STRUCTURE MAPPING THEORY AS A FORMALISM FOR INSTRUCTIONAL GAME DESIGN AND ASSESSMENT

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ABSTRACT

CyGaMEs, which stands for Cyberlearning through Game-based, Metaphor Enhanced Learning Objects, is a formal approach to the design of instructional learning environments through applied structure mapping theory. This paper summarizes the CyGaMEs research program: its origin; the CyGaMEs approach to design, development, and assessment; the experimental paradigm; and findings using CyGaMEs' online, single-player research environment, *Selene: A Lunar Construction GaME*.

A STRUCTURE MAPPING APPROACH TO LEARNING ENVIRONMENT DESIGN

A quarter of a century of cognitive science research has built consensus supporting major tenets of structure mapping theory: people conduct analogical reasoning through a mapping of structure from source to target domain, mapping is constrained by the analogizer's immediate goal (Holyoak, Gentner, & Kokinov, 2001), and mapping is more probable and profound when two domains share relational structure (i.e., systematicity, Gentner, 1983). Analogical reasoning is ubiquitous in higher order thinking and learning (Hummel & Holyoak, 1997), and it leads to inferences about a to-be-learned domain. Viable inferences make learning more intuitive. Unfortunately, superficial mappings based upon mere structural similarities can lead to misconceptions or alternative conceptions that interfere with learning (Gentner & Markman, 1997). For example, day-to-day lived experience in the physical world can lead to extremely robust "commonsense beliefs about motion and force incompatible with Newtonian concepts" (Hestenes, Wells, & Swackhamer, 1992, p. 141). Today, advances in computer-based technologies enable us to build worlds, albeit virtual worlds, through which lived experience can make complex concepts intuitive. This is because structure mapping theory can be applied as a formalism for designing virtual physical worlds that are analogs of targeted conceptual domains. Furthermore, game-based technologies, which are goal oriented, provide the means to design the pragmatic constraints necessary to guide learners toward viable inferences. CyGaMEs, which stands for *Cy*berlearning through *Ga*me-based, *M*etaphor *E*nhanced Learning Object*s*, is an approach to the design of instructional learning environments through applied structure mapping. A CyGaME translates an abstract concept into procedural, goal-driven, embodied interactions. Because a CyGaME is the analog of the to-be-learned, it prepares learners to make viable inferences about the targeted domain. When learners can infer relational structure of a to-be-learned domain, knowledge acquisition is more intuitive. As with methods proposed by Schwartz, Martin and their colleagues (2004), CyGaMEs is an approach for producing learning environments designed as "preparation for future learning."

This paper summarizes the CyGaMEs research program: its origin; the approach to design, development, and assessment; the experimental paradigm; and findings using CyGaMEs' online, single-player research environment *Selene: A Lunar Construction GaME*.

ORIGINS

The CyGaMEs approach has evolved over a decade during the course of theoretical and empirical research.

Designing an Instructional Interface to Carry Content

In the late 1990s I was conducting an introductory investigation of the effectiveness of visual tools—specifically, Thinking Maps® (Hyerle, 1995, 1995/1996)—within multimedia environments. I found that my participants learned the interface and interface narrative more strongly than other aspects of the environment (Reese, 1998). Hyerle's visual tools had included a map for analogical reasoning, and his dissertation literature review (1993) introduced me to George Lakoff's theory of conceptual metaphor (Lakoff, 1993; Lakoff & Johnson, 1980). Comparing and contrasting conceptual metaphor, pragmatic constraint approaches (Hummel & Holyoak, 1997; Spellman & Holyoak, 1996), and structure mapping (Gentner, 1983, 1989) led me to conjecture that multimedia instructional environment interfaces might themselves support learning if principles from these theories were included within the design approach:

- Embodied interactions. The virtual world would be the source (concrete) domain. It would be essential that learners conduct transactions (in the sense of Adelbert Ames' transactional anaysis, see Cantril, 1960) with the environment in order to discover its relational structure. Learners would engage in psychomotor and sensory interactions with virtual world objects.
- Structure mapping. These objects would function as components of a virtual world [relational] system that was the analog of a targeted to-be-learned domain's relational structure. That is, the system would be programmed as a translation of the targeted domain's relational system.
- Pragmatic constraints. The virtual world would motivate (scaffold) learners to form a viable conceptualization (mental model) of the relational structure of the relational system and its mapping from the virtual world to the to-be-learned domain.

Using the major premises of structure mapping and complementary work by other scholars, I developed a formalism as steps for specifying target domain structure that could be mapped from target domain to source domain according to structure mapping principles (Reese, 2003a, 2003b, 2008a; Reese & Coffield, 2005) and then developed into a virtual world. These premises concern the consistency of relational structure between source and target domains and systematicity, as derived by Gentner and colleagues (e.g., Gentner, 1983; Gentner & Markman, 1997; Kurtz, Miao, & Gentner, 2001), Lakoff and Johnson (Lakoff & Johnson, 1980, 1999), and Holyoak and colleagues (e.g., Hummel & Holyoak, 1997; Spellman & Holyoak, 1996):

- Relational structure. People tend to map according to relations rather than superficial similarities.
- Systematicity. People tend to map systems of relationships rather than isolated relations. Deeper systematicity makes mapping more probable.
- Consistency. People tend to construct isomorphic mappings (one-to-one mappings) that have identical relational structure (parallel connectivity).
- Highlighting. The mind naturally engages only those domain relationships it judges pertinent to the mapping.
- Mutual alignment. People align a source and target domain according to relational structure.

However, I was unable to satisfactorily address interactivity or incorporate pragmatic constraints until I investigated the possibilities for learning and assessment within videogames. The solution emerged in late 2006 when NASA eEducation launched an initiative to engage the public with NASA science through game-based environments (Laughlin, Roper, & Howell, 2006) and assigned our center to investigate game-based learning and embedded assessment.

Alignment Between Game Design Theory and Analogical Reasoning Theory

Conceptual domains are "psychologically viewed as systems of objects, object-attributes, and the relations between objects" (Gentner, 1983, p. 156). Videogame worlds can also be viewed as systems of objects, their attributes, their properties (which can be relational), and the relations that connect them (Bogost, 2006; Fullerton, Swain, & Hoffman, 2004; Wright, 2003). Players conduct transactions with a game world as gameplay, and gameplay is goal-directed behavior. Thus, game worlds could be designed to direct players' progress through interactivity engineered to highlight targeted relational structure. The game world would be an analog of the targeted domain, and the game goal would be an analog of the targeted learning goal. Gameplay would be embodied transactions with the relational structure of the targeted domain.

Contemporary approaches to instructional design explain that people construct conceptual knowledge by building and revising mental models formed and refined as personal theories of how the world works (Jonassen, 2006). Renowned game designer and theorist Will Wright (2006a) designs a game world and gameplay to scaffold the player construction of successive approximations of a sound mental model of the game world's relational structure. Thus, a formal approach to the design of instructional videogames could engage learners in theory building that supports construction of sound mental models of targeted content.

Game-based, Metaphor Enhanced (GaME) Instructional Design

In day-to-day living a person makes inferences by mapping from a concrete or relatively familiar domain to the unfamiliar target domain (see Figure 1). GaME design works in the opposite direction. The GaME design team specifies the targeted, to-be-learned concept and then maps out a concrete domain that highlights just the salient relationships that constrain it as isomorphic to the target.

GaME design begins with selection and specification of the targeted learning domain. This is followed by identification of candidates to serve as concrete analogs, selection of the analog, mapping from the analog to the target, and vigilant oversight during development to ensure alignment between game system, gameplay, and game goal (and subgoals) and analogs within the targeted conceptual domain and targeted learning goal (and subgoals).

Domain Selection and Specification

Other publications describe the specification process in greater detail (Reese, 2003a, 2003b, 2007, 2008a, 2008c; Reese & Coffield, 2005). The process has evolved as the method advanced to include game design. Here I use a very high and general level to summarize the steps as stages.

Stage 1. Select Complex, Introductory Concept

Systematicity is a core structure mapping principle: People prefer to make profound mappings[1]. Thus, the GaME design approach is suitable only for conceptual domains that have deep relational structure.

Furthermore, GaME design specializes in preparing learners for complex *introductory* concepts, such as functionalism in educational psychology (Reese, 2003b), the mole in chemistry (Reese, 2008a; Reese & Coffield, 2005), or lunar geology (Reese, 2008c). Domain novices who cannot construct viable intuitions for introductory complex concepts are often unsuccessful (e.g., chemistry, Gabel, 1999; physics, Hestenes, et al., 1992; science in general, especially chemistry, Johnstone, 1991;

[1] Analogously, successful game worlds are those designed on a game system with profound relational structure that supports deep play (Hawkins, 2000; Wright, 2003, 2006b).

genetics, Lawson, Alkhoury, Benford, Clark, & Falconer, 2000). GaME is an intervention to make learning more intuitive because it helps learners to infer apt relational structure for a targeted domain. For example, a GaME about lunar geology would engage a learner with gameplay that proceduralizes the targeted relational system. The domain's subconcepts of accretion, differentiation, impact cratering, and volcanism (also gravity, density, kinetic energy, etc.) interact to explain the formation and evolution of the earth's Moon.

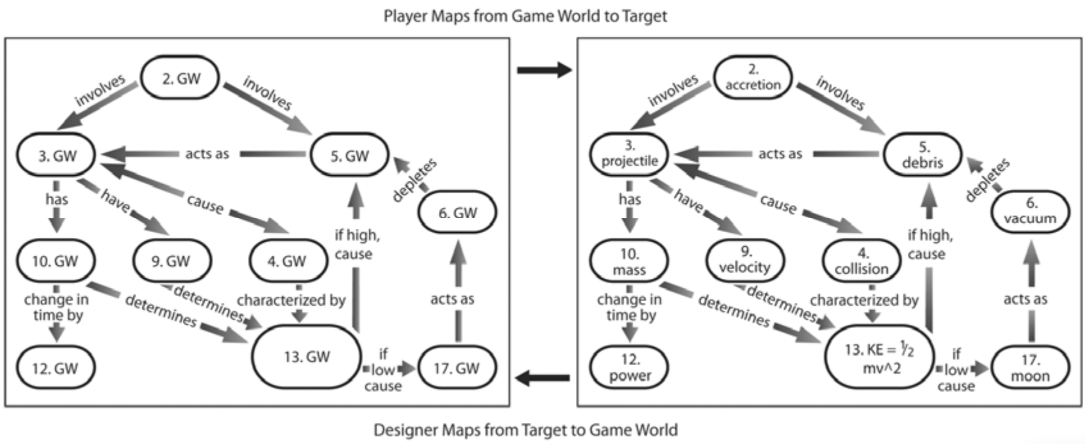

Figure 1. Mapping between source and target domains. People typically make inferences from source (left) to target (right) domains. The GaME approach specifies the target domain and then develops a game world (GW, left) that is relationally isomorphic to it. The player then maps from the game world to the targeted domain. In the figure the ovals represent objects in the source domain and subconcepts in the target domain. The directional arcs represent relations between two objects or two concepts. This mapping is excerpted from the 101 subconcept specification of lunar geology used to design Selene: A Lunar Construction GaME. During specification of the Selene game world, the initials GW were replaced by game objects or programming code. Copyright 2007 by Debbie Denise Reese and Charles A. Wood. Used with permission of the authors.

Step 2. Specify and Clean the Domain

Gentner and her colleagues used propositional networks for domain specification. However, she stipulated that alternative representation methods must (a) treat concepts as a whole, (b) distinguish between attributes and relations, and (c) present domain structure as hierarchical; that is, higher order concepts subsume lower order ones (Gentner, 1980, pp. 8-9). Concept maps meet these requirements (Novak & Gowin, 1984). The CyGaMEs team has used concept maps exclusively, but may supplement them in the future with other knowledge representation tools to both increase rigor and decrease ambiguity of alignment between the specification representation and the experts' intent (see examples of other knowledge representation tools in Hyerle, 1996; Jonassen, Beissner, & Yacci, 1993).

Structure mapping principles, especially parallel connectivity, constrain specification. This often leads to recursive iterations of specification during which designers clean the specification maps. Some housekeeping tasks[2] may occur during stage 1, and others involve subsequent stages. For example, during isomorphic straightening the designer looks for

[2] (See Reese, 2003b, for elaboration of housekeeping procedures.)

portions of the target domain map that would force one-to-many mappings between source and target domain analogs. Many-to-one mappings violate parallel connectivity and isomorphism. Many-to-one mappings may occur if a specification includes multiple terms for the same concept. During isomorphic straightening the designer must pick one term to represent domain synonyms and revise any redundant conceptual strands.

Stage 3. Source Domain Specification and Mapping

Game design specialists join the effort at this stage because the process of mapping and specifying the source domains is further complicated by the requirements of inventing engaging gameplay within a game world that supports targeted learning goals. The team may initially identify multiple domains as candidates for the source domain. Candidates will be rejected when irresolvable alignment inconsistencies are identified, gameplay concepts are weak, or game concepts cannot support targeted learning goals. While the source and target domain must maintain integrity of supporting one-to-one mapping (isomorphism and parallel connectivity) within any one game module, multiple modules may overlap, and game modules and game levels may realize (represent or model) subconcepts idiosyncratically. This means that components of the target domain (in the case of modules) or entire target domain (in the case of levels) may be mapped to multiple source domains. Within any one mapping, parallel connectivity is maintained. By providing the learner with multiple, aligned representations, GaME design addresses concerns identified by Rand Spiro and his colleagues (e.g., Spiro, Feltovich, Coulson, & Anderson, 1989) during the development of cognitive flexibility theory: Any one metaphor may introduce robust misconceptions, and this may be obviated through the use of multiple analogs.

Stage 4. Game Design and Development

Will Wright designs game concepts as analogs or models of targeted theories (Sheffield, 2006), which he translates into procedural gameplay. He designs game worlds as possibility spaces through which players build mental models through discovery and their own theory building (Wright, 2006a, 2006b). Thus, he uses a process similar to GaME design to produce entertainment games. What may be intuitive to Will Wright is not necessarily a natural process for the majority of contemporary game designers, no matter how gifted, who may collaborate within teams that design and develop instructional games (Langhoff, et al., 2009). It is essential that an instructional game design/development team maintain integrity of the mapping between the target domain map and the game world. In addition, the targeted learning goal (and subgoals), key understandings, and underlying science (or in non-science fields, their specific laws/principles) must be specified and guide design of the game goal/subgoals, gameplay, and core gameplay mechanic. In this way, the conceptual domain is translated into game system, gameplay, and game goals. The conceptual domain, as specified, becomes the game world.

SELENE: A LUNAR CONSTRUCTION GAME

I have applied structure mapping theory to produce three instructional environments. Of these, only *Selene* is a fully produced instructional videogame, the first CyGaMEs environment. *Selene* is an online, single-player game about the formation and evolution of the Earth's Moon. Players form the Moon through accretion and then pockmark its surface with impact craters and flood it with lava flows. The target domain specification contains 101 subconcepts (see Figure 1), most of which subsume under broader concepts of accretion, differentiation, impact cratering, and volcanism. The domain specification represents the mental model of lunar scientist and educator Dr. Charles A. Wood. *Selene* was produced to study learning, perceived experience, and assessment within GaME environments. *Selene* is a research game set within an online research environment. The encapsulating environment contains about 15 minutes of instructional videos during which Wood summarizes accretion, differentiation, impact cratering, volcanism, and history and nature of science. He concludes by challenging *Selene* players:

> Just as you have played/watched the *Selene* videogame, which allowed you to experiment with forming the Moon, scientists who put together the theories that *Selene* is based on feel they are playing a much more exciting game. They have faced the mystery of trying to understand how the Earth, planets, and Moon came to be. They collected data, sorted out the relevant from the dross, and explored how it could all be put together. Just like playing any game, there were false starts and frustrations as they tried to learn the rules by trial and error. And although some videogames last tens of hours, thousands of scientists playing the "How Did the Moon Form and Evolve" game have spent nearly 400 years gaining the understanding we have now. And like a videogame, many of the scientists were competing with each other to see who could have the pleasure and pride of first completing each level of the game. There are a lot more levels to play in the "How Did the Moon Form and Evolve" game. Maybe you will become a master player in that game too (Wood, 2007)!

More than 2000 youth have played *Selene* since its release in May 2007. The game targets youth 13-18, but has been used with undergraduates and younger learners. It is available 24/7 online at http://selene.cet.edu.

Assessment Toolset and Summary of Findings

Selene contains three embedded assessment tools and external assessments.

- The flowometer measures changes in an important aspect of players' perceived experience, called flow (Csikszentmihalyi & Csikszentmihalyi, 1988; Hektner, Schmidt, & Csikszentmihalyi, 2007). CyGaMEs has completed (Reese, 2008b) and replicated research that shows the flowometer logically, transparently, and accurately profiles players' experience.
- The timed report measures players' progress toward a learning goal every 10 seconds of gameplay. CyGaMEs has identified where *Selene* player learning is the strongest and found that direct instruction following gameplay enhances performance. Timed report analyses have also shown that *Selene* players successfully move toward the game goal more than 75 percent of the time.
- Gestures record all player interactions with the game. CyGaMEs has used this tool to identify where players have difficulty with the environment and how to revise *Selene* to enhance player success.
- CyGaMEs has used knowledge discovery techniques on *Selene* data to identify an *interface effect* (Reese & Hitt, 2009). This allows CyGaMEs to state confidently that the *Selene* interface effectively guides the player to make gestures that help them to succeed.

External Assessment: Mutual Alignment Tool

The CyGaMEs mutual alignment tool was derived directly from research conducted by structure mapping scholars. While structure mapping theory describes mapping as a process of putting two domains into *mutual alignment* according to shared relational structure, Kurtz, Miao, and Gentner (2001) investigated whether mutual alignment *tasks* can increase causal understanding of analogous scenarios, i.e., scenarios depicting heat flow. The researchers asked their participants to explicitly compare scenarios through mutual alignment tasks. Participants either used:

- Joint interpretation: Directed to “compare the scenarios and describe them together” (p. 424).
- Joint interpretation plus correspondence: Directed to perform joint interpretation and to place elements of both scenarios in alignment through a matching task (p. 425).
- Correspondence: Directed to place elements of both scenarios in alignment through a matching task.

The researchers found that joint interpretation plus correspondence increased learners’ understanding of analogous scenarios, and that correspondence alone was insufficient to enhance understanding.

The CyGaMEs mutual alignment task is an external assessment. That is, it is external to gameplay but delivered within the *Selene* online environment. For each of the four *Selene* superordinate concepts (accretion, differentiation, impact cratering, and volcanism), participants are prompted (“[Concept] is like”) by a short video clip of gameplay captured from that concept’s game module (see Figure 2). After the video concludes, the tool prompts the learner to “Write what you know or think you know about [targeted concept] in the text box below.”

Participants complete the assessment as a pretest, after playing the game once, and then again after playing the game a second time. CyGaMEs uses a double transfer paradigm experimental design (Schwartz & Martin, 2004). This means that half of the participants receive instruction before the second round of gameplay, and half do not. In a study conducted with 16 undergraduates, participants wrote significantly more targeted concepts related to lunar geology after playing round 1 than before playing (Reese, Diehl, & Lurquin, 2009). This strong main effect for test iteration, $F(2, 13)=18.62$, $p<.001$, partial eta squared=.74, suggests that playing the game (and creating a moon) in and of itself meaningfully increased participants’ understanding of moon accretion, supporting the viability of the GaME design approach.

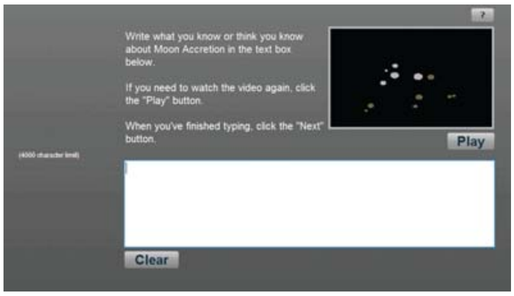

Figure 2. Screen capture from the CyGaMEs Selene mutual alignment assessment tool. Copyright 2008 Debbie Denise Reese. Used with permission.

ADVANCING PROGRESS TOWARD ENHANCED ACHIEVEMENT

Cyberlearning with aligned assessment toolsets is targeted as necessary for 21st century learner-centered education and science achievement in the United States (Borgman, et al., 2008). CyGaMEs has developed and successfully piloted an online instructional videogame and assessment toolset derived from structure mapping theory. Designers applied the principles of structure mapping as a formalism to translate abstract lunar geology concepts into an embodied and procedural game-based environment. *Selene* was designed to enable players to infer knowledge about the physics and geological processes that underlie the formation and evolution of the solar system. Results from both the timed report and mutual alignment assessment instruments demonstrate that the game causes learning of targeted concepts. Players who formed the Moon were able to infer targeted concepts regardless of whether they had listened to direct instruction.

Undergraduates aren’t the only students benefiting from *Selene.* According to Richard Soos, who teaches first and second grade gifted students at Meyer Elementary School in Hondo, TX, USA, “It’s great to hear [my] students talking about how the Moon was formed when we talk about the solar system. They are hypothesizing that perhaps the planets were formed the same way. We would not have reached these levels of discussion without the little bit of work they did on the *Selene* project" (CyGaMEs, 2009, ¶1).

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