The design of an exploratory learning environment to support Invention

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Abstract. We describe the design of the Invention Coach, an intelligent, exploratory learning environment (ELE) to support Invention, an exploratory learning activity. Our design is based on a two-pronged approach. Our own study of naturalistic teacher guidance for paper-based Invention uncovered phases in the Invention process. Prior research on the mechanisms of learning with Invention activities revealed specific instructional strategies. These two sources informed the design of the guidance offered by the Invention Coach. To our knowledge, this is the first design of a guided environment for Invention activities inspired by a model of naturalistic teacher guidance. Our work offers insight into styles of guidance that could apply to other exploratory learning environments.

Keywords: intelligent learning environment, human tutoring, exploratory learning, intelligent tutors

1 Introduction

While exploratory tasks support the constructivist nature of learning and have the potential to enhance 21st century skills, there is broad agreement that learners need guidance in their exploration [1]. But what kind of guidance will help learners to engage in productive exploration without eliminating the exploratory nature of the task? Designers of exploratory learning environments have investigated this question through various lenses – types of learner feedback [2, 3], “cognitive tools” for inquiry [4], and participation structures [5]. We explore the question of effective guidance for exploration in the context of an exploratory learning task called Invention, where learners invent their own formulas to describe scientific phenomena. We are now in the process of developing an intelligent, exploratory learning environment (ELE) called the Invention Coach, which scaffolds students through the Invention process.

Invention is an exploratory task that invites students to engage with deep, conceptual ideas by analyzing a set of data [6]. Students are asked to invent an expression of an underlying structure that runs throughout a set of contrasting cases. Cases are examples of phenomena with predesigned contrasts that highlight key features, providing students with clues to the abstract, underlying concepts. After exploring the cases and inventing their own structures, students are told the canonical structures, through traditional expositions (lecture, reading). Prior work suggests that Invention creates "a time for telling," preparing students to appreciate the "mathematical work" of equations [6] or "function of tools for solving relevant problems" [7].

Figure 1 shows an Invention task our computerized Invention Coach is designed to support. In this "Crowded Clowns" task, students are asked to invent a numerical "index" to describe how crowded the clowns are in each set of buses. Though students do not realize it, they are inventing the equation for density (d=m/v, where density is the number of objects crowded into a space). Most students initially attempt to describe crowdedness using a single feature – the number of clowns. They do not realize that crowdedness must consider two features related in a *ratio* structure (e.g. #clowns ÷ #boxes). The six buses in Figure 1 are contrasting cases designed to highlight the critical features of "crowdedness." For example, by contrasting cases A1 and B1 (see Figure 1), which both have 3 clowns but different-sized buses, students may notice that clowns alone cannot account for crowdedness, and space must be considered as well. Through an iterative process of generating and evaluating their inventions, students begin to realize that a workable solution must involve both features in some kind of relational structure. While many students do not produce the correct formula, the invention process prepares them to learn from a later lecture on ratio structures, which is the targeted content of our instruction.

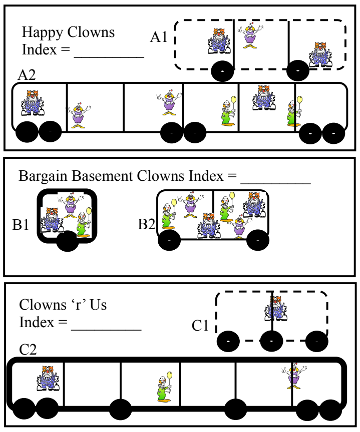


Fig 1. Invention task, adapted from Schwartz et al., 2011.

Invention activities are very successful in supporting transfer. In several studies, Invention has been more effective than traditional instruction at enhancing transfer and deep learning in science and math domains, both with adolescents and adults [6, 8, 9, 10]. But in most studies, students need subtle guidance from a teacher to engage in productive invention. In a move towards scaling up, we are developing a computer-based Invention Coach that will ultimately provide adaptive guidance as students engage in Invention. Through the design of the Invention Coach, we also explore what types of guidance are most effective in scaffolding an exploratory task.The most applicable related work comes from Roll, Aleven, and Koedinger [11], who developed an ELE for Invention activities in statistics. The learning environment we propose will share some characteristics with their Invention Lab but will differ in a fundamental way. While Roll et al.'s technology was developed through rational analysis of the task and empirical study of components of the Invention process, our Invention Coach is modeled on guidance from a human teacher.

To develop the Invention Coach, we are following a multi-phase approach of formal empirical research interspersed with design cycles and informal user testing. We began with a study of naturalistic human teachers' guidance of Invention and a review of the literature on learning with Invention. In the following section, we briefly review the results of both. We then describe the design of our current Invention Coach, focusing on the pedagogical elements of our design rather than the technical aspects underlying it. We are now in the process of implementing a Wizard-of-Oz version of the Coach, though we plan to build a fully adaptive system in the future.

2 A Two-pronged Approach to Design

The design of the Invention Coach was driven by a combination of our own empirical work and prior research and theory on Invention. Our study of naturalistic teacher guidance demonstrated the process of Invention by explicating the various subgoals teacher-student pairs tackle as they work towards a solution. The specific instructional strategies embedded in our Coach were drawn from research and theories on the mechanisms that make Invention a successful instructional paradigm.

Our analysis of naturalistic teacher guidance uncovered a process model of guided Invention with four phases [12]. In the "understand the problem" phase, teachers explained the task goal and constraints to students who were confused by the ill-defined goal of inventing an "index." In the "notice features" phase, teachers guided students to notice key features they often overlooked (most often bus size) or to think conceptually about what "crowdedness" means. In the "produce and reflect on an Invention" phase, students generated their numerical index and teachers helped them evaluate whether it was correct. There was also a "math calculation" phase, in which teachers and students worked to simplify and manipulate fractions or count key features. Informally, we noted that phases were not completed in a linear fashion; teacher-student pairs moved back-and-forth between them. As a result, our initial prototype Invention Coach supports each phase, without prescribing a specific phase order.

While the study of naturalistic tutor guidance revealed the subgoals of solving an Invention problem, specific instructional strategies were derived largely from the existing literature on Invention. Instructional strategies were designed to scaffold three core components of the Invention paradigm: noticing deep features of a domain, monitoring errors, and withholding direct feedback. First, noticing deep features of a domain is a critical step for problem-solving success. For instance, novices often focus on the surface features of a problem while experts focus on the deep principles that underlie a problem solution [13]. An effective way to help novice learners notice key features is to have them compare and contrast example cases that explicate the features [7]. Our carefully designed contrasting cases systematically differ on key features, so that certain pair-wise comparisons reveal the necessity of considering a not-so-obvious feature. Second, Invention helps learners to identify gaps in their understanding, which they can then seek to fill in later expository instruction [14]. Through the process of monitoring and reflecting on their solution attempts, learners often come to see that their invention is inadequate. When they later receive a lecture on the canonical problem solution, they are prepared to understand how it avoids the errors they made in their own solution attempts. We scaffold monitoring by encouraging learners to explain their solutions. Related work on self-explanation suggests that it strongly enhances metacognitive monitoring [15]. A third critical component of Invention is that giving away the answer or showing students how to solve the problem cuts off learners' exploration and hinders their ability to notice and monitor [9]. Thus, instead of providing direct right/wrong feedback and elaborative explanatory feedback, our system exposes inconsistencies in the learner's solution. In sum, the three instructional strategies our system employs are (1) encouraging learners to contrast cases (2) inviting learners to explain their solutions and (3) providing feedback that exposes inconsistencies in a learner's solution.

3 Design of Invention Coach Prototype

Our research findings along with prior work on Invention informed the design of the Invention Coach. We designed instructional components corresponding to each phase of the Invention process model derived from our study. Additionally, some components scaffold students as they engage in the core learning mechanisms of the Invention paradigm. Our initial prototype was designed to be operated by a "Wizard-of-Oz" (the experimenter), who can launch the student into instructional components in any order, based on her assessment of the student's current knowledge state. While we ultimately plan to build a fully adaptive Invention Coach, the Oz configuration allows for flexible application of process phases across students. Perhaps more importantly, the Oz configuration will help us identify the trigger conditions for each type of coach guidance. We are now in the throes of building our first prototype Invention Coach. We are using the Cognitive Tutor Authoring Tools (CTAT, [16]) to build our ILE as an example-tracing tutor with additional custom programming.

In our Invention Coach, the student is initially left to work independently on his invention. During this independent work time, students typically inspect the cases provided and begin entering potential index numbers for each case. Students can also click the "rules tab" to re-read the rules that their index must follow, the "calculator tab" to display an on-screen calculator, the "notepad" tab to display an on-screen notepad, or the "help" or "submit" buttons to request feedback from Oz. Oz only provides guidance in response to the student's request for feedback, or whenever the student has been working uninterrupted for five minutes.

There are two types of guidance that Oz can provide: modules and hints. A module is a short exchange between the computer and student focused on a particular subgoal.

For example, our “ranking module” (Figure 2A) asks students to rank the bus companies from most to least crowded. After the student ranks the companies, the system automatically provides feedback and, if needed, additional scaffolding. Once the student has successfully ranked the companies, the module ends, and the student is left to work independently again. Hints represent the second type of guidance Oz can provide. Hints are much simpler than modules, consisting of a single text bubble displayed to the student. The system provides largely high-level hints with broad suggestions and never gives a “bottom-out” hint, which would give away the answer.

Each of the instructional components included in the Invention Coach was designed to guide students through one of the four process phases revealed in our analysis of teacher guidance (Table 1). Most components employ one of three instructional strategies that support the mechanisms of learning with Invention: encouraging students to contrast cases, inviting students to explain their solutions, and provide feedback that exposes inconsistencies in the student’s inventions.

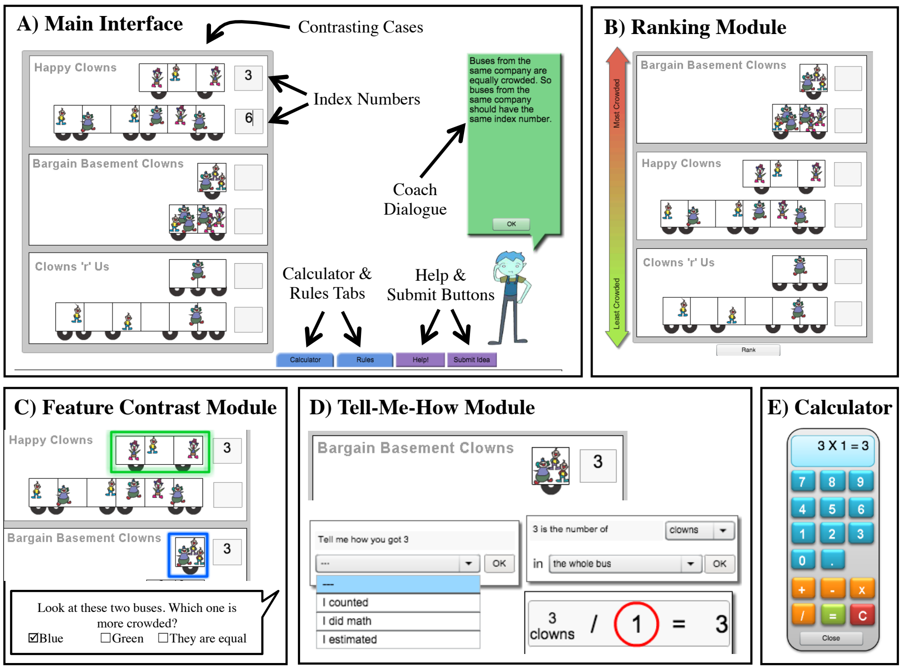
Table 1. Invention Process Model, Instructional Strategies, and Instructional Components

Process Phases	Process Description	Instructional Strategy	Instructional Component
Understand the Problem	Explain or describe task goal and constraints	Expose inconsistencies	Rule-related hints Rules tab
Notice Features	Notice key features of the underlying structure (e.g. #objects, space)	Contrast cases	Ranking module Feature Contrast module
Produce and Reflect on an Invention	Generate a solution (e.g. index) and evaluate its correctness	Explain solution	Tell-Me-How module
Math Calculation	Simplify/manipulate fractions	--	Calculator

The two instructional components that help students through the “understand the problem” phase are the “rules tab” and the rule-related hints. Rule-related hints provide feedback exposing inconsistencies in students’ inventions. For instance, if a student’s invention is not generalizable and only works for specific cases, Oz can provide the following hint: “Don’t forget: you have to use the exact same method to find the index for each bus!”

The Invention Coach also supports the “notice and understand features” phase of the Invention process via the “ranking” (described above) and “feature contrast” modules. Ranking the buses from most to least crowded helps students think about why some companies are more crowded than others, which starts to focus them on the features that determine crowdedness. In the “feature contrast” module (Figure 2C), Oz can select two specific buses to contrast. The student is then asked to note which features make one bus more crowded than the other. For example, Oz could ask the student to contrast cases A1 and C2 in Figure 1. Since the number of clowns is held constant across the cases while space changes, the student may begin to notice that clowns alone cannot account for crowdedness, the feature of bus size is important too.

Both “ranking” and “feature contrast” modules employ the instructional strategy of comparing and contrasting cases, to scaffold learners in noticing key features of the problem space.



Buses from the same company are equally crowded. So buses from the same company should have the same index number.

Look at these two buses. Which one is more crowded?
☑Blue ☐Green ☐They are equal

Tell me how you got 3
--- ▾ OK

I counted
I did math
I estimated

3 is the number of clowns ▾
in the whole bus ▾ OK

3 clowns / 1 = 3

Fig. 2. Prototype Interface and Modules.

The backbone of the Invention Coach is the “tell-me-how” module (Figure 2D), where students are asked to enter and explain their inventions. This serves to recreate the “produce and reflect on an invention” phase of the process while encouraging students to monitor their own errors. In this module, students explain how they arrived at their answer (by selecting whether they “counted,” “estimated,” or “used math”). Students who indicate that they “counted” are further prompted to identify what exactly they counted, while students who “used math” must then use a calculator feature to show how they derived their answers. Students are never provided with direct right/wrong feedback on their solutions. Instead, the tell-me-how module encourages students to explain how they arrived at their solutions, right or wrong. We hope that in the process of explaining their answers, and connecting the math to referents in the cases, students will begin to reflect on their answers and identify gaps in their own understanding. Another key function of this module is to help Oz (and eventually the fully adaptive system) understand how a student generated her index so it can determine appropriate feedback.

Finally, to enable the math calculation phase of the Invention process, students are provided with a calculator (Figure 2E). In our study of naturalistic teacher guidance, many students had difficulty engaging in simple math (e.g. 6 divided by 3), and a large proportion of teacher talk focused on math calculations such as simplifying fractions. The calculator enables students to off-load some of this challenging calculation work and instead focus on the larger concepts behind the math. The "calculator" tab is available in the main interface for students to call up at any time during the task. A calculator is also part of the "tell-me-how" module as described above.

Throughout the phases of the Invention process, the Coach's feedback points out inconsistencies in students' problem solutions. Instead of providing right/wrong or elaborative feedback when students create an incorrect invention, the Coach presents information to contradict the wrong invention. For instance, the Coach may remind the student that their Invention must generalize to all cases or that it must account for two cases that have the same crowdedness. The coach may also present pairs of cases that directly contradict the student. For instance, if a student believes that an irrelevant feature is important, the Coach will show two cases where the irrelevant feature varies but crowdedness does not. This type of feedback enables students to explore on their own, while encouraging them to self-monitor errors and "see" deep features.

In our current design, several components of the Invention Coach must be selected by Oz, while some intelligence is built into the system. The Oz selects whether to respond to a request for feedback by launching a student into a module (e.g. feature contrast, tell-me-how, or ranking) or by giving a single hint, adapting the path through the Invention space based on each student's individual needs. However, once inside a module, the system largely controls the interaction by selecting appropriate feedback and prompting the student to take action.

4 Discussion and Conclusion

We have described the design of a computer-based Invention Coach, which was inspired by a study of naturalistic teacher guidance of paper-based Invention and by prior research on the mechanisms behind Invention. The Invention Coach contains instructional components to address each phase in the Invention process, which can be adaptively selected. The system employs three instructional strategies that target key mechanisms in learning from Invention: contrasting cases, self-explanation of problem solutions, and feedback that exposes inconsistencies in students' solutions. While we are currently implementing a Wizard-of-Oz version of the Invention Coach, we ultimately aim to develop a fully adaptive system.

This work contributes more broadly to work on Invention and exploratory learning environments. To the best of our knowledge, the work presented here is the first design of a guided environment for Invention activities that is based on a model of naturalistic teacher guidance. Our design offers insight into possible strategies and phases of guidance that could be more broadly applicable in other exploratory learning environments and tasks. Specifically, if the Invention Coach we've built proves successful, it would argue that unguided exploration can be augmented by guidance that highlights inconsistencies in student work, contrasts cases to make relevant features salient, and invites students to explain their solutions. These forms of guidance may prove especially useful for developers who wish to retain the emphasis on active processing and construction of ideas inherent in exploratory learning environments, while avoiding the pitfall of unproductive aimless exploration [2, 3].

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