Dynamically Sequencing an Animated Pedagogical Agent*

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Abstract

One of the most promising opportunities introduced by rapid advances in knowledge-based learning environments and multimedia technologies is the possibility of creating animated pedagogical agents. These agents should exhibit three properties: timely domain coverage (they should clearly communicate fundamental concepts and relationships within the allotted time); contextuality (they should provide explanations in appropriate problem-solving contexts); and continuity (their activities and utterances should be pedagogically, visually, and aurally coherent).

We have developed the *coherence-structured behavior space* approach to creating animated pedagogical agents. This is a two-step approach. First, we design a behavior space of animation and audio segments that are structured by prerequisite relationships and a continuity metric. Second, we navigate coherent paths through the space to dynamically sequence behaviors. This creates seamless global behaviors that communicate fundamental knowledge and provide contextualized problem-solving advice. The coherence-structured behavior space approach has been implemented in Herman the Bug, an animated pedagogical agent for Design-A-Plant, a knowledge-based learning environment for botanical anatomy and physiology. Formative evaluations of the agent with middle school students are encouraging.

Introduction

Since their conception more than a quarter of a century ago, knowledge-based learning environments (Hollan, Hutchins, & Weitzman 1987; Lesgold *et al.* 1992) have offered significant potential for fundamentally changing the educational process. It has long been believed—and recently rigorously demonstrated (Mark & Greer 1995)—that presenting knowledgeable feedback to students increases learning effectiveness. Despite this promise, few learning environments have made the difficult transition from the laboratory to the classroom, and the challenge of developing learning environments that are both pedagogically sound *and* visually appealing has played no small part in this impasse. Fortunately, recent years have witnessed the appearance of a new generation of animation software that enables teams of animators to rapidly create life-like characters. This development raises an intriguing possibility: creating *animated pedagogical agents* that couple key feedback functionalities with a strong visual presence. Introduced immersively into a 3D learning environment, an animated pedagogical agent could observe students' progress and provide them with visually contextualized problem-solving advice.

An animated pedagogical agent's behaviors must exhibit contextuality, continuity, and temporality. An agent's advisory behaviors must be rhetorically contextualized within problem-solving episodes, and its physical behaviors must be graphically contextualized within the learning environment. To exhibit continuity of action, all of its behaviors must be visually coherent. Moreover, because many domains and tasks are highly complex and learning time is limited, sequencing a pedagogical agent's explanatory behaviors must take into account temporal resources to provide the greatest coverage of the domain in the given time. Together, these requirements call for a dynamic solution that marries inference with animation. Although knowledge-based graphical simulations (Hollan, Hutchins, & Weitzman 1987) are virtually *de rigueur* in contemporary learning environments, and the problem of planning multimedia presentations has been the subject of much study (Feiner & McKeown 1990; Maybury 1991; Roth, Mattis, & Mesnard 1991; André *et al.* 1993; Mittal *et al.* 1995), work on "self-animating" characters (Bates 1994; Tu & Terzopoulos 1994; Blumberg & Galyean 1995; Maes *et al.* 1995) is receiving increasing attention but is still in its infancy.

In this paper, we propose the *coherence-structured behavior space* framework for dynamically sequencing animated pedagogical agents' behaviors. We focus in particular on animated pedagogical agents whose purpose is to provide instruction about the structure and

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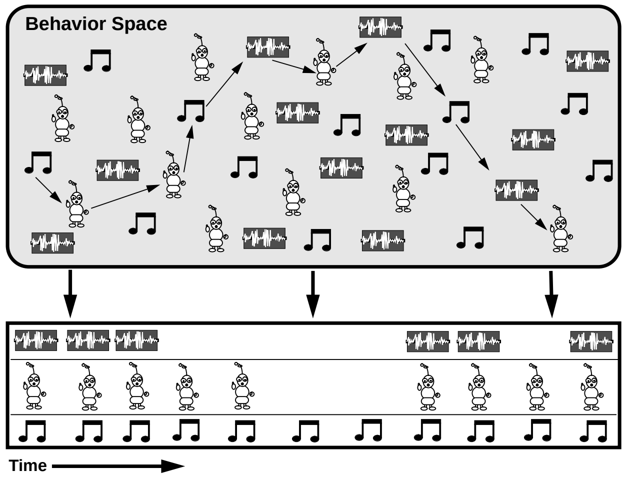

Figure 1: Sequencing coherence-structured behaviors

function of a particular device or organism. Applying this framework to create an agent entails constructing a behavior space, imposing a coherence structure on it, and developing a behavior sequencing engine that dynamically selects and assembles behaviors:

1. **Behavior Space Construction:** A behavior space contains animated segments of the agent performing a variety of actions, as well as audio clips of the agent's utterances. It is designed by a multidisciplinary team and rendered by a team of graphic artists and animators.
2. **Behavior Space Structuring:** The behavior space is structured by (1) a tripartite index of ontological, intentional, and rhetorical indices, (2) a pedagogically appropriate prerequisite ordering, and (3) behavior links annotated with distances computed with a *visual continuity metric*.
3. **Dynamic Behavior Sequencing:** At runtime, the behavior sequencing engine creates global behaviors in response to the changing problem-solving context by exploiting the coherence structure of the behavior space. The sequencing engine selects the agent's actions by navigating coherent paths through the behavior space and assembling them dynamically (Figure 1).

This approach creates seamless global behaviors in which the agent provides visually contextualized problem-solving advice. In addition, by attending to temporal resources, it selects and composes explanatory behaviors so as to achieve the greatest coverage of the domain within the allotted time.

This framework has been used to implement **Herman the Bug**, an animated pedagogical agent (Figure 2) for DESIGN-A-PLANT (Lester *et al.* 1996), a knowledge-based learning environment for botanical anatomy and physiology. Given a set of environmental conditions, children use DESIGN-A-PLANT to graphically assemble a customized plant that can thrive in the specified environment. In response to changing problem-solving contexts in DESIGN-A-PLANT, a sequencing engine orchestrates Herman the Bug's actions by selecting and assembling behaviors from a behavior space of 30 animations and 160 audio clips that were created by a team of 12 graphic artists and animators. It also employs a large library of runtime-mixable soundtrack elements to dynamically compose a score that complements the agent's activities. Formative evaluations of Herman the Bug with middle school students are encouraging.

Coherence Requirements

Pedagogical Coherence. Naturally, considerations of pedagogical coherence loom large in the design of animated pedagogical agents. Perhaps most central among these requirements is that an agent's explanatory behaviors be *situated* (Suchman 1987): all of its explanatory behaviors—not merely its advisory actions but also its communication of fundamental conceptual knowledge—should take place in concrete problem-solving contexts. For example, students using DESIGN-A-PLANT should learn about leaf morphology in the context of selecting a particular type of leaf as they design a plant that will thrive in particular environmental conditions. Moreover, prerequisite-based sequencing, content selection, and topical transitions of explanatory behaviors should exhibit pedagogical coherence.

Visual Coherence. Because animated pedagogical agents inhabit two-dimensional space—albeit one that, by design, closely emulates three-dimensional space—their behaviors should be governed by the conventions of visual coherence. Because the birth and maturation of the film medium over the past century has precipitated the development of a visual language with its own syntax and semantics (Monaco 1981), the "grammar" of this language should be employed in all aspects of the agent's behaviors. In addition to traditional film language, an agent's designers can also exploit the behavior cannon of the animated film (Noake 1988; Jones 1989; Lenburg 1993) by computationalizing classical animation principles (Lasseter 1987; Bates 1994). For example, the zoom levels of the shots and the positioning of the agent visually communicate what is—and is not—important. In DESIGN-A-PLANT, macroscopic shots of the agent and plant can depict the agent interacting with external morphological structures; median shots can depict the agent interacting with internal plant structures; and microscopic shots can show the agent interacting with cellular structures. Moreover, careful selection of the agent's spatial positioning and orientation, its accouterments (e.g., props such as microscopes, jetpacks, etc.), and visual expressions of its emotive state (Bates 1994) can emphasize the most salient aspects of the domain for the current problem-solving context.

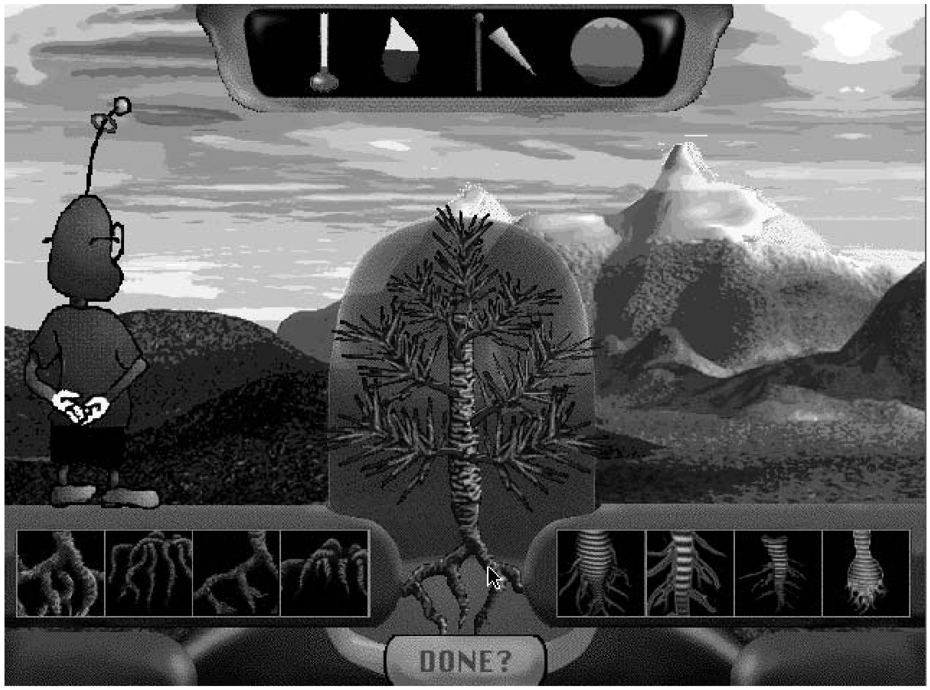

Figure 2: Design-A-Plant's animated pedagogical agent, Herman the Bug

Considerations of pedagogical and visual coherence suggest the following maxims for the design of animated pedagogical agents:

- **Agent Persistence:** Keep the agent in the frame. An omni-present agent in the problem-solving environment can reassure learners and increase their interest. Although brief excursions offscreen to obtain a prop can enliven the action, maintaining a strong onscreen presence provides visual consistency. For example, an agent for Design-A-Plant should remain in the onscreen design studio (where students select anatomical structures such as roots, stems, and leaves) at all times.
- **Pedagogical Object Persistence:** Maintain in frame a manipulable 3D model of the object (or task) being discussed. Keeping the primary pedagogical object onscreen reduces the cognitive load that would be imposed if it were to disappear and reappear with frequent scene changes. For example, the evolving 3D plant model—the one being designed by the students—should be visible at all times.
- **Agent Immersion:** Graphically immerse the agent in the problem-solving environment. Whenever possible, its behaviors should be conducted in close proximity to a manipulable 3D model of the primary pedagogical object. For instance, the Design-A-Plant agent should remain in close proximity to the plant itself, e.g., by flying around leaves, sliding down stems, or standing on chloroplasts.
- **Verbal Support:** *Audio-primary utterances*, i.e., verbalizations accompanied by little or no actions, should be used for brief reminders and interjections. Verbal meta-comments such as bridging phrases can also usher in transitions.
- **Contextualized Musical Score:** Complement the agent's behaviors with a context-sensitive soundtrack whose tempo and instrumentation are appropriate for the current context. For example, the Design-A-Plant agent should be accompanied by a score that employs internal consistency of voicing and melody within a problem-solving episode and thematic consistency across problem-solving episodes.

These maxims should inform all decisions about the construction of behavior spaces, the imposition of a coherent structure on the behaviors, and the design of the behavior sequencing engine.

Designing Behavior Spaces

To provide an agent with the flexibility required to respond to a broad range of problem-solving contexts, its behavior space must be populated with a large, diverse set of animated and audio-primary behaviors. In contrast to the linear storyboarding approach employed in traditional animation (Noake 1988), the pedagogical and visual connectivity of behavior spaces require a *networked storyboarding* approach. Posing significant pedagogical and aesthetic challenges, the design of a networked storyboard is a complex, labor-intensive task. Networked storyboarding consists of designing specifications for eight classes of animated and audio-primary behaviors and imposing a coherence structure on them.

Specifying Behaviors

Creating the agent's behavior repertoire entails setting forth precise visual and audio specifications that describe in great detail the agent's actions and utterances, rendering the actions, and creating the audio clips. The core of a behavior space is a highly interconnected web of animated segments depicting the agent performing a variety of explanatory behaviors. This is complemented by a set of audio clips of the agent's audio-primary utterances, as well as soundtrack elements (not discussed here) for the dynamically created score. To assist the sequencing engine in assembling behaviors that exhibit visual coherence, it is critical that the specifications for the animated segments take into account continuity. Accordingly, we adopt the principle of *visual bookending* to create animated segments that can more easily be assembled into visually coherent global behaviors. Visually bookended animations begin and end with frames that are identical. Just as walk cycles and looped backgrounds can be seamlessly composed, visually bookended animated behaviors can be joined in any order and the global behavior will always be flawlessly continuous.

It is important to note that visual bookending should be applied to topically-partitioned clusters of animated segments. In theory, all segments could begin and end with identical frames, but the global behaviors assembled from such a behavior space would depict the agent repeatedly leaving and returning to a single location. Because this would compromise visual coherence in most domains, partitioning the behavior space into clusters and then bookending segments within a cluster will yield superior global behaviors.

To construct a behavior space for an animated pedagogical agent, eight families of behaviors are specified collaboratively by the multi-disciplinary agent design team and then rendered by the graphic designers and animators:

- **Conceptual Explanatory Animated Segments:** The agent explicates the structures and functions of the primary pedagogical object. For example, the Design-A-Plant agent's behavior space contains an animated segment of the agent explaining how root hairs absorb water through osmosis.
- **Problem-Solving Advisory Animated Segments:** The agent provides abstract, principle-based advice. Students must then operationalize this advice in their problem solving activities. For example, one animated segment of the Design-A-Plant agent depicts him pointing out the relation between leaf size and low sunlight (plants in limited sunlight sometimes have larger leaves).
- **Animated Transition Segments:** These portray the agent moving from one *keyframe* (a frame initiating or terminating a segment in a bookended cluster) to another keyframe, or performing an action that will set the stage for several behaviors.
- **Audio-Primary Problem Overviews:** The agent introduces a student to a new problem. For example, the Design-A-Plant agent's behavior space contains audio clips of the agent describing environmental conditions. These utterances are played at the beginning of problem-solving episodes.
- **Audio-Primary Advisory Reminders:** The agent briefly reminds a student about principle-based advice that was presented earlier. For example, an audio clip in the Design-A-Plant agent's behavior space is a voiceover of the agent stating, "Remember that small leaves are struck by less sunlight."
- **Audio-Primary Direct Suggestions:** The advice presented by the agent is immediately operationalizable. For example, the Design-A-Plant agent's behavior space contains a voiceover of the agent stating, "Choose a long stem so the leaves can get plenty of sunlight in this dim environment." The agent makes these types of suggestions when a student is experiencing serious difficulties.
- **Audio-Primary Interjections:** The agent remarks about the student's progress and makes off-the-cuff comments. For example, the Design-A-Plant agent's behavior space includes Audio-Primary Interjections in which the agent congratulates the student about the successful completion of a plant design. Because a large repertoire of interjections contributes significantly to an agent's believability, a behavior space should include a variety of Audio-Primary Interjections.
- **Audio-Primary Transitions:** The agent makes meta-comments that signal an upcoming behavior. For example, the Design-A-Plant agent's Audio-Primary Transitions include a clip of him stating "It seems we're having some difficulty. Let's see if this helps ..."

Imposing a Coherence Structure

Once the behavior space has been created, it must then be structured to assist the sequencing engine in selecting and assembling behaviors that are coherent. Charting the topology of a behavior space is accomplished by constructing a tripartite behavior index, imposing a prerequisite structure on the explanatory behaviors, and creating annotations that indicate visual continuities between behaviors.

Tripartite Behavior Index. Just as the indexing of stories and advice is critical for case-based learning environments (Edelson 1993), indexing behaviors is of paramount importance for animated pedagogical agents. To enable rapid access to appropriate behaviors so they can be efficiently sequenced at runtime, behaviors are indexed ontologically, intentionally, and rhetorically. First, an *ontological* index is imposed on explanatory behaviors. Each behavior is labeled with the structure and function of the aspects of the primary pedagogical object that the agent discusses in that segment. For example, explanatory segments in the DESIGN-A-PLANT agent's behavior space are labeled by (1) the type of botanical structures discussed, e.g., anatomical structures such as roots, stems, and leaves, and by (2) the physiological functions they perform, e.g., photosynthesis. Second, an *intentional* index is imposed on advisory behaviors. Given a problem-solving goal, this structure enables the sequencing engine to identify the advisory behaviors that help the student achieve the goal. For example, one of the DESIGN-A-PLANT agent's behaviors indicates that it should be presented to a student who is experiencing difficulty with a "low water table" environment. Finally, a *rhetorical* index is imposed on audio-primary segments. This indicates the rhetorical role played by each clip, e.g., introductory remark or interjection.

Prerequisite Structure. The primary goal of an animated pedagogical agent is to guide students through a complex subject by clearly explaining difficult concepts and offering context-sensitive problem-solving advice. To assist the sequencing engine in making decisions about the selection of behaviors, we impose a prerequisite structure on the explanatory behaviors. Prerequisite relations impose a partial order on explanatory behaviors: a behavior can be performed only if all its (immediate and indirect) prerequisite behaviors have been performed. Prerequisites should be imposed conservatively; by imposing only those relations that are clearly mandated by the domain, greater flexibility is provided to the sequencing engine because the number of behaviors it may select at any given time will be greater.

Visual Continuity Annotations. Because visual bookending is not always possible, the behavior space should include knowledge about the visual continuities between animated segments in the prerequisite structure. Visual attributes including the shot's zoom level and the agent's frame position are represented as normalized numerical variables and are assigned weights based on priority. The visual continuity $v_{x,y}$ between behaviors B_x and B_y is defined as the distance in n-dimensional attribute space between the final frame of B_x and the initial frame of B_y:

$$v_{x,y} = \sqrt{w_1(x_1 - y_1)^2 + w_2(x_2 - y_2)^2 + \ldots w_n(x_n - y_n)^2}$$

where w_i is the prioritized weight of the ith visual attribute. The sequencing engine uses the continuity annotations to maximize visual continuity among sequenced animated segments.

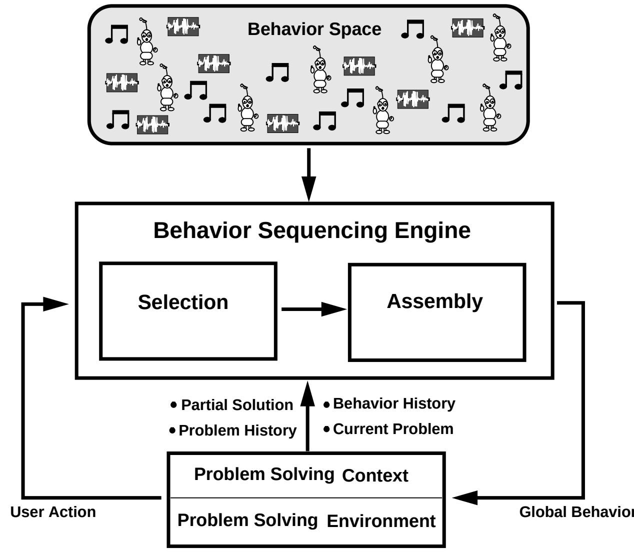

Figure 3: The behavior sequencing engine

Sequencing Agents' Behaviors

To achieve agent persistence, agent immersion, and pedagogical object persistence, the agent remains on-screen, visually immersed in the learning environment, and on or near the primary pedagogical object at all times. The moment a student requests assistance, constructs an incorrect (complete or partial) solution, or fails to take action for an extended period of time, the sequencing engine (Figure 3) is called into play to create the agent's next behavior. By exploiting the behavior space's coherence structure and noting different aspects of the current problem-solving context, the sequencing engine navigates through the space to weave the local behaviors into global behaviors. It employs the following algorithm to select and assemble local behaviors in realtime:

1. **Compute n, the number of explanatory behaviors to exhibit.** This quantity is computed by $\lfloor b/f \rfloor$. The quantity b is the number of explanatory behaviors that have not yet been exhibited. The function f, which is determined from empirical data, is the predicted number of future problem-solving situations in which explanatory behaviors can be exhibited. The floor is taken for non-integer results to be conservative—representing the number of Conceptual Explanatory Animated Segments that should be exhibited. Employing n has the effect of evenly distributing these explanations over the course of the learning session.
2. **Select all explanatory behaviors E^P that are pedagogically viable.** First, apply the ontological index structure to index into behavior space and identify all Conceptual Explanatory Animated Segments that are currently relevant. By noting the current structures, functions, and problem-solving

features that are active in the current problem, the sequencing engine can identify the animations that are pedagogically appropriate. Second, determine candidate behaviors whose prerequisite behaviors have already been exhibited by using the prerequisite structure to perform a topological sort of behaviors in the global behavior history.

3. **Select explanatory behaviors $E^{P,V}$ that are both pedagogically and visually viable.** Of the candidates in E^P chosen in Step 2, select a subset $E^{P,V}$ such that (a) the sum of the continuity annotations along the best path in $E^{P,V}$ is minimized, and (b) $\mid E^{P,V} \mid$ is as close as possible to n without exceeding it.[1]
4. **Select problem-solving advisory behaviors A that are pedagogically appropriate.** Use the intentional and rhetorical indices to identify advisory behaviors that are germane to the topic of the current problem. A may include both animated and audio-primary behaviors.
5. **Select the media with which to exhibit a subset $A^{'}$ of the behaviors in A.** Inspect the behavior history to determine if advisory behaviors about the current topic have been exhibited. If no prior advisory behaviors on this topic have been presented, select an animated advisory behavior on this topic. If an animated advisory behavior on this topic has been previously exhibited, select an audio-primary verbal reminder on this topic. If an animated advisory behavior on this topic has been previously exhibited but a significant amount of time has elapsed, select it for repeat viewing. If both an animated advisory behavior and a verbal reminder on this topic have been exhibited recently, select an audio-primary direct behavior in which the agent will explicitly tell the student what problem-solving action to take.
6. **Select animated and verbal transitions T.** Use the indices and prerequisite structure to identify transition behaviors for $E^{P,V}$ and $A^{'}$.
7. **Assemble the final global behavior.** Impose the following temporal ordering on the selected behaviors: (a) verbal transitions in T to introduce the upcoming explanations; (b) animated explanatory behaviors in $E^{P,V}$ ordered by prerequisite structure; (c) animated advisory behaviors in $A^{'}$; and (d) audio-primary reminders and direct advisory behaviors in $A^{'}$.

The resulting global behavior is presented onscreen and the sequencing engine sleeps until the next invocation. While it is sleeping, it pseudo-randomly schedules audio-primary interjections. In addition, the agent's actions are complemented at all times by a continuous soundtrack whose voicing and tempo are dynamically updated to reflect changes in problem-solving contexts. Introductory measures are played as problems are introduced, and additional voicing is added as partial solutions are successfully constructed. The net effect of the sequencing engine's activities is the students' perception that a life-like character is carefully observing their problem-solving activities and moving in and out of the primary pedagogical object to provide advice just when it is needed.

[1] Note that Steps (2) and (3) must be interleaved when selecting multiple behaviors because prerequisites can be met dynamically in the process of exhibiting a global behavior.

An Implemented Animated Agent

The coherence-based approach to dynamic sequencing has been implemented in Herman the Bug, an animated pedagogical agent for DESIGN-A-PLANT, which is a learning environment being developed in our laboratory to teach middle school students about botanical anatomy and physiology.[2] Herman the Bug is a talkative, quirky, somewhat churlish insect with a propensity to fly about the screen and dive into the plant's structures as it provides students with problem-solving advice. His behavior space consists of 30 animated segments[3] (twenty are in the 20—30 second range and ten are in the 1–2 minute range), 160 audio clips, several songs, and a large library of runtime-mixable, soundtrack elements. Throughout the learning session, he remains onscreen, standing on the plant assembly device when he is inactive (Figure 2) and diving into the plant as he delivers advice visually. In the process of explaining concepts, he performs a broad range of activities including walking, flying, shrinking, expanding, swimming, fishing, bungee jumping, teleporting, and acrobatics. All of his behaviors are sequenced in realtime on a Power Macintosh 9500/132.

To illustrate the behavior of the sequencing engine that composes Herman the Bug's actions, consider the following situation in a DESIGN-A-PLANT learning session. A student has seen Herman the Bug present an overview of basic anatomy, watched him explain external anatomy in a prior problem-solving episode, and very quickly (relative to her peers using the system) reached the third level of problem complexity. As she assembles a plant that will thrive in the cur-

[2] DESIGN-A-PLANT is a *design-centered* learning environment that embodies a strong constructivist approach to learning. Students use it to graphically assemble customized 3D plants from a library of plant anatomical structures. Their goal in each design episode is to create a plant that will survive under a specific set of environmental conditions. At the implementational level, DESIGN-A-PLANT is a constraint-based system, where the constraints imposed by the plant's environment must be satisfied by the anatomical structures selected by the student.

[3] Its animations were designed, modeled, and rendered on SGIs and Macintoshes by twelve graphic artists and animators.

rent environment, she selects a type of leaf that violates the environmental constraints. This action causes the problem-solving system to invoke the behavior sequencing engine, which has access to representations of: the student's partial (and incorrect) solution; the constraints and environmental settings in the current problem; a history of previous behaviors Herman the Bug has exhibited; and a history of the student's previous problem-solving episodes.

First, the number of explanatory behaviors to exhibit is computed. Because the student reached the third complexity level quickly, and there are four total levels, the sequencing engine predicts that there will be only two opportunities (including the current one) for presenting explanations. Of the four explanatory behaviors not yet seen, it will show two of them. By using the ontological index structure to find the relevant candidate behaviors and then using the behavior history and the prerequisite structure of the behavior space to perform a topological sort, three explanatory behaviors are selected which are pedagogically viable. Of these three candidate behaviors, two are chosen for which the the sum of the continuity annotations along the best path is minimized. This produces explanatory behaviors of internal anatomy and transpiration. Next, the sequencing engine exploits the the intentional and rhetorical indices to identify advisory behaviors that are germane to the structure of interest (leaves) and the environmental attributes of interest (low rain and high temperature). The media with which to exhibit the behaviors is then selected. The sequencing engine notes that the student has been given no prior principle-based advice about leaves, so a behavior depicting Herman the Bug giving principle-based explanations of leaves—and which she will then have the opportunity to operationalize—is selected. (Alternatively, if the student had already seen the principle-based explanations of leaves, an audio-primary reminder would have been selected instead.) The principle-based explanations are introduced by an audio-primary transition in which Herman the Bug explains that, "The low rain and high temperature make some leaves unsuitable for this environment. Here's why ..." Finally, the behavior sequencing engine orders the selected behaviors as follows: the animated segment of Herman the Bug explaining internal anatomy; the animated segment of Herman explaining transpiration; the verbal transition; the animated advisory segment about leaves in low-rain environments; and the animated advisory segment about leaves in high-temperature environments.

Because of recency effects and the fact that the advisory explanations were communicated last, the student can more easily apply the advice to refine her plant design. She chooses an alternate type of leaf and continues to puzzle out the remaining structures.

Evaluation

To gauge the effectiveness of the coherence-based approach to dynamically sequencing the behaviors of animated pedagogical agents, formative observational studies were conducted with thirteen middle school students using the DESIGN-A-PLANT learning environment and its accompanying agent, Herman the Bug. Each student interacted with the learning environment for forty-five minutes to one hour. As the students designed plants for a variety of environmental conditions, the agent introduced problems, explained concepts in botanical anatomy and physiology, provided problem-solving advice, and interjected congratulatory and off-the-cuff remarks. These studies suggest that animated pedagogical agents whose behaviors are selected and assembled with the sequencing engine can effectively guide students through a complex subject in a manner that exhibits both pedagogical and visual coherence.

Herman was unanimously well received. His pedagogical and visual coherence, together with his immersive property—the fact that it inhabits a 3D environment and interacts with 3D plant models to explain structural and functional concepts—produced strikingly life-like behaviors. Herman's visual behaviors seemed to so flow well that no student commented or displayed surprise during transitions. Because of book-ending, many of Herman's transitions were technically flawless. Herman's verbal reminders enabled students to continue with their problem solving uninterrupted, and during the study students made frequent (and unprompted) positive comments about Herman's physical actions and remarks. The variety of his behaviors maintained their interest throughout the session, and every student, without exception, commented positively about the continuously updated score. Perhaps not surprisingly—considering its seventh grade audience—Herman's quirky asides were well received.

The studies also revealed three problems with the initial algorithm. Each of these problems has been addressed in the algorithm presented in this paper, as well as in the current implementation. First, in the original version, the agent provided its advice *before* giving the conceptual explanations. Students tended to forget this advice because, we hypothesize, there were intervening conceptual explanations. The sequencing engine's assembly mechanism was therefore modified to present advisory behaviors at the end of global behaviors. Second, students were clearly irritated by the repetition of explanatory behaviors. We therefore modified the selection mechanism to ensure that explanations would be repeated only if sufficient time had elapsed. Third, the initial version permitted only isolated explanatory (non-advisory) behaviors to be exhibited. This ran the risk of limiting explanatory coverage, so the methods for sequencing multiple explanatory behaviors were developed. This in turn created a secondary problem: students who progressed quickly through the problem-solving episodes might be bombarded with a formidable number of explanations near the end of the learning session. This concern prompted the addition of the mechanism for selecting the number of explanatory behaviors based on the predicted number of opportunities during the remainder of the learning session.

Conclusion

Animated pedagogical agents can combine adaptive explanatory behaviors with great visual appeal. We have proposed an approach to dynamically sequencing these agents' behaviors that exploits (1) a behavior space containing animated and verbal behaviors, and (2) a coherence structure consisting of a tripartite behavior index of ontological, intentional, and rhetorical indices, a prerequisite structure, and continuity annotations that estimate the degree of visual continuity between pairs of behaviors. By navigating the behavior space and attending to the coherence structure, a behavior sequencing engine selects and assembles behaviors that exhibit both pedagogical and visual coherence. This coherence-based approach to behavior sequencing has been implemented in an agent that operates in realtime to dynamically sequence behaviors in response to rapidly changing problem-solving contexts. It has been tested in a learning environment with middle school children, and the results are encouraging.

This work represents a promising first step toward creating animated pedagogical agents with a large repertoire of communicative behaviors. Perhaps the greatest challenge lies in increasing agents' flexibility, and an effective technique for accomplishing this is to reduce the granularity of their behaviors. We will be investigating fine-grained behavior sequencing mechanisms for animated pedagogical agents in our future research.

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