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**Systems modelling and the development of coherent understanding of cell biology**

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# Systems modelling and the development of coherent understanding of cell biology

## Abstract

This article reports on educational design research concerning a learning and teaching strategy for cell biology in upper-secondary education introducing systems modelling as a key competence. The strategy consists of four modelling phases in which students subsequently develop models of free-living cells, a general 2-D model of cells, a 3-D model of plant cells and finally they are engaged in formal thinking by modelling life phenomena to a hierarchical systems model. The strategy was thought out, elaborated and tested in classrooms in several research cycles. Throughout the field-tests, research data were collected by means of classroom observations, interviews, audio-taped discussions, completed worksheets, written tests and questionnaires. Reflection on the research findings eventuated in reshaping and formalizing the learning and teaching strategy, which is presented here. The results show that although acquiring systems thinking competence at the metacognitive level needs more effort, our strategy contributed to improving learning outcomes, i.e. acquisition of a coherent conceptual understanding of cell biology and acquisition of initial systems thinking competence, with modelling being the key activity.

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Many students fail to acquire a coherent conceptual understanding of the cell as a basic unit of life. To address this problem we introduce *systems thinking* as a key competence. A main characteristic of systems thinking is distinguishing and linking the various levels of biological organization, i.e. molecules, cells, organs, organisms and populations, in describing and explaining life phenomena. To render phenomena that are either complex or not directly perceivable more readily visible, using models is an essential element of systems thinking at the cellular level.

## Introduction

A basic understanding of the functioning of the cell is essential for a sound understanding of the functioning of the multicellular organism. Therefore, students are taught a large variety of life structures and processes at the cellular level. The concepts used to describe these however, often remain fragmentary because they are mainly drawn from the sub-cellular level

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4 and not sufficiently integrated with concepts at the cellular and organism level. The latter  
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6 explains why many students fail to acquire a coherent conceptual understanding of the cell as  
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8 a basic unit of the organism (Dreyfus & Jungwirth, 1988; 1989; Flores, [Tovar & Gallegos](#),  
9  
10 2003). In addition, conceptual problems associated with a lack of interrelating the levels of  
11  
12 biological organization arise when studying other biological topics as well (Núñez & Banet,  
13  
14 1997; Songer & Mintzes, 1994). [Songer & Mintzes](#) for example, refer to a problematic  
15  
16 understanding of the relations between events of cellular respiration and various biological  
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18 phenomena such as breathing, circulation and energy flow in natural ecosystems.

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20 Douvdevany, [Dreyfus & Jungwirth](#) (1997) showed that even the knowledge of junior  
21  
22 high school teachers of cellular processes lacked coherence, although they had enough  
23  
24 specific declarative knowledge of the cell. Interviews that we conducted with Dutch upper-  
25  
26 secondary biology teachers, and content analysis of textbooks, revealed difficulties similar to  
27  
28 those identified in the research papers mentioned (Verhoeff, 2003). In Dutch textbooks the  
29  
30 cell has an important but very isolated place and is generally one of the first subjects dealt  
31  
32 with in upper-secondary education. In addition, cell biology, as it is introduced in the school  
33  
34 curriculum, mainly focuses on structures rather than on processes, although an understanding  
35  
36 of biological processes has been recognised as being essential for a comprehensive  
37  
38 understanding of biological systems (Chi, [Slotta & Leeuw](#), 1994; Songer & Mintzes, 1994;  
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40 Barak, [Sheva, Gorodetsky & Gurion](#), 1999).

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43 Our study is part of a research programme that focuses on the implementation of systems  
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45 thinking in upper-secondary biology education. We concentrated on learning and teaching cell  
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47 biology with the assumption that purposeful application of systems thinking provides a way to  
48  
49 address the acquisition of coherent understanding of cell biology. In this approach, the  
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3 development and use of models is crucial, so we introduced systems modelling as a key  
4 competence for students. This competence is defined here as the ability and willingness to  
5 link different levels of biological organization from the perspective that natural wholes, such  
6 as organisms, are complex and composite, consisting of many interacting parts, which may  
7 themselves be lesser wholes, such as cells in an organism (Mayr, 1997). The use of models is  
8 essential because in biology, structures and processes at different levels of biological  
9 organization are often abstracted into models. Especially at the molecular and cellular level,  
10 models are used to enable aspects of a system, which are either complex or not directly  
11 perceivable, to be rendered more readily visible. Moreover, models are potentially valuable  
12 learning and teaching tools for developing a scientific way of thinking (Gilbert, 1993).

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22  
23 Although the Dutch examination syllabus underlines the importance of systems thinking  
24 in biology education, the implementation in classroom practice falls short of expectations.  
25  
26 Against this background, our overall research question was formulated as follows:

27  
28 *How can systems thinking, including modelling, enable students to develop a coherent*  
29 *understanding of the cell as a basic and functional unit of the organism?*  
30

31  
32 This problem statement was the starting point of our developmental research project which  
33 entailed identifying the main criteria for designing an adequate learning and teaching strategy  
34 (LT-strategy), and optimising the strategy through cyclic empirical testing.  
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38

### 39 40 **Design of the study**

41  
42 Our developmental research approach (Lijnse, 1995) strongly resembles what Cobb, Confrey,  
43 DiSessa, Lehrer & Schauble, (2003) described as 'design experiments' conducted in a  
44 classroom setting. This approach implies the instructional design of a teaching and learning  
45 process, accompanied with a set of argued expectations of how the process is expected to take  
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place and why it should operate according to the expectations (Bulte, [Westbroek, De Jong & Pilot, 2006](#)). These expectations are based on the literature as well as on the results of previous research cycles. The learning and teaching process is optimised in several research cycles, focused on testing, reflecting on and adjusting the designed learning and teaching activities, in close co-operation with teachers. Testing the designed teaching and learning process takes place in a small-scale case study, with a classroom and its teacher as unit of analysis (Cobb, [Stephan, McClain & Gravemeijer, 2001](#)). Eventually this cyclic research approach leads to an optimised domain specific learning and teaching theory, which prescribes what learning and teaching activities should be placed in what sequence in order to obtain an LT-strategy that enables students to attain the desired learning outcomes. Since the relation between the activities and outcomes is studied in detail, the domain specific theory also explains how the intended learning outcomes of the strategy have been attained.

In our study, we initially identified the general characteristics and structure of a preliminary LT-strategy assumed to be effective for cell biology from a systems theory perspective. This strategy was optimised in four subsequent case-studies at two different schools. These were carried out in form four (students aged 15-16) of pre-university education at two different schools<sup>1</sup>. These schools can be typified as rural schools with few students from ethnic minorities (2% and 0% respectively; national level is 5%). Both participating teachers were experienced biology teachers with more than 20 years of teaching experience.

During each case-study, the question was answered to what extent the implemented LT-strategy was in accordance with the expectations and the underlying theoretical framework. Evaluation of the implemented LT-strategy, gave rise to improvement of the strategy, which was field-tested in a next case study. This way, the feedback of practical experience into the

<sup>1</sup> Average number of students per case study was 18; the total number of students was 72.

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3 improvement of the strategy induces a cyclic process of development and research.  
4  
5 Eventually, this resulted in a theoretically founded and empirically tested LT-strategy.  
6  
7

#### 8 9 *Data collection and analysis*

10  
11 Within each case study, the implementation of the LT-strategy was accompanied by the  
12  
13 collection of extensive data sets from multiple data sources during and in between the lessons  
14  
15 on cell biology, i.e. classroom observations, audio-taped classroom and group discussions,  
16  
17 completed worksheets, written tests and interviews with students and teachers (Verhoeff,  
18  
19 2003). All audio-tapes were transcribed verbatim. In analysing the data sets, the emphasis was  
20  
21 on discourse analysis and reconstruction of the learning and teaching process by inspecting  
22  
23 and comparing data from the different sources mentioned. Data collection and analysis was  
24  
25 guided by the following two questions:

- 26  
27 1) *What learning outcomes arise from the implemented learning and teaching strategy,*  
28  
29 *and what learning processes did these learning outcomes constitute of?*  
30  
31 2) *What indications can be derived from the observed learning processes and outcomes for*  
32  
33 *revising the learning and teaching strategy?*

34  
35 Answering these questions led to revision and further elaboration of the LT-strategy, to be  
36  
37 tested in the next case study. Therefore, each subsequent case study again addressed the above  
38  
39 questions.

40  
41 The observations made by the researcher in the classroom mainly focused on identifying  
42  
43 critical moments regarding students' motivation and learning problems (expressed through  
44  
45 content-related questions). These observations provided input for and were checked by  
46  
47 interviews with the teacher and students. Together these made clear both the students' and  
48  
49 teacher's perception of the learning and teaching processes that actually took place in the  
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4 classroom, and they provided a first impression of the adequacy of the content and sequence  
5  
6 of the learning and teaching activities. A more in-depth study of the actual learning and  
7  
8 teaching processes was achieved by transcription and detailed analysis of all audiotapes,  
9  
10 including the interviews. In the analysis, each learning and teaching activity was considered  
11  
12 as a meaningful unit. Analysis started with the transcripts of the teacher's audiotape, which  
13  
14 gave an overview of the complete learning and teaching activity, including the teacher's  
15  
16 guidance to various students/student groups. Subsequently, the group-discussions were  
17  
18 studied. The worksheets and written test were used to check or interpret the results of the  
19  
20 above steps and gave more insight into the learning outcomes per activity.  
21

### 22 23 **A theoretical underpinning of the learning and teaching strategy**

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24  
25 This paragraph aims to illuminate the process of designing a learning and teaching strategy  
26  
27 from three theoretical perspectives. First, the problem posing approach is described, which  
28  
29 constitutes our pedagogical perspective. Second, a systems theoretical perspective is  
30  
31 presented to deal with the learning problems described in the introduction. Finally, we  
32  
33 elaborate on the process of modelling and present the key elements of our designed modelling  
34  
35 strategy.  
36

### 37 38 *The pedagogic approach*

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39  
40 In order to actively engage students in their own learning process, we chose a *problem posing*  
41  
42 *approach*, which involves students on a content-related basis (Klaassen, 1995; Lijnse &  
43  
44 Klaassen, 2003). This pedagogic approach is based on the idea that students start on common  
45  
46 ground and continually have a sense of the direction in which the LT-strategy as a whole will  
47  
48 take them (Klaassen, 1995). An essential element during such a process is that students have  
49  
50 content-related motives for starting and continuing their learning process. These motives are  
51



1  
2  
3 evoked by content-related learning and teaching activities, designed in such a way that they  
4  
5 raise meaningful questions that are answered in a subsequent activity. This sequence of  
6  
7 questions and related activities is shown in appendix 1, which shows the LT-strategy in detail.  
8  
9 Answering a question during an activity raises a new partial problem that is addressed in the  
10  
11 next activity and so on. Eventually, successively answering the evoked questions during the  
12  
13 activities helps students to solve the main problem posed at the start of the strategy (the first  
14  
15 question in appendix 1) and to acquire the desired scientific knowledge.

16  
17 In our study, a systems concept was explicitly introduced and developed. During our  
18  
19 design experiments we formulated questions and answers from the perspective of the students  
20  
21 that facilitated this process, and empirically tested and rephrased drafts. As a consequence of  
22  
23 the problem posing approach, our hypothesis was that students should be given the  
24  
25 opportunity to develop a content-related motive that makes the introduction of a systems  
26  
27 concept desirable. Based on the first two explorative case studies (Verhoeff, [Waarlo &](#)  
28  
29 [Boersma](#), 2003), we agreed that a reasonable motive for introducing the concept 'system' was  
30  
31 evoked when students discovered that structures and processes at different levels of biological  
32  
33 organization can be abstracted into the same model representing a 'living system'. This  
34  
35 finding also justified our choice to include modelling as a central element of a systems  
36  
37 thinking competence.

#### 40 *Systems thinking and cell biology*

41  
42 The literature study on (cell) biology education showed some main difficulties regarding a  
43  
44 coherent understanding of the cell, as has been outlined in the introduction. These could be  
45  
46 typified as difficulties in interrelating different concepts at the cellular level and interrelating  
47  
48 concepts at the cellular and organism level. Our LT-strategy aims to cope with these  
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4 difficulties and in doing so, we suggest that intentional use of systems thinking is valuable.  
5  
6 This means that systems thinking is not only considered as a tool for developing coherent cell  
7  
8 biological knowledge, but it also constitutes a desired learning outcome of the LT-strategy.  
9  
10 The main outcomes of the LT-strategy thus reflect a systems thinking competence with the  
11  
12 major focus on the cellular level, i.e. students should be able to: 1) distinguish different levels  
13  
14 of biological organization, i.e. cell, organ and organism, and match biological concepts to  
15  
16 specific levels of biological organization; 2) interrelate the cell biology concepts at the  
17  
18 cellular level of organization (which we also refer to as horizontal coherence); 3) interrelate  
19  
20 the cell biology concepts with concepts at higher levels of organization (or vertical  
21  
22 coherence).

23  
24 To introduce systems thinking competence in cell biology education, we derived an  
25  
26 initial systems concept from the General System Theory (Von Bertalanffy, 1969). This  
27  
28 General System Theory is based on generalizations of the basic functions of life, i.e.  
29  
30 metabolism, growth and development, and responsiveness to environmental stimuli. It  
31  
32 emphasises the hierarchical structure and open nature of biological systems (metabolism for  
33  
34 example requires that a living system exchanges matter with its surroundings). In genetics  
35  
36 education the General Systems Theory has been used earlier by Knippels (2003) to cope with  
37  
38 the complex nature of genetics. Since we decided to use and explicitly introduce systems  
39  
40 thinking as a tool for developing coherent cell biological knowledge, the question ought to be  
41  
42 answered as to how to start the LT-strategy. Starting with an explicit introduction of systems  
43  
44 thinking could facilitate the development of cell biological knowledge. It would, however,  
45  
46 require a lot of effort since it implies the development of the abstract systems concept.  
47  
48 Therefore, we decided to first focus on the acquisition of a basic notion of the cell and its  
49  
50 organization, implicitly developed from a systems perspective. Subsequently the development

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3 of the systems concept would be facilitated by referring to the acquired notion of the cell 'as a  
4  
5 system' and furthering insight using a systems perspective.  
6

7 To develop a basic notion of the cell, an essential idea in cell biology was used: the  
8  
9 distinction between autonomous cells or unicellular organisms and functional cells that are  
10  
11 part of a multicellular organism (Verhoeff, 2003; see appendix 1, LTA 1 and 2). Since  
12  
13 characteristics of the General System Theory are generalizations of the basic functions of life,  
14  
15 our LT-strategy started with free-living cells, which can be observed through a microscope  
16  
17 (appendix 1, LTA 3 – 6). Consequently, acquiring a systems concept started at the cellular  
18  
19 level as well, followed by its application to other organizational levels. When students  
20  
21 consider the cell both as an autonomous system and as a functional part of a larger whole  
22  
23 (appendix 1, LTA 7- 11), distinguishing the level of organelles (as functional parts of the cell)  
24  
25 and organs (as structural organizations of functioning cells) would become logical (Dreyfus &  
26  
27 Jungwirth, 1980; Verhoeff, 2003). Finally, an adequate understanding of the cell as a  
28  
29 functional unit requires a final step in the LT-strategy in which the different levels of  
30  
31 biological organization are interrelated (appendix 1, LTA 12 – 15).  
32  
33

### 34 Models and modelling

35  
36 University biology textbooks as well as textbooks used in secondary education contain many  
37  
38 two- and three-dimensional models that focus on different aspects of cells. Therefore, it goes  
39  
40 beyond saying that models are essential in an introductory course on cell biology. As argued  
41  
42 in the introduction, the use of models is included in systems thinking, since models are very  
43  
44 helpful in visualizing abstract concepts or theories. The question we focused on was how  
45  
46 models can be used to optimize an LT-strategy that combines the introduction of systems  
47  
48 thinking with development of coherent cell biological knowledge.  
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In the last 15 years a considerable number of theoretical and empirical papers on the use of models and modelling in science education has been published, recognising the functionality of models in scientific thinking. For example, Gilbert (1993) considers models as integral to thinking and working scientifically because models are sciences' products, methods, and its major learning and teaching tools. Because of the large variety of models used in science and science education, typologies of models (as presented by Coll & Taylor, 2005; Gilbert & Boulter, 2000; Harrison & Treagust, 2000) are helpful in characterizing selected models. An important dimension seems to be the distinction between idiosyncratic, mental models and analogical, scientifically accepted consensus models (Gilbert & Boulter, op.cit.) or symbolic models (Harrison & Treagust, op.cit.).

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In cell biology we are dealing with expressed scale models (Harrison & Treagust, op.cit.) depicting the structure, or an idealised structure, of cells. In systems thinking, theoretical models are the central point, since they are primarily derived from systems theory and not from (abstracted) biological phenomena. Accordingly, the systems thinking competence described in the previous section was expanded with a fourth (modelling) component (see table 1); i.e. students should be able to think back and forth between general system models and more concrete representations of cells, e.g. ranging from abstract cell models to *real* cells seen under a microscope.

**[Insert table 1 about here]**

Linked to our decision to start with an introduction to cell biology before explicitly addressing systems thinking, the LT-strategy should start with the development of scale models, and result in the development of a theoretical systems model. A trajectory for such a learning

1  
2  
3 pathway, leading from students' idiosyncratic mental models, via intermediate models,  
4  
5 towards a theoretical target model, is presented by Clement (2000). Several authors (e.g.  
6  
7 Abell & Roth, 1995; Coll & Taylor, 2005) argue that it is preferable that students construct  
8  
9 and evaluate their own models rather than introduce expressed models developed by others,  
10  
11 since that would effectively support their conceptual development.

12  
13 Both ideas, a learning pathway ranging from mental models to a theoretical model, and  
14  
15 the construction of the models by the students themselves, come together in what could be  
16  
17 characterised as emergent modelling (cf. Gravemeijer, 1999). Having been inspired by  
18  
19 Gravemeijer's concept of emergent modelling, we distinguished three types of modelling  
20  
21 activities that should be present in the design of our LT-strategy: 1) Referential activity in  
22  
23 which students develop models of real cells. 2) General activity in which students develop a  
24  
25 general model of the cell. 3) Formal thinking, by modelling representations at the organism,  
26  
27 organ and cellular level to a general systems model. To optimise the LT-strategy in enabling  
28  
29 students to develop a coherent understanding of cell biology we further differentiated these  
30  
31 activities, as will be elaborated in the next section.

### 32 33 34 The modelling strategy

35  
36 Figure 1 shows the modelling strategy towards acquiring coherent cell biological knowledge  
37  
38 and systems thinking competence. It entails a succession of four modelling phases, preceded  
39  
40 by a general orientation that poses the main steering question of the learning and teaching  
41  
42 strategy and provides a general motive for studying the topic at hand (see appendix 1). Except  
43  
44 for this first phase, all phases address the active engagement of students in the physical  
45  
46 process of modelling, in which formation, revision and elaboration of cell models are  
47  
48 performed respectively. In this process, thinking back and forth between the constructed  
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4 models, real cells and expressed models of their learning materials, constitutes the fourth  
5  
6 systems thinking competence (see table 1).  
7  
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9  
10 **[Insert figure 1 about here]**  
11

12  
13 The four modelling phases in our LT-strategy can be described as follows:  
14

- 15 (M 1) Referential activity in which students develop models of free-living cells  
16  
17 (M 2) General activity in which students develop a general 2-D model of cells  
18  
19 (M 3) General activity in which students develop a general 3-D model of cells  
20  
21 (M 4) Formal thinking by modelling representations at the organism, organ and cellular  
22  
23 level into a general systems model.  
24  
25  
26

27 We decided to start the referential activity in phase M1 with the question whether students  
28 recognize the life functions of (familiar) organisms in free-living cells. A positive answer  
29 would make it plausible to start with modelling a general model of free-living cells before the  
30 general activity (phase M2) in which models of free-living cells, and models of plant and  
31 animal cells are transferred into one general cell model.  
32  
33  
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35

36  
37 We assumed that the step from 2-D modelling (M-2) to 3-D modelling (M3) would  
38 enable students to more clearly visualize the relations between cell organelles. Support for  
39 this decision was found in the work of Al-Thuwaini (2003), who showed in his study on the  
40 use of virtual reality techniques for visualising abstract scientific concepts that 3-D  
41 visualizations strengthen students' understanding of cell biology concepts more than 2-D  
42 visual support does. The main advantage of 3-D representations seems to be that they present  
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3 information in a manner that allows students to interact with phenomena as though in reality,  
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5 more than 2-D representations do.  
6

7 As appendix 1 shows, phase M4 was divided into two steps. M4a engaged students in  
8  
9 exploring human digestion by modelling structures and processes at the level of the organism,  
10  
11 organ and cell. The abstraction of structures and processes at each level showed that the three  
12  
13 levels together can be represented by a general (hierarchical) systems model in which the  
14  
15 initial cell model can be embedded. In order to widen the range of applicability of systems  
16  
17 thinking, and to provide insight into the added value of the competence in subsequent  
18  
19 learning, students applied the nested open-system model to another biological topic, i.e.  
20  
21 breast-feeding (M4b).  
22

23 The different levels of organization clearly structured the biological content-matter in the  
24  
25 LT-strategy. The strategy started at the level of the organism in the preceding learning and  
26  
27 teaching unit of growth and development, descended to the cellular level, addressed  
28  
29 horizontal coherence and eventually related the cellular level to the organism level, i.e.  
30  
31 ascended to the level of the organism and addressed vertical coherence. The strategy showed  
32  
33 that sufficient knowledge of a biological topic such as cell biology is needed as a vehicle to  
34  
35 develop a content-specific motive for systems thinking. Its application to several biological  
36  
37 topics that transcend several levels of organization further proved the added value of the  
38  
39 competence.  
40

#### 41 42 **Students' performance**

43  
44 The four components of a systems thinking competence, as described above, provided  
45  
46 evaluation criteria for testing the adequacy of the actual LT-strategy in four successive case  
47  
48 studies. The first two case studies were considered as pilot studies providing a first insight  
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4 into the key elements of our strategy as described in the previous section and appendix 1 (see  
5 also Verhoeff et al., 2003). The results presented here, are based on the third and fourth case  
6 study in which 28 students participated.  
7  
8  
9

10  
11 In general the nature and sequence of the learning activities constituting the four modelling  
12 phases of the tested LT-strategy could be considered adequate. The LT-strategy enabled  
13 students to explore the different functions of the cellular structures and complex interrelations  
14 within the cell based on concrete observations of real cells and different physically  
15 constructed cell models, resulting in an integrated view of the cell and its organelles. Hereby,  
16 the active engagement of students in the development of subsequent cell models guided them  
17 into the intended direction and improved students' insight into the (spatial and dynamic)  
18 organization of the cell (horizontal coherence). This started by developing a model of free-  
19 living cells and applying it to the cell as a functional unit in phase M1 and M2 respectively. In  
20 the subsequent modelling phases M3 and M4 the main results of our LT-strategy, i.e. the  
21 acquisition of both a coherent conceptual understanding of cell biology and systems thinking  
22 competence, could be derived. Therefore the last two modelling phases are illustrated in this  
23 section by two key activities: building the 3-D large-scale model of a plant cell and applying  
24 the hierarchical systems model to a topic that transcends several levels of organization.  
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40  
41 *M1: Developing a model of free-living cells*  
42

43 Observation of free-living cells through the microscope proved a meaningful starting point for  
44 developing a general model for multi- and unicellular organisms. Students referred to the  
45 fundamental life processes as feeding or taking up nutrients (and using it for energy or as  
46 building material), breathing, growing, regeneration, excreting waste material and self-  
47  
48  
49  
50



1  
2  
3 protection. Some of these processes were also displayed in their first drawings as illustrated in  
4  
5 figure 2.  
6  
7  
8

9 **[Insert figure 2 about here]**  
10  
11

12  
13 The question of how cells carry out the life processes was addressed within the context of  
14  
15 Antonie van Leeuwenhoek's observations of micro-organisms and his interpretation of the  
16  
17 inner structures of these cells. The analogy between free-living cells and (familiar)  
18  
19 multicellular organisms helped in discussing the general characteristics of organisms:  
20  
21

22 [3; 2; C; 1]<sup>2</sup>, T is teacher  
23

24 T: Why did Van Leeuwenhoek think that micro-organisms also had bowels like that of a large animal?  
25

26 Ilona: He knew little about it.

27 T: Yes, but why then did he expect that they had bowels?  
28

29 Elske: Because they could move.

30 T: And so...

31 Nienke: He just thought they were animals.  
32

33 Elske: And therefore there must be energy, and so he must eat, and thus there should be...  
34

35 T: Exactly, a combination of Elske's and your answer. They are animals, they can move so they probably  
36  
37 have bowels. This in itself is a very logical train of thought. Eh, why can't they have bowels?  
38

39 Ilona: Too small.

40 Elske: Composed of cells.

41 T: Yes, organs are composed of cells, so it's technically impossible. So, then the question is: how does a  
42  
43 micro-organism do it? And that's really the question and therefore I leave it open to you. If a  
44  
45 unicellular organism doesn't have bowels, how does he do it then? What should it have instead?  
46  
47

48  
49 <sup>2</sup> Protocol fragments are indicated as [case study number; lesson; source; serial number of fragment]. Data  
50 sources are abbreviated as follows: C = whole class discussion, G = group discussion, e.g. [4; 6; G; 3] indicates  
51 the 3<sup>th</sup> fragment in this article, which shows a group discussion during the 6<sup>th</sup> lesson of the 4<sup>th</sup> case study.  
52

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4  
5 The comparison between unicellular and multicellular organisms at a general level proved to  
6  
7 be useful in distinguishing functional units, i.e. organs and organelles, and explicating their  
8  
9 interrelations. At the end of phase M1 students had developed their model of free-living cells  
10  
11 based on their observations of *Paramecia* through the microscope. There was a consensus that  
12  
13 (1) cells have a membrane that enables input and output of materials, (2) cells contain  
14  
15 organelles that fulfil specific functions for the cell and (3) the organelles are interrelated.  
16  
17 Moreover, the intended question was raised by a student whether ‘the characteristics  
18  
19 displayed only apply to free-living cells or to our body cells as well?’ This question provided  
20  
21 the motive for investigating animal and plant cells at the beginning of phase M2.  
22  
23  
24

25 *M2: Developing a general 2-D model of cells*

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26  
27 The next step in the LT-strategy was to explore the cell and its organelles and construct a  
28  
29 general model of cells. This was achieved by applying their own model of free-living cells to  
30  
31 cells that are part of an organism, and adjusting it when necessary.  
32

33 Exploration of the cell as a functional unit, guided by their own constructed model in  
34  
35 phase M1, seemed to be an obvious step to most students: ‘Well, cells in our body are living  
36  
37 units too, so they have to perform the fundamental life processes as well’. To the students’  
38  
39 surprise, hardly any structures could be distinguished in the animal cells, and just a few in  
40  
41 plant cells, when viewing them with a light microscope. During the class reflection the  
42  
43 electron microscope was proposed as an useful alternative, providing a closer look at both  
44  
45 animal and plant cells:  
46  
47

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48 [4; 4; C; 2], T is teacher

49 T: Who has seen cells with organelles?

- 1  
2  
3 Elly: I haven't.  
4  
5 Mark: Of course you have.  
6  
7 T: Everyone, isn't it?  
8  
9 Ankie: Yes, I think I've seen them.  
10  
11 Sarike: ...But there weren't many inside.  
12  
13 T: It is less clear than you hoped for, and less clear than in the model. And now the big question is: Is  
14 that due to the model? Isn't the model right, don't cells consist of that (points to the organelles in the  
15 model on the blackboard)? Or is it something else? Should we doubt the model or the cells? Who has  
16 an explanation?  
17  
18 Birgit: I think they're too small to see under this microscope.  
19  
20 T: So, if you would have another microscope, with a higher magnification, you would be able to see  
21 those organelles?  
22  
23 Birgit: Yes, because even in the red onion you couldn't see the nucleus.  
24  
25 T: Whereas it is a huge cell.  
26  
27 Birgit: Yes.  
28  
29 T: Those chloroplasts, being organelles, could be easily seen in all kinds of cells. In the cheek cells you  
30 could see some dots, but not much more. So, this is already a very scientific way of reasoning, isn't it?  
31 You stick to your model until it turns out to be otherwise, which seems to be the case now. But then  
32 you could still say: well maybe the model is right after all, but I just need better equipment (...).  
33  
34  
35

36 Studying the electron microscopic photos brought on some unexpected reactions at first.  
37  
38 Instead of being struck by the enormous complexity of the cells, students were surprised by  
39 the fact that the 'standard structure' of the cell with the organelles, cell wall and nucleus was  
40 clearly visible. The fact that students 'saw' the structure as depicted in their general model  
41 can be ascribed to students' interpretations of the pictures. They only took the clear round  
42 shapes (mitochondria and chloroplasts) for being organelles. The majority of the students  
43 needed some help of the teacher to realise that the cell structure was more complex than they  
44 had assumed at first sight. In these cases the teacher stimulated students to not only focus on  
45  
46  
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2  
3 the round structures, but also on differently shaped structures. Students then concluded that  
4  
5 'in fact almost everything is an organelle!' realising that the number of (different) organelles  
6  
7 in the cell was larger than they had expected.  
8

9  
10 The complexity of the electron microscope photos brought on the need for a cell model,  
11  
12 providing a clear picture of the cell and its organelles. The model was introduced in a short  
13  
14 text as the result of the comparison between an enormous variety of plant cells and as an  
15  
16 orderly representation of the general and structural characteristics. By comparing the photos  
17  
18 with an orderly cell model as depicted in their workbooks, students could further explore the  
19  
20 cell and its organelles. For example, the mitochondria, Golgi-apparatus and nucleus were  
21  
22 directly recognised and labelled. At the end of this phase, reflection on the use of modelling in  
23  
24 acquiring a coherent understanding of the cell revealed that students realised the potential of  
25  
26 using models in labelling the organelles and reducing the complexity visible on the electron  
27  
28 microscope photos.  
29

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### 30 31 *M3: Developing a 3-D model of a plant cell*

32  
33 In the first two modelling phases, students developed a model of free-living cells and applied  
34  
35 it to the cell as part of a multicellular organism. During the LT-activities in these phases  
36  
37 students had come across various cell models, ranging from their own drawings to the  
38  
39 developed (general) cell model, and models of free-living, animal and plant cells. In phase M3  
40  
41 students were subdivided in groups, and each group constructed (and presented) a 3-D model  
42  
43 of a certain cell organelle which was to be placed in a large 3-D cell model. In doing so,  
44  
45 students used different models represented in their textbook, other biology books and on the  
46  
47 Internet. Some student groups, for example, used dynamic computer models to explain the  
48  
49 functioning of a specific organelle. In order to construct a 'consensus' 3-D model of the cell,  
50

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2  
3 students had to compare the different representations of their organelles, agree upon the real  
4 appearance of their organelle and translate it into their own 3-D representation. In other  
5 words, students were able to think back and forth between the different cell representations.  
6  
7 Cooperation between the different student pairs was essential in order to interrelate the  
8  
9 different organelles. Figure 3 shows the resulting 3-D model that students constructed by  
10  
11 placing their organelle in the cell in relation to the other organelles.  
12  
13

14  
15  
16  
17 **[Insert figure 3 about here]**  
18

19  
20  
21 The activity of building a cell model also addressed the horizontal coherence at the cellular  
22 level, as students were actively finding relations between the organelles. From schematic  
23 pictures of cells and pieces of text in their book, students got some first clues about which  
24 organelles were related. Patricia and Renske, two students who studied the endoplasmatic  
25 reticulum, realised that it was related to the nucleus. Immediately the next question came up:  
26  
27 ‘Okay, here is the nucleus on this picture but, and that’s still a problem for us, how are ‘we’  
28 connected to the nucleus?’ Subsequently, they turned to the students who studied the nucleus  
29 and asked them how their organelles were related. After the conversation, Patricia decided that  
30  
31 ‘the nucleus sends RNA to us ... so that we can make these eh proteins with our ribosomes ...  
32 So the connection is that they make RNA for our ribosomes’. At that moment she correctly  
33 stated that ribosomes are made of RNA. However, this brought up another problem that she  
34 presented to the teacher:  
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45

46 [3; 6; G; 3]

47 Patricia: Does the nucleus produce ribosomes or does it send RNA to us, so that we can make ribosomes? [...]

48 Because I couldn’t find where ribosomes are made.  
49

1  
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3  
4 Teacher: That's a point! Ribosomes are assembled outside the nucleus. Not by the ER, but it certainly happens  
5 somehow, I don't know.

6  
7 Patricia: There has to be a connection with the nucleus, since we need ribosomes.

8  
9 Teacher: Yes, and the RNA of which these ribosomes are made.

10  
11 Patricia: Yes.

12  
13 Teacher: You receive it from the nucleus indeed, and to be exact you receive it from the nucleolus.

14  
15 Patricia: Yes. Because in the nucleolus... so we need RNA, so that we have ribosomes, that contain protein  
16 molecules so that we...

17  
18 Teacher: Produce! They contain...yeah, they also contain...

19  
20 Patricia: Do they produce them also?

21  
22 Teacher: They do, that's the point. They produce proteins.

23  
24 Patricia: Oh, the book says 'contains'.

25  
26 Teacher: Yes, that's right in a way, but they produce proteins; that's what it's about.

27  
28 Patricia: And by doing so, the rough ER can make proteins and the smooth ER makes glycoproteins out of that.

29  
30 The discourse fragment illustrates that students were actively trying to grasp the nature and  
31 functions of the interrelations between the organelles. Students explicitly helped each other in  
32 gathering information on the relations between the organelles. Sometimes this cooperation  
33 became a kind of role-play in which students identified themselves with their organelle.

34  
35 At the end of the tenth LT activity (see appendix I), most students were able to interrelate  
36 the different organelles, in terms of describing the exchange of matter and information and  
37 connect them to cellular processes as could be concluded from their plenary presentations  
38 (learning activity 11). Moreover, the presentations brought on discussions during which  
39 students tried to attain a better understanding of the nature of the relations between the  
40 organelles. The next fragment illustrates this. It follows a presentation during which Elske  
41 puts forward the dynamic nature of the Golgi apparatus and deals with the continuity of the  
42 absorption and formation of vesicles by the Golgi:  
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5 [3; 7; C; 4]

6 Jerry: Does it move itself each time from the cell membrane to, in the direction of the nucleus, or in the  
7 direction of the rough ER, because it extends to the other side as a result of the vesicles that are  
8 added? And on the other side, each time they go...

9  
10  
11 Nienke: No, but the vesicles come from the ER, then go to the Golgi-system and are transported further. On  
12 the other side of the Golgi, the membrane is used for further transportation.

13  
14 Jerry: So, on one side membrane is added and...

15  
16 Elske: Yes, but on the other side membranes are separated, they pinch off.

17  
18 Teacher: So it stays at the same place.

19  
20 Elske: Yes, on one side it adds on and on the other side it goes off.

21  
22 Jerry: O, the membrane travels completely through it.

23  
24 Elske: O yes, the pieces of membrane themselves, they travel through the entire cell, that's right.

25  
26 Eric: But also through the entire Golgi-system.

27  
28 Teacher: Yes, you must realise that when you observe the ER and how it looks now, the same applies for the  
29 Golgi apparatus. Look at them ten seconds later and it is entirely different. It's disappointing about  
30 your model: that you didn't bring that into it. Still, it's an incredibly flexible whole.

31  
32 Patricia: Our model is flexible alright!

33  
34 Teacher: Take a look a few minutes later and its shape is totally different. There are vesicles coming and going,  
35 etcetera. Actually, it is not possible to make that; it is already difficult to make it in three dimensions.  
36 As a matter of fact there is also a fourth dimension because you could bring the time dimension into it.  
37 Well that's not possible to do, but in a few seconds the cell looks totally different.

38  
39  
40  
41 The above discussion illustrates the dynamic picture of the cell that emerged in the plenary  
42 discussions, including the interrelations between the organelles. The dynamic character of the  
43 cell was apparent in the majority of the student presentations. For example, the cell membrane  
44 was explained with the help of an animation of the transport processes that students had found  
45 on the Internet.  
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6 M4: Modelling representations at the organism, organ and cellular level to a general systems  
7 model

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10 The fourth modelling phase dealt with the introduction and explication of an hierarchical  
11 systems model. So far, the structural parts and their interrelations had been studied at the  
12 cellular level, and now the organ and organism level were added by means of a computer-  
13 aided programme. This programme enabled students to explore the processes of human  
14 digestion from the cellular level up to the organism level by different exercises, e.g dragging  
15 and dropping organs at the right place in the body, drawing arrows to indicate exchange of  
16 matter/information between cells. At each level, the structures and processes were formalised  
17 into the same systems model. At the cellular level students immediately recognized the  
18 general cell model developed during M3, and no difficulties were experienced in connection  
19 to the formalization at the level of the organ and organism. This led to our conclusion that the  
20 hierarchical systems model was introduced in a way that was meaningful to students.  
21 Moreover, the final assignment of the computer-aided programme that addressed the  
22 integration of the models at the different levels of organisation, was completed by all students  
23 engaged in the assignment. During this written assignment, students were asked to draw a  
24 hierarchical systems model of the organism by combining the models at the cellular, organ  
25 and organism level (see also Verhoeff, 2003).

Deleted: the cell, organ and organism  
into one hierarchical model

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41 Subsequently, students applied the hierarchical open-system model to a biological topic  
42 manifesting itself at different levels of biological organization, i.e. breast-feeding (see figure  
43 4). In applying the systems model to this topic, students had to interpret the representations of  
44 the process of breast-feeding by fairly realistic models, and think back and forth between  
45 those models and the more general hierarchical systems model. This process seemed to  
46  
47  
48  
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1  
2  
3 present no substantial problems to most of the students. Distinguishing the three levels of  
4  
5 biological organization seemed to be a sensible activity for students for understanding the  
6  
7 topic, and they showed that they were able to match the different concepts with a specific  
8  
9 level of organization. In applying the systems model at each level, students demonstrated their  
10  
11 ability to identify the different systems, including their input and output. Interrelating the  
12  
13 different concepts at the organism and organ level was difficult, in contrast to the cellular  
14  
15 level where students were inclined to go deeper into the nature of the relations between the  
16  
17 organelles. Therefore, in this case the difficulties described in the literature (see [Douvdevany](#)  
18  
19 [et al., 1997](#); Dreyfus & Jungwirth, 1988, 1989) concerning the lack of horizontal coherence in  
20  
21 students' understanding of cells were solved to a considerable degree.  
22  
23

Deleted: ; Douvdevany et al., 1997

24  
25 **[Insert figure 4 about here]**  
26

27  
28 Students were able to transfer their knowledge on the in- and output of the breast (hormones  
29  
30 and milk respectively) to the mammary gland cells and subsequently linked the different  
31  
32 organelles to the production of milk, starting with the nucleus 'receiving the hormone and,  
33  
34 say, translating the message':  
35

36  
37  
38 [3; 9; G; 5]

39  
40 Elske: From the nucleus it goes to the rough ER, because that's what we heard during the presentation about  
41  
42 the ER and then it goes to the Golgi and then to the mitochondrion.

43 Eric: But where does the milk come from, from what part of the cell?

44 Lisa: From the food vacuole.

45 Nienke: From the mitochondrion.

46 Lisa: O no, it comes from the membrane.

47 Nienke: Yes, but that's not one of the options!  
48  
49  
50

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3 [...] 4

5 Lisa: Production of proteins takes place and subsequently they're passed on to the Golgi apparatus. Hey! So,  
6 it goes from the ER to the Golgi apparatus!  
7

8 Elske: Yes, but from the ER it goes to the Golgi apparatus and from the Golgi apparatus it goes to the  
9 mitochondria. But, in my opinion, there isn't any milk coming from the mitochondria!  
10  
11

12  
13 This last activity also enabled the teacher to identify misconceptions or gaps in students'  
14 understanding in terms of horizontal or vertical coherence, and thus address these problems.  
15 For example, in the above fragment students link the production of milk to the production of  
16 proteins in the ER and the subsequent transport to the Golgi apparatus as intended (see also  
17 figure 4). However, there is uncertainty about the remaining pathway leading to excretion of  
18 the milk, mainly caused by the uncertainty about the role of the mitochondrion. For  
19 discovering the vesicular transport route in the cell and linking the input of hormones to the  
20 output of milk, it was essential for students to realise that the Golgi apparatus excretes the  
21 milk. To this end, the teacher referred students to the schematic picture of a mammary gland  
22 cell. Students realised that the Golgi apparatus produced the milk and from there the students  
23 were able to reconstruct the vesicular transport pathway, starting with hormones entering the  
24 nucleus.  
25  
26  
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36  
37 With respect to the interrelation of the different levels of organization, the teacher's  
38 guidance was essential. At this point the systems model was not self-explanatory. Thus,  
39 although the assignment stimulated students to think about the relationships at the different  
40 levels of organization, it did not stimulate students to think back and forth between different  
41 levels. As a result, students were for example not able to develop on their own a complete and  
42 coherent systems model of the process in the breast. For this purpose, the supporting role of  
43  
44  
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1  
2  
3 the teacher was essential. Fragment [2<sup>2</sup>:9.G.46] is exemplary for how the teacher supported  
4  
5 the different student groups.  
6  
7

8  
9 [4; 9; G; 6]

10 Teacher: Okay impulses arrive at the nerve cells here. What do these nerve cells do with it? [...] Try to go back  
11  
12 to this (organism) level. Where do they have to go, these impulses?

13  
14 Tim: To the mammary gland?

15  
16 Marc: Nerves.

17 Teacher: This is the mammary gland (points at the students' systems model). Two things left the mammary  
18  
19 gland [...] subsequently it gave off impulses to the central nervous system.

20  
21 Marc: Yes.

22 Teacher: If this is a nerve cell, then it passes on impulses to the pituitary gland. The pituitary gland produces  
23  
24 hormones.

25  
26 [...]

27 Teacher: What comes into the breast, a few moments later?

28  
29 Marc: These hormones.

30 Teacher: Hormones. Hormones are always in the...?

31  
32 Tim: Blood.

33 Teacher: So, these hormones go to a blood vessel and from there they can ...

34  
35 Tim: Muscles!

36 Teacher: Influence the muscles, indeed.

37  
38 Tim: And the mammary gland.

39 Teacher: They can also go directly to the mammary gland. And those muscles, when they contract and there is  
40  
41 a group of mammary glands in between.

42  
43 Marc: Then milk comes out there.

44 Teacher: Yes. Okay, now you're going to explore the mammary gland cell further for a while.  
45  
46  
47

48 As the above fragment demonstrates, the teacher helped students in thinking back and forth  
49  
50 between the level of the mother and the breast. In doing so, he strongly steered the students  
51

1  
2  
3 into the desired direction. In addition, thinking back and forth between the different levels of  
4 organization was not reflected on in a classroom discussion as intended. Nevertheless, the  
5 discussions between the students eventually resulted in completed systems models after the  
6 teacher helped them to commence. Therefore, the problems described in science education  
7 literature, which are related to a lack of vertical coherence in students' understanding of  
8 biological phenomena, could basically be considered as having been tackled. Figure 4 shows a  
9 completed systems model at the three levels of organization that students had accomplished  
10 during learning activity 15.

11  
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13  
14  
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16  
17  
18  
19 In the final test, we asked students to depict at three organizational levels the stress  
20 mechanisms in the human body described in a text. The majority of the students  
21 spontaneously used the hierarchical systems model during this test. The same was observed  
22 during some interviews one month later when students were asked to explain a (self-selected)  
23 biological topic manifesting itself at various levels of organization. Moreover, the test showed  
24 that most students were able to distinguish and label the cellular and organism level, including  
25 the constituent parts with their input and output and their interrelations, using the text on the  
26 specific topic. The majority of the students had difficulties with the level of the organ,  
27 although the systems thinking competence of a considerable minority of students  
28 encompassed the organ level as well.

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## 40 41 Discussion

42  
43 This study indicates how systems modelling can be introduced in upper secondary education,  
44 and supports our assumption that it enables students to acquire a coherent understanding of  
45 biological phenomena. More specifically, it provides an adequate solution to our problem  
46 statement that focused on how to integrate and explicate systems modelling in an LT-strategy

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2  
3 on cell biology. Modelling proved to be powerful in visualising both the dynamics of (cell)  
4  
5 biological processes and the hierarchical structure of biological systems. In this sense,  
6  
7 modelling has been a key to acquiring a coherent understanding of the cell both horizontally,  
8  
9 i.e. the cell and its organelles as a complex functioning whole, and vertically, i.e. the cell as  
10  
11 functional part of a higher level of organization. With respect to acquiring a systems thinking  
12  
13 competence, the assumption that sufficient knowledge of a biological topic such as cell  
14  
15 biology is needed as a vehicle to develop a content-specific motive for engaging in systems  
16  
17 thinking and the use of systems-models, has been proven justified.

### 18 19 20 21 *Highlights of the strategy*

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22  
23 In designing an LT-strategy that actively engages students in systems modelling, an important  
24  
25 issue dealt with the nature of the intermediate models: should the students' learning process  
26  
27 be based on (scientific) representations created by others or should they generate their own,  
28  
29 perhaps less accurate, representations? As depicted in figure 1, our strategy integrated the use  
30  
31 of microscope images of real cells with existing representations in (text) books and their own  
32  
33 developed representations in testing, building and applying successive systems models of the  
34  
35 cell. In the first phase (M1), the cell was meaningfully introduced as an autonomous,  
36  
37 functioning unit, which provided a basis for students to generate their own (cellular)  
38  
39 representations. These representations guided students' observations of animal and plant cells  
40  
41 in phase M2. Moreover, thinking back and forth between this representation, real cells and  
42  
43 cell models expressed in their textbooks provided a solid basis for developing an initial 2-D  
44  
45 systems model of cells. This model expressed students' prior knowledge of cells, broadened  
46  
47 with the representations of the organelles and their interrelations, in other words: the  
48  
49 horizontal coherence in students' cell biological knowledge. The third modelling phase

1  
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3  
4 subsequently established a collaborative modelling activity during which students expanded  
5  
6 their understanding of the dynamics and complexity of these interrelations, and resulted in a  
7  
8 3-D consensus model of living cells. In the final phase (M4), a computer-aided programme  
9  
10 initiated the process of thinking back and forth between concrete representations and an  
11  
12 abstract systems model of a biological topic. For students to grasp the additional value of this  
13  
14 activity, the application of the hierarchical systems model to a biological topic covering the  
15  
16 different levels of biological organization proved to be essential. In this phase the hierarchical  
17  
18 systems model emerged as a tool for exploring biological phenomena both horizontally and  
19  
20 vertically.

### 21 22 23 *Systems modelling at the metacognitive level*

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24  
25 The process of modelling engaged students in the scientific practice of using models as tools  
26  
27 for observation, exploration, synthesis and, to a lesser extent, prediction of biological systems  
28  
29 and their behaviour. Thus, developing systems models not only has the potential to help  
30  
31 students to learn about biological systems, it can also foster their understanding of the nature  
32  
33 of science as an enterprise that is largely concerned with extending and refining (systems)  
34  
35 models (Gilbert, [Boulter & Rutherford](#), 1998). In doing so, it seems worthwhile to engage  
36  
37 students in informed and purposeful modelling activities, to the extent that they have  
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39 command of the process of modelling and become aware of how modelling promotes  
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41 understanding of complex biological phenomena. These notions imply metacognition, which  
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43 is fundamental to purposeful inquiry, i.e. asking oneself specific evaluative questions  
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45 (reflecting) and implementing procedures to gain answers to these questions (acting) (Baird &  
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47 White, 1996; De Vries, 2004).

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3 Our study implicates that the introduction of systems thinking provides a meta-cognitive  
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5 tool for dealing with the study of biological topics that follow after an introductory course on  
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7 cell biology. To this aim, we used the systems thinking competence derived from the General  
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9 Systems Theory to order the biological content-matter. Moreover, we used systems thinking  
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11 to address both horizontal coherence in terms of structures and processes at specific levels of  
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13 organization and vertical coherence between these structures and processes at different levels  
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15 of organization. The 3-D modelling phase (M3) demonstrated advantages for understanding  
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17 complex phenomena or abstract scientific content, and enables students to visualise concepts  
18  
19 which could otherwise remain esoteric (cf. Al-Thuwaini, 2003). The acquisition of a systems  
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21 thinking competence at the metacognitive level, which was one of the main objectives of our  
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23 study, was a central aim of the final modelling phase. In this phase, the hierarchical systems  
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25 model introduced within the context of cell biology was explicitly utilized in relating cellular  
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27 structures and processes to higher levels of organization.

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29 The results of our strategy showed that each modelling phase could indeed be recognized  
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31 by students as worthwhile in further exploring the complex interrelations within the cell and  
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33 the coherence between cells and the organism. However, the claim that our LT strategy would  
34  
35 result in the desired systems thinking competence has not been justified. In this respect, the  
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37 importance of the teacher's guidance in the last activity, e.g. stimulating students to think  
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39 back and forth between the different levels of organization, was indicative. Evidently,  
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41 acquisition of systems thinking requires more effort than one series of lessons. The systems  
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43 model should be explicitly used when other biological topics such as evolution, behaviour and  
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45 metabolism are dealt with. These topics have in common the integration of knowledge of  
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47 processes and structures at several levels of biological organization.

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4 | Accepting systems thinking as a major competence for upper secondary biology students  
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6 obviously has implications for the content and structure of the biology curriculum. Biological  
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8 systems studied in the biology curriculum are open hierarchical systems; therefore all biology  
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10 topics could be approached from a systems theoretical perspective derived from the General  
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12 System Theory. For example, the molecular biology of any topic could be introduced by  
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14 extending the hierarchical systems model to the molecular level. At this additional level of  
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16 organization, molecules can also be seen as interrelated parts that have a function within the  
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18 system that they are part of (organelle or cell). The only prerequisite for a systems approach  
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20 seems to be that topics are defined in such a way that they cover different levels of biological  
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22 organization. Several topics in the Dutch biology curriculum in upper secondary school such  
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24 as cell biology, behaviour and ecology, are defined in such a way that they are limited to only  
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26 one level of biological organization, or they do not include the organism level that is closest  
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28 to students' experiences. Therefore, redefinition of curriculum topics could be worthwhile.  
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**Appendix 1: outline of the final learning and teaching strategy addressing systems modelling and the development of coherent cell biological knowledge**

Sequence of questions	Sequence of learning and teaching activities (LTA's) including time (minutes) and desired learning outcomes
To what extent are our body cells different from free-living cells? (main question)	<p><i>General orientation on cell biology</i></p> <p><b>LTA 1: Brainstorming in groups</b> (15 min). Bringing up prior knowledge about cells that is mainly related to the domain of growth and development.</p> <ul style="list-style-type: none"> <li>• Students raise questions and wonder if their knowledge about cells applies to all cells.</li> </ul> <p><b>LTA 2: Class discussion</b> (25 min) 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 cells specialise: Would these cells still be able to survive outside our body just as free-living cells can?</p> <ul style="list-style-type: none"> <li>• Students wonder what processes cells must carry out to maintain themselves and how they do this, leading to an interest in (autonomous) free-living cells.</li> </ul>
How do free-living cells carry out the fundamental life processes?	<p><i>M1 Developing a model of free-living cells</i></p> <p><b>LTA 3: Group work</b> (20 min). Reading a text about the smallest known 'free-living' cell (<i>Mycoplasma genitalium</i>), discussing the application of the fundamental life processes to free-living cells and drawing an idiosyncratic representation of the cell as an organism.</p> <ul style="list-style-type: none"> <li>• Students realise that the fundamental life processes apply to free-living cells, but wonder how they fulfil them.</li> </ul> <p><b>LTA 4: Microscope practical and reflection</b> (30 min) on the process of thinking back and forth between their own developed model and observations of real cells. Investigating real free-living cells (amongst others <i>Paramecium</i>) guided by students' idiosyncratic representations of unicellular organisms and comparing their observations to their representations.</p> <ul style="list-style-type: none"> <li>• Students understand that free-living cells have a general structure in which functional parts can be distinguished. They can describe the developed model as representing the fundamental life processes of unicellular organisms.</li> </ul> <p><b>LTA 5: Group work on a written assignment</b> (40 min). Exploring the functions of the organelles within the context of nutrition, resulting in a (final) general model of free-living cells.</p> <ul style="list-style-type: none"> <li>• Students understand that interaction between the (functional) organelles in free-living cells is essential to fulfilling the life processes.</li> </ul> <p><b>LTA 6: Class discussion</b> (20 min) 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.</p> <ul style="list-style-type: none"> <li>• Students appreciate the model based on free-living cells as a tool for addressing the question: Do our body cells possess interrelated functional parts, i.e. organelles, as well?</li> </ul>

<p>Does the general model of free-living cells also apply to cells that are part of an organism?</p>	<p><i>M2 Developing a general 2-D model of cells</i></p> <p><b>LTA 7: Microscope practical</b> (50 min). Studying real animal and plant cells through the microscope, guided by their model of free-living cells.</p> <ul style="list-style-type: none"> <li>• Students experience difficulties in observing the organelles and realise that they need a 'closer' look.</li> </ul> <p><b>LTA 8: Group work on a written assignment</b> (40 min). Studying electron microscopic photos of plant and animal cells, and labelling and drawing the organelles.</p> <ul style="list-style-type: none"> <li>• Students realise that the cell is a complex functioning whole and feel the need for a clear overall picture of the cell.</li> </ul> <p><b>LTA 9: Individual assignment and reflection</b> (10 min) 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.</p> <ul style="list-style-type: none"> <li>• Students realise that the model guided them in exploring the fundamental life processes. Moreover, they realise they need a more realistic (3-D) model to acquire a deeper understanding of how cells carry out the fundamental life processes, including all organelles and their interrelations.</li> </ul>
<p>How does the cell, as a functional unit of an organism, carry out the fundamental processes of life?</p>	<p><i>M3 Building a 3-D model of a plant cell</i></p> <p><b>LTA 10: Assignment in pairs</b> (100 min) . Using the systems model to explore the characteristics and cellular functions of one specific organelle. Building a 3-D organelle that will be placed into a 3-D model of a plant cell. Textbook and Internet are used as information sources.</p> <ul style="list-style-type: none"> <li>• Students value the systems model as a useful tool for reducing complexity. They can give a presentation about the functioning of one specific organelle and relate it to the cell and other organelles.</li> </ul>
<p>To what extent did the process of modelling help us in answering the main question (CQ)?</p>	<p><b>LTA 11: Class presentations</b> (50 min) of the results of LTA 10, followed by a reflection that addresses the main question, guided by the teacher. Placing the 3-D organelles into a 3-D plant cell, interrelating the organelles and explaining their cellular functions.</p> <ul style="list-style-type: none"> <li>• Students acquire a coherent understanding of the cell as a functioning whole. They realise that cells and the body as a whole are mutually dependent, yet wonder in what way.</li> </ul>
<p>In what way are cells and the body as a whole mutually dependent?</p>	<p><i>M4(a) Explication of systems thinking</i></p> <p><b>LTA 12: Group work on a written assignment</b> (30 min). Reading a text on stem cells and discussing the dependence of individual cells on external information.</p> <ul style="list-style-type: none"> <li>• Students realise that (specialization of) cells require(s) signals from their surroundings that can reach the cell, due to its structural organization of organ systems.</li> </ul>
<p>How are multicellular organisms organised?</p>	<p><b>LTA 13: Computer-aided programme in pairs</b> (20 min). Exploring the process of endocrine regulation at the level of the organism, organ and cell.</p> <ul style="list-style-type: none"> <li>• Students realise that the cell model also applies to cells and organs in an organism, and get a clear picture of how the body is organised.</li> </ul> <p><b>LTA 14: Plenary reflection</b> (10 min) on LTA 13. Explicating the levels of organization and the general characteristics of living systems. Explicitly</p>

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60	answering the main question in terms of the cell being a functional system within the system at a higher level of organization. • Students understand the hierarchical structure of the body and the general system characteristics, which apply to organisms, organs and cells.  <i>M4(b) Application of the systems model</i> <b>LTA 15: Group work and plenary reflection on systems thinking</b> (40 min). Applying the systems model and interrelating the different levels of organization within the context of a specific biological topic (a nursing mother). • Students view the systems model as a tool for explaining and acquiring a coherent understanding of a biological topic at different levels of organization and recognise the benefits of thinking back and forth between the different levels of organization.
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Table 1: Four elements of a systems thinking competence for cell biology education

Being able to distinguish between the different levels of organization, i.e. cell, organ and organism, and to match biological concepts with specific levels of biological organization.
Being able to interrelate concepts at the cellular level of organization (horizontal coherence).
Being able to link cell biology concepts to concepts at higher levels of organization (vertical coherence).
Being able to think back and forth between cell representations ranging from abstract cell models to <i>real</i> cells seen under a microscope.

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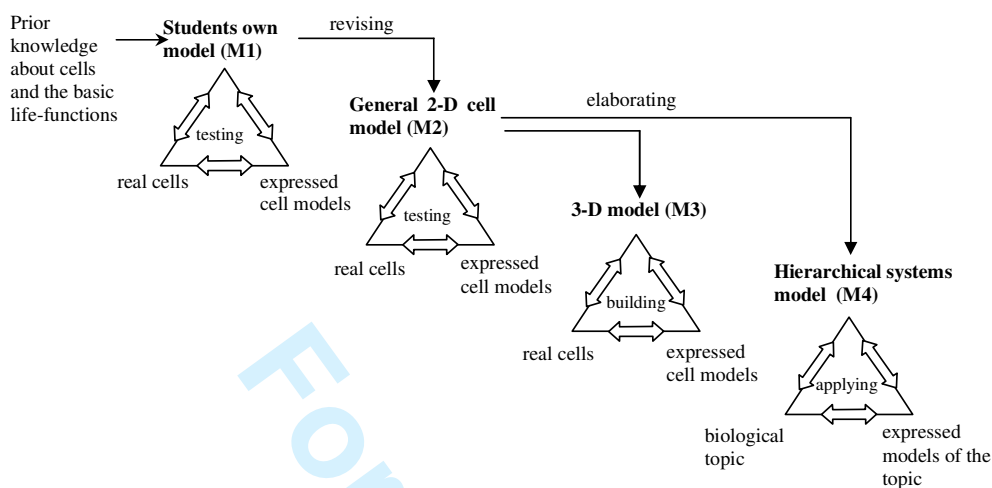


Figure 1: The learning trajectory from students' prior knowledge to the hierarchical systems model via intermediate models.



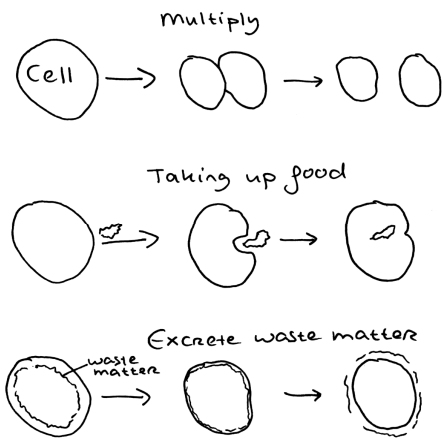


Figure 2: A student drawing of fundamental life processes fulfilled by a free-living cell

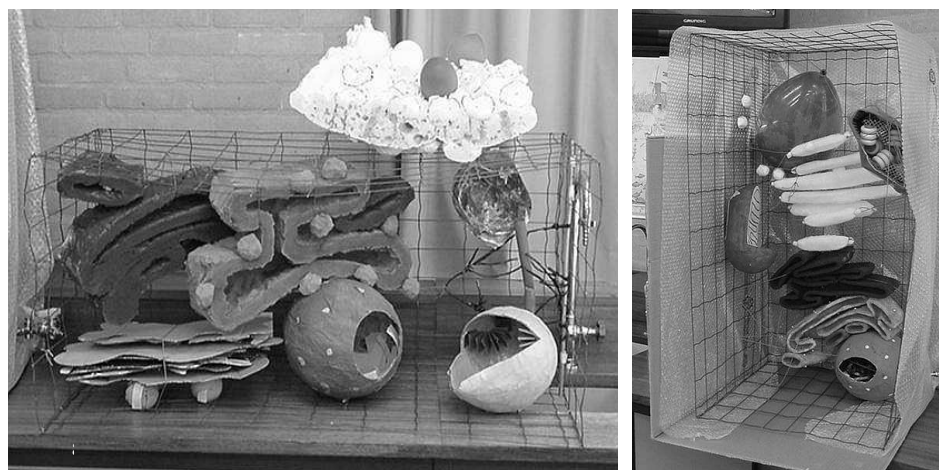


Figure 3: 3-D cell models constructed by students in a frame of  $\frac{1}{2}$  by  $\frac{1}{2}$  by 1 meter. The model includes the nucleus, endoplasmic reticulum (with ribosomes attached to it), Golgi apparatus (with lysosomes), cell membrane, chloroplast, mitochondrion and a vacuole.

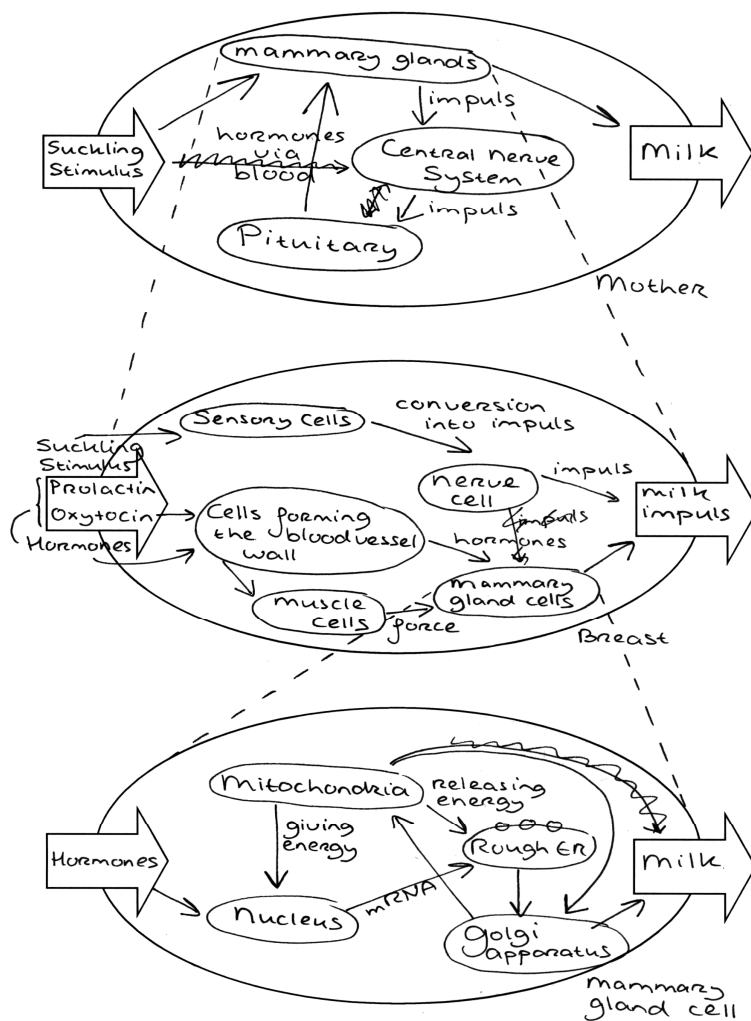


Figure 4: Students' completed systems model of breast-feeding, comprising of the organism- (top), organ- and cellular level. The teacher's help in constructing the model is illustrated at the cellular level: students initially depicted an arrow indicating that energy produced by mitochondria is directly released into the milk.