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Recurring patterns in the development of high school biology students' system thinking over time

Jaklin Tripto[1] · Orit Ben Zvi Assaraf[1] · Miriam Amit[1]

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Abstract The goal of this study was to identify and understand the mental models developed by 67 high school biology students as they learn about the human body as a complex system. Using concept maps, it sought to find an external way of representing how students organize their ideas about the human body system in their minds. We conducted a qualitative analysis of four concept maps created by each student throughout the 3-year learning process, which allowed us to identify that student's systems thinking skills and the development of those skills over time. The improvement trajectories of the students were defined according to three central characteristics of complex systems: (a) hierarchy, (b) homeostasis and (c) dynamism. A comparative analysis of all of our students' individual trajectories together revealed four typical learning patterns, each of which reflects a different form of development for systems thinking: "from the structure to the process level", "from macro to micro level", "from the cellular level to the organism level," and "development in complexity of homeostasis mechanisms". Despite their differences, each of these models developed over time from simpler structures, which evolved as they connected with more complex system aspects, and each indicates advancement in the student's systems thinking.

Keywords High school biology · Complex systems · Systems thinking

✉ Orit Ben Zvi Assaraf
ntorit@bgu.ac.il

Jaklin Tripto
triptoj@gmail.com

Miriam Amit
amit@bgu.ac.il

1 Department of Science and Technology Education, Ben Gurion University of the Negev, Beer Sheva, Israel

Introduction

System thinking is a necessary prerequisite to gaining a full and useful understanding of many aspects of our lives (from large-scale global phenomena like climate change to the microscopic epidemiological phenomena like the AIDS virus). However, such thinking requires thinkers to acquire and employ a variety of specific skills and kinds of knowledge, which are not always obvious or intuitive for students. The literature has provided extensive documentation of the strengths and weaknesses shown by students in their attempt to understand scientific systems and apply systems thinking (Evagorou et al. 2009; Vattam et al. 2011). These studies differ from one another in the extent to which they focus on: (a) knowledge of a particular system, (b) general knowledge about system principles, or (c) the use of system thinking skills.

The National Research Council (NRC) defined system 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," and marked this ability as a critical skill to have the twenty-first century (NRC 2010 p. 3). This importance was reiterated by the Next Generation Science Standards report (NGSS 2013), which emphasized the value of engaging in system thinking in the context of both structure and function. This awareness of system thinking's relevance has led to a growing emphasis on the topic of complex systems in science education. "The value of learning about complex systems relates both to the importance of these ideas in modern science as well as for the potential of complexity ideas to provide conceptual interconnections across different science subjects as a new perspective about scientific literacy" (Jacobson et al. 2017, p. 1).

In a topic such as human biology, for example, an understanding of complex systems is crucial. Understanding the human body as a biological system requires students to know and understand of a variety of facts and principles. Seeing the interactions between the different organizational levels of the multicellular organism and being able to identify the mutual interactions and influence of the different components is necessary to meaningful biological understanding (Lin and Hu 2003). It is therefore important to help students develop a perception of systems that uses the interactions between components to explain the function of the system as a whole. With the importance of helping students achieve such a perspective in mind, the study presented here sought to learn more about how different students perceive the human body system, and how this perception changes over time. In other words, it sought to identify and understand the *mental models* developed by students as they learn about the human body as a complex system.

Mental models are cognitive representations of the learner's knowledge that mirror the components and organization of the system (Johnson-Laird 2004). Meaningful learning occurs when learners connect new knowledge to their existing knowledge structure—to the mental models that already exist in their minds. Students' previous knowledge influences the verbal and visual representations they choose in processing their knowledge, and how these representations are organized in their mental models (Mayer and Anderson 1991; Mayer and Moreno 2003).

Studies have shown that an understanding of complex systems coincides with the presence of a sophisticated mental model of the system (Johnson-Laird 2001). Students' mental models can therefore be used as an indication of the extent and nature of their systems understanding. The literature on mental models of systems and on system thinking suggests that an important distinction between the mental models of system experts and novices is the presence of interactions and relationships between components, rather than just the visible structures or attributes of individual components (Goldstone and Wilensky

2008; Hmelo-Silver et al. 2000; Vattam et al. 2011). Tracking the presence and absence of such elements in students' mental models over time can therefore serve as an indication of learning.

In this study, we gained access to the students' mental models by asking them to draw concept maps, which served as an external, visual way of representing how students organize their ideas about the human body system in their minds. The use of concept maps is connected to the constructivist approach (Novak 1990; Novak and Canas 2007), according to which students generate their own knowledge, rather than being given it. Concept Maps were developed in the course of Novak's research program, in which he sought to follow and understand changes in children's knowledge of science. Novak's work was based on the learning psychology of David Ausubel (1968, 1978). The fundamental idea in Ausubel's cognitive psychology is that learning takes place via the assimilation of new concepts and propositions into existing concept and propositional frameworks held by the learner. This structure, as it exists in the learner's mind, is also referred to as the individual's *cognitive structure*. Concept maps were developed by Novak to represent these cognitive structures.

Based on the assumption that concept maps are reflective of how students' knowledge is organized in their mind, many studies have used them as a means of gaining access to what students understand, or how they *see* a given topic in their mind's eye (Schroeder et al. 2017). The study presented here expands upon this by using a series of successive concept maps to determine how each individual student's mental model of the human body system *develops* over time. We tracked the development of our students' mental system models throughout their high school biology education by asking them to generate concept maps at four strategic points throughout the learning process, generating a total of four concept maps per student, spread out over 3 years. The maps were analyzed qualitatively, using each student's four maps to produce a *story* about the development of their mental system model.

Understanding how different students' system thinking develops is essential in order to develop and facilitate a pedagogical *scaffolding* that allows students to engage in counterintuitive modes of thought and overcome the variety of cognitive barriers that can prevent them from fully understanding the system's complexity. Our study advances this goal not just by showing how concept maps can be used to identify such development, but by collectively analyzing the system thinking development of a relatively large sample of 67 students. One major advantage of this approach is that working with such a large sample allowed us to compare the system model development stories of different students to one another, and to identify a series of *recurring patterns* in how students' understanding of the human body system may tend to progress from a simpler system model to a more complex one.

The ability to identify such patterns can be a means of improving science education at the level of both planning and practice. In practice, understanding students' learning patterns can help teachers develop and adapt their teaching according to their students' specific needs. Such knowlede could, for instance, help teachers focus their teaching more efficiently, using the patterns as a basis for forming study groups (Kinchin et al. 2000). More generally, an awareness of the range of potential learning patterns could influence the development of available and appropriate teaching materials, as well as teaching and assessment methods. In our study, we found that the mental models reflected in the 67 sets of concept maps produced by our students could be divided into seven typical recurring types, each describing a different form of development in the complexity of the students' understanding of the human body system.

Literature review

The human body as a complex system

The difficulties students have with the topic of complex systems have been noted in a variety of studies (Ben-Zvi Assaraf and Orion 2010; Ben-Zvi Assaraf et al. 2013; Plate 2010). These describe a number of obstacles to understanding the different aspects of the system, among them difficulties drawing connections between the systems' different levels and understanding the function of the system as a whole (Hmelo-Silver et al. 2007). It is therefore important for the development of system thinking to be an integral part of the learning process.

A complex system can be generally described as an entity consisting of a large number of structures, at different levels of organization, in which various processes occur. With regard to biological systems, Hmelo-Silver et al. (2007) defined structures as either microscopic (like cells) or macroscopic (like organs), adding that "the micro level refers to the level of individual elements of a system, whereas macro refers to the aggregate level" (pp. 308–309). Thus, in the context of the human body, the micro level includes cells and molecules, and the macro level includes tissues, organs and systems.

Studies of complex systems have shown that students' understanding of the human body tends to focus on the system's structures and to favor the macro level over the micro (Hmelo-Silver et al. 2000). Thus, for instance, Ben-Zvi Assaraf et al. (2013) study of high school students' system thinking about the human body reported that they had difficulty representing the body's cellular level. Verhoeff et al. (2008) showed that students had difficulty making connections between the cellular (micro) level and other (macro) ones when explaining biological phenomena.

Hmelo-Silver et al. (2007) showed that understanding complex systems requires a recognition of the relationships among the system's different levels. For novices, the system's components are easier to comprehend than its functions, while experts organize their knowledge of the system around its behavior, meaning around the phenomena in the system. Understanding such interactions within the human body is particularly challenging for students (Ben-Zvi Assaraf et al. 2013; Tripto et al. 2017; Hmelo-Silver and Pfeffer 2004). More specifically, the system's micro level components (i.e. genes, cells and molecules) are those that students find most difficult to recognize as significant to the human body system's interactions (Duncan and Reiser 2007; Liu and Hmelo-Silver 2009).

Another key aspect of the human body as a complex system that students often find challenging is its dynamism. To understand the human body as a system, students must be able to identify the dynamic relationships that take place on and between the various levels of the system's hierarchy. In dynamic systems, two events may be connected, but separated from one another in space and time. Thus, recognizing dynamism also means identifying the interaction between events and predicting the consequences of changes (Sommer and Lücken 2010). Wilson et al. (2006) suggested that one major obstacle to dynamic thinking is the difficulty of following matter as it is transported through a system. Dynamism is one of the characteristics of another key aspect of complex systems—homeostasis (Verhoeff, et al. 2008). This concept has also been shown to be a source of students' difficulties (Boersma et al. 2011; Ben-Zvi Assaraf et al. 2013), especially when it comes to understanding the micro-level aspects of micro-level factors: small scale structures and local processes (Zion and Klein 2015).

Using concept maps to externalize students' mental models and characterize their system thinking

One of the key principles in planning the teaching of complex systems is representing the conceptual framework explicitly to the students, and helping them to represent their mental models explicitly (Jacobson and Wilensky 2006). One way to do this is to use models or concept maps as a visual means of externalizing and examining students' internal mental models (Hay, Kinchin and Lygo-Baker 2008; Ifenthaler 2010; Shavelson, Ruiz-Primo and Wiley 2005). The external representation of mental models is a helpful approach to both teaching and assessing students' understanding of the multilevel structure that characterizes complex, non-linearly organized biological phenomena (Buckley and Boulter 2000). Building models of biological systems can promote students' ecological literacy (Long et al. 2014) and system thinking skills (Ben-Zvi Assaraf et al. 2013; Vattam et al. 2011), and serve as a foundation for accreting and connecting new knowledge in biology (Dauer et al. 2013). Working with teachers who were content experts, Yoon et al. (2016) noted the critical role of professional development in providing timely support and persuading teachers of the necessity of building models when teaching about complex systems in the science classroom.

External representations of mental models (like concept maps) are used to evaluate not only conceptual understanding, but also the ability to solve problems in a complex system's content (Johnson-Laird 2001). Modeling is a central skill in scientific reasoning and provides a way of articulating knowledge. It emphasizes a particular way of constructing and representing knowledge, where a concept is known through its connections to other concepts and the product (i.e. the model) provides a visual representation of a portion of the student's cognitive structures (Nesbit and Adesope 2006). The cognitive structure, also called a knowledge structure, represents students' organization of biological concepts stored in their long-term memory (Ifenthaler et al. 2011; Jonassen et al. 2013). Though it exists in the long-term memory, the cognitive structure can be used as a foundation for a mental model in the working memory to be accessed during problem solving and modeling (Shell et al. 2010). Student constructed models provide insight into their thinking and emphasize the process by which students search for, search within, and represent their cognitive structures (Hay et al. 2008; Ifenthaler 2010; Shavelson et al. 2005).

Concept maps are diagrams that constitute a visual representation of the relationships between concepts and the framework of an individual's ideas within a given topic (Novak 1990). They are a useful means of identifying the components of an individual's knowledge (Hay 2007), since they reflect the semantic networks connected to the knowledge perceived, accumulated and constructed by learners (Hung et al. 2012; Wu et al. 2012). In other words, the concept map is a structure that provides a visual representation of a student's internal knowledge and thoughts (Novak and Gowin 1984; Novak 1990; Mintzes et al. 2000).

Novak (1993) examined several methods of externalizing students' knowledge, and concluded that concept maps tend to make the structure of a body of knowledge much more salient than other forms of knowledge representation for human users. While it is important to recognize that they are only *partial* depictions of students' cognitive structures, concept maps can nevertheless serve as useful tools for eliciting students' mental models. Based upon the similarities between mental models and concept maps, there is evidence to justify the adoption of concept maps as an accessible, external means of examining and understanding students' mental models.

Concept maps have already been used in a number of previous studies as a means of examining students' knowledge of complex systems. Several studies have used them as a means of externalizing and assessing students' mental models of abstract concepts, like the hierarchy and homeostasis involved in maintaining blood sugar levels in the human body (Chang 2007; Chang and Chiu 2004; Henige 2012). Raved and Yarden (2014) used concept maps to evaluate system thinking competence amongst junior high school students in the context of the circulatory system, and we have employed concept maps to externalize and analyze high school students' mental models of the human body as a system in several studies, using the information they provided about how students think to draw conclusions about their system thinking skills (Ben-Zvi Assaraf et al. 2013; Tripto et al. 2016, 2017). In this study, our use of concept maps allowed us to see how students draw connections between knowledge components and how they organize their mental structure (Novak and Canas 2007).

As representations of students' mental models, concept maps are also a means of identifying and examining the differences in how individual students think. The structure of a concept map reflects the concepts that the individual who made it associated with a given topic, and the relationships that individual sees between them. Each map is, therefore, unique to its author, reflecting his/her experiences, beliefs and biases in addition to his/her understanding of a topic.

In addition to providing a means of comparing the mental models of different students, concept maps can also be used to compare the mental models of the same student at different points in time. This was pointed out by Kinchin et al. (2000), who noted the importance of analyzing sequences of concept maps as a means of identifying developments in the mental models of the student who made them, which would indicate that student's progress in the learning process. They claimed that this tool could be much more sensitive to developmental changes in mental models than other, more traditional methods, which usually rely on question-based, isolated interviews. This strategy, of analyzing and comparing a series of concept maps created by each individual student over time, was adopted in our study as well. Using the concept maps to identify each student's mental model of the human body system at different stages in the learning process allowed us to identify several recurring patterns in the development of our population's understanding of this topic. These patterns show that our students' mental models of the human body system tended to evolve according a one of a handful of possible trajectories.

Methodology

Goals and research question

The goal of this study was to identify and understand how the mental models of high school students develop as they learn about the human body as a complex system. We therefore examined the sequential system model representations (concept maps) of a relatively large sample of students, examining these representations for possible recurring patterns in how the system models changed over time.

Our study therefore asks the question

What sorts of shared patterns emerge from the development of the students' mental models of the human body system over the 3 years of their high school biology education, as reflected in their concept maps?

Research participants

The participants in this study were 67 high school biology majors (25 boys and 42 girls). All of the students studied the same curriculum, since Israel has a centralized education system. The students were gathered from two schools in two different school districts—46 from one school (divided into two classes), and 21 from another. The schools were chosen for their willingness to cooperate with the researchers. All of the students came from similar (mid-to-high) socioeconomic backgrounds, and all had the requisite minimum biology grade required to study for matriculation in biology (80%).

Research setting

This study is part of a larger study, which followed these 67 students through the 3 years of their high school biology education, using a variety of tools throughout the learning process to learn about the development of their system thinking. This part of the study is based on data collected from concept maps, which were created by the students at four stages of the learning process: beginning of 10th grade (stage 1), end of 10th grade (stage 2), end of 11th grade (stage 3) and end of 12th grade (stage 4). In a previous paper, we described our quantitative analysis of these maps, using them to paint a general picture of the system thinking development of the population as a whole (Tripto et al. 2017). Overall, they showed that by the end of the 3-year learning process, the students' system models had become more complex, employing a wider range of concepts and spanning hierarchy levels ranging from the molecular and cellular to the system level. We also found an increase in references to dynamic interactions, but this did not encourage the students to use cellular level processes when explaining phenomena that occur at the systems level.

While the previous paper showed how concept maps could be used to draw general conclusions about all of our study participants as a group, this paper is based upon a series of 67 individual case studies that represent each student's personal story of development. This means that instead of comparing the concept map drawn by one student to the map drawn by another, we compared each individual student *to themselves*. We did this by looking at the four concept maps drawn by each student in relation to each other and using the successive changes in each student's representation of the human body system as evidence of how that student's understanding of the system has evolved.

In this context it is important to note that our focus in this study is *not* on identifying and overcoming students' particular misconceptions, but rather on changes in the *complexity of the system model* they present. Our interpretation of the students' system models is based on Hmelo-Silver and Pfeffer (2004), who showed that the transition from *novice* to *expert* in system thinking is a slow and gradual one, and that a rise in the complexity of a student's system model may be accompanied—as a transitional stage—by the temporary "sacrifice" of some of the model's accuracy. This means that our analysis of the students' concept maps can indicate progress in the complexity of their system model, even when the maps still show evidence of misconceptions. All of the student models presented below show that—whatever progress has been made throughout the 3 years of the study—the student still has much to learn.

The national biology curriculum

The students studied the standard national curriculum for biology majors (see Table 1). To overcome the difficulties of understanding the systemic nature of the human body, a national biology curriculum called "Human Biology: Emphasizing the Role of Homeostasis" was introduced into the Israeli high school education system (Israel Ministry of Education 2015). It was thought that unifying human biology around homeostasis would provide students with a more complete picture of the human body, allowing them to integrate its multiple components. Exploring homeostasis should also enable a deeper understanding of the human body's complexity, as homeostasis explains both the interactions between the body and its environment, and the processes that occur on different organizational levels within the system (Ben-Zvi Assaraf et al. 2013; Tripto et al. 2016, 2017).

The research approach

This study sought to determine the mental system models of the students it examined, as these are reflected in the concept maps they created throughout their 3-year learning process. Though it is a series of individual outcomes, the study was conducted on a relatively large sample of 67. It therefore employed a multiple Case Study approach—a

Table 1 Breakdown of national curriculum for biology majors

Grade	Number of hours per week	Goal	Subjects
10th grade	Three hours	Introduction to human body with an emphasis on homeostasis in the context of the seven human body systems	Vascular system Nervous system Immune system Endocrine system Respiratory system Digestive system Urinary system
11th grade	Six hours	(a) Teaching students about cellular level, which focusses on the structure and function of cells as a unit of life shared by all living things (b) Teaching students about what the curriculum defines as the "society and ecosystem" level, which refers to the interaction between organisms and their environment	The cell Ecological systems
12th grade	Six hours	Two elective subjects selected by the teacher from a list provided by the national curriculum	Nutrition (all three classes in the sample) Evolution (one class) Microorganisms (two classes)

qualitative methodology that provides a comprehensive view of the students' mental system models based on many individual concept maps.

Case study research is a qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time through detailed, in-depth data collection involving multiple sources of information (e.g., observations, interviews, audiovisual material, documents and reports) and reports a case description and case-based themes (Creswell 2007). In this context, it is important to note that this paper is the last in a set of four, which between them summarize a 3-year longitudinal study that used multiple research tools to analyze the system thinking of these 67 students. In addition to concept maps, for instance, we also used repertory grids, as well as metacognitive reflective interviews, in which the students were given explicit guidance in conducting a comparison between their first two concept maps, analyzing their respective contents and reflecting upon what they might have done differently (as described in Tripto et al. 2016, 2017). The information provided by the interviews contributed heavily to the definition of the students' mental models early in the learning process, and some of the data presented here was triangulated with data from each student's interview. Each of the 67 individual students in our study does therefore constitute a separate case, though unfortunately, due to considerations of scope, only one of the multiple sources through which we collected data on these students is presented here.

We used concept mapping to represent the personal mental models of the students in the study, and to compare these models to others from different stages of the learning process (Kinchin 2001). The students' repeated use of the concept map (four maps over 3 years) provided us with a visual representation of their learning (Hay et al. 2008) and with a way to empirically assess the qualitative changes in their understanding (Hay 2007). Analyzing the students' maps allowed us to track the development of their system thinking skills over the 3 years of their high school biology education, and to understand how—and to what extent—the students made sense of the human body's complexity. This in turn helped us as researchers to understand the processes that made it possible for the students to develop higher order system thinking, and to identify recurring patterns in the system thinking development of the entire sample as a group.

Research tools and their analysis

Concept map

As noted by Chang (2007), the concept map is an effective tool for revealing the mental models of students in the context of complex and abstract concepts, like the homeostasis of sugar in the blood. One of the basic assumptions of using concept maps as assessment tools is that learning is reflected by changes in the student's concept map. This assumption is based on the understanding that one map is not sufficient if we wish to assess students' learning. If we wish to see a change in the structure of the students' knowledge, we must follow their learning process by mapping the given topic sequentially over time and examining the changes in the picture created by the connections the students make between ideas (Kinchin 2011).

In light of the fact that transitioning immediately from a blank page to a complete concept map can be daunting and challenging for students, the process of making the concept maps involved three stages. The first two stages served as a *warm-up activity*. First, the students were asked to write 15 concepts that, in their opinion, were associated with the human body. Second, the students were asked to form sentences (at least ten) that draw connections between any two of these concepts (they could use the same concept more than once). Finally, after completing these two stages, the students were asked to make a new concept map about the human body by writing down concepts related to "the human body as a system," drawing connections (or *links*) between them with arrows to indicate directionality, and writing a word/sentence above the arrow to explain how the two concepts connect. It is worth noting that the students in this study had previous experience with concept maps, which were used as a knowledge organization activity in their study of ecology.

Externalizing the students' cognitive structures using concept maps throughout their 3 year learning process provided us with data on the system understanding of each student, which we then analyzed using the System Thinking Hierarchy (STH) model (see below). The STH model provided us with a framework in which to analyze the students' mental system models, and to track the changes in these models over time. Studies have shown that an increase in the number of concepts in the concept map—and in the number of links between concepts—is a reliable parameter for estimating students' system thinking (Ben-Zvi Assaraf and Orion 2005). Moreover, analyzing the patterns in the concepts and links can provide information regarding students' understanding, and their readiness to move on in a particular topic (Kinchin et al. 2000).

Data analysis

The data analysis for this study was conducted in two steps. First, we performed a qualitative inductive analysis (Merriam 2009) on all of the concept maps created by the students *individually*, to identify and characterize the system thinking represented by each. Adopting Ben-Zvi Assaraf et al. (2013) approach, we evaluated the maps according to the number of concepts, the links drawn between them, and their organization within the map. It is important to note that our analysis did not discard concepts or links that were rendered *invalid* because their meaning was vague or unclear. (For example, if a student drew a connecting line between two concepts and marked it with a very general link like "and," "or," "like," or even "?") Scoring only *valid* links risks missing the potential contribution of such *invalid* links; these can sometimes support other, valid links in the students' mental models (sometimes temporarily), and thus contribute to the overall knowledge structure that serves those students as a basis for further learning (Kinchin et al. 2000).

The students' concept maps were analyzed by means of the System Thinking Hierarchy (STH) model for assessing system thinking (Ben-Zvi Assaraf and Orion 2005). This model proposes that the way students think about and understand a system can be categorized

Table 2 Systems thinking hierarchy (STH) model for assessing systems thinking (Ben-Zvi Assaraf and Orion 2005)

Level A: analysis of system components	1. Identifying the components and processes of a system
Level B: synthesis of system components	2. Identifying simple relationships among a system's components 3. Identifying dynamic relationships within the system 4. Organizing the systems' components, processes and their interactions within a framework of relationships
Level C: implementation	5. Identifying matter and energy cycles within a system (not featured here) 6. Recognizing hidden dimensions of the system 7. Making generalizations about a system and identifying patterns 8. Thinking temporally

according to eight hierarchical characteristics or abilities, which can be arranged in ascending order of advancement into three sequential levels, as described in Table 2.

The STH model marks the *milestones* in the students' learning process, as their understanding of systems develops. Each group of skills in the model should serve as the basis for the development of the next higher group of skills (Evagorou et al. 2009), which means that students who do not have the ability to think systemically will remain at the lower levels of the model's hierarchy (Ben-Zvi Assaraf et al. 2013). These milestones can therefore be used as a means of assessing the progress of each individual student, of identifying both the extent and the changing form of their system understanding.

Based on the parameters of the STH model, we used the analysis of the students' concept maps to look for the following system thinking components. First, we looked for their ability to identify the system's components and processes at both micro and macro levels (level A). This was reflected by the number of concepts in their map and the presence of the different human body systems among these concepts. Second, we looked for attributes related to the synthesis level of system thinking (level B). Students' ability to identify dynamic relationships within the system was reflected in the number of linkages in their maps. In this context, *dynamism* was classified within two categories: "matter transportation" (statements that describe the dynamic nature of matter transportation in the system), and "dynamic concepts" (concepts connected by a node that described a process). The students' ability to organize components and place them within a framework of relationships was reflected in the number of junctions (i.e. concepts related to three or more other concepts). Analyzing the map's junctions in this way provides us with a more holistic view of the system as the students perceive it.

The implementation level (level C) was reflected in the concept maps in two ways. The first was students' representation of patterns in the system—namely hierarchy, homeostasis, and dynamism. *Hierarchy* includes statements referring to scale in nature, while emphasizing one scale in relation to another (e.g. "the circulatory system includes capillaries"). *Homeostasis* includes statements that directly and exclusively describe the body's internal stability, as well as additional, associated terms. *Dynamism* here refers to statements that describe the dynamic nature of matter transportation that involves at least two or three systems in the human body. Finally, level C was also indicated by students' references to the time dimension, more specifically, statements describing interactions that will take place in the future (prediction) or have taken place in the past (retrospection). For a full, step by step description of how the concept maps were analyzed and translated into reflections of the students' system thinking within the STH model, see Appendix.

Our analysis also included the qualitative analysis of the links the students made between the concepts in each of their maps. In this study, we adopted Chase's suggestion (2005), according to which each concept map can be translated by the researcher into a verbal description of the human body system, and thus *retold* in narrative form. The connections between concepts were therefore transcribed as statements. For example, the statement "the veins *transfer* blood *from the* heart *to the* body" is composed of four concepts (underlined), which were connected to one another in a student's map by arrows, with words written above the arrows describing the nature of the connection between them (italicized) (many more examples of such statements and their correlation to the students' concept maps appear in the results section). These sentences were then subjected to qualitative content analysis to determine how each map's description of the human body system reflects the various components of the STH model (see Appendix).

When all of the individual concept maps had been analyzed, we moved on to step 2, in which we used our analysis of the contents of each student's four successive concept maps to construct a *story* that describes the development of that student's system thinking over the 3 years of their biology studies. In other words, we conducted a comparative analysis of the four maps in relation to each other, searching for evidence of a coherent trajectory in how that student's system thinking was expressed over time. This trajectory is referred to in our paper as a *learning pattern.*

A *pattern* in a student's system thinking was defined, for the purpose of this study, by the presence of coherent connections between all four concept maps generated by each student. These connections are formed by the consistent presence in all four maps of an emphasis on a particular aspect of systems (e.g., on a system's structures, on cellular-level components and processes, or on homeostasis). Each pattern thus takes the form of a gradual change in the student's treatment of this prominent aspect that forms a visible trajectory between the student's first and final map (e.g., supplementing the emphasis on structures with references to processes, gradually increasing the complexity of representations of homeostasis, etc.). We found that all 67 students' understanding of systems tended to develop according to one of seven such patterns, which recurred amongst multiple students. For a detailed account of each of the seven patterns and its progression throughout the learning process, see Table 3.

Of these seven, the four most prominent are described more fully in the results section, using four representative students as examples. These four students were chosen to represent their patterns based on two central considerations. First, the progression in their concept maps was similar to the progression in the concept maps of other students associated with the same pattern, and could therefore serve as a useful representative example. Second, these students were particularly eloquent and cooperative in responding to the interviews and various other tools employed in the larger study of which this paper is a part. As a result, they provided us with a great deal of data with which to triangulate the data from their maps and supplement our understanding of their perception of the human body system.

The following steps were taken to ensure the objectivity, reliability and validity of the study. First, the maps were analyzed using the theoretical framework of the STH model, the components of which served as standard *units* for the concept map analysis (see Appendix). Second, the analysis was conducted as a collaborative social interaction over time (Clandinin and Connelly 2000), with the combined efforts of three researchers in the field of science education that were not involved in carrying out the research itself. The concept maps were read repeatedly, with the STH model serving to guide the reading and the analysis towards the formation of a series of stories, each based on the set of four concept maps generated by an individual student. For each of the students, each researcher generated a story that describes their personal system model. Next, the *stories* of the different students were compared and contrasted, in an effort to identify recurring learning patterns. In the final stage of this analysis, stories that recurred amongst different students were gathered into categories based on the maps' prominent characteristics, such as "emphasis on interactions," "emphasis on homeostasis as an indication of human body's complexity" (see Table 4). The participants in the concept map analysis discussed their conclusions until a consensus was reached that there were seven recurring patterns in the stories of learning told by the concept map sequences of the various students. Four of these recurred more often, so they are the ones presented here—each represented by one student. These four students were chosen because of their strong verbal skills, and because their stories most clearly and effectively represented their respective patterns.

Internal validity was established at the mapping stage of the analysis. The primary and sub-categorization was debated and agreed upon by the researcher and two additional

Table 3 Detailed characterization and development of the seven learning patterns

Pattern	10th grade	11th grade	12th grade
Structure to process	This pattern is characterized by a structural system model, expressed in the concept maps by descriptions of the various structures that make up the human body system (e.g. systems and the components of which they are constructed). Most of the detail in these maps consisted of "macro organs" like "brain" and "heart"	The students' introduction to the cellular level made it possible for their maps to transition to the micro level, with concepts like "nephrons," which were noted as components in the urinary system. Improvements were expressed in the maps' description of processes, while continuing to clearly emphasize the structural aspects of the human body system. The processes were described in connection to the structure in which they exist. Thus, for instance, references to matter transfer in the context of cells were expressed in statements like "matter absorption takes place in the small intestine" or "metabolism takes place in the pulmonary alveoli"	Even at the end of the learning process, these students continued to emphasize structure at the macro level, while improving their references to the micro level. They continued to connect processes with the place where they occur, with statements like: "gas exchange takes place in the pulmonary alveoli." The processes positive/negative feedback, which represent a higher level of sophistication, were also associated with structure, in statements like: "positive/negative feedback takes place in the ovaries" At the end of the process, these students still did not present system aspects of the human body, like connections between different systems in the body, despite the fact that many systems were noted in their maps
Macro to micro	Students who expressed this learning pattern emphasized these two hierarchy levels in their understanding of the human body's complexity as a system. Their maps showed a strong emphasis on macro level structures, such as "lungs" and "veins," and fewer references to the micro level (e.g. "red blood cells" and "plasma")	The students showed a marked improvement in their systems understanding in terms of the relationship between micro and macro. They transitioned from identifying components at the macro level to identifying components and processes at the cellular level. For these students, the subject of the cell as a basic unit of life served as a bridge between the structure and the process levels. This was expressed through more complex, micro-level aspects of the system (e.g. cell nucleus," "proteins," "RNA") and structures that encouraged them to refer to cellular level processes, like "mitosis as a process that occurs in cells and causes differentiation in gametes"	The transition from components at the macro level to components and processes at the cellular level continued to be expressed at the end of the learning process. The micro level was emphasized by the expression of microscopic structures like "cell membrane," and particularly by micro-level processes ("active transfer through the cell membrane," "glycolysis as a stage in the cellular respiration process"). Despite this improvement, there were still no references to homeostasis and its mechanisms

Table 3 continued

Pattern	10th grade	11th grade	12th grade
Cell to organism	A pattern in which the system's complexity is measured by representing the cellular level, and transitioning to the level of the organism as a whole. The micro level was already clearly present at the beginning of the learning process, in concepts like "mitochondria" and "ribosomes"	As in the previous stage, these students emphasized the micro level in great detail. The cellular level was reflected in concepts like, "white blood cells" and "platelets" and the molecular level in concepts like, "amino acids" and "DNA." These students also addressed dynamic processes like "hormone secretion from the pancreas," "transfer of mRNA to ribosomes." Homeostasis was noted as occurring in the body, but with no explanation	Using the micro level as a starting point allowed it to serve as a "springboard" for improving these students' ability to see the organism as a whole. At the end of the learning process, they presented system aspects like homeostasis and its characteristics as a means of describing the organisms as a whole ("homeostasis is maintained through processes of regulation and control") and as an expression of the biological principles learned in connection with homeostasis ("surface area to volume ratio is maintained in the digestive system, which allows matter to be more effectively absorbed into the blood") Nevertheless, these students did not represent connections between systems and the complex mechanisms of homeostasis
Development in complexity of homeostasis mechanisms	This system model is characterized by the integration of information about structures, processes and interactions, at the various levels of hierarchy. For example, the topic of matter transfer into cells, as one of the tasks of the circulatory system, encouraged these students to express the dynamic: "food is broken down into basic elements in the digestive system"	These students enhanced their expression of the human body system's complexity by presenting homeostasis and the measures that make the its maintenance possible in the human body (e.g. "temperature," "PH," "matter concentration" and "the specific structure of the enzymes")	Improvement in these students was expressed through the description of the mechanisms of homeostasis using different aspects of the pattern, to which they had referred earlier in the learning process. Temperature regulation, for instance, was expressed by statements like, "rising body temperature is a disruption of homeostasis." Students who followed this learning pattern did not stop at such descriptions, but also presented the mechanism for correcting this disruption, "when body temperature rises, the peripheral blood vessels expand, causing a large loss of heat and a return to homeostasis." Nevertheless, these students did not make connections between systems

Table 3 continued

Pattern	10th grade	11th grade	12th grade
Development in complexity of dynamic interactions	One of the characteristics of the human body as a biological system is the interactions that exist between its various components, at both the macro and the micro levels. Students with this thinking pattern represented interactions on two levels: simple interactions (between different components in the body, "veins carry blood to the heart") and dynamic interactions (which are part of matter transfer and involve micro-level elements like molecules, "blood goes into the lungs and comes out with oxygen for the brain")	Expressions of dynamic interaction increased in relation to references to simple interactions, presenting dynamic processes as expressions of matter transfer: "enzymes help with the process of metabolism," "enzymes help make energy in the cells"	These students showed visible improvement in the emphasis on dynamic interactions as expressions of two directional matter transfer: "oxygen from the lungs is absorbed in the blood and CO^2 in the opposite direction from the lungs," "oxygen from the lungs is used for cellular respiration in the mitochondria." They also showed an understanding of dynamic interactions at the level of the organism as a whole by presenting the influence of enzymes in maintaining homeostasis: "enzymes that help break down food in the stomach help maintain homeostasis." Despite extensive references to interactions that express matter transfer, the students very rarely used this aspect to draw connections between systems
Development in interaction between systems	Students who adopted this pattern made sure to express the cooperation between the various systems that make up the human body. For example, they described the dynamism of the system as a whole by connecting systems: "building blocks are brought to the circulatory system by means of the digestive system"	The students expanded their maps by presenting additional body systems and addressing additional aspects. Thus, for instance, in the context of the circulatory system as a system that connects different parts of the body and transfers materials between them: "oxygen is transferred to the brain by means of the circulatory system"	The students' maps showed their improved understanding of the connection between systems by acknowledging the importance of the systems at the level of the organism as a whole: "the circulatory system maintains homeostasis through metabolism," "capillaries as a component in the circulatory system transfer matter to the cells in a process of metabolism, thus maintaining homeostasis." The end of the learning process showed no significant improvement in expression of homeostasis mechanisms, only expressions of the connection between systems at the organism level

Table 3 continued

Pattern	10th grade	11th grade	12th grade
System to entire organism	These students were already using the various hierarchy levels in the human body system as part of their repertoire at the start of the learning process. They chose to represent the complexity of the human body by focusing on one or two of its systems and describing their organizational levels. The macro level was expressed primarily through macro organs ("heart," "arteries"), while the macro level included concepts like "plasma" and "blood cells"	The cellular aspect that is studied in this year helped these students emphasize the micro/cellular level, using concepts like "nerve cells," "synapse cells". It also helped them address processes at the micro level, including dynamic processes that include matter transfer in the nervous system ("chemical transfer," "electrical transfer that takes place in the synapse cells")	Improvement was expressed in the students' emphasis on dynamic processes, like "matter absorption that takes place in the liver," and in references to how homeostasis is maintained in each of the systems on the map (for example, "folds in the brain maintain homeostasis in the nervous system," "homeostasis is maintained in the respiratory system by surface area to volume ratio in the bronchi and the alveoli") References to homeostasis as a pattern in the human body were at the level of the phenomenon, and did not address the mechanisms underlying it. Moreover, though the different human body systems were detailed separately, no connections were drawn between them to express how the entire human body system functions as a whole

Table 4 The system characteristics that arose from a narrative analysis of the concept maps

Characteristic	Explanation	Example
Describing the human body as a system[b]	Map emphasizes the organization of the components as a system	The anus is located at the end of the digestive system; the cells are surrounded by a membrane; arteries split off into capillaries
Processes[a]	Map notes the occurrence of various processes in the body	Diffusion; insulin secretion; hormone secretion
Interactions[b]	Map presents the impact of one element on another	The circulatory system supplies matter to the muscular system; the respiratory and circulatory systems work together; the brain gives commands to the organs; the hormonal system affects the brain
Multiple systems as an index for human body's complexity[b]	Map describes systems in human body as index of its complexity as a system	The human body contains a circulatory system; the human body contains a digestive system
Hierarchy as index of human body's complexity[a]	Map presents human body components, emphasizing macro level	Sorting concepts by organ, like: lung, brain and arteries; and by systems like: respiratory, nervous, circulatory
	Map presents human body components, emphasizing micro level	Sorting concepts by cellular level, like: cell, nucleus. Sorting concepts by molecule, like: oxygen and carbon dioxide, hemoglobin
Dynamism as index of human body's complexity[b]	Map presents interactions that include matter transfer	The circulatory system brings oxygen to the lungs; oxygen moves through the cell membrane
Homeostasis as index of human body's complexity[a]	Map presents homeostasis pattern as a component in the internal stability of the human body system	Homeostasis, positive feedback, control regulation and coordination
Homeostasis as index of human body's complexity[b]		The hypothalamus works by negative/positive feedback; negative feedback is responsible for progesterone secretion; an excess of carbon dioxide triggers regulation for reinitializing respiration; metabolism maintains homeostasis

[a]Concept analysis

[b]Analysis of links and conversion to statements

science education researchers. To ensure the trustworthiness of our results, we drafted a comprehensive final report, including contextual information, proper quotations from informants and an explicit conceptual discussion, so other researchers could review the database evidence. The analysis process was also fully documented and preserved, and the final report offered and maintained a chain of evidence. Finally, the analysis of the different STH categories was carried out by the researcher and her advisor separately and simultaneously. The advisor was consulted after each stage to further strengthen the reliability of the results.

Results

The qualitative analysis of the students' *stories* produced seven patterns (see Table 3 and Fig. 1). Of the 67 students in our study, 39 expressed learning patterns in which the student's progress is revealed through a gradual change in emphasis that shifts from one of the human body's organizational levels to another. These patterns are: the cellular level to organism level pattern (20 students), the macro level to micro level pattern (14 students), and the system level to organism level pattern (five students). A second group of patterns consisted of transitions between an emphasis on the structural elements of the human body system to a fuller description of its processes. These were the structure to process level of the system pattern (eight students), the development in complexity of homeostasis mechanisms pattern (seven students), the development in complexity of dynamic interactions pattern (five students), and the development in interaction between systems pattern (four students). Finally, four of the students in the study generated maps that were inconsistent in their characteristics, and were therefore difficult to associate with a particular pattern.

It is important to note that while all seven patterns reflect a learning trajectory of some sort, they do *not* all reflect learning to the same extent. Thus, for instance, the eight students whose learning followed the "structure to process level of the system" pattern reflect a learning process that did not advance their system thinking as far as some of the others did. While these students did make some progress in their system thinking by shifting their focus from structures to processes, even the more complex processes they described were often still associated with the structure in which they function (for instance, "positive/negative feedback **occurs in** the ovaries, **in** the pituitary gland"). On the other end of the spectrum are the students whose learning followed the "development in complexity of homeostasis mechanisms" pattern. Of the 67 students we studied, only these seven showed mental models that integrate information about structures, processes and interactions at various organizational levels into a sophisticated description of homeostasis. At the end of the learning process, these students did not stop at simply describing the phenomenon of homeostasis; they also presented the complex control mechanisms

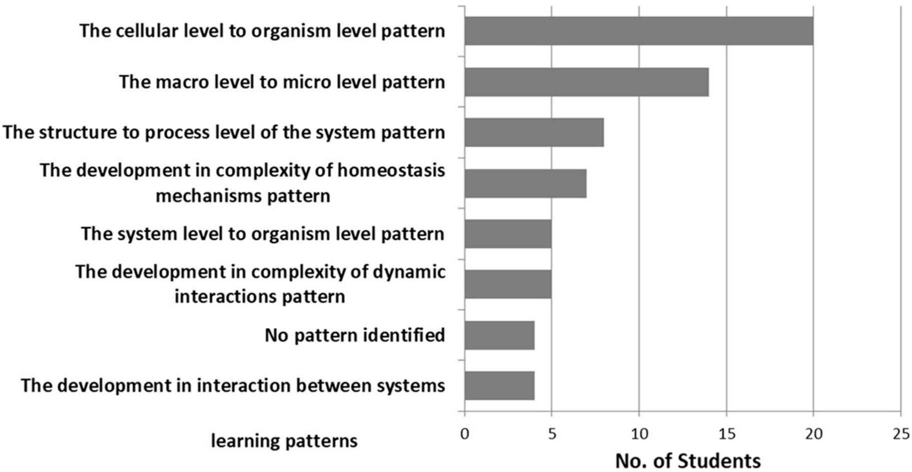

Fig. 1 Distribution of students between learning patterns

involved in maintaining it. Though the students in this learning pattern expressed the highest levels of system thinking, even they drew very few connections between different systems in the human body.

The remainder of the results section presents a detailed description of the four most dominant patterns, each of which is represented through the example of one student. Examples from the students' concept maps are presented below in the form of statements (see data analysis section), but the concepts and links from which they were constructed have been marked (concepts are underlined, and the links between them are *italicized*).

The structure to process level of the system pattern

This pattern, in which students gradually shift from representing the human body system as a series of structures to representing the processes in the system as well, is exemplified here through the case of Dan. Dan began the learning process in 10th grade by learning about seven different human body systems, and the different levels in their hierarchy, with an emphasis on homeostasis. Dan's map from this point includes mostly concepts that address the structural aspect of the human body system, especially at the macro level. The map focusses primarily on structures in the circulatory system, like the concept "blood" in a structural context: "blood is *composed of* red blood cells," "hormones are *located in* the blood." Dan also chooses to provide details about the heart as a component of the circulatory system, and the concept "heart" serves as a junction in his map, with a great many connections to other components that describe how this system is put together. For example: "cells *are located in* the heart," "the upper/lower vena cava is *in* the heart."

At the end of 10th grade, Dan placed a particular emphasis on *junctions* (concepts connected to at least 3 other concepts), taking care to highlight them visually in his map. One of these is "urinary system," which he addresses mostly structurally, and at both levels of hierarchy (e.g. "bladder" and "nephrons"). The more prominent level in Dan's map is the macro level (i.e. "veins," "small intestine" etc.).

Dan's 11th grade concept map (Fig. 2) shows that he is still largely concerned with the structural, creating a map that represents a way of organizing the body's systems. He notes

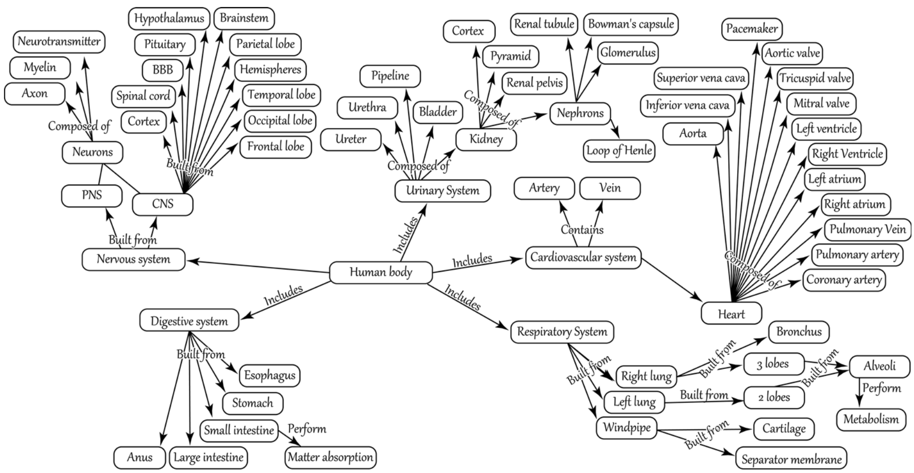

Fig. 2 Dan's concept map from Stage 3

a large number of concepts and makes many connections between them. Content analysis of these concepts and how they are linked to one another by the students showed an emphasis on the structural aspects of the human body system, which are those emphasized strongly in the curriculum. Dan describes five human body systems: respiratory, digestive, nervous, urinary and cardiovascular, making sure to specifically address structural elements in each. For instance, his map notes that the nervous system is "built from" both a "central" and a "peripheral" system (CNS and PNS). Dan offers further details on the central nervous system, addressing how the parts of the system come together using terms like "includes," "is composed of" and "is built from" ("the central nervous system *is built from* hemispheres/brainstem/hypothalamus" etc.). He notes the different structures in the brain in great detail (e.g. "occipital lobe," "frontal lobe," "pituitary") and even notes the blood–brain barrier (BBB) (see Fig. 2). Unlike the maps Dan made in 10th grade, this map also includes processes (matter absorption and metabolism), which are presented in the context of the system structure of which they are a part (e.g. "small intestine *performs* matter absorption," "alveoli *perform* metabolism") (see Fig. 2).

At the end of the learning process, in 12th grade, after having been introduced to different body systems, having studied the cell in depth and learned about reproduction, Dan expanded and elaborated the accuracy and complexity of his references to all the systems he had previously noted in his concept maps. With the exception of the immune system, Dan's final map (Fig. 3) goes into great detail about the body's systems (referencing the "digestive system," "hormonal system," "reproductive system," "respiratory system," "excretory system," "nervous system"), emphasizing their structural aspects at both hierarchy levels (Note: The "hormonal system" in Dan's concept map is a reference to the endocrine system, which Dan associates—as indicated by his word choice—primarily with the secretion of hormones. Similarly, his references to the reproductive system are presented through the concept "gynecology"). Moreover, at this point in the learning process Dan also enhanced his representation of each system's complexity in terms of its processes. For example, in the context of the endocrine system Dan notes the feedback processes that take place in the body: "negative feedback *takes place in* the

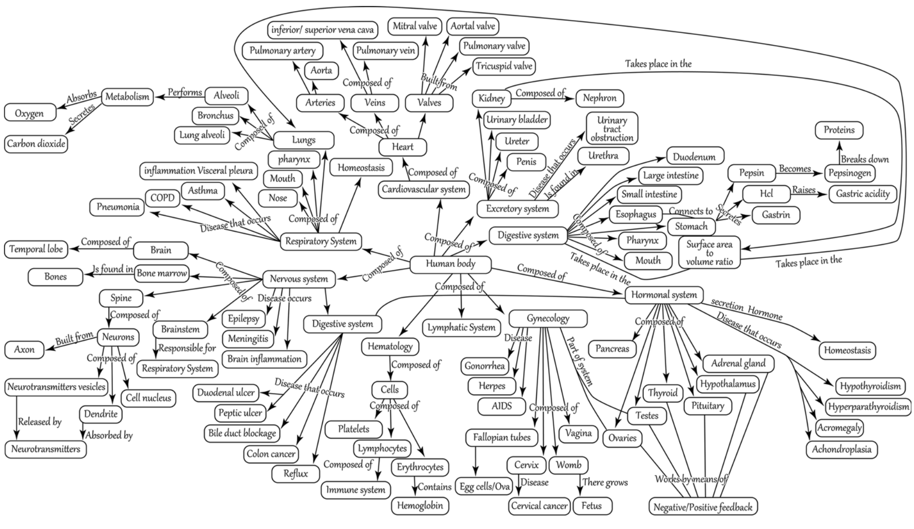

Fig. 3 Dan's concept map from Stage 4

hypothalamus," "negative feedback *takes place in* the ovaries." These processes are related to the central idea of homeostasis, which was emphasized throughout the 3 years of the students' biology studies (see Fig. 3).

In conclusion, Dan is an example of a student whose system model reflects high structural complexity, with an emphasis on the structural aspects of a large number of systems, which expanded as Dan progressed through the learning process to include processes as well. The analysis of Dan's maps presents a learning pattern that traces his transition from thinking structurally about the system, with an emphasis on the macro level, to thinking about the system's processes at the system level. Dan's structural perception of the system remained evident throughout the learning process, but his maps also showed that his understanding of the human body as a system did improve. At the beginning of the process, Dan's map did not express system characteristics, but rather a collection of components. Of the 30 concepts in that map, 16 emphasized the macro level, and the connections Dan made between concepts primarily addressed how components were organized within the system. However, as Dan progressed through 11th grade, his map showed processes that take place on the cellular level (2), such as "alveoli *perform* metabolism". (In his interview, Dan elaborated on this part of his map, explaining that "gas exchange takes place through the membrane of the lung alveoli"). Processes at the system level were still absent, but Dan's structural descriptions were more detailed and accurate, with more references to the micro level (like his identification of the blood brain barrier). After 12th grade, on the other hand, Dan's map showed a development in his system understanding, representing two processes at the system level in the context of homeostasis, and noting feedback processes like "negative feedback takes place in the hypothalamus."

The macro level to micro level pattern

This pattern, in which students start by focusing primarily on the larger and more visible elements of the human body system, but then learn to address its less accessible, micro level elements as well, is exemplified by the series of concept maps created by Tami. Tami's first concept map describes the structural aspects of various body systems, mostly at the macro level (e.g. "stomach," "veins") and without noting the systems' names. Unlike Dan, whose first map linked concepts in terms of their *location*, Tami also draws connections between different components in terms of their function (e.g. "circulatory system *transports* blood" "teeth *grind* food"). But compared to the amount of macro level concepts she uses in this map (22), the micro level components are few (5).

Later in the learning process, towards the end of the subject of "body systems" (end of 10th grade) Tami's second map (Fig. 4) presents six body systems (lymphatic system, digestive system, excretory system, circulatory system, nervous system, respiratory system), shown mainly in their structural aspects and at the macro level (e.g. "the digestive system *includes* the stomach," "the respiratory system *includes* a trachea which *is made of* cartilage"). At this point in the learning process, the micro level is not yet strongly represented, though it is worth noting that the molecular level ("proteins," "carbohydrates," "calcium") is represented in more detail than the cellular level ("red blood cells," "white blood cells"). The former was noted by Tami in connection to the presence of molecules in the blood (e.g. "proteins are *transported in* the blood"). Note: some biologists will argue that concepts such as "proteins," "carbohydrates" etc. should not be considered references to the molecular level if the student has not explicitly used the term "molecules" (e.g., "protein molecules"). We must stress, however, the students' teachers, within

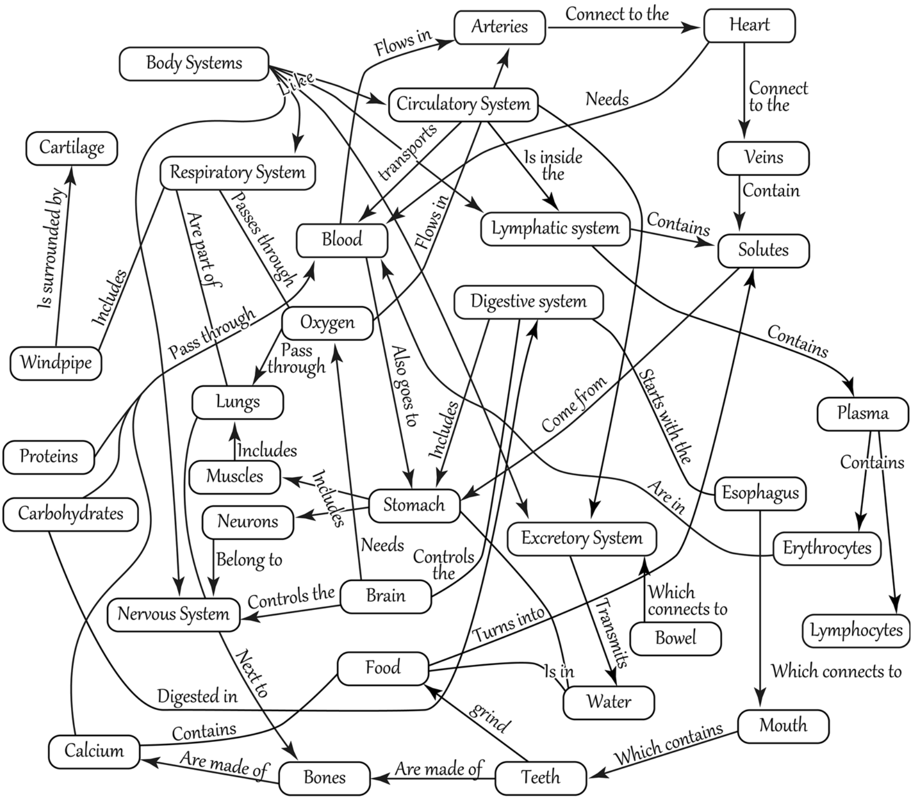

Fig. 4 Tami's concept map from Stage 2

the "shorthand" of their class discourse, allowed them to employ these more general terms, understanding them, in context, as references to the molecular level. We have therefore, based on our familiarity with the students' classroom culture and the supplementary information gleaned from their interviews, adopted a similar assumption.

Tami's third map (11th grade) shows an improvement in her understanding of the structural aspect of the human body system, since it includes details regarding different aspects of the cell (Fig. 5). Tami's understanding of the cell is reflected in the fact that though her third map mentions only three of the six systems mentioned in the previous one (circulatory, respiratory, digestive), these three systems are the basis for detailing different levels of hierarchy—most prominently the micro cellular level ("cells," "nucleus," "cytoplasm"). This map also includes references to processes that take place in the cell ("mitosis, "cellular differentiation"), as well as expanded references to the molecular level, adding concepts like "urea" and "fats." The structural aspect of the microcellular level was also reflected in the links Tami draws between concepts ("cell nucleus *contains* DNA"). She also connects the structural aspect to cellular level processes ("gametes perform meiosis," "cells perform mitosis").

In 12th grade, towards the biology matriculation exam, Tami's map emphasizes the improvement in her understanding of the processes that take place at the microcellular level. In addition to the processes noted in her third map, her final map introduces new micro level processes ("cellular respiration," "glycolysis" and "active transfer"). Tami's

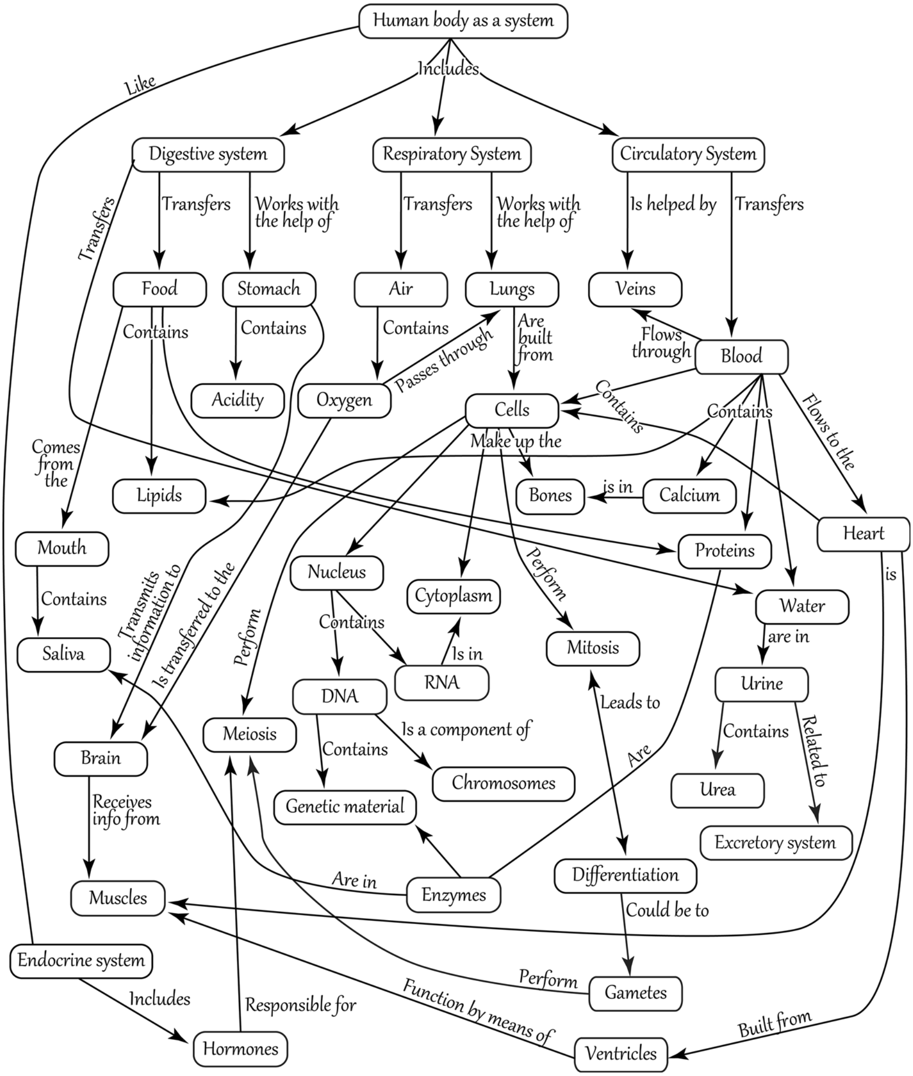

Fig. 5 Tami's concept map from Stage 3

last map shows a change in emphasis from the micro level components noted in her previous map to micro level processes.

In conclusion, Tami began the learning process by emphasizing the macro level of the structural aspect of the human body system. As she progressed, her understanding improved and she began to address the micro level more fully. Analysis of Tami's maps suggests that she has a hierarchical thought pattern: she emphasizes two hierarchy levels when describing the human body as a system. In 10th grade she primarily addressed the more accessible macro level, but her map from 11th grade showed improvement in her understanding and an increase in her references to the hidden micro level. At the end of 10th grade Tami was still emphasizing the macro level when listing the components of the system. Out of the 33 concepts in her map, 15 referred to macro level organs like "stomach" and "intestine," while only eight referred to the micro level (five molecular level concepts and three cellular level concepts). The map from 11th grade, on the other hand, includes microscopic structures that reflect an increased awareness and understanding of the micro level. In the human body this level includes the cellular and molecular levels, which together constitute 44% of the 41 concepts in Tami's 11th grade map (twelve molecular level and six cellular level concepts, for a total of 18), as opposed to 24% of the 33 concepts from the map she made at the end of 10th grade.

The cellular level to organism level pattern

In this pattern, exemplified by Roni, students began by focusing strongly on micro level details of the human body system. This initial grasp of the micro level served as a basis that ultimately allowed them to represent homeostasis at the level of the system as a whole. Roni's map from the beginning of the learning process addresses the structural aspect of the human body system ("veins," "brain"), without noting the names of systems. However, Roni's references to the system's structure emphasize micro level components like "cells" and "mitochondria." Her map also reflects cellular level processes in the links she draws between concepts (e.g. "in the cells *there are* mitochondria, which *make* energy," "nerve cells *transmit orders to* the lungs"). Roni emphasizes her understanding of the cell by making the concept "cells" a junction in her map. Her understanding of the cellular and molecular aspects of the system is reflected in connections like "cells *need* oxygen, which *is needed by* the digestive system." Though Roni mentions homeostasis explicitly through its presence in the digestive system ("homeostasis *takes place in* the digestive system"), this mention is structural rather than functional.

At the end of 10th grade, after learning about the human body system with an emphasis on homeostasis, Roni continues to emphasize and expand upon the micro level. Her second map describes two different cell types in the context of the circulatory system: "white blood cells" and "red blood cells." Here too, the concept "cells" serves as a junction to which she connects various cellular level components ("nucleus," "ribosome," "cell membrane"), while also addressing the molecular level in greater detail ("proteins," "DNA") and the micro-level process of cellular respiration. This junction also connects to the statements "the cell nucleus *is the control center of* the cell" and "the mitochondrion *performs* cellular respiration." These statements imply homeostasis, but Roni still does not explicitly connect them to the concept of homeostasis, which is noted elsewhere on the map.

Roni's 11th grade concept map (Fig. 6) was not significantly different from her previous one. She continued to address and emphasize the micro level, using the central junction "cells" to make connections between the body systems. Thus, for instance, proteins are noted in the context of the cellular structure and connected to the digestive system in which they break down: "ribosome *builds up the* proteins, which *are broken down in* the digestive system." She connects the micro level mitochondrion to the macro level respiratory system through the respiration process that takes place in it, noting in her map that respiration "takes place in" both the "respiratory system," and the "mitochondrion." Roni hints at the translation process that occurs in the cell: "mRNA *moves to* the ribosome," "tRNA *reaches* the ribosome." This map also includes an explicit reference to homeostasis, but here too Roni does not make any connections that indicate a complex systems understanding.

At the end of the process, in 12th grade, Roni replaces the micro level story with a range of aspects that express the systemic nature of the organism as a whole, using different body

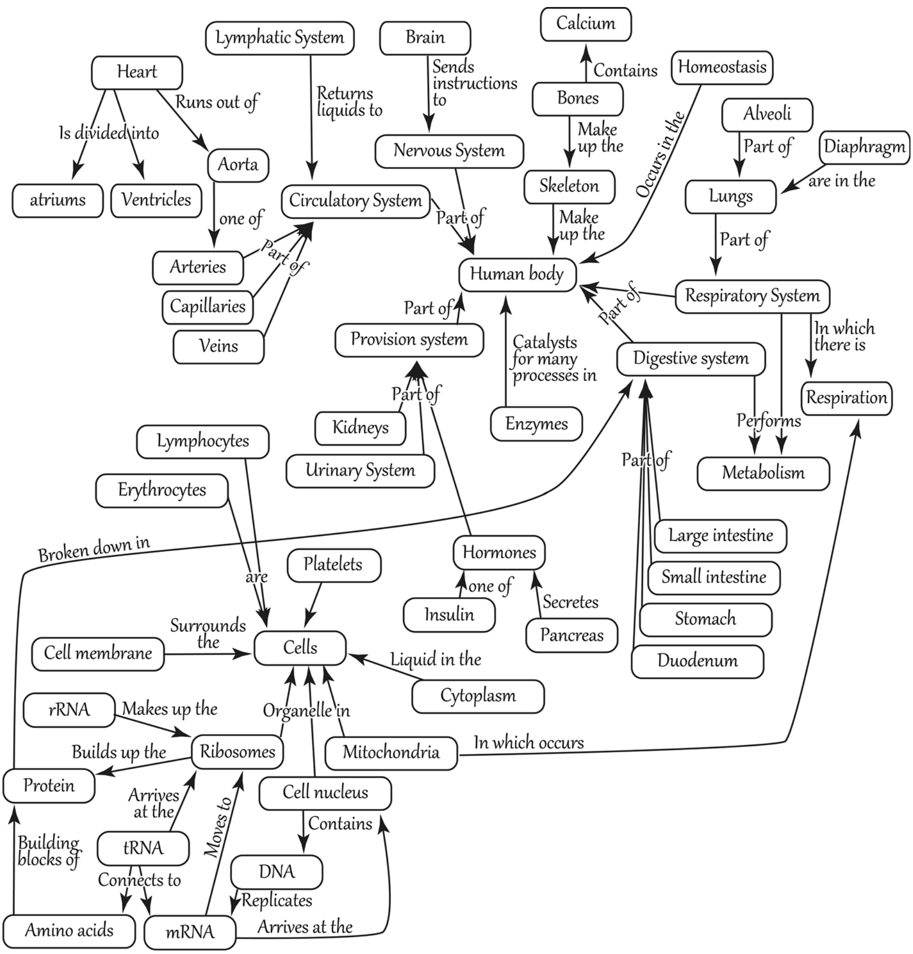

Fig. 6 Roni's concept map from Stage 3

systems as a basis for expressing the human body's complexity (Fig. 7). At this point in the process, Roni had learned about the topic of "nutrition," in which context she presents the digestive system, using it to express the biological principle of "surface area to volume ratio." This principle was learned in the context of homeostasis as what allows the efficient absorption food matter in the digestive system. Another expression of homeostasis is emphasized in this map by the concept "control and regulation processes" and the statement "homeostasis *is maintained by* control and regulatory processes."

Roni presents the systemic nature of the organism as a whole through her references to homeostasis, and through the connections she makes between different systems. She does this in the context of the processes of construction and deconstruction by enzymes in the digestive system, and of hormone secretion, which are part of the control and regulation processes that maintain homeostasis at the organism level.

In conclusion, at the beginning of the learning process, Roni described the human body system structurally and at the micro level. As the learning progressed, she began using more complex concepts—like homeostasis and its characteristics—to describe the

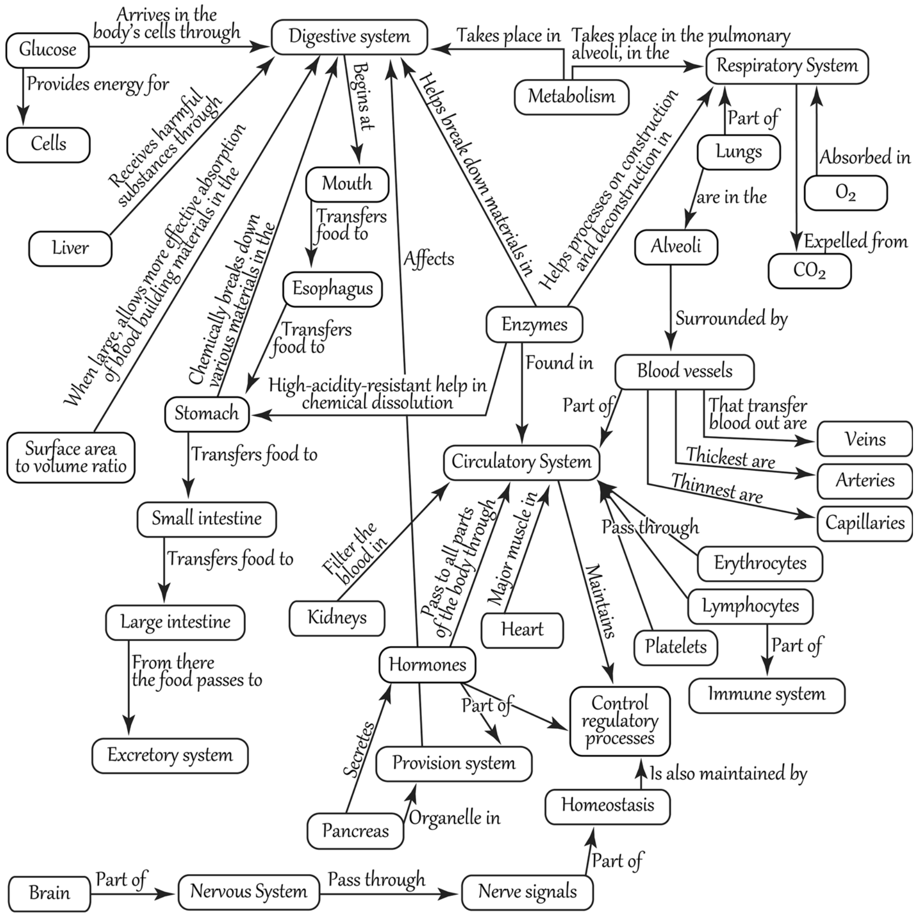

Fig. 7 Roni's concept map from Stage 4

organism as a whole. Throughout the beginning of the learning process (as expressed by the pre and post maps from 10th grade), Roni presented structural aspects of the human body, slightly stressing the micro level over the macro (38% vs. 36%), in the context of the cell, a topic that students are introduced to in 10th grade. Though her 11th grade map expresses the micro level, which requires a high level of abstraction that helps students perceive phenomena from a systems point of view and express the system's complex characteristics, only one of the 55 concepts in the map expresses homeostasis. In 11th grade, a year in which the central topic is the cell as a unit of life, it appears that Roni successfully used the cell as a means to improve her ability to see the organism as a whole. Her map from the end of the process reflected an awareness of system aspects that characterize the organism as a whole. Roni's expression of the micro level dropped by about 10% in the final map, but this seems to have been a drop in favor of an increase in references to homeostasis, indicating an improvement in her systems understanding. Roni's reference to the fact that homeostasis is maintained by processes of regulation and control reflects her understanding that the characteristic *homeostasis* refers to the result, namely to maintaining a stable internal environment through regulation processes that work by feedback. Thus, Roni emphasizes the systemic nature of the organism as a whole, both through her references to homeostasis and through the connections she makes between systems. She makes these connections in the context of the construction and deconstruction processes that take place in the respiratory and digestive systems by means of enzymes and hormone secretion, which are part of the regulation and control processes that maintain homeostasis in the organism as a whole.

The development in complexity of homeostasis mechanisms pattern

In this pattern, represented by Bar's concept maps, the students' first maps already contained explicit references to homeostasis. But while these initial references were relatively simplistic, they became progressively more complex as the learning process went on, particularly in their references to mechanisms of regulation and control. Bar's first map (Fig. 8) already represents a range of interactions that take place in the human body, at varying levels of complexity. For instance, she shows interactions between the component "brain" and different body systems, "the brain *sends instructions to* the respiratory/cardiovascular/nervous system." The map addresses dynamism through references to dynamic processes like "gas exchange," which includes "oxygen reception" and "CO_2 emission." This aspect is explicitly emphasized in the 10th grade curriculum in the context of matter

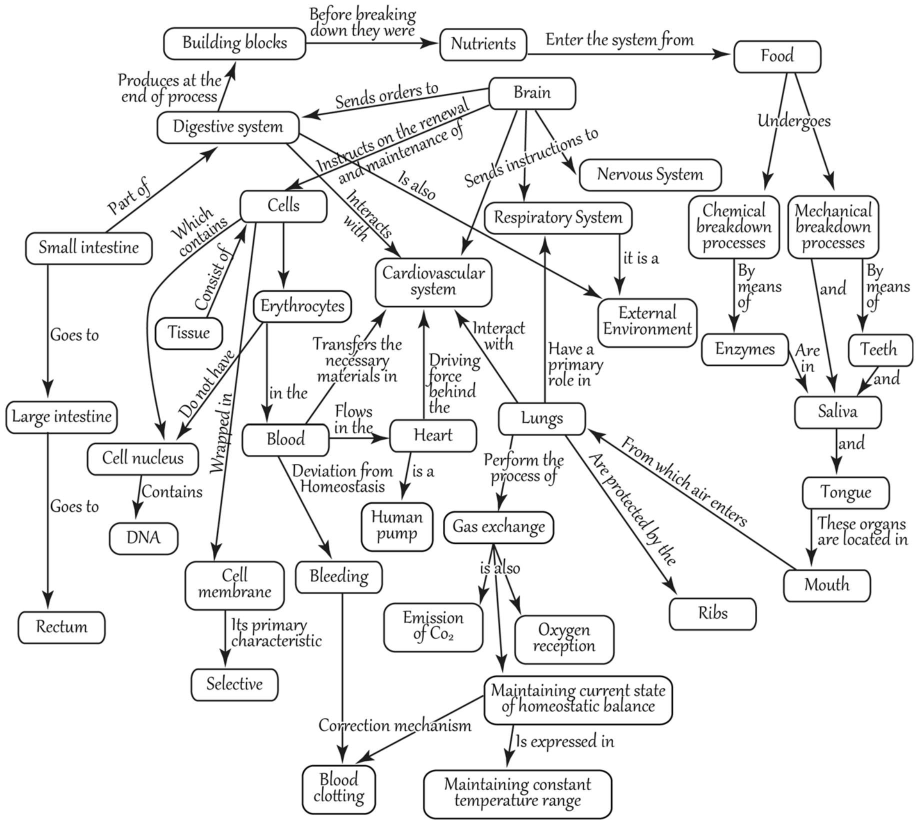

Fig. 8 Bar's concept map from Stage 1

transport, as one of the topics necessary for an overall understanding of the human body system. Bar draws connections between the dynamic process of gas exchange and homeostasis, noting that this is a process that maintains balance and homeostasis. Homeostasis is present in Bar's early map, both as a concept ("maintaining homeostatic balance") and as a connection between concepts ("correction mechanism").

At the end of 10th grade, after having learned about the human body systems based on the central idea of homeostasis, Bar emphasizes interactions, which she presents by drawing explicit connections between systems. For example, "there are *interactions between* the respiratory and circulatory systems." She makes direct connections between the circulatory system and others, noting dynamic interactions like, "plasma *is filtered and cleaned in* the kidney *by millions of* nephrons," "food matter *is broken down into* small molecules *so it can be absorbed in* the plasma." The interactions that take place in the human body, as the curriculum notes, are taught with an emphasis on the biological principle of "increasing surface area to volume ratio." This is expressed in Bar's map in the context of the digestive system, "surface area to volume ratio *increases in the* mouth *to increase contact with* the enzymes in saliva." The 10th grade curriculum also stresses homeostasis. While Bar's map does not yet show this concept directly, it is identifiable in concepts like "negative feedback," "positive feedback," and in links like "negative feedback *orders the creation and secretion of* enzymes" and "positive feedback *orders the creation and secretion of* enzymes *until stabilized*."

The 11th grade curriculum focusses on the cell as the primary unit of life and function in living creatures. It also addresses the shared contribution of cells, which helps the multicellular organism maintain a stable internal environment. The connection between homeostasis and the cell's structure and function is reflected in Bar's 11th grade map through the description of a range of structures and processes related to the cellular level. Thus, for instance, Bar notes that "cellular respiration *takes place in* the cell," adding more specifically that this process "*takes place in* an organelle *called* mitochondria *in order to produce* energy." (Note: though the concept of "energy production" is itself a misconception, our focus here is on Bar's ability to draw connections on the cellular level.) Bar also notes that part of that energy is released in deconstruction processes, and some is invested in construction processes, using the concepts "ATP" and "ADP." Bar connects this topic explicitly to homeostasis, noting that "energy *is produced in order to maintain* homeostasis."

In this map, "homeostasis" is a highly connected junction, which helps Bar describe that pattern through a range of its characteristics ("PH," "matter concentration," "temperature") and connect it to the respiratory and digestive systems that help maintain it. Bar also expands on the idea of adapting structure to function as one of the issues that help maintain homeostasis, noting that "homeostasis *is maintained by the particular structure of* enzymes."

At the end of the learning process, in 12th grade, Bar presents the homeostasis much more explicitly, expanding on the various mechanisms she noted in her 11th grade map (see Fig. 9). Her ability to identify mechanisms indicates a meaningful understanding of the human body as a system. Thus, for instance, Bar notes the duodenum as an organ that participates in maintaining homeostasis in a process of negative feedback, in which it secretes bicarbonate to regulate acidity. In another example, she notes the mechanism of *insulin secretion*, connecting it to a rise in blood glucose levels. Bar also provides examples of situations that can lead to disruptions of homeostasis, noting that low plasma volume and a rising body temperature both constitute a *deviation* from homeostasis. This map reflects a higher level of complexity by expressing the mechanisms that help address

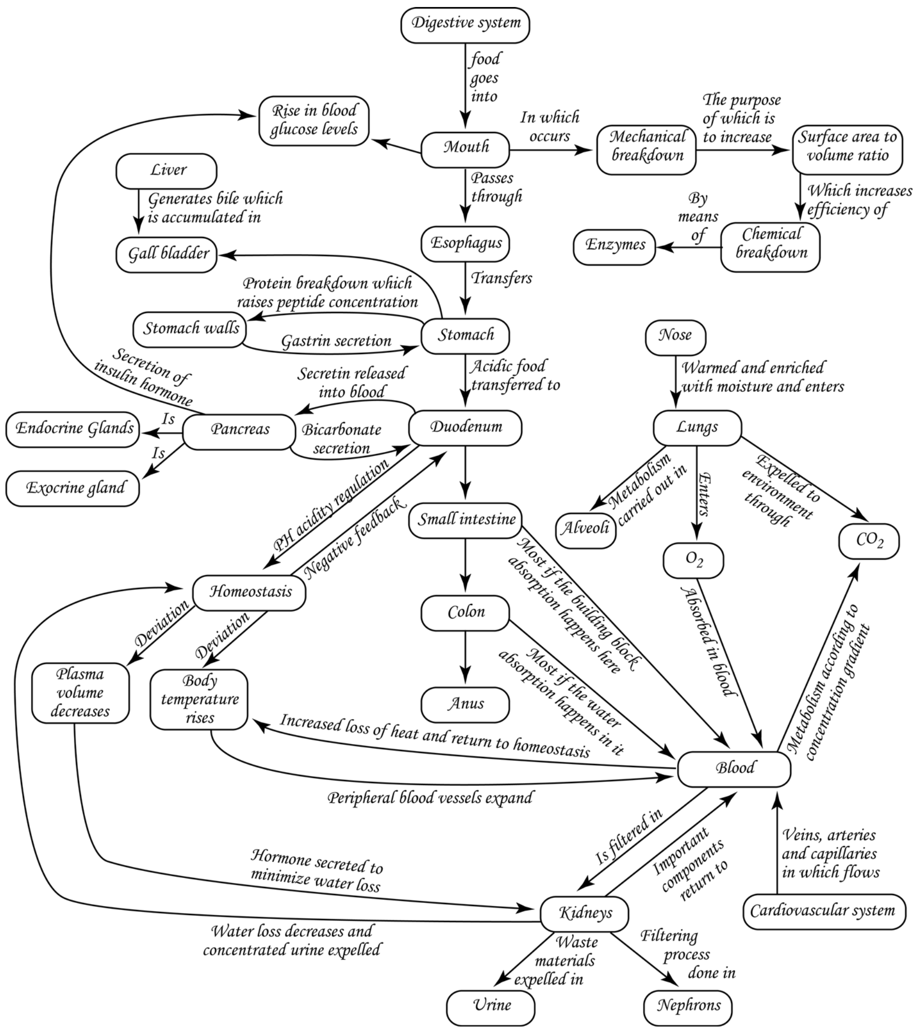

Fig. 9 Bar's concept map from Stage 4

these deviations and maintain homeostasis: "When body temperature rises, the *peripheral blood vessels expand*, which causes an *increased loss of heat and a return to* homeostasis," and when "plasma volume decreases, a *hormone is secreted to minimize water loss* in the kidneys." As a result, *water loss decreases, concentrated urine is expelled*, and plasma volume goes back to normal range, causing a return to homeostasis."

In conclusion: at the end of the learning process, Bar's map shows a high level of complexity, and an enhanced view of the mechanisms that underlie and enable homeostasis in the human body. Bar describes this pattern using various aspects of it, which she also noted at earlier stages of the learning process. Bar's first map already shows a high level of system perspective, which improves greatly as the learning process progresses. Thus, for instance, at the start of the process Bar's map already expresses interactions and the dynamic dimension as complex characteristics of the human body system. Dynamism is expressed in concepts like “gas exchange,” which she uses to describe the hidden dimension in the respiratory system (“oxygen absorption, CO_2 emission”). This is emphasized in the 10th grade curriculum as one of the topics necessary to understanding the human body system as a whole. Bar connects the dynamic process of gas exchange to homeostasis, noting its importance to maintaining balance. At this point in the learning process, Bar does not note homeostasis explicitly, but alludes to it at the system level by noting the need to maintain it (“maintaining temperature within a set range”) and by noting the mechanism for correcting any divergence form it (the mechanism “blood clotting”).

Bar’s expression of the mechanisms of homeostasis improved significantly at the end of the learning process. Her 12th grade map shows the human body with greater complexity, noting aspects that were absent from her 10th grade maps and expanding on others. One of these is the hidden dimension, which is presented in the context of different processes taking place in the digestive system (e.g. “secretin released into blood,” “bicarbonate secretion”) that help maintain homeostasis (11 links out of 37 addressed the hidden dimension, in comparison to just one in the first map).

The expansion of the hidden dimension helped Bar express the homeostasis pattern and present it explicitly, in the context of different mechanisms: the mechanism of insulin secretion following a rise in blood glucose levels, which she notes in the context of the digestive system and the topic of “nutrition,” learned in 12th grade. She notes another mechanism from the circulatory system, “as a result of a rise in body temperature, the peripheral blood vessels expand.” She also describes phenomena that constitute a deviation from homeostasis, like: “low plasma volume” and “high body temperature.” Bar’s last map integrates information about processes and structures at the system’s various hierarchy levels, including the hidden dimension and the dynamism that characterizes complex systems like the human body.

Discussion and conclusions

The goal of this study was to identify the learning patterns employed by students in constructing mental representations of the human body system. A qualitative analysis of the four concept maps created by each student throughout the 3-year learning process allowed us to identify the students’ system thinking skills, as well as typical patterns in the development of their systems understanding. The improvement trajectories of the students in this study were defined according to three central characteristics of complex systems: (a) hierarchy, (b) homeostasis and (c) dynamism. The data from the students’ concept maps was analyzed specifically for references to these elements. Our study revealed seven learning patterns, each of which reflects a different form of development for system thinking.

Applying the framework of the STH model to the data from the concept maps and conducting qualitative analysis allowed us to divide the students’ learning into different patterns, each of which represented a different form of sophisticated system thinking. The sophistication level of that thinking was evaluated based on the students’ references to different system aspects that reflect their understanding of the system as a whole. Kinchin et al. (2000) showed that concept maps can be used as representations of students’ ideas, and of the connections between them. Similarly, our study’s analysis of concept maps produced four principal map models, which we translated into models of the systems thinking of the students who wrote them. Overall, our findings indicated a progression in each of the seven models, throughout the learning process. These models developed over time from simpler structures, which evolved as they connected with more complex system aspects. Nevertheless, it is important to note that this progression in the models' complexity does not by any means mean that any of these learning patterns culminates in a *perfect* understanding of the human body system. On the contrary, each of the patterns presented here reflects a different aspect or emphasis through which it is possible for students' thinking to advance, as well as a different set of obstacles that the student who displays it has yet to overcome.

Dan—from the structure to the process level

For the students who follow this systems thinking pattern, a highly detailed description of the system's components is a measure of its complexity. Students often tend to focus on simple linear relationships in systems, and on easily visible components (Hmelo-Silver et al. 2007; Reiner and Eilam 2001). Thus, in this thinking pattern, the rise in the system model's complexity was expressed by an increase in references to organs on the "micro level." At the beginning of the learning process, different structures that make up the human body system are presented in great detail, including systems and the organs that compose them. The structural aspect in this pattern extends to high levels of detail, like the blood–brain barrier.

Jacobson (2001) claims that it is impossible to understand a system holistically if one approaches its complexity only by noting individual components. Empirical research has shown that while experts represent complex systems in terms of interconnected structures, behaviors and functions, novices tend to understand systems primarily by noting isolated structures, showing only a minimal understanding of the system's functions and behaviors (Hmelo-Silver et al. 2007; Hmelo-Silver and Pfeffer 2004). This novice-level understanding is reflected in the thinking pattern exemplified by Dan's maps.

The development of Dan's systems understanding as his learning progressed was expressed by the appearance of processes as a measure of the human body system's complexity, expressed as a series of naturally occurring actions/changes. At the end of the learning process, in 12th grade, Dan's portrayal of the systemic nature of the human body expanded to include process-based characteristics of homeostasis, like the positive/negative feedback that takes place in structures like the ovaries and the pituitary gland. It also included expressions of the biological principle "surface area to volume ratio," and its contribution to maintaining homeostasis in the human body system as a whole.

As Hmelo-Silver and Azevedo (2006) have noted, teaching approaches often stress the structural aspect of systems and overlook the processes. This structural emphasis may be exacerbating the existing propensities of students who tend to follow this thinking pattern. Hmelo-Silver and Azevedo suggest that students must be *scaffolded* for system thinking if they are to think systemically. For example, adopting an approach that portrays the human body as a single system, composed of many organizational levels and components that interact with one another, could promote students' understanding of biological processes and interactions (Raved and Yarden 2014). Knippels (2002) notes that understanding the connection between the micro and macro levels could help students understand the processes and mechanisms that take place in biological systems. She suggests employing a *yo–yo* strategy as a tool for teaching a complex topic like genetics. This strategy makes an explicit distinction between biological organization levels—from the full-organism level to the micro level, and moves back and forth between the levels making clear, explicit connections between concepts and phenomena at different levels.

Tami—from macro to micro level

Tami's maps represent a second thinking pattern, which addresses the structural aspect of the system at two levels—the macro and the micro—as an expression of the student's understanding of the human body system's complexity. This pattern recalls the findings of researchers in the field of ecology, who noted that while the students in their study did express the micro level, they did not express interactions between the two hierarchy levels, which are necessary for a more sophisticated understanding of an ecological system (Hmelo-Silver et al. 2011).

At the beginning of the learning process, Tami's map was dominated by structures at the macro level. These structures are easy to address because they are visible to the naked eye and their identification does not require a high level of abstraction. As she progressed through the learning process, and—it seems—following the introduction to the cellular aspects of the system, Tami's systems understanding of micro–macro relations improved. Micro-level components and hidden mechanisms are a significant challenge for learners, especially when they are not presented to them explicitly (Chi et al. 1994; Hmelo-Silver et al. 2007). Connections between the micro and macro levels must be incorporated into teaching and learning processes by explicitly moving back and forth between different levels of hierarchy, rather than teaching them separately from one another (Knippels 2002; Verhoeff et al. 2008). This could help contribute to students' meaningful learning of both the cellular level and the systems level (i.e., the level of the organism as a whole).

It is worth noting that for students like Tami, the subject of the cell as a basic unit of life serves as a bridge to more complex systems thinking. Learning this topic provides students with a systems language that encourages them to express more complex aspects of the system—at the micro level, which includes microscopic structures and molecules. The cellular level structures represented by the students encouraged them to address cellular level processes as well, like: "mitosis as a process that occurs in cells and causes cell division." The transition from describing macro level components to cellular level components and processes represents the significant improvement that occurred and the development in these students' systems understanding.

Despite this transition from macro to micro, Tami's final map is still lacking in vertical connections *between* the two levels of the human body system. The ability to see the interactions between the biological hierarchy levels and the mutual influence and interaction of various components is necessary to biological understanding (Lin and Hu 2003). One approach that seeks to promote thinking that would allow students to consider multiple interaction components and their fates is that of encouraging students to engage in Structure-Behavior-Function (SBF) thinking (Hmelo-Silver et al. 2007; Goel et al. 2009). SBF thinking provides a language through which students can both think about and describe the levels within the complex ecosystem: *structures* refer to the elements or components of a system, *behaviors* refer to the mechanisms within a system, and *functions* refer to outcomes or roles in a system. For example, the diaphragm would be one of the structures of the human respiratory system. The contracting and relaxing mechanism is an example of the behavior of the diaphragm. The function of the diaphragm is to create an air pressure differential inside the thoracic cavity so that the air can move in and out (Liu and Hmelo-Silver 2009).

SBF representation extends form and function analysis to account for both natural and designed systems (Hmelo-Silver et al. 2007). Because this representation differentiates function and behavior, it can help learners focus on explanatory mechanisms as part of constructing their understanding of systems. Furthermore, thinking about elements within a system using the SBF framework can also make micro level phenomena become more salient. The function-centered SBF conceptual representation is therefore a powerful way to promote complex systems understanding by engaging students in learning about functions and behaviors, particularly at the nonsalient level (Liu and Hmelo-Silver 2009).

With the goal of supporting learning about ecological systems, Hmelo-Silver et al. (2017) used modeling and simulations with a conceptual representation that they termed Components, Mechanisms, and Phenomenon (CMP), which they modified from the SBF conceptual framework. The students were required to represent a complex system around a particular phenomenon (P) that was posed as a problem to motivate students' learning. This encouraged the students to recall mechanisms (M) that may result in the phenomenon, and present the components (C) that interact to result in the mechanisms and phenomena.

Hmelo-Silver et al.'s study used the CMP model in conjunction with a curriculum that used critical questions, so the learners were encouraged to find and generate evidence in support of mechanistic explanations. The mechanisms in the study were made visible to students using simulations, so they could examine their ideas about the interactions in the system. Its results showed that the students who learned in this manner improved their ability to explain phenomena by referring to mechanisms. Moreover, it appeared that using CMP as a means of representation gave the students a useful way of organizing and investigating the components involved in the mechanisms. Thus, the study showed that providing students with an explicit mental framework through an intervention that specifically targets thinking about system relations can help them to see more than one link between the mechanism and the component, and promote their systems understanding. We believe such an approach can be adapted to include questions concerning the human body system, and used to improve students' understanding of its systemic nature.

Roni—from the cellular level to the organism level

Homeostasis is one of the central ideas of the high school biology curriculum. In 10th grade, it is learned at the level of the whole organism—the macro level. Later, students are introduced to additional organization levels—the cellular and molecular levels (i.e. micro). This principle is the basis for explaining many phenomena and processes at different organizational levels: molecular, cellular, tissue, organ and full organism. The third thinking pattern that arose from our study is a model in which the system's complexity is measured by a transition from representations at the cellular level to representations of the organism as a whole.

Understanding a system means understanding the "concept of levels" (Wilensky and Resnick 1999, pp. 17, 18), with the whole system representing the highest level that must be understood. For students who fit this pattern, the ability to represent the microscopic level, including any cellular structures that are present in their vocabulary, is a measure of the complexity of their mental system model at the very start of the learning process. This high starting level of micro-level representation served these students well as a springboard for improving their ability to see the organism as a whole, and to express their awareness of homeostasis and its characteristics as system characteristics of the entire organism at the end of the learning process.

The expressions of homeostasis as a characteristic of the whole organism consisted of examples in the concept maps, which emphasized the connection between different systems and their involvement in maintaining homeostasis. They also included references to the biological principle of "surface area to volume ratio" as an element that allows the body to maintain a stable internal environment in changing environmental conditions. Homeostasis is an example of a complex, abstract topic, which is difficult to teach and to learn and which requires higher levels of systems thinking skills (Boersma et al. 2011; Ben-Zvi Assaraf et al. 2013; Verhoeff et al. 2008). For the students who exhibited this pattern, learning about homeostasis early in the learning process encouraged them to address the more abstract levels of the system and helped them to see the system as a coherent whole.

Studies have shown that the explicit approach can help foster and strengthen students' holistic perspective. Providing students with an explicit a mental framework through intervention targeting thinking about system relations can help them see more than one link between the mechanism and the part (Jordan et al. 2013). This approach explicitly encourages students to look at the complex aspects that express the human body's systemic nature. In this context, Tripto et al. (2016) showed that a meta-cognitive approach to teaching the human body, using a reflective interview that explicitly encourages students to use systems language, was effective in improving high school biology students' systems thinking and learning processes.

Another study has shown that explicit teaching helped students draw connections between different topics in biology, specifically between genetics and evolution, a connection that requires students to understand the connection between interactions at the level of genes and molecules and their manifestations at the organism level (Tsui and Treagust 2013). Explicit teaching has been recommended by both Kalinowski et al. (2010) and Bray-Speth et al. (2014) to address students' difficulty in connecting the molecular level to the level of the evolutionary phenomenon. These researchers recommend explicitly integrating different levels of biological organization and the connections between them, so as to emphasize the links between genetics and evolution.

Bar—development in complexity of homeostasis mechanisms

The fourth pattern represents the most complex thinking model, and reflects a development in the complexity of the homeostasis mechanisms described by the student. One of the ideas described in detail in the biology curriculum is that homeostasis is maintained in the body through mechanisms of control and feedback, which help its various systems work harmoniously together. The initial mental model presented by the students who fit this pattern was marked by an integration of information about processes and structures at various organizational levels, taking note of the interactions, hidden dimensions and dynamism that characterize the human body as a full, complex system. For example, the topic of transporting matter to the cells as part of the role of circulatory system encouraged the students to express dynamism: "food is broken down into basic components in the digestive system."

As the learning process progressed, the students' expressions of the system's complexity became more sophisticated, as reflected in descriptions of homeostasis and the underlying mechanisms that make it possible in the human body. The improvement is expressed in how the mechanisms are described, addressing various aspects of the homeostasis that were introduced throughout the learning process. The biology curriculum details examples of functional homeostasis, as well as examples of how it could be disrupted, like “rising body temperature is a disruption of homeostasis”. The students who adopted this model did not stop at describing disruptions, adding the mechanism that corrects the problem as well, “when body temperature rises, the peripheral blood vessels expand, causing a massive drop in temperature and a return to homeostasis.” The complexity of the system was reflected in their maps’ concepts, and in the statements that connected the concepts to one another.

This pattern could perhaps be further developed by exposing students to the hidden, micro level organization of homeostasis. Addressing two levels of biological organization could push the students to achieve higher levels of knowledge about homeostasis, and an overall meaningful understanding of the system as a whole. Thus, for instance, Zion and Klein (2015) showed the contribution of the Lac Operon model to the development of an integrated perception of homeostasis on both organization levels (micro and macro). Boersma et al. (2011) noted that understanding complex biological systems like organisms requires thinking that is considered “higher order,” and that the thinking skills necessary to understand an idea like homeostasis can be fostered through meta-cognitive guidance. The development of students’ meta-cognitive awareness is crucial, and can help them learn about complex systems and understand the systemic nature of homeostasis (Schraw and Dennison 1994).

Pedagogical significance of identifying students’ learning patterns

The results of this study show that the development of different students’ system thinking can manifest in different ways. This means that to teach different students about complex systems, we as teachers must be able to adapt to these students’ varying needs. The thinking patterns identified in this study provided specific insights about how different students’ system thinking develops as they progress through the high school biology learning process.

Being able to identify and assess our students’ thinking patterns in this manner can provide us as educators with opportunities to present biological systems to them in ways that improve their skills, develop their meta-cognition, and help them apply and adapt their mental models in new contexts (Dauer et al. 2013). Knowing how students organize, store and make use of their biological knowledge can help teachers design teaching that fosters the development of strong cognitive structures throughout the learning process (Dauer and Long 2015). These structures will serve students as a foundation upon which to build a broader base of biological knowledge (Dauer et al. 2013).

Our study demonstrated the uses of the concept map as a means of discovering students’ learning patterns over time. The succession of concept maps provided by each of the students in our study provided us with a series of *learning progressions* with which to trace the development of their system thinking. Learning progressions are defined as sequences of ordered descriptions that illustrate the learning pathways students can take to improve conceptual competence in science (Alonzo and Steedle 2009). These ordered descriptions can provide a research-informed framework for structuring the learning of core scientific ideas (NRC 2007). The ability to identify progress in learning can serve as the first step in the creation of formative assessment, influence future teaching and learning decisions, and provide students with more focused and productive feedback. To best represent and assess student thinking, such learning progressions must be examined as part of long-term research, so as to gain as extensive a view as possible of how students' learning progresses and how their thinking develops over time (Alonzo and Steedle 2009).

Limitations of the study

Our study was marked by a number of noteworthy limitations. First, our choice of participants in the research was not random, but rather based on the schools' and the students' consent. The participants of the study therefore do not faithfully represent the total population of Israeli pupils, which limits the extent to which the results can be generalizable. Second, this study began by gathering data from 280 10th grade biology majors in four different schools. After 10th grade and throughout 11th grade, many students left the biology matriculation path, or chose not to participate in the study. As a result, the sample dropped to 67, which, while still quite large, is much smaller than the initial hoped-for sample.

Finally, while concept maps have been found to be a useful and reliable tool for characterizing students' system thinking, they have some limitations as well. In our study, we found it useful to supplement the creation of the concept maps with interviews. This made it possible for students to orally clarify areas in their maps where they either neglected or struggled to define the connection between two concepts in writing within the confines of the map's requirements (for instance, where a link was not marked with a directional arrow, or where a link was present, but no explanatory text was written above it).

More specifically, the particular structure of the concept map makes it unsuited to representing phenomena connected to the time dimension, the understanding of which is one of the markers of the highest level of system thinking. Understanding homeostasis requires several cognitive abilities, such as discerning that multiple phenomena occur simultaneously and comprehending that every process is comprised of several stages. However, concept maps are not necessarily a useful means of revealing the temporal aspects of this pattern, because it cannot be expressed through statements derived from the combination of only two concepts. Thinking temporally is based on the ability to make predictions, and to think retrospectively. This level of thinking requires an awareness of interactions upon a timeline, and an understanding of how processes develop over time. Concept maps are not well suited to representing this particular ability either, so accurately assessing and representing requires the use of additional narrative qualitative research tools such as interviews.

To compensate for the concept map's limitations, the researchers were present with the students as they created the concept maps. This allowed them to answer questions and to ask for clarifications when these were deemed necessary. Methodologically, this means that the concept map—though it can be used to elicit a great deal of information about students' system thinking –cannot be used *exclusively* to fully identify and characterize students' mental models.

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Appendix

Correlation between Concept Maps and the STH Model

Below is a step-by-step description of how concept maps can be read as indicators of system thinking, based on the correlation of their contents to the STH model. The description is divided according to the model's three basic levels, and further subdivided into the model's eight individual characteristics.

Level A: Analysis of System Components

Characteristic #1: *Identifying components and processes in the human body system.* Characterizing system thinking at the components and processes level requires the following steps:

(1) Selecting a suitable characteristic into which all the concepts written by the student may be pooled. In this study we chose *hierarchy in nature*.
(2) Dividing this master-characteristic into the categories—*Structure* and *Process*
(3) Further dividing each of these into the sub-categories of *Microscopic* and *Macroscopic* levels.
(4) Sorting the concepts written by the students into each of the categories now present under the master-characteristic *hierarchy in nature*.
(5) Counting all of the concepts provided by the student to arrive at an overall number of concepts.
(6) Counting the number of concepts in each category.
(7) Calculating distributions for the estimation of the student's relative ability to represent system components vs. system processes.

For a more thorough insight into the student's treatment of components vs. processes, the maps should also be analyzed according to the connections the student has made between the concepts. This necessitates the following:

(a) Counting all the connections made by the student. A connection is a word describing a connection between two concepts. For instance: The veins *transfer* blood *from the* heart *to the* body. The italicizes words represent the connections drawn between the (underlined) concepts.
(b) Analyzing the contents of the connections to derive statements. "*Veins transfer blood from the heart to the body*".
(c) Sorting the resulting statements and removing those that are irrelevant to the study topic.
(d) Sorting the statements into process/non-process related. A process-related statement refers to a string of actions or changes that are assigned a certain order within a gradual development. On the other hand, a merely descriptive statement would refer statically to an object's state or appearance.
(e) Calculating distributions to compare process/non-process oriented statements.

Level B: Synthesis of System Components

Characteristic #2: *Identifying simple relationships between system components.* Evidence in concept maps of relationships between system components can be gathered by identifying both the concepts in a student's body of knowledge, and the manner of their organization into meaningful connections. To do this one must:

(a) Analyze the connections and translate them into statements.
(b) Identify statements that address relationships between components (*i.e.* statements that address the effect of element 'x' upon element "y").

Characteristic #3: *Identifying dynamic relationships in systems.* This ability can be measured by the examination of the connection a student has formed between two concepts. To do this one must:

(a) Analyze connections and translate them into statements.
(b) Identify statements that express dynamism (*i.e.* statements in which the student refers to the transmission of a certain substance within the human body system).

Characteristic #4: *Organizing components and processes within a framework of relationships.* Students' ability to connect a single component to a large number of other components can be assessed by examining the number of junctions on their concept map. A "junction" is a concept that has connections to at least three other concepts on the map. The number of junctions students mark between their concepts provides insight into the level of knowledge integration they have undergone. For this reason, the junctions in each map should be counted.

Level C: Implementation

Characteristic #6: *Generalization and identification of patterns.* Concept maps allow us to identify students' understanding of patterns in human body systems by analyzing the contents of their connections. To do this, the statements derived from these connections must be sorted, and those statements that relate to patterns identified. The three patterns to be looked for are: Homeostasis, Hierarchy and Dynamism. **Homeostasis** includes statements that generally describe the body's internal stability ("*the concentration of urea and water in the body is regulated by homeostasis*"). **Hierarchy** includes statements referring to scale in nature, while emphasizing one scale in relation to another ("*the circulatory system includes capillaries*"). **Dynamism** includes statements that address dynamic processes as system characteristics that occur in the human body ("*oxygen enters the body through the lungs*").

Characteristic #7: *Identifying hidden dimensions.* To assess this characteristic, the statements derived from the map must be sorted, and those that refer to internal patterns and connections that are invisible on the body's surface must be identified.

Characteristic #8: *Temporal thinking.* This includes both retrospective thinking (backwards) and projection (forwards). To identify a student's understanding that interactions taking place in the present can bring about and influence future events, those statements from the map in which there are temporal references must be identified.

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