Focusing Problem Solving in Design-Centered Learning Environments

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Abstract. Design-centered learning environments offer great promise for providing effective, grounded learning experiences. Learners are given a set of design criteria and a library of components which they use to design artifacts that will satisfy the specified criteria. Despite their appeal, design-centered learning environments are plagued with complexities that can overwhelm learners. To address this problem, we have developed a proactive problem-solving focus mechanism that helps learners cope with the complexities inherent in design-centered learning. By exploiting a rich model of the design context, the focus mechanism selects design problems and intervenes with multimedia advice. The mechanism has been implemented in DESIGN-A-PLANT, a design-centered learning environment for botanical anatomy and physiology. Formative evaluations with middle school students are encouraging.

1 Introduction

Constructivism holds as its most central tenet that learning *is* building knowledge structures [11]. To promote constructivist learning episodes, it follows that learning environments should facilitate knowledge construction, and recent years have witnessed a remarkable growth in learning environments that purport to do exactly this. The resurgence of interest in microworlds [13, 7, 2, 8] demonstrates the growing belief that manipulable simulations offer experiences that are qualitatively different from more didactic approaches.

One of the most promising techniques in the constructivist's arsenal is *design*. Whether it is a child assembling a house from building blocks, an engineering student laying out a circuit, or a graduate student in mathematics constructing an axiomatic theory, the learner is actively engaged in a process that requires them to grapple with fundamental issues in their respective domains. In each case, they emerge from their experience with a deep appreciation for the rich conceptual interconnections that define their subject matters.

Unfortunately, it is precisely the characteristics of design-centered environments that offer the greatest potential that also pose the greatest challenge to their development. Because the size of the search space for design problems constantly threatens to overwhelm the learner, techniques must be developed to focus problem-solving activities on the most critical aspects of the concepts under consideration. While providing advice for design tasks is a much investigated topic [4] and efforts have been made to study how to automate the instruction of design per se [6], the primary contributions of other design-centered learning environments lie not in focusing problem-solving but rather in theories of remindings [3] and constraint negotiation [12].

To address this issue, we have developed a proactive problem-solving focus mechanism that helps learners cope with the complexities inherent in design-centered learning environments. The mechanism has been implemented in DESIGN-A-PLANT, a design-centered learning environment for botanical anatomy and physiology. DESIGN-A-PLANT provides middle school children with the opportunity to explore the physiological and environmental considerations that govern plants' survival. Given a set of environmental conditions, children use DESIGN-A-PLANT to graphically assemble a customized plant that can survive in the specified environment. To help focus students' problem solving as they graphically create plants from a library of "plant prostheses," the system monitors their interactions, adaptively selects environmental conditions, and provides both spoken and animated advice.

2 Design-Centered Problem Solving

The design-centered approach to learning can be applied to a broad range of domains. Design-centered learning environments can be developed for domains as diverse as biology (e.g., designing plants), chemistry (e.g., compound synthesis), or the social sciences (e.g., the popular Maxis SIM series). In each domain, design-centered problem solving revolves around a carefully orchestrated series of design episodes. Problems in design episodes are defined by a pair $(\mathcal{E}, \mathcal{L})$:

- $\mathcal{E}$: An *environment* consisting of a high-level set of design specifications defined by environmental factors $E_1 \ldots E_n$; a particular environment may specify only a subset of the E_is.
- $\mathcal{L}$: An *artifact component library* containing the "building blocks" from which artifacts are assembled; $\mathcal{L}$ is partitioned into component clusters $L_1 \ldots L_m$, where each L_i contains components of a particular type, and each component is defined by a feature vector of attribute-value pairs.

The student's task is to create an *artifact* A, which is a compound object composed of objects from $\mathcal{L}$. Critically, A must be able to function successfully in $\mathcal{E}$.

To illustrate, consider design episodes in the domain of botanical anatomy and physiology. Students are given an environment that specifies biologically critical factors in terms of qualitative variables. Environmental specifications for these episodes include the average incidence of sunlight, the amount of nutrients in the soil, and the height of the water table, as illustrated by several environments from DESIGN-A-PLANT (Table 1). Students consider these conditions as they inspect components from a library of plant structures that is segmented

Environment	*Feature*	*Value*
Alpine Meadow	water table	high
	temperature	low
	rain	low
	wind	high
Southern Marsh	rain	high
	sunlight	low
	water table	high
	temperature	high

Table 1. Sample Environments from Design-A-Plant

into roots, stems, and leaves. Each component is defined by its structural characteristics such as length and branching factor. Employing these components as their building blocks, students work in a "design studio" to graphically construct a customized plant that will flourish in the environment. Each iteration of the design process consists of inspecting the library, assembling a complete plant, and testing the plant to see how it fares in the given environment. If the plant fails to survive, students modify their plant's components to improve its suitability, and the process continues until they have developed a robust plant that prospers in the environment.

Constraints relating environmental factors to artifact structures govern the composition of artifacts. For example, a design-centered learning environment for botanical anatomy and physiology might include the constraint that a low incidence of sunlight requires large leaves. Hence, in the course of designing artifacts for a variety of environments, students acquire an understanding of the (possibly complex) effects of the environment on artifact functionalities. By continuously designing and redesigning artifacts until they satisfy the given specifications, students gradually bridge the conceptual gap that separates specific environmental factors from specific artifact components.

3 Focusing Design Episodes

Because design decisions require students to consider multiple environmental factors, multiple components, and multiple constraints simultaneously, it is critically important to focus their problem solving. In the absence of a mechanism for helping students attend to the most relevant aspects of their domain, they would easily become lost in the details and the pedagogical advantages of the design process would vanish. To address this problem, we have developed a proactive focus mechanism that exploits a representation of the evolving design context.

3.1 A Tripartite Model of the Design Context

Because students signal which sub-goal they are currently attempting through their design actions and because they indicate the conceptual difficulties they may be experiencing through their partial solutions (i.e., their incomplete artifacts), the focus mechanism can carefully monitor the design process. To make decisions about how and when to take actions that will focus problem solving, the focus mechanism maintains a tripartite contextual representation of design episodes. It consists of an environmental context, an artifactual context, and an advisory context:

- *Environmental Context:* Critical features of the environment which have been presented to the student:
  - Current Environment: Environmental factors (and their values) in the current design episode.
  - Environmental Intent: Associated with each environment presented to the student is the set of object types from the artifact library which that environment is intended to exercise, e.g., some environments are presented to exercise students' knowledge of leaf morphology.
- *Artifactual Context:* Critical features of the artifact under construction:
  - Partial Solutions: Selections of components for the current artifact under construction, e.g., the student may have completed the roots and leaves.
  - Focused Component: Artifact component to which the student is currently attending, e.g., the stem.
  - Design Evaluation: When the student completes the design, the artifact is evaluated as successful or not successful in the current environment.
- *Advisory Context:* Critical features of the advisory dialogue, where each entry consists of:
  - Topic: Environmental factors, artifact components, constraints, and/or design decisions explained.
  - Frequency Annotations: Indicate the number of times that the student has been advised about the topic(s).
  - Problem-Solving Idle Time: Time expired since the student's last action.
  - Media Annotations: Indicate the media, e.g., audio or animation, that were employed to communicate the advice.

3.2 The Proactive Focus Mechanism

By exploiting the tripartite model of the design context, the focus mechanism can proactively help students focus their problem solving on the most salient aspects of the problem at hand. It can inspect the environmental context to identify the design criteria that the student is attempting to satisfy and to determine which aspects of the design are most critical from a pedagogical perspective; it can inspect the artifactual context to monitor the student's progress and to note possible impasses; and it can inspect the advisory context to determine the nature of the student's request and to track previously presented advice. As the focus mechanism observes the design process, it selects environments, determines when and what type of interventions are appropriate, and presents spoken and/or animated advice.

Environment Selection. In a series of design episodes, the focus mechanism attempts to obtain a comprehensive coverage of artifact components. As the design process unfolds, it chooses environments with different *environmental intents* (see above). It bases its choice of environment on the student's rate of progress, which is indicated by the history of design evaluations. To make these decisions, the focus mechanism navigates its way through an *environment matrix*, each cell of which is a particular environment.[1] Environments in a given column have the same intent, e.g., they all exercise the student's knowledge of stems. Environments in a given row have the same complexity; the complexity of the activated constraints are the same, and they require students to grapple with the same number of components. For example, environments in the second row involve constraints with two components (the other components are "don't cares" with respect to the environment). Beginning in the upper-left cell, the focus mechanism selects an environment. If the student meets with success (as indicated by the quality of the partial solutions), they advance diagonally to an environment in the next column and the next row; if they experience difficulty, they remain in the same row (the same level of complexity) but move to a different column. The session ends when the student successfully completes a design for an environment in the final row, which represents the highest level of complexity.

Intervention. To proactively focus the design process, decisions must be made about when and how to intervene during problem solving. The focus mechanism monitors the state of the artifactual context to determine when the student requires assistance. If the student makes an incorrect design decision (as indicated by his or her partial solutions), or if the problem-solving idle time exceeds a threshold, then the focus mechanism will intervene. When an intervention is triggered, the focus mechanism must determine the topic of the advice it will provide to the student. If the current partial solution indicates that only a single component is inappropriate for the current environment, it will provide advice about that component. If multiple components are inappropriate, the focus mechanism inspects the focused component (the component to which the student is currently attending); if this component is incorrect, advice will be provided about it. Otherwise, the focus mechanism inspects the environmental intent of the current environment and determines if one of the inappropriate components is the subject of the environmental intent. If so, it will provide advice about that component.

Advice Presentation. Once the decision to intervene has been made and the topic of the intervention has been determined, a critical issue in learning environments

[1] This process is analogous to the navigation of discourse management networks [14].

is how to provide appropriate advice [9]. These decisions are governed by presentation strategies that first select the appropriate level of *directness* of the advice and then select a communication medium. Note that our emphasis is not on the generation of explanations per se but on selecting the "directness" of presentations and on intelligent media selection [1, 5, 10]. The directness spectrum of advisory presentations represents the degree of explicitness with which presentations inform students about design decisions. The least direct advice discusses the information about constraints, e.g., the functional relation between environmental factors and artifact components; the most direct advice suggests a specific design decision. While direct advice is easily operationalized, the opportunity for learning is reduced, so indirect advice is generally preferred.

The focus mechanism first selects a point on the directness spectrum, and then uses this decision to determine the presentation media. To select a point on the directness spectrum, the focus mechanism weighs four factors: (1) if the topic of the advice is the environmental intent, indirect advice is preferred; (2) as the student advances to higher levels of complexity (as indicated by their position in the environment matrix), indirect advice is preferred; (3) if the student is experiencing difficulty (as indicated by his or her partial solutions), more direct advice is preferred; and (4) if advice about a particular topic has already been presented (as indicated by the advisory context), more direct advice is preferred. The selected level of directness is then used to make media selection decisions. In general, the more indirect the advice is, the more likely it will be presented as animations depicting interactions between environmental factors and artifact components; the more direct the advice is, the more likely it will be presented as speech. Finally, the topic, the selected level of directness, and the selected medium are used to index into the *multimedia advice library*, and the advice is presented to the student.

4 Focusing Problem Solving in Design-A-Plant

Design-A-Plant is a design-centered learning environment that we and our colleagues have developed for middle school botanical anatomy and physiology.[2] Throughout the design process, students are accompanied by an animated agent in the form of a bug, which serves as the vehicle for both the animated and spoken advice. It presents natural environments to them, and they graphically assemble customized plants that will survive in those environments. Environments are rendered as intriguing landscapes, and specific environmental factors are depicted iconically. The roots, stems, and leaves in the artifact component library are 3D objects. "Rollover" definitions are provided for all environmental factors and components. Design-A-Plant currently includes:

[2] All of the 3D graphics and animations were designed, modeled, and rendered on Macintoshes and SGIs by a twelve-person graphic design team from North Carolina State University's School of Design. Design-A-Plant runs on a Power Macintosh 9500/132.

– an environment matrix with sixteen environments (four types of environments, each with four complexity levels);
– an artifact component library with eight types of roots, eight types of stems, and eight types of leaves;
– a domain model with thirty-one constraints that relate six environmental factors to the anatomical structures and six physiological functions;
– a multimedia advice library with thirty animations on botanical anatomy and physiology[3] and one hundred and sixty audio clips.

To illustrate its behavior, suppose that a student has just completed designing a plant for the first environment on complexity level one.

> Level 2 is selected because the first environment was completed after only a single error. The first environment focused on leaves. In this environment, roots and leaves are both in focus. The key environmental factors (those that affect objects in the environmental intent) are low temperature and high water table.

Animated Agent: Hooray, a pretty place. It's absolutely lovely. Of course the ground reminds me of a skating rink. Maybe that's because of the low temperature and high water table. Make sure that the stems are thick and well protected and that the roots and leaves can handle the pretty but harsh conditions.

> To focus on roots and leaves, the introduction gives specific advice about the stem only. At this point, the student clicks on the upper portion of the plant construction area to begin working on leaves.

Student: Spends thirty seconds going back and forth with the mouse from the rollover textual descriptions of the environment to the rollover textual descriptions of the leaf choices but cannot make a decision.

> The problem-solving idle time threshold is exceeded. There are three constraints that map cold temperature to leaf features. Because this is the first time that the student has required advice during leaf selection in this environment and leaves are in focus, three animated explanations are played in sequence. They explain the relationship between cold temperature and leaf size, leaf thickness, and leaf skin thickness. These explanations are followed by the first animated lesson on leaf anatomy.

Student: Makes two more unsuccessful attempts at selecting a correct leaf.

> The leaf choice still violates a constraint, but now the student has already seen a detailed animated explanation and has been given a verbal reminder. Therefore, short direct verbal advice is given.

Animated Agent: Why don't you try a small thick leaf with nice thick skin.

[3] Approximately twenty are in the 20—30 second range and ten are in the 1–2 minute range.

5 Formative Evaluation

DESIGN-A-PLANT, an ongoing project begun in 1994, has been the subject of a formative evaluation involving middle school students. Informal observational studies with thirteen students were conducted to obtain feedback about the layout and operation of the design studio, the pace, the appeal of the storyline (not discussed here) and the animated agent, and most importantly, the clarity of the advice and the behavior of the focusing mechanism. Each student interacted with the system for forty-five minutes to one hour.

Students seemed to benefit considerably from the design experience in general and the focus mechanism in particular. They enjoyed interacting with the learning environment and appreciated its animations, music,[4] and agent. Detailed design profiles were automatically accumulated for four of the students. Each profile records all of the environments, design decisions, and advice (both topic and media) in the series of design episodes undertaken by a student. Perhaps most encouraging is the fact that the vast majority of mistakes occurred on the components which were in the intent of their respective environments. This indicates that most of students' time was spent in making design decisions about features of the design that were most critical.

6 Conclusion

Because design-centered learning environments enable students to iteratively make, evaluate, and reconsider design decisions, they offer great promise for providing grounded, personalized learning experiences. Design episodes may become so complex, however, that decisions about multiple environmental factors, multiple artifact components, and multiple constraints could easily overwhelm students. By incorporating a proactive problem-solving focus mechanism that exploits environmental, artifactual, and advisory context models, a design-centered learning environment can help students focus on the most critical aspects of complex design episodes. In particular, it can select environments and intervene with multimedia advice to help students more effectively form, test, and refine their hypotheses about complex interrelationships.

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[4] The soundtrack uses the design context to adapt its tempo, mood, and number of instrumental voices to the student's progress.

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