

Using a Quantitative Model of Participation in a Community of Practice to Direct Automated Mentoring in an Ill-Formed Domain

David Williamson Shaffer¹ and Arthur Graesser²

¹ University of Wisconsin—Madison, Department of Educational Psychology
1025 West Johnson Street, Madison, WI 53711, USA. dws@education.wisc.edu

² Institute for Intelligent Systems, 365 Innovation Drive, University of Memphis, Memphis,
TN 38152, a-graesser@memphis.edu

Abstract. We describe a system for producing automated professional mentoring using a quantitative model of enculturation. We are developing an automated mentoring technology, AutoMentor, that builds on previous research on automated tutoring systems, specifically on AutoTutor, a computer tutor that helps students learn about science and technology topics by holding a conversation in natural language with the learner. We do this by exploring a specific hypothesis about mentoring in ill-formed domains: namely, that using a sociocultural model as the basis of an automated tutoring system can provide a computational model of participation in a community of practice, which will produce effective professional feedback from non-player-characters in a learning game.

Keywords: Epistemic frames, epistemic games, epistemic network analysis (ENA), automated mentoring, AutoTutor, AutoMentor, tutoring systems, learning games, educational games, mentoring.

1 Background

In this paper we address a critical research question about intelligent tutoring systems: Can a quantitative model of participation in a community of practice automate professional mentoring in a learning game?

We are developing and testing an automated mentoring technology within the context of a specific discipline (the study of ecology and the development of systems thinking more broadly) and within the context of a specific computer game for middle school students. In this paper we describe this specific example as well as the general principles and techniques that it explores for providing professional mentoring within the context of learning games in ill-structured domains.

1.1 Learning Theory: The Epistemic Frame Hypothesis

Learning to solve ill-formed problems typically comes from being part of a community of practice [1]: a group of people who share similar ways of solving problems. Learning does not end with the mastery of pertinent skills and knowledge; it must also include developing a sense of what kinds of judgments are compatible with the values and practices of a field. Within a ill-formed domain, there are particular ways of justifying decisions and developing solutions [2].

The epistemic frame hypothesis suggests that any community of practice has a culture [3] and that culture has a grammar, namely a structure composed of:

1. Skills: the things that people within the community do;
2. Knowledge: the understandings that people in the community share;
3. Values: the beliefs that members of the community hold;
4. Identity: the way that members of the community see themselves; and
5. Epistemology: the warrants that justify actions or claims as legitimate within the community.

This collection of skills, knowledge, values, identity, and epistemology forms the epistemic frame of the community [4].

This theory has been developed and tested in the context of epistemic games: games where players engage in simulations of training in professions such as engineering and urban planning to develop the epistemic frame of thinking [5, 6]. These games are developed by studying professional practica, and creating a game storyboard that describes the key activities of the practicum: the actions that professionals-in-training take in the practicum, and the occasions for reflection between professionals-in-training and their mentors [4, 7].

The storyboard for a game is then expanded into a frameboard that describes, for each activity: (a) the activity of the players in the game; (b) the activity of the mentors, including key dialogue moves or talking points; (c) the expected work product, output, or action of the players; (d) the criteria for evaluation of the work product or output; (e) the expected elements of the epistemic frame of the profession; and (f) the sources of evidence that will be used to determine whether the elements of the epistemic frame are used in that context.

The specific elements of the game are built from this frameboard. This includes simulations and other professional tools; non-player character (NPC) responses, requests for information and feedback; and instructions for game mentors who interact with players through instant messaging (IM) and e-mail. The game engine that controls an epistemic game automatically records player interactions with game mentors via IM and e-mail, which can be later analyzed for both the forms of mentoring and content they contain.

1.2 Ill-formed Domain: Ecological Thinking

The game we are using for this project, *Urban Science*, is a computer-based game in which late elementary, middle, and high school students learn ecological thinking by role-playing as members of an urban planning firm dealing with land use issues in ecologically sensitive areas. In the game, players interact with NPCs in the form of

stakeholders in the community and other planners in the firm. These computer-generated characters represent different interest groups with competing agendas, as well as supervisors and other members of the firm who provide professional resources, information about ecological issues, and advice about the planning process.

Urban planning is a domain of practice traditionally taught at the postsecondary level, but it is a potentially fruitful context for the development of science understanding in middle school students. Work in urban planning addresses elements of the National Science Education Standards [8] that call for understanding systems, order, and organization; evolution and equilibrium; and form and function in natural systems. The Geographical information system (GIS) tools that planners use make these complex processes, as well as the practices urban planners use to deal with such complexity, more accessible to middle school students. [9, 10]

To link the skills of the professional practice of urban planning to the science standards, we have constructed a set of land use models that integrate geographic features and sets of secondary attributes into interactive visual models of complex systems. In our previous studies of Urban Science, we developed five such models for Madison, Wisconsin. Land use models use a GIS system to generate feedback from virtual stakeholders in the community in response to players' land use decisions by integrating a land use impact model, which quantifies the impact of land use decisions on key environmental, economic, and social indicators, such as pollution, tax revenue, and acreage of wildlife habitat; utility quantification metrics, which express the weighted valuation of indicator levels to different stakeholder groups in the community; and a feedback generation algorithm which assembles predetermined responses from virtual stakeholders based on stakeholder satisfaction levels on different indicators. In this way, a land use model simulates the interaction between ecological and social systems in a local community. That is, such models represent ecological and ecosocial relationships in a computational form that players in Urban Science can use to explore, propose, and defend solutions to complex ecological and economic issues.

For example, one land use model we have built and tested for Urban Science explores development on the north side of Madison, Wisconsin, adjacent to a large wetland area known as Cherokee Marsh. The project raises a number of significant economic and ecological issues related to wetland ecology and conservation. Not surprisingly, while working in the Cherokee Marsh land use model, players of Urban Science have to investigate, analyze, understand, and communicate about a number of scientific issues, including local species, their life cycle, and their habitat; the role of wetlands in the local ecological system; and specific pollutants, their sources, and their impacts.

A key component of the game is that players interact with professional mentors: undergraduate and graduate students playing the role of more senior urban planners in the firm. These mentors help players in the game take action as urban planners to deal with ecological issues in the land use problems they are solving; but even more important, they help players reflect on their actions in the game. Previous research on Urban Science has shown that (a) the game is effective in developing ecological understanding for students, and (b) the time players spend reflecting with mentors is a key part of that process [5].

Automating professional STEM feedback in the game would be an important component for scaling up such interventions. Therefore our current project is exploring the use of virtual agents as professional mentors.

1.3 Existing Intelligent Automated Tutoring Research

Our project builds on previous research on intelligent tutoring systems. Intelligent tutoring systems track the knowledge states of learners in fine detail (called user modeling) and adaptively respond with activities that incorporate computational models in artificial intelligence and cognitive science, such as production systems, case-based reasoning, Bayes networks, theorem proving, and constraint satisfaction algorithms. Successful systems have been developed for mathematically well-formed topics, including algebra, geometry, programming languages, physics, and information technology. These systems show impressive learning gains (1.00 sigma, approximately), particularly for deeper levels of comprehension. Specifically, we base our project on previous research on AutoTutor, a computer tutor that helps students learn about science and technology topics by holding a conversation in natural language with the learner. Previous research on AutoTutor has focused on the learning of STEM topics, such as physics, computer literacy, biology, and scientific methods, and has shown that AutoTutor improves learning by nearly one letter grade compared with reading a textbook an equivalent amount of time, or compared with a pretest of students' abilities in a STEM domain [11, 12].

AutoTutor helps students compose answers to deep-reasoning questions and solutions to problems by expressing a variety of dialogue moves, such as: feedback (positive, neutral, negative), pumps for more information ("Tell me more"), hints, prompts to fill in missing words, summaries, corrections of student misconceptions, answers to student questions, and requests for students to perform actions in interactive simulation environments.

The system architecture of AutoTutor has five key components:

1. A state table that maintains and updates the states of the student-system dialogue and the tasks in the learning environment.
2. A student model that records the student's knowledge, progress on covering expected material, emotional states, and other learner characteristics.
3. A curriculum script of pedagogical tasks (problems to solve or difficult questions to answer), the expected correct answers for each task, alternative tutor dialogue moves, and other content that is task-specific.
4. A set of computational linguistic modules that include lexicons, syntactic parsers, speech act classifiers, shallow semantic analyzers, and latent semantic analysis (LSA) spaces [13, 14] for analyzing the meaning of what the student expresses verbally.
5. A dialogue planner that formulates the dialogue moves of the next conversational turn of AutoTutor in a fashion that is sensitive to the state table, the student model, and interpretation of student input via the computational linguistics modules.

The conversations managed by AutoTutor are imperfect, but smooth enough for students to work with minimal difficulties. Dialogue is sufficiently tuned so that a bystander who observes tutorial dialogue in print cannot tell whether a particular turn was generated by AutoTutor or by an expert human tutor [15].

1.4 Existing Research on Models of Participation in Communities of Practice

Finally, our project uses Epistemic Network Analysis (ENA), a methodology to assess students' ability to think and act like professionals through epistemic game play [16]. ENA is a measurement and modeling technique that is designed to be intellectually responsive to current theories of learning that emphasize the contextual and connected aspects of complex problem solving.

ENA is based on two key concepts: (a) that thinking in an ill-formed domain can be characterized by the application of an epistemic frame composed of the linkages between skills, knowledge, identity, values, and epistemology; and (b) that the development of thinking in an ill-formed domain can be quantified, analyzed, and visualized with a dynamic network model of the developing epistemic frame. In this sense, ENA provides a computational model of a player's (or a mentor's) participation in the culture of a profession—the extent to which a player has adopted the ways of knowing, being, talking, and acting that characterize a particular community of practice.

ENA adapts the tools of social network analysis to a different domain. Social network analysis provides a robust set of analytical tools for representing networks of relationships, including complex and dynamic relationships of the kind that characterize epistemic frames [17, 18]. If we take the epistemic frame hypothesis as a basis of a student model for assessment, then we can quantify the developing epistemic frame for each participant at time T by summing, for each pair of frame elements (i,j) the number of times they are coded as occurring at each point of time in the game $t < T$. That is, we can construct a cumulative adjacency matrix ${}_T A_{i,j}^P$ which shows the strength of association between each pair of frame elements (i,j) for a given player in the data set. Once an epistemic frame is represented as a series of cumulative adjacency matrices, we can quantify the hypothesized epistemic frame using concepts from social network analysis, such as density and centrality [16]. We can use ENA to track the state of the epistemic frame of players in an epistemic game, and also characterize events, actions, and interactions in an epistemic game in terms of their effect on the players' developing epistemic frames. That is, we can track how specific features and events in a learning environment (or combinations of events, the current state of a learner's network, and interactions with peers and mentors) lead to significant changes in understanding of the ill-formed domain. ENA is thus a model of the extent to which an individual has the ways of thinking, talking, and acting that are characteristic of a particular community of practice.

2 Hypothesis and Method

We bring together these lines of research in the following hypothesis: We hypothesize that if we use a sociocultural rather than traditional cognitive model as the basis of an automated tutoring system, we can build a computational model of participation in a community of practice, and use that instead of or in addition to task analysis models to produce professional feedback from NPCs in a learning game.

Our program of research is to link (a) epistemic games, which prepare players to participate in STEM communities of practice through professional mentoring, with (b) AutoTutor, which provides automated feedback on learner's actions. We will do so by creating expert feedback based on (c) ENA, which is a model of an individual's ability to participate in a community of practice.

We accomplish this using a Wizard of Oz methodology [19], in which we collect data about player/mentor interactions over multiple instances of game play. We use this database of player questions and actions, as well as the accompanying expert mentor responses, to develop and validate a system for automatically coding interactions for elements of the epistemic frame of urban planning: the skills, knowledge, identity, values, and epistemology (abbreviated as SKIVE) of the planning profession. We then use the coded database to generate automated responses to player actions in the game, and test whether players' learning with automated mentoring are comparable to outcomes with live mentors. As a result, we will determine if, how, for whom, and when automated professional mentoring (based on a computational model of participation in a community of practice) affects learning in an ill-formed domain.

We will produce and test a version of the game Urban Science that includes the AutoMentor module for producing automated mentor feedback through e-mail and IM during game play. That is, AutoMentor will be a conversational agent, but not a "talking head" or animated agent. This version will be a 10-hour game designed to be played in schools or as part of out-of-school enrichment programming for middle school students. It will be a Web-based game in which players become interns at the office of a fictitious urban and regional planning firm, Land Management Associates, that develops land use plans for local and national sites.

We will also produce a set of algorithms and code to implement AutoMentor within the context of epistemic games, and learning games more generally. One important companion module is AutoFramer, a set of algorithms and code for automated coding of epistemic frame elements in game actions and interactions that will be necessary to implement the AutoMentor system. AutoFramer may also be used separately to assess players' participation in a community of practice during game play.

While this is fundamentally a project to produce dialogic material, another contribution of the project is to produce appropriate quantification of the textual material. More specifically there are three forms of quantified data to analyze: (1) results from pre and post tests, (2) human-produced textual material, and (3) textual material produced by AutoMentor. As such, our fundamental data analytical techniques are (a) the statistical methods used to quantify textual material in general, and (b) comparative statistical analyses of the relationships between these three data

types. There will also be exploratory investigations of the applicability of innovative measurement models to extend, enhance, or tune the foundational ENA data.

3 Preliminary Results and Conclusions

Work began on this project in Fall 2009 with support from the National Science Foundation. As a result, we do not have complete results to report on any phase of the project. However:

1. We have developed a version of Urban Science suitable for data collection and are currently pilot testing it.
2. We have isolated a subset of interactive episodes where students and mentors are working in a focused manner. Limiting the range of game episodes for initial analysis (e.g., focusing on some checkpoints or common experiences that are important moments in game play) is allowing us to build more focused models of interactions, which will later be validated in the larger data set.
3. We have hand coded a subset of the observations on SKIVE elements and are refining the codes already in use for Urban Science by characterizing key aspects of situations and mentor interaction that are salient for statistical/measurement modeling. This includes codes for the kind and level of support that mentors provide and specific forms of urban planning skills, knowledge, identity, values, and epistemology.
4. We have used latent semantic analysis (LSA) and clustering techniques to extract a set of prototype exemplars of each coding category. We are currently implementing a snowballing methodology in which we identify a pool of initial prototype responses, and then use LSA to identify close matches to new discourse responses. We are adding additional prototypes and refining the matching parameters against hand coded schemes.
5. We are concurrently validating the initial AutoFramer algorithms on a second, larger subset of mentor/player interactions. We are currently able to achieve a Cohen's kappa of .70 or higher (for the presence of a category, or the selection of a category) between human and automated coding for some categories.

We conceive of this project as a form of design research, where initial hypotheses about game design, assessment, and automated mentoring technologies are revised by subsequent experiments in each area. An advantage of design research in this context is the relatively continuous stream of implementation activity that we have planned. Our primary objective of this work is to use this particular game as an occasion to develop and validate an automated assessment and mentoring system based on a model of participation in a community of practice. We have made substantial progress in developing the architecture to accomplish that aim.

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