An Analysis Framework for Collaborative Problem Solving in Practice-based Learning Activities: A Mixed-method Approach

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ABSTRACT

Systematic investigation of the collaborative problem solving process in open-ended, hands-on, physical computing design tasks requires a framework that highlights the main process features, stages and actions that then can be used to provide 'meaningful' learning analytics data. This paper presents an analysis framework that can be used to identify crucial aspects of the collaborative problem solving process in practice-based learning activities. We deployed a mixed-methods approach that allowed us to generate an analysis framework that is theoretically robust, and generalizable. Additionally, the framework is grounded in data and hence applicable to real-life learning contexts. This paper presents how our framework was developed and how it can be used to analyse data. We argue for the value of effective analysis frameworks in the generation and presentation of learning analytics for practice-based learning activities.

Categories and Subject Descriptors

J.1 [**Computer Applications**]: Administrative Data Processing—*Education* K.3.1 [**Computers and Education**]: Computer Uses in Education – *Collaborative learning, computer assisted instruction, computer managed instruction*

General Terms

Measurement, Design, Experimentation, Human Factors.

Keywords

Collaborative learning, problem solving, practice-based learning, analysis framework

1. INTRODUCTION

Learning Analytics (LA) rely upon effective frameworks that drive the analysis of data in a manner that answers the questions posed by researchers and educators. These questions can be diverse, as can the educational practices that are subject to analysis. We are particularly interested in collaborative problem solving processes in practice-based learning activities. Practice-based learning activities differ considerably in what they ask students to do and what they are trying to teach. In the research study reported here, we focus on open-ended, hands-on, physical computing design tasks. This type of practice-based learning activity is commonly used to improve collaborative problem solving processes [13], which in turn improve learning in this type of practice-based learning activities.

Practice-based learning activities have the potential to help educators to achieve high tier institutional and policy goals such as developing 21st century skills in STEM subjects at scale. They are becoming increasingly popular in both secondary and post-secondary learning institutions, particularly after the introduction of the 'Makers Movement' [3]. However, 21st century skills including collaborative problem solving skills are complex and non-linear in nature. Hence, although practice-based learning activities are widely recognised as an essential aspect of teaching these skills in STEM subjects, both by educators and by researchers [11]; our understanding of practice-based learning still remains scant and there is still little agreement on how it should be used effectively and how it should be supported [1].

LA is introducing a number of new techniques and frameworks for studying learning in general, nonetheless practice-based learning activities are one of those educational areas to which learning analytics have yet to contribute significantly [18]. Systematic investigation of the collaborative problem solving process in practice-based learning activities requires a framework that highlights the main process features, stages and actions. Those identified process actions and stages can then be used to provide 'meaningful' LA data. The main purpose of this paper is to provide such a framework.

2. Analysis Frameworks in LA

The development of appropriate frameworks for analysing students' engagement processes is a key aspect of research in LA [2, 7, 8, 10, 15]. Designing and validating analysis frameworks for LA is a challenging task and requires expertise in multiple research domains including educational design, educational psychology, human-computer interaction and computer sciences. There appear to be two fundamental approaches to the development of analysis frameworks in the literature. The first approach starts with a theoretical model. Researchers derive a theoretical model of the process they are investigating, either from the previous literature or from expert opinions (Delphi Method), and deploy it to data generated from real world contexts to validate, reshape or refute it (see for instance [5]). This approach has the drawback of overlooking the essential aspects of what makes a learning process unique. The second approach is to use a grounded-theory approach. In a grounded-theory approach, researchers attempt to ignore all prior assumptions and categories and to describe the process as it emerges from the data (see for instance [6]). However, this approach could lead to generation of very data-specific frameworks, which cannot be used in other contexts. We believe, a mixed methods approach (see for instance [10]) could lead to more effective analysis frameworks that highlight the main process features, stages and actions of a learning process. They can be both theory-driven and therefore broad enough to observe learning processes on the basis of theoretical assumptions, and data-driven and therefore grounded enough to be applicable to the real-life learning contexts.

2.1 Development Process of the Analysis Framework

Here we present the methodology we adopted to develop a mixed-methods analysis framework for the collaborative problem solving process in practice-based learning. There are three main stages: identification of the theory-driven framework; adaptation of the theoretical framework to fit the research purposes and merging the fine-grained actions from the data to the adapted theoretical framework (figure 1).

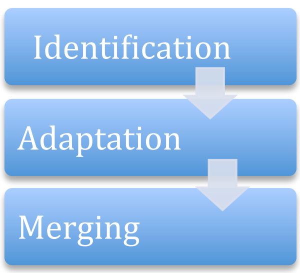

Figure 1 Three-stage development process

2.1.1 Identification of a theory-driven framework from the literature

We started with a framework that was developed by the OECD to assess collaborative problem solving competence [12]. This framework met our requirements, because it is a rare attempt to merge collaboration and problem solving skills in one framework. The approach taken by the OECD also takes into account a very broad educational context, because their focus is upon the evaluation of knowledge and skills at an international comparison level.

The OECD defines collaborative problem solving competency as "the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and efforts to reach that solution" [12, p.6]. The definition identifies three core competencies particularly related to collaboration and four competencies particularly related to problem solving. Competencies related to collaboration: 1. Establishing and maintaining shared understanding; 2. Taking appropriate action to solve the problem; 3. Establishing and maintaining team organization. Competencies related to problem solving: 1. Exploring and Understanding; 2. Representing and Formulating; 3. Planning and Executing; 4. Monitoring and Reflecting. These competencies are then used as dimensions in the OECD's assessment framework for collaborative problem solving (see Table 1).

	(1) Establishing and maintaining shared understanding	**(2) Taking appropriate action to solve the problem**	**(3) Establishing and maintaining team organisation**
(A) Exploring and Understanding	(A1) Discovering perspectives and abilities of team members	(A2) Discovering the type of collaborative interaction to solve the problem, along with goals	(A3) Understanding roles to solve problem
(B) Representing and Formulating	(B1) Building a shared representation and negotiating the meaning of the problem (common ground)	B2) Identifying and describing tasks to be completed	(B3) Describe roles and team organisation (communication protocol/rules of engagement)
(C) Planning and Executing	(C1) Communicating with team members about the actions to be/ being performed	(C2) Enacting plans	(C3) Following rules of engagement, (*e.g.*, prompting other team members to perform their tasks.)
(D) Monitoring and Reflecting	(D1) Monitoring and repairing the shared understanding	(D2) Monitoring results of actions and evaluating success in solving the problem	(D3) Monitoring, providing feedback and adapting the team organisation and roles

Table 1. Matrix of Collaborative Problem Solving for PISA 2015

2.1.2 Adaptation of the OECD framework to fit our research purposes

The framework was originally developed for assessment purposes. However, it does not meet the requirements for analysing the *process* of collaborative problem solving, because it does not include the component of knowledge deficiency.

	(1) Establishing and maintaining shared understanding	**(2) Taking appropriate action to solve the problem**	**(3) Establishing and maintaining team organisation**
(A) Identifying facts	(A1) Discovering perspectives and abilities of team members, making knowledge explicit	(A2) Discovering the type of collaborative interaction to solve the problem, along with goals	(A3) Understanding roles to solve problem
(B) Representing and Formulating	(B1) Building a shared representation and negotiating the meaning of the problem (common ground)	(B2) Identifying and describing tasks to be completed	(B3) Describe roles and team organisation (communication protocol/rules of engagement)
(C) Generating Hypotheses	(C1) Critically analysing the problem representation	(C2) Generating and Communicating potential solution paths	(C3) Present Hypothesis, encourage feedback from others and offer feedback on others' hypotheses
(D) Planning and Executing	(D1) Communicating with team members about the actions to be/ being performed	(D2) Enacting plans	(D3) Following rules of engagement, (*e.g.*, prompting other team members to perform their tasks.)
(E) Identifying Knowledge and Skill Deficiencies	(E1) Comparing the team's knowledge and skills with the proposed actions	(E2) Identifying and specifying individual deficiencies	(E3) Specification of team deficiencies and their relationship to proposed problem solution
(F) Monitoring, Reflecting and Applying	(F1) Monitoring and repairing the shared understanding	(F2) Monitoring results of actions and evaluating success in solving the problem	(F3) Monitoring, providing feedback and adapting the team organisation and roles

Table 2. Combined Matrix that merges PBL and CPS concepts adapted from PISA 2015

Knowledge deficiency is an important aspect of the problem solving process [4]. To address both the assessment and the tuition aspects of the collaborative problem solving process, we adapted and integrated the knowledge deficiency element of Hmelo-Silver (2004)'s tuition framework into the OECD's assessment framework (Please see table 2). A detailed discussion of this adaptation process as well as its implications were discussed in a recent research conference [8].

2.1.3 Merging the data-driven fine-grained actions of collaborative problem solving

A multi-step qualitative methodology was used, taking into account the procedures and techniques developed in qualitative content analysis methods [17]. Our dataset consisted of video recordings from two different events,

a) A Hackathon event in which three groups of five secondary school students (aged 14-15 years) were assigned to work on an open-ended, hands-on project using physical computing (Arduino modules[1]),

b) A workshop event in which two groups of adult pairs worked on two different open-ended, hands-on physical computing projects using an Arduino-like kit (SAM Labs[2]).

First, fine-grained actions from the data are identified. These were observable actions that occurred during the collaborative problem solving process. 31 fine-grained actions were identified. To validate these actions, two coders, applied these 31 actions to a different set of data collected from the same event. This procedure was suggested as a way of testing the validity of actions generated with a grounded theory approach by Mayring [9] as cited in Meier et al. [10]. Where there was disagreement, the researchers discussed the data and revised the categorisations accordingly. Then, the emerging actions were assigned to the coordinates of the theory-driven framework previously developed. First the fine-grained actions were assigned to three core competencies particularly related to collaboration, and then they were assigned to six competencies particularly related to problem solving. Merging those two activities resulted with table 3.

We argue that the mixed methods approach to generating analysis frameworks is a productive one. It helps to generate frameworks, which are theoretically robust, and generalizable while being grounded in data and applicable to real-life learning contexts. The real value of this framework (table 3) is that it has observable actions as its codes rather than broad definitions. Such broad definitions are hard to identify, track and interpret in data analyses both for human annotators and to a greater extent for machines, which makes them hard to use in learning analytics research.

The analysis framework has been generated as part of a bigger research project and our next step is to apply this framework at scale using data collected from practice-based learning activities. The goal is to observe if there are any fundamental differences in different groups of students. Once we establish that machine collected data correlates with the human analysis of the collaborative problem solving process, we plan to use the Learning Analytics System (LAS) we design to compare successful students to novice ones, and STEM experts to STEM students in order to map which actions and stages of the collaborative problem solving process differ for those different groups. We aim to use this information to generate visualisations to support the collaborative problem solving process in open-ended, hands-on physical computing design tasks. It is important to make it clear here that we do not hope to provide a measure of determination but a way of effectively supporting practice-based learning activities in STEM teaching. In this sense we see learning analytics as a means of seeking to "augment human intellect" [14] rather than define it.

	(1) Establishing and maintaining shared understanding	**(2) Taking appropriate action to solve the problem**	**(3) Establishing and maintaining team organisation**
(A) Identifying facts	(A1) Vocalising knowledge; Confirming shared understanding; Communicating regarding an answer to a question; Asking questions to verify a suggested solution; presenting skills	(A2) Identifying a problem (a situation which stops/hampers students from the natural progression of the practice-based activity)	(A3) Confirming the actions to be taken, engaging with rules
(B) Representing and Formulating	(B1) Sharing the identified problem with other teammates; Explaining an hypothesis/suggestion in detail	(B2) Communicating about actions to take	(B3) Assigning roles to team mates; Giving responsibilities to team mates
(C) Generating Hypotheses	(C1) Critically analysing a problem; Critically analysing a suggestion	(C2) Suggesting a solution to a problem; Hypothesising regarding the source of problem	(C3) Suggesting an improved version of an hypothesis suggested by others
(D) Planning and Executing	(D1) Negotiating on actions to take; Approving a suggested solution	(D2) Taking actions to progress	(D3) Prompting other team members to perform their tasks; Taking actions related to suggestions of other teammates
(E)Identifying Knowledge and Skill Deficiencies	(E1) Identifying individual deficiencies	(E2) Making knowledge or skill deficiency explicit	(E3) Identifying a team mistake
(F) Monitoring, Reflecting and Applying	(F1) Verifying what each other knows; Asking questions regarding the actions being taken; Observing an agreed action being taken; Observing the attempts of another teammate to solve a problem	(F2) Testing a solution to check its validity; Reflecting on previous actions; Correcting simple mistakes of others	(F3) Warning teammates regarding a possible mistake

Table 3. Combined Matrix that merges fine-grained actions and theoretically suggested stages

3. DATA COLLECTION AND ANALYSIS WITH THE FRAMEWORK

As has been mentioned, the framework was created in the context of a larger EU project X (http://blinded.review), which is commissioned by the EC 7th Framework Programme. The overall aim of the project is to develop learning analytics tools for hands-on, open-ended STEM learning activities using the Arduino platform. Within the project we have generated tools that can detect some of the fine-grained actions in the analysis framework. Given the complexity of the collaborative problem-solving process even at the fine-grained level identified in our analysis framework, we cannot automatically track each of those actions with the current technology. However, we can automatically track some of the fine-grained actions, which are presented in this section.

[1] https://www.arduino.cc/

[2] https://samlabs.me/

3.1 Learning Analytics System (LAS)

The LAS collects data from both ambient and live sources. The ambient collection of data includes a computer vision system integrated in specially designed furniture. The learning environment is designed to foster collaboration and includes an integrated screen and round shape to allow people to share and work together. A new Arduino electronics platform with plug-and play electrical components, and visual programming tool has been developed to allow learners to more easily and build and program artifacts. The system collects what components are plugged in and how the students manipulate the programming environment. A lightweight mobile application has been developed to allow learners to plan, document, and reflect on their projects with text and multimedia. The mobile system also allows teachers to mark critical incidents, and researchers to time stamp the different stages of the learners project, based on the framework. This on the fly first round of coding provides a foundation for the hand coding of the video documentation post activity. A set of "sentiment" buttons has been developed with thundercloud and sunshine icons to allow the students to mark critical events in their activities. The system is seen below in figure 2. The live data will provide the self-declared data from students and teachers including the cycle of planning, documenting, and reflecting through the mobile system. The computer vision system and the log files of the Arduino software collect the ambient data. This data set includes the capture of objects, the positions of people, arm movement, faces and audio levels from the vision system; and from the Arduino the log files of components are collected as are the manipulations in the visual programming platform. In table 4, the detailed types of data collected, the instruments of collection, the type of events, the description, the extraction methods as well as fine-grained actions we aim to track are summarised.

Figure 2. LAS in action

The LAS is now up and running, and the first round of trials with learners are being conducted. The framework presented in this research paper is being used as a guide to design the algorithms for processing and visualising the data.

4. DISCUSSION

The analysis framework we generated offers a flexible approach to the analysis of data collected regarding the collaborative problem solving process in practice-based learning activities. Although this type of analysis usually needs to be completed by humans, we see our framework as an initial step to generate useful analysis frameworks for data collected and analysed by a machine. At this point we make the distinction between frameworks that can only be completed by humans as we strive to understand how learning happens and those employed in data analysis by a machine. However, this does not mean that they do not contribute to our understanding of such learning processes.

Data Collector	Computer Vision System	Arduino IDE (Visual Electronics Platform)	Mobile System	Sentiment Buttons	Video Capture
Types of Data /Events	DATA:Shared Gaze, Body Closeness, hand tracking, object manipulation, motion around the special furniture and audio levels EVENTS: people and objects	DATA: Number of components and inputs EVENTS: Arduino modules and codes	DATA: Number of posts, transitions between activities EVENTS: self-documentation	DATA and EVENTS: Critical Incidents	Occasion of Codes/ Qualitative analysis
Brief Description	More granular details of who around the table and what their arms are doing, how close are they to each other, what are they are looking at, and the motion around the table -location of bodies, direction of gaze	How students designed and built the tasks - types and number of components and manipulation in the IDE	How did the students plan, document, and reflect on the task - Teacher critical incident marks Researcher coded activities	Marking of critical incidents	Coding Annotating moments on the video/audio
Extraction Methods	Frequency of hand movements Time spent looking at screen Time spent looking away	Frequency of components plugged in Frequency of interactions with IDE	Number of Mobile submits Number of words in text submitted Duration of different activities Content of text and multimedia	Frequency and duration between types of incidents	Rating of codes, Amount of time
Types of Analysis	Machine	Machine	Machine and human	Machine and human	Human
Fine-grained actions aimed to be tracked	(D2) Taking actions to progress, (D3) Prompting other team members to perform their tasks; Taking actions related to suggestions of other teammates, (F1) Observing an agreed action being taken; Observing the attempts of another teammate to solve a problem	(A1) Presenting skills, (A2) Identifying a problem (a situation which stops/hampers students from the natural progression of the practice-based activity), (E2) Making knowledge or skill deficiency explicit, (E3) Identifying a team mistake	(F1) Verifying what each other knows; Asking questions regarding the actions being taken; (F2) Testing a solution to check its validity; Reflecting on previous actions; Correcting simple mistakes of others, (F3) Warning teammates regarding a possible mistake, (E1) Identifying individual deficiencies, (C1) Critically analysing a problem; Critically analysing a suggestion, (C2) Suggesting a solution to a problem; Hypothesising regarding the source of a problem, (C3) Suggesting an improved version of an hypothesis suggested by others	(A2) Identifying a problem (a situation which stops/hampers students from the natural progression of the practice-based activity), (F3) Warning teammates regarding a possible mistake	All identified fine-grained actions

Table 4. The detailed types of data collected, the instruments of collection, the type of events, description, the extraction methods, and the codes

In the same way that computers were not invented in order to make word-processing or the Internet possible, but once the space of possible computer applications was rendered accessible, design processes went into overdrive creating all the software we now rely on everyday, analysis frameworks for learning analytics and associated tools have the potential to lead to the production and use of effective technologies for teaching and learning.

One possible criticism of our mixed-methods approach could be that there is a low possibility of researchers generating fine-grained actions from the data while bracketing out all a priori assumptions and categories. This is obviously a much broader question than the scope of this research study and it relates to all research studies that use a grounded theory approach. It is clear to us that somehow, every observation is theory-driven. We recognize the difference between looking and identifying what one looks at. Whilst the first one is a physical action, the latter requires a theoretical framework and clearly the generation of fine-grained actions from data requires the identification of collaborative problem solving actions. However, our focus on the data-driven, fine-grained actions is particular to the observable actions of what we, as educators and researchers, think of as part of the collaborative problem solving process.

5. CONCLUSIONS AND FUTURE WORK

In this paper we present the development of an analysis framework for the collaborative problem solving process in practice-based learning activities (Table 3). We then, briefly present the learning analytics system we developed to collect data regarding the fine-grained actions and dimensions of collaborative learning processes from practice-based learning activities (Table 4). We argue that the three-stage development process we describe in this paper is a useful one to generate analysis frameworks that can be used to identify crucial aspects of the learning process in practice-based learning activities. The stages, dimensions and fine-grained actions of our analysis framework can be used to provide 'meaningful' LA data. Although, the framework is generated in the context of practice-based learning environments, we believe the development process we generated can be used in different educational contexts particularly in face-to-face learning environments where detecting and tracking student interactions is extremely challenging. Our next research aim is to apply this framework at scale and generate learning analytics data for teachers and students, which will support their teaching and learning process during practice-based activities.

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7. REFERENCES

[1] Abrahams, I., & Millar, R. (2008). Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science. *International Journal of Science Education, 30*(14), 1945-1969.

[2] Gibson, A., Kitto, K., & Wills, J. (2014). *A cognitive processing framework for learning analytics.* Paper presented at the LAK'14 Proceedings of the Fourth International Conference on Learning Analytics and Knowledge, New York. Doi: 10.1145/2567574.2567610

[3] Halverson, E. R., & Sheridan, K. M. (2014). The Maker Movement in Education. *Harvard Educational Review, 84*(4), 495-506.

[4] Hmelo-Silver, C. E. (2004). Problem-based Learning: What and How do Students Learn. *Educational Psychology Review, 16*(3).

[5] Jarvela, S., & Hakkinen, P. (2003). The levels of web-based discussions: using perspective-taking theory as an analytical tool. *Cognition in a digital world*, 77-95.

[6] Koschmann, T., Zemel, A., Conlee-Stevens, M., Young, N., Robbs, J., & Barnhart, A. (2003). Problematizing the Problem. *Computer-Supported Collaborative Learning, 2*, 37-46.

[7] Lee, Y. C. E., Chan, C. K. K., & van Aalst, J. (2006). Students assessing their own collaborative knowledge building. *Computer-Supported Collaborative Learning, 1*, 57-87.

[8] Luckin, R., Mavrikis, M., Avramides, K., & Cukurova, M. (2015). *Analysing Project Based Learning Scenarios to inform the design of Learning Analytics: Learning from related concepts.* Paper presented at the AIED2015 Artificial Intelligence in Education, Madrid.

[9] Mayring, P. (2003). *Qualitative content analysis. Foundations and techniques*. Weinheim: Beltz.

[10] Meier, A., Spada, H., & Rummel, N. (2007). A rating scheme for assessing the quality of computer-supported collaboration process. *Computer-Supported Collaborative Learning, 2*, 63-86.

[11] Millar, R. (2004). The role of practical work in the teaching and learning of science. *High school science laboratories: Role and vision*.

[12] OECD. (2015). *Draft Collaborative Problem Solving Framework*. Retrieved from http://www.oecd.org/pisa/pisaproducts/Draft PISA 2015 Collaborative Problem Solving Framework .pdf

[13] Rummel, N., & Spada, H. (2005). Learning to Collaborate: An instructional approach to promoting collaborative problem solving in computer-mediated settings. *Journal of the Learning Sciences, 14*(2), 201-241. doi:10.1207/s15327809jls1402_2

[14] Santos, J. L., Verbert, K., Govaerts, S., & Duval, E. (2011). *Visualising PLE usage.* Paper presented at the EFEPLE11 1st Workshop on Exploring the Fitness and Evolvability of Personal Learning Environments.

[15] Scheffel, M., Drachsler, H., & Specht, M. (2015). *Developing an Evaluation Framework of Quality Indicators for Learning Analytics.* Paper presented at the LAK'15 Proceedings of the Fifth International Conference on Learning Analytics and Knowledge, New York.

[16] Segal, J. W., Chipman, S. F., & Glaser, R. (2014). *Thinking and Learning Skills* (Vol. 1). London: Routledge.

[17] Spannagel, C., Glaser-Zikuda, M., & Schroeder, U. (2005). Application of Qualitative Content Analysis in User-Program Interaction Research. *FQS Forum: Qualitative Social Research, 6*(2), 29.

[18] Worsley, M., & Blikstein, P. (2014). Analyzing Engineering Design through the Lens of Computation. *Journal of Learning Analytics, 1*(2), 151-186.