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Bringing systems thinking into the classroom

Melde G. R. Gilissen, Marie-Christine P. J. Knippels and Wouter R. van Joolingen

Freudenthal Institute, Utrecht University, Utrecht, Netherlands

ABSTRACT
Systems thinking is the ability to reason about biological systems in terms of their characteristics and can assist students in developing a coherent understanding of biology. Literature reports about several recommendations regarding teaching systems thinking, while it seems that systems thinking has not reached classroom practice. The main aim of this study was to identify design guidelines to implement systems thinking in upper-secondary biologyeducation. Based on the recommendations of literature and experience a teacher team developed, tested and evaluated two lessons in two upper-secondary biology classes (15–16 years old students, $n = 26$, $n = 19$) using Lesson Study. Lesson one focused on the application of seven system characteristics: boundary, components, interactions, input & output, feedback, dynamics, and hierarchy. Lesson two focused on the improvement of students' understanding of the characteristics feedback and dynamics by using a qualitative modelling approach. Based on classroom observations, student products and interviews, the results suggest that a first step is made: most students are able to name and apply the seven characteristics. It seems important to pay attention to the: (1) introduction of the seven characteristics; (2) application of the characteristics in a wide variety of contexts; (3) individual characteristics; (4) explicit use of system language.

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Introduction

Systems thinking or (complex) system learning has recently received a lot of attention in science education research. According to Yoon et al. (2018), the emphasis on systems thinking started after publication of the Benchmarks for Scientific Literacy in 1993 (American Association for the Advancement of Science, 1993). Since then, systems thinking has been included in many curriculums internationally. For example, the Next Generation Science Standards (NGSS) includes the crosscutting concept *systems and system models* which focuses on defining systems, specifying their boundaries and using models (NGSS Lead States, 2013).

Science education researchers work towards teaching and learning approaches that foster students' systems thinking in various science education fields, from earth science

CONTACT Melde G. R. Gilissen m.g.r.gilissen@uu.nl Freudenthal Institute, Utrecht University, Princetonplein 5, 3844 CC, Utrecht, Netherlands
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(Ben-Zvi Assaraf & Orion, 2005), geography (Cox et al., 2018), sustainable development (Molderez & Ceulemans, 2018), chemistry (Hrin et al., 2017) to biology (Ben-Zvi Assaraf et al., 2013). The current study focuses on systems thinking in biology education.

Defining systems thinking

Even though most studies (e.g. Hmelo-Silver et al., 2007; Raved & Yarden, 2014; Verhoeff et al., 2008) claim that systems thinking can improve students' coherent understanding of biology, different definitions have been used to describe systems thinking varying from basic to elaborated definitions.

The National Research Council (NRC, 2010, pp. 63–64) defined systems thinking as,

> the ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a 'big picture' perspective on work. It includes judgment and decision-making; system analysis; and systems evaluation as well as abstract reasoning about how the different elements of a work process interact.

Evagorou et al. (2009, p. 655) describe systems thinking as 'the ability to understand and interpret complex systems.' Ben-Zvi Assaraf and Orion (2005) developed a Systems Thinking Hierarchical (STH) model that reflects their definition of systems thinking. This model is built on four levels of a sequential growth of levels of systems thinking, which include the ability to: (1) identify the system components and processes; (2) identify relationships between separate components and the ability to identify dynamic relationships between the system components; (3) understand the cyclic nature of systems and organise components and place them within a network of relationships, and make generalisations; (4) understand the hidden components of the system and the system evolution in time (prediction and retrospection). Ben-Zvi Assaraf and Orion indicate that each group of skills should serve as the basis for the development of the next higher group of skills. Based on experts' way of thinking about complex systems, Liu and Hmelo-Silver (2009) describe systems thinking in terms of structure, behaviour and function. Structure represents the system components and the relations between them. Behaviour represents the dynamic interactions between the system components and existing mechanisms in the system. Function represents the essence of the system and its components. Breaking down complex systems into structure, behaviour and function (SBF) can assist students to understand complex systems. Later on, this SBF model is refined into the Components-Mechanisms-Phenomena (CMP) conceptual representation (Hmelo-Silver et al., 2017). This representation supports students to think about the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon. Sommer and Lücken (2010) describe systems thinking as the ability to identify and describe the structure of a system and the ability to understand its operating principles. They operationalised different system characteristics (i.e. elements, relationships, identify, integrity/emergence, dynamics, effects) into abilities regarding modelling and dealing with system properties.

As illustrated, there are many different descriptions of systems thinking (abilities). According to Boersma et al. (2011), this is due to the implicit or explicit emphasis on the key concepts of one or more systems theories that systems thinking was originally derived from, i.e. General Systems Theory (GST), Cybernetics (C)and Dynamics Systems theories (DST). Each of these theories focuses on a different perspective of

Table 1. Summary of the three systems theories in terms of seven system characteristics. This table is based on the system theoretical concepts of three systems theories described by Boersma et al. (2011) and the input from systems biologists and biology teacher educators in a previous study (Gilissen et al., 2019).

System characteristics		Systems theory GST	C	DST	Description
Emergence: Behaviour or properties that arise on the systems level caused by the interactions of the system components	Boundary	x			A system can be identified by determining the system boundary.
	Hierarchy	x			A system consists of partial systems, but is also a partial system in a higher-order system itself. The different (partial) systems can be categorised at the different levels of biological organisation, i.e. from molecular to the biosphere level.
	Components	x	x	x	Biological systems consist of different components which play a role in (partial) system(s).
	Interactions	x	x	x	The different system components interact with each other.
	Input output	x	x	x	Biological systems are open systems which exchange matter, energy and/or information with the environment.
	Feedback		x		Systems are self-regulating. Some of the system components form a control loop. Negative feedback loops tend to reduce the fluctuations in the input, whether caused by changes in the input or by other disturbances. Positive feedback loops increase the effect of a disturbance in a system.
	Dynamics			x	The input and output of a system can change (regularly) over time (seconds, minutes, hours, days, months, years).

(biological) systems, i.e. their hierarchical structure (GST), self-regulation (C) and dynamic behaviour of systems (DST).

In a previous study (Gilissen et al., 2019), the perspectives of current systems biology experts were studied in the light of these three systems theories. This study led to a description of systems thinking in terms of seven system characteristics as summarised in Table 1. In addition, one overarching system characteristic can be identified – i.e. emergence – which can be described as *The whole is more than the sum of its part* (Aristotle). Systems have properties which emerge from the interactions between the components of the system but do not belong to any part of that system. For example, a single ant cannot accomplish complex tasks, but a group of collaborating ants, an ant colony, is able to build hills and move huge amounts of food. In our view, emergence also reflects the combination of the seven system characteristics to understand a system as a whole.

In this paper, we use the following definition of systems thinking: *the ability to reason about biological phenomena in terms of system characteristics to create a more coherent understanding of biology as a whole.*

Recommendations from literature

In the literature, several recommendations are given on how to support students' systems thinking. Verhoeff et al. (2018) indicate that a trajectory targeting the development of a complete system concept by students should include the characteristics of all three systems theories. These characteristics can be used as a metacognitive tool for students to acquire more understanding of biological phenomena. Attention should be paid to the step from empirically observable phenomena to a systems theoretical conceptualisation of such phenomena from the three perspectives. They suggest that it is possible to start by approaching a biological phenomenon from one system theoretical perspective, guided by conceptual representations or models like Verhoeff et al. (2008) did. Later on, other biological topics can be approached from a systems theoretical perspective also. Thereby, it is important that each of these topics are approached in such a way that they cover different levels of biological organisation (Knippels, 2002; Knippels & Waarlo, 2018).

Because many system characteristics are defined as abstract entities, *modelling*, qualitatively or quantitatively, provides a way to make the invisible visible (Hmelo-Silver et al., 2007). Qualitative modelling approaches focus on representation of systems in a more abstract way showing some system characteristics (Verhoeff et al., 2008) and quantitative modelling approaches focus on the (mathematical) prediction of the system's behaviour (Wilensky & Reisman, 2006). In both modelling approaches, the focus is on identifying the system components ('agents') and their interrelations ('actions'). Verhoeff et al. (2018) recommend qualitative modelling to develop an initial system concept. An example of a qualitative design approach is that of Hmelo et al. (2000) who taught students about the human respiratory system by designing artificial lungs and building partial working models.

Another recommendation that is given by several researchers (i.e. Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016, 2018; Westra, 2008) is to make use of explicit approaches and scaffolds to improve students' systems thinking and their use of system language. Tripto et al. (2016) interviewed students non-explicitly and explicitly with system language with the aim to encourage students to organise their knowledge. The results seem to indicate that the explicit system language interview questions encourage metacognitive thinking processes because students made more use of system language themselves. Our interpretation of these explicit approaches and scaffolds is that teachers use the system characteristics explicitly during teaching and learning activities to get students acquainted with the appliance of system language when reasoning about biological phenomena. This will lead to more abstract reasoning about systems by students which should make the transfer to other contexts easier.

In summary, several recommendations are given in literature on how to support students' systems thinking. Nonetheless, the results of a previous study (Gilissen et al., 2019) suggest that Dutch secondary biology teachers rarely include systems thinking in their teaching practice, while systems thinking has been included as a domain-specific skill in the curriculum for secondary biology education since 2010 (Boersma et al., 2010, p. 33). To improve the implementation of systems thinking in education teachers need to be supported to foster students' systems thinking. Literature provides recommendations regarding teaching systems thinking, but in our view, there seems to be a lack of an integral pedagogy that provides clear guidelines for teachers to implement systems thinking in their regular lessons. Therefore, the main aim of this study was to identify design guidelines to implement systems thinking in upper-secondary biology education by designing and evaluating a teaching and learning strategy, together with teachers, based on the recommendations from literature.

The research question is: *What design guidelines for introducing systems thinking emerged during a Lesson Study in a secondary biology classroom?*

Methods

Overall research design

The lessons were designed in the context of two Lesson Study cycles. Lesson Study (LS) is an approach in which a team of teachers (sometimes assisted by researchers) collaboratively designs, performs, observes, and evaluates a research lesson (Fernandez & Yoshida, 2004; Hart et al., 2011). In observing the lesson, focus is on individual student learning. While LS is commonly used as a teacher professional development approach (Lewis et al., 2006), this approach also shares some features with design research and is nowadays also used for research purposes (Bakker, 2019, p. 16; Gilissen, Knippels, & van Joolingen, submitted; Jansen, Knippels, & van Joolingen, submitted). In this study, LS is not primary used as a professional development approach, but as a research, approach to gain new scientific knowledge about student learning, specifically regarding systems thinking in biology education. Student learning can be made visible with the LS-approach because specific students are observed individually, student worksheets are analyzed and interviews are conducted with individual students, for example, to determine what they think they learned during the lesson, and to questioning them about specific events during the lesson. Another advantage of LS is the close involvement of teachers in the design and evaluation of the lessons.

In this study, two LS-cycles were performed. Each LS-cycle consists of a series of steps. First, the team determines the student learning goals of a lesson and discussed which key activities could be used to achieve these goals. Second, the lesson is taught by the first teacher while the other three team members observe specific case students to determine the effect of key activities on student learning and whether they achieved the learning goals. Third, the lesson was evaluated and improved and taught a second time in another class by the second teacher. In total, we report on four different cases which are related: lesson 1 in class 1, adjusted version of lesson 1 in class 2, lesson 2 in class 1, adjusted version of lesson 2 in class 2.

Participants

Convenience sampling was used to select the participants for this study. Systems thinking is part of the national curriculum in The Netherlands, and therefore we have chosen to involve teachers and students of a general Dutch secondary school. The LS-team consisted of the first author, two teachers, and an observer. Julia (pseudonym) is female, has a background in physiotherapy and has eight years of experience as a secondary biology teacher. Frans (pseudonym) is male, has a background in tropical forestry and has ten years of experience as a secondary biology teacher. The school facilitated their participation by reducing their workload for other tasks. The first author is female and has five years of experience as a secondary biology teacher. She functioned as knowledgeable other (Takahashi, 2014) in the LS-team: she chaired, prepared and summarised the meetings of the LS-team. The school belongs to a school community in the eastern part of the Netherlands and offers senior general secondary education and pre-university education. During the research lessons and the evaluation meetings the LS-team was accompanied by an extra observer, i.e. the second or third author or a staff member of the school. For each research lesson, three case students (and three back-up students) were selected in each

Table 2. Pseudonyms of the case students and teachers in lesson one and two.

Case student	Class 1	Class 2	Description
Lesson 1			
A	Arthur (male)	Anna (female)	obviously motivated and hard-working student
B	Belle (female)	Berit (female)	quiet but hard-working student
C	Chloe (female)	Cas (male)	a passive student
Lesson 2			
A	Amy (female)	Alain (male)	scored high on the insight and application questions
B	Bowe (male)	Boris (male)	scored especially good on the application questions
C	Coco (female)	Celia (female)	scored especially good on the reproduction questions
Teacher	Julia (female)	Frans (male)	

Note: The first letter of the case students' name represents which type of student they represent.

class. For the first research lesson, it was not possible to select students on their average scores, since students did not have biology the previous year. Therefore, the selection was based on teachers' knowledge about student engagement during classroom activities, because the teachers did not have insight into students capabilities in biology at the beginning of the school year. Case student A represented an obviously motivated and hard-working student, student B represented a quiet but hard-working student, and student C represented a passive student. For the second research lesson, it was possible to make a selection based on students' average scores on the regular biology test that was conducted in the first period of the school year: case student A scored high on the insight and application questions, student B scored especially good on the application questions, student C scored especially good on the reproduction questions. Pseudonyms are used for different case students (Table 2).

The 60-minute research lessons were performed in two senior general secondary education biology classes ($n = 26$, $n = 29$, 15–16 years old students) during the first two months of the school year. The students who were present during both research lessons and for whom parents provided informed consent were included in this study (class of Julia, $n = 14$ (7 girls and 7 boys), class of Frans, $n = 19$ (9 girls and 10 boys)).

LS-cycles

In Figure 1 an overview is given of the different steps that are taken in each of the two LS-cycles. During a kick-off day, the first author informed the teachers about the workings of LS, and presented recommendations from literature about systems thinking in biology, which are described in the introduction. During this day, the LS-team discussed possible ways to implement systems thinking in biology education. In the three preparation meetings of LS-cycle 1 (approximately 2 hours each), the team determined specific student learning goals for research lesson 1 and 2, discussed which key activities could be used to achieve this goal and designed the lesson with input from recommendations in literature and their own practice. The team selected three different case students to observe during the research lessons. The team described the expected behaviour for each case student during each lesson activity in an observation schedule. Julia performed the designed lesson, while the other three members each observed a specific case student and described the behaviour in the observation schedule. After the research lesson, the observers conducted a short interview (approximately 5 min) with the case students, e.g.:

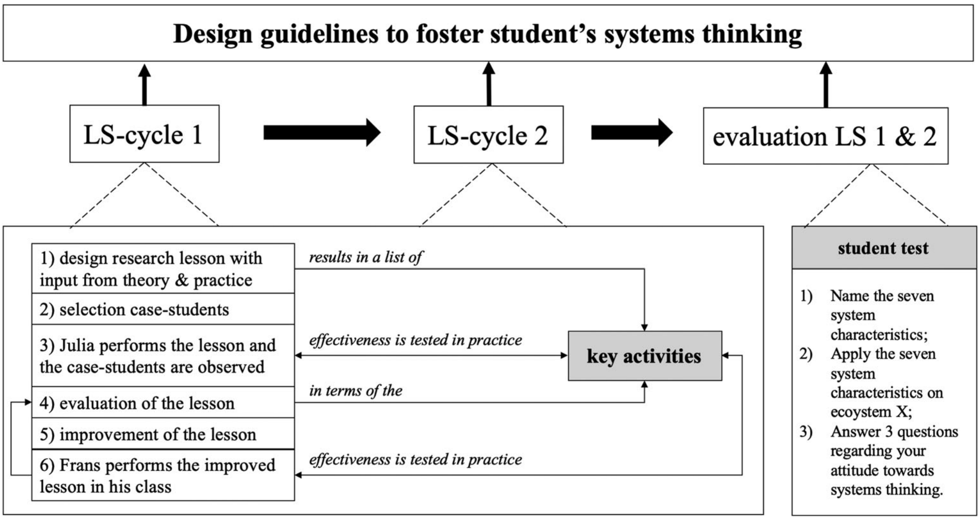

Figure 1. A representation of the outline of this study to arrive at design guidelines to foster students' systems thinking. During the two LS-cycles different key activities are designed, tested and evaluated. By using the observation notes, student worksheets, post-lesson interviews, and the student test results the effectiveness of these key activities is determined which resulted in design guidelines to foster students' systems thinking.

- What have you learned this lesson?
- What did you value in this lesson?
- How can this lesson be improved?

In the post-lesson discussion (approximately 1 hour), the team evaluated and improved the lesson based on the observation notes from the lesson made by the observers, student answers on the worksheets, and the input from the case students during the interview. Frans performed the improved lesson in his class. During the post-lesson discussion of the improved lesson, the team evaluated which key activities were crucial to achieve the student learning goal. Afterwards, aforementioned steps were repeated for the second LS-cycle which consisted of four preparation meetings of approximately 2 hours each.

Evaluation LS-cycles

After enactment of each of the two research lessons the case students of both classes (n = 12) were interviewed individually (approximately 20 min) by the first author while the other students received the same questions on a paper-and-pencil test (see Appendix A). The aim of the interview and paper-and-pencil test was to determine to what extent the students achieved the learning goals in terms of naming and applying the characteristics, and therefore determine the effectiveness of the key activities (see Figure 1). The students were asked to name the seven system characteristics. Additionally, they received an image of ecosystem X, a pond with some plants and animals, and where asked to apply the system characteristics to this system. All students were asked to answer three additional questions:

- Do you experience systems thinking as important? Explain your answer.

- Do you use systems thinking by yourself? In what situation?
- How often and in which way does your teacher pay attention to systems thinking?

Data collection

Research lesson 1 was performed in the first period of the school year (beginning of October 2019), and research lesson 2 in the second period (end of November 2019). The evaluation of the two cycles took place mid-December 2019. The designed and tested research lessons consist of specific key activities to support students' systems thinking. While repetition of the key activities took place in the regular biology lessons, this study focused on the research lessons only. During this study, various data-sources were collected and processed with different purposes (see Table 3).

Data analysis

This study focuses on student learning regarding systems thinking. We have tried to make a narrative of student learning during the different key activities in the two lessons. This could be done by finding indications for student learning in the different data-sources (see Table 3):

- Based on the summaries of *the audio-recorded LS-meetings* the first researcher identified which design choices have been made by the LS-team. In the results section, a description of these design choices is given which resulted in different key activities.
- The first author also checked the implementation fidelity: did the teacher perform the lesson as intended (Bakker, p. 82–83). The *video recordings*, in which the whole class situation is recorded, were compared with the lesson plan to determine whether the teacher implemented it as intended. In the results, we noted when a teacher deviated from the plan.

Table 3. Overview of the various data sources that were collected in this study.

Data source	Processed	Purpose of collecting the data-source
LS-meetings	Audio-recorded and summarised	Identify design choices of the LS-team based on implications from literature and/or practice
Video recordings research lessons	Video-recorded	Determine implementation fidelity by the teacher (Bakker, *p.* 82–83)
Observation notes research lessons	Transcribed	Determine learning progress of students during the different key activities
Student products of the research lesson	Digitised and scored by the LS-team using intersubjective agreement (Patton, 2003)	
Post-lesson interviews with case students	Audio-recorded and transcribed verbatim	Determine learning progress of students and identify ideas for improvement of the lesson which has been used as input for the design of the improved lesson
Paper-and-pencil test after LS-cycle 1 and 2	Digitised and scored by the first author	Determine learning progress and attitude towards systems thinking of students, and to determine to what extent their teachers pay attention to systems thinking in classroom.
Interviews with case students after LS-cycle 1 and 2	Audio-recorded, transcribed verbatim and scored by the first author	

Table 4. Key activities of research lesson 1α.

Research lesson 1α
(1) Introduction system characteristics in a teacher-student conversation – 25 min
• The teacher gave some examples of systems and introduced the seven system characteristics through the use of icons on a tangram (see Figure 2). The teacher asked the students to apply the characteristics to a well-known non-biological system in which the system characteristics could be made very clear, i.e. the school.
(2) Application of the system characteristics on a well-known biological system – 20 min
• The students applied the characteristics to a well-known biological system, i.e. the cell, in groups of 3 or 4 students. The cell was chosen, because this topic had just been taught to the students.
(3) Naming and describing system characteristics – 15 min
• The students had to individually name and describe the characteristics in their own words.

- The observers made notes of quotes and specific behaviour of individual case students during the different key activities. In the results section, these *observation notes* have been used to demonstrate how students performed during the different key activities.
- Most key activities included a worksheet for students to write their answers down (see Table 4 and Table 6). During the LS-meetings, answer sheets were developed to score *student products*. Using intersubjective agreement (Patton, 2003) the LS-team scored the answers good or wrong. In the results section, we report about the achievement of the learning goals by the (case) students.
- The post-lesson interviews with the case students were transcribed verbatim and are used to describe what improvements are proposed by the case students, and to determine what they have learned from the lesson. In the results section, we use quotes to describe students' attitude and learning.
- The evaluation at the end of LS 1 and 2 included *interviews* with case students and *paper-and-pencil test* for the rest of the students. The first researcher scored how many system characteristics the students were able to name, and determined whether they were able to apply the system characteristics to an ecosystem context. Quotes of students have been used to give insight in students' attitude towards systems thinking and to determine how much attention their teacher paid attention to systems thinking in practice.

Results

This section describes the design and evaluation process of the two LS-cycles in terms of design choices, the (improved) key activities and their (learning) effect on case students and the entire class, and the evaluation of the two cycles. Each result is based on one or more data sources (see Table 3) which are mentioned explicitly in the text.

Research lesson 1

Design choices

The focus of the first LS-cycle was to introduce students to the concept of emergence and the seven system characteristics which were extracted from three systems theories (see Table 1). Since Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016, 2018; Westra, 2008 indicate that an explicit approach improves students' systems thinking and their use of system language, the team decided to explicitly introduce the characteristics to students. Additionally, they decided to start with the explicit introduction of the concepts from all three systems theories and related system language instead of focusing

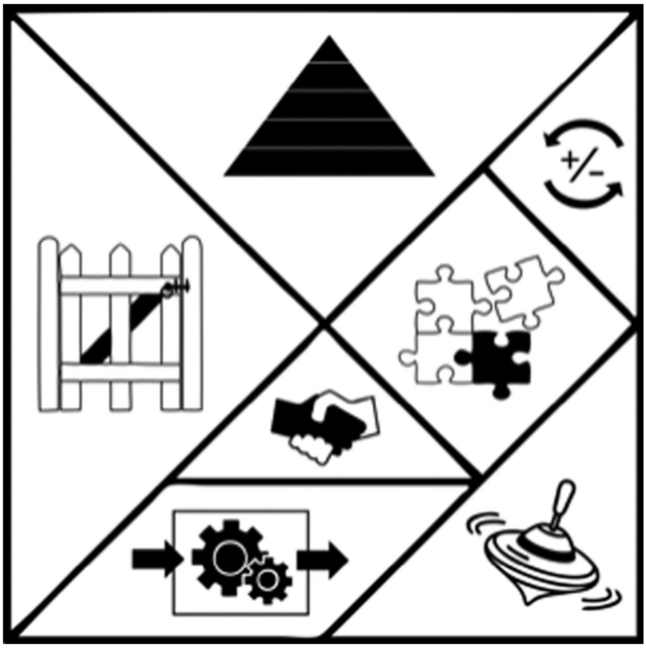

Figure 2. This tangram was created as a prompt for a system in which the seven system characteristics can be distinguished: boundary = fence, components = puzzle pieces, handshake = interactions, input and output = scheme with arrows, feedback = plus minus with arrows, dynamics = humming top. The different parts of the tangram together illustrate the concept of emergence, because the pieces together form a bigger shape (in this case a square, but it could also be another shape).

on one systems theory to support students' holistic view on systems. The learning goal of lesson 1 was: *students are able to name, apply and describe the system characteristics*.

To assist students in remembering the characteristics, the different system characteristics were visualised using icons in a tangram as a metaphor for a system (see Figure 2). The individual pieces represent specific system characteristics, and together they illustrate the concept of emergence: the different pieces form a shape together, e.g. a square.

The team formulated guiding questions related to the characteristics, which could be used by students as a cognitive toolbox to investigate the different characteristics of the system (see Appendix B). An example of a guiding question for 'boundary' is: *What is the boundary of the system: what belongs to the system and what belongs to the environment?* Lesson 1 consisted of three key activities (KA) (see Table 4).

Results LS 1

Results KA1[1]: introduction of system characteristics in a teacher-student conversation. The observation notes indicated that Arthur and Chloe were listening to the teacher, but did not give input to the conversation. Belle answered one of the teacher's questions, i.e.: Julia: 'What is the boundary of the school as a system?' Belle: 'A fence or something literally. Figuratively: age limit.' When the teacher finished the first activity Chloe said: 'A half-hour instruction is far too long: it is impossible.' In the post-lesson interview, Chloe also mentioned that the introduction was very clear, but that it was too long: 'I think we might needed the information, but a certain point it became a bit too much.'

Results KA2[1]: application of the system characteristics on a well-known biological system. The observers noted that after the introduction the students could easily start with the second activity. This was also confirmed by Belle in the post-lesson interview who indicated that the introduction activity fitted well with the group activity. The observation notes indicate that the students worked actively together to come to a description of the cell from a systems perspective, so it seems that the group task-evoked student discussion. Analysis of the student worksheets show that the student groups in class 1 applied the characteristics boundary, components, interactions and input–output mostly correctly (see Table 5). Several groups did not describe the characteristics hierarchy, feedback and dynamics, and if an answer was given, most of the time it was incorrect. These results might indicate that students encounter more difficulties with the application of the characteristics hierarchy, feedback and dynamics.

Results KA3[1]: naming and describing system characteristics. After the application of the system characteristics, the students had to describe the characteristics in their own words. An observer noted that Arthur first looked at the tangram before he wrote down the different characteristics. When the observer asked Arthur in the post-lesson interview if he thought he would be able to name the different characteristics in the next lesson, the student answered: 'I think I need to see the icons, then it would be easier.' This indicates that the icons assist students in remembering the system characteristics more easily. The results of the students on the individual task are presented in Table 5. Analysis of the worksheets indicates that most of the students were able to name the seven system characteristics and to describe the characteristics boundary, components, interactions and input–output. Students seem to have more difficulties with describing the characteristics hierarchy, feedback and dynamics. A few examples of worksheet answers that are scored as (partially) incorrect are:

- Hierarchy 'The ranking: who is higher or lower in ranking.' (Chloe)
- Feedback: 'Without feedback you do not know what to improve.' (Arthur)
- Dynamics: 'The system is always in motion.' (Belle)

Based on above answers, it seems that students use the daily life meaning to describe hierarchy and feedback instead of the biological (system) meaning and language. The characteristic dynamics is described in a very general way, and it is not clear whether students understood what exactly is meant with this characteristic (see Table 1 for our definition). The results suggest that students need more in-depth support to develop an adequate understanding of all seven system characteristics related to biology.

Improvements made to research lesson 1α. The team decided to shorten KA1[1], because the observers noted that students were not actively engaged in the conversation with the teacher, and Chloe explicitly mentioned during the lesson and in the post-lesson interview that 25 min of listening is too long. Therefore, KA1[1] has been changed to a plenary explanation by the teacher with a maximum of 10 min. The members of the team concluded in the evaluation meeting that they missed an opportunity to evaluate the answers of KA2[1]. Therefore, they included a feedback moment in the improved lesson, in which the groups

Table 5. Number of students in class 1 and 2 that were able to apply, name and describe the different system characteristics during key activities 2 and 3 in research lesson 1.

				System characteristics						
Key activity	Learning aim	Class	Total	Boundary	Hierarchy	Components	Interactions	Input output	Feedback	Dynamics
KA2[1]	*Application* of the system characteristics on a well-known biological system	1	6 groups of students	6	1	6	6	5	1	2
		2	6 groups of students	5	5	5	5	5	3	4
KA3[1]	*Naming* system characteristics	1	14 students	14	13	13	14	14	14	14
		2	19 students	16	4	12	9	16	3	3
	Describing system characteristics	1	14 students	13	4	12	10	13	6	4
		2	19 students	7	7	6	9	11	2	1

Notes: The third column represents the number of students (class 1, $n = 14$, class 2, $n = 19$) or groups of students. Key activity 2 was a group assignment: each group consisted of 2–4 students, and key activity 3 was an individual assignment.

had to exchange their answers to give feedback on each other's answers. Afterwards, the received feedback was discussed within the groups.

Results improved research lesson 1β. To check whether the shorter explanation did not have a negative effect on students' learning outcomes, the results of class 1 (analysis of student worksheets) on KA2[1] were compared with class 2 (see Table 5). The results suggest that the groups in class 2 made the task slightly better than class 1. The students also described hierarchy, feedback and dynamics correctly more often. After KA2[1], the groups exchanged their filled in assignments to give feedback with a red pencil. A student in the group of Berit immediately asked: 'Without an answer sheet?' The group of Cas also asked for an answer sheet. The observers noted that students compared the answers with their own answers and rated them with points or grades, though this was not in the teacher's instruction. After the feedback session, the groups received their own work back. The students looked critically at the feedback, and asked each other how well they had made the assignment, i.e. 'How well did you make it [the assignment]?'. The groups of Anna and Berit did not agree with the received feedback. The reactions of the students, described by the observers, suggest that they are used to their being only one right answer. In the context of applying the system characteristics, several (correct) answers can be given depending on the underpinning and the systems perspective that is used. The scores on KA2[1] (analysis of the worksheets) suggest that class 2 would have scored better on KA3[1], but this was not the case (see Table 5). The students often described the system characteristics in the context of the cell as a system, while the intended instruction of the task was to describe the characteristics in general terms. The video-recording of the lesson showed that the teacher's instruction of KA3[1] was not clear for the students, and did not follow the lesson plan: Frans: 'What did you write down first and which example did you include?' Student: 'Boundary.' Frans: 'And what did you write down?' Student: 'I thought we should do the same as before, so I wrote down the cell membrane.'

Because of the inadequate instruction, the results of class 2 for KA3[1] are not really representative of students' capacity. However, it is interesting to see that especially the characteristics hierarchy, feedback and dynamics were named correctly less often by the students in class 2.

Evaluation LS-cycle 1. During the evaluation meeting, the LS-team concluded that a first step had been made: students are aware of the presence of systems (in biology) and the corresponding system characteristics. Frans added: 'Students need to see more examples of systems to be able to get a deeper understanding of systems.' This is also in line with student learning results regarding the characteristics hierarchy, feedback and dynamics because students often describe these characteristics from their daily life perspective instead of from a systems perspective. The feedback activity did not work out as the team hypothesised. It appears that students need more specific guidance to give feedback to each other. It also seems that students are used to their being only one right answer, which does not have to be the case when applying the system characteristics. For example, in KA2[1] different examples can be given for each of the characteristics, e.g. the cell consists of various feedback loops.

Research lesson 2

Design choices

The main aim of research lesson 2 was to repeat the application of the different system characteristics in a new context, to support students' system understanding of specific characteristics and use of system language. LS-cycle 2 took place when the topic homeostasis was being taught. The team chose to focus the research lesson on the human regulation of blood glucose. According to the teachers, this topic is perfect to pay in-depth attention to the abstract characteristics feedback and dynamics. In the pre-research lesson, the students had to describe the boundary, components, input–output and hierarchy of glucose regulation system after a short introduction by the teacher. The students also had to describe the interactions between the components by completing a scheme of glucose regulation.

To visualise the abstract system characteristics in the context of the glucose regulation the team has chosen to incorporate a modelling activity (see Figure 3) which is recommended by Hmelo-Silver et al. (2007). The learning aims of lesson 2 are: (*1*) *Students are able to recognise and describe the system characteristics in a new biological context; (2) Students are able to formulate questions related to the system characteristics to identify and unravel an unknown system.* Lesson 2 consisted of five key activities (see Table 6).

Results LS 2

Results KA1[2]: visualising the blood glucose regulation. Based on the observation notes, it seems that, to start with, all case students encountered difficulties or felt insecure about indicating the glucose level for the different activities in mmol, e.g.: Amy: 'What should I write down here [on the axis]? How much?' The questions of the case students led to in-depth group discussions about how the glucose level is regulated and affected by intake of food and activity. Interestingly, based on student worksheets all groups drew the glucose line across the upper and lower limit. This was, for example, the case when Glucia woke up in the morning and was very hungry (<4 mmol), or after dinner, when she ate too much (>8 mmol) (see Figure 3(B)). However, most students only represented the fluctuations of glucose influenced by intake of food or activity and did not notice that the glucose level is also regulated by glucagon and insulin.

Results KA2[2]: explaining glucose fluctuation in graph. Analysis of the worksheets showed that the students indicated for each individual activity whether there was an influence of food intake or activity and glucagon or insulin. Thus, it was not clear from their graph whether they understood the cause–effect relations over time. For example, food intake causes an increase in glucose, which causes an increase in insulin, which causes a decrease in glucose.

Results KA3[2]: describing feedback and dynamics. Based on students' worksheets, almost all (case) students were able to describe the characteristics of feedback and dynamics for the example of glucose regulation (see Table 7).

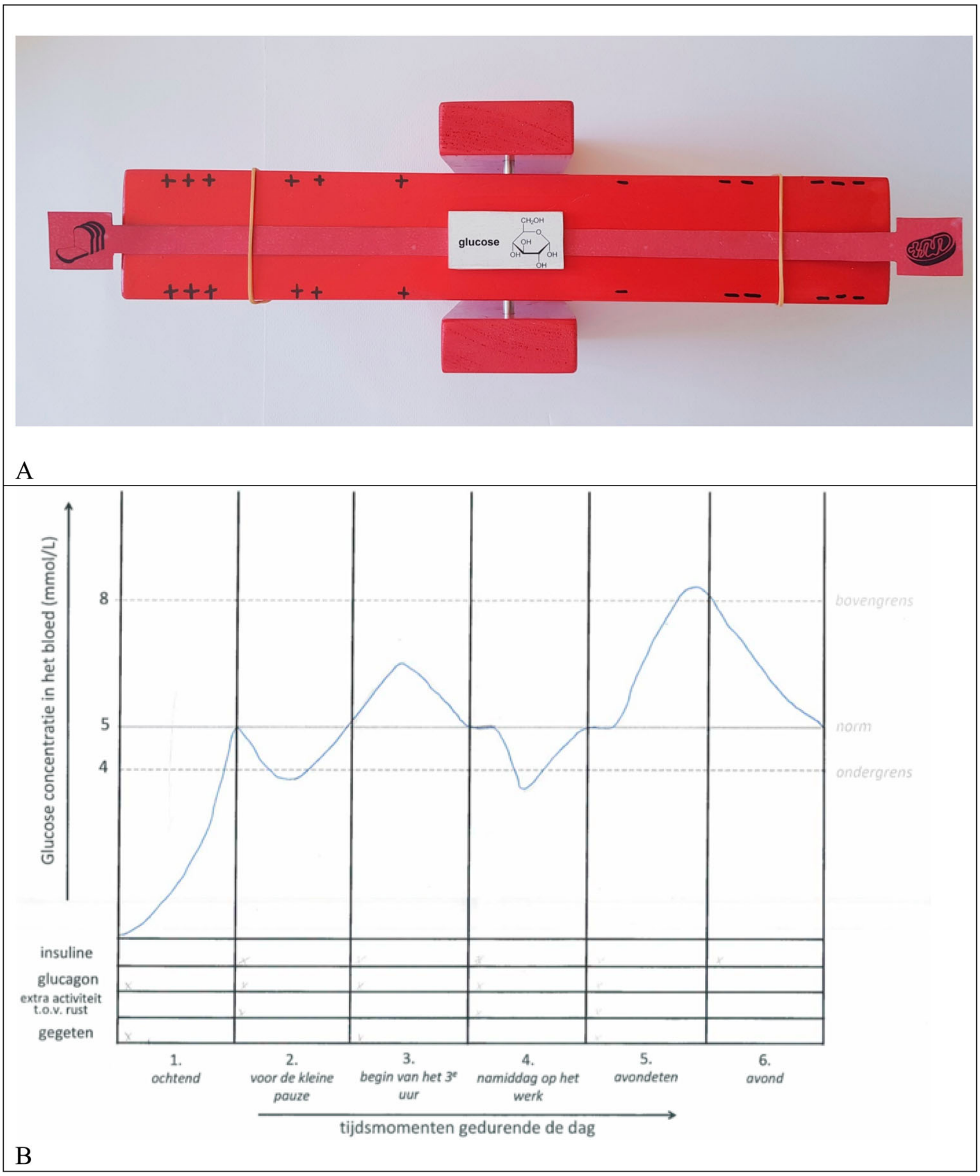

Figure 3. Seesaw and graph used during modelling activity (KA1[2]). During this activity students had to visualise the human glucose regulation with a seesaw (A) in a roleplay in groups of four and in a graph (B). The graph is an example of one of the student groups. The y-axis presents the glucose concentration (mmol/L) and the x-axis presents different moments of the day, e.g. morning, lunch, dinner, evening.

- Amy gave a correct description of dynamics: 'Sometimes the blood glucose level rises or falls. Eating increases the glucose level, but sometimes it is difficult to estimate how much it will exactly rise.'
- Bowe described the dynamics partially correct: 'By making other substances. It makes insulin or glucagon to maintain the [glucose] system.' This description lacks what is changing (glucose level) and only gives a partial answer on the causes of the change (glucose level is also influenced by the intake of food and activity).

Table 6. Key activities research lesson 2α.

Research lesson 2α
(1) Visualising the blood glucose regulation – 20 min • Three or four students visualised the glucose regulation of Glucia over one day with a seesaw in a roleplay. The case student had to draw a graph of the fluctuating glucose level. The other roles were: the control centrum, the alpha and beta cells in the pancreas (detailed description in the online supplementals).
(2) Explaining glucose fluctuation in graph – 10 min • The students had to explain the different causes of the glucose fluctuations in the drawn graph.
(3) Describing feedback and dynamics – 10 min • The students had to describe the system characteristics feedback and dynamics for the context of the glucose regulation individually.
(4) Recognising dynamic behaviour – 10 min • After a short evaluation of the different drawn graphs in relation to the causes of the fluctuations, the teacher asked students: 'Can you think of another (biological) system which shows dynamic behavior?'
(5) Formulation questions to unravel system X – 10 min • Students formulated questions to unravel what system X is and how it works, individually. The aim of this activity was to determine whether the students formulated questions implicitly or explicitly to the system characteristics.

- Coco described feedback correctly: 'As soon as your body measures that there is too much or too little glucose your body will adjust it. There is negative feedback, because it [glucose level] returns back to the set point.'

Results KA4[2]: recognising dynamic behaviour. As intended, the teacher showed the different graphs to the class and pointed out that the students did not represent the fluctuation of glucose between the activities caused by glucagon and insulin. The observers noted that the students did not ask questions during the evaluation. After the evaluation, the teacher asked the students if they could think of another example of a biological system which shows dynamic behaviour. The observers indicated that the case students were not able to come up with an example. Other students came up with the following examples: change of hormones during pregnancy, increase and decrease of heartrate, and uptake and release of water in the cell by osmosis.

Results KA5[2]: formulation questions to unravel system X. Amy formulated six questions on her worksheet to unravel system X: '(1) What tasks does system X have? (2) What goals does system X have? (3) What is the input and output? (4) Does the system have a cycle? (5) Is the system in the human body? (6) What is the size of the system? (7) Is the system switched on by something, for example by eating?' Only question 3 explicitly refers to a system characteristic (input–output). The remaining questions implicitly refer to the characteristics boundary, components, input–output, dynamics and hierarchy. Bowe formulated three questions: '(1) Which components are included? (2) What is the input and output? (3) How are the components collaborating?' All questions refer explicitly to components, input–output and interactions. Coco formulated two questions: '(1) What are the boundaries of the system? (2) What is the input and output?' These questions explicitly refer to the boundary and input–output. Analysis of the answers of the worksheets of the entire class are represented in Table 7. The results show that only a few students formulated questions that implicitly or explicitly refer to one or more system characteristics, except one student: 'What is the boundary? What components does it consist of? What are the functions of the components? What is the input? What is the output? Does it have a negative or positive feedback? How does the system change within time? How do the components work together?'

Improvements made to research lesson 2α. During the post-lesson interview, the case students mentioned that they did not know how the research lesson could be improved:

- Amy appreciated the lesson and says:

> The textbook was not clear [about glucose regulation], but now it is clear. Glucagon and insulin ensure that the glucose set-point will be achieved. […] It was clear. First the instruction. I thought it was good to draw the graph, with several tasks (roles), after that to discuss it. I thought that was a good idea.

- Bowe indicated the lesson as: 'Good enough.'
- Coco appreciated the different activities: 'The way of working. That you all had an individual role, the role play, that you know what you have to do.'

The team concluded that the represented (causes of) fluctuations of glucose by students in activities 1 and 2 were not detailed enough. A cause for this was the format of the graph on the worksheet. The x-axis of the graph represented different moments during the day (see Figure 3), e.g. morning, morning break, afternoon, while the description of Glucia's day also included sub-activities within these moments, e.g. in the morning Glucia wakes up, eats a sandwich and cycles to school. The goal was to explain each fluctuation in glucose level. Therefore, the team decided to change the x-axis from different activities to time in hours of the day. Additionally, the students in the improved lesson would receive four different coloured pens during activity 2 (explaining the graph), each pen with its own sticker: intake of food, activity, glucagon and insulin. The students had to indicate to which cause an increase or decrease of glucose could be ascribed by using the different pens. They had to identify what Glucia does (eating or activity) and how her body is reacting (release of glucagon or insulin).

Results improved research lesson class 2β. The worksheets with the graphs of the different groups, made during KA1[2], were compared to determine whether the adjusted format of the graph had an effect on the representation of the glucose level. Whereas the groups of the case students in class 1 all drew the glucose line across the upper and lower limit, all case students in class 2 drew the glucose level between the lower and upper limits. Additionally, the students did not indicate glucose fluctuations between two longer eat moments caused by glucagon. In KA2[2] Alain marked an increase of glucose from the intake of food and a decrease of glucose from activity or insulin. It seems that the student did not fully understand the effect of glucagon, because this colour was used for a moment of glucose decrease. Boris marked an increase of glucose with glucagon or the intake of food. The release of insulin after food consumption was represented, causing, together with more activity, a decrease in the glucose level. Celia especially represented the influence of food intake and activity on the respective increase and decrease of glucose. The role of glucagon or insulin was not very clear in the graph. The results of class 2 regarding the description of feedback and dynamics (KA3[2]) were compared with class 1 to see whether the adjusted format of the graph led to a difference in scores between the two classes (see Table 7). It seems that the students in class 1 scored a little better on the task than class 2. Respectively six and

Table 7. Number of students in class 1 and 2 that were able to describe feedback and dynamics (key activity 3), and that were able to formulate questions to unravel system X (key activity 5) in research lesson 2.

				System characteristics						
Key activity	Learning aim	Class	Total	Boundary	Hierarchy	Components	Interactions	Input output	Feedback	Dynamics
KA3[2]	Describing feedback and dynamics	1	$n = 14$						14	14
		2	$n = 19$						13	14
KA5[2]	Formulating questions to unravel system X	1	$n = 14$	7	3	8	5	9	3	4
		2	$n = 19$	5	6	4	2	6	6	0

Note: The third column represents the number of students (class 1, $n = 14$, class 2, $n = 19$).

Table 8. Number of students in class 1 and 2 that were able to name and apply the different system characteristics in the paper-and-pencil test after the two research lessons.

Learning goal	Class	Total	System characteristics						
			Boundary	Hierarchy	Components	Interactions	Input output	Feedback	Dynamics
Naming system characteristics	1	$n = 14$	14	4	9	10	14	11	10
	2	$n = 19$	14	2	6	9	13	7	3
Application system characteristics on an ecosystem	1	$n = 14$	11	11	1	10	11	9	10
	2	$n = 19$	14	13	3	12	7	4	5

Note: The third column represents the number of students (class 1, $n = 14$, class 2, $n = 19$).

five students in class 2 were not able to describe feedback and dynamics properly, whereas only one student in the first class did not describe feedback properly.

Evaluation LS-cycle 2. The results of activity 1 and 2 suggest that students find it difficult to distinguish between two factors that can be related to a decrease or increase of glucose. Frans said in the evaluation meeting: 'They struggled with the fact that two things are taking place in the graph simultaneously. They don't want to see the complexity.' The results of KA4[2] suggest that most of the students achieved the first learning goal 'to be able to recognise and describe the characteristics feedback and dynamics in the glucose regulation'. The results of KA5[2] suggest that most students did not achieve the second learning goal 'to formulate questions to identify and unravel how system X works'. The formulated questions, that show implicit or explicit references with the system characteristics, are most of the time related to 'components' and 'input output'.

Evaluation LS-cycles

Naming and application of the system characteristics by students

The scores of the students in class 1 and 2 on the paper-and-pencil tests in terms of naming and applying the system characteristics are presented in Table 8. In class 1, the students remembered the characteristic boundary, input–output and feedback the best, and hierarchy the least (see Table 8). It seems that the students of this class encountered difficulties with applying the characteristic hierarchy: Some students refer in their description to 'food chains': 'There are animals at the water that are higher in the food chain than other animals.' Other students are talking about a certain 'ranking': 'Certain biological aspects have more influence and power than others'

In class 2, the students remembered the characteristics boundary and input output the best, and hierarchy and dynamics the least. It seems that the students of this class encountered difficulties with applying the characteristics hierarchy, feedback and dynamics. Examples of wrong answers: hierarchy – 'That one animal is higher [in ranking] than the other.', feedback – 'I would not know how to apply it to a system, but just the good and bad points, say what is good about a system and what is less good about a system', dynamics – 'Not too much of everything, not too little of everything.'

Students' attitude towards systems thinking

In class 1, all six case students indicated the value of systems thinking in biology education:

Arthur: '[…] because I then retook the biology test and then I applied it [system characteristics] and then I achieved a higher mark. […] Look how everything is related with each other. Making interrelations like that.'

Belle: '[The characteristics] feedback and input and output really helped me to understand biology better.'

Chloe indicated the value of systems thinking, but also indicates that she experienced it as an additional burden. 'If you can receive grades for it then I would find it really helpful, but otherwise I think it is too much. But it does offer a slightly different view [on biology], you start looking at things differently due to the use of that [system characteristics], especially if you understand those correctly.'

Amy: 'These things [system characteristics] are logical themselves. You know them, but you have to remember that they are really there. I really learned that. Recognize that these system characteristics are always present in systems.' She also indicated that she uses the system characteristics herself: 'Just during the assignments or during a test you think about the seven things [characteristics] which are applicable for all systems and then you start to think better about what this could be. […] Then you start thinking about each thing [characteristic] and how you can find it [in the system].'

Bowe: 'I would say that I get to know a system a little better, that I know more about it directly, that it then lingers more in my head.'

Coco: 'There are just so many things that you can divide under these [system characteristics].'

In class 2, also all six case students indicated in the interview the value of systems thinking. The systems perspective offers them a way to organise biology, e.g.:

Berit: 'To understand it [biology] better and that you have an overview of what belongs [to the system] and how it works.'

Celia: 'I think it is nice, but I just have to learn them [characteristics] a bit better so they can assist me in biology, because I find biology quite difficult so I would like to understand it better.'

Alain: indicated that he made use of the system characteristics in his own way: 'In the end it is nice because it gives you a better overview of the things you learn. In the notebook of mine I also have this diagram in my own words and then I try to process the information of the lesson in this diagram. So I give it some kind my own twist. […] that just gives a lot of overview when I am learning. Suppose I have a test in a week, then I take the notebook and the text book and the diagram and then I first determine the systems and the parts that are involved, and how the different parts work on their own and how they work together. If I have this clear for myself I will put it away for a moment and then I will go deeper into that.'

While Alain for example already applied the system characteristics himself, other students did not make use of the system characteristics themselves, e.g.:

Boris: 'There are so many systems in biology and I think it is helpful to think about all these systems and the corresponding system characteristics, but at this moment it does not give me much assistance when I am making the [biology] assignments.'

Systems thinking in the regular lessons

According to the students in class 1, Julia referred to the different system characteristics within the regular lessons. Arthur: 'If she is explaining something then she sometimes refers to the corresponding system characteristic.' Chloe: 'She shows the picture [tangram] very often and then she refers for example to the boundary or the glucose control or something different.' Bowe: 'Then she shows a new system, for example muscles and nerves. Then she applies the characteristics again.' Coco: 'She refers to this [tangram]. I think she says that you have to think about the boundary [of the system], and which components [the system consists of].' Most students indicated that Julia pays enough attention to systems thinking, but Coco indicated that she would appreciate some extra explanation regarding the meaning of the characteristics: 'Yes, to freshen up our memory, I think it can be done more often.'

According to the students in class 2, Frans regularly paid attention to the system characteristics in the regular lessons by referring to them and by applying them to different contexts, e.g. Anna: 'Just naming it. He simply explains something and then he says this is input and output. He mentions that every lesson and sometimes he comes back to those parts [the system characteristics].' Cas:

> Every two weeks he repeats that [system characteristics], but he does not explicitly comment on it. Then he has this plate [tangram] hanging on the wall and then he says this is the hierarchy, but he does not explicitly explains what that means again.

This student indicated that he would like to have some extra explanation about the meaning of the different characteristics. Boris indicated that the teacher spent too much time on systems thinking:

> I think personally that we pay a bit too much time in that, because the biology itself sometimes suffers from it. We are now far too much concerned with all those blocks [system characteristics] and the real knowledge is receiving less attention. […] As a student I want to have instruction about the theory we need to know for the test. Something like that [system characteristics] is fun sometimes, i.e. one a week maybe or every two weeks, but now I think we spend too much time on it.

Conclusion and discussion

While the importance of systems thinking is recognised internationally, and several recommendations can be found in literature regarding teaching systems thinking, to our knowledge systems thinking did not find its way into the regular biology lessons yet. In the context of Lesson Study (LS) two research lessons were designed, tested and evaluated with the aim to triangulate these recommendations from literature and bring them into classroom practice.

The strength of this study is the use of LS as a research instrument. In this set-up, teachers are involved from the design to the evaluation phase which leads to ownership, but also to implementation integrity because the teachers know what they want to achieve with the lesson and with which teaching and learning activities they want to do this. One of the biggest advantages of LS are the close observations of case-students during the research lessons and the interviews afterwards which give in-depth insight in the learning (and thinking) progression of different types of case students.

Based on the findings of this study we formulated four design guidelines that seemed effective in supporting students' systems thinking:

(1) *Get students acquainted with the seven system characteristics that are related to the three systems theories.* This design guideline is in line with Verhoeff et al. (2018) who indicate that students should develop a systems concept from all three systems theories where systems thinking originally is derived from (Boersma et al., 2011). Students are not used to see biological phenomena as systems which have universal characteristics. A way to get students acquainted with this is to introduce different types of (non)biological systems and describe the system characteristics in general terms and in the context of a specific system which is well-known to students, for example as we did with the school as system. To assist students in remembering the different system characteristics the metaphor of the tangram pieces with icons can be used (see Figure 2). Based on the results of KA3[1] (Table 5), the introduction of the system characteristics in the context of the school as a system together with the tangram as metaphor seem to assist students in remembering the characteristics. Based on the observation notes,

we also saw that students first looked at the tangram before they wrote down their answers. Moreover, quotes from the interviews with the case students after LS 1 and 2 show that students see the value of systems thinking and some of the case students already use the characteristics without explicit instruction from their teacher.

(2) *(Let students) apply the system characteristics to a wide variety of contexts during the school year, varying from the cellular to the biosphere level, at different times within the school year.* Knippels (2002) and Verhoeff et al. (2018) recommend to approach various biological contexts and levels of organisation from a systems perspective. In this way, students develop a better understanding of the different characteristics and recognise their broad applicability. In this study, the students applied the characteristics in two contexts: the cell and the human glucose regulation. With assistance of the guiding questions, which are related to the system characteristics, students described both systems in terms of their characteristics. During the interviews with the case students after LS 1 and 2, it became clear that students do know most of the system characteristics, and that they are applicable to more (biological) systems. However, we also saw that students still had some difficulties with naming all seven system characteristics and applying them to a new context, e.g. as we saw in the evaluation test (see Table 8). This suggests that students need to practice more often with the characteristics in different contexts.

(3) *Focus on one or two system characteristics specifically to deepen and/or improve students understanding of these characteristics in relation to the others.* From our study, it seems that students need more support to understand the characteristics hierarchy, feedback, and dynamics. Based on student answers, we think that students thought of the daily life meaning of the characteristics feedback and hierarchy instead of their meaning in biology. This could be induced by using an example from students' daily life, e.g. the school as a system. Also, students found it difficult to describe the meaning of the characteristic dynamics. This is in line with Hmelo-Silver et al. (2007) who already concluded that students have more difficulties with the dynamic behaviour of systems because these processes are invisible. When it seems that students do not understand a specific characteristic it is possible to focus on this characteristic in a specific lesson. This can be in the context of the topic that is taught at that moment or by comparing different contexts with each other. In this study, we paid specific attention to feedback and dynamics in the context of the glucose regulation. The students first had to describe the system in general: what is the boundary of the system?, what are the components of the system?, what is the input and output? Afterwards the students visualised the system in a modelling activity and they had to identify the feedback mechanisms and the dynamic behaviour in this specific context and in other biological contexts. This activity led to a better understanding of dynamic behaviour and feedback from a biological systems perspective by students.

(4) *Pay attention to the use of system language and encourage students to do so*. This guideline is in line with several researchers (i.e. Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016; Tripto et al., 2018; Westra, 2008) who all claim that systems thinking should be taught explicitly. To get students used to the use of system characteristics (system language) and to see the wide applicability of them (see also guideline two), teachers can explicitly use the characteristics in their instructional vocabulary. Moreover,

teachers can encourage students to use system language when they are reasoning about biological phenomena or by reformulating their answers by making use of the system characteristics. In the evaluation interviews we saw that students recognised that the teachers paid attention to systems thinking in the regular lessons, because the teacher was using systems language explicitly.

Overall, in this case study the described recommendations from literature are empirically substantiated and expanded by a team of teachers. A first step is made in introducing students to systems thinking. The students are aware of the different system characteristics and are able to apply them in different biological contexts. However, students' understanding of one of the overarching system characteristics, i.e. emergence, was not studied, because students first need to develop a basic understanding of the other system characteristics. This could be a next step in a follow-up study.

Moreover, the case students in both classes indicated systems thinking as important to understand (systems in) biology. Nevertheless, only two students indicated that they themselves made explicit use of systems thinking. They used the characteristics to create an overview of their biological knowledge which assisted them in preparing for a biology test. Thus, it seems that most students do not yet internalise systems thinking as a metacognition tool yet. Verhoeff et al. (2008) also encountered the difficulty of developing a motive for students to apply a system concept. In a follow-up study attention should be paid to fostering students' internalisation of systems thinking. The challenge is to let students experience systems thinking as a way to create a more coherent view of biology, and as a way to reason about biological systems in abstract terms to gain more insight in biological systems and to solve complex problems.

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ORCID

Melde G.R. Gilissen http://orcid.org/0000-0002-0668-4525
Marie-Christine P.J. Knippels http://orcid.org/0000-0003-4989-1863
Wouter R. van Joolingen http://orcid.org/0000-0002-4271-2861

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Appendices

Appendix A: Assignment part 1

Name:______________________

Teacher:______________________

(1) Try to give at least three examples of a system.

(2) Try to describe a system in your own words.

(3) Name the seven system characteristics.
(1) ______________________
(2) ______________________
(3) ______________________
(4) ______________________
(5) ______________________
(6) ______________________
(7) ______________________

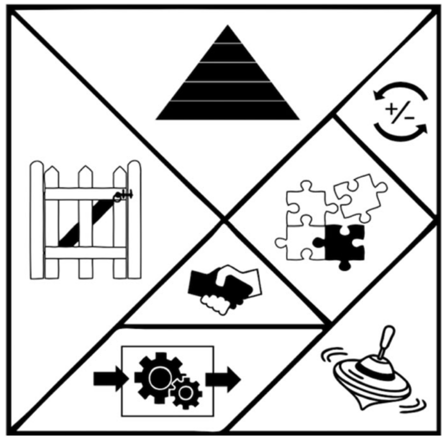


Image 1. Tangram with the system characteristics.

(4) Explain what the system characteristics have to do with biology.

(5) To what extent do you find the system characteristics useful / valuable on a scale from 1 (not at all useful) to 6 (very useful)? Explain your choice.

1 – 2 – 3 – 4 – 5 – 6
Explanation:

(6) Have you ever used the system characteristics yourself without your teacher telling you to do that? In what situation was this?

(7) How often does your teacher pay attention to the system characteristics on a scale from 1 (never) to 6 (very often). Also indicate how your teacher pays attention to this, for example: refers to tangram (see Figure 1), names the characteristics, has assignments with questions that refer to the characteristics, and so on.

1 – 2 – 3 – 4 – 5 – 6
Explanation:

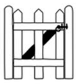
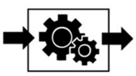
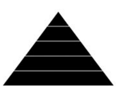
If you have answered questions 1–7, you can submit part 1 and you will receive part 2 of the questionnaire.

Assignment part 2

Name:________________________
Teacher:________________________

Assignment 'applying the system characteristics'

In addition to this worksheet, you also received a picture of an ecosystem of a pond. Try to apply the seven system characteristics to this system.

Icon + system characteristic	**Answers**
Boundary 	
Components 	
Interactions 	
Input output 	
Feedback 	
Dynamics 	
Hierarchy 	

Appendix B

Guiding questions

The guiding questions are related to the seven system characteristics and can be used by students as a cognitive tool to investigate the characteristics of a specific system.

System characteristic	Guiding question
Boundary	Where can you draw a systems boundary? What belongs to the system, and what belongs to its environment?
Hierarchy	In which subsystems (and to which larger system) can you divide the system? And, to which levels of organisation does these (sub)systems belong?
Components	Which components does the system consist of? What is the function of the individual components within the system?
Interactions	What are the relations between the different system components?
Input and output	What (energy, information or matter) enters the system? And what leaves the system?
Feedback	Which feedback loops are present in the system components? • Does the feedback lead to opposing changes within the system? → negative feedback • Does the feedback lead to enhancing changes within the system? → positive feedback
Dynamics	Which regular changes occur in the input and output? In what way do changes take place within the system over time (hours, days, months, years)?