organisms (criterion 4). Exploration of the fundamental life processes (Dutch: levensfuncties) in LTA 2 provides a meaningful starting point. During this activity, the focus will be on the hierarchical structure of plants and animals and on their interaction with the environment.

The system characteristics according to the General Systems Theory can be seen as abstractions from the fundamental life functions: metabolism, growth and development, and responding to environmental stimuli (metabolism for instance requires that a living system exchanges matter with its surroundings). Therefore, phase II introduces the cell as an autonomous unit, while phase IV and V address the cell as a functional unit of the organism. By implication, acquiring an initial systems thinking competence will start at the cellular level as well, but followed by its application to other levels. In LTA 3 students read a newspaper article about *Mycoplasma genitalium* and investigate *Paramecium* in LTA 4 and 5, so as to discover that single cells must also perform the life processes (criterion 1 and 2). When students view the cell as an autonomous system, distinguishing organelles as functional parts of the cell seems logic. In LTA 4 and 5 the cell and its organelles are explored and interrelated (criterion 7 concerning horizontal coherence at the cellular level) by analogy with the human body. In this phase students observe free-living cells through the microscope and use different (schoolbook) representations of these cells (criterion 6).

Phase III, criterion 3, 4, 5 and 6 – The next step moves to a higher level of abstraction by developing a systems model of the organism (LTA 7). When students view the cell as a functional part of a larger whole, distinguishing the organs as the structural organisation of functional cells seems logic. However, developing motives for systems thinking will likely take some doing. Why making use of abstract concepts like system and level of organisation when more familiar concepts like organism, organ and cell are satisfactory? In phase III students start to find out some general characteristics of organisms, organs and cells *(criterion 3 and 4).* When they do so, the systems concept becomes functional because it provides a general label for the set of characteristics. The computer-aided programme is embedded in the LT-strategy to address this problem. The generalisation of systems characteristics parallels the exploration of the process of digestion *(criterion 5 and 6).* So, exploration of the process of digestion may provide a learning motive and systems thinking joins in.

Phase IV, criterion 6 and 7 – In LTA 8 and 9 the systems model is used to guide students' exploration of cells that are part of multicellular organisms. In this phase students apply the developed systems model to cells that are part of organisms and are stimulated to think backward and forward between different representations of cells (on the Internet and in their schoolbooks) to acquire an overview of the structural organisation of the cell *(criterion 6).* Hereby a general image of a typical eukaryote cell is formed that mainly focuses on the cells' autonomy and requires interrelating the different organelles within the context of the life processes that have to be carried out by the cell *(criterion 7 concerning horizontal coherence at the cellular level).*

Phase V, criterion 2 and 7 – The final step, LTA 10 and 11, addresses the functionality of cells and the organisation of cells at the tissue and organ level *(criterion*

7 concerning vertical coherence). Stem cell therapy was chosen as a context because it is a topic that gets a lot of attention in the current media. Moreover, discussing the possibilities or restrictions of using stem cell therapy in replacing dysfunctional tissues or organs focuses students on the structural organisation of cells at higher level of organisation. In this context the distinction between autonomous cells and cells as functional parts was also explicated.

To conclude the LT-strategy, the answer to the central problem elicited in LTA 1 about the regenerating salamander limb could be formulated in terms of the functional relationship between the regenerated cells and the required conditions for regeneration at the cellular, organ and organism level.

Table 3.3 ***Outline of the initial strategy for the cell as a system.***

Sequence of problems	Learning and teaching activities (LTA's)
	I. General orientation on cell biology
How can we explain a biological phenomenon?	**LTA 1: plenary discussion** focusing on explaining a biological phenomenon, i.e. a regenerating salamander limb. • Students realise that biological phenomena can be described at the level of the organism, organ and cell and that a more detailed description at the cellular level provides a deeper understanding.
	II. Introduction of the cell as an organism
What characteristics (besides regeneration) do animals and plants have in common?	**LTA 2: Thinking individually, sharing ideas in groups and exchanging plenary, respectively.** Eliciting prior knowledge on the life functions by comparing animals and plants. Reflecting on the life functions emphasising the hierarchical structure and the interaction of organisms with their environment. • Students realise that animals and plants have some general characteristics in common.
Do the fundamental life processes of multicellular organisms also apply to unicellular organisms?	**LTA 3: group work.** Reading a text about the smallest known unicellular organism and discussing the application of the fundamental life processes to unicellular organisms. • Students realise that the life functions apply to free-living cells but wonder how they achieve them.
How do organisms including free-living cells carry out the life processes?	**LTA 4: microscope practical** aimed at the fundamental life processes. Observing unicellular organisms (Paramecium). Plenary reflection on the observations focusing on the structural components of the cell. • Students understand that unicellular organisms have functional parts similar to multicellular organisms
What functions do the different units in Paramecium have?	**LTA 5: written assignment in pairs**. Comparing schematic representations of Paramecium and the human body. Using the analogy between organs and organelles to explore the functions of the different organelles. Subsequently elaborating the input and output of the organism and interrelating the organelles within the context of digestion, again using the analogy with the human body. • Students acquire a coherent understanding of unicellular organisms
Does the general model, which applies to free living cells, also apply to cells that are part of an organism?	**LTA 6: plenary reflection** directed by the teacher. Reflecting on the life processes performed by the structural components. Uniting the schematic representations of the unicellular and multicellular organism in a general organismic model. Introducing the next question. • Students understand the organismic model and wonder if it also applies to cells that are part of an organism.

Sequence of problems	Learning activities
	<u>*III. Explication of systems thinking*</u> **LTA 7: computer-aided programme in pairs.** Exploring the process of digestion on the organisational level of the organism, organ and cell. In a reflection the systems model explicated as applying to all living systems Students realise that the systems model applies to cells, organs and organisms and get a clear overview of how the body is organised.
How do cells that are part of an organism carry out the fundamental processes of life?	<u>*IV. Application of the systems model to the cell as a functional unit*</u> **LTA 8: Group work (3 students).** Formulating questions based on the systems model that direct the subsequent exploring of the characteristics and functions of one specific organelle. The schoolbook and Internet are used as information sources. **LTA 9: Class presentations and plenary reflection.** Presenting the results of LTA 8 and drawing a model of a cell including all organelles at an overhead. The teacher directs reflection on the cell model by comparing it with the systems model. • Students acquire a coherent understanding of the functional cell and realise that the cell model is a more concrete filling-in of the systems model.
To what extent is the cell as a functional unit of an organism, autonomous?	<u>*V. Interrelating the different levels of organisation*</u> **LTA 10: Group work on a written assignment.** Discussing about differences between free-living cells and cells in multicellular organisms. Subsequently elaborating on the process of cell specialisation on the basis of a newspaper article about stem cells. • Students realise that the cell and organism are mutually dependent and that cell specialisation is controlled by signals from the cells environment. **LTA 11: Plenary reflection on the covered learning pathway** directed by the teacher. • Students acquire more insight into the covered learning pathway and in the nature of the distinction between autonomous cells and functional cells that are part of a tight organisation at higher levels, i.e. organ and organism.

Designing a initial strategy requires interrelating the outcomes of different theoretical and practical explorations as well as creativity. Beforehand, it was not expected that the strategy as presented in table 3.3 would solve all learning problems mentioned. The first case study should also generate further ideas and contribute to improvement of the strategy to be tested in the second case study. A main point of interest is whether the content-related problem sequence engages students in using the systems model. *To what extent do students use the model when exploring the cell as functional system of the organism? Are students able to apply the systems model?* The answer to these questions should result from LTA 8 and LTA 9. These activities mainly deal with acquiring insight into the horizontal coherence at the cellular level. The next question that should be addressed focused on the vertical coherence: *To what extent can students relate their knowledge about cells to phenomena at higher levels of organisation.* This question cannot be answered completely on the basis of a series of lessons about cell biology because we cannot expect the competence of systems thinking to be developed after one series of eight lessons. However, students should be able to name the different levels of biological organisation and relate the acquired concepts at each level to each other.

Chapter 4

Towards a strategy for the cell as a system

4.1 Introduction

The explorative phase of our research has been discussed in chapter 1 and was further elaborated in chapter 3. The main problems in learning and teaching cell biology were determined and a systems theoretical approach to tackle these problems was explored. The design-criteria that emerged from the explorative phase were converted into an initial Learning and teaching (LT) strategy for the cell as a system as presented in section 3.4.5.

This section describes the cyclic research phase in which the LT-strategy was optimised and reshaped so as to constitute an empirically founded, bottom-up sequence of learning activities as intended in a problem posing approach. The first and the revised LT-strategy were elaborated into a scenario and field-tested in two successive case studies.

Firstly, the specific contexts of the two case studies will be presented in section 4.2 as well as the specific data sources used per case study in evaluating the scenario and reflecting on the LT-strategy. Section 4.2 also outlines the method of data-analysis with an important role for the scenario. In section 4.3 and 4.4 respectively, the results of the first and second scenario in classroom practice will be presented and discussed by a description of the essential learning and teaching activities in both case studies. Hereby, the main focus is on a description of the results of the second (revised) scenario. Testing this scenario in the second research cycle, finally resulted in the final LT-strategy for the cell as a system, which will be elaborated in chapter 5.

4.2 Procedures and research context

In this section we will outline the specific classroom contexts in which the first and second case study were carried out. This completes the more general description of the case studies in section 2.3 where the developmental research design of this research was outlined. Furthermore, this section describes the methods of data collection and analysis in more detail.

4.2.1 Some practical information

Table 4.1 provides an overview of the general characteristics of the schools and more specific details about the classes and number of lessons per case study. The data of the schools were based on national school statistics 2002 and quality-indication of the Inspection of Education (www.trouw.nl/scholen/).

The schools in both case studies can be typified as rural schools, located in a small city surrounded by countryside. Both schools have students coming from a wide area and few of them belong to an ethnic minority. The quality-indication of the school in the first case study is somewhat above the national average while the school in the second case study is average. Both case studies were carried out in form four of pre-university education (abbreviation 4V). In the Dutch school system this means that the students have had three years of lower secondary education, which is the national core curriculum for lower secondary level. Form four is the beginning of the upper-level secondary education, which takes a period of three years in case of pre-university education.

Table 4.1 ***Characteristics of schools and classes involved in both case studies.***

School indicators	First case study	Second case study
Name and place (number of inhabitants)	ORS Lek en Linge Culemborg (26.000)	CSG Dingstede Meppel (25.500)
Signature	Public	Denominational
Number of students	1025	1118
% Ethnic minority students	2 (5)*	0 (5)*
% Secondary students graduating without delay	72 (57)*	57 (57)*
Average grade national exam	7,0 (6,5)*	6,5 (6,5)*
Specific indicators	First case study	Second case study
Time period	October – November 2001	March – April 2002
Form and level	Two classes: 4th form, pre-university	Two classes: 4th form, pre-university
Number of students (♀/♂)	4V1: 21 (14/7) 4V2: 23 (11/12)	4V1: 15 (12/3) 4V2: 13 (10/3)
Age students	15-16	15-16
Participating teachers	2	1
Number of biology lessons a week	3 (45 minutes)	2 (50 minutes)
Number of cell biology lessons	9	10

(…) Indicates the national level for pre-university education.*

In practice, selection of the schools was mainly based on the willingness and intentions of their biology teachers to participate in our research. We contacted approximately 14 teachers by mail followed by a telephone call one week later. The teachers that were contacted had to teach biology at the pre-university level and had a minimal teaching experience of five years. After a first description of our research, including its timescale and the teacher's role in it, five teachers appeared willing and able to cooperate in our research. In choosing between those five teachers we tried to maximize the chance that the intended LT-strategy would be carried out as intended. We conducted an open interview in which we tried to find out to what extent the teacher was really interested in our research and its focus on optimising the learning processes of (their) students. Moreover, the teacher had to show an open mind regarding the use of a LT-strategy that might differ from his or her usual teaching method. Subsequently, one biology lesson of the teacher was observed. Hereby, we tried to find out if the teacher strived for an open atmosphere during his or her lessons regarding the interaction with students and between students. For example, the teacher should make effort to engage multiple students in a class discussion and pay attention to their input in guiding the discussions.

Finally, two teachers were selected to cooperate in our research project and one teacher joined in at the beginning of the first case study. This teacher, an interested colleague of the teacher selected for the first case study, had a limited experience as a biology teacher. While the other two teachers had more than 20 years of teaching experience before the start of this research project, he had worked only for two years as a teacher and consequently was still concerned about his own performance in the class.

The teacher in the second case study also participated in an earlier developmental research project (January - February 2000) concerning genetics (Knippels, 2002) and was familiar with our developmental research approach.

Selection of the classes was based on the fact that our research focused on an introductory course on cell biology. Because cell biology is usually introduced at the beginning of upper-level secondary school (form four), we designed a substituting course for this introduction. In addition, teachers mentioned that form four offers more time space than the last two classes because of the more intensive preparation for the final exam in these last two years. The choice of the pre-university level was made because of the explorative character of our research and the fact that it should provide indications about how the problem of designing biology education from a systems perspective could be solved. Pre-university education (vwo) was supposed to provide a more ideal context to explore the possibilities of our systems approach to cell biology than general secondary education (havo).

The course requires some basic knowledge about the functions of some important organs and their interrelations, which is dealt with in lower secondary education. In the second case study we had the advantage that cell biology was introduced later in the fourth form (class 4V) after the theme ‘growth and development’. Consequently, we could start our course from the organismic level by building on the preceding theme. Students’ prior knowledge about cells did not differ much between the two case studies. All students had seen some plant and cheek cells under a microscope during lower secondary education and their knowledge about cells was limited to some basic structural characteristics: i.e. all plants and animals are composed of cells and cells are made of cytoplasm with a nucleus, surrounded by a cell wall or membrane whereby the difference between the cell wall and membrane remained problematic.

4.2.2 Data collection

In both case studies extensive data sets were collected through classroom observations, audiotaped classroom and group discussions, completed worksheets, written tests and interviews with students and teacher. During each lesson data collection was guided by some central questions as described in table 4.2. The intended LT-strategy and expected behaviour of the students and teacher were described in the scenario, so in practice the scenario directed the observations. Section 4.3 describes the role of the scenario in more detail. In Table 4.2 the data sources used in both case studies are outlined.

The whole sequence of lessons was observed and audiotaped in the classroom. During the observation, striking events and statements of both students and teacher were noted as much as possible. By ’striking events’ we mean crucial events that validated the expectations described in the scenario as well as crucial deviations from the scenario, like a sudden drop in students’ motivation or students getting stuck during a certain learning activity.

The teacher carried a tape recorder during the lessons and before the start of group work the tape recorders were placed on the tables of the students to record the group discussions. For practical reasons, in each class four tape recorders were used to record the group discussions and to provide an indication of the course of the discussions that took place. The groups consisted of three or four students. In practice this meant that

during the first case study not all group discussions were recorded because of the large number of students (see table 4.1) in contrast to the second case study where all students participating in group discussions could be recorded.
During the class discussions notes were made of what was put forward by the teacher and students, and the drawings or notes on the blackboard were copied. During the observation, students' motivation and the questions they asked were an important focus. The group work was observed to see what students were doing and whether they were on task. Sometimes help was given to the students when they asked for it. During the first case study the observation mainly focused on one of the groups.

Table 4.2 ***Overview of the data sources used in both case studies to answer the general analysis questions.***

Data sources / **Questions guiding the analysis**	Observation	Audio-tapes			Student interviews	Teacher interview	Completed worksheets	Written questionnaire	Written test
		Teacher	Group discussions	Class discussions					
What are remarkable events (positive or negative) in the learning and teaching processes?	✓	✓	✓	✓	✓	✓			
At what moments does the teacher not comply with the intended teaching processes?	✓	✓		✓					
What are the teacher's reasons for non-compliance?	✓	✓				✓			
In what respect does the actual learning process of the students differ from the expected/ intended learning processes and how can this be explained?	✓		✓	✓	✓			✓*	
To what extent do students realise the intended learning outcomes?	✓				✓		✓	✓*	✓

**Indicates that the data source has only been used in the first case study.*

After each lesson, the completed worksheets of all students were copied. Furthermore, the course of the lesson was evaluated with the teacher in an interview based on the notes that had been made. The length and moment of this interview was dependent on the available time of the teacher, but if possible it was done on the same day as the lesson took place. These interviews were always audiotaped. Noted differences between the intended and performed learning and leaching processes were discussed together with the consequences for the next lesson.

During the first case study students had to fill out a written questionnaire at the end of each lesson. The questionnaire was based on the 'Learner Report' as introduced by De Groot (Van Kesteren, 1989) and contained sentences that the students had to complete: *I have learnt this lesson that…; I had trouble with…; I would like to know* *more about…; I found it interesting to…; What I didn't like about this lesson was….* Because it yielded little valuable information in addition to the other data sources and because it took valuable time of each lesson it was decided to leave out this method of data collection in the second case study.

Another aspect that differed between the two case studies was the participating role of the researcher. During the first case study the researcher had a more active participating role in the teaching process than in the second case study. The researcher walked around the classroom during group work and answered students' questions or asked questions instead. This setting offered the opportunity to have conversations with individual students, and thereby to investigate how activities were interpreted or what the students meant by certain words or remarks they had said or had written down. The focus hereby was on getting more insight in students' problems related to the learning activities and the revisions that were needed for the second case study. In the second case study on the other hand we tried to reduce the effects related to the presence of the researcher. Also, it was expected that the learning and teaching process would run more like intended and that only minor revisions would be necessary. Therefore, the researcher made his observations mainly from the back of the classroom. Consequently, most conversations with students and teacher took place after the lessons. When possible, a brief consultation with the teacher took place during the lesson, concerning the way that the lesson had proceeded so far, what still needed to be done or how specific outcomes could be used in the remaining part of the lesson.

Introduction to the students

The lesson before the start of both case studies, the researcher was introduced to the students as a PhD-student/researcher of the University of Utrecht. The researcher shortly explained a few aspects of his research project and its goals and mentioned some important implications for the students, i.e. presence of microphones during the lessons, intake of worksheets, presence of the researcher. The students were asked to answer all questions honestly and to utter their answers and negative or positive feedback on the learning materials, in the microphones. It was also stated that the data and worksheets would be handled confidentially and would not be given to the teacher. The teacher stated that the series of lessons were a substitute for the normal lessons in cell biology and that it would be concluded by a written exam. The teacher also pointed students at the study guide, in which the contents (and homework) per lesson were described as usual. During this lesson the students also had the opportunity to ask questions to the researcher. In all classes they came up with few questions like: 'Why do you want to record us?' 'What are you going to do with the recordings?' 'Why are you interested in the way we learn?' The answers given by the researcher mostly satisfied students' curiosity and during the remainder of the lesson little attention was paid to the researcher sitting in the back of the classroom.

4.2.3 Data analysis

Data analysis aimed at answering the question if the desired learning and teaching behaviour was put into practice and if the desired learning outcomes were attained (see table 4.2). Furthermore, analysis focused on answering where and frequently also which adaptations of the scenario (and LT-strategy) were required. Evaluation of the LT-strategy took place by comparing the actual or executed learning and teaching processes and outcomes with the intended or expected processes and outcomes as outlined in the scenario.

A scenario is a more detailed explicit, context-specific description and justification of the expected learning and teaching processes, including learning and teaching activities and intended learning outcomes. In testing the adequacy of the LT-strategy the scenario guides the analysis of the actual learning and teaching process in classroom practice. When the LT-strategy was executed as intended, the empirical data were directly useful to determine whether or not the strategy was good enough. When, on the other hand, the intended LT-strategy differed from the executed LT-strategy it had to be determined if the discrepancy was for the better of worse with consequences for revising the scenario. Severe discrepancies do not only require adaptations of the scenario, but also of the LT-strategy.

The role of the scenario

The scenario is considered here as a theoretical framework as described by Smaling & Maso (2002). It consists of a set of suppositions and hypotheses about the intended learning and teaching processes. These suppositions and hypotheses are formulated on the basis of the beliefs we have articulated in the explorative phase of our research. So the scenario can be described as theory-based and practice-oriented description of our beliefs, concerning a successful LT-strategy for the cell as a system. This description implies that if the learning and teaching activities are not performed properly, the underlying theoretical conceptions may turn out to be of little practical relevance (Lijnse, 2003). In this respect, the scenario is an important instrument for the teacher to prepare the actual lessons. It can be considered as a rather detailed teachers guide, which describes the learning and teaching activities including their intentions, interrelatedness and a description of how they should be carried out. The scenario also gives rise to the development of the learning materials, i.e. students' workbooks (see figure 2.2).

The scenario or hypothetical learning and teaching trajectory as Klaassen (1995) named it, predicts and theoretically justifies in detail the expected learning and teaching processes. Thus, it forces the researcher to make his didactical knowledge, expectations and theoretical perspective explicit in detail and thereby empirically testable (Lijnse, 2003). In addition to testing the formulated hypothesis and suppositions, the scenario supports the analysis of the acquired data in our case studies. In other words, the analysis consists of a confrontation of the theoretical framework, i.e. the scenario, with the gathered empirical data.

As will be clear from section 4.2.2, a large amount of qualitative data was gathered during both case studies. In order to select and interpret the data, the scenario provided essential guidance, as it enables us to focus on particular moments where something unexpected or something crucial happened. Moreover, the scenario also pointed out moments where about the expectations were uncertain. The analysis of the different data sets was structured by distinguishing different curriculum levels (Van den Akker, 1988; Kuiper, 1993). In her thesis, Knippels (2002) uses the different curriculum levels in a developmental research approach, which is very similar to ours. In line with her description our data sets were considered to give information on and insight in five different items: the curriculum documents (scenario, learning materials and teachers manual), the learning and teaching activities in the classroom, the teacher's perceptions, the students' perceptions and the learning outcomes. For example, the audio-records gave insight in the actual learning and teaching activities and both students' and teacher's perceptions.

Data processing

The various data sources gave information about the executed learning and teaching process and its outcomes. All audiotapes where transcribed verbatim, including line numbers. When necessary, students' worksheets and written exams were typed out and put in matrices in order to get a clear overview of all answers. The transcripts of the audiotaped class and group discussions constituted the main data source in reconstructing the executed learning and teaching process, because they contain the most complete and authentic information. The notes that were made during the classroom observations guided interpretation of these transcripts (triangulation). In addition, the interviews with the teacher after each lesson were used to compare the researcher's observations with the teachers' interpretation and experiences during the lesson. In analysing the outcomes, the worksheets and written tests were used in addition to the transcribed audio material. Figure 4.1 shows the various complementing data sources, which enhance the validity of the analysis.

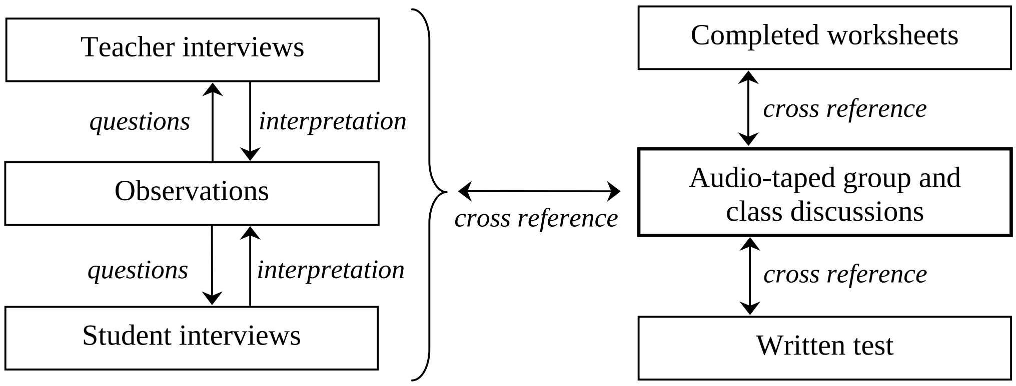


Figure 4.1 ***Complementing data sources***

As figure 4.1 shows emphasis was on discourse analysis and reconstruction of the learning and teaching processes by inspecting and interrelating data from different sources. Both the observations and subsequent analysis of the transcripts were guided by our domain specific philosophy on cell biology education and systems thinking and by expectations about the LT-strategy as outlined in the scenario. The observations in the classroom were mainly focused at identifying critical moments regarding students' motivation, problems and questions.

During the case study the analysis started with the classroom observations. During the case study, the observations also gave input to and were checked by interviews with both teacher and students. Together they provided a first impression of the adequacy of the content structure and the sequence of the learning and teaching activities. This impression comprehended the behaviour of both students and teacher, i.e. verbal reactions, questions, answers and motivation, and the perception of the learning and teaching processes in the lessons of both students and teacher.

After the case study all audiotapes, including the interviews with teacher and students, were transcribed, enabling a more detailed analysis of the actual learning and teaching processes. In the analysis, each learning and teaching activity was taken as a meaningful unit. Analysis started with the transcripts of the teacher's audiotape, which gave an overview of the complete learning and teaching activity, including the teachers' guidance to various students/student groups. Subsequently, the group-discussions were studied. The worksheets and written test were used to check or support the results of the above steps and gave more insight in the learning outcomes per activity. Analysing the transcripts included the following steps:

1. Close reading with the first impression obtained during the case study in mind. Marking crucial phrases, noting key words and ideas that came up.
2. Identifying students' reasoning patterns and assigning key words. Labelling fragments in terms of discontinuities in their reasoning patterns. Identifying crucial support given or not given by the teacher.
3. Repeating the previous steps guided by the scenario. Identifying crucial moments that support or reject the suppositions in the scenario.

The process of data analysis ran parallel with the reconstruction and description of the actual learning and teaching processes. In reconstructing the learning and teaching processes, we tried to do so from the students' point of view. So the frame of reference from which we interpreted the classroom discourse could be described as *bottom up*. We tried to interpret students' utterances from their point of view, which means that, as long as their discussions deal with events or content related to our LT-strategy, we agree of most what they say (Klaassen, 1995). Hereby we follow the view of Dennet (1992) who states that to interpret people properly, it is necessary to regard them as reasonable rational acting persons, who have beliefs, desires and other mental states that have to do with intentionality. This perspective offers us the possibility to acquire a coherent understanding of the entire process of learning and teaching that went on in the classroom, as Lijnse states:

> Thus, in our case, we have to adopt the view that pupils and teachers are reasonable rational persons, who say reasonable things in view of the circumstances and all the evidence available. So one should try to put oneself in the places of pupils and teachers, and interpret what they say as much as possible in view of what we ourselves would have said in their position in the same situations. Starting from *common ground*, one should be able to make a reasonable coherent story of what has been going on in a classroom. Not just interpreting them on the basis of disconnected incidental utterances, as, e.g., is done in questionnaires, but by connecting all the evidence available into a reasonable coherent story, implying that we seem to understand the actual teaching-learning process in sufficient detail (Lijnse, 2003).

4.3 The first case study

During the explorative phase of our research, described in chapter three, promising learning activities and options for sequencing them emerged. These were transformed into a preliminary strategy for learning and teaching cell biology from a systems perspective. Table 3.3 shows the most important steps of the preliminary strategy, which took eight lessons and was tested in the first case study. The arrangement of learning and teaching activities is depicted in table 4.3.

As described in section 4.2.2, extensive data sets were collected through various methods in order to get insight in the actual learning and teaching processes. In 4.2.3 the role of the scenario in testing the adequacy of the underlying LT-strategy was elaborated.

Table 4.3 ***Arrangement and duration of the LTA's in the first case study.***

Lesson	Time (min.)	Learning and Teaching Activities
1	45	LTA 1: Class discussion on explaining a biological phenomenon by describing it at the organismic, organ and cellular level respectively.
2	30	LTA 2: Successively thinking individually, sharing ideas in groups and exchanging plenary during which the fundamental life processes of multicellular organisms are introduced and explored.
	15	LTA 3: Group work on applying the processes of life to free-living cells.
3	45	LTA 4: Microscope practical and plenary reflection focusing on investigating the life processes of free-living cells (Paramecium).
4	45	LTA 5: Written assignment in pairs focussing on exploring the organelles and their relations in Paramecium within the context of digestion by using the analogy with the organs in the human body.
5	20	LTA 6: Plenary reflection on the fundamental life processes resulting in a general model of both unicellular and multicellular organisms.
	25	LTA 7: Computer-aided programme in pairs addressing the process of digestion from the organismic dawn to the cellular level and explication of the systems model on each level.
6	45	LTA 8: Group work in which the characteristics of one specific organelle are explored, guided by the systems model.
7	45	LTA 9: Class presentations and plenary reflection of the results of LTA 8, including drawing a cell model and comparing it with the systems model.
8	30	LTA 10: Group work on a written assignment addressing the differences between free-living cells and cells in multicellular organisms and elaborating cell specialisation.
	15	LTA 11: Plenary reflection on the covered learning pathway.

The expectations and learning objectives explicated in the scenario provided evaluation criteria. These expectations and objectives referred to the meaningful introduction and application of an initial systems model so as to acquire coherent understanding of the cell as basic and functional unit of the organism. They reflect a systems thinking competence with the central focus on the cellular level, as described in section 3.3.2, i.e. are students able to:

① distinguish different levels of organisation, i.e. cell, organ and organism, and match biological concepts with specific levels of biological organisation?

② identify different systems at each level of organisation, including their input and output?

③ interrelate the (cell) biology concepts at each level of organisation? (horizontal coherence)

④ interrelate the (cell) biology concepts on the different levels of organisation? (vertical coherence)

Reflection on the expectations and objectives described above and on the internal consistency of the learning and teaching processes should answer the general research questions introduced in section 1.2:

❶ What learning outcomes arise from the executed learning and teaching strategy and what learning processes constituted these learning outcomes?

❷ What indications can be derived from the observed learning outcomes and processes for revising the learning and teaching strategy?

Sections 4.3.1, 4.3.2 and 4.3.3 describe the main results of the first case study, which gave indications for revision of the LT-strategy. The results of the first case study are not described in full detail but intend to provide a more general insight in the development of the preliminary strategy that was tested in the second case study. It should be noted here that theoretical suppositions about the sequence of learning and teaching activities were tested for the first time in a multiple lesson case study. Moreover, the theoretical notions gathered in the exploration phase of our research were for the first time translated into practicable lesson material. As a result it was expected that minor design errors would occur and interfere with testing the suppositions as described in the scenario. In other words, the first case study supported the learning process of the researcher regarding the specific topic under investigation (see also section 2.3). In the second research cycle the design errors should be largely overcome. The results of the second case study, which forms the core of this chapter, are presented in full detail in section 4.4.

4.3.1 General orientation and introduction of unicellular organisms

The purpose of the global orientation was to enable students to acquire a content related motive to participate in the cell biology course. Furthermore, this global motive should drive students through the remaining part of the course (for a further explanation see the elaboration on the problem posing approach in section 1.4). As mentioned in section 3.4.2, finding an explanation for a phenomenon at the level of the organism would provide a motive to descend to the cellular level. As an example of such a phenomenon, regeneration of a salamander limb was selected and presented to students in a class discussion. When the teacher asked the students who had heard of regeneration before, one student directly related the process to the cellular level: '…that is when cells are regrouping and form a new body. But not all organisms are able to do it …' When asked how the process of regeneration could be accomplished in the specific case of the salamander limb, the students engaged in a discussion that dealt with 'cells'

[1[1]:1.C.1][1], T is teacher

T: A salamander limb is made of bones, blood vessels, skin and things just like my arm, but how is it possible that it all regenerates?

Sanne[2]: Maybe that the cell has information what the cells next to it must do and can thus take over its function …eh like it can make the cell next to him.

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[1] Protocol fragments are indicated as **[case study number [class]: lesson. Source. Serial number fragment]** Data sources are abbreviated as follows: C = whole class discussion, G = group discussion, W = worksheet. E.g. [2[2]:6.G.7] indicates that it is the 7th fragment in this thesis, which shows a group discussion in class 2 during the 6th lesson of the second case study.

T: Nice theory, so cells are capable of telling the cells around them what to do. Very thoughtful, why not ……
Edwin: But cells have to know what to do themselves, don't they?
T: You mean: a cell has to know for itself what to do?
Edwin: Yeah that's in the chromosomes or something.
T: But Sanne just said that a cell could tell other cells what to do.
Edwin: But that means there are like smart cells and stupid cells (laughing).
T: No, it means there is communication between cells, okay?

The context of growth and development (regeneration) stimulated students to descend to the cellular level as expected. Many students engaged actively in the class discussion and especially wondered to what extent cells are autonomous or dependent on getting information from outside. As a consequence, reflecting on the class discussion, which presented cell biology as essential for understanding biological phenomena in general, could provide a global motive for cell biology.

The next learning activity (LTA 2) focused at the fundamental life processes of the multicellular and unicellular organism respectively. As expected the life processes provided a meaningful starting point. According to the teacher it provided a much needed and useful perspective when looking at free-living cells through the microscope. Moreover, not being able to see the functions clearly under the microscope, gave the students a motive to look at a more schematic picture of free living cells in the next activity. Although a meaningful introduction of free-living cells succeeded, students didn't quite see the point of thinking about the life processes of multicellular organisms first, before looking through the microscope. After the lesson many students mentioned that they already knew the functions and didn't learn much. As a consequence, the students were less motivated.

Another unexpected problem arose during the comparison of schematic representations of the unicellular and multicellular organism within the context of digestion, resulting in a general model of organisms. Students' prior knowledge about the functions of different organs in the human body and their interrelations was less developed than expected. Therefore students couldn't use this knowledge in order to arrive at a deeper understanding of the cell as an autonomous functioning unit. Earlier, Roebertsen (1996) also reported that Dutch pre-university students (age: 14-15 years) have little knowledge of various body processes.

In the plenary reflection (LTA 6), however, a comparison of the unicellular and multicellular organism on a more general level was promising. After drawing the general model on the blackboard, the students were able to explain the meaning of the different characteristics in the context of the multicellular organism. Subsequently, the class discussion dealt with the application of the model to free living cells:

[1[1]:4.C.2], T is teacher
T: Does this model apply to unicellular organisms Barbara?
Barbara: I don't think so
Peter: I think so
T: Firstly, why not?
Barbara: Because it's a little weird for a one cell … organs are made out of cells, aren't they?

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[2] All students are given fictive names.

T: That's right and my organs are made of cells and a unicellular organism has just one cell, how can there be something in just one cell?
Barbara: Well, there can be something in it, but…
Sanne: It must perform the same basic processes, so I think it works the same more or less.
Edwin: Yeah, it has no organs, but it does have organelles
T: Thanks, very well

Hereafter, the class discussion focused on reflection on the observations through the microscope and the schematic representation of the unicellular organism. To structure the discussion, the teacher explicitly and repeatedly referred to the general model of the organism. This way all the general characteristics of 'the cell as autonomous system' were dealt with.

Based on the deficiencies of the LT-strategy so far, some clues for revising the strategy were defined:

- The general orientation needs to be directed to the cellular level more explicitly in order to be able to make the subsequent step to free living cells. Growth and development provides a meaningful context in which the step to free living cells can be guided by the question to what extent cells in our body resemble or differ from autonomous living cells.
- Unicellular organisms provide a meaningful starting point for developing a general model of organisms. On a general level the comparison of unicellular and multicellular organisms can be useful, for instance in distinguishing the functional units, i.e. organs and organelles, and explicating their functional interrelations.

4.3.2 Explication of systems thinking

As described in section 3.4.4 the process of digestion in humans was explored at different levels by means of a computer-aided programme. The aim of the learning activity, in which the programme was embedded, was to provide students with a content-related motive for explication of the levels of organisation and the general characteristics of living systems. The computer-aided programme was designed and tested in an explorative study (see section 3.4.4 or Verhoeff, 2002) and proved to be adequate, albeit that a plenary reflection should be added. The interactive nature of the programme stimulated students to explore the human digestive system on the different levels of organisation. On being asked, most students concluded that the schematic (systems) representation was helpful to them because it provided a clear overview. This insight was mentioned after descending to the level of the organs and cells respectively. In the plenary reflection Kim summarised the schematic presentation as follows:

[1^2:5.C.3]
Kim: A body is made of organs and organs are made of cells, and actually the organs and organelles have the same kind of eh... function. Only organs are for the body and organelles are for cells…and they all have (…) the same models.

Although Kim's description meets the intended learning outcome, audio recordings of discussions between individual students showed that some students persisted in describing the cells and organs in the schematic model as 'things'. Thus, showing a need for the right vocabulary. This provides a basis for introducing concepts like level of organisation and system. However, due to a lack of time the levels of organisation and the general characteristics were not explicated in a reflection on the computer-aided programme. This learning outcome should be stressed in revising the strategy and in informing the teacher.

4.3.3 The cell as a functional unit of the organism

In the strategy so far, a systems model was introduced at the level of the organism. In the next step the systems model was used to develop a coherent understanding of the cell as a functional unit. First by exploring the cell and its organelles guided by the systems model, and second by explication of the relation between the cell and higher levels of organisation (organ and organism).

The class was divided into groups of three students and each group explored one organelle guided by the basic system characteristics. Students could use various information sources, such as biology textbooks and a selected website. Afterwards students presented the different characteristics of 'their' organelle. These presentations were combined in a plenary reflection, resulting in a drawing of the cell as a functional unit of the organism, on the blackboard.

Application of the systems model to the cell as a functional unit seemed an obvious step to most students: 'Well, cells in our body are living units too, so they have to perform the fundamental processes as well'. In the group discussions students explicitly referred to the systems model and some systems concepts when exploring their model: 'I cannot find what the output of the nucleus is' and 'how is it (nucleus) related to other organelles?' So students tried to answer the right questions. This is demonstrated for example by students who studied the Golgi apparatus:

[1^2:7.C.4]

Lotte: Our presentation is about the Golgi apparatus. It's an apparatus in the cell that looks very strange. It was already discovered in 1898 by Mericus Golgi and that's why it's called Golgi apparatus. He found it in brain cells of the owl and later in the nerve cells of a cat.

Linda: The electron microscope showed that it is in almost every cell and people think the Golgi apparatus collects and packs proteins that are built by the cell. Proteins that are produced by the endoplasmic reticulum go to the Golgi apparatus and are stacked in its hollow spaces (…) The function of the ER is transportation of the proteins.

Lotte: The Golgi apparatus exists of stacked hollow bubbles surrounded by a membrane. It looks like this (points at a picture in her text book). The inputs of the Golgi are proteins, because they collect them. The outputs of the Golgi are proteins in an altered form….

However, the classroom presentations of the organelles showed difficulties in developing a coherent picture of the cell only on the basis of the systems model and their textbooks. This was mostly due to the fact that students descended quickly to the molecular level when searching for answers and lost the overall picture of the cell as a whole. For example students who studied the nucleus in their textbook were confronted with many concepts on the molecular level. Instead of focusing on the organelle in the context of the cell as a whole, they tried to understand DNA end RNA.

The plenary reflection resulted in a general picture of the cell as a functional unit of the organism. Subsequently, the class discussion focused on the difference between various cell types. Functional considerations about these differences motivated students to make the transition to higher levels of organisation, i.e. the organ and the organism. After an individual assignment in which the similarities and differences between the cell as an autonomous and as a functional system were explicated, there was a final plenary reflection on the functional relation between the cell and the organism.

Analysing the problems of students in this last phase of the LT-strategy showed a lack of competence in using the systems model as a 'tool' to explore the cell as a functional unit of the organism. To solve this problem it was proposed to engage students more actively in the development of the model itself. Modelling cells needs to be a central activity in the LT-strategy whereby the complex character and microscopic scale of cells could provide a motive for developing a model, which gives more insight in the structural organisation of the cell. In the next section the revised LT-strategy, based on the results of the first case study is presented.

4.4 Revising the learning and teaching strategy

This section presents the revised LT-strategy that has been tested in the second case study of our cyclic research phase. Before presenting the second strategy in table 4.4 we will shortly go into the main revisions based on the results of the first case study as described in the previous section. These revisions concern three important elements of our LT-strategy and apply to different phases in the revised LT-strategy as outlined in table 4.4: the general orientation on cell biology (phase I), the process of modelling cells (phase II, III and IV) and the explication of systems thinking in phase V.

General orientation on cell biology, phase I - In contrast to the initial LT-strategy the general orientation phase in the revised strategy is connected with a teaching unit on growth and development. Although the process of cell division was not dealt with in detail, the preceding teaching unit shortly addressed cell division as a cellular explanation of body growth. Students' prior ideas about the relation between the organismic level and the cellular level within the context of growth and development provide a starting point to descend to the cellular level just from the beginning. Therefore the revised strategy started with eliciting this prior knowledge in LTA 1. In the subsequently class discussion the theme growth and development provided a central question to be addressed in the remaining course on cell biology (see LTA 2 in table 4.4): To what extent do our cells function autonomously?

Modelling cells, phase II-IV - In the first case study, the life processes proved to provide a meaningful starting point for both cell biology and systems thinking. The systems model also stimulated students to ask appropriate questions during their learning process, i.e. questions about the coherence of structures on the cellular level and questions concerning the relations between the cell and the organism. However, students showed a lack of competence in using the systems model as a tool in acquiring a coherent understanding of the cell as basic unit of life. To solve this problem, the revised LT-strategy focuses on engaging students more actively in the development of a systems model. This major revision went hand in hand with a better insight in the translation of the criteria formulated in section 3.4.5 into a LT-strategy that addresses the acquisition of a systems thinking competence, i.e. students should be able to distinguish the levels of biological organisation and to interrelate those levels within the organism. Moreover, systems thinking can be described as being able to think backward and forward between real biological phenomena and a general systems model of these phenomena at different levels of organisation. In order to achieve the intended learning outcome, modelling (as described in section 5.3) became an important element of the revised LT-strategy.

After the general orientation on cells in phase I, Phase II to IV engaged students in modelling cells and preceded the development of a general hierarchical systems model in phase V (see table 4.4). Phase II comprehends the development of an initial (still implicit) systems model of free-living cells that is based on students' idiosyncratic representations (LTA 3-6). Hereby students are stimulated to think backward and forward between their own representations, their observations of real cells and expressed models in their workbooks. Phase III addresses the application of the developed model to cells that are part of multicellular organisms (LTA 7 and 8). In this phase, students are stimulated to think backward and forward between different representations of animal and plant cells (see table 4.4, LTA 7-9). Subsequently students construct a 3-D model of a plant cell in phase IV (LTA 10). The choice for this LTA was also made because the teacher that participated in the second case study had positive experiences with this activity in terms of students' active engagement and acquiring insight in the spatial organisation of cells.

Explication of systems thinking, phase V - The final modelling step in the LT-strategy is the extension of the cell model and relating it with higher levels of organisation. This step goes hand in hand with the explication of systems thinking (see section 3.4.2 and 3.4.4). In contrast to the initial LT-strategy, explication of systems thinking occurs after students have explored the cell as a functional unit of the organism. The computer-aided programme (see table 4.4, LTA 13) is now integrated in the LT-strategy as a means to explore the relation between the cell and the organism. Moreover, reflection on the programme and the benefits of the hierarchical systems model should result in a recognition that the model can be useful to acquire insight in the relation between the cell and the organism it is part of: i.e. interrelate the cellular and organismic level. Finally, LTA 15 focuses on actually using the systems model to acquire coherent understanding of a biological topic that crosses several levels of biological organisation. This final step further consolidates students' systems thinking competence and addresses the acquisition of the hierarchical systems model as a metacognitive tool.

Based on a critical appraisal and revision of the LT-strategy in the first case study, it is reasonable to expect that the second case study will be more to the point in studying the characteristics of an adequate LT-strategy for cell biology based on systems thinking.

Table 4.4 ***Outline of the 2nd strategy for the cell as a system.***

Sequence of problems	Sequence of LT activities and learning outcomes
	<u>*I. General orientation on cell biology*</u> **LTA 1: Brainstorming in groups.** Eliciting prior knowledge about cells that is mainly related to the domain of growth and development. Students individually think of what they already know, discuss this in groups and formulate questions. • Students raise questions and wonder if their knowledge about cells applies to all cells.
To what extent do our body cells function autonomously (central question)?	**LTA 2: Class discussion** directed by the teacher. Introducing and orientating on the cell as a basic unit of the organism within the context of growth and development, which raises students' interest in questioning: All organisms develop from a single cell. At some point the different cells specialise in different ways, but who or what tells the cell what to do? Unicellular organisms are introduced as autonomous living cells. • Students wonder what functions (and how) cells must fulfil themselves leading to an interest in (autonomous) free-living cells.
What are the general characteristics of free-living cells?	<u>*II. Developing a model of free-living cells*</u> **LTA 3: Group work.** Reading a text about the smallest known 'free-living' cell (Mycoplasma genitalium), discussing the application of the life processes to free-living cells and drawing a schematic representation of the cell as an organism. • Students realise that the fundamental life processes apply to free-living cells but wonder how they achieve them.
How do free-living cells carry out the fundamental processes of life?	**LTA 4: Microscope practical and reflection**, introduced by a text about Antonie van Leeuwenhoek. Investigating real free-living cells (Paramecium) guided by the students' own schematic representations of the general characteristics of unicellular organisms and comparing their observations with their schematic representations. • Students understand that free-living cells have a general structure in which functional parts can be distinguished.
	LTA 5: Group work on a written assignment. Exploring the functions of the organelles within the context of nutrition resulting in a (final) general model of free-living cells. • Students understand that interaction between the (functional) organelles in free-living cells is essential to fulfil the life processes.
	LTA 6: Class discussion directed by the teacher. Reflection on the general model of free-living cells and raising interest in cells as part of an organism. • Students wonder if the model based on free-living cells also applies to cells in a multicellular organism.
Does the general model of free-living cells, also apply to cells that are part of an organism?	<u>*III. Application of developed model to cells as part of an organism*</u> **LTA 7: Microscope practical**. Studying real animal and plant cells through the microscope, guided by the model of free-living cells. • Students experience difficulties in observing the model characteristics and realise that they need a 'closer' look.

Sequence of problems	Sequence of LT activities and learning outcomes
	LTA 8: Group work on a written assignment. Studying electron microscopic photos of plant and animal cells and labelling and drawing the organelles. • Students realise that the cell is a complex functioning whole and feel the need for a clear overview of the cell.
What use are cell models in answering the central question?	**LTA 9: Individual assignment,** introducing a cellular model. Reading a text about the use of cell models and reflection on the process of modelling cells in this course. • Students understand the function of cell models.
	IV. Building a model of a plant cell
How does the cell as a functional unit of an organism carry out the life processes?	**LTA 10: Homework assignment (in pairs).** Exploring the characteristics and cellular functions of one specific organelle, guided by the systems model and building a 3-D model, which will be placed in a 3-D model of a plant cell. The schoolbook and Internet are used as information sources. • Students value the systems model as a useful tool to reduce the complexity. They can give a presentation about the functioning of one specific organelle and relate it to the cell and other organelles. Students are enabled to engage actively in LTA 11.
	LTA 11: Class presentations, combined by the teacher. Presenting the results of LTA 10, listening to the other presentations, placing the 3-D organelles in a 3-D plant cell and interrelating the organelles and explaining their cellular functions. • Students get a coherent understanding of the cell as a functioning whole.
	V. Explication of systems thinking
How do cells as functional units fulfil their functions?	LTA 12: Group work on a written assignment. Reading a text about stem cells and discussing the dependence of individual cells on information from their environment. • Students realise that (specialisation of) cells require(s) signals from their surroundings and cells fulfil their functions in an organised whole.
How are multicellular organisms organised?	**LTA 13: Computer-aided programme in pairs**. Exploring the process of digestion, on the organisational level of the organism, organ and cell. • Students realise that the cell model also applies to cells and organs in an organism, and get a clear overview of how the body is organised.
	LTA 14: Plenary reflection on LTA 13. Explicating the levels of organisation and the general characteristics of living systems. • Students understand the hierarchical structure of the body and the general system characteristics, which apply to organisms, organs and cells.
What is the function of a systems model?	**LTA 15: Group work.** Applying the systems model and interrelating the structures and processes at different levels of organisation within the context of a specific biological phenomenon (a nursing mother). • Students view the systems model as a tool to explain and acquire a coherent understanding of a biological phenomenon at different levels of organisation.

4.5 The second case study

The revised strategy for the cell as a system was elaborated in a second scenario to be tested in the second case study. Table 4.5 shows the LTA's and their duration in order of appearance in the subsequent lessons. The scenario was field-tested in two groups of students with the same teacher (see table 4.1). Between the lessons of both groups there was little time so only minor changes could be made with respect to the implementation of the scenario in the classroom practice when problems in the first group were observed. The results described in this section are mainly based on the lessons of the first group of students; the results of the second group will only be discussed when they differ from the first group.

Table 4.5 ***Actual arrangement and duration of the LTA's in the 2nd case study*** *(hw = homework assignment). For a more detailed description of the LTA's see table 4.4.*

Lesson	Time (minutes)	Learning and Teaching Activities	
1*	15	LTA 1:	Brainstorming in groups, eliciting prior cell biological knowledge
	25	LTA 2:	Class discussion on the cell as a basic unit of the organism.
2*	10 (hw)	LTA 3:	a) Reading an article about Mycoplasma genitalium
	10		b) Group discussion on the fundamental life processes of free-living cells and drawing a schematic presentation
	30	LTA 4:	Microscope practical on free-living cells and reflection
3	20 (hw)	LTA 5:	a) Written assignment. Exploring the functions of the organelles
	20		b) Group work resulting in a general model of free living cells
	20	LTA 6:	Class discussion on the general model of free-living cells.
4	50	LTA 7:	Microscope practical on animal and plant cells, guided by the model of free-living cells.
5	40	LTA 8:	Group work. Studying electron microscope photos of plant and animal cells.
	10	LTA 9:	Individual assignment. Reflecting on the process of modelling cells in this course.
6	50 (hw) + 50	LTA 10:	Homework assignment. Exploring a specific organelle, guided by the systems model and building a 3-D model.
7	50	LTA 11:	Class presentations on the results of LTA 10, placing the 3-D organelles in a plant cell and interrelating the organelles.
8	30	LTA 12:	Group work on stem cells and discussion on the dependence of individual cells on their environment.
	20	LTA 13:	Computer-aided programme in pairs. Exploring the process of digestion on the level of the organism, organ and cell.
9	10	LTA 14:	Plenary reflection on LTA 13. Explicating the levels of organisation and the general characteristics of living systems.
	40	LTA 15:	Group work. Application of the hierarchical systems model to a specific biological topic.

*Indicates lessons of 40 minutes due to meetings of the teaching staff

As will be clear from section 4.2.3 describing the results reflects a process of thinking backward and forward between the scenario and the actual learning and teaching processes in practice. This section analyses to what extent the intended processes of learning and teaching actually took place. It outlines the processes in chronological order and aims to provide a narrative in order to make the learning and teaching processes accessible for discussion and reflection, which follows in chapter 5. The evaluation criteria and research questions of the first case study, presented at the beginning of section 4.3, also apply to the second case study. In addition and due to revision in the second LT-strategy that underlined the importance of 'modelling' another analysis question is formulated:

⑤ Are students able to think backward and forward between the general systems model and more concrete representations of cells, i.e. ranging from cell models to *real* cells seen under a microscope?

4.5.1 General orientation on cell biology

The first two LTA's accounted for the introduction of cell biology, connected to the theme of the foregoing lessons (growth and development) and raised students' interest in free-living cells. During these activities students also raised their own questions giving them a personal interest in following the course. The first assignment activated students' prior knowledge about cells and let students experience difficulties in integrating these concepts in their own words. As expected students' prior knowledge was largely derived from form one (age 12-13, Dutch: brugklas), which dealt with the very basics of the structure of cells, and the domain of growth and development. Students were able to relate body growth to cell division. However, the cellular basis of growth and development evoked questions and provided a meaningful starting point to engage students in questioning the autonomy of body cells in the following class discussion. Questioning the autonomy of body cells will then raise an interest in free-living cells, which will be introduced as complete autonomous cells.

After handing out the workbooks the teacher gave the students a short moment to glance through the material and points them at the study guide, which was handed out the previous lesson. Without further introduction he instructed the students to start with the first assignment: 'Write down what comes up in your mind (when you think of the word cell) and then discuss it with each other'. From form one, in which students had seen cheek cells and some plant cells under the microscope, students remembered that cells were made of a centre (they didn't mention the nucleus), a cell membrane, a cell wall and cytoplasm. Many students, however, wondered if these characteristics are general to all cells:

[2[1]:1.G.5]

Elske: I have cell membrane, nucleus, cytoplasm, relatively small, cell division and microscope preparation.

Nienke: I have small, being present in an organism for instance for transport of food, unicellular or multicellular organism, nucleus, and cell membrane.

Lisa: I have blood, plants, cell wall, cell membrane, microscope, organism, and…

Together: Unicellular and multicellular …the cell is a part of an organism, but you also have unicellular organisms…

[…]

Elske: …But not all cells do have a cell wall.

Lisa: Don't they? They do, don't they?

Elske: We learned that in the eighth or in the seventh class, we really looked at a standard cell then.

Nienke: We looked at a plant then, didn't we?
Elske: Yes, and there was a difference, I think eh…. well, so we don't know that, but that is coming with those next questions, isn't it?
[…]
Elske: And membrane, nucleus, but is that always the case. I think not all cells have a nucleus…well that is a question. Are all cells composed of…?
Nienke: Not always, but mostly they do. I think they don't always have a nucleus and a cell wall neither.
Lisa: They do have a nucleus, don't they?
Elske: Well, that's what we're going to ask.

These students referred explicitly to form one, which dealt with some general characteristics of a 'standard cell' and they doubted whether these characteristics are indeed general or not. These doubts were translated into some questions about the composition of cells as their workbooks show:

[2[1]:1.W.6]
– What (which parts) are cells made of?
– Do all cells have a centre, cell membrane, cell wall and cytoplasm?
– Are all cells built according to the same building plan?

These questions can provide an important motive to engage in this course during which students will find out the general characteristics of cells themselves and build a cell model based on these characteristics.

The uncertainty of students about the general characteristics went together with the awareness that cells are specialised to perform a specific function as the discussion between the same students shows.

[2[1]:1.G.7]
Nienke: I don't have everything yet…what it (the cell) takes care of
Lisa: What do you mean, what it takes care of?
Nienke: I've written for example: transport of food
Esther: Growth too, isn't it? That it's going to divide.
Elske: No, I mean support, I mean: white blood cells close a wound eh, you have different, …there are so many different.
Elske: Wasn't to fight diseases?
Nienke: Yes, and red cells were for transport of oxygen
Elske: Yes and blood plasma was for curing wounds

As expected, the domain of the previous chapter, growth and development was an important domain that students' prior knowledge referred to as fragment [2[1]:1.G.8] illustrates. This provided a starting point to put forward the main question in LTA 2: '*To what extent are our body cells autonomous?*' In the foregoing chapter cell division or mitosis was connected to body growth, and thus related to the level of the organism. Therefore students knew that growth and development can be described at the cellular level and tried to formulate the relationship between cell division and body growth:

[2[1]:1.G.8], T is teacher
Jaklien: We know something about mitosis, meiosis, blood cells, and cell division. We could also write down division of a zygote first and then cleavage. Okay?
T: You're thinking and talking but you have to write it down too, try to put into one sentence what you know about cells now.

Jaklien: They have to divide to grow for example.
T: For instance. You know they divide and what else did you say?
Jaklien: By doing so they can grow, or do they have to divide first to be able to grow?
T: Are cells able to divide just by growing?
Jaklien: No.
T: So, when a cell hasn't divided it isn't able to grow.
Jaklien: Yes it is.
Marja: Yes, but then it's huge, and then it cannot grow any further, does it?
Jaklien: It divides first.
T: But, then it becomes smaller through division.
Marja: Yes, and then it grows again till his normal size, after which it divides again.

In the discussion above, Jaklien and Marja try to formulate a cellular description of growth and development that makes sense to them. As the worksheets show, many students spontaneously related the cellular level with the organismic level within the context of growth and development, including regeneration.

[2[1]:1.W.9]
– You're able to grow because your cells divide and grow to their normal size again.
– Cells divide and grow: mitosis in the whole body and meiosis in the germ cells.
– Body cells are replaced when they are broken.

Thinking about the cellular basis of growth and development generated questions as: 'Does a cell have a maximum size?', 'Which part of a cell divides first?', 'How does a cell get its function?' These questions formed a good starting point for the class discussion. The teacher combined them and placed them within the context of growth and development: 'Suppose there is a maximum size of cells, how does a cell know when to stop growing?' The discussion focused on the autonomy of cells in the human body.

At first the brains were thought to regulate a cellular process like cell division but because plants don't have brains this possibility was turned down. Then the teacher asked students to recall the title of the last chapter: 'from zygote to scholar'. Students remembered the cell cleavages after fertilisation, which result in a lot of small cells, and no growth of the beginning embryo. So, besides cell division, growth of the organism requires growth of individual cells. Because each organism originates from only one cell, it was decided that cells themselves must have information to regulate cell division and growth.

Later in the discussion the teacher asked how the cells around a skin wound know when to start dividing and specialising. It was put forward that cells have certain characteristics, which are fixed in the DNA of the cell. Students had an important input in the discussion, which focused at getting a better understanding of the regulation of cell division. The central issue was the relation between the body and its cells: Are cells regulated by signals from outside or do they have some kind of information, which gives them the opportunity to trigger division themselves? This information was supposed to be DNA, although it was acknowledged that every cell contains the same DNA. The question how the DNA is translated into the specific characteristics in each cell remained open.

The class discussion provided a useful starting point to engage students in LTA 3, which dealt with autonomous or free-living cells. However, in this first lesson the teacher didn't refer to the next activity or make the contrast between autonomy and dependence of the organisation in the organism explicit. In the group discussions most students noted that cells can be a whole organism or can be a part of an organism and students also brought this forward directly during the class discussion. As in the group discussions, the contrasting difference between these cells wasn't noticed or questioned by students or by the teacher. After the lesson, the teacher explained in an interview that he wanted the students to question it themselves, not steered by him, and the group discussions showed that students already understood that cells could be part of an organism or a whole organism. Apparently, at that moment, the teacher did not realise the importance of questioning the contrast between free-living cells and cells in a multicellular organism in raising a motive for LTA 3. Instead, the teacher summarized the answers given by the students and concluded that 'they know almost everything about cells', and that 'we only have to fill in the details'. In the remaining class discussion the teacher asked questions of what parts of our body, or other stuff outside our body, are made out of cells. This question was triggered by a student who said that everything is made out of cells. In the following class discussion she was corrected by other students, where after the teacher started a discussion about which parts of the body are (not) made up of cells.

Before the start of the microscope practical at the end of LTA 3, the teacher asked the students why they are going to study a free-living cell first:

[2^2:2.C.10], T is teacher

T: Why are we going to… and then we can start reading and subsequently look through the microscope, why are we going to look at unicellular organisms? Why don't we start with looking at muscle cells, nerve cells, and eh intestine cells? Why do we start with a unicellular organism?

Tim: Because you first have to know how one cell works

T: Uh, couldn't you do that on the basis of a blood cell or a cheek cell?

Tim: No, because then you would see several cells.

T: Then you would soon see several cells and you would like to concentrate on one cell first, all right. Besides, what is interesting about a unicellular organism? What must that one cell be capable of doing? Who can say in one word what a unicellular cell must be able to do?

Elly: To live.

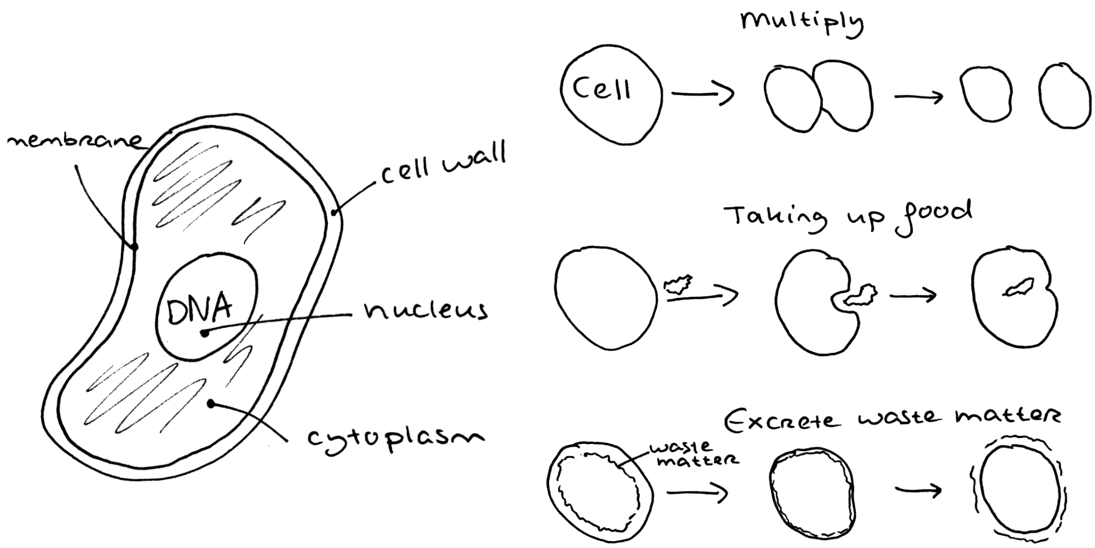
T: That's correct. I would have wanted to hear something else…No that's good; it has to live. It must, and that is what I wanted to hear, be able to do everything. And a muscle cell doesn't need to be able to do everything, etc. Yes, so why do we start with a unicellular organism, then you know that is has to be able to do everything.

The reason to begin with studying free-living cells seems logic to students because they are orderly and a good basis to start with because these cells must fulfil all life functions by themselves. In turn, the context of growth and development provided a promising domain to involve students in a discussion about the autonomy of cells. Moreover, interviews showed that students were positive about the lessons, because their own questions were central in the discussions. However, in order to enhance the general motivation to focus on the contrasting differences between the cell as an organism and the cell as part of an organism should be made explicit and evoke more amazement.

4.5.2 Developing a model of free living cells

In LTA 1 and 2 students questioned the general applicability of their knowledge about cells. The cell was presented as a basic unit of multicellular as well as unicellular organisms. In this phase the general functions of life served as a meaningful basis to investigate free-living cells. LTA 3 started subsequently with answering the question what a unicellular organism must do to be able to live independently.

Because the second lesson appeared to be only 40 minutes of duration due to a shortened school timetable that day, LTA 3 was given as a homework assignment. This LTA came largely up to our expectations. Students referred to some general descriptions of the fundamental life processes as feeding or taking up nutrients (and utilize it for energy or as building material) breathing, grow, regeneration, excrete waste material and protecting itself. The drawings of the unicellular organism in both classes could be classified in two groups. One group, consisting of twelve drawings, displayed students' prior knowledge concerning the basic structural elements in plant and animal cells. All cells were nearly empty, except for the nucleus with DNA and the cytoplasm surrounded by the cell membrane and cell wall (see figure 4.2a). The other group, consisting of seven drawings, were made by students who tried to depict the life processes more dynamically (see 4.2b). Six students did not hand in their drawings or were not present during the lesson.



a. **b.**

Figure 4.2: ***Two representative (first) student drawings of a unicellular organism resulting from LTA 3.*** *Drawing* ***a.*** *focuses on structural elements, drawing* ***b****. focuses on the life processes. See text for further explanation.*

So, although students were asked to depict the solutions of unicellular organisms to achieve the life processes, the majority drew the cellular structures they could recall. However, a substantial group of students already came up with some possible solutions. For instance, the drawings showed three solutions could be distinguished that students came up with for the food uptake of a cell surrounded by a membrane (see also fragment [2[1]:2.C.11].

Both groups of drawings provided an input for the subsequent class discussion on the fundamental processes of life. Students realised that these functions apply to free-living cells but wondered how they are actually able to fulfil them. In the class discussion the problem of the food uptake is discussed further and the three options, were put forward.

[2[1]:2.C.11], T is teacher

T:	In what way do you think the mycoplasm takes up its food?
Lisa:	I think by means of vesicles, since that was said in the book, but that's it.
T:	Vesicles, is that a normal way of taking up? How do you take up food?
Lisa:	With my mouth.
Nienke:	(whispering) a hole.
T:	Could you compare those vesicles with a mouth?
Lisa:	Yes, I think so.
T:	But what's the difference. If you take up something with your mouth, and swallow it, what happens then with your mouth?
Lisa:	O, it's still in the same place.
T:	And the vesicle?
Lisa:	That's also going inside.
T:	Exactly, so that could be the difference. Who has thought of another way of taking up food, as mycoplasma does?
Judith:	It's going to enclose it and takes it up.
T:	So then you will get a vesicle. So that is in different words, totally differing from those of Gabrielle. Who has thought of still another way? Who has something else then vesicles?
Judith:	Cell mouth…

The teacher then noticed that the question how the cell takes up its food, remains to be answered by means of observations. The question how cells carry out the life processes is somewhat reformulated by reading a text about Antonie van Leeuwenhoek who thought to observe organs in his micro-organisms:

[2[1]:2.C.12], T is teacher

T:	Why did Van Leeuwenhoek think that micro-organisms also had bowels like that of a big animal?
Ilona:	He knew little of it.
T:	Yes, but why then did he expect that they had bowels?
Elske:	Because they could move.
T:	And so…
Nienke:	He just thought they were animals.
Elske:	And therefore there must be energy, and so he must eat, and thus there should be…
T:	Exactly, a combination of Elske and you. They are animals, they could move so they probably have bowels. This in itself is a very logical train of thought. Eh, why can't they have bowels?
Ilona:	Too small.
Elske:	Composed of cells.
T:	Yes, organs are composed of cells, so it's technically impossible. So, then the question is: how does a micro-organism do it? And that's really the question and therefore I leave it open to you. If a unicellular organism doesn't have bowels, how does he do it then? What should it have instead?

So the motive to look at free-living cells under the microscope is answering the question of how cells carry out the processes of life, knowing that they don't have organs.

Although Van Leeuwenhoek observed ‘organs’ in unicellular organisms, students were still not convinced that a cell must have some functional parts in it. To them a cell is empty and cannot contain organs (for example for digestion), or as Elske whispered after the class discussion mentioned above: ‘I think it just takes up things that it can use as energy immediately.’

Consistent with the above statement, the students were surprised to see structures in the cell, which they called things, granules, rounds, and dots etcetera (see figure 4.3). The students reacted enthusiastically when seeing the rapid moving creatures or animals. Although *Paramecium* is animal like, ‘because plants don’t move’, they were sure that *Paramecium* does not have organs because it is unicellular. The students questioned what the observed structures in the cell might be.

[2^1:2.G.13], R is researcher

Peter: Sir, when you look at that cell, you see all kinds of small circles. Have those things been taken up?
R: Let’s have a look…what do you think they are?
Peter: Yes, things that have been taken up or so… I don’t know what it could be else.
R: But is there more inside cells?
Peter: Cytoplasm, DNA-nucleus and cell wall.
R: And is there still more inside cells?
Peter: I don’t think so…

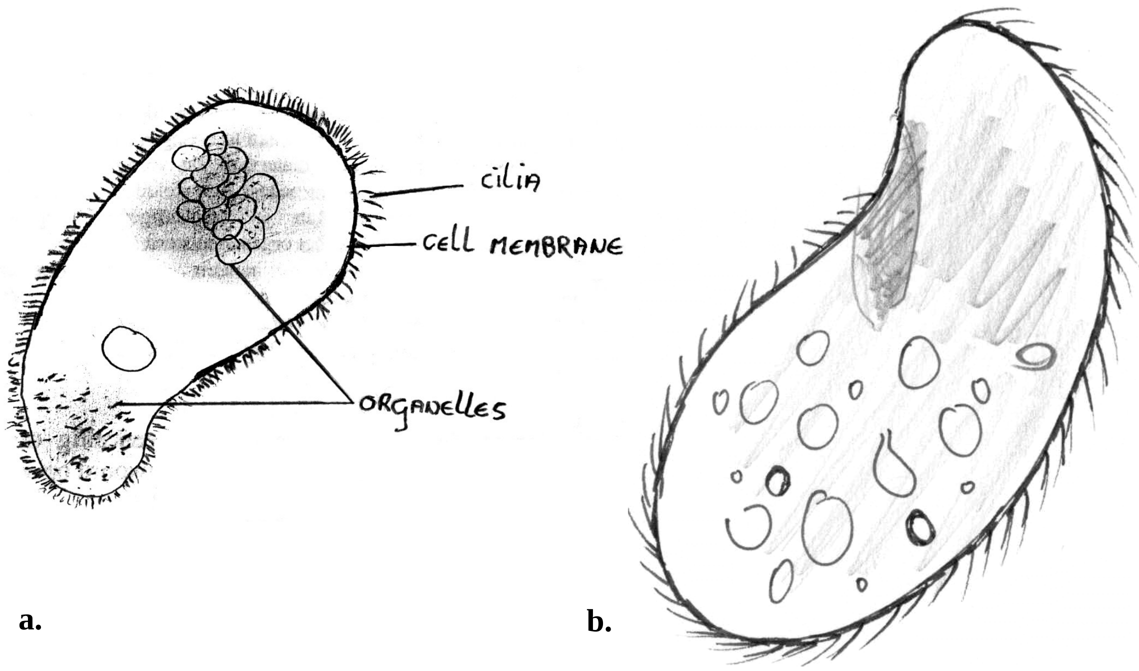


Figure 4.3 Two student drawings of *Paramecium* (Dutch: Pantoffeldiertje) resulting from LTA 4. Both drawings clearly show the cilia on the outside of the cell membrane and the multiple food vacuoles, which are named dots, circles, etcetera by students during the observation. In 4.3a the students added some labels afterwards. The left dark spot against the membrane in 4.3b represents the cell mouth.

As figure 4.3 shows, the cellular parts, that in reality represent food vacuoles was observed and depicted by nearly all students. After the lesson, 25 students handed in drawings that resemble the drawings in figure 4.3. At that time, six students had labelled the dots already with the term ‘organelles’. However, during the lesson the students did not suggest that the parts in cells could be some kind of organs. At first some students concluded that it must be food, but at the end of the lesson students started discussing whether these parts could be the organs that Van Leeuwenhoek had observed after all:

[2[1]:2.G.14], T is teacher

T: Are these the organs that Van Leeuwenhoek could have seen?
Esther: Well, I think they aren’t organs.
T: No, but could this be what he thought it was?
Esther: I think so...what are they then?
T: That is the next point, but what do you think they are? […] Could they be the organs he meant even though they are not organs? Or have they been taken up, are they the vesicles Lisa was talking about…keep that in mind in the next lesson.

At this moment students had studied the unicellular organisms and decided that they must be moving animals. There was no doubt that these animals have to fulfil the functions of life. The question how they fulfilled them disappeared to the background. Instead, students focused on the question what the parts were in the living cells that they were observing. So the next step in the strategy was to link these observations to the life processes and to introduce the organelles as ‘organs of the cell’. This was done in a short text in the students’ worksheet, which now provided the right information at the right time and answered the question about the cellular parts:

[2[1]:2.C.15]

Teacher: ‘If you looked well through the microscope, you were able to see that we can distinguish different parts in unicellular organisms. You could call these parts ‘the organs of the cell’. They fulfil specific functions for the organism that they are part of. But instead of organs we call those parts in unicellular organisms *organelles*. So *organelles* are the organs of cells. Because the different organs are difficult to see under a microscope, there is a schematic representation of *Paramecia* at the next page. This representation is the result of microscopic investigations of many researchers under which those of Antonie van Leeuwenhoek.’

Next, as introduction to LTA 5, the different organelles were introduced by means of a schematic representation of *Paramecium*. In order to get a more coherent understanding of the free-living cell, students explored the functions of the different organelles starting with a picture of the whole cell and its organelles. In order to acquire a more dynamic understanding of the functioning cell and the relations between the organelles, the process of digestion was studied.

The exploration of the organelles came up to our expectations. The previous LTA evoked interest in the specific organelles and students recognised the picture of *Paramecium* from their observations. Some students explicitly referred to their observations during the foregoing lesson and remembered seeing the membrane, the flagella, and the cell mouth: ‘you could see the cell and a large vesicle or something next to the membrane and smaller globules coming inside there, so I think that was the cell mouth’. Although the other organelles were completely new to the students, no student doubted that the schematic representation was the same cell as they had seen under the microscope. Moreover there was no doubt anymore about the functionality of the observed rounds, dots etc. in LTA 4 and the fact that they were the same organelles as depicted in the worksheets.

The functions that students came up with were mostly formulated similar to the fundamental processes of life as described in LTA 2: uptake of food, digestion, excreting waste material, protection and reproduction. Students were also stimulated to discuss about the organs that fulfil the functions in the human body. It was expected that within the context of the human body, students would come up with new functions. Moreover, comparing a multicellular organism with a unicellular organism would show that the functions are indeed general for all organisms.

Although students realised that the different functions they linked to the organelles also have to be fulfilled by organs in their body, as the worksheets show, the comparison between organs and organelles did not stimulate students to link some bodily functions to unknown organelles. The discussions about the organelles remained at the cellular level and only afterwards students linked the function to the right organ. As the discussion in the next protocol shows, thinking backward and forward between organelles and organs was problematic and did not help students in their discussion about the functioning organelles:

[2[1]:3.G.16], T is teacher

Rachen:	What is a contractile vacuole?
T:	Didn't you come up with something?
Judith:	No.
T:	You could also turn it around. Then you could say what kind of function does a cell have to fulfil? And thinking of contractile, what does contractile mean? Where does it come from?
Rachen:	Contraction, isn't it?
Judith:	Yes, contraction.
T:	Yes, and your muscles are able to contract too, and what is a vacuole?
Rachen:	A vesicle.
T:	So, it is a vesicle that can contract…. and what kind of association do you now have if you think about organs?
[…]	
Rachen:	I don't know, but I think you shouldn't reason like this. Because in such a cell everything is different, so you can't say that something that contracts is the same as a muscle.

Rachen apparently knew that organs and organelles are both functional parts, but differ in the way they fulfil their functions. During this activity in most student groups the differences between the cellular (microscopic) level and the organismic (macroscopic) level were discussed explicitly. Students realised that the characteristic of being a cell has specific consequences in the way it functions and in no group discussion students just establish an isomorphism between the functioning of multicellular organisms or unicellular organisms. Instead, as the next fragment shows, when discussing the cellular process of digestion students tended to stay at the cellular level or even to descend to the molecular level. The next piece of protocol deals with the question which characteristic of the membrane allows nutrients to leave the feeding vacuole:

[2[1]:3.G.17], T is teacher

Elske:	… Those blue arrows, we said, that's where it is taken up. But, how to say with what kind of process that happens; *how* that happens.
Lisa:	Yes, we now you have to say *how*; whether that wall suddenly disappears or opens all at once or…

Nienke: It's not a wall, it is a membrane and it just passes.
Lisa: Yes.
Elske: Okay, it has to go pass it, but how that is a mystery to me. (...) How actually are those nutrients going out?
Nienke: Yes, it has to pass that cell membrane, isn't it? But…
[…]
Lisa: Are there holes in such a cell membrane?
T: How do you imagine the cell membrane?
Lisa: Well, a thin film but closed, so it can't pass then. So, then there should be holes or something alike in it.
T: But what are membranes composed of, always?
[…]
Elske: They're composed of atoms.
T: Everything is composed of molecules, yes. So, does such a membrane, a thin film then consist of molecules?
Lisa: Well, it probably does.

Then the teacher made an analogy between the membrane and a T-shirt and explains to students that both are permeable to some materials like water, air or sweat. Students conclude: 'I think the membrane remains connected indeed; these nutrients have been made so small that they're able to pass through (the membrane) and the indigestible stuff cannot pass…'

In fragments [2^1:3.G.16] and [2^1:3.G.17] the discussions about the process of cellular digestion are focused on the functioning of a certain organelle. The question how an organelle does work directed students to the molecular level. Another objective during this LTA was to focus on the relations between the organelles. However, students' reasoning about relationships continued to be rather superficial. The nucleus for example was proposed to be an organelle that '*contains all kinds of information and regulates everything in the cell'*. The nature of this regulation was not questioned. The same applies to answering the question what happens with the nutrients (in the feeding vacuole) when they reach the cytoplasm. Only few students answered that the nutrients were needed by other organelles as energy source or building material and thus had to be transported there in some way. Most students, however, just answered that the nutrients are being circulated in the cell and consumed by the cell 'to live'.

The teacher also noticed that the cooperation between organelles wasn't really an issue for students as he said in an interview afterwards. For him, this was an important reason to deal with it in the following plenary discussion (LTA 6). So in order to achieve the learning objective, i.e. acquiring a coherent understanding of the free-living cell, LTA 6 focused on both functionality of the organelles and on cooperation between them.

In LTA 6 the LT strategy so far was reflected on. The objective was to build a general model of free-living cells, based on the students' input. The model should become a meaningful tool to explore animal and plant cells. In other words, LTA 6 should introduce or evoke the question: *Does the general model of free-living cells also apply to cells that are part of an organism?*

The teacher started the class discussion by drawing a very simple cell (an empty circle) on the blackboard that resembled the first drawings of most students in LTA 3. He explicitly referred to these and then directed the discussion to what's inside the cell.

Students came up with the names of the organelles as depicted in the workbook. In this phase the input of the teacher was crucial in bringing students to a more general level. During LTA 5 students were mainly focused at the specific organelles and their functions in *Paramecium,* but also looked at other unicellular organisms, e.g. amoeba, to grasp the general nature of the characteristics distinguished. Now the teacher summarised their empirically based input and described it on a more general level as functional parts of the cell. 'Van Leeuwenhoek thought they were organs, but we now know these parts as organelles, which can be seen through a light microscope'. Then the teacher went deeper into the functions of the different organelles and emphasized the relationship between them:

[2^2:3.C.18]

T: What does the nucleus do?

Mary: We think to regulate all kinds of stuff and storing information.

T: Did you compare it with the brains?

Mary: Yes.

T: (pointing at the picture on the blackboard) Okay, storing information and regulating stuff. That means, if this is the nucleus, it has to send the information there, but it must also receive information. So it must send and receive information. (The teacher draws arrows on the black board to and from the nucleus). I have drawn four of them, so that they fit in this scheme but you could draw five or six arrows as well. (…) So, the different organelles influence each other. If one fails, the system will be totally different. Without a nucleus: that's very sad. Without a contractile vacuole: where do I leave my water then? Without a cell anus: and what about my waste?

In the last phase of the plenary reflection the teacher summarised the characteristics of the whole living cell and related the life processes to the model of the free-living cell, which he had drawn on the blackboard. Although the students' contribution is mainly related to concrete characteristics of *Paramecium*, students realised at the end that the characteristics discussed so far apply to all free-living organisms. This was indicated by Peter's spontaneous question put forward during the class discussion after the teacher's above mentioned summary: 'Does that (the characteristics displayed in the model) just apply to free-living cells or does it apply to all cells'.

At the end of LTA 6 an empirically based model of free-living cells was developed, based on the notion that free-living cells must perform the basic processes of life. Students' observations and drawings of real cells formed a concrete basis for the development of a general model of all free-living cells. Peter apparently is convinced that the developed model goes for all free-living cells and raises the question if the model could be applied to all cells, including animal and plant cells.

The teacher acknowledged Peter's question as being very important and summarised the characteristics of free-living cells once more: (1) A cell contains a membrane which enables input and output of materials, (2) a cell contains organelles that fulfil a specific function for the cell, (3) the organelles are interrelated. Then the teacher repeats the question of Peter as the central question to be answered in the next lesson: 'Do our body cells also have to perform the fundamental processes of life? So, do the characteristics also apply to cells in our body?'

At that moment the question could not be answered yet with full confidence as a short interview with two students showed. On being asked they both disagreed. In favour of a positive answer they mentioned that our body cells are alive and thus have to fulfil the fundamental life processes. However, specialised cells 'don't need to be able to do everything' made the students doubt of the general applicability of the model, thus providing students with a motive for the next step in the LT-strategy: investigation of plant and animal cells.

4.5.3 Application of developed model to cells as part of an organism

In LTA 7 students studied real animal and plant cells under the light microscope from the cheek, bone, pancreas, intestine, blood, waterweed, red onion, buttercup and hyacinth. Students were instructed to focus on the presence of the organelles and the membrane in order to answer the main question: *Does the general model of free-living cells also apply to cells that are part of an organism?* The structures of the selected cells were very different, but in answering the question students were stimulated to look for similarities. In interpreting the observations through the microscope the teacher played an important role. He helped students with finding the right magnification and made sure that students were able to focus at individual cells. In doing so students had difficulties in seeing the organelles in all cells. In some cells, like waterweed, multiple organelles could be observed, while in cheek cells only the nucleus was visible. Other animal cells were to small to see anything in it. This raised the problem of how a better understanding of the structure of animal and plant cells could be obtained. In the final class discussion it was concluded that on the basis of light microscopy it is impossible to say more about cells. So, a motive was raised to introduce an alternative: electron microscopy. A more detailed description of the application of the developed model to cells as part of an organism is given below.

LTA 7 started by explicating students' expectations by answering the following question on their worksheets: *Do you expect that the characteristics as you depicted in the model of free-living cells also apply to plant and/or animal cells? Explain your answer.*

In the first group most students (10 out of 12) expected that the characteristics also go for animal and plant cells. In explaining their answer they referred to the need of performing the fundamental processes of life in general or to performing one process in particular: 'A cell also has to take up food and to emit it in order to remain alive.' This was not surprising, because the model of free-living cells was developed to a large extent within the context of nutrition. However, two students who agreed that the model applied to all cells, remarked that taking up food was not necessary because some cells 'do photosynthesis'. Apparently these students had the idea that photosynthetic cells don't need input of food, but acknowledged the fact that these cells do have functional organs and need some other kind of input (sunlight).

Contradictory to the beginning of the strategy (LTA 1), when students questioned the fact if some known structures like the nucleus and cell membrane were general cell structures, the majority of the students in the first group now expected the characteristics as depicted in the model of LTA 6 to be general. The difference with the second group of students was striking: 7 out of 12 students still expected animal and plant cells to have characteristics different than free-living cells. Four of them remarked that animal and plant cells also fulfil additional processes (not further specified), thus acknowledging that the fundamental processes must be fulfilled too. Three students rejected the applicability of the model to animal and plant cells based on the fact that these cells do not have to fulfil all fundamental processes themselves, because they are able to cooperate. Apparently these students had some notion of cell specialisation, but could not yet differentiate between the fundamental processes and processes that enable the cell to fulfil specific functions. Taking into account fragment [2^2:2.C.10] on page 90, the discussion in LTA 2 might have resulted in students having this idea. In that fragment the teacher explicitly stated that ‘a muscle cell doesn’t have to do everything itself’. Most students assumed however, according to their completed worksheets, that animal and plant cells have to contain some organelles, especially a nucleus.

Despite the different expectations of students described above, the motive to investigate animal and plant cells under the microscope still was the same from the perspective of the fundamental life processes. The central question during this LTA (*Does the general model of free-living cells also apply to cells that are part of an organism?*) stimulated students to focus on single cells and the presence of organelles in it. So, the students who stated that plant and animal cells had to fulfil the fundamental processes of life, linked this to the presence of organelles. Observing the organelles then proved the general applicability of the model developed in the previous LTA. However, during the practical, searching for the organelles became a goal in itself, while the life processes, which should provide students with a global motivation during the whole LT-strategy, disappeared to the background.

At the start of the practical there were some visual image difficulties. When studying animal tissues, most students had trouble with finding and selecting single cells. The teacher played an important role in interpreting the microscopic images by explaining the structures visible at the tissue level. This sometimes raised unexpected questions about the organisation of the cells at a higher level. ‘We saw all cells, but they were all in one larger cell again. Or, I mean in one large whole because there are more large wholes in that thing we saw under the microscope. Is there a name for that?’

So, students realised that the observed cells were part of a larger whole. However, students’ observations were mostly directed at the cellular level. In practice, answering the central question stimulated students implicitly to differentiate between the cellular level and higher levels of organisation, because students put a lot of effort in trying to focus on individual cells. In doing so, the teacher’s guidance seemed essential for students to interpret the microscopic images, for example in determining the size or three-dimensional form of individual cells.

As expected, students were surprised when seeing cells under the microscope. In some plant cells students could not distinguish structures at all, while other cells contained multiple dots, which were supposed to be the organelles. Most animal cells were too small to see anything in it, except for the nucleus in cheek cells that students had studied before in lower secondary school. Although beforehand, most students described the processes of life as essential processes for both plant and animal cells, the observed differences between the various cell types made students doubt about the general applicability of the characteristics of free-living cells. Within this context fragment [2^2:4.G.19] is exemplary:

[2^2:4.G.19]

Mary:	Does your drawing of a plant or animal cell correspond to your model of a unicellular organism?
Birgit:	There are far less things in it.
Evi:	In plant cells you don't see organelles.
Mary:	There are fewer organelles in them.
[…]	
Birgit:	There are no organelles in them and they don't move.
Evi:	I don't think so; I think there are organelles inside them.
Hanna:	I don't think so either.
Birgit:	In blood there were no organelles.
Evi:	That's because in blood there is nothing at all.
Hanna:	No, in blood not really.
Birgit:	And here neither.
Mary:	So there are almost no organelles inside.
[…]	
Evi:	What are the similarities?
Birgit:	They both have a cell wall.
Evi:	I don't think they all have actually.
Hanna:	They do have a cell wall and a cell membrane, and eh they don't all have a nucleus.

Fragment [2^2:4.G.19] shows that although the discussion dealt with the application of the developed model based on the general functions of life, these functions do not play a crucial role in the discussion. Instead, the discussion focused on the presence or number of organelles in different cell types. And instead of reasoning on a more general level, the presence of specific organelles became an issue. The observed differences between cell types or rather the lack of organelles in some cells, is an important reason to doubt the model. Mary, Birgit, Evi and Hanna therefore did not decide whether or not the model applies to animal and plant cells. As the completed worksheets of all students show, after the practical they did not conclude that the model applies to animal and plant cells. Most students still had doubts while some students explicitly rejected the model. In doing so, they referred to the fact that they detected fewer organelles in animal and plant cells than in *Paramecium* or that they detected no organelles at all. Most students differentiated between the presence of organelles and a nucleus. Plant cells were generally described as lacking a nucleus, while animal cells were supposed to contain no organelles at all.

An important aim of LTA 7 was that students should realise that in order to draw a final conclusion about the cell model, using the light microscope does not suffice. Few students explicated this way of thinking in their worksheets spontaneously while referring to the shortcomings of their observations. However, during the class reflection the electron microscope was proposed as a useful alternative, offering a closer look at both animal and plant cells:

[2^2:4.C.20], T is teacher

T:	Who has seen cells with organelles?
Elly:	I haven't.
Soued:	Of course you have.
T:	Everyone, isn't it?

Ankie: Yes, I think I've seen them.
Sarike: …but there weren't many inside.
T: It is less clear than you hoped for, and less clear than in the model. And now the big question is: Is that due to the model? Isn't the model right, don't cells consist of that (points to the organelles in the model on the blackboard)? Or is it something else? Should we doubt the model or the cells? Who has an explanation?
Birgit: I think they're too small to see under this microscope.
T: So, if you would have another microscope, with a higher magnification, you would be able to see those organelles?
Birgit: Yes, because even in the red onion you couldn't see the nucleus.
T: Whereas it is a huge cell.
Birgit: Yes.
T: Those chloroplasts, being organelles, could be seen easily in all kind of cells. In the cheek cells you could see some dots, but not much more. So, this is already a very scientific way of reasoning, isn't it? You stick to your model until it turns out to be otherwise, which seems to be the case now. But then you could still say: well maybe the model is right after all, but I just need better equipment (…).

In the following plenary discussion the teacher reminded to a visit to the natural history museum 'Boerhave' with the entire group of students three weeks before, especially to the exhibited electron microscope there. The students indeed remembered it. The teacher then referred to the observations of Antonie van Leeuwenhoek with his primitive microscope, to the students' observations with the light microscope and subsequently explained the next activity, in which the electron microscope will be used to further investigate animal and plant cells. Although it seemed needless because students remembered the size of the electron microscope in the museum, the teacher concludes the class discussion by explaining that photo's will be used instead of a real microscope.

As a preparation for LTA 8, students made a homework assignment, dealing with research on cell biology with the light and electron microscope from a historical perspective. This text continued, very briefly, with the story about research on cell biology that had started by Antonie van Leeuwenhoek (LTA 4). As expected, after reading the text most students realised the importance of technical progress for the development of cell biological knowledge. As a matter of fact, a large majority of the students (20 out of 22) referred to the lack of improvement of microscopes when asked to give possible explanations for the fact that it took two centuries for the cell theory of Schwann to be developed after Van Leeuwenhoek had seen the first living cells. Some students also reasoned that scientists stuck to the theory that seemed logical at that time, although 'these scientists did not yet understand the relations between form and function'. When asked what theory they meant, the theory of Van Leeuwenhoek that 'cells are like little organisms with organs' was mentioned. The students' own development regarding their attitude towards the model based on free-living cells after observing cells with the light microscope, mimics the historical process. At that moment most students rejected the model as being applicable to animal and plant cells, while earlier in the learning process they believed it to be a general cell model. The class discussion at the end of LTA 7 was essential to make students realise that, based on their observations so far, the cell model could not be rejected.

Studying the electron microscopic photos elicited some unexpected reactions at first. Instead of being struck by the enormous complexity of the cells, students were surprised by the fact that the pictures were very sharp and clear with many details visible. On the written question what strikes them when looking at the photos they refer to the 'standard structure' of the cell:

[2[1]:5.G.21]
Amanda: What do you notice about the photos?
Judith: Well, you can see the organelles
Amanda: Yes
Renske: Organelles, cell wall and nucleus
Judith: You can see, say, the standard structure of the cell

The fact that students 'saw' the standard structure as depicted in the general model before, can be ascribed to students' interpretations of the pictures. They only took the clear round shapes (mitochondria and chloroplasts) for being organelles:

[2[1]:5.G.22], R is researcher
R: Why do you think these are the organelles?
Christine: Because they are round and you can see things in them
Cynthia: It's different from the cytoplasm. It differs from the rest of the cell
R: And are there any more organelles to be seen on the picture?
Christine: Maybe these are small organelles
Cynthia: No, I think that is food in the cytoplasm

It was expected that most students would point out different structures as organelles themselves when comparing the photos of different cells and recognising the same structures in different cells. This happened in only two groups. These students, in contrast with other groups of students, focused spontaneously at similarities between the different cells directly from the start of the activity. When seeing the endoplasmatic reticulum or 'stripes' for example at different pictures they decided that these structures must be organelles too.

[2[1]:5.G.23]
Elske: What do we notice?
Nienke: They differ from each other, but you do see similarities…they look like each other, don't they?
Lisa: Okay, they do have similar characteristics.
[…]
Nienke: Indicate the organelles on the photos. This is a part of a liver cell, so then these should be the organelles.
Elske: And what about these?
Nienke: Cytoplasm.
Elske: No, I think it is one.
Nienke: Yes, those stripes are also an organelle.
Elske: Yes (looks at an intestinal cell), this is probably an organelle, you come across this one everywhere, I think it is, what else should it be…. look, this is again comparable with this, see?
Nienke: Yes, and here they are again, those long-drawn things, so that could probably be an organelle.

The majority of the students needed some help of the teacher to realise that the cell structure was more complex than they assumed at first sight. In these cases the teacher stimulated students to not only focus at the round structures, but also at differently shaped structures. Students then concluded that 'in fact almost everything is an organelle!', realising that the number of (different) organelles in the cell is larger than they expected. This contributed to the positive appreciation of the content of the cell biology course, as the remarks of Lisa and Elske at the end of LTA 8 illustrate.

[2[1]:5.G.24]
Lisa: I think it's cool that all that stuff is inside it.
Elske: Nice isn't it? I mean, it really works and that's what it's devised for.

The next activity (LTA 9) consisted of drawing and labelling some of the organelles. During this activity the complexity of the electron microscopic photos should elicit the need for a cell model, offering a clear overview of the cell and its organelles. By comparing the photos with an orderly cell model as displayed in their workbooks, students should further explore the cell and its organelles. However, in the first group of students, they did not turn to the cell model in their workbook as expected, although the teacher had suggested to use it in the introduction of the LTA in order to label the organelles. Apparently, the worksheets did not direct enough. Consequently, students got stuck during the assignment, because they didn't know how to find out the names of the organelles and a drop in their motivation could be observed. At the same moment, there was an unexpected incident. One of the students almost fainted, which took the attention of the teacher and caused some tumult. Therefore, the course of the LT-process could not be re-adjusted during the lesson.

To prevent the problems that where experienced with the first group of students, the teacher instructed the students in the second group to study the page on which a model of a plant cell was introduced. The model was introduced in a short text as the result of the comparison of an enormous variety of plant cells and as orderly representation of the general and structural characteristics.

After reading the text and/or seeing the model, most students used it to label the organelles on the electron microscopic photos. For example the mitochondria, Golgi apparatus and nucleus were directly recognised and labelled. When asked which model they preferred to explore the functioning of the functioning cell in more detail, i.e. their own model based on free-living cells or the model of the plant cell, students chose the latter because it contained more specific information in an orderly way. At the end of this phase, a reflection on the use of modelling in acquiring a coherent understanding of the cell was not executed as intended. Still, the students in the second group seemed to see the benefit of using models, because it helped them to label the organelles and to reduce the complexity that was visible on the electron microscopic photos.

4.5.4 Building a model of a plant cell

At the end of lesson 5, the teacher introduced LTA 10 and divided the students into pairs. Each pair received an electron microscopic photo of an animal cell on which 'their' organelle was marked: the nucleus, the endoplasmatic reticulum (rough and smooth), the Golgi apparatus (with lysosomes), the cell membrane, the mitochondrion, the chloroplast, the vacuole or the cytoskeleton. The teacher instructed students and pointed at the frame of the cell model (0.5 by 0.5 by 1.0 meter) in the back of the classroom in which the three-dimensional organelle models of the students would have to be placed in LTA 11. Additionally, students were instructed to prepare a presentation about ‘their’ organelle to the other students and to hand in a short paper focusing on some essential points regarding ‘their’ organelle. For a more detailed description the teacher referred to the students’ workbook (see box 4.1).

To provide a more clear description of the actual learning and teaching processes during the fourth phase of our LT-strategy, the three main elements that constituted this phase, will be elaborated in different subsections, i.e. modelling a plant cell, interrelating the organelles and acquiring insight in the cell as a functional unit.

The organelles: a further exploration.
In this assignment you and a fellow student will get assigned one specific organelle that you have to explore. While doing so, you have to answer the questions mentioned below. They must look familiar by now, since they arose from the developed cell model:

- What function does the organelle fulfil for the cell?
- What structural characteristics does the organelle have?
- How many of these organelles are in one cell? Are they present in all cells?
- With what other organelles does it cooperate? What does this cooperation comprehend?

Formulate your answers on a half A-4 size sheet of paper and hand it in to your teacher. This will be copied and distributed among your classmates, so that everyone will receive the information of each organelle that is explored.

Constructing a 3-D cell model
You and your classmates will construct a 3-D cell model. To achieve this, each pair of students constructs a 3-D model of their organelle, which will subsequently be placed in a frame in the back of the classroom (½ to ½ to 1 meter) that constitutes the cell. This way the 3-D proportions of the cell, its organelles and their place in the cell will become clear.

- Discuss what material suits best to construct your organelle of. Label the organelles with their name and function.
- Discuss with other student pairs in what way your organelle is related to other organelles and the consequences for placing the organelle in the cell.

Box 4.1: ***The assignment (LTA 10) in students’ workbook addressing the exploration of a specific organelle and constructing a 3-D cell model.***

Modelling a plant cell

In contrast with the first case study, students actively participated in developing a systems model of the (free-living) cell during the LT-strategy so far. Consequently, at the start of LTA 10, the model should support their exploration of the organelles. The questions, derived from the model, should direct students in their explorations. Instead of focusing on molecular details of ‘their’ organelle, the model should help students to interrelate ‘their’ organelle with other organelles and the cell as a whole.

During LTA 10, we asked four student pairs what clues they could derive from the cell model, which was drawn on the blackboard, in order to explore ‘their’ organelle. All eight students mentioned the interrelation between the organelles as an important focus:

[2[1]:6.G.25], R is researcher
R: Do you recall what this model was based on?
Nienke: On exchange between the organelles.

R: Does the model on the blackboard give you any clues as to what questions you could ask about your organelle?
Nienke: Which organelles are in the cell and how they are interrelated?
R: Do you think the model is useful when exploring an organelle?
Jaklien: Well, I think it's not detailed enough for that.
R: Okay, so you'd rather look for another cell model yourself.
Nienke: Yes.

To students the developed cell model clearly represented a cell with interrelated organelles and directs them in exploring 'their' organelle. However, as expected the model did not provide enough detailed information, which was a reason to look for more detailed or specific models like the standard animal cell in their textbook. We observed a lot of students looking for more specific models, mainly to gather more information about the three-dimensional structure of their organelle. Questions, raised during LTA 8 such as: 'Does a membrane surround all organelles?' or 'Do both plant cells and animal cells contain a Golgi apparatus?', could now be answered. The different models also helped students to find out some new and specific structural characteristics about the organelles. For example students found that the rough endoplasmatic reticulum had ribosomes stuck on it, that the cell membrane was at the inner side of the cell wall or that mitochondria were made of an outer membrane and a folded inner membrane:

[2[1]:6.G.26]
Arnaud: I have seen another picture of this, but there it looks like if there is something around it. I think there was a membrane around it or so… and you can't see that on this picture.
Jaklien: You can see it over here. There are two membranes: an inner membrane, that is totally invaginated, and an outer membrane.
Arnaud: That white stuff isn't anything, isn't it?
Jaklien: That white stuff should then be the space in between the membranes.
Arnaud: Oh, okay.

Arnaud in fragment [2[1]:6.G.26] gathers information about the mitochondria by critically comparing different models. Likewise, students who explored the Golgi apparatus used different models and criticised the one that displayed the Golgi apparatus and endoplasmatic reticulum at both ends of the cell because they found them to be working closely together. So, the process of modelling a 3D-cell stimulated students to think backward and forward between different cell models. Additionally, building a model also stimulated students to think backward and forward between (their) model and *real* cells. Students realised that the colours of the organelles in the different cell models were not the *real* organelle colours except for the chloroplast, which was stated to cause the green colour of plants. Students also wondered what material they could use best in order to display some specific properties of the organelle. For example 'the cell membrane has to be made of flexible material because the membrane can change its shape continually.' In fragment [2[1]:6.G.27] Judith and Amanda wonder how to build their vacuole:

[2[1]:6.G.27], T is teacher
Elske: Couldn't you make it of styrofoam?
Amanda: But there has to be...there is fluid inside, isn't there?
Judith: Yes, there is.

Elske: It looks like nothing is in it.
Judith: Its function is storage of substances.
Amanda: So, it must be able to have something inside it.
Elske: We can make it of a vacuum cleaner bag! Haha.
[…]
Judith: Sir, how could we ever make such a vacuole? We thought about a balloon with water inside since it has such a strange shape and it's rather big.
Elske: But is it all right if you put water inside?
T: I don't know, what is in it?
Judith: Or should we add further substances? Because it contains waste matters.
[…]
Amanda: Isn't it possible to make something around it so you could… so that the balloon remains intact?
T: Because a balloon full of water is very risky.
Elske: If we put paper-mâché around it, then the balloon would better remain intact?
T: But why do you want to put it around it?…What does the paper-mâché imply?
Elske: Well, than the balloon remains intact.
T: Yes, but what does that imply, that thin layer? You're making a model.
Judith: The wall of the vacuole.
T: The wall of the vacuole.
Judith: That is said here, ...the membrane of the vacuole.
T: Yes, exactly: a membrane. And membranes are tremendously thin; they are those thin layers of two…
Judith: And it is not possible to put two balloons in each other or so?
T: And waste matters you could of course also symbolise. What substances are further in it?
Judith: Salts. We should take salt with us too, yes.

As fragment [2^1:6.G.27] also shows, being invited to build a three-dimensional model stimulates students to stay at the cellular level and not to descend to the molecular level. They rather focused at the structural characteristics and the function of the organelle for the cell. However, when studying some books, including their biology textbook, students came across a lot of difficult terms at the cellular and molecular level. For

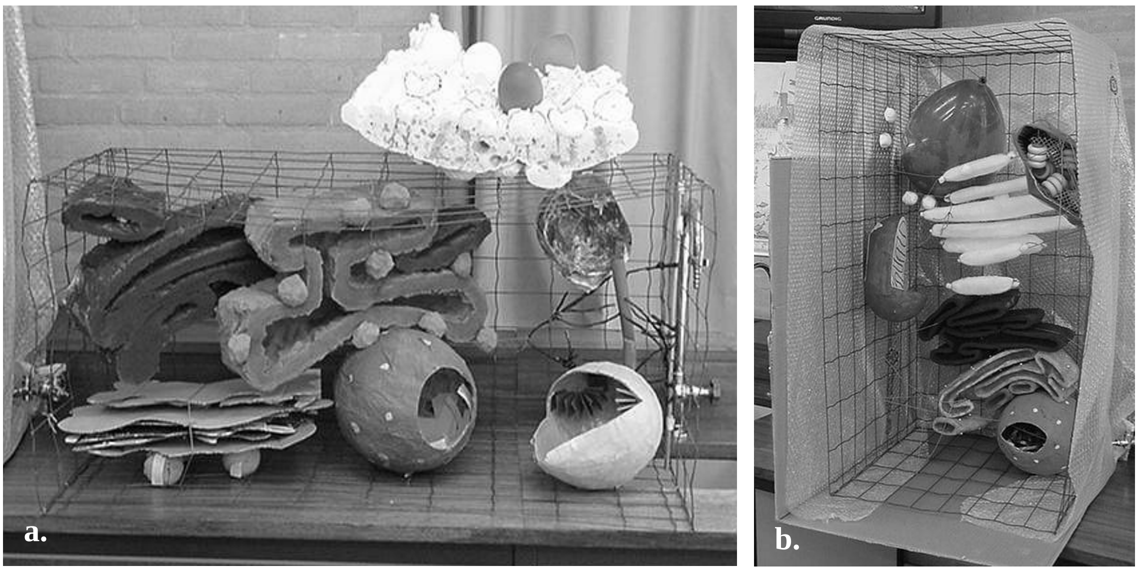


Figure 4.4 ***3-D cell models constructed by students of the first (a) and second group (b) in a frame of ½ to ½ to 1 meter.*** *It includes the nucleus, endoplasmatic reticulum and ribosomes, Golgi apparatus and lysosomes, cell membrane, chloroplast, mitochondrion and vacuole.*

example, exploring the vacuole elicited problems with the process of osmosis and the term semi-permeability. Students who explored the endoplasmic reticulum (ER) had difficulties with terms as ribosomes and glycoprotiens, and exploring the nucleus elicited difficulties with the terms nucleolus and RNA. The teacher played an essential role in helping students to interpret the texts and getting students back on the cellular level, by referring to the questions to be answered during their presentations.

During LTA 11, before the class presentations, the three-dimensional cell model was built by placing all the organelles in the framework in front of the classroom. When entering the classroom all students were eager to place their organelle in it. The ER was placed against the nucleus, the Golgi next to the ER, etcetera. One student pair brought an organelle (mitochondrion) that was crushed by a car on their way to school. In order to complete the cellular model they spontaneously proposed to make a new one in order to complete the cell model. Figure 4.4 shows the final 3-D model of the first (4.4a) and the second group (4.4b) of students respectively.

Interrelating the organelles

An important goal of LTA 10 was acquiring insight in the 3-D structure of the cell and its organelles. As described in the previous section, the process of modelling had a real added value when compared to the first case study. Additionally, LTA 10 should stimulate students to interrelate the different organelles in order to get a coherent and more dynamic understanding of the functioning cell.

At the beginning of lesson 6 the teacher reminded students that all cells, as basic units of life, have to fulfil the basic processes of life, including cells that are part of multicellular organisms. ‘To fulfil these functions, the organelles cooperate with each other but each organelle has a specific task as we now know.’ LTA 10 offered the opportunity to work together as a study group in order to find out how the cell fulfils the functions and how the organelles cooperate. ‘And that’s why we are all together in one classroom, working as a study group’. So LTA 10 was presented as an activity, which required cooperation between the student pairs in interrelating the organelles and building a coherent model of a cell.

As expected, interrelating the organelles was indeed an important focus to students. From schematic pictures of cells and pieces of text in their book, students got some first clues about which organelles are related. Patricia and Marja for example, who studied the endoplasmatic reticulum, realised that the ER is related to the nucleus. Immediately the next question came up: ‘Okay, here is the nucleus on this picture but, and that’s still a problem for us, how are we attached to the nucleus’. Subsequently, Patricia turned to Renske, who studied the nucleus and asked her how their organelles are related. After the conversation with Renske she decided that ‘the nucleus sends RNA to us … so that we can make these things eh proteins with our ribosomes ... So the connection is that they make RNA for our ribosomes’. At that moment she correctly states that ribosomes are made of RNA. However, this elicited another problem that she presented to the teacher:

[2[1]:6.G.28], T is teacher

Patricia: I have a question: does the nucleus produce ribosomes or does it send RNA to us, so that we can make ribosomes? […] Because I couldn’t find where ribosomes are made.

T: That's a point! Ribosomes are assembled outside the nucleus. Not by the ER, but it certainly happens somehow, I don't know.
Patricia: There has to be a connection with the nucleus, since we need ribosomes.
T: Yes, and the RNA of which these ribosomes are made of.
Patricia: Yes.
T: You receive it from the nucleus indeed, and to be exact you receive it from the nucleolus.
Patricia: Yes. Because in the nucleolus... so we need RNA, so that we have ribosomes, that contain protein molecules so that we…
T: Produce! They contain...yeah, they also contain...
Patricia: Do they produce them also?
T: They do, that's the point. They produce proteins.
Patricia: Oh, the book said contains.
T: Yes, that's right in a way, but they produce proteins; that's what it's about.
Patricia: And by doing so, the rough ER can make proteins and the smooth ER makes glycoproteins out of that.

With the help of Renske and the teacher, Patricia found out that the function of the ER is to make proteins and that the nucleus helps by sending the RNA to the ER. Moreover, the teacher explained that the nuclear envelope is made of the inner layer of the ER and the ER thus protects the DNA in the cell. In explaining the link between the nucleus and the ER the students stayed at the cellular level as intended. Although the students mentioned RNA, its exact role remained obscure as the class presentation of Patricia and Marja also showed: 'the nucleus sends RNA and forms the ribosomes, together with proteins. The ribosomes attach to the ER and synthesise or produce proteins.' Somewhat later during the lesson Patricia found out that the ER is also related to the Golgi apparatus:

[2[1]:6.G.29]
Nienke: What's your organelle?
Patricia: We have the endoplasmic reticulum with ribosomes.
Elske: Is that the same as ER?
Patricia: Yes.
Nienke: Yes? So then ours (Golgi system) works together with yours.
Patricia: Hey…
Nienke: So yours sends the lysosomes, or no, it sends something to our Golgi system (points at a picture in her book)
Patricia: Yes, I see.
Nienke: And then it goes via the lysosomes again to the mitochondrion.
Patricia: Aha …lysosomes go to another mitochondrion. Did you know that?

So, in contrast to the first case study, in interrelating the different organelles cooperation between the different student pairs was an important activity. Students helped each other and explicitly asked each other about the relations between the organelles. Sometimes this cooperation became a kind of role-play where students put oneself in the position of their organelle:

[2[1]:6.G.30]
Patricia: How do you help me?
Elske: How do I help you? …I don't have a clue.
Patricia: You don't know how we help each other? I know how I help you!
Elske: Yeah I know, you give off vesicles that are taken up by me.
Judith: Hey did you have endoplasmatic reticulum?

Patricia: Yes I do.
Judith: Formation of the vacuole from the endoplasmatic reticulum.
Patricia: Oh, so we help you too!
Judith Yes, I originate from you.
Patricia: He Cynthia, we make the vacuole!

Apart from the role-play, fragment [2[1]:6.G.30] also shows Patricia discovering that the vacuole originates from the ER. During LTA 10 most students discovered the relationship with other organelles and its nature: mainly vesicular transport. With this way of transport, the ER, Golgi, vacuole and mitochondria were interrelated and at the end of the lesson the membrane was also considered to be part of this transport system. At first Lisa and Ilona, who studied the membrane, did not have a clue about the relationship with other organelles. Their image of the membrane was rather static.

[2[1]:6.G.31], T is teacher
Lisa: So the membrane makes sure that food goes into the cell and waste out again, and provides protection. But we haven't found yet that it really cooperates with another organelle.
T: How can you get more membr…eh, how do you take up food?
Lisa: O, with those food vesicles, isn't it? It did have them, didn't it?
T: Okay, here I've one of your membranes, with a dent in it… An even bigger dent and at a particular moment it invaginates over here. As a result, my total membrane has become shorter, hasn't it?
Lisa: Shorter?
T: Of course.
Together: O yes.
T: Can I have your scarf for a while?
Lisa: Sure.
T: Look, suppose this is a membrane,
Ilona: Hey, we can build that (membrane) from a scarf.
T: And I wrap this up… then I have to have the scissors now.
Lisa: Yes, but don't do it.
T: Okay, imagine: I cut this piece out now, and it becomes a vesicle that goes inside the cell. But your scarf has actually become a lot shorter now.
Lisa: Yes.
T: And I'll do that about ten times more, producing those vesicles, and how will I get new pieces of cell membrane?
Ilona: It produces them.
T: How? All right? That's your relationship with the other cell parts. Because actually there are parts over here that continuously produce pieces of membrane.
Ilona: And that's what we have to find out.

Lisa remembered the way *Paramecium* takes up its food 'with food vesicles' and thus realised once again that the membrane is not just a static structure. After the above-mentioned discussion, Lisa and Ilona went searching for other organelles that produce membranes, by asking around. Again with the help of other students, Elske in this case, they found out how the Golgi apparatus produces vesicles who merge with the membrane and thus contributes to the production of the membrane.

[2[1]:6.G.32]
Ilona: Hey, I already know about Elske's organelle. (…) Some lysosomes produce a membrane, that's it […]. Do you know how they do that too, Elske? How do they produce membranes?
Elske: Well, you know, there is just a piece of membrane around it....
Lisa: Around those lysosomes? Really?

Elske: And that fuses with the cell membrane, which subsequently increases in size.
Ilona: Okay, we have to...
Lisa: The lysosomes produce...
Ilona: Yes, eh no, there is a piece of membrane around...
Lisa: We thought: the lysosomes produce the cell membrane.
Elske: Look here: Lysosomes are vesicles that are enclosed by membrane.
Lisa: Yes, here it is.
Ilona: Lysosomes are vesicles enclosed by membrane...
Elske: Vesicles are coming form the Golgi and these vesicles subsequently fuse with the membrane
Lisa: Oh, so they fuse, they fuse.

Elske explained that the Golgi, lysosomes and the membrane are not static organelles but that the membrane of the Golgi, lysosomes and cell membrane are exchanging. The question remains however if 1) students understood the dynamic and continuous nature of this process of transport and exchanging membranes and 2) if other students as well are aware of the dynamic nature of the interactions between the organelles. Here the class presentations appeared to be indispensable, including a class discussion directed by the teacher, to build a coherent picture of the cell as a whole.

In line with fragment [2^1:6.G.32] Elske puts forward the dynamic character of the vesicular transport in the cell:

[2^1:7.C.33]
Elske: In reality, the Golgi apparatus are stacked-up membranes […] Via the ER, vesicles are going to the Golgi-system and those vesicles are filled with proteins, sugars and fats. Having arrived at the Golgi-system, the membrane of the vesicles fuse with the membrane of the Golgi-system, whereby these proteins, sugars and fats can be taken up in the system. […] A lysosome is eh like the result of the Golgi system. The nutrients have to be transported further and that happens through pinching off pieces of membrane on the other side of the Golgi-system, whereby substances can be transported further to other organelles. There are three kinds of vesicles that can originate from the other side of the Golgi. When these vesicles only consist of membrane, they serve to maintain the cell membrane. When enzymes are present in the membrane-enclosed vesicles, they are called lysosomes…

In her presentation Elske put forward the Golgi as a dynamic structure. Additional to the above fragment she linked the Golgi, by formation of vesicles and enzyme-containing lysosomes, to the formation of the cell membrane and the digestion of food particles respectively. In the subsequent discussion about the continuity of the uptake and formation of vesicles by the Golgi, a dynamic picture of the cell emerged. At that moment the teacher took up the remark of Rachen to draw the attention to the fourth dimension that is missing in the 3D-model: the time dimension.

[2^1:7.C.34], T is teacher
Rachen: Does it move itself each time from the cell membrane to, in the direction of the nucleus, or in the direction of the rough ER, because it extends at the other side as a result of the vesicles that are added? And on the other side, each time they go…
Nienke: No, but the vesicles come from the ER, subsequently go to the Golgi-system and then they are transported further, and on the other side of the Golgi, the membrane is given up for further transportation.
Rachen: So, at one side membrane is added and…
Elske: Yes, but on the other side membranes are going off, they pinch off.
T: So it stays at the same place.
Elske: Yes, at the one side it adds up and on the other side it goes off.

Rachen: O, the membrane travels completely through it or something.
Elske: O yes, the pieces of membrane themselves, they travel through the entire cell, that's right.
Rachen: But also through the entire Golgi-system.
T: Yes, you must realise that when you observe the ER and how it looks now, the same applies to the Golgi apparatus. Look at them ten seconds later and it is entirely different. It's disappointing about your model: that you didn't bring that into it. Still, it's an incredibly flexible whole.
Patricia: Our model is flexible all right!
T: Take a look a few minutes later and the twists are totally different. There are vesicles coming and going, etcetera. Actually, it is not possible to make that; it is already difficult to make it in three dimensions. As a matter of fact there is also a fourth dimension because you could bring the time dimension in it. Well that's not possible to do, but in a few seconds the cell looks totally different.

In group 2 the dynamic nature of the cell also played an important role in the presentation of the cell membrane. Students had found an animation of the transport processes (different from endocytosis and exocytosis) in the membrane on the Internet (www.bioplek.org), and used it to show the dynamics of the membrane.

As we have described so far, during LTA 11 a dynamic picture of the cell emerged in which the different organelles were interrelated. However, during the presentations it became clear that relating some specific organelles, i.e. the nucleus, mitochondrion and chloroplast, remained unclear. Students knew that the nucleus 'regulates the processes in the cell' but it remained unclear how, although students also knew that the nucleus sends messenger RNA to the ribosomes at the ER. Similarly, the mitochondrion was known to need carbohydrates and fats to produce energy for the cell, but how it was transported to and from the mitochondrion remained unclear, while Elske had included the mitochondria as destination for the vesicles originating from the Golgi. It was expected that these problems would be noticed during the lesson and could be reflected on during a class discussion directed by the teacher. However, the teacher mentioned afterwards that a pressure of time made him decide to keep the discussions short while more discussion was needed.

Acquiring insight in the cell as a functional unit

In retrospect, the LT-strategy so far mainly focused on the general characteristics of cells. However, the strategy provided students some insight in cell specialisation during LTA 1, within the context of growth and development. Subsequently, during LTA 7 and 8 students noticed any microscopic structural differences between some observed cell types, although the focus was again on the general characteristics of cells. During LTA 10 and 11 students got the opportunity to find out more about the differences between different cell types. The worksheets asked students to find out 'how many of 'their' organelles could be found in a typical cell and whether these organelles are present in all cells or not'. Additionally, the teacher instructed students not only to focus on differences between animal and plant cells, but also on the differences between human body cells. The differences between cells, in terms of the number or size of certain organelles, provided students insight in the form-function relationship of specialised cells.

As the presentations of the students showed, the majority of the students made the link between a specific cell function and the role of 'their' specific organelle. For example it was explained that the number of mitochondria in cells varied strongly: ‘Cells that consume a lot of energy, like muscle and brain cells, contain many mitochondria too. Also animal cells contain more mitochondria than plant cells, because they consume more energy’. Similarly, the size of the Golgi apparatus (‘every cell contains one’) was correctly linked to the production of hormones and in a class discussion a student linked the formation of vesicles to the production of digestive enzymes. On the other hand, students who explored the chloroplasts and the vacuoles only differentiated between animal and plant cells, while the difference in (the shape of) cell membranes was only linked to the shape of cells.

As expected, the teacher had an important role in directing the class discussion from the cellular level to the organ level. For example, Ilona in fragment [2^1:7.C.35] only links the function of the ER to the importance of proteins. The input of the teacher is needed to link it to the cellular function like the production of hormones and at the end of fragment [2^1:7.C.35] the teacher explicitly asks students to go to a higher level.

[2^1:7.C.35], T is teacher

Ilona Since all cells require proteins to grow, there is ER in each cell. This applies to both plant and animal cells. But each cell has a different function. If for the cell it is more important to be able to grow fast, that one will contain more ER. So, it (ER) is in both plant and animal cells, but in some cells there is more than in others […]. The difference is just; let me see…it just depends how many proteins it needs. (…)

T: Are there cells or cell types that contain a lot of ER? What kind of cells should contain a tremendous amount of ER?

Christine: Skin cells I guess.

T: Because?

Christine: Well, they have to eh… You’re skin gets old fast, so they have to grow a lot, so you need a lot of ER.

T: Yeah, but then you could make a new cell.

[…]

T Tell me, what does the ER produce?

Christine: The rough one produces proteins.

T: So, which cells have to produce an extra amount of proteins, to emit? What kinds of cells?

Christine: Ehm…I don’t know.

T: Well muscles contain a lot of proteins of course, but these stay in the cells. It’s not necessary to produce extra ones. What about cells that produce digestive juices? Endocrine glands, hormone producing cells? They have to produce more proteins, so they need more ER, right? And you (turns to student) just talked about detoxification, where in our body does detoxification happen?

Rachen: In the ER.

T: Yes, but where in your body, think one level higher.

Rachen: The stomach, I think.

Renske: Liver.

T: Not the stomach, liver yes. So liver cells will probably contain a lot of ER. One last question, as far as I’m concerned: Those ribosomes, what are they doing actually?

Christine: Those ribosomes produce the protein molecules […] and pass them on to the ER, etcetera etcetera...

As fragment [2^1:7.C.35] shows, the input of the teacher is important to ascend one level of biological organisation and to link the specific cellular characteristics to the function of the cell in the body. The discussions about the differences between specialised cells provide a starting point for LTA 12, which goes deeper into the relation between cells and the body within the context of specialisation. However, at this moment students do not see the relevance of ascending to a higher level of organisation when addressing the problem of how cells are specialised to fulfil a specific function. In her presentation about the membrane for example, Ilona states that the shape of the membrane just depends on the shape of the cell, without addressing the structural organisation that cells are part of. In the following class discussion students soon pointed at DNA, when addressing the specific shape of the membrane:

[2^1:7.C.36], T is teacher

Ilona: (…) The cell membrane forms itself at the cell. It's like a sort of skin, say. So when the cell is round, the membrane has a round shape and if the cell is square then the membrane has a square shape. So, it adapts to the shape of the cell.

[…]

Arnaud: What determines that such a cell has a square shape?

Judith: Well, I don't know actually.

T: The cell membrane also determines the shape and very rightfully you say that the cell's shape is there and the membrane is very flexible. But when you stick cells together, you force them in a particular shape and when cells get a lot of space, they will flow out and perhaps expand a little… The function (of the cell) also determines its shape, so where has it been fixed?

Renske: In the DNA.

T: Exactly, in the DNA. Is it possible that membranes are a lot bigger around one cell than around another?

Judith: I don't have a clue; I think so. I think there must be a difference.

T: Okay, in one of the electron microscopic photos that you've seen, there is one example of a cell membrane that is far far bigger. It just has such bulges and goes like this (draws a bulged shape on the blackboard). And you could find that one in – where do you require a very big surface? Where do you have to be able to take up or throw out a lot?

Arnaud: The digestive tract.

T: So, on places where you need a lot of membrane, there's just extra.

Although the teacher shortly addresses the physical influence from the surroundings on the cell, he soon focuses on the cell's function. The fact that specific cell characteristics are not just 'determined' by the DNA, but develop regulated by signals from outside the cell, was not discussed. Apparently, to both teacher and students this interaction of the cell with its environment is not an important issue at this phase. So to provide a meaningful starting point for LTA 12, the dependence of cell specialisation on signals from the cell's environment had to be made explicit.

In the next lesson the teacher introduced LTA 12 by shortly referring to the beginning of the LT-strategy and by posing the same problem as in LTA 2 (see table 4.4), i.e. the problem of cell differentiation: How can it be that different cells evolve from one single ancestor: the zygote?

[2^1:8.C.37],

Teacher: …We have started with unicellular organisms. They divide by mitosis and form two identical cells that again are able to maintain themselves independently. We're just going one step up now, right. At the moment we're dealing with cells in a body. […] But you originated from - from zygote to study head – from one cell that divided by mitosis, mitosis again: 4 identical cells, mitosis: 8 identical, 16, 32, 64, in short: all identical cells. Whereas, the way you're sitting here, you're not composed of identical cells. Then you would have been a rather formless whole, but instead you're composed of a few hundred different cell types. […] Well, that problem: How is it possible that at one moment a cell does not just develop in a similar, but in another kind of cell? That's what the first half of this lesson is about.

After the introduction presented in fragment [2[1]:8.C.37], students started with the written assignment. They had to read a newspaper article about stem cell therapy: 'steering stem cells'. The article dealt with research into the environmental conditions regulating the specialisation of stem cells and it was questioned if it would be possible in the future to grow complete organs in a laboratory. After reading the article, students realised that cells are dependent of signals from their surroundings. To the question what the signals could be that steer the development of stem cells, students' typical answers were 'a kind of signal from the surrounding tissue that passes on the function or signals to the stem cell that results in the stem cell becoming a specific cell. Remarkably, only four students in both classes mentioned the signals to be hormones. This was unexpected, because in the preceding chapter hormones in general were mentioned to play an important role in growth and development.

Within the context of stem cell therapy students were stimulated to think about the structural organisation in which cells fulfil their function. Hereby the transition to LTA 13, in which the hierarchical structure of the human body was explored, would be logical. At the end of LTA 12 students had to describe the difference between a tissue and an organ and then explain whether or not it would be possible in the future to grow a complete organ in a laboratory. Although some students just sufficed with 'yes, because of the advanced techniques in the future', most students referred to the importance of environmental conditions, enabling the growth and development of organs. Some typical answers were formulated in the completed worksheets as follows:

[2[1]:8.W.38]

- No, tissues will be possible but with organs the problem is vessels and contact with other tissues and growth and development.
- No, shape and size is determined by the environment in the body and grow is determined by hormones.
- No, support of surrounding cells is absent, so it would be rudderless.
- It's very difficult because there has to be coherence between all the signals.

As the answers show, students understood that the growth and development of an organ require specific conditions, which are present in the human body only, like 'hormones', 'support', 'vessels' or 'coherence'. Moreover, most conditions mentioned were related to the structural organisation of the human body ('contact with other tissues, support of surrounding cells') or the organs themselves ('it has a specific form and size'). Students seemed to have a rather vague idea of these (structural) conditions, and it was expected that these uncertainties would provide a motive to address the structural organisation of the human body in LTA 13, from the cellular level up to and including the organismic level. However, as the class discussion after LTA 12 showed, students were more interested in the nature and origin of the signals regulating cell specialisation. In a class discussion about the possibility of growing organs in a laboratory, one student (Peter) stated that it is not possible because the growth of organs is regulated by the brain: 'Like the brain, they regulate the growth and you cannot just put a brain on a dish and connect it with the heart'. Next, it was discussed if the brain regulates body growth and the teacher recalled the discrimination between the autonomous and somatic nervous system:

[2[1]:8.C.39], T is teacher

T: …But you have an autonomous and a somatic nervous system, right. So, what goes via the autonomous one, you can't have influence on, as opposed to what goes via the somatic (nervous system). But we've already dealt with that. Like digestion, respiration, and blood circulation, growth does not belong to the somatic nervous system. […]

Amanda: And hormones neither?

T: Indeed, hormones regulate growth, and there exists an interaction with the brains of course…

Nienke: But hormones come from cells too.

T Yes.

Nienke And growth, that's dividing cells […] That's strange though, say, hormones cause growth and, how do I say that, eh They (hormones) come from within the cell.

T Yes, so your first remark saying that the environment of the cell determines the growth, is correct. But how does it do that? Well, amongst others, by emitting substances. And the more complicated and larger the organism becomes, the more you need something to control things, like hormones that are given to the blood and hopefully they'll do something in your toes. Whereas, till that time you can just manage by giving messages to your neighbour cells. Okay, that's something that we have to accomplish the last two lessons. […] Okay, paragraph five: 'from organelle to organism: organisation on a level', ehm, on the computer, it's self-explaining…

After the above discussion, students started with LTA 13. As the end of fragment [2[1]:8.C.39] shows, the teacher had difficulties with the transition from LTA 12 to LTA 13. Afterwards the teacher mentioned that he thought the transition from LTA 12, with cell specialisation as central issue to LTA 13, which started with the organisation on the level of the organism was to big. Indeed, the step to LTA 13 resulted in neglecting the questions of students dealing with hormonal regulation. However the teaching method, i.e. a computer-aided programme, seemed to enthuse students to engage in LTA 13.

4.5.5 Explication of systems thinking

In the LT-strategy thus far, each LTA up to LTA 12 tried to elicit meaningful and content related questions and answers in order to involve students in the process of learning and teaching cell biology. So the explicit purpose of the LT-strategy was to attain a better understanding of cell biology. Although the LT-strategy was developed from a systems perspective on cell biology, this perspective had not been explicated yet. Moreover, in the reflection on LTA 9 the process of modelling was explicated to contribute to a better understanding of cell biology. As a consequence, it was accepted that a motive for introducing a general systems model, including the level of the cell, organ and organism, could not be raised at this point. Instead and in line with the problem posing approach thus far, the motive for students to engage in LTA 13 was derived from the domain of cell biology and focused on answering the question: 'How are cells in multicellular organisms organised?' as described in the previous section. The structural organisation at the level of the organ and the organism that is dealt with in LTA 13, connected to students' notions about the fact that cells are part of a larger and 'coherent' whole. Hereby, the context of digestion provided a meaningful starting point to explore the different levels of organisation. As described in section 3.4.4, at each level of organisation, the general system characteristics were depicted in a model, being the same model as developed earlier for the cell.

In other words, exploration of the organisation of the human body within the context of digestion provided a learning motive and the generalisation of the system characteristics at each level of organisation joined in. During LTA 13 students realised that the same model developed earlier for the cell, applied to organs and organisms as well. Moreover, in a final assignment students integrated the models at the three levels of organisation into one model, giving them an understanding of the hierarchical organisation of the human body. Subsequently, students applied this new insight within the context of the process of breast-feeding.

After LTA 12, students were instructed to take place behind a computer in pairs and start with the learning programme *Models from body to cell*. In the accompanying worksheet the digestive system was presented as an example of cooperation between organs. Two student pairs spontaneously drew the parallel with regulation of hormones:

[2[1]:8.G.40]

Christine: ‘The body consists of parts that cooperate. They exchange materials, like for instance hormones. And that comes from the Golgi-system […] All right, what are we supposed to do? (Reads the question.) A group of cooperating organs is called an organ system. Name three other organ systems besides the digestive system’.

The next moment, after mentioning some organ systems like the circulatory system, the nervous system and the reproductive system, students explored the way the food goes through the digestive system at the organismic level. So, exploring the digestive system was exemplary for exploring the coherence between organs in the human body. In response to the question: ‘Do you know why you are doing this?’ Nienke spontaneously linked the activity to a previous activity: ‘well we have looked at the coherence between organelles and now we are looking at coherence between cells and what they have got to do with tissues and organs’. So, although the transition from LTA 12 to LTA 13 was not self-explaining, we gathered some indications that the step to LTA 13 was not illogical to students.

In addition, LTA 13 largely came up to our expectations. At the organismic level, some students had some trouble in filling in the exact pathway of the food through the body. For example two students thought that the food went from the stomach into the blood. Additionally many students had to be reminded (by the computer programme) that the circulatory system supplies all other organs, including the organs of the digestive system with nutrients. On the organ level students applied their description of the difference between tissues and organs from LTA 12 to decide if the muscle in the arm is a tissue or an organ. Most students (16 out of 24) decided it was an organ, because it comprised multiple cell types as depicted in the model. The other students rejected that the nervous cells and blood cells are part of the muscle; the muscle itself was made of muscle cells only and thus they decided it to be a tissue.

The main goal of the computer-aided programme was that students would realise that the cell model, which was developed earlier in the strategy and was derived from the organism, could be applied to organs as well. During LTA 13, students immediately recognised the model as the cell model and no difficulties were observed in connection with the general representation of the organism and organ, similar to the cell model. Moreover, from the observation of the students it looked as if most students thought the activity to be rather simple and they hadn't learned much from it. Elske formulated this as follows:

[2[1]:8.G.41], R is researcher

R: Did you understand the intention of the computer-aided programme?

Elske: Yes, that you can make a model of the body and this model can also be seen in the organs and in the organs there are cells and with cells you can do the same again.

R: What did you think about that?

Elske: It's logical, actually. I liked it somehow, but it wasn't really instructive…

As in fragment [2[1]:8.G.41], most students seemed to think that they had not learned much. On the other hand, they showed to understand the hierarchical structure of the body, which was the main aim of this LTA. In the final assessment, all students were able to integrate the three system models into one model of the body. Moreover, at the beginning of LTA 15, when students had to apply the systems model within the context of breast-feeding on different levels of organisation, Elske explicitly referred to the computer-aided programme: 'Look, the same kind of picture as we saw on the computer! …But now we have to fill in other relationships'.

After LTA 13, there was no teaching time left, so the plenary reflection on LTA 13, which was scheduled right after LTA 13, was postponed to the next lesson. Instead, students studied a text as homework in which LTA 12 and LTA 13 were reflected on and the levels of organisation and the general characteristics of living systems were explicated (see box 4.2).

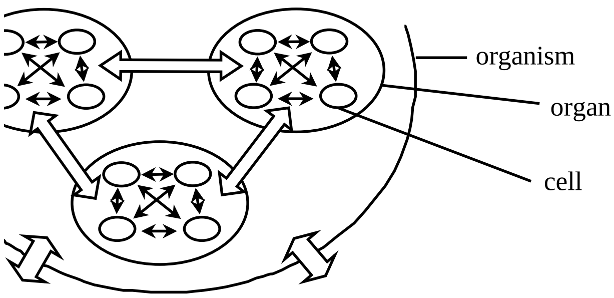
The explication of systems thinking was based on a structural description of living systems. Initially, the development of the cell model in LTA 6 was based on students' drawings of the cell and its structural components, the organelles. In the following LTA's the exploration of the cell was linked to the activity of building a structural model of the cell, whereby the systems model stimulated students to focus on the coherence or cooperation between the different organelles. As we have showed, students were indeed focused on the nature of the relationships on the cellular level, which were explicated afterwards as exchange of information or materials. In LTA 13 the hierarchical model of the body was again introduced as a more general view of the structural organisation of the organism. Similar to the cell model it formed a starting point to focus on the relationships between the structural parts, but now at three different levels of organisation. The context in which these relationships were explored was a biological topic crossing several levels of organisation: breast-feeding. Students were already familiar with this process at least at the organismic and organ level because it was dealt with in the previous chapter 'from zygote to scholar'.

The plenary reflection on LTA 13 was combined with the introduction of LTA 15 during which the teacher shortly referred to the computer-aided programme and repeated the general characteristics of all living organisms as described in the worksheets (see box 4.2). Subsequently, the teacher introduced LTA 15 during which students had to apply these characteristics on a specific biological phenomenon: a nursing mother. The phenomenon was presented by the teacher as 'a familiar example that was already dealt with less extensively in the previous chapter'. For more detailed instructions about the assignment he referred to the students' handout, containing some explaining images (see box 4.3). Before starting with LTA 15, the process of modelling the cell and the subsequent application of the model to the level of the organ and the organism in LTA 13 was not reflected on plenary as intended. So the introduction and explication of systems thinking was highly dependent on the teaching material and the written reflection.

Levels of organisations and systems

With the computer-aided programme you followed the way of food through the organism from uptake up to and including the place where the nutrients are finally used: in one of the body cells. In doing so, you descended from the organismic level, via the organ level to the cellular level (muscle cell) with the organelles. The organismic, organ, cellular and organelle level are different levels of organisation that can be distinguished. Consequently, we call them 'levels of organisation' (Dutch: organisatieniveaus).

At each level of organisation there is close cooperation between the different parts. […] Such a group of cooperating parts at the organismic, organ, or cellular level, is also named a system. Similar to the representation in the computer programme, we can represent a system in the same way as we've done earlier by means of the general cell model:



Cooperation at the organismic and organ level

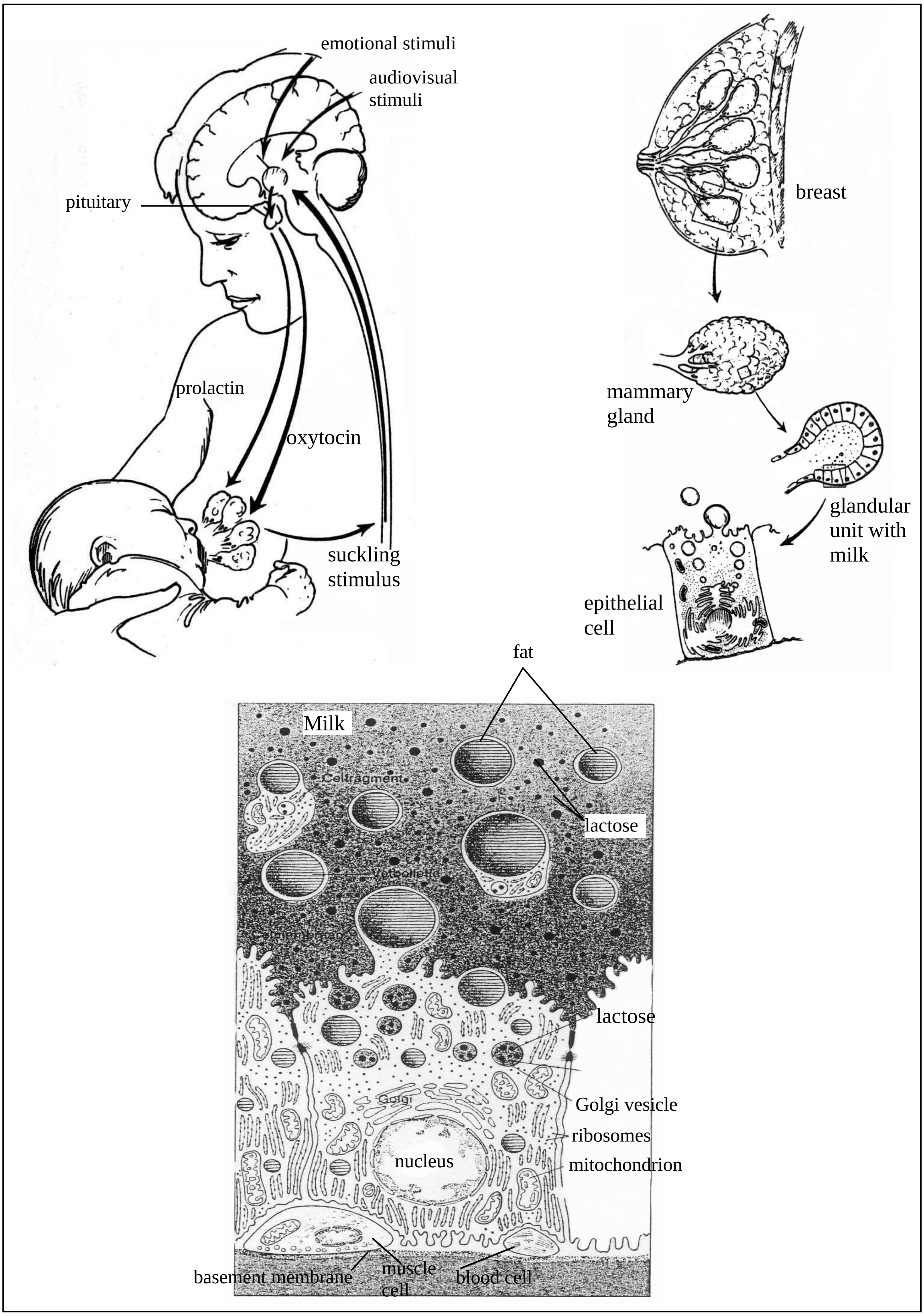
[…] When you investigate a living system, there are a few important questions that you could ask: What is the systems input and output in terms of materials and information? Which parts can be distinguished in the system and what is the nature of the cooperation between those parts? What functions do the parts fulfil for the system and what function does the system itself fulfil for the systems that it is part of?

Summarising, we could describe the system characteristics as follows:

- A system is surrounded by an open boundary through which there is exchange of materials, energy and information. Thus, there is a continuous exchange between the system and its external environment.
- In a system we can distinguish different levels of organisation. At each level of organisation, we can distinguish structures (subsystems) that closely cooperate.
- Each (sub) system fulfils a specific function for the system it is part of.

Box 4.2: ***A fragment of students' workbook in which the general characteristics of living systems are explicated.***

After the introduction of LTA 15, the teacher handed out the worksheets, which consisted of a description of the assignment, a sheet with three empty system models, one below the other, and some selected schoolbook pictures concerning breast-feeding on the level of the mother, breast and mammary gland cell (see box 4.3). Students were divided into groups of three or four and started working on the first assignment, which dealt with the process of breast-feeding on the level of the organism or mother. So, they started at the organismic level. Soon, all students were focused on the task except for



Box 4.3 ***Handout students received on breast-feeding at different levels of biological organisation.***

one group of three students, who showed very little interest in the assignment during the entire lesson. They only put some effort in solving the task in the presence of the teacher, who walked around and supported the different groups. The few discussions taking place between these three students were mainly dealing with difficulties related to a limited understanding of the biological content. The systems model itself was hardly point of discussion, while it was meant to help students in acquiring more insight into the biological content. This indicates that, at least for these students, the motive to engage in LTA 15, i.e. application of the systems model, was lacking and the LTA did not succeed in eliciting students' prior knowledge within the context of breast-feeding. Also, the prior knowledge of these students concerning breastfeeding at the organismic level seemed less than expected. At the end of LTA 15, this group had only filled in the systems model on the level of the mother and the breast with substantial help of the teacher.

The remaining six student groups ran largely as expected. Figure 4.5 (page 128) shows a final and typical hierarchical systems model of breast-feeding as completed by students during LTA 15. All groups started with filling in the systems model at the level of the mother. As given in the instructions, the 'suckling stimulus' was filled in as input and 'milk' was filled in as output. Also the breast, central nervous system (CNS) and pituitary were added in the model. The discussion soon focused on the coherence between the three 'organs'. Two groups started with linking the suckling stimulus directly to the CNS. The other groups started with the suckling stimulus coming into the breast, linked the breast to the CNS and the CNS to the pituitary, which stimulated the breast to give off milk: '(…) as soon as the stimulus enters they (the breasts) don't know at first what it is, so it goes to the pituitary via the CNS and it thinks: well, the child is thirsty so I'll give a stimulus to the CNS and that goes via the CNS to the mammary gland and then they give off milk'.

Students' prior knowledge regarding the regulation of bodily processes was mainly limited to the first chapter in their book, which dealt with the nervous system. Therefore the nature of the relations between the different organs was described as stimuli passed on by neurons. However, this view changed during the group discussions when students involved the first picture in their worksheets, either or not stimulated by the teacher. The picture showed two arrows from the pituitary to the breast, labelled with prolactine and oxytocin.

[2[1]:9.G.42]

Jaklien: Suckling stimulus goes via the mammary gland. Next: impulses to the central nervous system and these impulses have to arrive eventually at the pituitary.

[…]

Cynthia: And the pituitary?

Jaklien: From the pituitary it goes to the mammary gland.

Cynthia: Okay, so we draw an arrow here, but what does it take along? Milk? Or a stimulus again?

Jaklien: A stimulus isn't possible; it has to be an impulse (points at the picture). No it doesn't give an impulse, it gives a whole hormone!

Cynthia: Yeah, hormones. He gives off hormones and these are prolactin and oxytocin.

At this phase, students added hormones to their systems model but how hormones are able to reach the breast was no point of discussion. When the teacher asked students how hormones are transported, only one of the three groups answered that hormones are transported in the blood. The other two groups still held on to the CNS regulating milk production:

[2[1]:9.G.43]
T: What does the pituitary produce?
Rachen: Hormones.
T: Hormones, and how do hormones reach the breast?
Rachen: I guess via the central nervous system again.

Subsequently, the teacher referred to the first chapter, where some general differences between the nervous system and the endocrine system had been put forward, but none of the students remembered it at this moment.

The next step was to fill in the systems model at the level of the breast. At that level students had to ‘map’ two kind of relationships: 1) the sensory cells that transform the suckling stimulus into an impulse that leaves the breast via the nervous cells and 2) prolactine and oxytocin entering the breast stimulating the mammary gland cells to produce milk and the muscle cells to contract, resulting in milk leaving the breast. In order to separate these two kinds of relationships, students had to use their knowledge at the level of the mother.

As instructed, all students started by filling in the input and output of the breast in the systems model. Students seemed to have no difficulties in applying the same systems model to the breast. They just took the second model as a magnification of the breast in the first model. When filling in the input and output of the breast, most students copied it from the first model as intended:

[2[2]:9.G.44]
Tara: Here look! Here (mother) comes out milk already, so there has to come out milk here (breast) again.
Hanna: Yes of course, we’ve descended one level of organisation […] there still has to come out milk.
Petra: Okay, so what goes in and what goes out?
Hanna: Prolactine and oxytocin goes in.

Because Tara, Hanna and Petra had linked the suckling stimulus directly to the CNS, they did not draw it into the model of the breast (see also figure 4.5, organismic level). However, when the teacher stimulated them to think through the process on the level of the mother again: ‘The suckling stimulus arrives directly at the CNS. So, the child sucks on your spine?’, the students also added the suckling stimulus to the model of the breast and linked it to the sensory cell ‘that receives the stimuli and transfers them into impulses and pass it on to nervous cells’.

The next step was drawing the relations between the different cell types and describing them. As intended the group discussions largely focused on the nature of the relations between the different cell types, being impulses and hormones. The relationship between the muscle cells and mammary gland cells was correctly described as ‘force’, ‘movement’ or ‘squeeze’, which resulted in milk leaving the mammary gland.

During this assignment there was a clear difference between the different student groups in their ability to relate the different cells. Only one group, the same that knew the blood transports hormones, succeeded in linking the suckling stimulus to the production of milk by the mammary gland cell in a correct way and with little help from the teacher. This group could be characterised as the only group that included the first model on the organism level in their discussion to get a better understanding of the breast as fragment [2^2:9.G.45] shows.

[2^2:9.G.45]
Soued: Indicate these five cell types in the breast.
[…]
Soued: Sensory cells first, I think, and then mammary gland cells at the end…and muscle cells before them.
Elly: Yes, but I think that these nerve cells do something too.
Anne: Yes, but these nerve cells, they go to the pituitary. And these cells in the wall of the blood vessel, that is with hormones, so they come back again, it's a circle.
Soued: Yes.
Anne: Here, sensory cells pass it on to nerve cells. Well, the nerve cells go to the brains … pituitary […] and the hormones pass it on to the mammary gland itself.
[…]
Soued: Hmm and cells that form the wall of the blood vessel?
Anne: They pass on the hormones.

As fragment [2^2:9.G.45] shows Anne describes the pathway from the breast via the brains, pituitary and back to the breast again. Hereby, the students were able to draw the chain of relations in the breast starting with the suckling stimulus and eventually resulting in the production of milk by the mammary gland cell. It must be noted however, that the muscle cells were not involved in this chain.

The other student groups had more difficulties in relating the different types of cells in the breast. On the one hand students like Tara, Hanna and Petra started with the suckling stimulus entering the breast. These students linked the suckling stimulus to the mammary gland cells via the sensory cells, nerve cells and muscle cells respectively. They did not know how to include the cells of the blood vessel wall. On the other hand there were students who started with the hormones entering the breast. These students related oxytocin to the muscle cells in the breast via the cells of the blood vessel walls. They had difficulties in relating the sensory cells and the nervous cells.

So, although the assignment stimulated students to think about the relationships at the organ level, it did not stimulate students to think backward and forward between the level of the organ and the level of the organism. As a result students were not able to develop a complete and coherent systems model of the process in the breast on their own. For this purpose, the supporting role of the teacher was essential. Fragment [2^2:9.G.46] is exemplary for how the teacher supported the different student groups.

[2^2:9.G.46], T is teacher
T: Okay impulses arrive at the nerve cells here. What are these nerve cells doing with it? […] Try to go back to this (organismic) level. Where do they have to go, these impulses?
Tim: To the mammary gland?
Marc Nerves.
T: This was the mammary gland (points at the students' systems model). Two things left the mammary gland […] subsequently it gave off impulses to the central nervous system.
Marc: Yes.

T: If this is a nerve cell, then it passes on impulses to the pituitary. The pituitary produces hormones.
[…]
T: What comes into the breast, a few moments later?
Marc: These hormones.
T: Hormones. Hormones are always in the…?
Tim: Blood.
T: So, these hormones go to a blood vessel and from there they can …
Tim: Muscles!
T: Influence the muscles, indeed.
Tim: And the mammary gland.
T: They can also go directly to the mammary gland. And those muscles, when they contract and there is a group of mammary glands in between.
Marc: Then there comes out milk.
T: Yes. Okay, now you're going to explore the mammary gland cell further for a while.

As the above fragment illustrates, the teacher helped students in thinking backward and forward between the level of the mother and the breast. In doing so, he strongly steered the students into the desired direction. The intervention of the teacher succeeded in giving the students a better understanding of the process of breastfeeding. For example, students now realised that the hormones first have to pass the blood vessel in order to reach the muscle cell and the mammary gland cell. The subsequent group discussion between the students resulted in a completed model on the level of the breast. However, the strategy to think backward and forward between the systems models on different levels of organisations and use the system model on a certain organisational level to acquire a coherent understanding of a biological phenomenon that crosses different levels of organisation, remained to be explicated in a final reflection on LTA 15.

The third and last assignment of LTA 15 focused on completing the systems model at the cellular level. Students were able to transfer the input (hormones) and output (milk) of the breast to the mammary gland cells. Some also referred to the contracting muscle cells squeezing the gland cells together, but this 'force' was rejected as having an effect on the cellular processes. Instead, the input of hormones is directly related to the nucleus: 'The nucleus, say, governs everything. So, it seems clear to me that it receives hormones and, say, translates them'. From there students could relate to LTA 10 and 11 as the first part of fragment [2^1:9.G.47] shows.

[2^1:9.G.47]
Elske: From the nucleus it goes to the rough ER, because that's what we heard during the presentation about the ER and then it goes to the Golgi and then to the mitochondrion.
Rachen: But where does the milk come from? From what part of the cell?
Lisa: From the food vacuole.
Nienke: From the mitochondrion.
Lisa: O no, it comes out of the membrane.
Nienke: Yes, but that's not one of the options!
[…]
Lisa: Production of proteins takes place and subsequently they're passed on to the Golgi apparatus. Hey! So, it goes from the ER to the Golgi apparatus!
Elske: Yes, but from the ER it goes to the Golgi apparatus and from the Golgi apparatus it goes to the mitochondrion. But, in my opinion, there isn't coming milk from the mitochondrion!

Fragment [2[1]:9.G.47] also illustrates that students linked the production of milk to the production of proteins in the ER and the subsequent transport to the Golgi apparatus as intended (see also figure 4.5). However, there is uncertainty about the remaining pathway leading to excretion of the milk, mainly caused by the uncertainty about the role of the mitochondrion. For solving the vesicular transport route in the cell and linking the input of hormones to the output of milk, it was essential for students to realise that the Golgi apparatus excretes the milk. To this aim the teacher referred students to the schematic picture of a mammary gland cell. Students realised that the Golgi apparatus produced the milk and from there the students were able to reconstruct the vesicular transport pathway, starting with hormones entering the nucleus.

Except for the two students who explored the mitochondrion during LTA 10, all students had difficulties in understanding the mitochondrion. As Elske in fragment [2[1]:9.G.47] stated, most students concluded that the mitochondrion did not produce milk. Instead the mitochondrion was thought to be involved in the process by converting proteins into energy that was 'put into the milk'. This misunderstanding of the concept of energy was unexpected, because students were assumed to have a basic understanding of the concept of energy from their physics classes. Earlier, when explicating systems thinking, the exchange of energy was not discerned from the exchange of materials, because energy does not exist in a free form. However, during this phase students seem to think that energy does exist in a free form that can be added to the milk. The teacher explained the role of the mitochondrion by linking the mitochondrial function 'providing energy' to the other cellular processes. Instead of energy being a product to be excreted by the cell, the cellular processes were mentioned as a destination for the energy. The conception of energy itself was not discussed:

[2[1]:9.G.48]

T:	What's again the purpose of mitochondria?
Renske:	Supplying energy.
T:	Okay, so does the nucleus need energy to give off messenger RNA?
Judith:	Sure it does.
T:	Sure it does, hop, an arrow towards the nucleus. Does the ER need energy to produce proteins?
Judith:	Yes.
T:	Certainly. Is energy required to pinch off vesicles from the Golgi?
Renske:	Okay, so there have to be arrows to all organelles?

As fragment [2[1]:9.G.48] illustrates, support of the teacher was essential for students to be able to depict the cell as a coherent whole in which the organelles were interrelated correctly. The same applied to the level of the organism and organ. Afterwards, students often mentioned that 'it seems so simple when the teacher explains it' and in the subsequent group discussions (after the teacher had give them support) students were able to complete the systems models at each level. At the end of LTA 15, the completed systems models that were handed in depicted a coherent view of breast-feeding at different levels of organisation (see figure 4.5).

All together, during LTA 15 the systems model proved to be an important tool for the teacher to detect conceptual problems and to structure his support to students. For example, when students got stuck at the level of the organ, he stimulated students to ascend to the organism level first. After the lesson the teacher acknowledged that the activity, structured by the systems model, enabled him to detect were students got stuck and to help them back on track again. He explained that students had to do a lot of effort in completing the task in contrast to earlier LTA’s; his help was indeed needed to prevent students from giving up. Apparently, the teacher had noticed a break between

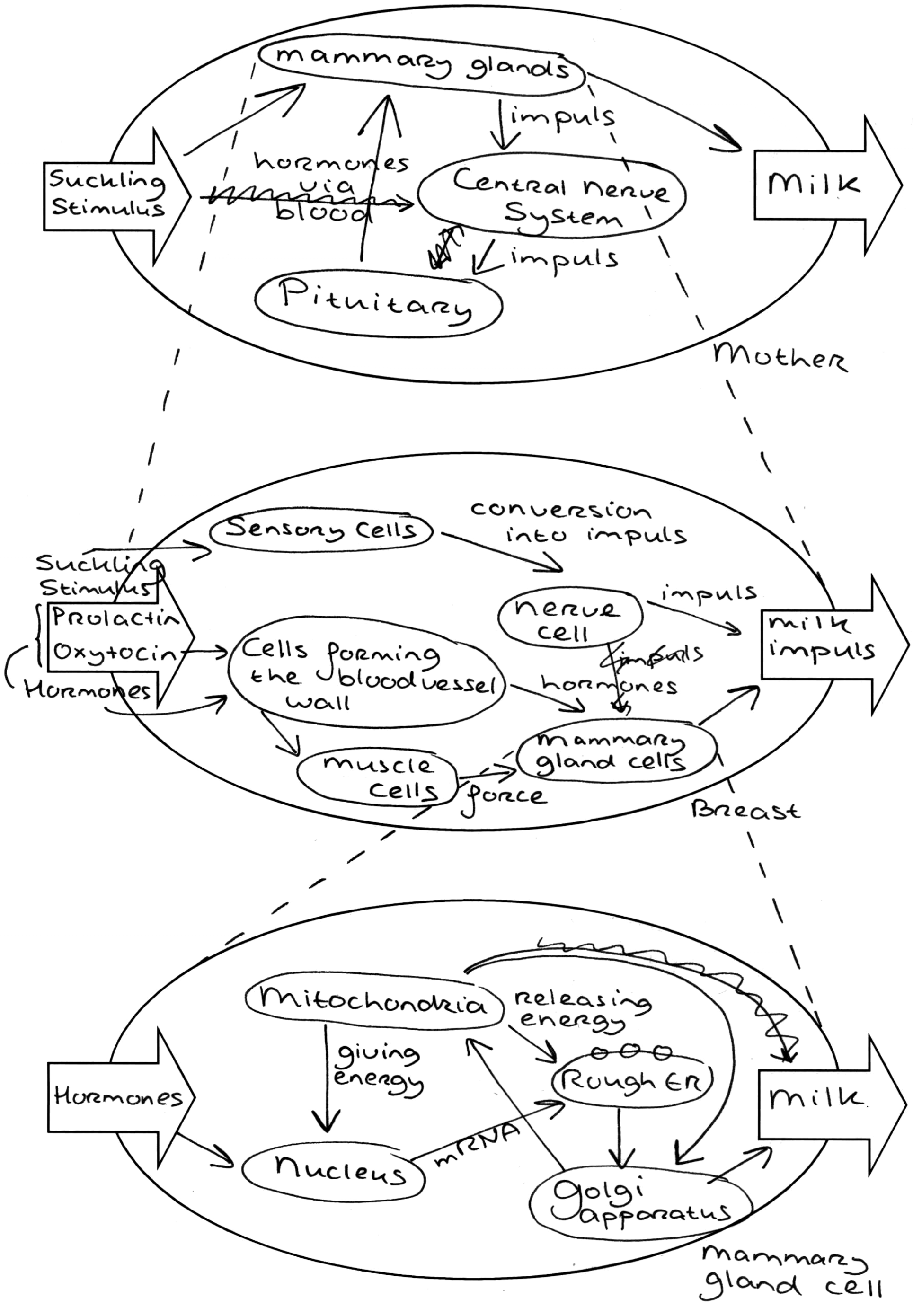


Figure 4.5 ***Students’ (Tara, Hanna and Petra) completed systems model of breast-feeding on the organismic (top), organ and cellular level as it was handed in after LTA*** *15. The model was realised with help of the teacher as illustrated by the cellular model. It shows that initially students depicted energy from the mitochondrion to be released directly into the milk (further explanation: see text).*

this and earlier LTA's, which forced him to intensify his intervention. However, he stated that LTA 15 had a real added value in comparison to his usual teaching approach providing him a reason to hold on to it in future lessons. The LTA stimulated students to go deeper into a certain body process. As mentioned earlier, LTA 15 was developed in close cooperation with the teacher. Usually, the teacher designed a similar assignment, i.e. explicitly exploring a body process at different levels of organisation, but it was not introduced until one or two years later. Therefore the teacher valued LTA 15 as a potential starting point for other themes that will be dealt with later in the curriculum.

Although the teacher did not explicate the strategy of LTA 15, i.e. thinking backward and forward between the different levels of organisation, students realised afterwards that a good understanding at the organismic level was indispensable to explore lower levels of organisation. This insight was linked to students' difficulties with completing the systems model at the organ and cellular level. When asked what level they thought was the most difficult one to complete, students answered without exception the cellular level, followed by the organ level. Three out of six students explained that in order to fill in the cellular model correctly, a correct and completed model of the organ was needed. The same applied to completing the organ model whereto students needed a completed model of the organism.

LTA 15 also showed that the systems model had been introduced in a meaningful way. The entire lesson students were engaged in applying the model to the process of breast- feeding, and relating the different parts at each level of organisation contributed to a better understanding of the phenomenon.

However, explication of systems thinking as a competence requires more time as well as reflection on the application of the systems model. LTA 15 was the final LTA of our strategy 'the cell as a system'. As intended the LTA included a reflection on the application of the systems model. But instead of a plenary reflection the teacher decided to reflect on the assignment per group at different moments during the LTA, because the students got stuck during the assignment. As a consequence, there was no time left for a plenary reflection on the application of the systems model. In addition, the reflection per group was focused on the biological content, i.e. acquiring a coherent understanding of breast-feeding. Therefore to students, this became the main aim of the LTA, instead of applying the hierarchical systems model. The strategy of thinking backward and forward between the concrete process of breast-feeding and the more general systems model was not explicated. Additionally, the strategy of thinking backward and forward between the different levels of organisation was not explicated either.

4.5.6 Follow up of the learning and teaching strategy

The results of LTA 15 and the cancellation of the plenary reflection because of time pressure cannot be separated from the educational context in which the LT-strategy was tested. When we contacted the participating teachers we presented our LT-strategy as a substitute for the regular cell biology course. However, our systems approach to cell biology resulted in the formulation of learning outcomes different from the regular cell biology course. In contrast to our LT-approach which focused on the cell as a whole and its relation with higher levels of organisation, the regular cell biology course focuses more on the molecular basics of cell biology as a prerequisite for understanding themes that are scheduled later in the curriculum. As a consequence, the teacher decided to use the lesson after LTA 15 to deal with the aspects that were left out of our LT-strategy, mainly concerning transport processes at the molecular level. Because this lesson was not part of our intended LT-strategy, we will only shortly describe this last lesson. On the other hand, this last lesson illustrated the constraints of testing our systems approach within the context of the current biology curriculum.

The teacher started the lesson by drawing the systems model of the cell on the blackboard and introduced the topic of this lesson by referring to the model:

[2^1:10.C.49]

Teacher: This will be the very last rounding off lesson about transport and cell membranes. […] You've got a cell and there are things coming in and out and inside there are organelles that are interrelated somehow. You already know that all. What's important now, is finding out how things come in and how things go out the cell, and how transport does take place within the cell. The previous lesson you thought, well hormones just come in the cell and present a message. But how does that actually happen? Only when you know how transport happens, you'll know how exactly organelles can mutually cooperate. When you know how things enter the cell, then you'll also know how cells are able to receive a message from another cell.

The teacher introduced the topic of transport within the cell and transport through the cell membrane by referring to the arrows in the cell model. The aim of this lesson is to descend one level of organisation and to deal with the transport processes at the molecular level. However, this aim was not communicated to the students at this moment. As a consequence, this final LTA was hardly related to the LT-strategy so far and a motive to engage in this final LTA apparently was lacking.

The teacher was lecturing all the time and students were listening passively. The teacher first went into the transport processes within the cell. Hereby he made a distinction between passive transport, diffusion and cytoplasmic streaming, and vesicular transport facilitated by the microtubili of the cytoskeleton. The latter was explained in terms of the elongation and dissemblance of 'tubes that consist out of actin and myosin proteins'.

Next the transport processes across the cell membrane, 'consisting of a lipid bilayer with cholesterol molecules and protein molecules at both sides', was dealt with. Here again diffusion of water, oxygen and carbon dioxide was distinguished from active ('ATP consuming') transport, by formation of vesicles or transport through the membrane facilitated by membrane proteins. Although the latter was mainly dealt with at the molecular level, the teacher concluded the topic by relating the molecular level to cellular, organ and organism level within the context of the disease cystic fibrosis. Cystic fibrosis is caused by a single mutation in the genetic material, which results in a permanently closed protein pore within the membrane of pancreas cells:

[2^1:10.C.50]

Teacher: With your cell biological knowledge right now, you'll able to tell such a story: There's one failure in the DNA sequence, so the messenger RNA also contains one failure and as a consequence the ribosome put an amino acid at the wrong place and so the endoplasmatic reticulum can't fold the protein properly. So, in the vesicle that should eventually put the hormone receptor at the outside of the membrane there's a wrong protein. […] And how do you notice that? Not in that cell. You'll notice it at the organ level: the mucus that I told you about, actually. And you'll notice it at the organismic level: you'll always have a cold. You'll start each

> morning by coughing and sitting at the edge of your bed tapping yourself on the back to loosen the mucus and throw it up… So then you're thinking at the organismic level. Can you make those steps? Eventually there is something wrong at the molecular level. Well, if you can think with me on that by now, you're already at the level of the average student in form five…

The teacher describes the characteristics of cystic fibrosis at different levels of organisation. However, the strategy of thinking backward and forward between the different levels is not explicated. Another remarkable characteristic of fragment [2[1]:10.C.50] is that similar to the introduction at the beginning of the lesson, the molecular level is not put forward as a level of organisation below the cellular level. In other words, instead of extending students' understanding of the organisation of the cell on the molecular level, this final lesson interfered with the students' learning process of acquiring a coherent picture of the cell as an organised whole. Moreover, during the last lesson the students were taught a large variety of new structures and processes, both on the molecular and cellular level. For example, the process of osmosis was introduced in the last part of the lesson.

The final lesson is illustrative for the overload of information that has to be dealt with in the current Dutch curriculum. This leaves little space for the introduction of systems thinking as a domain specific competence. At the same time, the break between the LT-strategy up to LTA 15 and the final lesson illustrated that the learning goals of our 'systems approach to cell biology' clearly differ from the learning goals of the current curriculum.

To acquire more insight in the outcomes of the LT-strategy regarding students systems thinking competence we interviewed some students and included an assignment in the final written test. The latter focused on (1) students' ability to adequately distinguish and name the three levels of organisation, i.e. cellular, organ and organism level in a biology text. Furthermore it tried to answer whether students were (2) able to (spontaneously) use the systems model in drawing a schematic representation of the concerning text, describing a biological phenomenon at different levels of organisation. The interviews focused on (3) how students appreciated and (4) understood the systems model. In addition, the interviews probed if students referred to their cellular knowledge when explaining the process of digestion, starting at the level of the organism (5).

The written assignment alternately described the stress mechanisms in the human body on three levels of organisation, i.e. the organismic, organ and cellular level. Students had to divide the text into six fragments and name the organisational level to which each fragment was related. Furthermore, the second part of the assignment asked students to draw a schematic representation of the text including the relations between the different parts at three levels of organisation.

The assignment was included as the last one of the entire test. 22 students completed the written test; two students apparently did not have time for the assignment, which required some reading. Students indicated afterwards that they did not have enough time to complete the test. In addition, the assignment was described as 'taking too much time and scoring low (the maximum score per question was mentioned in the test) because the assignment required substantial reading. So, although the written text provided some indications about students' ability to apply the systems model, it does not give a definite answer.

The results of the first part of the assignment, focusing on students' ability to adequately distinguish and name the three levels of organisation in a biology text, are outlined in table 4.6. The two students who did not complete the assignment were assumed to have put no effort in the assignment at all. Therefore, their responses were not included in the relative score concerning the elements of systems thinking as outlined in table 4.6 leaving a student number of 22.

Table 4.6 ***Relative test scores (%) concerning elements of systems thinking competence after completion of the cell biology course in 4V (n =22).*** *A more detailed description of the results is given in the text.*

Category of analysis		% of correct responses	% of false/incomplete responses
Division of text in fragments		68	32
Labelling the level of the:	Organism	55	45
	Organ	45	55
	Cell	59	41
Use of correct labels		86	14

To the question if students were able to adequately distinguish the different levels of organisation we could give an affirmative answer. 68 percent of the students correctly divided the text into six fragments. When labelling the different levels of organisation a large majority of the students (86%) used the correct concepts, being organism, organ, cellular, and molecular level (The molecular level was considered as a correct concept because it was addressed in the last lesson). However, students' ability to relate each fragment to the right level of organisation depended on the specific level. The fragments on the cellular level were labelled correctly by the majority of the students (59%). The other students mainly labelled it as the molecular level (23%) or organelle level (14%), indicating that the last lesson, which dealt with the molecular level had interfered with the LT-strategy.

It was remarkable that 21 percent of the students labelled the fragment on the organ level as tissue level. This indicates that the theory in their schoolbooks could have interfered with the introduction of the levels of organisation in the LT-strategy. In contrast to our worksheets the biology book made an explicit distinction between tissues and organs when introducing the structural organisation of cells. Taking into account this distinction and the part of the fragment that described impulses travelling from 'specialised cells in the sino-atrial node to the muscle cells in the wall of the heart', it becomes difficult if not impossible to choose between the organ and tissue level.

The ability of labelling the fragments at the organismic level differed strongly between the three fragments. The majority of the students (64%) correctly labelled the first fragment. The second fragment on the organism level was categorised to be on the molecular or cellular level by 45 percent of the students, probably because of the concepts of adrenaline and glucose. Students also had difficulties with the third fragment on the organism level. 45 percent of the students related the fragment to the organ level.

The second part of the final assignment in the test sought to probe if students were able to (spontaneously) use the systems model in drawing a schematic representation of the stress related events at different levels of organisation. The results concerning this ‘modelling’ competence are outlined in table 4.7.

18 out of the 24 students (75%) started with the assignment by drawing a hierarchical systems model similar to LTA 15, in which three levels of organisation were distinguished. 14 students also labelled all three levels correctly as cellular, organ and organism level. Of the remaining students who had drawn the systems model, two of them choose to depict the organ, cellular and organelle level and two students had only drawn a general model without adding a further description of the different levels and the stress-related events per level. For four students the assignment ended at this stage. At the end of the written test they had only depicted a general hierarchical systems model, without any reference to concrete elements mentioned in the text. Because we assumed that these students did not put effort in the rest of the assignment, their responses were not included in the relative score concerning the three remaining categories of analysis in table 4.7.

Table 4.7 ***Relative test scores (%) concerning modelling as an element of systems thinking competence after completion of the cell biology course in 4V (n =24).*** *A more detailed description of the results is given in the text. *Indicates that n = 20.*

Category of analysis		% of correct responses	% of false/incomplete responses
Spontaneous use of systems model		75	25
Labeling levels of organisation		58	42
Indicating and naming the *constituting parts* at the level of the:	Organism	70*	30*
	Organ	40*	60*
	Cell	60*	40*
Indicating and naming the *relations* at the level of the:	Organism	65*	35*
	Organ	45*	55*
	Cell	65*	35*
Indicating and naming the *input en output* at the level of the:	Organism	60*	40*
	Organ	30*	70*
	Cell	45*	55*

The quality of the completed systems models varied strongly with respect to indicating and naming the constituting parts, relations and input and output per level of organisation. Only four students completed the systems model at all three levels adequately. The results seem to indicate that although the majority of the students spontaneously used the systems model to depict the stress-related events to different levels of organisation, the ability of students to apply the systems model on concrete biological phenomena still meets substantial problems. As table 4.7 shows the problems were most prominent at the level of the organ. 60 percent of the students had difficulties in identifying the constituting parts and even 70 percent could not identify the input and output adequately. This is in line with students’ problems with dividing and labelling the text fragment at the organ level as described above. With respect to indicating the output of the (muscle) cell it was remarkable that 5 students (25 %) still thought energy to be leaving the cell. Apparently, energy is a problematic concept that needs special attention to be understood sufficiently.

To acquire more insight in students' system thinking competence we interviewed four pairs of students approximately one month after the written test. The interviews mainly focused at their attitude towards and their understanding of the systems model.
The interview also probed students' reference to their cellular knowledge when explaining a biological phenomenon, starting at the level of the organism.

During the interviews a hierarchical systems model was laid down in front of the students. When asked what the model represents, all four student pairs mentioned the different levels: organism, organs and cells with the organelles added by 'cooperation' or 'communication' between the different parts. Only one student also mentioned the molecular level on which 'the constituting parts of the organelles' could be distinguished. When asked if the molecular level was dealt with in the lesson series on cell biology she could not give a confirmative answer.

In their explanation of the systems model, two student pairs introduced the term 'level of organisation' themselves. In the interview with the other students, they did not bring in the concept themselves. But on being introduced by the interviewer, they immediately reminded what the levels of organisation were. However, they did not adopt the term when answering subsequent questions.

When asked to describe the communication between the cells, the students were able to distinguish impulses, hormones and exchange of materials, but they hesitated in giving a concrete example. Only one pair of students directly gave a concrete description: 'For instance, a kick is given against your leg or so. And that's being perceived by a sensory cell. That is passed on to a nerve cell in the CNS and that goes to your brains again … and then it goes back again …'

On being asked to describe the coherence on the cellular level two groups, among which the pair that gave a description at the level of the organism, gave a description of the relations between the different organelles and related to the vesicular transport system: 'When these ribosomes had to produce proteins they made a kind of copy of the DNA and that went to a ribosome and that's represented by one of those arrows (points at the systems model)...'. The other students had again difficulties in giving a more concrete description of the relations between the organelles and attributed it to the length of the period between the interview and the lesson series about cell biology. One pair of students put forward the lack of reflection during the lesson series, especially on the lesson about breast-feeding (LTA 15). She explained that the activity raised questions (dealing with the relations between the organelles and cells), but she didn't get the opportunity to ask them. Moreover, she doubted if the answers given and depicted in the systems model on her worksheet were correct.

Students' attitude towards the systems model was probed by asking them to explain what model they preferred when they had to explain a novice 'how a cell works'. They could choose between a 'realistic' model like the one in their schoolbooks and the systems model. Except for one pair, the students choose the systems model with the argument that 'it is orderly and shows all important aspects of the cell'. One pair of students added the comment that the other picture would be a helpful supplement, because it gives an idea 'what the different parts look like and what proportion they have in comparison to each other. Two pair of students appreciated the model, because the model comprises all important aspects of the cell biology course: 'the functioning organelles within the cell and the way cells eventually function in an organ and an entire body'. The student pair that preferred the model in their schoolbook argued that they experienced difficulties in filling in the systems model during the lesson on breast-feeding. This emphasises again the importance of a reflection after LTA 15 in which the systems model is presented as a tool that guides the exploration of a complex biological phenomenon crossing several levels of organisation.

Finally, the interview focused on students' reference to their cellular knowledge within the context of digestion, being a fundamental life process that was addressed in the computer-aided programme (see section 3.4.4). They were asked to explain the purpose of eating. All students answered that the purpose of eating is to provide the body with energy. When asked how food can provide the body with energy, three of the four groups spontaneously descended to the cellular level.

[2[1]:10+.C.51], R is researcher

R:	A long time ago you worked on an assignment about digestion on the computer… Can you tell me what the purpose is of the uptake of food?
Both:	For energy.
Nienke:	It is digested to supply energy …to keep your body functioning.
R:	And how does food keep your body functioning?
Nienke:	By combustion.
R:	And where in your body does combustion take place?
Nienke:	Eventually in the mitochondria, because they supply the energy.
[…]	
R:	Are there types of cells that are specialised in supplying energy?
Elske:	No, I don't think so because every cell contains mitochondria.
Nienke:	Except for red blood cells, they only contain oxygen, isn't it?

As fragment [2[1]:10+.C.51] shows, Elske and Nienke were able to relate the food uptake at the level of the organism to the combustion of nutrients in the cell. Moreover, the fact that all body cells (except for red blood cells) contain mitochondria means that combustion takes place in all cells and thus all cells need nutrients. Subsequently, on being asked how the nutrients reach the cells, students refer to the blood that transports nutrients from the stomach and small intestines.

One of the four pairs got stuck at the level of the organ and did not descend to the cellular level spontaneously. They explained that the nutrients are needed by the muscles and are transported there via the blood. Remarkably, the students only mentioned the muscles needing energy, the same 'organ' that was taken as example in the computer aided programme about digestion (LTA 13). In response to the question what happens with the food in their muscles, they stated that it was combusted there to supply for energy. They could not explain where exactly the combustion takes place. When the researcher mentioned the name 'mitochondrion', students immediately were drawn into the context of cell biology. At that moment they also realised that all cells do have mitochondria, which supply the cell with the required energy.

So far, the main results of the second LT-strategy in classroom practice have been outlined. In general the nature and sequence of the learning and teaching activities of the strategy can be considered fairly adequate. However, we also indicated some problematic elements in the strategy that need revision. In section 5.2 the adjustments to the second strategy are described and a final LT-strategy for the cell as a system is presented. In the remains of chapter 5 this third and final strategy is reflected on.

Chapter 5

Reflection on the cell as a system

5.1 Introduction

The preceding chapters described the aims, design, process and results of this developmental research study. In chapter 3 the process of developing a first LT-strategy for the cell as a system was outlined, and chapter 4 described two successive case studies, which provided the empirical basis for a final revision of the strategy. Section 4.4 described the results of the second case study in a chronological order and aimed to reflect on the internal consistence of the learning and teaching processes in classroom practice. It also reflected on the process of thinking backward and forward between the expectations as described in the scenario and the actual learning and teaching processes and their outcomes. The results in section 4.4 have been outlined in accordance with the five subsequent phases that constituted the LT-strategy, i.e. general orientation on cell biology, developing a model of free-living cells, application of the developed model to cells as parts of an organism, building a model of a plant cell and explication of systems thinking.

In this section a final LT-strategy for the cell as a system will be described and reflected on. Section 5.2 will present the final LT-strategy after revision of the strategy that was tested in the second case study. Subsequently, the final strategy will be formalised in section 5.3 through elaborating on the three main pillars that founded the strategy. First, the didactical structure of the final LT-strategy will be formalised. Second, the way our strategy addresses the acquisition of coherent cell biological knowledge will be outlined and third the process of modelling in our strategy is elaborated. These reflections result in answering the central research question at the end of section 5.3. Next section 5.4 focuses on the wider applicability of systems thinking for biology education and section 5.5 proposes some directions for future research. Finally, section 5.6 phrases the final conclusion of our research project.

5.2 Revising the second learning and teaching strategy

In this section the scenario executed in the second case study will be reflected on in order to revise the LT-strategy. Focus will be on the expectations and objectives described in the scenario and on the internal consistency of the learning and teaching processes. The general research questions that were introduced in section 1.2 will be answered:

❶ What learning outcomes arise from the executed learning and teaching strategy and what learning processes constituted these learning outcomes?

❷ What indications can be derived from the observed learning outcomes and processes for revising the learning and teaching strategy?

The expectations and learning objectives explicated in the scenario provided evaluation criteria. The latter reflect systems thinking competence with the central focus on the cellular level as described in section 3.3.2, i.e. are students able to:

① distinguish different levels of organisation, i.e. cell, organ and organism, and match biological concepts with specific levels of biological organisation?

② identify different systems at each level of organisation, including their input and output?
③ interrelate the biology concepts at each level of organisation? (horizontal coherence)
④ interrelate the biology concepts on the different levels of organisation? (vertical coherence)
⑤ think backward and forward between the general systems model and more concrete representations of cells, i.e. ranging from cell models to *real* cells seen under a microscope.

Conclusion of the second scenario in practice

Before presenting the third and final LT-strategy in the next section, this section will discuss the results of the second LT-strategy in the light of the evaluation criteria mentioned in the previous section. In general the nature and sequence of the learning activities constituting the five phases of the second LT-strategy could be considered adequate. In the first phase, the cell as an autonomous functioning unit was meaningfully introduced although the contrast between the autonomy of free-living cells and the interdependence of cells of a multicellular organism deserved more attention. The fundamental processes of life provided a useful starting point to explore free-living cells with a light microscope. The visual image difficulties that were experienced by looking at *real* cells resulted in a smooth introduction of more schematic representations of free-living cells. These enabled a further exploration of the life processes. At the end of the second phase the general characteristics that students had depicted in their drawings of a cell, formed the basis to develop a general model of free-living cells. At this moment, students' understanding of free-living cells showed horizontal coherence in terms of the constituting organelles and their interrelations (question ④, restricted to autonomous cells). Moreover, comparing the characteristics of unicellular organisms and multicellular organisms elicited discussions about the differences between microscopic and macroscopic phenomena. Hereby the problems described in science education literature regarding students' isomorphic representation of multicellular organisms and cells (see section 3.2.1) were addressed.

The developed model of free-living cells proved to guide students' observations of animal and plant cells. However, visual image difficulties related to the relatively small size of the cells and the limited magnification of the light microscope, asked for a closer look. At this point the introduction of electron microscopic photos was welcomed. The complexity and the amount of details visible on the photos helped students to realise the function of using models in getting a clear and orderly view of the cell. Within this context, students started with the construction of a 3-D cell model in the next phase. Although students were motivated to actively engage in the modelling activity, it could be questioned whether students grasped the point of why precisely modelling was addressed in this phase of the LT-strategy. Namely, a plenary reflection to explicate the function of using (cell) models, including the systems model, was not executed as intended.

In the first three phases students developed a model of free-living cells and applied it to the cell as a part of a multicellular organism. During the LT-activities in these phases students came across various cell models, ranging from their own drawings, the developed (general) cell model, and models of free-living, animal and plant cells. In constructing a 3-D cell model themselves, students used different models represented in their schoolbook, other biology books and on the Internet. For instance, some students used dynamic computer models to explain the functioning of a specific organelle. To construct a ‘consensus’ 3-D model of the cell, students had to compare the different representations of their organelles and finally agree upon the concrete appearance of their organelle and translate it into their own 3-D representation. So, in doing so students showed to be able to think backward and forward between the different cell representations (question ⑤).

The phase of building a cell model also addressed the horizontal coherence at the cellular level. Most students were able to interrelate the different organelles and connect them to cellular processes (question ④) as could be concluded from their plenary presentations. In this phase the differences between specialised cells were discussed in terms of the different number and shape of the organelles. The teacher played an important role in relating these specific characteristics to the function of the cell in the body by addressing the problem *how* cells fulfil their function. In a reflection concerning the difference between free-living cells and cells that fulfil specific functions in the organism they are part of, the teacher introduced the problem *how* cells specialise. Although the reflection was mainly carried out by the teacher and not by the students, the next activity succeeded in focusing students on the organisation of cells in the body. On the other hand, students were more interested in the regulation of cell specialisation than in the structural organisation that was addressed in the subsequent activity. Therefore, to students the transition from LTA 12 to LTA 13 was not a matter of course. In order to improve the problem posing character of this transition, it should address the student questions mentioned. Therefore, exploring the endocrine system instead of the digestion system would improve this step in the LT-strategy.

The fifth phase of the LT-strategy dealt with the introduction and explication of a systems model. So far, the structural parts and their interrelations had been studied on the cellular level, and now the organ and organismic level were added by means of a computer-aided program. By exploring a biological process that takes place on the cellular level up to the organismic level and by abstracting the structures and processes at each level, students realised that the phenomena at the three levels can be depicted in the same systems model. It could be concluded that the hierarchical systems model was introduced in a way that was meaningful to students. Nearly all students were able to complete the final assignment of the computer-aided program that addressed the integration of the models at the cellular, organ and organismic level into one hierarchical model.

In the last phase, students applied the hierarchical open-system model to acquire coherent understanding of a biological topic manifesting itself on different levels of biological organisation, i.e. breast-feeding. In acquiring an initial systems thinking competence, guidance of the teacher proved to be essential. Breastfeeding had already been dealt with in the foregoing teaching unit on growth and development and students obviously had difficulties in grasping the topic. Now, the systems model was used as a tool to acquire a more coherent understanding of breast-feeding, including integration of students improved cell biology knowledge.

In applying the systems model to a biological topic students had to interpret the process of breast-feeding as represented by fairly realistic models, and think backward and forward between those models and the more general hierarchical systems model. This process seemed to meet no substantial problems for most of the students (question ⑤). Distinguishing the three levels of biological organisation seemed a sensible activity for students to understand the topic and they showed to be able to match the different concepts with a specific level of organisation (question ①). In applying the systems model at each level, students showed to be able to identify the different systems including their input and output (question ②). Interrelating the different concepts at the organism and organ level was difficult, in contrast to the cellular level where students were inclined to go deeper into the nature of the relations between the organelles (question ③). So in this case the difficulties described in the science education literature concerning the lack of horizontal coherence in students' understanding of cells (see section 3.2.1) were solved to a considerable degree.

This last activity also enabled the teacher to identify misconceptions or gaps in students' understanding in terms of horizontal or vertical coherence, and subsequently to address these problems. However, in contrast to what was intended, the learning activity and the teacher's guidance focused on understanding the topic instead of using the systems model. This could have impeded metacognition, i.e. an appreciation of the systems model as a tool to learn about other phenomena as well.

With respect to interrelating the different levels of organisation (question ④) the teacher's guidance was essential. At this point the systems model was not self-explaining. In addition, thinking backward and forward between the different levels of organisation was not reflected on in a classroom discussion as intended. Nevertheless, the discussions between the students resulting in completed systems models, after the teacher had helped them on the way, were promising. Therefore the problems described in science education literature related to a lack of vertical coherence in students' understanding of biological phenomena (see section 3.2.1) could basically be tackled.

Concluding, our study showed that it is possible to integrate and explicate systems thinking in an LT-strategy on cell biology. However, the claim that our developed strategy would result in the desired systems thinking competence was premature. Acquiring such a competence requires more effort than one series of lessons. The systems model should be explicitly used when other topics, crossing several levels of organisation are dealt with. In this respect, the importance of the teacher's guidance in the last activity, e.g. stimulating students to think backward and forward between the different levels of organisation, was indicative.

Despite the marginal notes above, the questions ① to ⑤ could all be largely affirmed on the basis of the final test and interview. The last phase showed that the introduction of a systems model as a tool to explore biological phenomena was successful but it did not yet function completely on a metacognitive level. In the final test and in the interview afterwards the majority of the students spontaneously used the systems model to depict and explain respectively a biological topic manifesting itself on various levels of organisation. Moreover, the final test showed that most students were able to distinguish and label the cellular and organismic level, including the constituting parts with their input and output and their interrelations on the basis of a text concerning a specific biological topic. It must be noted here that the majority of the students had difficulties with the level of the organ, although the systems thinking competence of a large number of students encompassed the organ level as well.

Points of revision

The results of the second case study, described in section 4.4 yielded indications for fine-tuning and revision of the LT-strategy for the cell as a system. The main revisions concern 1) the explication of and reflection on the process of modelling, 2) the adjustment of LTA 13 so as to improve the problem posing character of the transition from LTA 12 to LTA 13 and 3) explicitly answering the central steering question in LTA 14. The second LT-strategy for the cell as a system has been changed accordingly, resulting in the third and final LT-strategy (see table 5.1). The revisions have been highlighted in grey. Not all revisions highlighted in table 5.1 concern major revisions. Also minor revisions, i.e. more accurate descriptions of the activities due to an advanced insight after the second case study, have been highlighted. The three major revisions will be elaborated below.

1) Reflection on the process of modelling, LTA 4, 6, 9, 11 and 15 – After the first case study the main revision of the first LT-strategy was aimed to engage students more actively in the process of modelling. In the first four phases of the second LT-strategy, modelling was used to enhance more coherent understanding of the cell. This culminated in a three-dimensional model of a plant cell. From the fifth phase the process of modelling focused on systems thinking. This started by elaborating the cell model into a hierarchical model including the cellular, organ and organismic level (= systems model) and ended with applying the systems model to the breast-feeding process. Although the LT-activities guided students to recognise the use of models in acquiring coherent (cell) biological knowledge, it seems questionable whether students realised the necessity of modelling at every step during the LT-process for answering the central steering question. To overcome this, the different steps in the modelling process should be marked more clearly. This could be achieved in a more explicit reflection by raising awareness about how modelling helps students to integrate the cell biology concepts they learn. Reflection activities should be planned at several moments in the LT-strategy. In table 5.1 the revisions concerning these reflection moments have been highlighted in grey in LTA 4, 6, 9, 11 and 15.

The scenario prescribed that the teacher should guide the reflection activities while the students were bringing in the content by discussing their learning difficulties and outcomes. Because the questions of the students were mainly content related and did not focus on the process of modelling, the reflection activities were not executed as intended. As an alternative approach we propose to invite students to reflect on the added value of the different successive models in terms of their contribution to answering the partial and central steering questions. This could start individually or in groups. Subsequently, the teacher could structure a plenary reflection aiming at defining the outcome of the process of modelling so far and identifying how to proceed, i.e. phrasing and answering the next partial question. In other words, students should value the reflection as essential to answer the central steering question.

2) Improving the transition from LTA 12 to LTA 13 – In LTA 12 students discussed the dependence of individual cells on signals from their environment within the context of stem cell therapy. This LTA raised a content-specific need for more knowledge concerning the endocrine regulation of cell division and specialisation. Instead of focusing on students' questions that were raised in LTA 12, the subsequent activity (LTA 13) went further with exploring the process of digestion on the level of the organism, organ and cell. So, the content that was chosen to be addressed in LTA 13 resulted in an interruption of the LT-strategy in terms of its problem posing character. To improve the transition from LTA 12 to LTA 13, the latter should focus on exploring the process of endocrine regulation at the cellular, organ and organismic level instead. Consequently, the computer-aided program will also pave the way towards formulating a final answer on the central steering question in LTA 14 in terms of the hierarchical structure of the body and the interrelation between the cellular and the organismic level, i.e. the mutual dependence between the cell and the body. As a matter of fact, hormones can be described as the input of information at the cellular level that regulate the cells actions. The structural organisation of the body makes it possible for hormones, produced by endocrine gland cells, to reach the cells via the blood circulation. Finally, LTA 15 further explores endocrine regulation by application of the systems model to the process of breast-feeding.

3) Answering the central steering question, LTA 14 – In the revised strategy, the central steering question should be answered explicitly in LTA 14. Although the central question was referred to several times during the LT-sequence in the second version, it could not be answered adequately yet. The answer should comprise an explication of the autonomous perspective and the functional perspective on the cell. The autonomous perspective should contain the concepts previously dealt with in the first three phases. The functional perspective includes explication of the concept of level of organisation. Also, it requires explicating the functional relationship between these levels of organisation, which was explored in the computer-aided program (LTA 13). So, highlighting the functional perspective in LTA 14 will help students in recognising the systems model as being useful not only to explore the structures and processes at each level of organisation but also the relations between the different levels of organisation. This way, answering the central steering question results in the recognition that the systems model can be useful to interrelate the cellular and organismic level. The latter is subsequently practised in LTA 15, by application of the model to a second biological topic.

Summarising, we can state that the second strategy needs some adjustments to improve the adequateness of the LT-strategy for the cell as a system. With these adjustments we consider the final strategy to be an adequate way to acquire coherent understanding of cell biology and to introduce an initial systems thinking competence.

Table 5.1 ***Outline of the 3rd and final strategy for the cell as a system***

Sequence of problems	Sequence of LT activities and learning outcomes
	I. General orientation on cell biology **LTA 1: Brainstorming in groups**. Eliciting prior knowledge about cells that is mainly related to the domain of growth and development. Students individually think of what they already know, discuss this in groups and formulate questions. • Students raise questions and wonder if their knowledge about cells applies to all cells.
To what extent are our body cells different from free-living cells? (central question)	**LTA 2: Class discussion** directed by the teacher. Introducing and orientating on the cell as a basic unit of the organism within the context of growth and development, which raises students' interest in the following problem: All organisms develop from a single cell by cell division. At some point the cells specialise in different ways, but are these cells still able to survive outside our body just as free-living cells can? • Students wonder what processes cells must carry out to maintain themselves and how they do so, leading to an interest in (autonomous) free-living cells.
	II. Developing a model of free-living cells **LTA 3: group work.** Reading a text about the smallest known 'free-living' cell (Mycoplasma genitalium), discussing the application of the fundamental life processes to free-living cells and drawing an idiosyncratic representation of the cell as an organism. • Students realise that the fundamental life processes apply to free-living cells, but wonder how they fulfil them.
How do free-living cells carry out the fundamental life processes?	**LTA 4: microscope practical and reflection** on the process of thinking backward and forward between their own developed model and observations of real cells. Investigating real free-living cells (amongst others Paramecium) guided by students' idiosyncratic representations of unicellular organisms and comparing their observations with their representations. • Students understand that free-living cells have a general structure in which functional parts can be distinguished. • Students can describe the developed model so far as representing their points of interest, i.e. the fundamental life processes of unicellular organisms.
	LTA 5: group work on a written assignment. Exploring the functions of the organelles within the context of nutrition resulting in a (final) general model of free-living cells. • Students understand that interaction between the (functional) organelles in free-living cells is essential to fulfil the life processes.
	LTA 6: Class discussion directed by the teacher. Reflection on the general model of free-living cells, including the process of modelling so far, and raising interest in cells as part of an organism. • Students appreciate the model, based on free-living cells, as a tool to address the central question: Do our body cells possess interrelated functional parts, i.e. organelles, as well?
Does the general model of free-living cells, also apply to cells that are part of an organism?	*III. Application of developed model to cells as part of an organism* **LTA 7: microscope practical.** Studying real animal and plant cells through the microscope, guided by the general model of free-living cells. • Students experience difficulties in observing the organelles and realise that they need a 'closer' look.
	LTA 8: group work on a written assignment. Studying electron microscopic photos of plant and animal cells and labelling and drawing the organelles. • Students realise that the cell is a complex functioning whole and feel the need

Sequence of problems	Sequence of LT activities and learning outcomes
	for a clear overview of the cell.
How does the cell as a functional unit of an organism carry out the fundamental processes of life?	**LTA 9: individual assignment and reflection** on the application of the cell model. Reading a text about the use of cell models and reflection on the process of modelling cells in this course. • Students realise that the model guided them in exploring the fundamental life processes. • Students realise they need a more realistic model to acquire a deeper understanding of how cells carry out the fundamental life processes, including all organelles and their interrelations.
	IV. Building a model of a plant cell LTA 10: Homework assignment (in pairs). Using the systems model to explore the characteristics and cellular functions of one specific organelle. Building a 3-D model, which will be placed in a 3-D model of a plant cell. Schoolbook and Internet are used as information sources. • Students value the systems model as a useful tool to reduce complexity. They can give a presentation about the functioning of one specific organelle and relate it to the cell and other organelles. Students are enabled to engage actively in LTA 11.
To what extent did the process of modelling help us in answering the central question (CQ)?	**LTA 11: Class presentations**, combined by the students, guided by the teacher, followed by a reflection that addresses the central question. Presenting the results of LTA 10, listening to the other presentations, placing the 3-D organelles in a 3-D plant cell and interrelating the organelles and explaining their cellular functions. In the reflection activity: • Students get a coherent understanding of the cell as a functioning whole. • They realise that cells and the body as a whole mutually dependent, yet wonder in what way.
In what way are cells and the body as a whole mutually dependent?	*V. Explication of systems thinking* LTA 12: Group work on a written assignment. Reading a text about stem cells and discussing the dependence of individual cells on information from their environment. • Students realise that (specialisation of) cells require(s) signals from their surroundings that are able to reach the cell by the structural organisation of organ systems in the body.
How are multicellular organisms organised?	**LTA 13: Computer-aided program in pairs.** Exploring the process of endocrine regulation on the level of the organism, organ and cell. • Students realise that the cell model also applies to cells and organs in an organism, and get a clear overview of how the body is organised.
	LTA 14: Plenary reflection on LTA 13. Explicating the levels of organisation and the general characteristics of living systems. Explicitly answering the central question in terms of the cell being a functional system to the system at higher level of organisation. • Students understand the hierarchical structure of the body and the general system characteristics, which apply to organisms, organs and cells.
What is the added value of the systems model?	*VI. Application of the systems model* **LTA 15: Group work and plenary reflection on systems thinking.** Applying the systems model and interrelating the different levels of organisation within the context of a specific biological topic (a nursing mother). • Students view the systems model as a tool to explain and acquire a coherent understanding of a biological topic at different levels of organisation and recognise the benefits of thinking backward and forward between the different levels of organisation.

5.3 Reflection on the learning and teaching strategy

Our study aimed at the development of an adequate LT-strategy in terms of acquiring both a coherent conceptual understanding of the cell as a basic and functional unit of the organism, and the competence of systems thinking. Systems thinking was not only used as a tool for designing coherent cell biology education, but it was also considered to be a desired learning outcome.

This section provides a critical appraisal of the final LT-strategy that was presented in the previous section. It aims to provide more insight into the didactical benefits of our LT-strategy from the perspective of the educational problems that have been introduced in section 1.2. The main characteristics will be discussed from three different viewpoints. Together the three viewpoints will provide more insight into how the integration of systems thinking and cell biology education was operationalised.

First, the didactical structure of the final LT-strategy will be formalised. This didactical structure could be seen as a content-specific educational theory and is based on the problem posing approach that has been described in section 1.4. It shows the different phases in our strategy and their didactical function in acquiring the intended outcomes. Furthermore, it outlines the conceptual and content-related motivational pathway that students go through. Second, it will be discussed how our LT-strategy addresses the acquisition of horizontal and vertical coherence in understanding cell biology, as this was an important aim of our developmental research. Third, an important element of our systems approach to cell biology will be discussed that emerged during our cyclic research phase and concerns the process of modelling. Hereby we will go deeper into the central role of modelling as a process to actively engage students in the development of systems thinking on the cellular level.

Finally, the three viewpoints will be integrated to give a final answer to the central research question of our study. At this point it must be noted that although our LT-strategy was reflected on from three different viewpoints, some overlap between these reflective elaborations is inevitable. Yet, each viewpoint illuminates a main component of our content-related theory and the didactical insights that it might contribute to the distinct research areas and educational practice.

The didactical structure

In the introduction of this thesis we described the context of our research, concerning recent developments in biological science and education, and we defined our position in between current learning and teaching theories adhered to by educational researchers. We presented the problem posing approach as a didactical starting point for our research. This section elaborates the problem posing character of our LT-strategy in terms of its consistency and appropriateness from the perspective of the educational problems that have been described in section 1.2. First, we present its general didactical structure, i.e. the didactical phasing and the functions of each phase in reaching the intended outcome that was defined as a competence. This enables us to compare our didactical structure with the didactical structures of some other researchers that have developed a problem posing approach to other topics. Next, we will present the problem posing structure in more detail to show in what way the didactical phases contribute to the development of cell biological knowledge or of systems thinking competence and how the phases come forward naturally to students because of the motives that they developed. Hereby it becomes apparent that at a more detailed scale within each didactical phase, a problem posing approach can be distinguished as well.

As we described in section 1.4, the problem posing approach aims to guide students in a bottom-up learning process in which they are actively and purposefully involved, i.e. students should at any time be able to justify what they are doing and why they are doing it. The learning activities are sequenced in such a way that students themselves experience the need to expand their knowledge into the direction of the desired outcomes. An important aspect of the LT-strategy shown in table 5.1 is that acquiring initial systems thinking competence was strongly integrated with acquiring coherent cell biological knowledge. Moreover, the strategy shows that sufficient knowledge about a biological topic such as cell biology is needed as a vehicle to develop a content-specific motive for systems thinking. The LT-strategy comprises a succession of six phases, which pave the way towards coherent cell biological knowledge and acquiring systems thinking competence. These phases have been marked in table 5.1, i.e. general orientation on cell biology, developing a model of free-living cells, application of the developed model to cells as part of an organism, building a model of a plant cell, explication of systems thinking and application of the systems model. In retrospect, we could formalise these six phases into a general structure for acquiring this competence in biology education:

1. General orientation and posing a central steering question that provides a global motive for studying the topic at hand
2 a) Narrowing down the global motive into a more content-specific motive for extending knowledge
  b) Subsequent investigation/ acquiring information: extending knowledge
3 Application of the knowledge acquired so far to a new situation
4 Further extension of students' knowledge and creating a need for reflection on the desired competence developed so far
5 Explication and further extension of the competence by widening the range of application.
6 Application of the competence, which also provides an outlook on the added value of the competence in subsequent learning

The successive phases in our LT-strategy for the cell as a system resemble the didactical phasing of Vollebregt (1998) and Kortland (2001) but are not identical to theirs. The main focus of these structures lies on the transition from the life-world level to the level of empirical generalisations, i.e. scientific explanations, by means of stimulating students to pose a for them meaningful main practical problem, that they are willing to solve. The successive phases in the problem posing structure reflect the subsequent steps in solving the main problem. For a description and reflection on their problem posing structures, we refer to Lijnse (2002) and Lijnse & Klaassen (2003).

With respect to the intended outcome of our study defined as a competence, our study could be compared to the study of Kortland (2001). Kortland has presented in his study on decision-making about the waste issue, a general problem-posing structure for the integrated teaching/learning of content knowledge and the competence to use this knowledge, i.e. students' cognitive and metacognitive abilities. Both learning processes are formulated in terms of two consecutive levels, indicated as an everyday life level and an operational level, respectively. The everyday life level indicates the starting point of the learning and teaching unit: students have a willingness to tackle a practical problem, while their competence to solve this problem is not sufficient and consists of a still intuitive procedure. The operational level for the competence indicates the endpoint of the intended learning processes in terms of the relevant knowledge and skills to tackle the practical problem under consideration. Having arrived at this level, students have available an explicit metacognitive tool. As Kortland already states, the use of these labels implicates that his didactical structure is restricted to teaching/learning processes within a practical orientation, i.e. processes starting from practical problems inherent in everyday life situations that ask for a solution.

In our study the general motive for studying the topic resulted from a general orientation on the content matter and, in contrast to Kortland, did not start with a practical problem in phase 1. Instead, students' interest in the topic to be learned was raised by a meaningful problem within the context of the foregoing theme: growth and development. In this theme, students' intuitive notions concerning systems thinking were appealed to in formulating the central steering question. However, systems thinking was not explicated in everyday life terms in the orientation phase or presented as an outcome of the LT-strategy. Instead, the systems thinking competence was gradually and implicitly developed by engaging students in the process of modelling cells, which explicitly aimed at extension of the content knowledge.

As Lijnse & Klaassen (2003) have stated, two phases represent the main points of a problem posing approach: the second phase in which the global motive is narrowed down into a content-specific need for more knowledge and the fifth phase which creates a need for a reflection on the developed knowledge or competence so far. In our strategy these phases can be recognised, but the fifth phase is different in nature due to the fact that systems thinking was not explicated from the start. In the first four phases of our strategy developing the required knowledge about a biological topic was addressed to serve as a basis to justify the explication of systems thinking. Subsequently, reflection on the developed knowledge and modelling competence in the light of the central steering question provided a justification to introduce a systems concept in the fifth phase. The last two phases explicitly aimed at developing and practising the systems thinking competence at a metacognitive level, based on the systems concept and the modelling competence. So, for students the fifth phase marked a transition. Instead of acquiring a better understanding in terms of content knowledge that is needed to answer the central steering question, in the last two phases students are acquiring insight into *how* the central steering question can be tackled on the basis what they have done so far. The final phase addresses the development of the systems model as a metacognitive tool for an improved performance of the competence.

The didactical structure in more detail

The problem-posing structure of the LT-strategy is outlined in figure 5.1. The figure shows how the process of learning and teaching switches between the cell biological content knowledge (left column) and the development of the systems thinking competence (right column). The figure reflects the main content related steps to be taken in developing a systems thinking competence within the context of cell biology. It shows that sufficient knowledge about a biological topic is needed as a vehicle to develop a systems thinking competence.

The questions that are elicited and answered in the LT-strategy (Table 5.1) are now reformulated into the local motives. The latter drive to either expanding their content knowledge or increase their systems thinking competence. The beginning of each new phase is marked by a local motive. In table 5.1 these motives are incorporated as content-related questions that are elicited by LT-activities in the previous phase and answered by the subsequent LT-activities. In the first phase of the LT-strategy a general introduction to the topic results in eliciting a central steering question that will be gradually answered in the total series of lessons. It forms a more precise formulation of the general motive for students to engage in studying the topic at hand. The subsequent questions in the left column of Table 5.1 are partial questions that serve as local motives to engage in the subsequent phases of the LT-strategy.

Together, the successive phases in the problem posing structure discussed above reflect the subsequent way in which the main problem is solved. In retrospect, a problem posing structure was also identifiable within each phase, so in fact it is a matter of problem posing cycles. As mentioned above, each phase is initiated by a local motive, which narrows down the general motive that was evoked at the beginning of the learning process. This motive is formulated in a partial question that phrases the need for more specifically formulated knowledge in view of the central steering question. The next step within each phase is extending knowledge by means of investigation. The LT activities during the investigation step aim at answering the partial question by extending students’ knowledge. In this phase students should realise that this knowledge brings them closer to answering the central question, but at the same time they should realise that additional information is still needed. A reflection step concludes each phase in which the answer on the partial question is formulated and it is verified to what extent the central question has been answered. In addition, a new partial question is formulated that arises from students’ experiences in the investigation phase.

For students the transition to the next phase is then marked by a new LT-activity, which addresses the next partial question. As a consequence, phase 2 up to and including phase 6 as mentioned above could be regarded as cycles that consist of the following steps:

a. formulating a partial question
b. extending knowledge by means of investigation/gathering information and creating a need for reflection
c. reflection on the extended knowledge in view of the central steering question and creating a need for more specifically formulated knowledge

Development of cell biological understanding	Motive	Development of systems thinking
General orientation on the cell as a basic unit of organisms		
	should result in feeling a tension between the autonomy of body cells and their dependence on the body as a 'whole'	
that is addressed by investigating the autonomy of (free-living) cells,		
	resulting in questioning how free-living cells carry out the fundamental life-processes,	
Answered in a process of thinking backward and forward between prior ideas, real cells and cell models	→	on which is reflected, resulting in a general model of free-living cells
	that is appreciated as a useful tool to acquire coherent understanding of animal and plant cells,	
Which is achieved in a process of thinking backward and forward between the developed model, real cells and EM-photos that asks for	→	reflection on the process of modelling so far in relation to the central question,
	resulting in appreciating modelling as an activity to acquire a coherent understanding of the cellular parts and their interrelations	
to be achieved by making a 3-D model of a plant cell	→	providing an answer to the question how cells carry out the fundamental life-processes, yet leaving the mutual dependence of cell and body unanswered,
	resulting in a recognition that we need to focus on the relation between the cell and the organism	
That is done within the context of a biological topic that crosses the cellular up to the organismic level,	→	leading to the explication of the hierarchical structure of the organism (levels of biological organisation)
	resulting in a recognition that the systems model can be useful to interrelate the cellular and organismic level,	
		which is practised by application of the systems model to a second biological topic
		on which is reflected in terms of the added value of the systems model so as to acquire coherent understanding of biological topics

Figure 5.1 *The problem-posing structure of the LT-strategy for the cell as a system.*

The problem posing cycle that constitutes one phase in the general problem posing structure is in accordance with the description of Knippels (2002). Similar to Knippels a more detailed description of each problem posing phase (or cycle) underlines the importance of reflection within each phase. In this respect, we differ from Vollebregt and Kortland who do not necessarily add a reflection step in each phase. Hereby we define reflection as a time-out in which restructuring of the experiences (during the step of investigation) takes place in the light of the newly acquired knowledge. More concretely, it means that the partial question is answered and that it is verified to what extent this answer sheds new light on answering the central steering question. The teachers' role in this is to guide the process of reflection while students bring in the content by referring to their experiences during the investigation phase, i.e. things they do or do not understand, their answers to the partial question and their need for more knowledge to answer the central steering question. In conclusion, both creating a need for reflection and reflection itself become part of every phase. The latter explicates the direction of the next step in the learning sequence.

Addressing horizontal and vertical coherence

Systems thinking includes both interrelating biology concepts at each level of organisation and interrelating biology concepts on the different levels of organisation, i.e. horizontal and vertical integration respectively. Coherent understanding of cell biology requires acquiring both horizontal and vertical integration. In this section we will give a critical appraisal how coherence is addressed in our LT-strategy. Subsequently, we will discuss the differences with the yo-yo strategy of Knippels (2002) in which the content was also structured according to the levels of biological organisation.

The general orientation phase in our strategy was connected with a teaching unit on growth and development. Students' prior ideas about the relation between the organismic level and the cellular level within the context of growth and development provided a starting point to descend to the cellular level just from the beginning. So the orientation phase elaborates on students' prior knowledge of the vertical coherence of growth and development, whereas the second phase addresses the horizontal coherence at the cellular level: the cell as an autonomous unit achieving the fundamental processes of life. By investigating living cells under the microscope students discover the constituting parts or organelles analogous to the organs in multicellular organisms. Subsequently, the organelles, including their cellular functions and their interrelations, are explored.

In phase 3 animal and plant cells are explored with a light microscope with the autonomous cell in mind. The 'hidden' complexity of these cells is uncovered by investigating electron microscopic photos of cells. The complex interrelations within the cell are further explored in phase 4, including a co-operative and active process of making a 3-D model of the cell and its organelles. Looking back on the cell biology knowledge developed so far and verifying to what extent the central steering has been answered, students' realise they need more information about the relation between the cell and the organism, i.e. they need to address vertical coherence. In this 5th phase, the perspective of autonomy changes into the functional perspective on the cell, i.e. the cell as part of a hierarchical system. The cellular, organ and organismic level are explicated and students discover that, through abstracting, structures and processes at different levels of biological organisation can be represented in the same way. Vertical coherence is hereby explicated in terms of the functional relationship between systems at lower levels of organisation and the system at a higher level they are part of.

In the last phase of our LT-strategy the systems model is applied to further consolidate conceptual understanding of both horizontal coherence and vertical coherence of a biological topic that students are acquainted with at the organismic level. The horizontal coherence at the organismic level, in terms of the interrelations between the organs, should be fairly known to students so that it serves as a starting point to explore the interrelations between the cells at the organ level and between the organelles at the cellular level. Hereby the main concepts used to describe the topic are linked to the right level of organisation. In addition, students are engaged in thinking backward and forward between the different levels of organisation so as to relate the concepts of the different levels to each other.

Our study succeeded the study of Knippels (2002) who also explicitly used the hierarchical organisation of biological systems to cope with the complex nature of genetics, which is mainly due to the fact that inheritance manifests itself at various levels of organisation. In her study the concept of level of organisation has been used as a tool to structure the learning sequence, but is not meant to develop systems thinking. In her problem posing strategy, students start on the organismic level from where students feel the necessity to descend to lower levels of organisation. Her strategy has a problem posing structure of content related questions and reflection activities. These engage students in the learning activities in which certain key concepts on a specific level of biological organisation are explored. The essence of her so-called yo-yo strategy is that that per level of organisation at least one complete problem posing cycle is executed. Such a cycle does not only aim at answering a partial question per level of organisation, but also includes coming back to the previous partial questions at higher levels of organisation.

Knippels has argued that her so-called ‘yo-yo strategy’ is suitable for all complex biological topics that cover different levels of organisation. Although the yo-yo strategy was not yet available when the major choices for designing our LT-strategy were made, we were aware of its main points: starting at the organismic level and descending and ascending the levels of biological organisation by means of subsequent problem posing cycles.

Our strategy differs from the yo-yo strategy since it does not descend from the organismic level to the cellular level. We had a good reason for doing so, since descending from the organismic level was already accomplished in the preceding teaching unit on growth and development. Furthermore, finding a central question that relates to students everyday knowledge at the organismic level seemed difficult, because of the microscopic nature of the cellular life phenomena (cf. reproduction and heredity, which also belong to the world of one’s experience). Therefore we introduced a central steering question within the context of growth and development. This enabled a smooth transition towards the cellular level and directed the LT-strategy towards acquiring more insight into the relation between the organismic and cellular level. However, it must be noted that although the second phase addressed horizontal coherence at the cellular level, it could also be argued that it started on the organismic level because it was based on investigating unicellular organisms, albeit microscopic ones.

The topic of our LT-strategy was restricted to the cellular level since acquiring coherent understanding at the cellular level was an important aim. It was decided not to engage students in several phases of ascending and descending between the levels of organisation. Nevertheless, the relation between the cellular and organismic level has been addressed in several phases. The organismic level has been introduced several times as a preparation to systems thinking, since at least two levels of biological organisation were considered necessary to justify the explication of systems thinking. For that reason the organismic level has already been introduced in the second phase by discussing free-living cells (*Mycoplasma* and *Paramecium*) performing all fundamental life processes. Hereby the analogy is made (and discussed) with multicellular organisms. Furthermore, the fifth and sixth phase address the relations between the different levels of organisation and engage students in thinking backward and forward between these levels.

As a consequence our strategy could not only be viewed as a sequence consisting of six problem posing cycles (see previous section on the didactical structure) but also as one problem posing cycle, which starts at the organismic level in the preceding teaching unit of growth and development, descends to the cellular level, addressing horizontal coherence and eventually relates the cellular level to the organismic level, i.e. ascending to the organismic level. From the above, it can be concluded that our approach differs substantially from the yo-yo strategy of Knippels that comprises several problem posing cycles, which each address a particular organisational level. As we have argued, these differences are the result of well-considered choices and relate to the fact that our study focused on one particular level of organisation: the cellular level.

Modelling

In our approach students are actively engaged in the process of modelling, in which formation, revision and elaboration of a cell model are performed respectively. Modelling occurs in four of the six phases that constitute our problem posing approach (see figure 5.2). Based on their idiosyncratic representations, in phase 2 students are developing a model of free-living cells, which is subsequently applied to cells as parts of multi-cellular organisms in phase 3. In a reflection activity the model is revised, so that it better describes the general characteristics of both free-living cells and cells that are parts of an organism. The development of cell models is completed in phase 4 in which students build a 3D-model of a cell. This process could be seen as consolidation and elaboration of students cell biological knowledge through assimilation and expression of what has been learnt in a three dimensional way. The last step in the modelling process is executed in phase 5 and 6. In phase 5 students explore human digestion by modelling structures and processes at the organismic, organ and cellular level by means of a computer-aided program. By abstracting structures and processes at all three levels students discover that the three levels can be represented by one systems model. In this phase the initial cell model is elaborated by embedding it in the general (hierarchical) systems model. Finally in phase 6 students apply the nested open-system model to the topic breast-feeding.

The models that are constructed in the various phases can be generally described according the definition of Ingham & Gilbert (1991): a simplified representation of a system, i.e. objects, events or ideas, which concentrates attention on specific aspects of the system. Moreover, models enable aspects of a system, which are either complex or not directly perceivable, to be rendered more readily visible (Gilbert, 1995).

Modelling, or model formation addressed in the phases above is considered as the construction of a model of some phenomenon by 1) integrating pieces of information about the structure, function, mechanism and behaviour of the phenomenon, 2) mapping from analogous systems, or 3) through induction (cf. Gobert & Buckley, 2000). As described in the previous section each phase concludes with a reflection step. Within the context of modelling, reflection on the developed model in a specific phase invites students to reject, revise or elaborate the model in the next phase. Model revision involves modifying parts of the model so that it better describes or explains a given situation. Model elaboration might involve combining or making additions to the model by processes such as embedding a model in a larger system or adding more parts to the model (Gobert & Buckley, 2000). Our modelling activities can be characterised as follows:

A. Modelling of concrete cells to a general 2-D portrayal of the cell (phase 2 and 3 in table 5.1)
B. Constructing a 3-D large scale model of the cell (phase 4)
C. Modelling visual representations of the organismic, organ and cellular level to a general systems model (phase 5 and 6)

The three modelling phases constitute the way towards systems thinking in cell biology education and will be described in more detail below. Next, in retrospect on the three phases, a trajectory for the development of complex systems models will be presented. In figure 5.4 the three modelling phases are depicted.

Modelling of concrete cells to a general 2-D portrayal of the cell

In the first modelling phase an initial model is developed on the basis of students' representations of their prior ideas about cells; organelles are lacking. Observation of real cells through a light microscope provides the need to extend the model so as to include the organelles that could be detected. Interpretation of the observed cells and extending knowledge about the functioning of free-living cells provides a need for a more concrete model of the free-living cell. So, thinking backward and forward between real cells and orderly representations of these cells is functional in acquiring a coherent understanding of the living cell, in terms of labelling the organelles (structure), their functions, and their interrelations (mechanism) that enable the cell to fulfil the life processes (behaviour). In a reflection on the learning process so far, a true 2-D portrayal of the cell is developed that expresses students' prior knowledge, extended with the representations of the organelles and their interrelations. In this reflection students should be actively engaged and they need to be guided in order to adjust their own representations of the cell into the intended direction. Also, in this reflection activity the model should emerge as a useful tool to address the central steering question and

explore animal and plant cells. In doing so, students are once more engaged in thinking backward and forward between real animal and plant cells and the developed cell model. In this phase the model can prove its usefulness in interpreting the light microscopic images and in reducing the complexity of the electron microscopic photos. As with free-living cells students again feel the need for a more concrete model to acquire coherent understanding of cells that are part of multicellular organisms.
At the end of the first modelling phase reflection on the process of modelling so far is essential. Students need to appreciate modelling as an activity to acquire a coherent understanding of the cellular parts and their interrelations. Hereby the model is explicated as a tool to acquire understanding of the cell in terms of its interrelated parts, their functions and its input and output.

Constructing a general 3-D large scale cell model

In the second modelling phase a large 3-D model is built in a co-operative and active learning setting. Each student pair is responsible for building a specific organelle and acquiring knowledge about its 3-D shape, size, function and relations with other organelles. An important purpose of modelling in this phase is to facilitate communication through a visualisation of the relation between the intention (acquiring coherent understanding of the cell) and the outcome of the activity (the model). This way the 3-D model becomes the product of a collaborative process that leads to the establishment of a consensus model. An important aspect of this process is sufficient guidance and stimulation of students to think backward and forward between their own model and expressed 'scientifically' acceptable models. For example, students could explore the computer-based model 'the virtual cell', which has been stated to be a valuable aid to students' visualisation of the complex 3-D structure of cells (Carmichael, 2000).

In a plenary reflection, all individual products of the students are integrated into a large model of a plant cell. Since integration of structure, mechanism and behaviour are essential for model building, active engagement of the students in this activity is challenging. Therefore it was decided that the students should present their results of the modelling process plenary as a preparation for engaging actively in the reflection.

This reflection is essential in both getting a coherent understanding of the cell and realising that the developed model is not adequate to answer the central steering question about the mutual dependence of the cell and the body. Subsequent modelling activities therefore need to focus on the relation between the cell and the organism.

Modelling visual representations into a general systems model

In this last modelling phase the process of thinking backward and forward between concrete representations and abstract systems models of a biological topic is initiated by means of a computer-aided program. For students to grasp the added value of this activity, they are subsequently invited to apply the hierarchical open-system model to a biological topic crossing the different levels of biological organisation.

Application of the systems model to a biological topic implies interpretation the different realistic (schoolbook) representations of the topic at different levels of organisation, and thinking backward and forward between these representations and the hierarchical systems model. The teacher needs to observe this learning activity closely as it provides the possibility to identify the deficits in students' understanding in terms of horizontal of vertical coherence and to deal with them accordingly.

In this activity, acquiring a systems competence at the metacognitive level is central. Therefore, the acquired competence should be reflected on resulting in an appreciation of the systems model as a tool to explore biological phenomena both horizontally and vertically. To this aim, the competence must be decontextualised from the biological topic that was addressed in the strategy. Although so far, two phenomena were explored with the use of the systems model, i.e. digestion and breast-feeding, it cannot be expected that the strategy would result in students fully acquiring the desired competence. Acquisition of systems thinking demands that it pervades the entire biology curriculum. However, the final reflection should provide an outlook on the added value of the competence in subsequent learning of biological topics such as evolution, behaviour or metabolism that have in common the integration of knowledge of processes and structures on several levels of organisation.

A trajectory for developing a hierarchical systems model

Together the three modelling phases form a sequence of learning and teaching activities that can take the students from prior knowledge and their idiosyncratic representations of a cell towards a target model, i.e. the hierarchical systems model. Inspired by Clement (2000) we will describe the, in our view most important elements of such a learning and teaching sequence. Figure 5.4 depicts these elements in more detail.

Clement (2000) has designed a basic theoretical framework for model based learning in which the process of developing a target model, starting from students' prior knowledge is outlined (see figure 5.3). As figure 5.3 shows, a framework for 'model-based' learning 1) indicates the necessity of having insight into students' prior knowledge and skills present before introduction and 2) specifies the goal of a target model or desired knowledge that students should acquire. The target model may not be as sophisticated as the expert consensus model that is currently accepted by scientists. Instead the target model from an educator's point of view should reflect qualitative, simplified, analogue or tacit knowledge that is often not recognised by experts. The hierarchical systems model in our study resulted from the description of systems thinking as a competence for (cell) biology education and reflects both horizontal and vertical coherence (see section 3.3.2). Moreover, it was intended to develop a model that could function as a metacognitive tool for students. Insight into students' prior knowledge and skills includes useful conceptions and skills that could serve as building blocks for developing target models. In our case the LT-sequence elaborated on students' prior knowledge about cells and the fundamental life processes and students' experiences with observing and drawing cells.

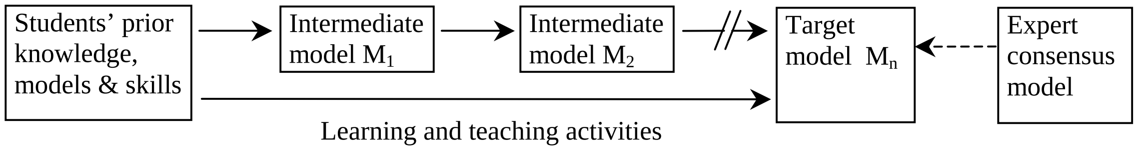


Figure 5.3 ***A general outline of a model based learning trajectory***, *after Clement (2000).*

According to Clement, a learning trajectory that takes the students from their prior knowledge towards the target model should include several intermediate models that serve as partial models on the way to developing the target model. The framework in figure 5.3 provides a general outline of the process of modelling in our LT-strategy. However, such a framework leaves unanswered which choices should be made regarding how the entities in the framework should be shaped.

In designing an LT-strategy that actively engages students in the process of modelling, an important issue is the nature of the intermediate models, as also followed from testing the first LT-strategy (see section 4.4). Should students use representations created by others to build models or should they generate their own representations? In our final LT-strategy both activities are integrated in the three phases that are mentioned above (see figure 5.4).

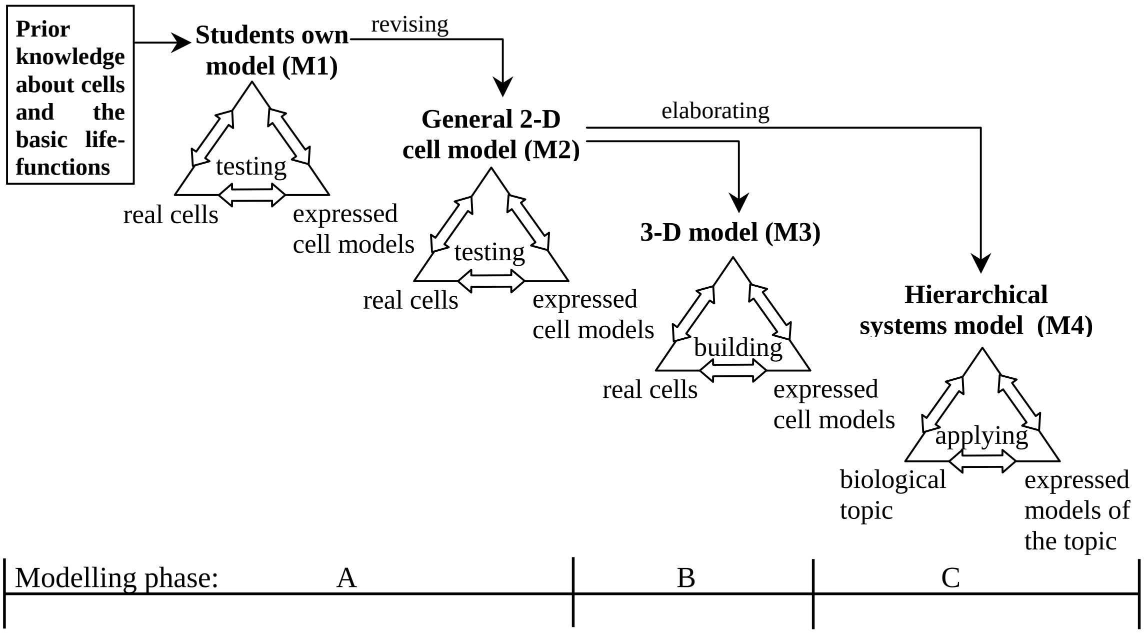


Figure 5.4 ***The learning trajectory from prior knowledge towards the hierarchical systems model via intermediate models.*** *For explanation see text.*

Modelling phase A starts with depicting students' idiosyncratic representations of free-living cells. Next, students are engaged in testing their own representations by means of investigating real cells and schematic representations as presented in their workbook, i.e. expressed models. In a reflection activity a first intermediate general model of cells is developed by revising students' own models.

In modelling phase B the general cell model is elaborated into a second intermediate model: a 3-D model of a plant cell. Building this model requires extension of students' knowledge of the size, function and interrelations of the parts of the cell. This could be achieved by investigating electron microscopic photos of real cells and expressed models in their workbook. Very recently, Al-Thuwaini (2003) showed in his study on the use of virtual reality techniques to visualise abstract scientific concepts, that 3-D visualisations strengthen students' understanding of cell biology concepts more than 2-D visual support. The main advantage of 3-D representations seems to be that they present information in a manner that allows students to interact with the concepts as if in reality more than 2-D representations. They enable students to visualise the concepts, which otherwise remain esoteric.

In the third and last modelling phase the second intermediate model was elaborated by embedding it in a general systems model. This was achieved by exploring a biological topic and abstracting it into a hierarchical systems model that included the former cell model.

Answering the central research question of this thesis

As presented in chapter 1 the overall research question of this study was as follows:

What learning and teaching strategy based on systems thinking results in an adequate and coherent understanding of the cell as a basic and functional unit of the organism?

At this point we are finally able to formulate an answer to the question above. Before we do so, we will clarify the essentials of our LT-strategy that emerged during the explorative phase and the cyclic research phase of our study. The explorative phase of our study disclosed that many conceptual problems at the cellular level are related with the fact that many cell biology concepts are drawn from the sub-cellular level, without being integrated with the cellular and organismic level. As a consequence, many students have difficulties in acquiring a meaningful and coherent understanding of the cell, which requires both interrelating different concepts at the cellular level (horizontal coherence) and interrelating different concepts at the cellular and organismic level (vertical coherence). The explorative phase of our study also enhanced the plausibility of bringing systems thinking into action as a domain specific competence, based on the concepts ‘open system’ and ‘levels of biological organisation’, in order to tackle the problems in learning and teaching cell biology. Moreover, it helped to define the intended outcome of our LT-strategy in terms of what a coherent understanding of cell biology entails (section 3.3.2).

Our LT-strategy ‘the cell as a system’, as presented in table 5.1, introduces the cell and its organelles by addressing the fundamental life processes that have to be achieved by unicellular organisms. The analogy between multicellular organisms and the cell as an organism helps in meaningfully introducing the organelles. In addition, discussing the differences between cells and multicellular organisms turned out to prevent conceptual problems related to isomorphism between the cellular and organismic level that have been described in the literature (Dreyfus, 1990; Flores & Tovar, 2003). The LT-strategy enables students to explore the different functions of the cellular structures and complex interrelations within the cell, on the basis of concrete observations and different cell models, resulting in an integrated view of the cell and its organelles. Hereby, the active engagement of students in the development of subsequent cell models guides them into the intended direction and improves students’ insight into the (spatial and dynamic) organisation of the cell. Furthermore, the cell biology vocabulary is tuned to the cellular level. The molecular level is deliberately left out to prevent making cell biology abstract.

The problem posing character of the LT-activities, that subsequently raise and answer questions (see figure 5.1), engages students in each activity that helps them to acquire more insight into the cell as part of a hierarchical system, i.e. the organism. The LT-strategy integrates cell biology with systems thinking. It gradually develops a reasonable motive for students to introduce and explicate systems thinking. The levels of organisation are explicated and vertical coherence is explicated in terms of the functional relationship between systems at lower levels of organisation and the system at higher level that they are part of. Moreover, in the last phase of our strategy students acquire an initial systems thinking competence in a process of thinking backward and forward between a general hierarchical systems model and concrete representations of a biological topic at different levels of organisation.

Thus, based on the qualitative indications mentioned above, the answer on the overall research question is that the strategy 'the cell as a system' is an adequate strategy that enhances the development of coherent cell biological knowledge and meaningfully introduces and develops an initial systems thinking competence.

Although it was beyond the scope of this developmental research project to test the retention of the competence, we have some indications that the competence helps students in acquiring coherent understanding of biological topics that are dealt with later in the curriculum (Van der Rijst, 2002). In her doctoral study, Van der Rijst investigated if students' system thinking competence could be drawn upon and used in learning and teaching about the process of 'sun tanning of the skin'. Her study was performed with the same teacher and students that participated in our second case study six months after they had followed the course 'the cell as a system'. She concluded that the systems model as introduced within the context of cell biology, helped students in descending from the organismic level to the cellular level and contributed to the improvement of students' integration of the processes of sun tanning at different levels of organisation.

5.4 Wider application of systems thinking for biology education

Contemporary biology education should reflect the international trend that in biological research the levels of biological organisation are increasingly integrated. Moreover, it should offer teachers the possibility to show students that biology in the 21st century is the science of complexity. In dealing with this complexity the current curriculum seems to fall short. As we demonstrated for cell biology, biology textbooks deal with the different topics in great detail leading to an overload of concepts that students have to acquire. In addition, the different themes are covered quite isolated of each other, and many cross-references are implicit. The Biological Council argues that focus should be on the development of coherent biological knowledge, amongst others by selecting a limited number of key concepts, and by applying these concepts in different contexts. This advice warrants our plea that in upper secondary biology education a considerable amount of time should be spent on the development and application of systems thinking.

Our study shows that it is possible to develop a motive for systems thinking by integrating and explicating systems thinking in a LT strategy on cell biology. Moreover, the study indicates how systems thinking can be introduced in upper secondary education and supports our assumption that systems thinking enables students to acquire coherent understanding of biological phenomena. The claim that our strategy would result in the desired competence was premature. Acquisition of systems thinking demands that it pervades the entire biology curriculum. In addition, the systems model as developed in our LT-strategy should be explicitly used when other biological topics such as evolution, behaviour and metabolism, are dealt with. These topics have in common the integration of knowledge of processes and structures on several levels of biological organisation.

Accepting systems thinking as a major competence for upper secondary biology students has evidently implications for the content and structure of the biology curriculum. Biological systems studied in the biology curriculum are open hierarchical systems; so all biology topics could be approached from a systems theoretical perspective derived from the General System Theory. The only prerequisite seems to be that the topics are defined as topics that cross different levels of biological organisation. Several topics of our biology curriculum in upper secondary schools, like cell biology, behaviour and ecology are defined in such a way that they are limited to only one level of biological organisation, or that they do not include the organismic level. Reconsideration of curriculum topics could be worthwhile.

As Knippels (2002) has stated earlier the development of coherent biological knowledge is promoted if biological topics are defined in such a way that they include several levels of biological organisation. In her study on genetics, she showed that the yo-yo learning and teaching strategy successfully copes with the complex and abstract nature of biological phenomena by explicitly distinguishing the levels of biological organisation, by descending and ascending these levels starting from the concrete organismic level, and by interrelating phenomena and concepts on the different levels.

Our study implicates that the explication of systems thinking offers students a meta-cognitive tool to deal with studying biological topics that follow after an introductory course on cell biology. To this aim, the systems thinking competence derived from the General Systems Theory should be explicitly integrated with the biological content matter. It should be used to address both horizontal coherence in terms of structures and processes at specific levels of organisation and vertical coherence between these structures and processes at different levels of organisation. The hierarchical systems model introduced within the context of cell biology offers the possibility to explicitly relate cellular structures and processes to higher levels of organization.

The hierarchical systems model also offers a starting point to introduce the molecular level as an additional level of organisation where molecules can be seen as interrelated parts that have a function for the system they are part of (organelle or cell). Our study already shows that the introduction of the molecular level needs extra attention (cf. Vollebregt, 1998; Lijnse *et al.*, 1990).

In section 3 we described two other systems theories besides the General System Theory that are relevant to biology education: Cybernetics and Dynamic Systems

Theory. Based on the concept of the open system, a cybernetic systems concept could be developed when regulation of biological systems is addressed. The dynamical systems approach becomes useful when development or evolution is addressed.

In designing biology education from a systems perspective we state that modelling must be a central activity. Systems thinking means thinking backward and forward between (concrete representations of) biological phenomena and abstract systems models. Each systems theory has its own scientific models and from these models a target model that is useful for biology education must be developed. The LT-processes that promote acquiring systems thinking competence, i.e. thinking backward and forward between a phenomenon and the target model, requires engaging students in a process of modelling that goes via several intermediate models. The model introduced in our LT-strategy presents a model that could act as a starting point to address cybernetic and dynamic systems models.

A possible sketch of some building blocks on systems thinking, that can be elaborated into four interrelating curricular lines. We propose to recognize the following four building blocks

1) The cell as a system: development of the concept open hierarchical system: relation between the organismic and cellular levels of organisation; input, throughput and output (General Systems Theory), and applied to various multilevel topics (Knippels, 2002), including the molecular level.
2) Regulation and homeostasis: development of the concepts (self-)regulation, feedback, homeostasis/dynamic equilibrium (Cybernetics, see section 3.3.1) (Buddingh', 1997; Kamp, 2000) on the organismic level, extended to other levels of biological organisation (Boersma & Schalk, 2001), and applied to various multilevel topics.
3) Ecology: further development of the concept open hierarchical system in terms of the relation between the organismic and ecosystem levels of organisation; input, throughput and output (General Systems Theory); extended with the concepts regulation, feedback, homeostasis/dynamic equilibrium (Cybernetics), applied to various biological topics that cross multiple levels of organisation, including the molecular level.
4) Development and evolution: development of the concepts, evolution, development and emergent properties on the organismic and population levels of biological organisation (Dynamic Systems Theory, see section 3.3.1), extended to the other levels of biological organisation.

5.5 Further research

This study has shown that initial systems thinking competence, based on the General System Theory, can be developed within the context of cell biology. By integrating systems thinking with cell biology a reasonable motive can be developed to explicate the levels of organisation from the cellular up to and including the organismic level and to meaningfully introduce an initial systems model. Considering the wider application of systems thinking, as described in the previous section, it may be suggested that the acquisition of systems thinking competence, i.e. being able and willing to use different systems models as metacognitive tools, deserves further study.

Additional levels of biological organisation

In our study the cellular level of organisation was central. The molecular level was not addressed because it was not considered essential for a coherent insight into the cellular structures and processes. Contemporary biology education, reflecting today's biological research, should include the molecular level of genetics, metabolism, endocrine regulation, etc. However, the introduction of the molecular level brings along specific difficulties due to the theoretical nature of the concept molecule (see also section 3.4.2; cf. Vollebregt, 1998; Lijnse *et al.*, 1990). As Knippels (2002) has already argued, the molecular level should be explored and taught as an extra level of organisation where molecules can be seen as interrelated parts that have a function for the complex system they are part of (organelle or cell). The hierarchical systems model could function as a useful tool to introduce and elaborate the structures and processes at the molecular level. We suggest that the transition to and elaboration of the cellular level should be the focus of further research whereby the hypothesis that systems thinking facilitates this transition could be tested.

Another extension of systems thinking, based on the concept open hierarchical system could be into the direction of the organism and higher levels of organisation, e.g. population and ecosystem level (building block 3 in the previous section). Several studies have reported that students have difficulties in grasping the dynamic nature of ecosystems (e.g. Barman *et al.*, 1995; Hogan, 2000). We suggest that a systems approach might be profitable. As we have shortly described in section 3.4.2 an initial ecosystem concept according to the General System Theory may be developed on the basis of a worked out food chain in a biotope with clear system boundaries. Hereby it is important that students can see how a systems model could help them in understanding phenomena and solving problems at the population and ecosystem level. Subsequently, based on student's knowledge about the interrelations between populations and the concept food chain, students' understanding of the concept ecosystem could be extended by engaging them in the development of more dynamic and quantitative models. Studying ecosystems through cybernetic, computer-based modelling in particular could provide students with valuable experiences in analysing complex systems and understanding their emergent behaviour. Further research could provide more insight into how this could improve students' insight into ecological phenomena, while giving them new conceptual tools for understanding complex biological systems everywhere around them.

Modelling and metacognition

In our research modelling has been supportive for acquiring coherent understanding of the cell and for acquiring systems thinking competence. The process of modelling engaged students in the scientific practice of using models as a tool for observation, exploration, synthesis and to a less extent prediction of biological systems and their behaviour. Thus, developing systems models not only has potential to help students to learn about biological systems, it can also foster their understanding of the nature of science as an enterprise that is largely concerned with extending and refining (systems) models (Gilbert *et al.*, 1998). In doing so, it seems worthwhile to engage students in informed and purposeful modelling activities, to the extent that they exert control over the process of modelling and become aware how modelling promotes understanding of complex biological phenomena. These notions imply metacognition, which is fundamental to purposeful inquiry, i.e. asking oneself specific evaluative questions (reflecting) and implementing procedures to gain answers to these questions (acting) (Baird & White, 1996). In our final LT-strategy, reflection is included in each problem-posing phase. Students are invited to reflect on the added value of the different successive models in terms of their contribution to answering the partial and central steering question and to identify how to proceed. In other words, students should value the reflection as essential to answer the central steering question.

As may have become clear from section 5.2, our study has not provided a solution to how exactly reflection should be employed in classroom practice to foster metacognition. It became clear that engaging students in active reflection requires more effort and change of both students and teachers as they seem not used to direct a process of purposeful inquiry. We suggest that, with respect to the acquisition of systems thinking competence at the metacognitive level, further research could provide deeper insight into how reflection activities should be shaped in classroom practice. We refer hereby to the Project for Enhancing Effective Learning (PEEL) (Baird & White, 1996) that involved large numbers of secondary school students and their teachers in detailed collaborative reflection and action about everyday classroom practices. The project was designed to improve the quality of classroom teaching and aimed students to engage in active reflection and to develop metacognitive strategies. Although the PEEL-project determined some useful procedures in this sense, it also demonstrated that application of metacognitive strategies places high demands on both students and teacher. Following our study and the indications from the PEEL project, future research could provide deeper insight into effective ways of developing systems thinking at the metacognitive level and how teachers could best orchestrate this development.

5.6 Final conclusion

Systems thinking holds great implications for learning and teaching biology subjects. It implies distinguishing and interrelating different levels of organisation and interrelating the different concepts at each level. It is helpful in fostering *coherent* biological understanding. In addition, systems thinking implies awareness of the fact that biological phenomena can be represented by models that range from very concrete portrayals to highly abstract systems models. The systems models reflect the main characteristics of a chosen systems perspective, i.e. General Systems Theory, Cybernetics or Dynamical Systems Theory. Thinking backward and forward between these systems models and real biological phenomena enables students to explore the phenomenon from a specific systems perspective and fosters deeper understanding of the structural, regulation or developmental aspects of that phenomenon.

Our LT-strategy actively engaged students in a modelling trajectory that resulted in the development of a hierarchical systems model via several intermediate cell models.

Each modelling activity is functional to acquire further insight into the cell as a basic and functional unit of the organism. As a consequence, we consider the strategy ‘the cell as a system’ to be an adequate first step towards the development of systems thinking competence in biology education.

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Summary

This thesis describes a developmental research project that was performed at the Centre for Science and Mathematics Education at Utrecht University from June 1999 till August 2003. The project addresses the introduction of an initial systems thinking competence in pre university cell biology education. The aim of this study is to develop a theoretically founded and empirically tested learning and teaching (LT) strategy for 'the cell as a system' in upper secondary biology education. It should provide more insight into dealing effectively with the problems in cell biology education and also yield some indications about how to proceed in designing biology education from a systems perspective. The overall research question is formulated as follows:

What learning and teaching strategy based on systems thinking results in an adequate and coherent understanding of the cell as a basic and functional unit of the organism?

Chapter 1 describes the context of the central problem that is addressed in this thesis and reflects the first part of the explorative phase of our study that is further elaborated in chapter 3. The developments in biological science and biological education, as well as current notions on learning and teaching that are discussed, serve as a basis for a domain-specific philosophy of learning and teaching.

Biological education research literature reveals that many conceptual problems both at the organismic and at the cellular level are associated with a compartmentalised approach to dealing with life phenomena and a lack of interrelating the different levels of biological organisation. The origin of this approach can be found in the development of biology itself. The division of the domain in many subjects and the focus on detailed knowledge within each subject are deeply rooted in the history and research practice of biological science and related to the emphasis on reductionist approaches within biology. Current biology education in the Netherlands still reflects the reductionist research approach and shows a cognitive overload, poor coherence and a shortage of relevance to students.

The strong development of biological sciences has resulted in more emphasis on understanding organisms in holistic, dynamic and interactive terms. Important new insights at the molecular level are gradually connected to higher levels of organisation and reversibly much research at the molecular or cellular level derives its questions from new insights at the level of the organism or ecosystem. As a consequence, biological knowledge at all levels of organisation, from the molecular level up to the community level is linked inextricably.

Although the developments in biological science have had its implications for biological education, a coherent and integrative approach to dealing with life phenomena has not been adequately implemented in school practice. In our view, biology education should focus on development of domain-specific competences in which the required biological knowledge is connected to practices that are relevant and meaningful to students. In this study we present systems thinking as a key competence. Systems thinking competence is the ability and willingness to link different levels of biological organisation from the perspective that natural wholes, such as organisms, are complex and composite, consisting of many interacting parts, which may be themselves lesser wholes, such as cells in an organism. Our assumption is that purposeful

application of a systems perspective leads up to more coherence in learning and teaching of cell biology.
In developing an adequate LT-strategy for the cell as a system, the problem posing approach was chosen to actively involve students in their learning process on a content-related basis. In our view the problem posing approach is compatible with the situated cognition perspective in actively involving students in social interactions within an appropriate educational practice in the classroom to learn the new competence of systems thinking.

Chapter 2 describes the interpretative research approach applied to answer the central research question of this study, which is characterised as developmental research. The developmental research approach comprises an explorative phase and a cyclic research phase.

In the *explorative phase*, the general characteristics and structure of the (supposedly effective) learning and teaching process for cell biology from a systems theoretical perspective were identified. A significant part of the theoretical foundation of the study was articulated during this phase. This foundation includes the domain specific subject matter, i.e. its contents and conceptual structure, and reported solutions to learning problems within the domain. Studying relevant literature and testing some first theory-based ideas in the context of a classroom setting resulted in a problem diagnosis and inventory of solutions. At the same time, this phase enabled the researcher to develop a more articulated view on the content specific methodology.

Based on the results of the explorative phase design criteria were defined and transformed into a preliminary LT-strategy that was tested in the *cyclic research phase*. In this phase two case studies at different schools were planned. In testing the adequacy of the LT-strategy, the strategy was firstly elaborated in a scenario, which guided the analysis of the actual learning and teaching process in the classroom practice. When the scenario was carried out, various data sets were collected and analysed. Reflection on and evaluation of the scenario in practice gave rise to improvement of the LT-strategy, which was elaborated into a second scenario and field-tested in a second case study. This way, the feedback of practical experience into the improvement of the strategy induces a cyclic process of development and research. Finally, this resulted in a theoretically founded and empirically tested LT-strategy.

Following chapter 1**, Chapter 3** further elaborates the explorative phase of our study. In this phase we re-analysed the research literature on cell biology education, interviewed teachers and students and analysed schoolbooks. It was found that many conceptual problems at the cellular level are related with the fact that many cell biology concepts are drawn from the sub-cellular level, without being integrated with the cellular and organismic level respectively. As a consequence, many students have difficulties in acquiring a meaningful and coherent understanding of the cell, which requires both interrelating different concepts at the cellular level (horizontal coherence) and interrelating different concepts at the cellular and organismic level (vertical coherence). Despite some reported suggestions to tackle these problems, mainly by approaching the cell and its processes from the concrete macro-level, an adequate strategy for acquiring a coherent understanding of the cell and its processes could not be found. Some explorative interviews with Dutch upper-secondary biology teachers and content analysis of schoolbooks showed difficulties similar to those identified in the research papers mentioned. Although systems thinking is included in the Dutch examination requirements, it is applied to cell biology.

Subsequently, based on the theoretical exploration of the three major systems theories, a systems thinking competence is described as enabling students to develop a coherent understanding of (cell) biological phenomena. The three systems theories and their central ideas each offer a different perspective on living systems. The General Systems Theory (GST) mainly emphasises the structural organisation of living systems, Cybernetics deals with regulatory aspects and the Dynamic Systems Theory offers a developmental and evolutionary perspective on living systems. Based on the exploration of the three theories in relation with the conceptual problems concerning cell biology, it was chosen to integrate cell biology education with the introduction of a systems concept derived from the GST. The systems thinking competence was specified in terms of the key concepts of the GST, i.e. ‘open system’ and ‘levels of biological organisation’. An important aspect of this competence is ‘being able to distinguish different levels of organisation, i.e. cell, organ and organisms, and matching biological concepts with a specific level of biological organisation’. In addition, the competence comprises ‘being able to think backward and forward between the general systems model and more concrete representations of cells’.

The first step towards integration of cell biology education and systems thinking was to present a coherent description of the cell biology content from a systems perspective. This conceptual background for developing a LT-strategy for the cell as a system addressed the autonomy, complexity and functionality of the cell as a basic unit of life respectively. In a further theoretical underpinning of the integration of cell biology education and systems thinking the question is raised whether:

1) Systems thinking should be introduced and used as a framework to develop a coherent understanding of cell biology, or
2) Systems thinking should be developed as a second outcome of a series of lessons about cell biology and applied to another biological topic.

To choose between the two approaches and to articulate a more precise picture of a supposedly adequate LT-strategy for the cell as a system two pilot studies were conducted. First an explorative case study concerning two lessons on endocrine regulation was carried out. Emphasis was on relating students’ prior cell biology knowledge to higher levels of organisation. Another exploration focused on a computer-aided development of a hierarchical systems model of human digestion.

From the first explorative case study it was concluded that a cell biology course should pay explicit attention to the cell and its relation with higher levels of organisation. The second study, showed that developing a systems model can go hand in hand with descending from the organismic level down to the cellular level of organisation. Both studies provided indications as to how to start the LT-strategy, either with cell biology or with systems thinking. Instead of choosing between the two approaches, a synthesis seemed possible in which the development of cell biological knowledge parallels the development of systems thinking competence.

The different research activities in the explorative phase generated ideas about how cell biology education could be shaped from a systems theoretical perspective. This included some promising learning activities and a defined criteria. These were transformed into a preliminary strategy for the cell as a system consisting of a sequence of problems and a sequence of learning and teaching activities with their outcomes. The strategy comprises five phases, i.e. I) general orientation on cell biology, II) exploration of the fundamental life processes and introduction of the cell as an organism, III) explication of systems thinking, in which a systems model was introduced at the organismic level, IV) exploration of the cell (as a functional unit) and its organelles guided by the systems model and V) interrelating the cell and higher levels of organisation.

Chapter 4 describes the cyclic research phase in which the LT-strategy was optimised and reshaped so as to constitute an empirically founded adequate sequence of learning activities. The initial and the revised LT-strategy were both elaborated into a scenario and field-tested in two successive case studies. The results of the first case study are not described in full detail but intend to provide a more general insight into the development of the strategy that was tested in the second case study. Based on a critical appraisal and revision of the LT-strategy in the first case study, it was expected that the second case study was more to the point in studying the characteristics of an adequate LT-strategy for cell biology based on systems thinking. Therefore the results of the second case study are the essence of this chapter. They are described in chronological order and focus on the internal consistency of the learning and teaching processes in classroom practice. The results also reflect the process of thinking backward and forward between the expectations as described in the scenario and the actual learning and teaching processes and their outcomes.

The results of the first case study, showed some deficiencies of the initial LT-strategy. Most importantly, the LT-strategy proved to be inadequate in enabling students to acquire a sufficient competence in using the systems model as a ‘tool’ to explore the cell as a functional unit of the organism. To solve this problem, the revised LT-strategy focused on engaging students more actively in the development of different cell models and eventually in a hierarchical systems model. Modelling cells became a central activity in the LT-strategy whereby the complex character and microscopic scale of cells provided a motive for developing a model, which gives more insight into the structural organisation of cells.

The revised LT-strategy to be tested in the second case study comprises five phases. After the general orientation on cells in phase I, Phase II to IV engages students in modelling cells and precedes the development of a general hierarchical systems model in phase V. Phase II comprehends the development of an initial (still implicit) systems model of free-living cells that is based on students’ idiosyncratic representations. Hereby students are stimulated to think backward and forward between their own representations, their observations of real cells and expressed models in their workbooks. Phase III addresses the application of the developed model to cells that are part of multicellular organisms. In this phase, students are stimulated to think backward and forward between different representations of animal and plant cells. Subsequently students construct a large-scale 3-D model of a plant cell in phase IV. The final modelling step in the LT-strategy is the extension of the cell model and relating it with higher levels of organisation. This step goes hand in hand with the explication of systems thinking. Reflection on the benefits of the hierarchical systems model should result in the recognition that the model can be useful to acquire insight into the relation between the cell and the organism. This insight is further consolidated in the final LTA, which addresses the acquisition of the hierarchical systems model as a metacognitive tool to understand a biological topic that crosses several levels of biological organisation.

In general the nature and sequence of the learning activities constituting the five phases of the second LT-strategy could be considered adequate. The LT-strategy enabled students to explore the different functions of the cellular structures and complex interrelations within the cell, on the basis of concrete observations and different cell models, resulting in an integrated view of the cell and its organelles. Hereby, the active engagement of students in the development of subsequent cell models guided them into the intended direction and improved students' insight into the (spatial and dynamic) organisation of the cell (horizontal coherence). Although students were motivated to actively engage in the modelling activities, it seemed questionable whether students grasped the point of why precisely modelling was addressed at every step during the LT-process. The fact is that, reflection to explicate the function of using (cell) models, including the systems model, was not always executed as intended.

The problem posing character of the LT-activities engaged students in subsequent activities that helped them to acquire more insight into the cell as part of a hierarchical system, i.e. the organism. The strategy gradually developed a reasonable motive for students to introduce and explicate systems thinking although some transitions between activities could be improved.

In the last phase of our strategy students acquired an initial systems thinking competence in a process of thinking backward and forward between a general hierarchical systems model and concrete representations of a biological topic at different levels of organisation. This last phase showed that the introduction of a systems model as a tool to explore biological phenomena was successful but it did not yet function completely on a metacognitive level. With respect to interrelating the different levels of organisation the teacher's guidance, e.g. stimulating students to think backward and forward between the different levels of organisation, was essential. At this point the systems model was not self-explaining.

In Chapter 5 the final LT-strategy is presented after revision of the strategy that was tested in the second case study. Subsequently, the final strategy is formalised through elaborating on the three main pillars that founded the strategy: the problem posing structure, the acquisition of coherent cell biological knowledge and the process of modelling. This results in answering the central research question.

The results of the second case study yielded indications for fine-tuning and revision of the LT-strategy for the cell as a system. The main revisions concern 1) the explication of and reflection on the process of modelling, 2) the adjustment of the biology content of the computer-aided program so as to improve the problem posing character of the transition to the next activity and 3) explicitly answering the central steering question in the plenary reflection after explication of the levels of organisation in the computer-aided program. The second LT-strategy for the cell as a system has been changed accordingly, resulting in the third and final LT-strategy. With these adjustments we consider the final strategy 'the cell as a system' to be adequate in enhancing the development of coherent cell biological knowledge and in introducing and developing an initial systems thinking competence.

The way towards coherent cell biological knowledge and acquiring systems thinking competence is paved by a succession of six phases, which constitute the didactical structure. These phases have been marked as general orientation on cell biology, developing a model of free-living cells, application of the developed model to cells as part of an organism, building a model of a plant cell, explication of systems thinking and application of the systems model.

With respect to the way the LT-strategy addresses the acquisition of coherent cell biological knowledge the strategy could be viewed as one problem posing cycle that starts at the organismic level in the preceding teaching unit of growth and development, descends to the cellular level, addresses horizontal coherence and eventually relates the cellular level to the organismic level, i.e. ascends to the organismic level and thus addressing vertical coherence.

The strategy shows that sufficient knowledge about a biological topic such as cell biology is needed as a vehicle to develop a content-specific motive for systems thinking. In retrospect, we formalised the six phases of the strategy into a general problem posing structure for acquiring this competence in biology education:

1. General orientation and posing a central steering question that provides a global motive for studying the topic at hand
2. a) Narrowing down the global motive into a more content-specific motive for extending knowledge
   b) Subsequent investigation/ acquiring information: extending knowledge
3. Application of the knowledge acquired so far to a new situation
4. Further extension of students' knowledge and creating a need for reflection on the desired competence developed so far
5. Explication and further extension of the competence by widening the range of application.
6. Application of the competence, which also provides an outlook on the added value of the competence in subsequent learning

A problem posing structure could also be identified within each phase, so in fact it is a matter of problem posing cycles. For students the transition to each next phase is then marked by a new LT-activity, which addresses the next partial question. Each cycle consists of the following steps:

a. formulating a partial question
b. extending knowledge by means of investigation/gathering information and creating a need for reflection
c. reflection on the extended knowledge in view of the central steering question and creating a need for more specifically formulated knowledge

In our approach students are actively engaged in the process of modelling, in which formation, revision and elaboration of a cell model are performed respectively.

Modelling occurs in four of the six phases that constitute our problem posing approach. Based on their idiosyncratic representations, in phase 2 students are developing a model of free-living cells, which is subsequently applied to cells as parts of multi-cellular organisms in phase 3. In a reflection activity the model is revised, so that it better describes the general characteristics of both free-living cells and cells that are parts of an organism. The development of cell models is completed in phase 4 in which students build a large-scale 3-D model of a cell. This process could be seen as consolidation and elaboration of students cell biological knowledge through assimilation and expression of what has been learnt in a three dimensional way. The last step in the modelling process is executed in phase 5 and 6. In phase 5 students explore human digestion by modelling structures and processes at the organismic, organ and cellular level by means of a computer-aided program. By abstracting structures and processes at all three levels students discover that the three levels can be represented by one systems model. In this phase the initial cell model is elaborated by embedding it in the general (hierarchical) systems model. Finally in phase 6 students apply the nested open-system model to the topic breast-feeding.

Our modelling activities can be characterised as follows:

A. Modelling of concrete cells to a general 2-D portrayal of the cell (phase 2 and 3)
B. Constructing a 3-D large scale model of the cell (phase 4)
C. Modelling visual representations of the organismic, organ and cellular level to a general systems model (phase 5 and 6)

Together the three modelling phases form a sequence of learning and teaching activities that can take the students from prior knowledge and their idiosyncratic representations of a cell towards a target model, i.e. the hierarchical systems model.

Our study shows that it is possible to develop a motive for systems thinking by integrating and explicating systems thinking in a LT strategy on cell biology. Moreover, the study indicates how systems thinking can be introduced in upper secondary education and supports our assumption that systems thinking enables students to acquire coherent understanding of biological phenomena. The hierarchical systems model introduced in our LT-strategy represents a model that could act as a starting point to address cybernetic and dynamic systems models. It also offers a starting point to deal with additional levels of organisation as the molecular and ecosystem level. Considering the wider application of systems thinking, the acquisition of systems thinking competence, i.e. being able and willing to use different systems models as metacognitive tools, deserves further study.

Samenvatting

Dit proefschrift beschrijft een ontwikkelingsonderzoek dat werd uitgevoerd bij het Centrum voor Didactiek van de Wiskunde en Natuurwetenschappen aan de Universiteit Utrecht van juni 1999 tot augustus 2003. Het onderzoek richtte zich op de introductie van systeemdenken in celbiologieonderwijs in de bovenbouw van het vwo. Het doel was de ontwikkeling van een theoretisch gefundeerde en empirisch geteste onderwijsleerstrategie voor 'de cel als systeem'. Deze strategie zou de gesignaleerde problemen in het leren en onderwijzen van celbiologie moeten oplossen en daarnaast indicaties moeten opleveren voor het ontwerpen van biologieonderwijs vanuit systeemtheoretisch perspectief. De centrale onderzoeksvraag is als volgt geformuleerd:
Op welke wijze kan een onderwijsleerstrategie, gebaseerd op systeemdenken, worden vormgegeven, opdat leerlingen een samenhangend en adequaat begrip verwerven van de cel als basis- en functionele eenheid van organismen?

Hoofdstuk 1 beschrijft de context van het centrale probleem van dit onderzoek, alsmede het eerste deel van de verkennende fase van het onderzoek waarop hoofdstuk 3 voortborduurt. De ontwikkelingen in het onderwijs en onderzoek in de biologie, evenals de huidige ideeën over leren en onderwijzen, fungeren als basis voor het beschrijven van onze domeinspecifieke visie op leren en onderwijzen.

Literatuuronderzoek laat zien dat veel conceptuele problemen in het biologieonderwijs ontstaan door de fragmentarische benadering van levensverschijnselen en het onvoldoende met elkaar in verband brengen van de structuren en processen op verschillende organisatieniveaus. Deze benadering lijkt zijn oorsprong te vinden in de historische ontwikkeling van de biologie zelf: de opdeling van de biologie in meerdere disciplines en de grote aandacht voor detailkennis binnen iedere discipline. De reductionistische onderzoeksbenadering was lange tijd dominant. Het huidige biologieonderwijs in Nederland weerspiegelt deze benadering nog steeds met als gevolg een overladen curriculum, een gebrek aan samenhang en een geringe relevantie voor leerlingen.

In het huidig biologisch onderzoek is er meer voor de holistische, dynamische en interactieve aard van levende systemen. Ook is er sprake van een steeds sterkere integratie van het onderzoek op verschillende biologische organisatieniveaus. Nieuwe inzichten in moleculaire processen zijn geleidelijk aan verbonden met fysiologische en ecologische processen en andersom ontleent veel onderzoek op het moleculaire niveau haar vragen aan nieuwe inzichten op het organismaal en ecosysteemniveau. Daarnaast speelt biologie een steeds grotere rol in het persoonlijk en maatschappelijk leven.

De wetenschappelijke ontwikkelingen in de biologie hebben in beperkte mate geleid tot inhoudelijke bijstellingen van het biologiecurriculum, maar dit heeft niet geresulteerd in een samenhangende en geïntegreerde aanpak van levensverschijnselen in de onderwijspraktijk. In onze visie moet in het biologieonderwijs het ontwikkelen van domeinspecifieke competenties centraal staan waarbij de benodigde kennis wordt gekoppeld aan voor leerlingen relevante en betekenisvolle praktijken. In deze studie wordt het systeemdenken gepresenteerd als en sleutelcompetentie. De competentie systeemdenken is hierbij gedefinieerd als het willen en kunnen relateren van de verschillende organisatieniveaus vanuit het perspectief dat natuurlijke gehelen, zoals organismen, complexe organisaties zijn die bestaan uit vele interagerende onderdelen die op hun beurt kleinere gehelen zijn, zoals cellen in een organisme. Onze aanname is dat bewuste toepassing van het systeemperspectief leidt tot meer samenhang in het leren en onderwijzen van (cel)biologie.

Voor het ontwikkelen van een adequate onderwijsleerstrategie voor de cel als systeem is gekozen voor een probleemstellende benadering, waarbij leerlingen op inhoudelijke gronden actief worden betrokken bij hun eigen leerproces. In onze opvatting is een probleemstellende benadering compatibel met het perspectief van gesitueerde cognitie. Het is er namelijk op gericht om leerlingen actief te betrekken in sociale interacties binnen een geschikte onderwijspraktijk, waarbij het ontwikkelen van nieuwe concepten, vaardigheden en attitudes centraal staat.

Hoofdstuk 2 beschrijft de interpretatieve onderzoeksbenadering die is gekozen om de centrale onderzoeksvraag te beantwoorden: het zogenoemde ontwikkelingsonderzoek. Deze benadering omvat een verkennende fase en een cyclische onderzoeksfase.

In de *verkennende fase* werden de algemene kenmerken en structuur van het beoogde onderwijsleerstrategie voor de cel als systeem geïdentificeerd. De theoretische onderbouwing van het onderzoek, onder meer bestaande uit doordenking van de conceptuele structuur van het vak en gerapporteerde oplossingen voor leerproblemen, vond grotendeels in deze fase plaats. Relevante literatuur werd bestudeerd en veelbelovende ideeën in de klassenpraktijk uitgeprobeerd. Dit resulteerde in een nadere probleemdiagnose en toespitsing van mogelijke oplossingen. De onderzoeker gebruikte deze fase eveneens om meer inzicht te verkrijgen in de vakdidactiek.

Op basis van de resultaten van de verkennende fase werden ontwerpcriteria gedefinieerd voor een voorlopige onderwijsleerstrategie die werd ontwikkeld en getest in de *cyclische onderzoeksfase*. Daartoe werden twee casestudies op verschillende scholen gepland. Alvorens de strategie te testen, werd deze eerst uitgewerkt in een contextspecifiek scenario dat het verwachte onderwijsleerproces gedetailleerd beschrijft en verantwoord. Dit scenario stuurde de analyse van het feitelijk onderwijsleerproces in de klas. Bij het uittesten van het scenario in de praktijk werden verschillende datasets verzameld en geanalyseerd. Evaluatie van en reflectie op het uitgevoerde scenario gaven aanwijzingen voor het verbeteren van de onderwijsleerstrategie. Het gereviseerde scenario werd uitgetest in een tweede casestudy. Op deze manier werd de onderwijsleerstrategie gevormd in een cyclisch proces waarin ontwikkeling en onderzoek elkaar afwisselen. Dit leidde uiteindelijk tot een theoretisch gefundeerde en empirisch geteste onderwijsleerstrategie.

In **Hoofdstuk 3** wordt het grootste deel van de verkennende fase beschreven. In deze fase werden de belangrijkste problemen met betrekking tot het leren en onderwijzen van celbiologie geïdentificeerd middels literatuurstudie, interviews met docenten en leerlingen, en een schoolboekanalyse. Hierbij viel op dat veel begripsproblemen op het cellulaire niveau gerelateerd zijn aan het feit dat veel celbiologische begrippen het subcellulaire niveau betreffen en dat deze niet verbonden worden met het cellulair en organismaal niveau. Als gevolg hiervan hebben veel leerlingen moeite om zich een samenhangend beeld van de cel te vormen. Dit laatste vereist zowel het kunnen verbinden van verschillende begrippen op het cellulair niveau (horizontale samenhang) als het verbinden van verschillende begrippen op het cellulair en organismaal niveau (verticale samenhang). Een aantal oplossingen die in de literatuur worden aangedragen voor de gesignaleerde problemen, hebben met name betrekking op het benaderen van de cel en zijn processen vanaf het concreet macroscopisch niveau. Een adequate strategie voor het verkrijgen van een samenhangend begrip van de cel werd echter niet aangetroffen. Een aantal interviews met Nederlandse biologieleraren en een schoolboekanalyse lieten vergelijkbare problemen zien als die genoemd worden in de literatuur. Ondanks het feit dat systeemdenken staat vermeld in de exameneisen, is het niet geïntegreerd in het celbiologieonderwijs.

Als basis voor een nadere uitwerking van de competentie systeemdenken wordt in het vervolg van hoofdstuk 3 een uiteenzetting gegeven van de drie belangrijkste systeemtheorieën. De theorieën verschaffen elk een specifieke kijk op levende systemen. De Algemene Systeemtheorie benadrukt voornamelijk de structurele organisatie van levende systemen; de Cybernetica werkt voornamelijk de regulatie en communicatie uit, en de Dynamische Systeemtheorie biedt een historisch perspectief op levende systemen. Op basis van deze verkenning en het verkregen inzicht in de genoemde leerproblemen in de celbiologie, is gekozen om de competentie systeemdenken nader te specificeren in termen van de Algemene Systeemtheorie, i.c. ‘open systeem’ en ‘organisatieniveau’. Een belangrijk aspect van de aldus geformuleerde competentie is ‘het onderscheiden van de verschillende organisatieniveaus (cel, orgaan en organisme) en het kunnen verbinden van biologische begrippen met de specifieke organisatieniveaus. Een meer algemeen aspect van de competentie systeemdenken is ‘het heen-en-weer denken tussen algemene systeemmodellen en meer concrete representaties van verschijnselen.

De eerste stap op weg naar het integreren van systeemdenken en celbiologieonderwijs bestond uit een samenhangende beschrijving van het kennisbestand van de celbiologie vanuit systeemtheoretisch perspectief. Daarin wordt de cel achtereenvolgens als autonome, complexe en functionele eenheid geconceptualiseerd. Voor de integratie van systeemdenken en celbiologie werden op theoretische gronden twee mogelijke benaderingen gepresenteerd:

1) Introductie van systeemdenken als kader voor de ontwikkeling van celbiologische kennis, of
2) Ontwikkeling van systeemdenken als meeropbrengst uit een aantal lessen over celbiologie en daarna toe te passen op een ander biologisch thema.

Om te kunnen kiezen tussen deze benaderingen en om een scherper beeld te krijgen van een mogelijk adequate onderwijsleerstrategie voor de cel als systeem zijn twee vooronderzoeken uitgevoerd. In het eerste vooronderzoek werden twee lessen over het onderwerp hormonale regulatie ontwikkeld en beproefd. Hierbij lag de nadruk op het verbinden van de celbiologische voorkennis van leerlingen met verschijnselen op hogere organisatieniveaus. Het tweede onderzoek richtte zich op het ontwikkelen en beproeven van interactief lesmateriaal waarin een hiërarchisch systeemmodel van de vertering wordt geïntroduceerd. Uit het eerste vooronderzoek werd onder andere geconcludeerd dat een lessenserie celbiologie expliciet aandacht moet besteden aan de relatie tussen de cel en bovenliggende niveaus. Het tweede vooronderzoek liet zien dat het ontwikkelen van een systeemmodel goed samen kan gaan met het afdalen van het organismaal naar het cellulair niveau. Beide studies leidden ook tot het oplossen van het probleem of de strategie voor de cel als systeem zou moeten beginnen met celbiologie of met systeemdenken. In plaats van een keuze te maken voor één van de genoemde benaderingen, leek een synthese mogelijk waarin het verwerven van celbiologische kennis parallel loopt aan de ontwikkeling van de competentie systeemdenken.

De verschillende onderzoeksactiviteiten in deze verkennende fase genereerden verschillende ideeën over hoe celbiologieonderwijs vanuit systeemtheoretisch perspectief vorm te geven en leidde tot de definiëring van een aantal ontwerpcriteria. Deze werden omgezet in een voorlopige onderwijsleerstrategie bestaande uit een sequentie van inhoudelijke vragen en een daarmee samenhangende sequentie van onderwijsleeractiviteiten met de beoogde uitkomsten. De strategie omhelst in totaal vijf fasen: I) globale oriëntatie op de celbiologie, II) verkenning van de levensfuncties en introductie van de cel als organisme, III) explicitering van systeemdenken waarbij een systeemmodel op organismaal niveau wordt geïntroduceerd, IV) verkenning van de cel (als functionele eenheid) en de organellen met behulp van het systeemmodel, en V) het verbinden van de cel met bovenliggende organisatieniveaus.

Hoofdstuk 4 geeft de cyclische onderzoeksfase weer. In deze fase werd de onderwijsleerstrategie aangepast en geoptimaliseerd tot een empirisch gefundeerde en adequate sequentie van leeractiviteiten. De aanvankelijk ontwikkelde strategie en de gereviseerde strategie werden beide uitgewerkt in een contextspecifiek scenario en vervolgens beproefd in twee opeenvolgende casestudies. Het hoofdstuk besteedt voornamelijk aandacht aan de resultaten van de tweede onderzoeksronde, dat wil zeggen aan het gerealiseerde onderwijsleerproces op basis van het in de eerste ronde verbeterde onderwijsmateriaal. Een kritische beschouwing en het vervolgens reviseren van de eerste strategie stelde ons beter in staat om de essentiële elementen te bestuderen van een systeemtheoretische benadering van de celbiologie. De resultaten van de tweede casestudy geven de feitelijke onderwijsleerprocessen chronologisch weer en spiegelen deze aan de verwachtingen zoals vooraf geëxpliciteerd in het scenario.

In de eerste casestudy kwam een aantal tekortkomingen van de aanvankelijke onderwijsleerstrategie naar boven. Zo bleek de strategie niet doeltreffend genoeg voor het verwerven van een belangrijke deelcompetentie van het systeemdenken: leerlingen bleken onvoldoende in staat om het systeemmodel te gebruiken als instrument voor de verkenning van de cel als functionele eenheid. Om dit probleem op te lossen richtte de aangepaste onderwijsleerstrategie zich meer op het actief betrekken van leerlingen bij het ontwikkelen van verschillende (cel)modellen, inclusief het hiërarchisch systeemmodel. De complexe aard en de microscopische schaal van de cel vormde hierbij het motief om een model te ontwikkelen dat meer inzicht verschaft in de structurele organisatie van de cel.

De gereviseerde onderwijsleerstrategie, zoals getest in de tweede onderzoeksronde, omvat vijf fasen. Na een globale oriëntatie op cellen in fase I, betrekken de fasen II, III en IV de leerlingen bij het modelleren van cellen voorafgaand aan de ontwikkeling van het ontwikkelen van een algemeen hiërarchisch systeemmodel in fase V. Fase II bestaat uit de ontwikkeling van een aanvankelijk (nog impliciet) systeemmodel van vrij levende cellen op basis van de representaties die leerlingen zelf hadden voorafgaand aan de lessenreeks. Hierbij worden leerlingen gestimuleerd om heen-en-weer te denken tussen hun eigen representaties, hun observaties van ‘echte’ cellen, en de modellen zoals die in hun schoolboek staan. Fase III richt zich op het toepassen van het tot dan toe ontwikkelde model op cellen van een meercellig organisme. In deze fase worden leerlingen gestimuleerd om heen-en-weer te denken tussen verschillende representaties van dierlijke en plantaardige cellen. Vervolgens bouwen leerlingen in fase IV een driedimensionaal model van een plantaardige cel.

De laatste modelleerstap betreft het uitbreiden van het celmodel naar de bovenliggende organisatieniveaus en het onderling verbinden van de verschillende niveaus. Deze stap gaat hand in hand met het expliciteren van het systeemdenken. Tenslotte leren leerlingen het hiërarchisch systeemmodel als instrument te gebruiken om inzicht te verkrijgen in een onderwerp dat meerdere organisatieniveaus doorkruist. Deze laatste stap tracht het systeemdenken op metacognitief niveau te ontwikkelen.

Uit het testen van de tweede onderwijsleerstrategie bleek dat de aard en sequentie van de leeractiviteiten in het algemeen als adequaat konden worden beschouwd. Door middel van concrete observaties en het gebruik van verschillende celmodellen werden leerlingen in staat gesteld om de verschillende cellulaire structuren te verkennen met de bijbehorende functies en onderlinge relaties in de cel. Dit resulteerde in een geïntegreerd beeld van de cel als basis en functionele eenheid van organismen. Het actief ontwikkelen van verschillende celmodellen stuurde leerlingen in de gewenste richting en vergrootte het inzicht in de ruimtelijke en dynamische organisatie van de cel (horizontale samenhang). Ondanks het feit dat leerlingen actief betrokken waren bij de verschillende modelleeractiviteiten, leek het twijfelachtig of leerlingen van iedere stap in het onderwijsleerproces de functie van het modelleren begrepen. Een belangrijke oorzaak hiervoor leek het feit dat reflectie op het modelleerproces en het expliciteren van de functie van de verschillende modellen, inclusief het hiërarchische systeemmodel, niet altijd werden uitgevoerd zoals bedoeld.

Het probleemstellende karakter van de leeractiviteiten stimuleerde leerlingen om deel te nemen aan de opeenvolgende activiteiten die hen in staat stelde meer inzicht te verkrijgen in de cel als onderdeel van het organisme als hiërarchisch systeem. In de strategie werd geleidelijk een motief ontwikkeld voor de introductie en explicitering van het systeemdenken. Een klein aantal onderwijsleeractiviteiten bleek nog aanpassing te behoeven ter verbetering van het probleemstellende karakter van de overgang tussen de betreffende activiteiten.

In de laatste fase van de strategie verwierven leerlingen een basiscompetentie in het systeemdenken. Dit werd bewerkstelligd in een proces van heen-en-weer denken tussen een algemeen hiërarchisch systeemmodel en concrete representaties van een biologisch onderwerp dat meerdere organisatieniveaus doorkruist. Deze laatste fase liet zien dat de introductie van een systeemmodel als instrument voor het verkennen van een biologisch onderwerp succesvol was verlopen. Tegelijkertijd bleek echter dat leerlingen het model niet spontaan inzetten als instrument om de structuren en processen op verschillende organisatieniveaus onderling te verbinden. Hierbij bleek sturing door de docent onmisbaar. Er kon dan ook geconcludeerd worden dat de onderwijsleerstrategie onvoldoende leidt tot de ontwikkeling van het systeemdenken op metacognitief niveau.

In hoofdstuk 5 wordt de definitieve onderwijsleerstrategie gepresenteerd na aanpassing van de in de tweede casestudy geteste strategie. Vervolgens wordt een formele beschrijving van de strategie gegeven door een nadere uitwerking van de drie belangrijkste elementen: de probleemstellende benadering, het verwerven van samenhangende celbiologische kennis en het modelleerproces. Daarna wordt de centrale onderzoeksvraag beantwoord.

De tweede onderzoeksronde leverde een aantal indicaties op voor het aanpassen en bijstellen van de onderwijsleerstrategie voor de cel als systeem. De belangrijkste punten van verbetering betroffen: 1) het expliciteren van en reflectie op het modelleerproces, 2) het bijstellen van de biologische inhoud van het interactief lesmateriaal (waarin de organisatieniveaus werden geëxpliciteerd) om het probleemstellende karakter van de overgang naar de volgende activiteit te verbeteren, en 3) het expliciet beantwoorden van de centrale vraag in de plenaire reflectie na de explicitering van de organisatieniveaus. Met deze aanpassingen beschouwen we de definitieve strategie voor de cel als systeem als een adequate strategie voor het ontwikkelen van samenhangende celbiologische kennis en een basiscompetentie systeemdenken.

De weg naar systeemdenken in celbiologieonderwijs bestaat uit een opeenvolging van zes fasen die samen de didactische structuur vormen. Deze fasen bestaan achtereenvolgens uit een globale oriëntatie op de celbiologie, ontwikkeling van een model van vrij levende cellen, toepassing van dit model op cellen in een organisme, het bouwen van een driedimensionaal model van een plantaardige cel, explicitering van systeemdenken, en toepassing van het hiërarchisch systeemmodel. Met betrekking tot de ontwikkeling van samenhangende celbiologische kennis, kan de strategie gezien worden als één probleemstellende cyclus. Deze begint bij het voorgaande thema over groei en ontwikkeling op het organismaal niveau, daalt af naar het cellulaire niveau en richt zich daar op de ontwikkeling van horizontale samenhang in de celbiologische kennis. Vervolgens wordt het cellulaire niveau verbonden met het organismaal niveau en staat dus de verticale samenhang centraal.

De strategie laat zien dat voldoende kennis van een biologisch onderwerp, zoals celbiologie, nodig is om een inhoudelijk motief te ontwikkelen voor systeemdenken. Terugkijkend op de fasering van de didactische structuur, onderscheiden we de volgende stappen voor het verwerven van de competentie systeemdenken in biologieonderwijs:

1. Algemene oriëntatie en het stellen van een centrale sturende vraag die een globaal motief verschaft voor het bestuderen van het betreffende onderwerp
2. a) Toespitsing van het globale motief op een meer inhoudsspecifiek motief voor kennisuitbreiding

   b) Uitbreiding van de kennis middels onderzoek en/of het aanreiken van informatie
3. Toepassing van de verkregen kennis in een nieuwe situatie
4. Uitbreiding van de kennis en het creëren van een behoefte tot reflectie op de tot nu toe verworven competentie
5. Explicitering en uitbreiding van de competentie door verbreding van het toepassingsgebied
6. Toepassing van de competentie en het inzicht verschaffen in de bruikbaarheid van de competentie bij het leren van volgende onderwerpen

Bij nadere beschouwing kan binnen de bovengenoemde fasen eveneens een probleemstellende structuur worden herkend. In plaats van over ‘fasen’ kan er dus beter over probleemstellende ‘cycli’ worden gesproken. Voor de leerlingen wordt de overgang tussen de opeenvolgende cycli gemarkeerd door een volgende leeractiviteit waarin een nieuwe deelvraag centraal staat. In iedere cyclus kunnen de volgende stappen worden herkend:

a. Formulering van een deelvraag
b. Kennisuitbreiding middels onderzoek en/of aanreiken van informatie en het creëren van ene behoefte tot reflectie
c. Reflectie op de opgedane kennis in het licht van de centrale sturende vraag en het creëren van een behoefte tot kennisuitbreiding in een specifieke richting

De ontwikkelde strategie betrekt studenten actief in een modelleerproces waarbij achtereenvolgens vorming, revisie en uitbreiding van een celmodel centraal staan. Het modelleren vindt plaats in vier van de zes probleemstellende cycli. In de tweede cyclus ontwikkelen leerlingen, op basis van hun eigen representaties van cellen, een model van vrij levende cellen die vervolgens wordt toegepast op dierlijke en plantaardige cellen in cyclus 3. In een reflectie hierop wordt het model aangepast, zodat het een betere afspiegeling is van zowel vrij levende cellen als van cellen in een meercellig organisme. De ontwikkeling van het celmodel wordt gecompleteerd in cyclus 4 waarin leerlingen een driedimensionaal model bouwen met als doel de consolidatie van de geleerde celbiologische kennis en uitbreiding van het ruimtelijke inzicht in de cellulaire organisatie. De laatste stap van het modelleerproces wordt uitgevoerd in cyclus 5 en 6; In de vijfde cyclus verkennen leerlingen het verteringsproces door structuren en processen te modelleren op het organismaal, orgaan en cellulair niveau middels interactief lesmateriaal. Door de structuren en processen op ieder niveau te abstraheren, ontdekken leerlingen dat ieder niveau gerepresenteerd kan worden door eenzelfde systeemmodel. Hierbij wordt het tweedimensionale celmodel uitgebreid door het in te bedden in het algemene hiërarchische systeemmodel. Tenslotte passen leerlingen dit model van geneste, open systemen in de zesde cyclus toe op het onderwerp borstvoeding. De modelleeractiviteiten kunnen als volgt worden gekarakteriseerd:

A. Het modelleren van concrete cellen tot een algemeen 2-D portret van de cel
B. Het bouwen van groot 3-D model van de cel
C. Het modelleren van visuele representaties van het organismaal, orgaan en cellulair niveau tot een algemeen hiërarchisch systeemmodel

Bij elkaar vormen de drie modelleerfasen een sequentie van onderwijsleeractiviteiten startend bij de voorkennis en idiosyncratische representaties van leerlingen en eindigend bij het beoogde hiërarchische systeemmodel.

De resultaten van dit onderzoek laten zien dat het mogelijk is om een motief te ontwikkelen voor het leren systeemdenken door de competentie te integreren in een onderwijsleerstrategie over celbiologie. Bovendien ondersteunt het de veronderstelling dat het systeemdenken helpt bij het verkrijgen van een samenhangend begrip van biologische verschijnselen. Het hiërarchisch systeemmodel dat in de onderwijsleerstrategie wordt geïntroduceerd kan tevens als beginpunt dienen voor de introductie van cybernetische en dynamische systeemmodellen in het biologieonderwijs. Daarnaast kan het dienen als opstap naar het moleculair of het ecosysteem niveau. Gezien de bredere toepasbaarheid van het systeemdenken verdient het aanbeveling dat de competentie, geformuleerd als het kunnen en willen gebruiken van verschillende systeemmodellen als metacognitieve instrumenten, verder onderzoek verdient.

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Curriculum Vitae

Roald Verhoeff werd geboren op 14 augustus 1973 te Schoonhoven. In 1990 behaalde hij zijn havo-diploma en in 1992 zijn vwo-diploma aan het Schoonhovens College te Schoonhoven. Hierna begon hij aan de studie Werktuigbouwkunde in Enschede die werd afgebroken om in 1993 Biologie te gaan studeren aan de Universiteit Utrecht. De specialisatiefase omvatte een tweetal stages. Tijdens de eerste stage op de afdeling Moleculaire Celbiologie van de Universiteit Utrecht deed hij onderzoek naar het effect van ischemie op het glucosetransport in geïsoleerde hartspiercellen. Vervolgens volgde hij bij de leerstoelgroep Didactiek van de Biologie de wetenschappelijke beroepsopleiding Gezondheidsvoorlichting. Hiervoor werd gedurende 5 maanden onderzoek gedaan bij de Maag Lever Darm Stichting te IJsselstein naar de distributie van schriftelijk voorlichtingsmateriaal in ziekenhuizen. In samenwerking met de leerstoelgroep Didactiek van de Biologie werd tevens een scriptie geschreven bij de wetenschapswinkel resulterende in een uitgegeven brochure over de invloed van de woon- en werkomgeving op het ontstaan van neuraalbuisdefecten. Na het halen van zijn doctoraal examen Biologie in 1998 trad hij gedurende een jaar in dienst bij een klinisch onderzoeks bedrijf. Hier begeleidde en controleerde hij klinisch onderzoek volgens de richtlijnen van Good Clinical Practice in een projectteam van artsen en verpleegkundigen. Tevens onderhield hij externe contacten met klanten in de farmaceutische industrie. In Juni 1999 begon hij als assistent in opleiding bij het Centrum voor Didactiek van Wiskunde en Natuurwetenschappen (CD-β) te Utrecht onder begeleiding van Prof. dr. K. Th. Boersma en Prof. dr. A.J. Waarlo. Binnen deze functie is het onderzoek uitgevoerd waarover in dit proefschrift wordt gerapporteerd.

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