Using Knowledge Space Theory to Analyze Concept Maps

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Abstract: This study examines use of knowledge space theory as a novel method of analyzing concept maps. Concept mapping is a technique for expressing relationships between ideas, using two-dimensional node-link diagrams to visually display relationships between ideas. We introduced concept mapping as a voluntary exercise in an upper-level undergraduate immunology course. The students were assigned ten concept maps (for which concept lists were provided) at intervals during the semester-long course. We utilized knowledge space theory (Folmagne & Doignon, 1988) to systematically analyze and compare concept maps drawn by students to their instructor's "expert" concept maps. Using this novel analysis method, we were able to reveal students' level of understanding of course material, changes in student knowledge across time, as well as identify students' alternative conceptions. We found knowledge space theory a productive tool for systematically analyzing and comparing students' concept maps across time and to expert's concept maps.

Introduction

Concept mapping is a technique for externally depicting students' internal knowledge structures. Students construct concept maps by using labeled linking lines (propositions) to show relationships between ideas or objects (concepts). The process of constructing a concept map helps students build a deeper and more meaningful understanding of content material (Novak & Gowin, 1984). Concept maps are a useful pedagogical tool because they allow teachers to visualize students' knowledge structures. This allows teachers to structure lessons to expand upon students' existing knowledge structures (Edmondson, 2000; Marbach-Ad et al., 2007; Okebukola, 1990). Despite the successful instructional use of concept maps, they have proven difficult to use for assessing student knowledge.

In part this difficulty is due to the various concept map assignments, instructions and analytical techniques or scoring procedures. Some concept mapping assignments ask students to generate the important concepts for a topic, others ask students to fill in the propositional statements on the linking lines on a pre-drawn concept map, and still others ask students to construct a map from a list of important concepts. Concept mapping instructions might ask students to draw hierarchical relationships and crosslinks between concepts whereas others simply ask students to connect concepts together using propositions. Some concept map analytical techniques evaluate maps based on the degree of hierarchy and crosslinking between hierarchies, other scoring procedures are based upon the number of concepts and propositions in the map, and still other methods attempt to rate the quality of the propositions and crosslinks in the map. Ruiz-Primo and Shavelson (1996) wrote a review highlighting the myriad array of concept mapping tasks and analytical techniques or scoring procedures. In their paper, Ruiz-Primo and Shavelson call for researchers to more carefully design concept mapping assessment tasks to align with cognitive theories. They also stress the need to establish the validity and reliability of analytical techniques for concept map assessments before widespread implementation of the assessment.

Many researchers (e.g., Okebukola, 1990; Markow & Lonning, 1998; Trowbridge & Wandersee; McClure et al., 1999) have experimented with different concept mapping tasks and analytical techniques to develop concept mapping assignments that provide effective assessments of student knowledge. Novak and Gowin (1984) outlined a quantitative scoring procedure for hierarchical concept maps in their original book introducing the concept mapping technique. In this scoring method, each valid proposition was assigned 1 point, each hierarchical level of the map was assigned 5 points, and each valid and significant crosslink between branches was assigned 10 points. The sum of these points established the overall score for the concept map. Novak and Gowin's scoring technique is useful because it differentiates between simple and complex maps numerically; however, the technique depends upon the hierarchical nature of the concept map. In contrast, Kinchin, Hay, and Adams (2000) developed a qualitative method of analyzing student's concept maps. The method involves determining if the concept map's structure is best described as a spoke, chain, or net of propositions connecting concepts. This technique allows for a rapid determination of the complexity of the concept map. However, it does not account for the quality of the concept map. McClure et al. (1999) conducted a study in which they attempted to establish the reliability and validity of a relational scoring procedure for concept maps. The technique involves assigning a numerical quality rating to each proposition in a concept map.

Similar to Novak and Gowin, the sum of the numerical quality ratings for each proposition was used to represent the score for the concept map. This technique is useful because it incorporates the quality of each proposition into the concept map score. However, the relational scoring technique only provides information about a student's knowledge relative to other students. The relational scoring technique does not provide instructors with information about students' alternative conceptions or concepts that may need further instruction.

Despite the utility of each of the above analytical techniques, many questions remain about the theoretical rationale behind such techniques and the validity and reliability of each procedure. There is a need for the development of alternative procedures for systematically analyzing concept maps to reveal information about students' knowledge structures. Knowledge space theory (Folmagne & Doignon, 1988) offers one potentially useful procedure for systematically analyzing concept maps. Knowledge space theory (KST) is a mathematical theory that allows researchers to represent the state of a student's knowledge, referred to as a knowledge space, at a precise point in time using a series of assessments. The first step in determining a student's knowledge space involves carefully designing a set of questions that each measure knowledge of a discrete concept. The set of questions is administered to the student and scored for correctness. The unique combination of concepts, represented by the correctly answered questions, comprises a students' knowledge space. KST is useful to educational researchers because it allows for the systematic comparison of students' knowledge in a particular domain across time and compared to experts (Folmagne & Doignon, 1988). KST was originally designed to help researchers examine students' knowledge spaces in mathematics domains, but has also been shown to successfully represent student knowledge in science (Taagepera et al., 1997). By administering the same survey throughout a semester of chemistry, the researchers determined potential learning pathways. That is, students appeared to learn additional concepts in discrete series. Figure 1 illustrates an example critical learning pathway for chemistry students.

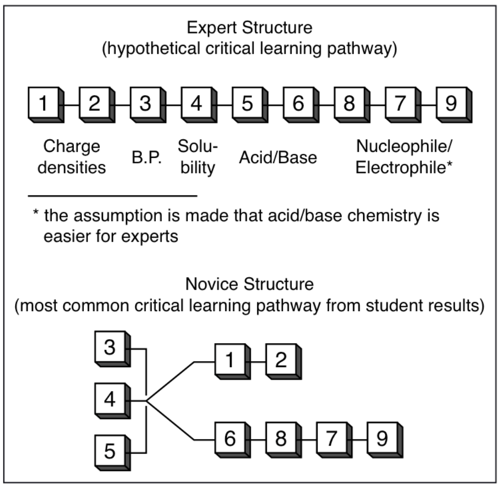


Figure 1. Critical learning pathways for novices and experts. (Taagepera & Noori, 2000).

In the present study, we applied a modified KST framework to analyze concept maps created by students enrolled in an undergraduate immunology course. We focused on examining the composite of students' knowledge spaces across time and to the instructor's knowledge spaces. In contrast to the KST approach of identifying correct answers to assessment questions, we built student knowledge spaces by identifying the presence or absence of propositions linking concept pairs on concept maps. Due to the voluntary nature of the concept mapping assignment, our data was not conducive to comparing change in individual students across time. Rather, our results indicate that analysis of concept maps with the KST framework permits the identification of the relative frequency of domain concepts in a population of students as well as notable alternative conceptions. The KST framework is also useful for highlighting similarities and differences between instructor's and students' concept maps.

Methods

An instructor employed concept maps as instructional aids in a team-taught undergraduate introductory immunology course. The course consisted of two 1-hour lectures and one 1-hour discussion per week. Students were given a brief overview of the concept mapping technique and the instructor demonstrated construction of a sample concept map at the start of the course. On 10 separate occasions in the course, students were assigned concept maps on specific lecture topics: B Cell Development, Germinal Centers, Major Histocompatability

Complex, T Cell Development, Costimulation, Cytokines, Autoimmunity / Tolerance, Alloreactivity / Immunosuppression, Vaccines, and Immune Responses to Tumors. For each map, the instructor provided students with 11 to 17 concepts (M = 14) central to the corresponding lecture topic to use while constructing each concept map. Note that several of these concepts were present on multiple concept map assignments. Students received 1% extra credit towards their final course grade for completing 5 of the concept maps. After students submitted their concept maps, the whole class received a concept map on the same topic created by the professor. We analyzed 208 concept maps collected from 89 students enrolled in the course of 98 students. Of the 89 participants, 52 completed one or more concept maps and 37 completed five or more concept maps. Table 1 illustrates the total number of concept maps completed for each lecture topic. Due to the voluntary nature of the assignment, a different set of students completed concept maps for each lecture topic.

Table 1. Number of submitted concept maps for each lecture topic.

Lecture Number	**Lecture Topic**	**Number of Submitted Concept Maps**
6	B Cell Development	27
6	Germinal Centers	25
8	Major Histocompatability Complex	24
11	T Cell Development	23
13	Costimulation	17
15	Cytokines	18
21	Autoimmunity / Tolerance	20
22	Alloreactivity / Immunosuppression	27
24	Vaccines	17
25	Immune Responses to Tumors	10
Total = 26		Total = 208

The concept maps constructed by the instructor and students were exclusively network concept maps that included "a semantic network with concept nodes linked directionally by labeled lines (arrows) to produce propositions" (Ruiz-Primo & Shavelson, 1996, p. 572). Unlike hierarchical concept maps, network concept maps are not arranged in a hierarchical nature (Novak & Gowin, 1984). Figure 2 illustrates an example student concept map for the B Cell Development lecture topic.

All of the concept maps were analyzed using the KST framework. We used the propositions in each concept map in place of the discrete conceptual questions used in traditional applications of KST. For each set of concept maps from a lecture topic, every unique proposition was assigned a letter or number code. All propositions generated by the instructor (those that appeared on the instructor's map for the topic) were assigned a number; the list of numbered propositions for each topic was set by the instructor's concept map. This list was then compared to each student's concept map to identify the instructor-generated propositions on students' concept maps. All propositions generated by the students (those that appeared only on students' maps for the topic) were assigned a letter. The list of lettered propositions for each topic grew as each student's concept map was analyzed. This list was then compared to each student's concept map to identify the student-generated propositions. Akin to the techniques used in traditional KST, the unique combination of propositions, represented by numbered and lettered codes on each concept map, represent a student's knowledge space for that lecture topic.

In this study, we did not focus on comparing individual student's knowledge spaces; instead we focused on comparing a composite of students' knowledge spaces across time and to the instructor's knowledge spaces. The frequency of numbered (instructor-generated) and lettered (student-generated) propositions was calculated for each lecture topic. We constructed composite maps (See Figures 3 and 4) for each lecture topic to help interpret and visualize the changes across time and the differences between the students' and the instructor's knowledge spaces. Instructor-generated propositions were highlighted in **bold** text on the composite map if they appeared on less than 50% of student concept maps. The threshold was set at 50% indicating the potential need for instructional intervention in the classroom as opposed to individual student errors. Correct student-generated propositions that were not indicated by the instructor, were highlighted in CAPITAL text. Incorrect student-generated propositions were highlighted in *ITALICIZED CAPITAL* text if they appeared on more than 25% of student concept maps. The threshold was set at 25% indicating the possible presence of a shared alternative conception among students as opposed to an individual student's misunderstanding.

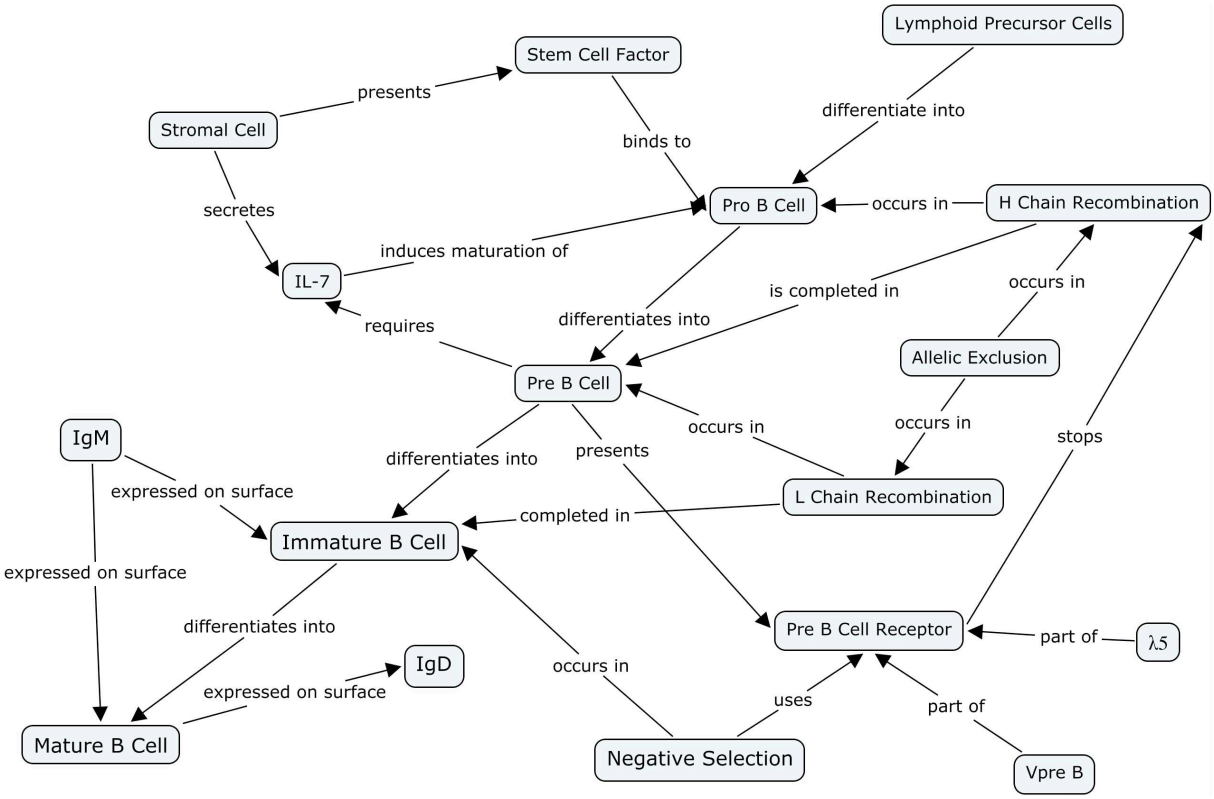


Figure 2. Example Student B Cell Development Concept Map. Concepts are the ideas enclosed in rounded boxes. Propositions are represented as directional arrows labeled with a linking phrase.

Results

Knowledge space theory proved useful for comparing students' concept maps across time and to their instructor's "expert" concept maps. Generating the composite maps for each concept map lecture topic, systematically summarized the knowledge spaces represented by the students' concept maps in comparison to the instructor's "expert" concept map. By calculating the frequency with which the propositions from the instructor's concept map appeared on student's concept maps, the researchers were able to systematically highlight the differences in knowledge structures between the students and the instructor.

Despite the uniqueness of each concept mapping lecture topic, we were able to compare students' knowledge spaces across time, because some of the same concepts appeared in several of the assigned concept maps for different lecture topics. The B and T cell development concept maps provided a unique opportunity to compare the development of students' knowledge spaces over the course of the semester. The B cell development lecture topic concept map was the first map assigned during the semester. The T cell development lecture topic concept map was the fourth concept map assigned during the semester, after the students had taken and received feedback for an exam on B cell development. B cells and T cells both initially share similar development processes that diverge later in the developmental process. However, several of the processes that regulate the development of B cells are common to T cells as well. This unique situation allowed the researchers to analyze the change across time of students' knowledge spaces on the common processes in B and T cell development. Figures 3 and 4 illustrate the composite maps for the B and T cell development lecture topics. KST analysis of the B and T cell development concept maps revealed both positive and negative changes in students' knowledge and relatively stable student knowledge structures.

Comparison of the B and T cell development concept maps revealed an improvement in students' understanding of some concepts across time. Analysis of the B cell development composite map indicates that only 30% of the students included information about the interaction of the lymphoid precursor cells with the stromal cells. The T cell development composite map indicates that information about the interactions between the lymphoid precursors and the stromal cells appeared in 95% of the students' knowledge spaces. This dramatic change in the appearance of a proposition indicates a significant improvement in students' understanding across time.

KST was also useful for identifying positive changes in students' knowledge, such as student-generated propositions that were not emphasized by the instructor. More than a quarter of students' concept maps from the T cell development concept maps included student-generated propositions about the interactions between the lymphoid precursor cells and the stromal cell effector molecules, IL-7 and stem cell factor. These interactions were not indicated by a significant percentage (more than 25%) of students on the B cell development concept maps. Despite the accuracy of these student-generated propositions, the instructor had not included the propositions on his "expert" concept map because he was not trying to emphasize these particular relationships between the concepts. KST analysis proved useful for highlighting improvements in students' knowledge that would not necessarily have been identified using other assessment techniques.

Using KST to analyze students' concept maps also allowed researchers to show the change over time in the frequency of alternative conceptions in students' knowledge spaces. An average of 50% of students' B cell development knowledge spaces indicated a correct understanding of the role of allelic exclusion in B cell development. The appearance of the correct understanding of the role of allelic exclusion had decreased to less

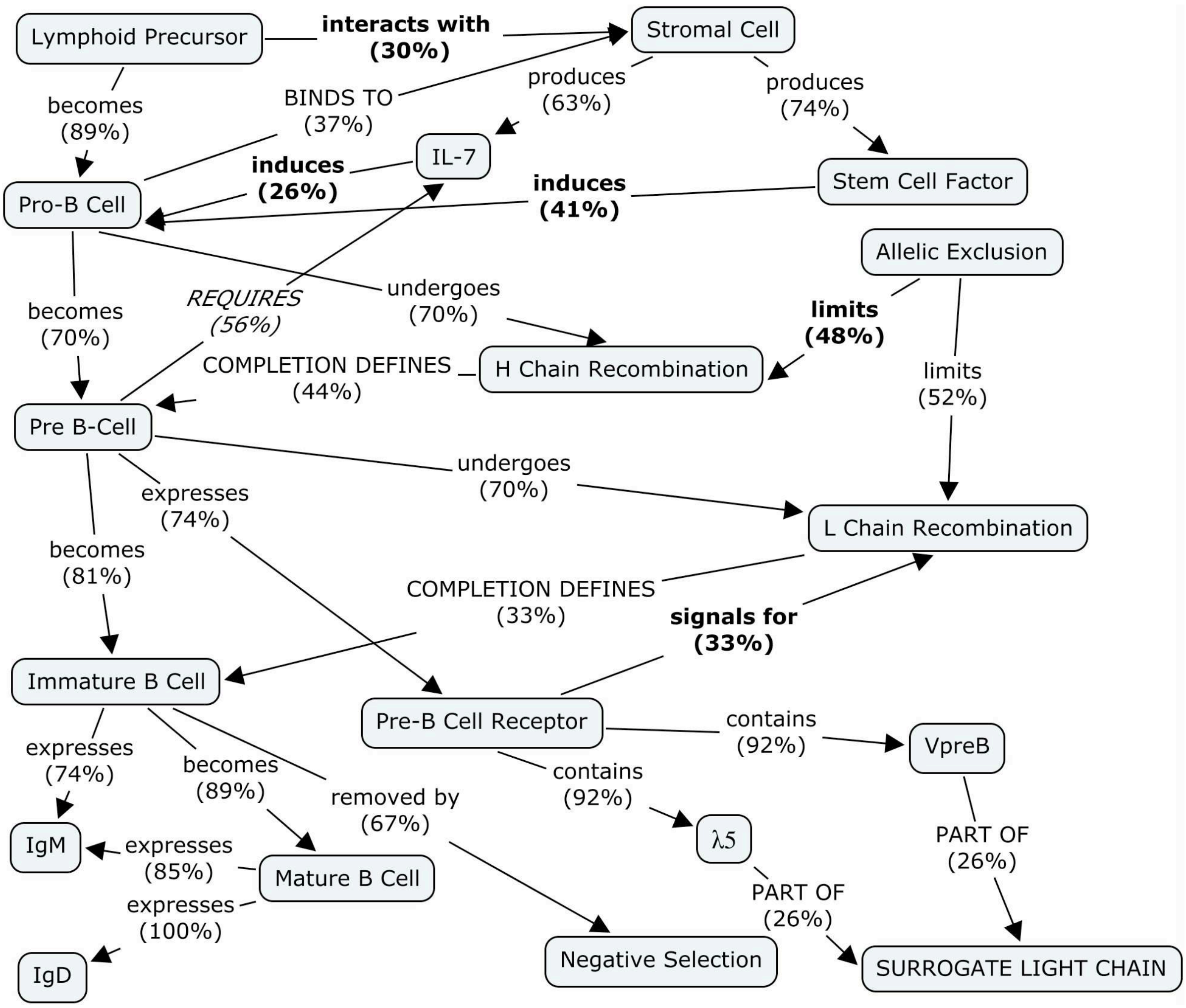
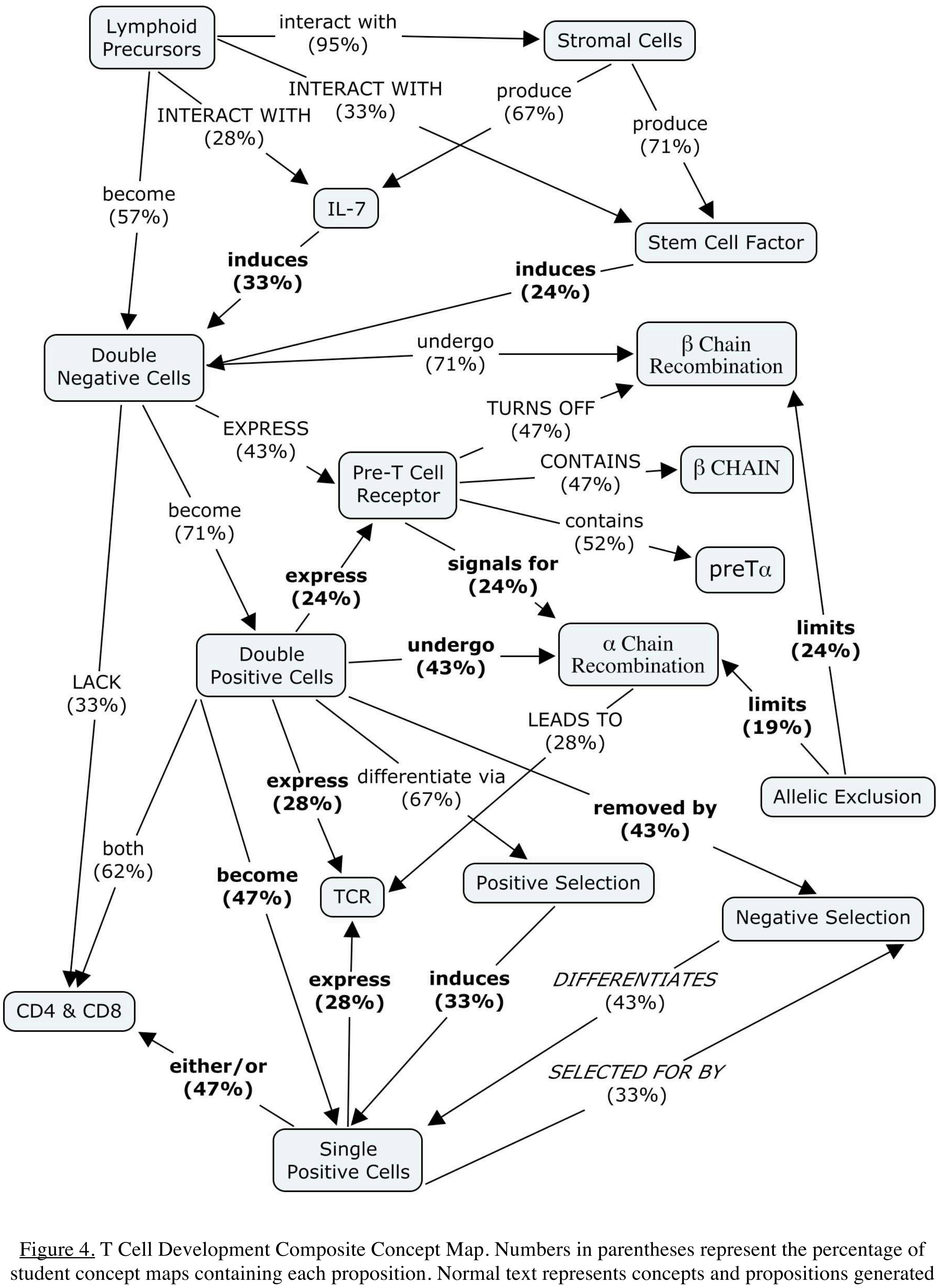


Figure 3. B Cell Development Composite Concept Map. Numbers in parentheses represent the percentage of student concept maps containing each proposition. Normal text represents concepts and propositions generated by instructor. **Bold** text represents propositions generated by the instructor that appear on less than 50% of student concept maps. CAPITAL text represents correct concepts or propositions generated by more than 25% of students. *ITALICIZED CAPITAL* text represents incorrect propositions generated by more than 25% of students.



<u>Figure 4.</u> T Cell Development Composite Concept Map. Numbers in parentheses represent the percentage of student concept maps containing each proposition. Normal text represents concepts and propositions generated by instructor. **Bold** text represents propositions generated by the instructor that appear on less than 50% of student concept maps. CAPITAL text represents correct concepts or propositions generated by more than 25% of students. *ITALICIZED CAPITAL* text represents incorrect propositions generated by more than 25% of students.

than 25% in the students' T cell development knowledge spaces. A possible explanation for this change is that on average, students had a weak understanding of allelic exclusion in B cell development. T cell development is a more complicated process compared to B cell development and perhaps this exacerbated students' misunderstandings of allelic exclusion.

The technique of KST analysis of concept maps was limited by its ability to detect students' alternative conceptions at low frequencies. The process of negative selection was correctly indicated in less than 50% of students' T cell development knowledge spaces. Two incorrect alternative conceptions about the role of negative selection appeared in more than 25% of students' T cell development knowledge spaces. Our initial analysis did not reveal alternative conceptions about negative selection in students' B cell development knowledge spaces. Upon further analysis, 10 different alternative conceptions about negative selection were identified in student' B cell development knowledge spaces; however, all appeared at frequencies less than 25%. The thresholds set by the researchers limit KST analysis of concept maps, but these thresholds are flexible and can be adjusted as needed to detect different frequencies of students' alternative conceptions.

KST analysis of the B and T cell development concept maps also revealed concepts for which students' understanding did not improve over time. There was no significant change in the appearance of propositions about the interactions between the two stromal cell effector molecules, IL-7 and stem cell factor, with the lymphoid precursor's respective progenitor cells, the pro-B cells or double negative cells. On the B cell development composite concept map, only 26% (IL-7) and 41% (stem cell factor) of students' maps included propositions relating the stromal cell effector molecules to the pro-B cells. On the T cell development composite concept map, only 33% (IL-7) and 24% (stem cell factor) of students' maps included propositions relating the stromal cell effector molecules to the double negative cells. KST analysis revealed problematic concepts for which student knowledge remained relatively stable and did not improve over time with further instruction.

By analyzing students' concept maps with KST we were able to extract very fine detailed information about changes over time in students' knowledge spaces for lymphocyte development. KST analysis highlighted both targeted and unexpected improvements in students' knowledge across time. Analysis of students concept maps by KST revealed alternative conceptions and allowed us to track the changes in frequency of these alternative conceptions as further instruction was given about the concepts over time. KST analysis also highlighted problematic concepts for which students' knowledge was relatively resistant to instruction and remained constant over time.

The above examples have strong technical content that can obscure the critical viewpoints generated by this research. The research above used examples of immunology based concepts; however, we propose that the KST method of analyzing concepts maps can be expanded to any subject at the primary, secondary, undergraduate and even graduate levels. Using KST to analyze concept maps enhances the instructional usefulness of concept maps for both students and instructors. KST is a powerful technique for analyzing concept maps to understand a student's knowledge space at a given time, elucidate misconceptions held by a significant proportion of the students, and identify correct student-generated ideas. KST combined with concept mapping assignments has the ability to improve instructor clarity and students' perception, increase students' understanding of concepts, and assist instructors in constructively addressing students' misconceptions.

Conclusion

Concept mapping is an effective pedagogical technique; however, concept mapping has proven challenging to use as an assessment. The KST framework is a theory driven, systematic method of analysis that can be used to evaluate the content of concept maps. We found that analysis of concept maps with the KST framework is a productive method for examining change across time in students' knowledge spaces. We also found that analysis of concept maps with the KST framework effectively highlights details of the similarities and differences between students' and instructor's knowledge spaces.

KST analysis of concept maps is productive because it is sensitive to both the omission of conceptual ideas from students' knowledge spaces and the addition of alternative conceptions to students' knowledge spaces. The technique also allows instructors to rapidly and systematically identify major themes in students' knowledge from the vast array of information contained in students' concept maps. The range of analysis times for each set of concept maps from a lecture topic was between 1 and 4 hours. The analysis time depended on the number of concepts assigned for each lecture topic and the overall similarity between the students' and instructor's concept maps. The median analysis time for the sets of concept maps was approximately 2 hours. There is the potential for computer software to assist in the analysis of concept maps using KST and shorten the analysis time. An ideal program would generate a list of all propositions linking two concepts. From this list, the researcher could easily count the number of propositions similar to the instructor's and identify frequently occurring alternative conceptions.

One limitation of using KST to analyze students' concept maps is that the researcher sets the thresholds for highlighting differences between students' and instructor's concept maps. If the threshold is set too high, it can reduce the sensitivity of the technique to subtle differences in students' knowledge spaces. The analysis time of the KST method increases as the thresholds are lowered. Lowering the thresholds also dilutes the major findings of the analysis by highlighting minor, possibly less important differences in students' knowledge structures. Despite this limitation, KST enhances the pedagogical usefulness of the concept mapping technique as a formative assessment because it provides instructors with a productive framework for systematically analyzing students' patterns of understanding and misunderstanding.

Future research can expand upon our use of KST for analyzing concept maps to include comparison of individual student's concept maps across time to identify changes in individual student's knowledge structures. In addition, more research is needed to establish the reliability and viability of using KST for analysis of concept maps from a wide variety of subject matters across a range of levels of students. KST analysis of concept maps should be compared to other established techniques of measuring students' knowledge structures, such as traditional KST applications and other standardized assessment techniques. We hope that other researchers will elaborate upon and expand the application of the KST framework for analyzing concept maps to many different disciplines of study.

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