Iyer, S. et al. (Eds.) (2022). Proceedings of the 30th International Conference on Computers in Education.
Asia-Pacific Society for Computers in Education

Adaptive Scaffolding to Support Strategic Learning in an Open-Ended Learning Environment

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Abstract: An important goal for intelligent learning environments is to provide adaptive support for learners. This paper presents an adaptive scaffolding framework designed to support strategic learning in Betty's Brain, an open-ended learning-by-teaching environment. The framework includes an online strategy detector that identifies students' sub-optimal use of cognitive-metacognitive strategies, and a conversational adaptive feedback mechanism to help students overcome their difficulties. We ran a pilot study with undergraduate students to determine how well they applied the adaptive scaffolds provided by our framework. Our qualitative case study analysis used students' activity logs, one-on-one interactions with researchers, and eye-gaze patterns on the Betty's Brain screens, to infer their learning behaviors and performance. Findings suggest that some scaffolds helped students develop more effective and strategic behaviors to overcome their difficulties. The results also suggest a roadmap to improve scaffold design and better support long-term learning strategies in Betty's Brain.

Keywords: Adaptive scaffolding, learning strategies, open-ended learning environments

1. Introduction

External scaffolding adapted to students' learning difficulties can help them achieve their learning goals while working on open-ended learning tasks, such as constructing models of science phenomena (Basu et al., 2017). Adaptive scaffolding is especially needed in open-ended learning environments or OELEs (Land, 2000), where students can develop and refine their problem-solving approaches. In this paper, we build and evaluate an adaptive scaffolding framework in Betty's Brain (Leelawong & Biswas, 2008), an OELE where students learn about scientific processes by modeling them as cause-and-effect relations to teach a virtual agent Betty.

The goals of this paper are to present our adaptive scaffolding framework and study its usefulness. Learners who apply effective learning strategies to build, monitor, debug and refine their models achieve higher success in their learning outcomes in Betty's Brain (Munshi et al., 2018b; Segedy et al., 2013). We have previously designed scaffolds in the Betty's Brain environment that tracked 'inflection points' in students' behaviors during learning, and offered timely feedback to help them regulate their behaviors (Munshi et al., 2022). While evaluating these scaffolds, we noted that high and low performing students reacted differently to the scaffolds they received. Low performers often lacked the ability to interpret the feedback, causing them to continue to exhibit ineffective behaviors and fail to successfully complete their tasks. This suggests a need to develop more systematic strategy-oriented feedback that students can interpret and adopt in the context of their learning tasks. We use such findings from our prior work to inform the scaffolding approach presented in this paper.

The rest of this paper is organized as follows. Section 2 provides a background for our scaffolding design framework. Section 3 presents an overview of the Betty's Brain environment. Section 4 discusses the design and implementation of our adaptive scaffolding framework in Betty's Brain. Section 5 outlines the pilot study and data collection scheme (involving students' activity logs, in-the-moment interviews, and eye-tracking data) to evaluate the scaffolding framework. Section 6 reports the findings from data analysis, and the lessons learned, that provide an opportunity to further improve the feedback design to support the needs of a more novice middle school population in our future studies. Section 7 presents our conclusions and directions for future work.

2. A Framework for Adaptive Scaffolding

Scientific model-building is a multi-faceted process achieved by developing, debugging, and refining the model in stages. Typically, K-12 students have little experience with such cognitively demanding practices, and have difficulties engaging in the model-building process (Gilbert et al., 2016). To address such challenges, we develop an adaptive scaffolding framework to support learners as they build causal models of a scientific process in Betty's Brain. *Scaffolding* describes pedagogical support calibrated to the learner's current level of understanding. It helps them accomplish tasks they could not accomplish alone (Wood et al., 1976). This difference between what a learner can accomplish by themselves versus with external assistance is characterized by the *zone of proximal development* (ZPD) (Vygotsky et al., 1978), that informs how students' range of understanding and problem-solving can be extended in a way that provides sufficient challenge but prevents frustration or boredom. Puntambekar & Hubscher (2005) note some key features of scaffolding: a shared understanding of the activity and goals; ongoing diagnosis of the task, subtasks, and the student's current level of understanding; tailored assistance. The goal for scaffolding is to improve students' self-directed learning skills and strategies (Kim et al., 2018).

The challenges for adaptive scaffolding are to ensure that the intervention does not happen too soon or too often, that students do not become too reliant on feedback for making progress, and to avoid feedback that is perceived negatively and evokes frustration. Identifying individual students' ZPD thus becomes an important aspect to trigger adaptive scaffolds. In this paper, we seek to adhere to these principles in constructing the adaptive scaffolds. Our scaffolds are real-time conversational feedback delivered by virtual agents within Betty's Brain. They seek to directly influence students' cognitive strategies, thereby also impacting their metacognitive processes. The feedback is provided when students face difficulties in their model-building, debugging, and problem-solving tasks while learning.

3. The Betty's Brain Learning Environment

Betty's Brain (Leelawong & Biswas, 2008) is an OELE that uses learning-by-teaching to help K-12 students learn about scientific processes like climate change. Students teach a virtual agent Betty about *causal links* (cause-and-effect relations) between concepts, to build a map of the scientific process.

The learning environment provides students with a set of tools to learn and teach Betty. The ***science book***, a set of resource pages, helps students access information about cause-and-effect relations in the science domain (e.g., climate change) to teach Betty a causal model of a scientific process (e.g., the greenhouse effect). The ***causal map*** provides a drag-and-drop interface to build causal models (by adding, deleting, or modifying concepts and causal links). The **quiz** tool allows students to probe Betty's understanding by asking her to take a quiz, where the quiz results help them to evaluate the correctness of the current causal map. A mentor agent Mr. Davis scores these quizzes. *Overall*, these tools provide students with the resources needed to complete their learning goals. But novice learners, who fail to invoke cognitive and metacognitive strategies to aid their model-building and debugging processes, often find it difficult to use these tools effectively. Adaptive scaffolding, provided at opportune moments during learning, can help these students become better learners as they teach Betty.

4. Designing Adaptive Scaffolds in Betty's Brain

Triggering scaffolds in students' ZPD is important to support strategic learning. Weinstein et al. (2000) define *strategic learning* in terms of students' knowledge of learning strategies, ability to apply strategies, and their self-regulation, including cognitive and metacognitive processes. Applying the ZPD framework to support strategic learning requires first identifying *students' current abilities* in terms of their cognitive and metacognitive processes and their *difficulties* in the *context of their current tasks*. Identifying the trigger conditions and the context for scaffolding is especially challenging in OELEs like Betty's Brain where students can pursue their own strategies. This requires a good understanding of how students apply cognitive and metacognitive strategies during learning, and how to interpret their activities in the context of their current task. Selecting meaningful scaffolds and providing them 'as-needed', to help students engage in more effective behaviors, is also a challenge.

The Betty's Brain task model (Kinnebrew et al., 2017) provides a framework for identifying students' cognitive and metacognitive behaviors from their activity patterns, by mapping tasks and activities (viz., **Read**ing science book pages; **Build**ing causal models by adding, deleting, or modifying links; checking the models by taking a **Quiz**) to higher-level cognitive processes like information acquisition (**IA**), solution construction (**SC**), and solution assessment (**SA**). Cognitive strategies relate to IA, SC, and SA activities. Metacognitive strategies result from meaningful combinations of the IA, SC, and SA processes. When combined sequentially, these actions can be expressed as binary relations (Basu et al., 2017) and further interpreted as "effective" behaviors (e.g., *Read→Add Correct Link*). Prior Betty's Brain research has used sequential pattern mining on activity sequence data to detect behavioral patterns that suggest the use of productive or unproductive strategies (Munshi et al., 2018b). In this paper, we track such strategies *online* to trigger appropriate scaffolds.

Figure 1 presents the implementation of our scaffolding framework in Betty's Brain. Students' mouse clicks, interpreted as *events* by the system, are recorded as their current *action* (e.g., adding a *"A increases B"* link) and the active *view*, or context, of the current action (e.g., the student is engaged in the Build view). The 'learner model controller' uses this information to construct sequential relations, or behaviors. To ensure that we scaffold *only* when a student has difficulties, our framework specifically tracks behaviors that suggest ineffective strategy use. A *pattern counter* ensures that a scaffold is triggered only when an ineffective strategy is used multiple times, thereby giving the student some agency the first time to monitor their situation and refine their strategy without external intervention. An ineffective strategy used more than a set number of times (say, 2) is considered an active 'pattern' and placed on a *priority queue* (Figure 1). The scaffolds, triggered by the highest-priority active pattern at a time, are delivered by the mentor agent Mr. Davis or Betty. The agent keeps track of the time that has passed since the student was last scaffolded, to avoid intervening too often. If this time exceeds a threshold (say, 5 minutes), the agent fetches the current highest-priority pattern, which becomes the **triggering condition** to find relevant scaffolding. Each trigger condition is mapped to a **conversation tree** (Segedy et al., 2013) that allows feedback delivery in a back-and-forth conversational manner tailored to address students' gaps in strategy use at that trigger condition.

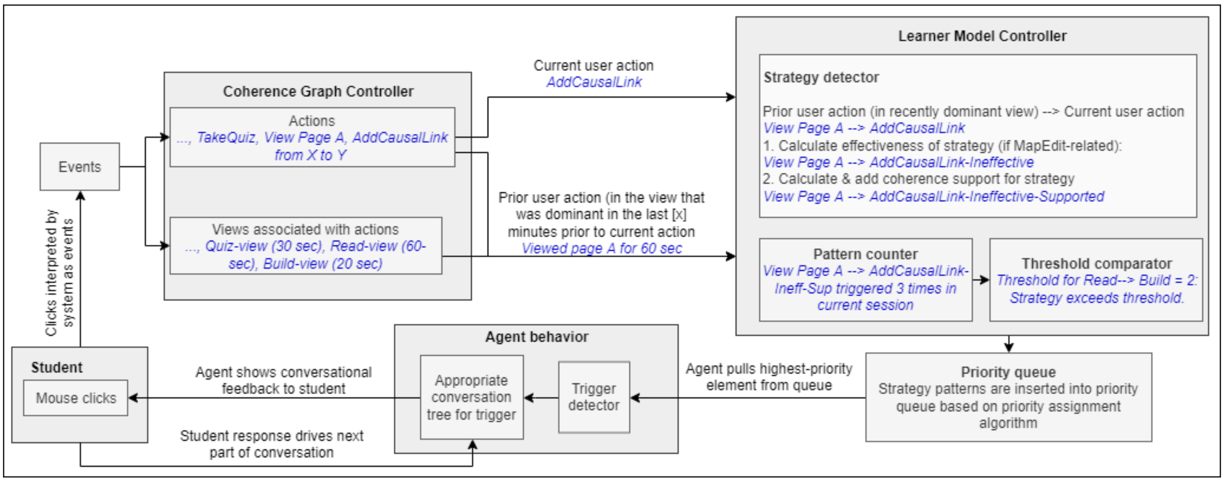


Figure 1. Implementing the adaptive scaffolding framework in Betty's Brain *(examples in blue)*

A "scaffold level" parameter further determines if a student receives *general feedback* (level 0) or more *contextual feedback* (level 1). A student is initially provided a Level-0 scaffold but if the same type of scaffold is triggered again, suggesting that the student has been unsuccessful in developing the associated strategy so far, they would now receive a Level-1 (more direct) scaffold. In the current design iteration (Table 1), we did not assign multiple levels to some scaffolds, because their trigger conditions required contextual feedback directly at Level-0 for the scaffold to be useful and actionable. Table 1 lists the seven types of scaffolds included in the current iteration of our scaffolding framework. In the first column, the three broad types of behavior patterns appear in **bold**: *Read→Build* (IA→SC), *Quiz →Build* (SA→SC) and *Quiz→Read* (SA→IA), while the additional task contexts tracked by the pattern detection framework for triggering scaffolds are indicated in *italics*. In the second column, the levels of specificity of the scaffold, where applicable, are indicated in **bold**.

5. Methods

To evaluate the usefulness of scaffolds, we conducted a pilot study with six undergraduate students (median age: 20 years; 2 males, 4 females) at Vanderbilt University, USA. We ran this study with undergraduates to see how this more mature group interpreted and used the feedback, so that we may derive actionable insights to refine the feedback before testing it out with middle schoolers. Since the objective of the pilot study was to observe each student's learning process, interact one-on-one, and perform a qualitative analysis of feedback usefulness, the low number of participants was sufficient.

At the beginning of the study, participants were provided an overview of Betty's Brain. Then they worked on an introductory unit for 15 minutes, to get hands-on experience using the learning tools. They then switched to the "climate change" unit and worked on building their causal models for 2 hours. An experimenter observed each student and interacted with them when needed.

Table 1. *Types of strategic adaptive scaffolds in current iteration of scaffolding framework*

Scaffold Type	Excerpt from Conversation Tree
Read→Build Correctness: Shortcut Link **(the Build is a shortcut i.e. A→C link, instead of A→B→C)**	**Level 0:** Mr. Davis: "... Your map may have shortcut link(s) from … part of the science book. Do you want me to tell you more about shortcut links? ..."
	Level 1: Mr. Davis: "… you still have a shortcut link coming out of [Concept A]. ... Review pages [X, Y] to find out more about the missing link(s) ...."
Read→Build Correctness: Incorrect Link **(Build incorrect but not shortcut)**	**Level 0:** Mr. Davis: "You may have incorrect links ... There are three ways a link may be incorrect: … (a) linking two unrelated concepts; (b) sign (increase/decrease) is wrong; (c) direction is wrong. Review Pages [X, Y] ..."
	Level 1: Mr. Davis: "… incorrect link out of [Concept A]. Review pages …"
Read→Build Coherence **(Build is not coherent to prior Read)**	**Level 0:** Betty: "This … is not related to what we read." Mr. Davis: "... A good strategy is to work on one topic at a time … helps .."
	Level 1: Mr. Davis: "... you just added a link [A→B] from Page [Y] but you were reading Page [X]. Try to add all links from Page [X] first …"
Quiz→Build Correct Link Annotation **(unmarked correct links)**	Mr. Davis: "... There are correct links .. that you have not marked on your map yet. ... Select a quiz question graded 'correct' (green checkmark). …"
Quiz→Build Incorrect Link Annotation **(unmarked incorrect links)**	Mr. Davis: "... Select a quiz question graded incorrect (red X). … This means that at least one of the links… is wrong. Mark these as 'maybe wrong'..."
Quiz→Build Coherence **(when Build is not coherent to last Quiz)**	Mr. Davis: "... After Betty takes a quiz, … first teach her the concepts she did not answer correctly. This way, she can get these right the next time …"
Quiz→Read Coherence **(when Read is not coherent to last Quiz)**	Mr. Davis: "... I can help you find information from the science book to correct Betty's wrong answers. Type … in the *search bar* of the page …"

We collected the following data: **(a) Activity logs:** Students' system interactions logged as activities with timestamps. **(b) Screen recordings:** System interface visible on laptop screens recorded as video files using OBS Studio. **(c) Interviews:** An experimenter interviewed each student one-on-one at different points while learning, especially after they received scaffolds, to know their thoughts on the feedback and how they planned to use it. Interviews were recorded using OBS, transcribed using Otter.ai software, and manually checked for transcription errors. **(d) Eye-gaze logs:** Tobii 5C eye-trackers recorded students' eye-gaze movements which were superimposed on OBS screen videos.

6. Findings

6.1 Count of Scaffolds Received by Participants

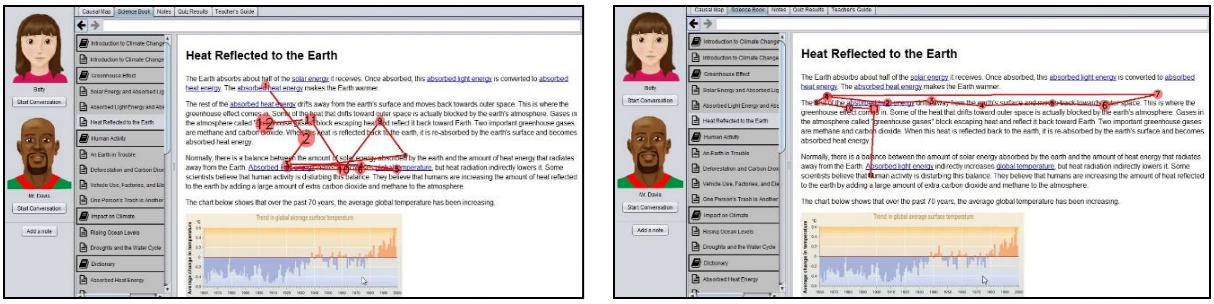
Table 2. *Count of different types of adaptive scaffolds received by study participants*

Participant ID	Count by Scaffold Type				Total Count
	Read→Build Shortcut Link	**Read→Build Incorrect Link**	**Read→Build Coherence**	**Quiz→Build Correct Link Annotation**	
P01	2	4	1	-	7
P02	-	2	-	-	2
P03	1	2	-	1	4
P04	3	2	-	4	9
P05	-	2	-	-	2
P06	2	2	2	4	10
Total (n=6)	8	14	3	9	34

From Table 2, 34 scaffolds were triggered across the 6 participants. Only 4 of the 7 adaptive scaffolds from Table 1were triggered during the study and are included in Table 2. Of these, *Read→Build: Incorrect Link* was triggered most frequently, and received at least twice by every student. The dominance of this scaffold across students suggests that they frequently attempted a *Read→Build* strategy to teach Betty but were often unsuccessful with applying it on their maps.

6.2 Case Study Results

We study usefulness of the scaffolds received by students in Table 2 by doing a qualitative analysis that combines information from the different data streams (Section 5) to assess how each type of adaptive feedback affected students' subsequent strategic learning behaviors and performance. Due to space constraints, we discuss the results for two randomly selected representative students - P03 and P06.



Heat Reflected to the Earth

The Earth absorbs about half of the solar energy it receives. Once absorbed, this absorbed light energy is converted to absorbed heat energy. The absorbed heat energy makes the Earth warmer.

The rest of the absorbed heat energy drifts away from the earth's surface and moves back towards outer space. This is where the greenhouse effect comes in. Some of the heat that drifts toward outer space is actually blocked by the earth's atmosphere. Gases in the atmosphere called "greenhouse gases" block escaping heat and reflect it back toward Earth. Two important greenhouse gases are methane and carbon dioxide. When this heat is reflected back to the earth, it is re-absorbed by the earth's surface and becomes absorbed heat energy.

Normally, there is a balance between the amount of solar energy absorbed by the earth and the amount of heat energy that radiates away from the Earth. Absorbed light energy indirectly increases global temperature, but heat radiation indirectly lowers it. Some scientists believe that human activity is disturbing this balance. They believe that humans are increasing the amount of heat reflected to the earth by adding a large amount of extra carbon dioxide and methane to the atmosphere.

The chart below shows that over the past 70 years, the average global temperature has been increasing.

(a) Unsystematic reading (b) Systematic line-by-line reading

Figure 2. Contrasting gaze patterns of student P03 while reading a Science Book page

<u>Read→Build Shortcut Link Feedback:</u> This scaffold was triggered by a *Read→AddShortcutLink* pattern where, after reading, the student added "shortcut links", i.e., a direct link between two concepts, e.g., A→C, instead of building the more complete relations A→B→C. The scaffold provided pointers on how to read the Science Book more strategically so as not to miss important causal chains. <u>Student P03</u> received this feedback once. She followed Mr. Davis' suggestion and started reading the Science Book. Eye-gaze movements from this period (Figure 2) show that her gaze initially moved between unrelated sections of the page (Figure 2a), suggesting an inability to find the information needed to fix the shortcut link. Then she studied the links on her map more closely and came back to reading. Then she started more systematic line-by-line reading (Figure 2b), that was followed by fixing the shortcut link. This suggests that the feedback helped the student develop a better map-debugging strategy. <u>Student P06</u> received this feedback twice. After the first feedback at t=13 min, she corrected the shortcut links, although she did not review the Science Book as suggested. At t=22 min, P06 received the second feedback. Eye-gaze fixations show that she ignored a part of the feedback that suggested her to "read Science Book pages". After the scaffold, P06 did not read again, instead adding links she assumed would fix the shortcut link. But she was unable to fix the errors. We notice a reliance on intuition versus carefully reading the feedback here. *<u>Overall</u>*, the *Shortcut Link Feedback* was useful as a map-debugging-by-reading strategy at times when students read and followed the feedback carefully.

Read→Build Incorrect Link Feedback: This scaffold was triggered by a *Read→IncorrectLinkEdit* pattern. Mr. Davis explained *why* links may be incorrect, and pointed to certain pages to identify incorrect links. Student P03 received this feedback 2 times. At t=36 min, after a Level-0 one, she fixed one of two incorrect links. In an interview, she surmised that she only fixed her last link since Mr. Davis showed up right after she had added it, making her guess it could be wrong. After getting the more direct Level-1 feedback, P03 fixed her other errors. But she continued to add incorrect links, suggesting that she had not internalized the suggested strategy. Student P06 also received this feedback 2 times. After the first feedback at t=29 min she went to the suggested Science Book page but could not extract the correct causal information, so her map errors remained. At t=38 min, P06 received a Level 1 feedback that she quickly scanned (gaze movements) and treated more as a 'corrective' hint versus a 'strategic' one. Instead of the suggested reading, she deleted a link which did not fully solve the issue. *Overall*, this feedback had partial success in helping students address their model-building errors. We need to make the feedback logic more transparent so that students avoid acting on their assumptions of the feedback.

Read→Build Coherence Feedback: This scaffold was triggered by a *Read→IncoherentLinkEdit* pattern, i.e., adding links unrelated to recent reading. Mr. Davis suggested a coherent *Read→Build* strategy to better organize the causal model and prevent potential errors. This feedback was not triggered for P03, suggesting that she showed coherent *Read→Build* behaviors. Student P06 received the feedback twice. Eye-gaze movements after the first feedback show the student pay more attention to a piece of text in the Science Book, which she then used to refine her understanding and correct map errors. At t=33 min, P06 received the next feedback but did not follow the suggestion this time.

Quiz→Build Correct Link Annotation: This feedback was triggered by a *Quiz→Build* pattern, where a student did not annotate ("mark as correct") the links proven correct in a quiz. Mr. Davis suggested that the student use the 'Checkmark' feature to annotate the link(s), explaining how this could help spot incorrect links. Student P03 received this feedback once. After the feedback, she looked at the quiz questions graded as correct, used the Quiz Explanations feature to look at associated links (verified from gaze movements) and marked the unmarked correct links on her map. Student P06 received this 4 times. Gaze movements from the first time suggest that P06 followed Mr. Davis' suggestion by marking correct links. She continued marking links associated with other correct quiz answers, suggesting that she found the strategy useful and internalized it. However, from an interview, the feedback was not as useful to her later, because she was already aware of this strategy by that time. This shows a need to better monitor students' behaviors and look for evidence of strategy internalization. *Overall*, this feedback was followed by students and helped them to adopt the intended strategy in their work.

7. Conclusions

This paper discusses our strategy-oriented adaptive scaffolding framework in Betty's Brain. Scaffolds were triggered when students displayed continued ineffective use of strategies as they worked on their model-building tasks. Four out of seven scaffolds were triggered in the pilot study, but that may be attributed to the more mature undergraduate participants. The combination of log traces, screen recordings, interview responses, and eye-tracking data for qualitative case studies allowed us to make deep inferences about student behaviors and scaffold usefulness. Findings from Section 6 show that some scaffolds were useful while others require further contextualization and elaboration. As next steps, we want to use these results to refine our scaffolds. For instance, we will revise the agent conversations to make the purpose of the strategies clearer to students and help them understand the contexts in which they may apply. Such additional clarification is especially important to support more novice middle schoolers, who often find it hard to understand and apply productive learning strategies (Munshi et al., 2022). We would then like to a quantitative study in a middle school classroom for scaffold evaluation. We will extend our framework to explicitly study relations between students' cognition and affect in self-regulation (Munshi et al., 2018a), and how these influence their strategies in Betty's Brain. Our goal will be to combine cognitive-metacognitive strategy triggers with affective triggers, to generate more engaging and productive scaffolds for learning.

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