Narrative-Centered Tutorial Planning for Inquiry-Based Learning Environments

Bradford W. Mott and James C. Lester

Department of Computer Science
North Carolina State University
Raleigh, NC 27695 USA
{bwmott, lester}@ncsu.edu

Abstract. Recent years have seen growing interest in narrative-centered learning environments. Leveraging the inherent structure of narrative, narrative-centered learning environments offer significant potential for inquiry-based learning in which students actively participate in engaging story-based problem-solving. A key challenge posed by narrative-centered learning is orchestrating all of the events in the unfolding story to motivate students and promote effective learning. In this paper we present a narrative-centered tutorial planning architecture that integrates narrative planning and pedagogical control. The architecture continually constructs and updates narrative plans to support the hypothesis-generation-testing cycles that form the basis for inquiry-based learning. It is being used to implement a prototype narrative-centered inquiry-based learning environment for the domain of microbiology. The planner dynamically balances narrative and pedagogical goals while at the same time satisfying the real-time constraints of highly interactive learning environments.

1 Introduction

Narrative is central to human cognition. Because of the motivational force of narrative, it has long been believed that story-based education can be both engaging and effective. Much educational software has been devised for story-based learning. These systems include both research prototypes and a long line of commercially available software. However, this software relied on scripted forms of narrative: they employed either predefined linear plot structures or simple branching storylines. In contrast, one can imagine a much richer form of narrative learning environment that dynamically crafts customized stories for individual students at runtime. Recent years have seen the emergence of a growing body of work on dynamic narrative generation [4, 21, 23], and narrative has begun to play an increasingly important role in intelligent tutoring systems [10, 20].

Narrative offers significant potential for inquiry-based learning. In inquiry-based learning, the student iterates through cycles of questioning, hypothesis generation, data collection, and hypothesis testing. In a narrative-centered inquiry-based learning environment, the student could be featured as the central character in a dynamically generated story. She would be presented with problems to solve, and the plot would be shaped in such a way that she would at pedagogically appropriate times "discover" evidence confirming or disconfirming her hypotheses.

Narrative-centered learning environments for inquiry-based learning should satisfy three requirements. First, they should strike a delicate balance between advancing the plot and achieving tutorial goals. The former cannot be ignored without making the narrative less engaging and coherent; the latter cannot be ignored without reducing pedagogical effectiveness. Second, narratives should be customized for individual students. Plots driven by students' problem-solving activities should be tightly coupled to hypothesis-generation-testing cycles to create the best possible learning outcomes. Third, narrative generation must interleave planning and execution to satisfy the real-time requirements of highly interactive learning environments. Because of the complexities of narrative planning and the dynamic tutorial state on which it depends, narratives must be planned incrementally, plans must be monitored, and they must be revised as the storyworld and tutorial state change.

This paper introduces a narrative-centered tutorial planning architecture for inquiry-based learning environments. The architecture integrates narrative planning and tutorial control via a hierarchical task network (HTN) planner [6] that operates in two coordinated planning spaces. In the tutorial planning space, the planner constructs tutorial plans to achieve pedagogical goals such as topic sequencing, problem introduction, problem solving, and advice generation. In the narrative planning space, the planner constructs narrative plans to achieve story goals such as how to direct the characters' actions, how to devise coherent plots, and how to create engaging experiences for the student. The dual planning space approach achieves modularity for authoring and maintenance of plan operators, and it enables the planner to guide the student's actions at both the pedagogical and narrative levels. The architecture is being used to implement CRYSTAL ISLAND, a prototype inquiry-based learning environment for the domain of microbiology. Preliminary experience with the narrative planner and the learning environment suggests that the architecture can effectively balance pedagogical and narrative goals, create customized narratives for individual students, and interleave planning and execution.

2 Narrative-Centered Inquiry-Based Learning

Narrative experiences are powerful. In his work on cognitive processes in narrative comprehension, Gerrig identifies two properties that readers of narrative experience [5]. First, readers are transported, i.e., they are somehow taken to another place and time in a manner that is so compelling it seems real. Second, they perform the narrative. Like actors in a play, they actively draw inferences and experience emotions as if their experiences were somehow real. It is becoming apparent that narrative can be used as an effective tool for exploring the structure and process of "meaning making." For example, narrative analysis is being adopted by those seeking to extend the foundations of psychology [3] and film theory [2].

Learning environments may utilize narrative to their advantage. One can imagine narrative-centered curricula that leverage a student's innate metacognitive apparatus for understanding and crafting stories. This insight has led educators to recognize the potential of contextualizing all learning within narrative [25]. Because of the active nature of narrative, by immersing learners in a captivating world populated by intriguing characters, narrative-centered learning environments can enable learners to participate in the construction of narratives, to engage in active problem solving, and to reflect on narrative experiences [15]. These activities are particularly relevant to inquiry-based learning. *Inquiry-based learning* emphasizes the student's role in the learning process via concept building [27] and hypothesis formation, data collection, and testing [7]. For example, a narrative-centered inquiry-based learning environment for science education could foster an in-depth understanding of how real-world science plays out by featuring science mysteries whose plots are dynamically created for individual students.

Historically, learning effectiveness has functioned as the sole metric by which learning environments are gauged. However, from a practical perspective, it has become clear that educational software that fails to engage students will go unused. In Malone's classic work on motivation in computer games and educational software [11], he distinguishes between game playing experiences (and educational experiences) that are extrinsically motivating and those that are intrinsically motivating. In contrast to extrinsic motivation, intrinsic motivation stems from the desire to undertake activities sheerly for the immediate pleasure to be derived from them. By emphasizing qualities such as challenge, curiosity, and fantasy, Malone argues that learning environments can create intrinsically motivating experiences [12]. Hence, in addition to their potential cognitive benefits, narrative-centered learning also offers significant potential for providing intrinsic motivation.

Several projects have begun to explore narrative-centered learning environments. Some have begun to devise powerful models of ITSs that can be informed by narrative [20]. Of particular interest here are approaches that enable children to be creative storytellers in collaborative, play-oriented environments [10]. Narrative-centered learning environments have also been employed in the service of creative writing [22], story creation [14], second language learning for training applications [8], individualized video-based lesson planning customized to particular students [9], social behavior education [1], and problem-solving for health education [13]. The narrative-centered tutorial planning architecture proposed in this paper seeks to bridge the gap between tutorial planning and narrative planning in order to provide story-based problem-solving experiences that complement those explored in other efforts in narrative-centered learning.

3 Narrative-Centered Tutorial Planning Architecture

The narrative-centered tutorial planning architecture directs all of the core activities of the learning environment (Figure 1). All student activities are mediated through the interface manager for the virtual environment. The interface manager interacts with the world model, which houses the 3D object and character models, the properties of manipulable objects, and the scene geometries. The world model drives both the rendering and sound engines. The planner consists of three components: a tutorial planner, a narrative planner, and a plan executor and monitor. The tutorial planner oper-

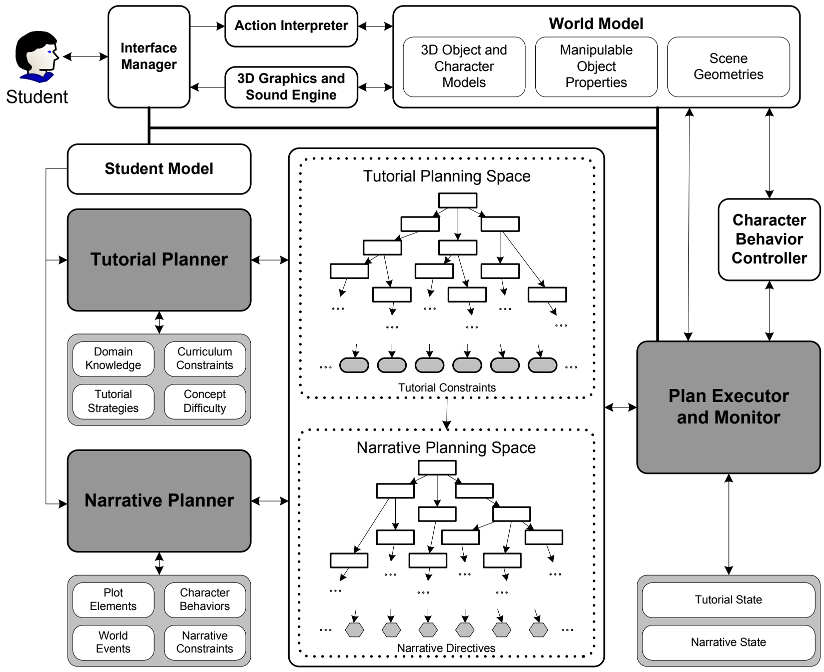

Fig. 1. Narrative-Centered Tutorial Planning Architecture

ates in the tutorial planning space. It utilizes domain knowledge, curriculum constraints, tutorial strategies, and concept difficulty annotations to make its decisions. The narrative planner operates in the narrative planning space. It utilizes a library of plot elements, a library of character behaviors, a set of world event categories, and narrative constraints on possible stories to make its decisions. The plan executor and monitor interact with both the tutorial and narrative planning spaces. It sends directives to the character behavior controller and the world model. All three planning components are influenced by the student model, and the plan executor and monitor also reads from (and updates) the tutorial and narrative states.

The narrative-centered tutorial planning architecture provides all of the functionalities that classic tutorial planners provide, as well as the functionalities that narrative planners provide. With regard to tutorial planning, it selects and presents problems, sequences content from the curriculum, provides timely and context-specific advice and explanations, manages the initiative, and selects and executes tutorial strategies [17, 19, 24, 26]. To address the requirements of inquiry-based learning, its tutorial strategies support question formation, hypothesis generation, data collection, and hypothesis testing. With regard to narrative planning, it generates all plot elements, sequences plot elements into coherent and engaging stories, and directs characters' actions and storyworld events to achieve tutorial and narrative goals.

Dynamically reasoning about narrative-centered tutorial strategies is inherently a planning problem. Planning has been used for tutorial strategy formation and execution [19] and for narrative generation [4, 21]. A multitude of formalisms have been developed for automatically constructing plans to achieve a given set of goals or tasks

[6]. However, planning is a challenging problem: in the worst case it is worse than NP-complete. While many prototypes have been devised over the decades, it has been challenging to create planners that function well in practical applications. Hierarchical task network (HTN) planners [6] have found a much broader use in fielded systems than competing approaches. If one has application-specific knowledge about a problem, then it can be incorporated into an HTN planner. HTN planners employ a problem reduction approach that supports reasoning about constraints, resolving interactions, and backtracking to alternate decompositions if necessary [6]. Because HTN planning can be very efficient with sufficient application knowledge – this is the case with both tutorial planning and narrative planning – the narrative-centered tutorial planning architecture utilizes an HTN planning system based on SHOP2 [18].

In addition to being expressive and efficient, it is critical that tutorial planning and narrative planning support one another: they cannot be permitted to diverge. All (or most) tutorial goals should be realized through plot elements, and all (or most) plot elements should be generated in support of tutorial goals. Although some learning might occur through non-narrative means, e.g., providing textual and animated explanations external to the story, the student should remain immersed in the story to the greatest extent possible. Moreover, although engaging story events could be created that served no tutorial purpose, the interests of pedagogy must drive the student's experience.

Two distinct approaches can be taken to reasoning about tutorial and narrative planning in a manner that ensure that tutorial and narrative planning are mutually supportive. One approach uses a single planning space and the other uses two planning spaces. In the *single planning space* approach, tutorial methods, operators, preconditions, and effects are scattered throughout one planning space. In this approach, a single method can have preconditions on both tutorial goals and narrative goals, and the effects of operators can be on both tutorial states and narrative states. However, such an approach requires the construction of methods and operators that are difficult to author and maintain. By intermixing tutorial and narrative predicates and effects throughout a single planning space, modularity is violated and expanding HTN libraries become increasingly difficult as domain complexity grows.

In the *dual planning space* approach, one planning space is allocated to tutorial planning and a second is allocated to narrative planning. This approach offers the advantage of modularity: narrative planning issues can be considered separately from tutorial planning issues. However, for the two planners to work in concert, they must effectively coordinate their actions, which will result in a single stream of events occurring in the virtual storyworld. To this end, the tutorial planner posts goals in the tutorial planning space that are achieved by operators in the narrative planning space. Thus, appropriate customized narratives can be generated in the service of pedagogical objectives.

One can distinguish three alternate coordination models for communication between the two planning spaces. First, in the *parallel* model, the two planning spaces could operate "side-by-side." Tutorial goals could be posted and achieved by the tutorial planner while narrative goals could be posted and achieved by the narrative planner. However, resolving inconsistencies between the sequences of actions suggested by the two planners would be very challenging and would not scale to larger, more complex domains. Second, in the *narrative-driven* model, the narrative planner could post goals in the narrative planning space that would be achieved by operators in the tutorial planning space. While such an approach might produce coherent and engaging narratives, these would at times be produced at the cost of effective learning. Third, in the *tutorial-driven* dual planning space model, the tutorial planner could post goals in the tutorial planning space that would be achieved by operators in the narrative planning space. Here, appropriate customized narratives would be generated in the service of pedagogical objectives. The architecture thus adopts the tutorial-driven model.

The *tutorial planning space* houses all concepts, goals, methods, and operators for reasoning about the student's learning experience, as well as the tutorial state. These encode domain (subject matter) knowledge, curriculum sequencing constraints represented as a partial order on concepts, the student model (the current implementation uses a simple overlay student model), and difficulty annotations on concepts. They also encode inquiry-based learning strategies that guide hypothesis-generation-testing cycles. HTN methods represent decompositions of higher level tutorial goals to lower level tutorial goals. All HTNs eventually bottom out in tutorial constraints, which collectively guide narrative planning and focus it on the most relevant regions of the narrative planning space that are consistent with the current tutorial plan.

The *narrative planning space* houses all goals, methods, and operators for reasoning about the storyworld. These encode plot construction knowledge, character behaviors, storyworld event categories, and narrative constraints, including coherence and flow constraints. All narrative HTNs eventually bottom out in primitive narrative events, which play out in the storyworld. These primitive events are directives that will be physically interpreted in the virtual environment.

In narrative-centered tutorial planning, tutorial and narrative plans can be very complex. Moreover, the specifics of plans are highly dependent on the current tutorial and narrative state, which are highly dynamic and are themselves highly dependent on the actions of the student in the storyworld. It would therefore be infeasible for the planner to attempt to construct fully specified tutorial and narrative plans. Planning and execution must be interleaved at runtime to permit replanning as needed. Planning is initiated when top-level tutorial goals are posted. It operates in four highly interleaved phases of operation:

- *Plan construction*: During construction, HTN methods, operators, preconditions, and effects are instantiated, and the methods recursively invoke lower-level methods. Construction in the tutorial space builds a full set of conceptual and inquiry-based problem-solving constraints. Construction in the narrative space creates the plot and character behaviors.
- *Plan execution*: During execution, narrative operators drive events in the storyworld. (Tutorial operators are not directly executed *per se*; rather, the tutorial constraints are used to guide the selection of narrative HTNs and their instantiation.)
- *Plan monitoring*: During monitoring, the planner tracks all activities in the world. It checks for unanticipated violations of preconditions brought about by changes in the tutorial and narrative states. These changes result from actions taken by the student in the storyworld.

- *Replanning*: During replanning, the planner uses the current tutorial and narrative states to modify the current plan so that the preconditions of upcoming methods and operators (i.e., methods and operators that are as of yet unexecuted) will be re-established. Sometimes replanning in the narrative space causes a cascading of re-planning in the tutorial space.

The HTN-based narrative-centered tutorial planning architecture operates in the four phases, incrementally constructing and executing plans while continuously monitoring the tutorial and narrative states and replanning as necessary until all of the tutorial goals have been achieved and student completes the interactive story.

4 An Implemented Narrative-Centered Tutorial Planner

The narrative-centered tutorial planning architecture is being used to implement CRYSTAL ISLAND, a prototype inquiry-based learning environment for the domain of microbiology being constructed for middle school students (Figure 2). CRYSTAL ISLAND features a science mystery set on a recently discovered volcanic island where a research station has been established to study the unique flora and fauna. The user plays the protagonist attempting to discover the origins of an unidentified infectious disease at the research station. The story opens by introducing her to the island and the members of the research team for which her father serves as the lead scientist. As members of the research team fall ill, it is her task to discover the cause of the outbreak. She is free to explore the world and interact with other characters while forming questions, generating hypotheses, collecting data, and testing her hypotheses. Through the course of her adventure she must gather enough evidence to correctly choose among candidate diagnoses including botulism, cholera, giardiasis, paralytic shellfish poisoning, salmonellosis, and tick paralysis as well as identify the source of the disease.

The narrative-centered tutorial planning architecture has been implemented with an HTN planner that is based on the SHOP2 planner [18] and was constructed in our laboratory to meet the specific needs of narrative and tutorial planning. For efficiency, it was designed as an embeddable C++ library to facilitate its integration into high-performance 3D gaming engines. The implementations of the tutorial planner and the narrative planner were both built with the custom HTN planner. Their respective planning spaces have well defined APIs that support appropriate accesses but establish modularity. The virtual world of CRYSTAL ISLAND, the semi-autonomous characters that inhabit it, and the user interface were implemented with Valve Software's Source™ engine, the 3D game platform for Half-Life 2. The Source engine also provides much of the low-level (reactive) character behavior control. The character behaviors and artifacts in the storyworld are the subject of continued work. The tutorial and narrative planners are fully implemented, a decision-theoretic "director" agent based on dynamic decision networks has been implemented to guide the narrative in the face of uncertain student actions [16], and the method and operator libraries for the microbiology domain are currently being built out.

To illustrate the behavior of the narrative-centered tutorial planning architecture within the CRYSTAL ISLAND learning environment, consider the following situation.

Fig. 2. Crystal Island Learning Environment

A student has been interacting within the storyworld and learning about infectious diseases and related topics. In the course of having members of her research team become ill, she has learned that an infectious disease is an illness that can be transmitted from one organism to another. As she concludes her introduction to infectious diseases, she learns from the camp nurse that the mystery illness seems to be salmonellosis and that the source of the disease must be identified. The narrative planner has decided to have her pursue satisfying the tutorial constraints associated with the *Spread-of-Infectious-Diseases* topic by constructing a plan which has the unfolding story involve the spread of a disease by means of contaminated food. Specifically, it chooses salmonellosis as the illness and contaminated eggs as the source of the bacterial infection. Although, the student has made steady progress while learning about infectious diseases, the task of identifying the source of the illness has left her wandering aimlessly around the storyworld to locate the source. As the execution and monitoring components of the system assess the unfolding story, it determines that the student's progress towards identifying the origins of the illness is lagging. To address this, the narrative planner updates the narrative plan to include a hint action realized in the camp nurse revealing that she believes the source of the disease is something that the victims ate.

Experience to date suggests that tutorial and narrative planning libraries are relatively straightforward to construct. First, as others have found, HTN-based plan methods and operators seem to be intuitively authored, even with fairly complex planning tasks. We anticipate that the modularity inherent in HTN's "recipes" will support the complexities to be faced in building out the domain. Second, separating the activities of the architecture into two distinct but coordinated spaces seems to be essential for efficient authoring; other approaches that were considered early in the project were discarded because of the resulting complexity. Third, the practicalities of real-time planning call for a planning formalism (and system) that could easily be integrated with other components and operate with high efficiency. HTN planners can more easily incorporate domain-specific knowledge than classic STRIPS-style planners. This property can be leveraged by narrative-centered learning environments such as Crystal Island, which are highly interactive.

7 Conclusion

The HTN-based narrative-centered tutorial planning architecture addresses the three requirements set forth above for inquiry-based learning environments. First, it balances plot advancement and tutorial goal achievement seamlessly by the built-in coordination of the two planning spaces via the lower-level tutorial constraints and the upper-level narrative goals. Second, it customizes narratives for individual students by basing both tutorial and narrative planning on the student model and tutorial state. Third, it interleaves planning and execution by operating in the four phases of construction, execution, monitoring, and replanning; it satisfies the real-time performance requirements through the efficiency provided by HTN planning.

The architecture represents a first step towards inquiry-based learning environments that offer students effective and engaging problem-solving experiences in rich, interactive storyworlds. It suggests several lines of promising work. Of particular interest here are investigating approaches for incorporating models of affect that support students, both with respect to their interactions with characters in the virtual world and their problem-solving activities *per se*. It will also be important to incorporate much more expressive student modeling techniques that can be used for plan recognition in "narrative diagnosis," i.e., how to most accurately predict a student's current goals given the openness of the learning environment but exploiting the model of narrative on which the unfolding story is based. Finally, it will be important to develop a precise, empirically grounded understanding of the kinds of problem-solving interactions that narrative can most effectively promote in inquiry-based learning.

References

1. Aylett, R., Louchart, S., Dias, J., Paiva, A., and Vala, M. 2005. FearNot! – An Experiment in Emergent Narrative. In *Proceedings of the Fifth International Conference on Intelligent Virtual Agents*, 305-316. Kos, Greece.
2. Branigan, E. 1992. *Narrative Comprehension and Film. London*: Routledge.
3. Bruner, J. 1990. *Acts of Meaning*. Cambridge, MA: Harvard University Press.
4. Cavazza, M., Charles, F., and Mead, S. 2002. Interacting with Virtual Characters in Interactive Storytelling. In *Proceedings of the First International Joint Conference on Autonomous Agents and Multi-Agent Systems*, 318-325. Bologna, Italy.
5. Gerrig, R. 1993. *Experiencing Narrative Worlds: On the Psychological Activities of Reading*. New Haven: Yale University Press.
6. Ghallab, M., Nau, D., and Traverso, P. 2004. *Automated Planning: Theory and Practice*. Morgan Kaufmann.
7. Glaser, R., Schauble, L., Raghavan, K., and Zeitz, C. 1992. Scientific reasoning across different domains. In E. De Corte, M. C. Linn, H. Mandle, and L. Verschaffel (eds.), *Computer-Based Learning Environments and Problem Solving*, 345-373. Berlin: Springer.
8. Johnson, L., Beal, C., Fowles-Winkler, A., Narayanan, S., Papachristou, D., Marsella, S., and Vilhjálmsson, H. 2004. Tactical Language Training System: An Interim Report. In *Proceedings of the Seventh International Conference on Intelligent Tutoring Systems*, 336-345. Maceió, Alagoas, Brazil.
9. Luckin, R., Underwood, J., du Boulay, B., Holmberg, J., and Tunley, H. 2004. Coherence Compilation: Applying AIED Techniques to the Reuse of Educational Resources. In *Pro-*

ceedings of the Seventh International Conference on Intelligent Tutoring Systems, 98-107. Maceió, Alagoas, Brazil.
10. Machado, I., Brna, P., and Paiva, A. 2001. Learning by Playing: Supporting and Guiding Story-Creation Activities. In *Proceedings of the Tenth International Conference on Artificial Intelligence in Education*, 334-342. San Antonio, Texas.
11. Malone, T. 1981a. Toward a Theory of Intrinsically Motivating Instruction. *Cognitive Science* 5(4):333-369.
12. Malone, T. 1981b. What makes computer games fun? *Byte* 6:258-277.
13. Marsella, S., Johnson, L., and LaBore, C. 2000. Interactive Pedagogical Drama. In *Proceedings of the Fourth International Conference on Autonomous Agents*, 301-308. Barcelona, Spain.
14. Marshall, P., Rogers, Y. and Scaife, M. 2002. PUPPET: A Virtual Environment for Children to Act and Direct Interactive Narratives. In *Proceedings of the Second International Workshop on Narrative and Interactive Learning Environments*. Edinburgh, Scotland.
15. Mott, B., Callaway, C., Zettlemoyer, L., Lee, S., and Lester, J. 1999. Towards Narrative-Centered Learning Environments. In *Proceedings of the 1999 Fall Symposium on Narrative Intelligence*, 78-82. Cape Cod, MA.
16. Mott, B. and Lester, J. 2006. U-DIRECTOR: A Decision-Theoretic Narrative Planning Architecture for Storytelling Environments. To appear in *Proceedings of the Fifth International Conference on Autonomous Agents and Multi-Agent Systems*, Hakodate, Japan.
17. Murray, W. 1989. Control for Intelligent Tutoring Systems: A Blackboard-based Dynamic Instructional Planner. In *Proceedings of the Fourth International Conference on Artificial Intelligence and Education*, 150-168. Amsterdam, Netherlands.
18. Nau, D., Muñoz-Avila, H., Cao, Y., Lotem, A., and Mitchell, S. 2001. Total-Order Planning with Partially Ordered Subtasks. In *Proceedings of the Seventeenth International Joint Conference on Artificial Intelligence*. Seattle, WA.
19. Peachey, D. and McCalla, G. 1986. Using Planning Techniques in Intelligent Tutoring Systems. *The International Journal of Man-Machine Studies* 24(1):77-98.
20. Riedl, M., Lane, H., Hill, R., and Swartout, W. 2005. Automated Story Direction and Intelligent Tutoring: Towards a Unifying Architecture. In *Proceedings of the Workshop on Narrative Learning Environments at the Twelfth International Conference on Artificial Intelligence in Education*, 23-30. Amsterdam, Netherlands.
21. Riedl, M. and Young, M. 2004. An Intent-Driven Planner for Multi-Agent Story Generation. In *Proceedings of the Third International Joint Conference on Autonomous Agents and Multi-Agent Systems*, 186-193. New York.
22. Robertson, J. and Good, J. 2003. Ghostwriter: A narrative virtual environment for children. In *Proceedings of the 2003 International Conference on Interaction Design and Children*, 85-91. Preston, England.
23. Si, M., Marsella, S., and Pynadath, D. 2005. Thespian: Using Multi-Agent Fitting to Craft Interactive Drama. In *Proceedings of the Fourth International Conference on Autonomous Agents and Multi-Agent Systems*, 21-28. Utrecht, Netherlands.
24. Vassileva, J. and Wasson, B. 1996. Instructional Planning Approaches: from Tutoring towards Free Learning. In *Proceedings of the European Conference on Artificial Intelligence in Education*, 1-8. Lisbon, Portugal.
25. Wells, C. 1986. *The Meaning Makers: Children Learning Language and Using Language to Learn*. Portsmouth, NH: Heinemann.
26. Woolf, B. and McDonald, D. 1984. Building a Computer Tutor: Design Issues. *IEEE Computer* 17(9):61-73.
27. Zachos, P., Hick, L., Doane, W., and Sargent, C. 2000. Setting Theoretical and Empirical Foundations for Assessing Scientific and Discovery in Educational Programs. *Journal of Research in Science Teaching* 37(9):938-962.