CONCEPTUAL PROGRESSION – ARE THERE ANY *PATHS*? USING CONCEPTS MAPS TO MONITOR STUDENT PROGRESSION AND CAUSAL PATHS IN LONG-TERM INQUIRY

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Abstract : Sustainable development requires critical thinking and scientific knowledge. Inquiry learning, promoted across Europe, could promote skills to help future citizens understand and take responsible informed decisions about long-term effects. Inquiry can be conceptualized as a process where student's naïve explanatory models of biological phenomena are progressively refined, and where student's understanding - initially vague ideas - are refined as students experiment or read about experiments into additional and more precise concepts and causal links guided by questions. Understanding the paths that this progression follows is crucial in designing learning environments, in assisting and guiding students and in assessment. It is often assumed that concepts are acquired linearly from "simple" to "complex". Learning progression has also been proposed to be "roaming a landscape" rather than "climbing a ladder" (Zabel & Gropengiesser, 2011). However, determining diverse and unpredictable student conceptual paths is quite difficult and pre- / post-tests do not document the multiple steps students might follow. Furthermore, assessing students' mental models is not directly possible, and generally relies on analysis of student productions. Here we propose a method for monitoring student progression that is based on extracting concepts and causal links expressed in successive students' written productions and mapping them onto concept maps of institutionalized models (the models instruction is geared towards) for each version. In order to test the instrument, we will analyze one year of students' productions in a shared writing space during inquiry. We argue that this method could inform inquiry guidance, help designing learning environments, and identify conceptual difficulties in student progression. Time sequence in which concepts / links appear (early or late) allows discussion of causes for late-appearing model items as i) difficulties in learning, ii) weaknesses of designs or iii) epistemic specificities of the knowledge structure in resources used by students.

Keywords: conceptual paths, inquiry, student progression measure, concept mapping, visualizing conceptual change.

INTRODUCTION

A major aim of science teaching is developing skills to help future citizens understand and take responsible informed decisions about long-term effects to manage sustainable development, the focus of the ESERA 2015 conference. Inquiry learning has been promoted to develop both critical thinking and scientific knowledge. This contribution addresses one issue in guided inquiry learning: how to follow and assess student's progress *during* the process of learning. Designing learning environments for inquiry with guidance during instruction requires insight into students' conceptual progression. Monitoring student progression is quite difficult and pre- / post-tests cannot document the multiple conceptual steps students follow during their learning processes.

The goal of this research is to explore conceptual progression of students during the learning process, to analyze the paths - if any - it might follow, and discuss the sequence of conceptual progression in order to gain insight into learning difficulties, design limitations, or epistemological constraints.

It is often assumed that concepts are acquired linearly, from "simple" to "complex". Some research suggests that learning progression might well be "roaming a landscape" rather than "climbing a ladder" (Zabel & Gropengiesser, 2011). Determining such diverse and unpredictable conceptual paths is quite difficult, especially in long-term interventions. Documenting the multiple conceptual steps students might follow during their learning processes requires multiple points of data along the duration of learning progression that are not commonly available.

The central questions in current biology research are explanations of underlying mechanisms (Morange, 2003). Scientific explanations are by essence *models* of phenomena (Tiberghien, 1994). Natural phenomena can only be accessed in science by experiments, which are designed within models. Models, according to Martinand (1996) are i) hypothetical, ii) modifiable (with new data, progress of knowledge, new interpretations…), iii) relevant to a particular class of problems and iv) of limited validity (i.e. cannot be 100% "true"). Science teaching should guide students towards model-using skills for explaining or predicting phenomena, monitoring should focus on learning outcomes such as using a given model for prediction or explanation (Biggs, 2003).

Assessing student's mental models of natural phenomena is not directly possible. We would like to stress that we do not present an assumption about what *form* these models might take within students' minds, when we refer to understanding we refer to *expressions* of students' understanding. More precisely, as we shall explain below, we analyze written data produced by students.

Models to be learned and taught are defined by the school or other authorities and such choices will not be discussed here. We will refer to these particular models that instruction is aiming at as *institutionalized models* (Brousseau, 1998). This implies that there certainly are *other* models – some much more elaborate - than the one chosen in this particular curricular context. Indeed, a crucial idea here is that the particular model students should be capable of using is neither true nor false, it is appropriate for the problems addressed and can explain the data the students will be confronted to. So this *institutionalized model* is neither a model of student's knowledge structure, nor a model of expert knowledge. This *institutionalized model* could be considered an ideal-type (Weber, 2009), an abstraction of some characteristics of the phenomenon, used for analysis purposes (ideal does not refer here to *perfection*).

We propose using diagrammatic representations of institutional models as a method for visualizing traces of student progression. This methodological choice might suggest a rather cognitivistic view of student knowledge, but that does not reflect our view of understanding. We will discuss a method for monitoring student progression that is based on extracting concepts and causal links expressed in student's successive written productions and mapping them onto concept maps for each version. Models can be expressed as concept maps (Novak & Cañas, 2008), a powerful way of visualizing concepts (nodes) and their relations (causal links). Indeed, for this research, the institutionalized model was expressed as an ideal-typical concept map onto which model items (concepts and causal links) present in versions of students' productions can be visualized.

This method provides insight into progression of students' understanding. It can visualize stages of progression in ways that allows comparison across years and different designs.

Our main research question is: I) How can we identify and model conceptual *paths (if any)* that students follow while investigating biology in an Inquiry Based Learning (IBL) design? This led to other sub-questions: IIa) Can this method reveal over years repeated time patterns for concepts, causal chains? On a semantic level: IIb) Can this method help identify conceptual difficulties in the learning landscape (such as conceptual obstacles or cognitive construals), weaknesses of designs or epistemic specificities of the knowledge structure in resources used by students?

METHODS

This research is part of a long-term design-based (Brown, 1992; Collins, Joseph, & Bielaczyc, 2004) research study on inquiry learning being conducted since 2006 in advanced high school classes in Geneva, totaling nearly one hundred students so far. Each intervention lasted most of one school year, in a standard class, with standard time and assessment requirements; we believe it can be considered a real-world teaching situation. The curriculum covered molecular biology, genetics, and immunology. The learning design was inspired by a knowledge-building community of learners, was structured for cooperative learning and was scaffolded by a shared wiki in which students wrote their current understanding. They investigated answers to inquiry questions by experimenting and reading authentic resources. Early in the investigation process and close to the end, students presented their understanding to peers, leading to confrontation of knowledge, question redefinition. The student's efforts resulted in a brochure critical for student's preparation of important exams, making it a crucial document to them. An inquiry cycle lasted 3 to 4 weeks, after which the class addressed a new chapter.

Data was collected from the wiki's history recordings. Conceptual progression was traced by comparing all revisions of student text, i.e. multiple records of students' productions in a shared writing space (wiki) supporting inquiry. Since the teacher is also one of the authors, using only data from written student productions minimizes possible biases.

We plan to compare seven cohorts of students in the same learning design and to search for common patterns and epistemological components such as concept links and linear or multiple causalities. For this first exploratory methodological study, we selected one year (2006) and one student inquiry question: "How do the correct antibodies appear in response to a given pathogen called X" as it was explored by one group of 3-4 students that year during the investigation process (2-3 weeks).

The coding procedure identifies presence and absence of nodes with respect to an ideal-type: We structured the model items (concepts and links) of the institutionalized model in the form of a concept map (Novak & Cañas, 2008) shown in Figure 1. This model was developed by three experienced biology teachers, compared to curriculum requirements and confronted to a large sample of student productions to confirm all concepts and links could be situated on that map.

Institutionalized model

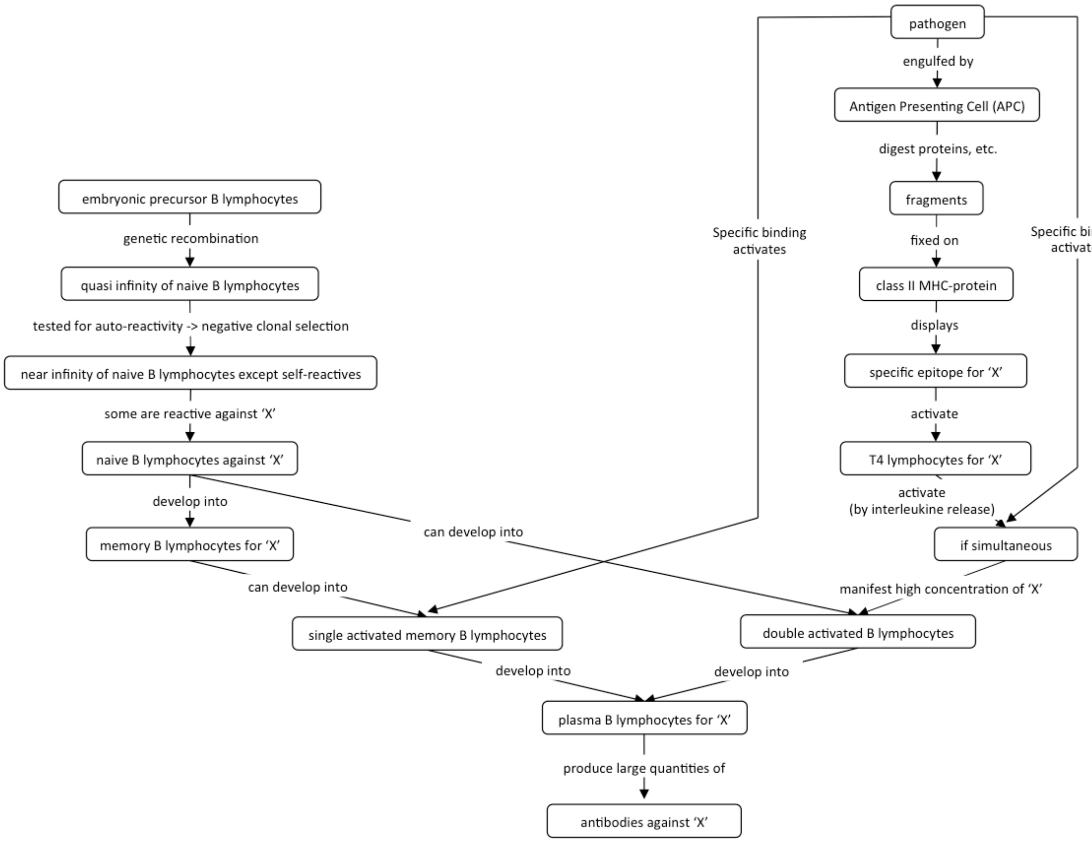
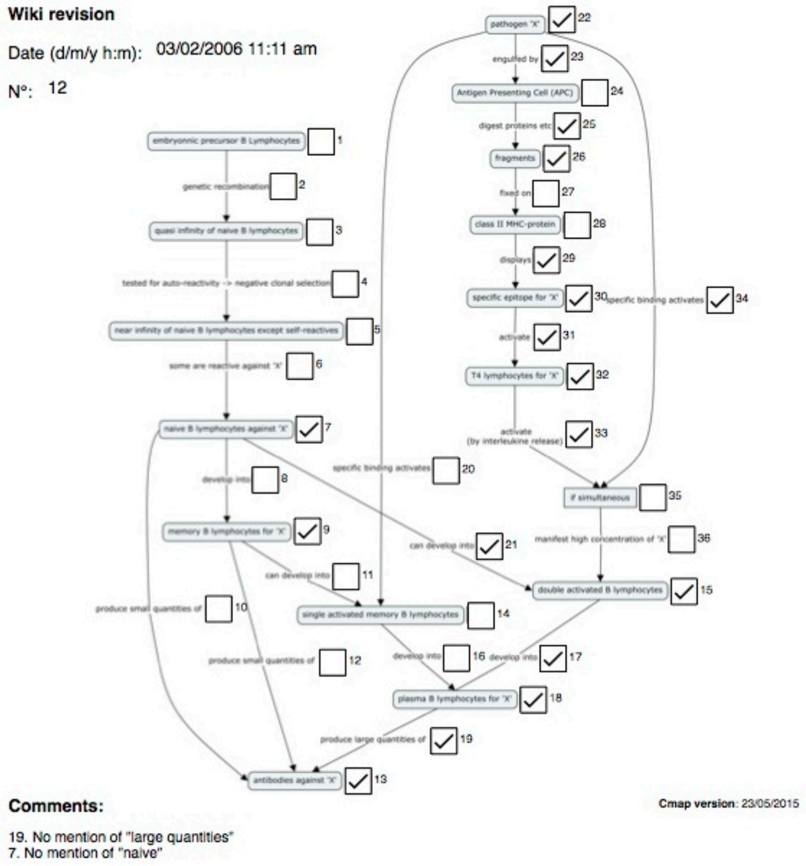


Figure 1. Methodological construct for visualizing traces of student productions in a wiki: the institutionalized model on which were mapped the progression of each group analyzed (see methods).

We searched all 95 versions of students' text for traces of model items (concepts and links). We coded presence or not of each model item by analyzing semantic units of student text for each version. Students' text production grew during 3 weeks of investigation to reach 3820 words. Different possible wordings were accepted as long as semantic equivalence was found. Many revisions did not contain changes in terms of model items but other revisions such as language correction or text reorganizing. In the group analyzed, we found eight *significant* versions, giving insight into as many understanding steps of this particular group.

Coding sheets were produced for each significant version; a sample is shown in Figure 2. When model items were largely present, but some discrepancy was noted, the discrepancy was indicated in a footnote. Model items that were insufficiently explicit were not considered present. Double coding was used to stabilize criteria until more than 90% agreement was reached, then simple coding was applied by the one of the researchers to all versions.

Sample coding sheet



Wiki revision

Date (d/m/y h:m): 03/02/2006 11:11 am

N°: 12

Comments:

19. No mention of "large quantities"
7. No mention of "naive"

Cmap version: 23/05/2015

Figure 2. Sample coding sheet for one version (version 12, year 2006). Model items found in that version of student text were checked. Footnotes indicate concepts or links that were partially present and state discrepancies.

A first analysis concerns presence of items: A count of model items is plotted against version numbers (see Figure 3). It was not found to be very informative with respect to monitoring students' progression in model acquisition so other visualizing methods were sought.

A second type of analysis visualizes partial model patterns that appeared in student productions over time: A map visualizes model items found in each significant version by highlighting them on a grayed-out map (cf. Figure 4). Concepts were visualized as dots and links as lines.

A third type of analysis consolidates counts of model items across multiple versions to reveal time patterns. For each model item found we counted occurrences across all significant versions, producing a *prevalence count* for that concept or link. Since a model item never disappeared from student text, we considered this a good indicator of how *early* this item appeared in the progression. To produce the prevalence index, we then standardized these numbers to the total of versions for that year (item *prevalence count* / number of significant versions), and expressed on a percentage scale rounded to the closest integer attached to the item as a dark badge. The size of badges was chosen so that early appearing items got a large badge as in Figure 5.

Together, these three visualization methods allow to investigate and analyze student progression from various angles. Firstly, this method analyzes the time sequence in which concepts / links appear (early or late). This opens possible discussion of causes for late-appearing model items as difficulties in learning, weaknesses of designs or epistemic specificities of the knowledge structure in resources used by students.

Second, this method can search for evidence of conceptual obstacles (Bachelard, 1947) that would render some concepts or links difficult to understand, we would expect them to appear later. Also Coley and Tanner (2015) propose that cognitive construals could explain many misunderstandings in learning biology. We would therefore expect concepts that go against finalism and animism such as clonal selection in our example of immunology to appear *later*.

Third, this method can help searching for structuring concepts (Wiggins & McTighe, 2000) and threshold concepts that are often the points at which students experience difficulty (Meyer, Land, & Baillie, 2010): since their understanding is transformative (occasioning a significant shift in the perception of a subject), and helps understanding several other concepts, we would expect them to systematically appear later and precede the appearance of many other links and concepts. However, fascinating this perspective might be, pinpointing that specific moment of student conceptual progression would require very numerous productions by students that might be difficult to obtain in real-world situations.

RESULTS

A first visualization of concept and links count is shown in Figure 3. It gives some insight into student progression that confirms regular learner's progression. It does not inform about possible paths that are the focus of this article, but implicitly reinforces the conception of student's progression as a ladder-like path. We have elsewhere discussed more relevant measure of global learning achievement (epistemic complexity) that confirmed that adequate learning occurs in the design (Lombard & Schneider, 2013), however the independence of content which was the strength of that approach did not allow investigating conceptual progression trajectories we explore here.

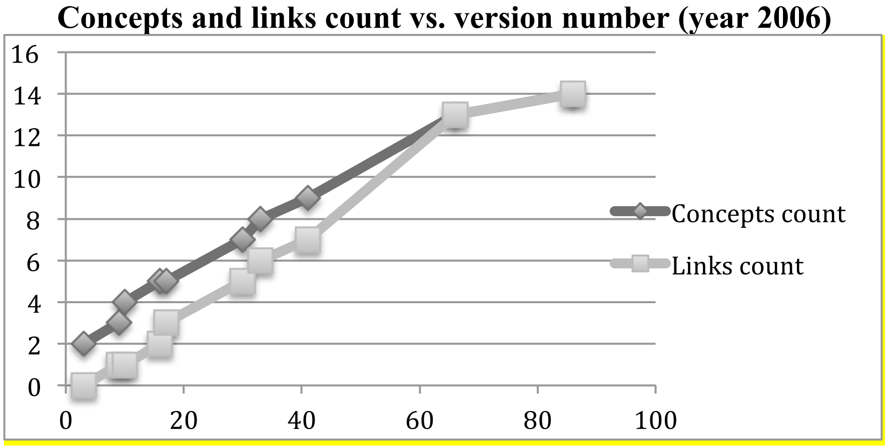


Figure 3. Concepts and links count vs. version number (year 2006). This visualization shows the need for more informative visualization.

A second type of analysis looks at successive versions of student's text during inquiry. By mapping nodes and links onto the institutionalized model, we gain insight into steps and paths of learners understanding. Figure 4 shows all the significant intermediary steps of the progression for one group.

The most striking - and surprising - result is that we did *not* find connected *paths* in student productions. We definitely did not find a ladder, nor a roaming trail: model items appeared in a sort of mosaic manner, gaps in causal chains closing here and there in no understandable pattern. "Path" does not even seem an appropriate term: we might speak of *kangaroo jumps* completing causal chains in small mosaic steps. Causality patterns appear first as numerous short sequences and progressively are connected. Simple linear and short causal chains are linked to include multiple causalities forming a complex model as shown in latest images of Figure 4.

Only late in the investigation were causal chains fully linked. In fact, some remained incomplete even at the end of inquiry in the year analyzed here (2006). In other words, students did not show evidence of having fully achieved the learning goals. We are studying other years and preliminary results show it was fully attained only for one year (2015).

Concepts and links present in successive versions of student productions (2006)

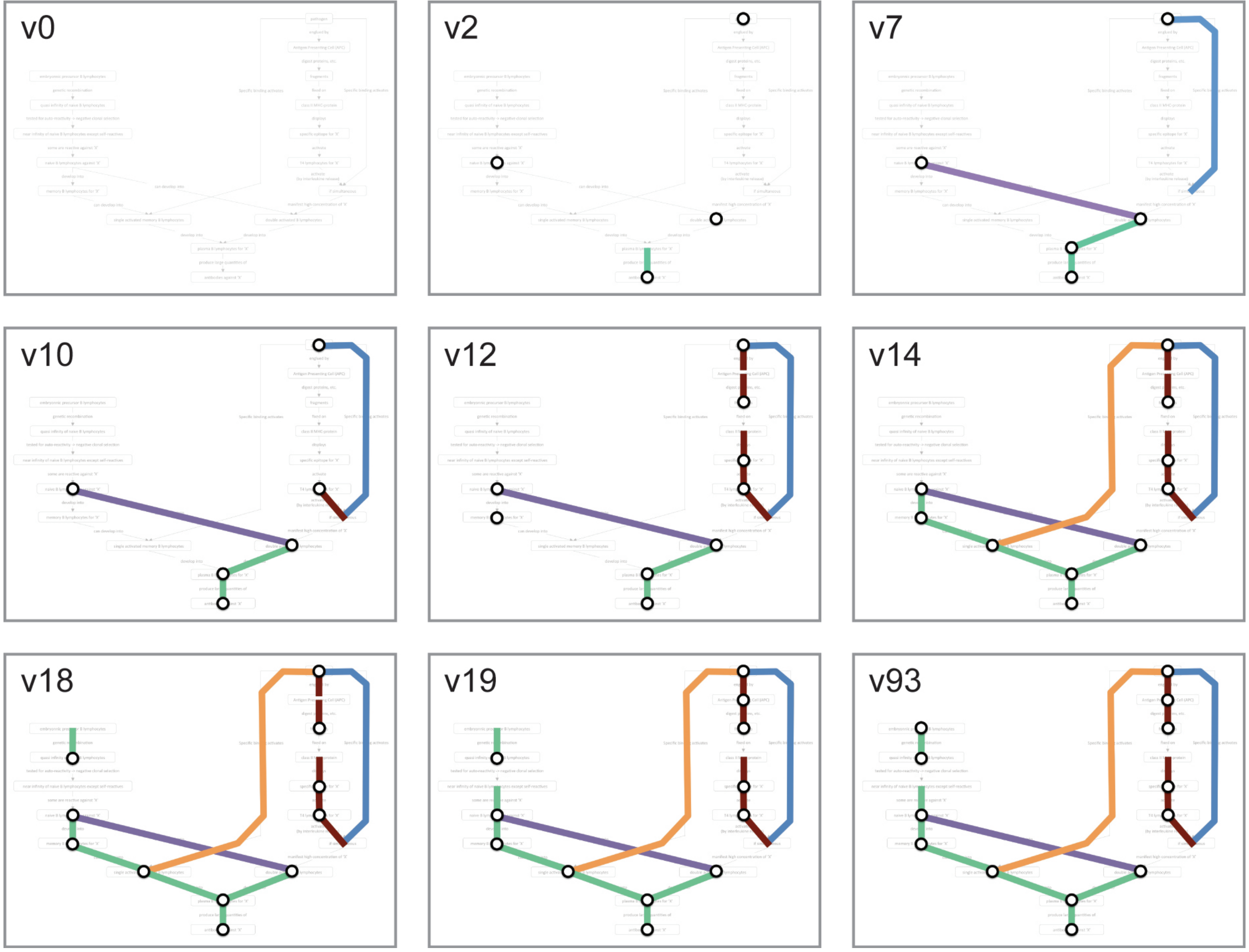


Figure 4. All significant versions along the learning process of one student group. Concepts figured as dots, links as lines (mapped against the grayed-out concept map of the institutionalized model, see methods).

A third type of analysis shows which concepts links appeared early or late as can be seen in Figure 5. Indeed some local causal chains (e.g. B cell activation to produce antibodies) were expressed very early in the investigation process and others were completed later, towards the end of the training sequence (e.g. negative clonal selection of auto-reactive clones, MHC class-II presentation of antigen fragments).

Preliminary analysis (after ESERA conference) of 6 other years suggests that this happened repeatedly: some late-appearing and some early-appearing model items can be identified in each group. This opens the possibility of basing the discussion of student difficulties with complex biology models on explicit data. In other words, we suggest that these visualizations allow analyzing what concepts might be difficult for students, or how we could improve a pedagogical design.

Prevalence index (2006)

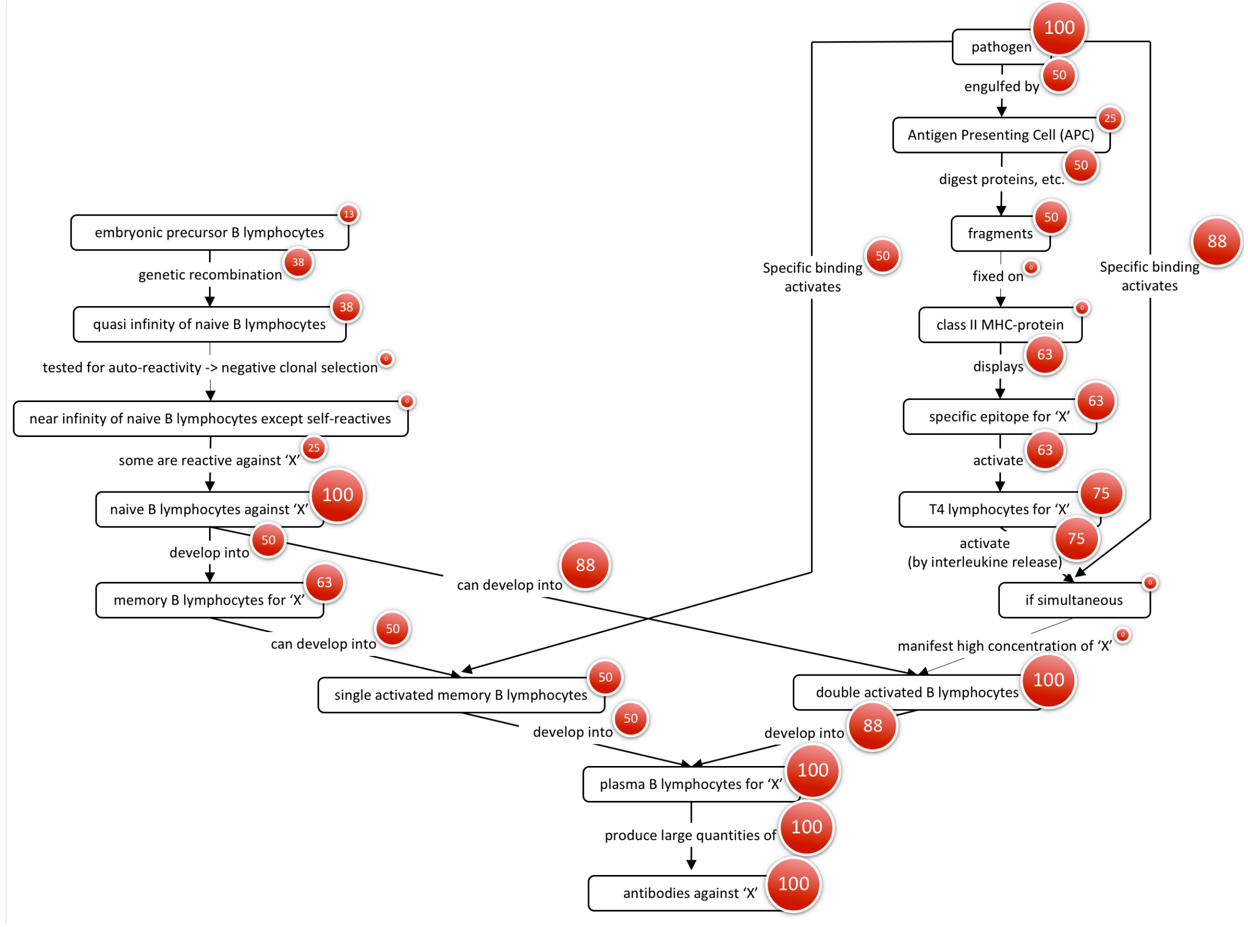


Figure 5. Prevalence index computed for all versions (2006) reveals early and late appearing concepts / links. Prevalence index 0 indicates model items that student did not expressed at all that specific year.

DISCUSSION AND CONCLUSIONS

First, our results confirm that important – and rarely available - insight into conceptual development during inquiry can be produced by this method. Results of this exploratory study show i) a non-linear conceptual progression and ii) a messy, incoherent progression (or a coherence that eludes us). Preliminary multi-year comparison suggests this method can reveal iii) differences in progression both over years and between groups, and iv) common patterns distinguishing *early* and *late*-appearing concepts or links.

Our data suggests - at least in the context of this study - that learning is an iterative, messy, difficult to predict process, without clear beginning or end, nor identifiable path. Progress appears to happen by refining and linking small bits of knowledge in mosaic fashion. One might be tempted to draw a parallel between this iterative messy unpredictable process of learning and the process of science (Abd-El-Khalick, 2011; Giordan, 1994, Latour & Gille, 2001).

Being able to know that (non-linear) progression is happening, and that there are common patterns offer opportunities to better understand how conceptual understanding develops or does not. This allows enhancing teacher guidance and informing the design of better learning environments.

Firstly, these results argue for including instructional design elements that reveal to students incoherencies in their models (as expressed in activities) and design elements that help them fill in gaps in causal chains. Also, these results highlight the potential of designs built around interactively improving a conceptual artifact (Bereiter, 2002; Scardamalia & Bereiter, 2006) to develop scientific understanding.

The data presented here along time in Figure 4 and Figure 5 shows that some model items form local causal chains early in the investigation process and others are completed much later, towards the end of the inquiry sequence.

Second we explore why some of the most crucial concepts do not appear until late or not at all (prevalence index 0) for year 2006 (e.g. simultaneous double activation of B cells by specific binding of antigen and T4 cells presenting the same specific epitope, negative clonal selection producing B-cell clones reactive against a near infinity of antigens except self and the presentation of antigen fragments by class II MHC proteins).

Third, looking again at which concepts / links appear early or late, we searched for evidence of conceptual obstacles (Bachelard, 1947) that would render some concepts or links difficult to understand. Coley and Tanner (2015) propose that cognitive construals could explain many misunderstandings in learning biology. We would therefore expect concepts that go against those construals to appear later. It could be argued in this light that clonal selection goes against a finalistic and animistic view of explanation and that would explain the late appearance of these model items and low prevalence index on Figure 5. Other late appearing concepts could be discussed similarly.

This method could be used over many years to search for stronger evidence of such late appearing concepts. Some preliminary results suggest this is the case.

Finally, we explored if this method could help reveal threshold concepts (Meyer, et al., 2010) since their understanding opens the door to understanding several other concepts. We would expect them to appear later and systematically precede the appearance of a group of links and concepts. We have not been able to demonstrate this clearly without over-interpreting.

Our results stress the importance of highlighting inconsistencies and gaps in the causal chain of students' explanations of phenomena and of organizing activities to fill them and lead students toward effective predictive and explanatory models. The relevance to modern biology seen as explanations – causal links – underpins this analysis, in particular in the perspective of conceptual change, student model confrontations, and teacher training.

Within its limits, our data suggests that science learning of complex phenomena is a non-linear process in which learners iteratively construct or transform a model. The implications for education are important: We could speculate, that in learning situations where learning is organized in linear process, only those students that are capable of processing iteratively what is presented - during instruction itself or while revising - learn efficiently. This would imply that only students with good self regulation of their learning processes benefit from linear designs such as lectures, some very linearly guided lab work or even some form of inquiry that requires students to follow a given path. This view of learning as iterative idea improvement is supported by much research in the knowledge building community: e.g. Scardamalia & Bereiter (2006). However, the relevance of our results -produced in an inquiry design designed around iterations of knowledge building - is a matter open to discussion and needs further research.

This interpretation might be seen as challenged by centuries of successful learning in teaching formats such as ex-cathedra courses that appear to be linear. We speculate that good learners have the skills to perform alone (during the course or revisions) these conceptual iterations in order to develop coherent usable models. We could define “deep learning” as capacity of using a given institutionalized model (Jungck, 2011) for prediction or explanation, not just repeating a given description of the model (also referred to as mastery goals rather than performance goals (Darnon, Muller, Schrager, Pannuzzo, & Butera, 2006)). The need for repeated iterations to attain such goals is also well highlighted by some literature: to organize learning as a knowledge improvement process (Scardamalia & Bereiter, 2006).

On a more practical side, this method could inform how we design for i) student awareness of conceptual gaps, ii) student drive towards knowledge improvement (completing causal chains), iii) focus on the model items of the model iv) how we structure iterations for that progression.

Our second research sub-question was about the factors that might orient student’s conceptual development. We mentioned the design (including teacher attitude, rules, assignments, etc.) cognitive constraints that might hinder or facilitate some type of explanations, "cognitive construals" (Coley & Tanner, 2015) and the resources students use – in which the epistemological structure of the conceptual field is embedded. We have suggested elsewhere (Lombard, 2012) that there might there be some sort of *conceptual centripetal force* in the resources and scientific paradigm of the field driving student progression towards some concepts and links that are central in our current understanding of immunology. While the sequence of model items appearance that this method reveals has offered some insight, methodological difficulties have till now prevented us from dissecting these factors orienting student progression. We have to leave this fascinating field of exploration open.

Whatever the causes, the repeated late appearance of some causal chains has implications on pedagogical design and guidance. The late – but systematic - appearance of the most important concepts (structuring concepts) opens venues of research: what design features or epistemic structure of the knowledge body can contribute to guide student progression towards these concepts? This could be useful in very different pedagogies. In a direct instruction view, for example, this method offers critical data to inform how we organize learning advancing from concepts we have found to be *early-appearing* towards late - probably difficult - concepts that are more fundamental. Indeed teachers’ perception of difficulties does not always reflect difficulties students encounter – especially about recent scientific advances (Yarden, Norris, & Phillips, 2015).

Overall potential for educational methods could include i) developing designs around a conceptual map of the model for institutionalizing ii) organize discussion of learning objectives by policy makers or teachers iii) identifying learning difficulties to prepare activities, questions, resources for helping students overcome these conceptual hurdles in completing causal chains iv) guidance during activities by visualizing the conceptual: field teachers might track conceptual progression and understanding gaps in order to raise questions, offer resources, at the appropriate time.

However establishing a conceptual map takes time and is likely to be seen as too demanding by many teachers and opens again a discussion on sharing designs within teacher communities. It could be argued that the need to define clear learning objectives takes time anyway.

The presented framework has some limits. One limit of time-related analysis of student productions is that students only write in the wiki when required to do so for an assignment such as presentation to peers or assessment of the page, etc. So written production probably lags behind the understanding progress; students may have acquired concepts or links but only write them some time later, possibly at the same time as other concepts that became easy to understand by passing this conceptual threshold. Writing might reveal previous progression in conceptual spaces and but not the exact time of the transition, and limits interpretation of time sequences.

Another fundamental limitation stems from our coding and data analysis method: analysis of text by searching for a given set of model items cannot reveal other concepts that might be present in student texts. It also presents the results in a more cognitivist manner than we would have liked. It doesn't show to which extent the learners were capable of *using* that model to explain or predict phenomena. We have discussed elsewhere (Lombard, 2012) evidence showing that they did so. However we would like to argue that the unusual detail in conceptual progression and long-term comparison revealed by this method seem worth this limitation.

The scope of our analysis is also limited by the small sample and the single investigation design in which they were established. While it is tempting to think that these results have a broader scope, it is probably reasonable to consider them as exploratory and we are currently developing this research into this data set for other years and other subject questions. It would be interesting to explore it in other settings and with larger samples. A challenge will be to get this type of relevant traces of conceptual learner progress in other learning designs than wiki-supported IBL. With the increase in technology supported learning this will probably become easier.

With data accumulating we hope to find ways to dissect the i) effects of learner difficulties such as cognitive construals, ii) weaknesses of designs or iii) epistemic specificities of the knowledge structure in experiments and resources used by students.

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