SEEING THE ENTIRE PICTURE (STEP):

AN EXAMPLE-ELICITING APPROACH TO ONLINE FORMATIVE ASSESSMENT

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ABSTRACT

Attempts to reform mathematics teaching in the past decades have endorsed the view that mathematical reasoning and strategic competence are central learning goals. The affordances of technology for creating learning environments that nurture mathematical reasoning have been developed and investigated for the past decades. Recent efforts bring diagnostic tools from cognitive research to technological platforms that automatically assess students' work to provide immediate feedback. Such feedback is used for assessment, to support conceptual adaptive learning, and to help teachers with formative assessment in the classroom. Yet, automatic feedback has usually been limited to tasks that require procedural interactions that do not necessarily offer teachers opportunities to assess various dimensions of conceptual understanding. In the past few years, across design-based research cycles, we developed and tested an innovative online assessment approach and supporting platform (STEP) that provides meaningful immediate feedback. We used STEP to study the affordances of example-eliciting tasks (EETs) and articulate design principles for an online example-based formative assessment environment. The article focuses on the rationale and principles of the development and of the design-based research. I analyze cognitive aspects of the conceptual online feedback and of our attempts to articulate the potential of technology for making EETs less demanding for teachers to manage.

Keywords: Automated formative assessments, Example-eliciting task, Elaborated feedback, Task design patterns

TECHNOLOGY-BASED ASSESSMENT: NEED FOR NEW PERSPECTIVES

There is agreement that to have immediate and long-lasting effect on teaching and learning, online educational assessment should: (a) be aligned with institutional goals and views; (b) rely on strong evidence that can be analyzed online; (c) use data to analyze student learning within the norms and the environment in which they are learning, and across a variety of learning situations and contexts; and (d) capture the social aspects of learning by providing tools for analyzing submissions of large groups or of an entire class, or by reporting on the roles of individual students in dialogic interactions, rather than just on one individual student (Shepard, Penuel and Pellegrino, 2018).

Formative assessment of student skills and understanding, as well as more recent efforts to bring diagnostic tools from cognitive research to technological platforms, support teachers in various ways that include: (a) tools that help teachers collect and present differences in student work to the whole class (e.g., Clark-Wilson (2010) with TI-Nspire); (b) environments that provide feedback and suggest expected misconceptions (e.g., Heffernan & Heffernan (2014) report on ASSISTments); (c) dynamic technology-based approaches that analyze student work online to follow solution processes and provide feedback (e.g., Sangwin & Köcher (2016) use STACK) or construct student model (e.g., Advice Me project Heeren et al. (2018)); and (d) learning analytics tools that analyze big data online in anticipation of a near future in which assessment and instruction are one process (e.g. Wise, Vytasek, Hausknecht and Zhao (2016; Cope & Kalantzis, 2015).

The presentation focus on the Seeing The Entire Picture project (STEP) that investigates innovations in formative assessment in mathematics teaching through the use of automatic assessment technology, to provide teachers with diagnostic competence in everyday classroom assessment, and to provide students with online feedback. Specifically, the research and development investigate the potential of technology for making example-eliciting tasks (EETs) less demanding for teachers to manage, thereby supporting students' inquiry-centered learning.

EXAMPLE GENERATION IN MATHEMATICS TEACHING AND LEARNING

Mathematical reasoning is the backbone of many reform-based curricula and may include processes of conjecturing, pattern recognition, generalizing, comparing, contrasting, separating, and validating. Example generation is a crucial aspect of many of these processes, and as such it is both a process and an indicator of mathematical reasoning (Zaslavsky & Zodik, 2014). Watson and Mason (2005) have studied student "response spaces"—collections of learner-generated examples that fulfill a specific requirement. Given suitable exemplification tasks, such response spaces can provide insight into the correctness and richness of students' concept images (Sinclair, Watson, Zazkis, & Mason, 2011). EETs need to be focused on mathematically important conceptual structures, whose characteristics are revealed by the examination of multiple examples and of how they relate to each other. Such tasks can be especially powerful when they build on existing research, which has identified persistent alternative conceptions whose presence can be identified in examples submitted by students. Because student responses to EETs can provide teachers with information about a variety of concept definitions and concept images that students hold, teachers can use them to make instructional decisions. Yerushalmy, Nagari-Haddif, and Olsher (2017) have articulated certain design principles for such tasks, based on interactive diagrams that provide multiple representations of mathematical objects (e.g., functions, tangent lines), together with dedicated tools for generating examples that can be automatically assessed. Realized as design patterns (DPs), these design principles are conceived as ways to describe similarities across tasks in what they ask of students, and what can be algorithmically analyzed.

EETs are not yet commonly used as tools for formative assessment of students' conceptual understanding in classrooms. A possible reason for the infrequent use of such tasks in school is that tasks that can elicit many different correct and incorrect solutions are demanding for teachers to assess. With a wide range of potential solutions, students need elaborated feedback that goes beyond indications of correctness, and teachers must use, and often expand, their own mathematical knowledge to examine and provide feedback to each solution; the time needed to routinely review classroom responses is liable to overwhelm teachers.

EETs AS A TOOL FOR ONLINE FORMATIVE ASSESSMENT

STEP was designed and developed to support EETs that are formulated to be implemented as online assessment tasks based on specific DPs. Following Mislevy, Haertel, Riconscente, Rutstein, and Ziker (2017), the DPs developed offer a several different approaches that can be used to obtain evidence about reasoning processes. The STEP platform (Olsher et al., 2016) is built around interactive diagram (ID) that students use to produce and submit their examples. The IDs (the dynamic construction and tools) offer means for the exploration of tasks with multiple solutions. The two main components of STEP EETs are claims that define the goal and examples submitted as answers. The submitted example is an instance of exploration with the given diagram and tools. According to Buchbinder and Zaslavsky (2011), the presence of both the claim and of multiple examples can provide important insights into the learners' understanding of a concept, as well as of their understanding of the logic of the coordination of examples, and of claims that are central to mathematical argumentation. STEP makes possible the online monitoring of work on rich EETs, followed by analysis focused on the student's submitted work. At the same time, the student is expected to save, revisit, and review more self-generated examples and explanations in the allocated personal space. The submitted examples can be analyzed automatically to classify various characteristics of the mathematical object included in it, as well as heuristics that were probably used to construct them. Users (teachers, researchers, or developers) can specify the mathematical characteristics required of examples that are deemed correct, and the mathematical characteristics expected in typical incorrect examples. But because we cannot assume that the algorithmically determined indication of correctness of the answer is a comprehensive one, based on these predefined specifications, STEP can indicate only whether the examples meet task requirements. STEP characteristics, however, can provide information to help answer the following questions: What other characteristics do the solutions have, beyond the correctness? Do the answers represent familiar misconceptions? Do they indeed support the chosen claim, and if yes, how? How similar or different from one another were the examples generated by the same student or by different students? The elaborated feedback is constructed out of these characteristics and reported to the teacher in various formats (see Olsher et al., 2016, and Olsher, 2019, for details).

A *STEP* EXAMPLE

The following task analysis demonstrates the central aspects of designing assessment with EETs. The task lists four conditions: two conditions of relations between two quadratic functions f(x) and g(x), and two conditions of properties of g(x). f(x) is given by a function expression and graph: f(x)=-2x^2+4x+5. g(x) can be set using three independent sliders controlling the coefficients of the function expression. The goal is to find and submit three examples where g(x) and f(x) satisfy the maximum possible number of conditions. The answer consists of the marked chosen statements and the examples that demonstrate the choice. The conditions are: (1) The graph of f(x) intersects the graph of g(x) in exactly one point; (2) The two functions have the same symmetry axes; (3) g(x) passes through the origin (0,0) of the system; and (4) The function g(x) has a minimum. There are three possible triplets that fulfill the requirements. Here are examples for each triplet.

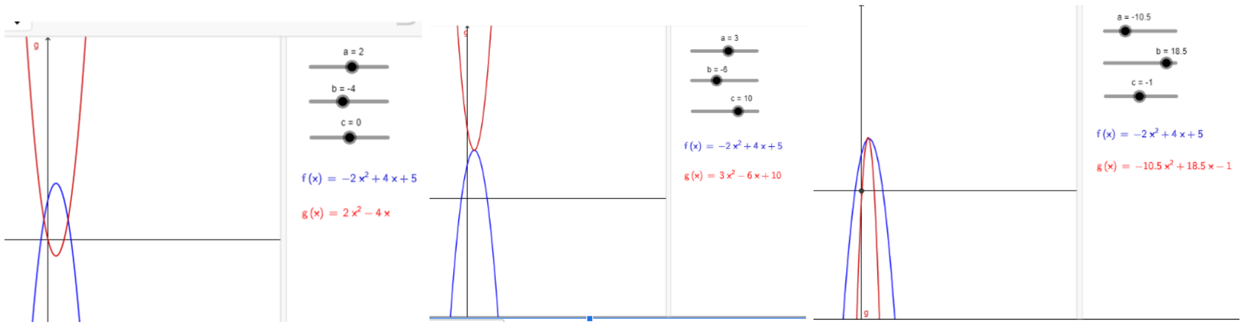

Figure 1. Answers submitted to meet the requirements of conditions 2, 3, 4 (left, g(x)=2x^2-4x), of 1, 2, 4 (center, g(x)=3x^2-6x+10), and of 1, 2, 3 (right, g(x)=-10.5x^2+18.5x-1).

Note that the submission presented in Figure 1 (right) ‘looks right’ and might be filtered as possible answer, whereas g(x)=-10.5x^2+18.5x-1 is incorrect. The platform collected and automatically analyzed the students’ answers (Figure 2), based on predefined characteristics and predefined thresholds for accuracy (Table 1). The submission presented at the first row of Figure 2 is of a student who simplified the task and constructed a claim relating to two conditions. Two of the examples are correct instances of the claim: There is a function g(x) that passes through the origin and its graph intersects the function f(x) in exactly one point. In the three examples presented on the second row, the values chosen for the coefficients are accurate options that may suggest that the student attended to the symbolic aspects of g(x): g1(x)=1x^2-2x+8, g2(x)=10x^2-20x+17, and g3(x)=3x^2-6x+10. The submission presented in Figure 2 (middle of the bottom row) also suggests that the student focused on the visual aspects by adjusting the slider to graph a ‘peculiar’ graph through the maximum of f(x), whereas the function expression is inaccurate.

The criteria for online analysis may be organized into three groups, as shown in Table 1.

Table 1: A partial list of STEP analysis criteria

Meet the requirements: Marked vs. submitted example	**Example characteristics**: Of mathematical objects	**Example characteristics**: Of methods of construction - heuristics
Marked 3 valid triplets Submission includes Demonstration of the marked statements	The functions share symmetry line The graph of g intersects the origin f(x)=g(x) at exactly one point g(x) is a function with minimum The graphs do not intersect The graphs intersect in two points The graphs intersect in the extremum	Solved simpler task (less than 3 conditions) “Peculiar” example Sketch (looks right but not correct symbolically) Easy to compute coefficients

	The intersection is not in the extremum Marked invalid triplet Marked 4, 2 or 1 conditions Examples demonstrating the marked **and** additional conditions Example demonstrating **part of** the marked conditions.	

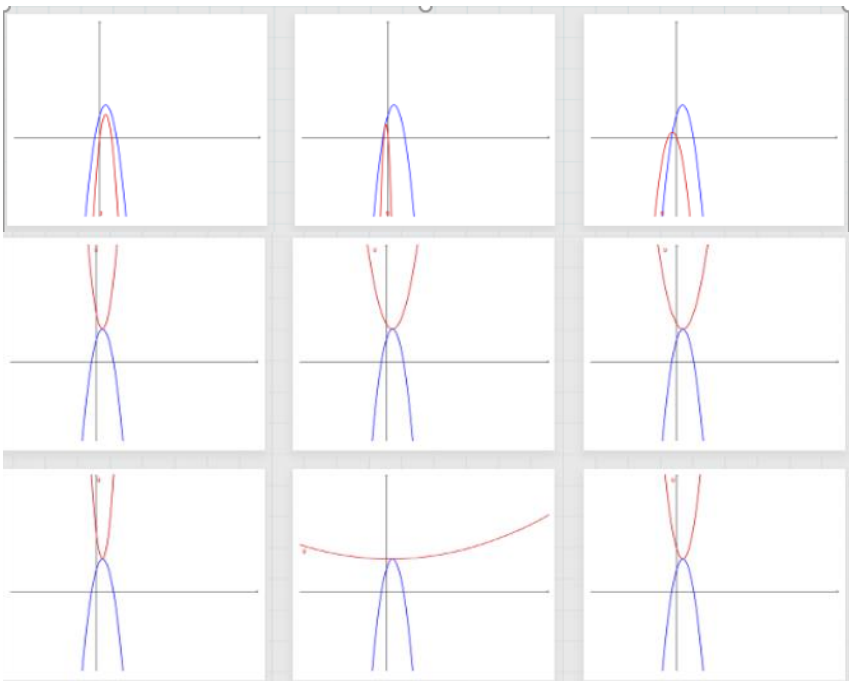

Figure 2. A collection of three submissions (a student's submission consists of one row)

WHAT IS IT AN EXAMPLE OF?

To summarize, the guiding principles and terms are: (a) each of the tasks requires the construction of example(s) for one or more statements; (b) the example is a static instance created by using the interactive diagram with specifically designed tools; and (c) the context of the example is set by a given or constructed claim, and the example could be provided by different mathematical input channels, which are part of the interactive diagram. In the task shown above, the requirement was to submit examples, but the claim is not explicitly stated. The task requires students to find out what is the maximum number of conditions that can form a claim, then support the answer by submitting existential examples. The interactive diagram is created in a multiple-linked representation (MLR) environment, and the means to create the example (construct the resulted graph) are sliders that can be dragged to independently change each parameter of g(x).

Returning to the question that guides our efforts: What are the structures and design patterns of tasks that could assess students' mathematical conceptions? Table 2 is an attempt to create a conceptual organization of the different tasks designed and studied so far. The demonstrated task is an example of the marked cell in Table 2. Next, I will describe the central aspects of this organization and explain why they are chosen as sources for assessment.

Table 2: Interactions that form the context of an answer to an EET

Mathematical content	**Provide evidence for:**			
	A given claim		**A given set of conditions**	
Input modalities	Provide an example(s)	Support or refute	**Specify the claim**	**Specify the claim** with reflecting feedback
Embodied: Supporting sensual attempts				
MLR: Supporting experimentation with reflecting feedback			X	

Assessing the interactions with input modalities

Using an interactive diagram in an MLR environment, and accepting answers in a variety of forms, encourages students to first "sense" the problem, control their actions and reflect on them during assessment, observe the effect of what they have created, and decide which of the examples should be submitted (Yerushalmy et al., 2017).

(i) The embodied input channel

such as sketching with a pen tool (Yerushalmy et al., 2017), fitting a graph by dragging a set of points (Nagari-Hadif, 2019), sketching lines or points related to graphs (e.g., tangent) using dedicated tools (Nagari-Hadif, 2017), using ready-made iconic constructs that serve as building blocks of graphs, or constructing and dragging soft constructions of geometric shapes or graphsFree-hand sketching (e.g., sketching with a pen tool (Yerushalmy et al., 2017), fitting a graph by dragging a set of points (Nagari-Hadif, 2019), sketching lines or points related to graphs using dedicated tools (Nagari-Hadif, 2017)) involves a sensory attempt that is as close as possible to a hand-drawn paper-and-pencil sketch, and can provide insights into students' conceptions and the mathematical resources they use. Each of these options may lead students to particular functions, constructions, or characteristics (e.g., continuity), and affect the learner-generated example space, even if other examples may be accessible in a different setting. The digital environment does not provide reflecting online feedback, but sketches are analyzed automatically, and STEP provides elaborated feedback consisting of the identified characteristics (Yerushalmy et al., 2017).

(ii) Input that generates reflecting feedback

The design of tasks based on MLR offers students an environment that encourages inquiry through systematic experimentation with embedded mirror feedback. For the designer of the task, MLR offers opportunities to control the interaction, for example, by determining the leading input representations, and by doing it in a way that reflects the purpose of the task (Naftaliev & Yerushalmy, 2017). For the designers of STEP assessment tasks, MLR is a source for characterizing the mathematics of the skills to be assessed. Below are a few design principles used and studied across cycles of design-based research:

a. Based on cognitive research related to MLR, we designed the assessment as an activity that progresses from using sensory/embodied knowledge, manipulating soft constructions or freehand drawings, toward experimenting with the interactive diagram to produce robust constructions or generalization with mathematical symbols. MLR has been the appropriate setting for designing a task that presents a cognitive conflict between representations that teachers may find valuable.

b. We designed the assessment to create learning opportunities in the course of experimentation. For example, the challenge of constructing an accurate symbolic representation, when stated and assessed within the MLR environment, should be considered a constructive assessment activity that can engage students in productive trial and error.

c. We designed the assessment in a way that attends to the student's preferences. Giving a choice of input types makes it possible to assess student's preferences, suggesting where each student's strengths lie. For example, when given the choice of sketching or using a symbolic function expression, many students prefer sketching, even if they do not necessarily provide examples that fit the requirements of the task. This design also allows assessing the tendencies of an entire class, or to follow a student along several activities and identify whether this tendency amounts to a habit.

Assessing the interactions with the given claims

The tasks that Yerushalmy and Nagari-Haddif studied (Nagari-Haddif & Yerushalmy, 2015; Nagari-Haddif, 2017) fall into three main categories: proving existential claims by means of appropriate examples, refuting universal claims by means of counter-examples, and demonstrating a definition by means of examples and non-examples. Although the first two categories (which are logically equivalent) require only a single example, in some cases students may be instructed to submit many different examples. What students consider "different" is in itself an indicator of mathematical reasoning. Certain types of examples suggest a richer concept image. These include degenerate functions or non-prototypical functions, and the attributes of the mutual relations between mathematical objects (e.g., an altitude coinciding with one of the vertices of the triangle). Students' choice of representations and transitions between them also serve as an indication of proficiency, strategy preference, or both. According to a key design principle of EETs, the number of examples required is part of the definition of a correct answer. The majority of STEP tasks ask for submission of a few examples as an answer. Requesting three different supportive examples enriches the response space, making possible an automatic analysis that distinguishes between the different characteristics appearing in each response and in the group response space. This design encourages students to move out of the comfort zone of the first immediate example, with the freedom of doing it in various ways. The request for several different examples also aims at motivating students to search for special or "peculiar" examples (in the sense of Mason & Watson, 2001), such as boundary examples or degenerate cases. The search for such examples must involve observation of the wide range of possible examples.

Assessing students' constructions of claims

The task described above did not provide a claim that needed to be exemplified. It is an example of another category of STEP DPs, characterized by tasks that require students to decide what can be constructed into an existential claim based on the given conditions, statements, and information. Such a decision must involve more than mere exemplification reasoning. In particular, it requires classification skills needed to establish a conjecture that could be a valid existential claim. Students experience the properties stated in a given condition by interacting with the ID, after which they may complete the converse or complementary process of classifying all the functions having those properties. Next, they may decide which of the given conditions can be grouped into a compound class of properties, and state a compound existential claim. Doing so in different situations may be considered an essential mathematical reasoning process (Mason, 2001), and it extends the range of example-based reasoning skills that we attempt to assess. To support the processes involved in formulating the claim and to decrease the cognitive load of analyzing the different classes that each condition defines, we developed another DP that allows stating the claim by choosing from a given set of relations. In this DP, each checked relation is reflected in the interactive diagram in a way that limits the domain of examples to those for which the checked relation is true, enabling interaction with more complex mathematical objects..

FURTHER LOOK AT USES OF EXAMPLE-BASED FORMATIVE ASSESSMENT

This concluding section looks at studies suggesting innovative perspectives on the use of example-based assessment for offloading part of the burden of teaching inquiry-based mathematics. Briefly, we will look at using technology to facilitate learning formats that make it easier for teachers to support personalization of learning. Whereas personalization refers to supporting the agency of students over ideas by providing online domain-specific evidence to the teacher, and providing elaborated conceptual feedback to the student.

Adaptive example-based assessment

Adaptive assessment methods are formative in that they adaptively adjust assessment level to the students' level or to their personalized learning preferences. Luz and colleagues (for details, see Luz, 2019, and Soldano, Luz, Arzarello, & Yerushalmy, 2019) suggest a different approach to adaptive assessment of an inquiry-based learning process. We introduced a dynamic geometry environment (DGE)-based activity that prompts students to generate examples for an unknown statement whose properties can be gleaned from the construction in the DGE. We asked students to find strategies that would lead them to the desired result (e.g., a conjecture or a proof of a conjecture that describes the statement embedded in the construction). Rather than starting with a claim, here the process starts with an activity that generates examples; for example, competing in an inquiry game in which the student and the computer assume different roles, is a way that motivates the generation of examples. Students go back and forth between cycles of identifying and formulating patterns and generalizations, as they struggle with conditions formulated in mathematical or natural language.

Evidence-based discussions

When using rich tasks in the classroom, teachers usually base the discussions either on their expectations of the student's work, or preferably, on actual student examples. Several studies explored the different ways in which teachers used topic-centered learning analytics. Olsher and Abu-Raiya (2019) claimed that when teachers have access to analytics regarding the mathematical characteristics of student answers, which are not limited to student mistakes, they use these insights in classroom discussions, expanding the range of discussions based on student work beyond correctness. Another example (Olsher, 2019) describes how a teacher uses online assessment to classify different examples into categories in a guided inquiry lesson. The classified examples are then used in a class discussion to refine student conjectures. Another opportunity for inquiry discussed by Hess-Green & Olsher (2018). The interactions with many, at times extreme, examples often generate opportunities to attend to the definitions. As all the examples submitted are of a mathematical object, and as mathematical objects are well defined, the automatic assessment of the examples requires precise specification of the algorithm used for the identification of these mathematical concepts.

Automatic grouping

As suggested above, fostering learning by inquiry with a DGE in the mathematics classroom is often inhibited by the teachers' limited ability to interpret and support learning by several students at once (Clark-Wilson & Noss, 2015). Group learning is one way to foster DGE-based inquiry learning (e.g., Stahl, 2009). At the same time, the formation of the groups is yet another activity that requires investment on the part of teachers. Grouping students is usually done over extended timeframes and often with minimal considerations of the students' work on a given task (Lou et al., 1996). Abdu, Olsher, and Yerushalmy (2019) studied the use of the STEP platform for multi-faceted automatic analysis of student answers to a single activity, to create a method that groups them in ways that are mutually beneficial to all students in the group, and provide teachers with recommendations on how to group students. This is part of a larger project, in which it may be possible to offer the teacher suggestions based on automated grouping using STEP data on students' work.

A FINAL NOTE

The pedagogical opportunities of research and implementation of Learning Analytics (LA) in the domain is yet to be explored. Shifting the attention from the big data to design of models that will allow LA be part of pedagogical *interventions* (rather than *implementation*s as termed by Wise et al., 2016) has the potential to introduce an important change in formative assessment.

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