# Using Physical Constraints to Augment Concept Mapping on a Tangible Tabletop

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*Abstract*—**The Tangible Concept Mapping project investigates using a tangible interface to solicit direct user input for the purposes of user model creation in a learning environment. This paper describes a prototype implementation of the system, presents some preliminary analysis of its ease of use and effectiveness, and discusses how elements of tangible interaction support concept mapping by helping users organize and structure their knowledge about a domain. The role of physical constraints in supporting the mental activity of creating the concept map is explored as one of the benefits of a tangible approach to learning.**

***Index Terms*—learning, tabletop systems, tangible computing, user modeling.**

## I. Introduction

A key issue in the area of adaptive systems is the development of techniques for quickly and accurately building models of users. These models are used to tailor system responses on an individual level, providing adaptive support for a range of tasks. This paper discusses a project focused on adaptive support for learning, which requires an understanding of the cognitive capabilities and prior knowledge of the user in a specific domain. Constructing these models often entails a certain amount of bootstrapping to get a "good enough" model established quickly, so that adaptive support can begin as soon as possible during the user's interaction with the system. More robust and effective techniques for computationally capturing the user's existing knowledge are desirable.

In the last decade, there has been a growing research effort in using tangible interfaces for educational purposes [1, 2]. Computationally enhanced objects and tabletop systems have been argued to be beneficial to learning for a variety of reasons, such as facilitating collaboration and providing external scaffolding for cognitive processes. However, some researchers have pointed out that there is little empirical work that explicates the exact nature of the learning benefits of tangibility, and even less work that touches on the possible disadvantages [3, 4]. More general claims about tangible interfaces' intuitiveness, naturalness and enhanced ability to cause enjoyment and engagement have also been questioned [5, 6]. With these issues in mind, the research question addressed in this paper is to explore how the characteristics of a tangible tabletop application can support users to easily and effectively represent their current knowledge about a domain for the purposes of creating a user model.

This paper discusses a prototype implementation of the Tangible Concept Mapping (TCM) system, a tabletop application for creating concept maps. The system supports users in expressing their knowledge of a domain by physically arranging concepts on an augmented tabletop and specifying relationships between the concepts. The physical interaction of placing the concepts and creating the relationships is designed to support the mental activity of organizing and structuring domain knowledge. This connection between physical and mental activity is argued to be one of the benefits of using a tangible system for learning-oriented applications. The results of a small user study are presented and implications for future designs are discussed.

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## II. User Modeling

The field of user modeling frequently utilizes the techniques of artificial intelligence to address issues in human-computer interaction.

### *A. User Modeling Components*

In *Adaptive User Support*, a foundational work on user modeling, Oppermann identifies three parts of an adaptive system: "an afferential, an inferential and an efferential component" [7]. The *afferential* component deals with how the system learns about the user. A variety of techniques are used to collect this information, from unobtrusive monitoring of user actions to directly querying the user for relevant data. Choosing what to take as input to build a user model is often a compromise between what would be desirable to know and what can actually be known given the practicality of the technology and the ability to interface directly with the user. While running the user through an exhaustive quiz may be the most accurate method of creating a user profile, few users are going to be willing to put in so much effort. The *inferential* or reasoning component takes the gathered input data and attempts to extract meaning from it. To minimize error, most system designers look for a theory in which to ground the decisions made for this component. Typically this is not an AI-based theory but rather one related to the content domain; in the case of this system, an inferential component would rely on the learning theory behind concept mapping to make an assessment of the user's competence. Finally, the *efferential* component deals with what kinds of action the system can take based on the gathered and interpreted data. The output component faces similar issues to the input component, balancing on the edge of what is desirable versus what is practical.

### B. User Modeling Implementation

There are a number of different levels of implementation available with the idea of a tangible concept mapping system for user modeling. The fullest instantiation would involve a system that takes the user input from the tabletop, interprets it as representing a certain level of knowledge, and then provides feedback to the user to correct and expand their knowledge. This covers all three components of an adaptive system as described above. With this prototype implementation, we have focused primarily on the afferential component of this process, where the system attempts to capture something about the user based on their actions within the computational environment. Many forms of direct user profile creation are taxing on the user, involving lengthy pages of survey questions or parameters that must be set. The opposite approach, to monitor the user without contacting them directly, suffers from a paucity of input as well as a lack of knowledge on how to connect meaning to the observed user actions. This paper examines the ease and effectiveness of using a tangible tabletop to generate direct user input for the purposes of user model creation.

## III. Concept Mapping

One technique for eliciting prior knowledge employed by teachers is a "concept map", a system of knowledge representation that allows students to structure their understanding of a domain.

### A. Concept Maps

Concept maps grow out of the constructivist tradition of "meaningful learning", which emphasizes the role of prior knowledge on the learning process [8]. Novak further expanded on this idea at Cornell in the 1970s where he developed the idea of concept mapping as a tool which helps students articulate prior knowledge and makes that knowledge visible to teachers [9]. The construction of concept maps facilitates learning by encouraging reflection on the organization and structure of knowledge rather than just memorization of facts [10]. Concept maps provide a template or scaffold on which to construct knowledge, and have been shown to be beneficial in helping students to prepare for new lessons, review past lessons, and assess current understanding [11].

Novak went on to help develop the CMap Tools software at the Institute for Human & Machine Cognition (IHMC), an open source program that allows users to build and share concept maps in a Graphical User Interface (GUI) environment. [10] Work has also been done on developing automated tools for scoring concept maps generated by students [12, 13]. This assessment is typically done by comparing several dimensions of student maps to "expert" maps created by teachers. The generation and assessment of concept maps has not yet been used as a technique for building user models for an adaptive learning environment, but it holds some promise in this area [14]. Student

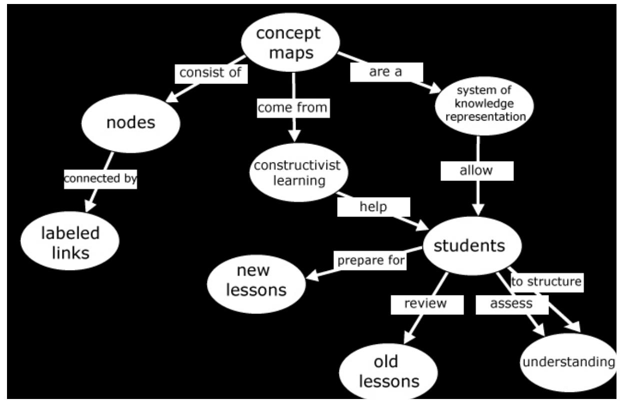


**Fig. 1 Concept map on concept maps**

constructed maps can highlight where learners have incomplete or incorrect understanding of a domain, and this knowledge can be used to recommend specific educational modules or areas for future learning.

### B. Design Requirements

Concept maps are constructed in response to a focus question [11]. Structurally, concept maps consist of a set of nodes (circles or boxes representing a concept). These are connected by labeled links (lines representing a relationship). Fig. 1 shows an example of a concept map created in response to the question "What is a concept map?" Novak outlines the recommended method for constructing a concept map in response to a question. First, start by being provided with or generating a list of 15-25 concepts, and rank these roughly in order of importance. Second, construct a preliminary map of relationships between these concept nodes, starting with the broadest or most important concept at the top. Third, revise the map with new concepts and add additional cross-links between nodes [10]. A computational concept mapping system must support all of these activities in order to be functional.

In evaluating our prototype, we are concerned with two distinct criteria. One is *ease of use*, and the other is *effectiveness*. *Ease of use* data deals with the quality of the interaction between the user and system and looks at whether all of the functions discussed in the proceeding paragraph can be easily accomplished with the system. Investigations into this area ask questions like: Did the control system make sense? Did users get confused or forget how to work the system? Were they able to accomplish the basic functions of moving nodes around and setting up relationships to create a map? *Effectiveness* data deals with the ability of users to create a map that accurately reflects their current knowledge and is useful for creating the user model. Questions on this theme include: Could users use the mapping technique to organize and structure their knowledge? Were they satisfied with the final map that they produced? How do user-created maps compare with expert maps?

## IV. Tangible Interaction

In this section we consider two different frameworks for understanding tangible interaction and the opportunities it affords for designing learning environments. We connect elements of these frameworks with aspects of the design of the TCM prototype to show how the task of concept mapping is supported by the characteristics of the tabletop system.

### *A. How Bodies Matter*

Klemmer et al.'s 2006 paper on *How Bodies Matter* presents five themes for interaction design that arise from focusing on embodiment and physicality in order to understand how to approach the integration of physical and computational worlds [15]. One of their core points is that GUI systems in general reduce all computational activity to the same set of physical interactions: moving a mouse and typing on the keyboard. In contrast, non-computational tasks like riding a bicycle, playing catch, or even just walking are characterized by a variety, richness, and complexity of physical action. In designing a concept mapping system for a tabletop instead of a screen, the goal was to take advantage of the human capacity of rich physical action in a way that is not possible in GUI systems. While Klemmer et al.'s focus is not just on tangible interaction, several of the examples they use in their analysis are from tangible applications and the resultant themes have clear relevance in thinking about designing for tangibility. We discuss the two themes that have the greatest relevance for understanding how the TCM system makes use of the affordances of tangible interaction.

#### *1) Thinking through Doing*

The Thinking through Doing theme ties together several different strands of research which show that physical action is a crucial component to cognitive development in children and cognition in general. The authors touch on the educational theories of Piaget and Montessori, which stress the importance of sensorimotor skills and object manipulation for learning. The authors also discuss the difference between *pragmatic action*, which is action undertaken to accomplish a task, and *epistemic action*, which involves changing the world, often through physical manipulation, in order to make the task easier to solve. These ideas all support the notion that interacting with a tangible system affords greater opportunity to use physical activity as a cognitive scaffold for mental activity than a GUI system.

The authors also discuss the role of representation and how "the representational form of the problem makes visible the most relevant constraints implicit in the problem" [15]. In designing the TCM prototype, we have considered how the physical act of creating the map can reinforce the mental act of organizing and structuring concepts and relationships, and how the representations used can signal the constraints present in the activity.

#### *2) Performance*

The theme of performance looks at how a person can act *through* an artifact when they consider it as an extension of themselves, and what the effect of that extension is. Performative aspects of physical interaction leverage tacit and kinesthetic knowledge that is not necessarily explicable in language or smoothly transferred to non-physical interaction since it often operates beyond conscious awareness. Even something as simple as using both hands to manipulate objects can yield a much richer interaction than the single finger interaction of typing and mouse clicking. Tabletop systems, including the TCM prototype, are ideal platforms to encourage bimanual, asymmetric performance that makes greater use of the dexterity and complexity of human motor abilities. Tangible systems can make use of a variety of physical actions such as moving, twisting, squeezing, and rotating objects. *Kinesthetic memory* allows users to associate system functions with these different physical behaviors in robust way that is pre-reflective and experiential. In contrast, all actions with a GUI system entail the same set of physical actions, forcing differentiation of function to take place via explicit cognition rather than motor recall.

### *B. Perspectives on Learning*

Marshall's 2007 paper *Do Tangible Interfaces Enhance Learning?* lays out an analytical framework for discussing and researching the learning benefits of tangible systems [3]. The six perspectives he discusses in the paper include: Learning Domains, Learning Activity, Integration of Representation, Possible Learning Benefits, Effects of Physicality, and Concreteness and Sensory Directness. Each of these perspectives can be used to highlight different elements of a system and to spur empirical research on the interaction between tangibility and learning. In this section we discuss the first three perspectives and situate the TCM prototype within them. The latter three perspectives overlap each other a great deal and also intersect with the discussion on bodies above, so we do not address them here.

#### *1) Learning Domains*

In discussing *Learning Domains*, Marshall points out that most existing tangible systems focus on domains which have an inherent physical or metaphorical spatiality to them, such as programming, narrative, and dynamic systems. The TCM prototype concerns the spatial task of organizing nodes and links to create a concept mapping. The spatial nature of the task makes a tangible approach feasible and appealing. A pen-and-paper version of concept mapping also supports this spatial task, but revising the map requires repeated erasing and redrawing of the structure in order to add, delete or move items around. The computational version makes dynamic construction and manipulation much easier.

#### *2) Learning Activity*

For *Learning Activity*, Marshall classifies learning into two types. One is *Exploratory Activity*, where the user can explore an existing representation that has been created by an expert or based on expert understanding. The other is *Expressive Activity*, where the learners create their own representations based on their understanding. The TCM system has been designed to support Expressive Activity, with the users representing their personal knowledge for user modeling purposes.

#### *3) Integration of Representations*

The *Integration of Representations* perspective looks at how the physical and digital representations relate to each other temporally and spatially. In the TCM system, as described in detail in the next section, concepts and links are represented primarily in a digital format, but they are created and manipulated via tangible objects. The relationship between the digital and physical representations is dynamic and user-controlled, as the users can choose to associate different digital items with the physical control objects at different times. In later sections of this paper we discuss the user response to this method of physically creating digital-physical representation links, and show how a more one-to-one relationship between the physical and digital representation might be desirable.

## V. Prototype Implementation

The goal of this implementation was to build a digital tabletop-based application in order to investigate how this approach can be designed to support users to create, manipulate, revise and save a concept map. The technical specifications and design process for creating the prototype are described below.

### A. System

This application was developed on the EventTable system [16]. The system consists of a wooden table frame which supports a clear acrylic tabletop surface and conceals a camera and projection system underneath. (See Fig. 2) The table surface is 92 x 70 cm and is 61 cm off the ground. Infrared lights along the left edge of the inside of the table illuminate the underside of the acrylic surface. Objects placed on the tabletop are visible to a camera with an infrared pass filter over its lens. The camera looks up from a crossbeam at the underside of the surface and connects to a laptop. Visual data is processed by the reacTIVision Engine, an open-source camera vision framework developed by Jorda et al. [17, 18]. It tracks specially designed "amoeba" fiducial symbols, which can be placed on the bottom of any objects to be used on the tabletop. The tracking data is used by a Processing application and the display is output from the laptop to a short-throw projector pointed down at the ground. The projected image is bounced off a mirror and up to the tabletop. A thin sheet of Mylar laid over the acrylic surface acts as a diffuser to catch the projected image so it is visible to the user.

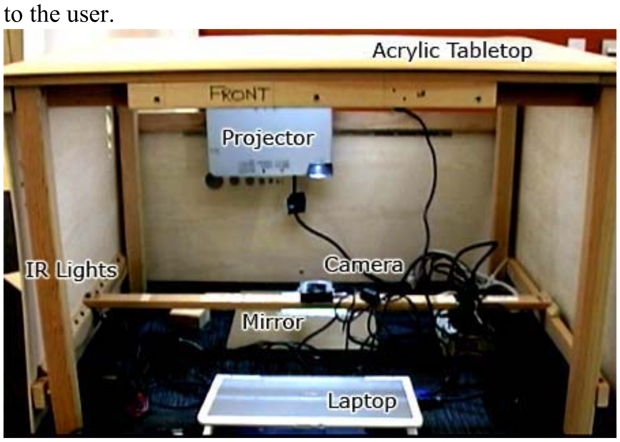


**Fig. 1. Tabletop hardware and frame.**

### B. Interface

The focus question used for this study was "How does photosynthesis work?" There are a four crucial activities involved in producing a concept map: creating or moving around concept nodes, creating links between the nodes, revising the map and saving the map. Revisions involve iterations of adjusting, deleting, and adding concepts or links. Below we describe how the TCM system allows users to accomplish all of these activities.

*1) Projected Display*

The node and link content was pre-determined and programmed directly into the interface. Pre-defining node content is a technique often used in classroom instruction using concept mapping, where teachers provide a "parking lot" full of relevant concepts and the students select which nodes to use and provide their own relationship labels [10]. Fig. 3 shows the projected display when setting up a relationship between two nodes. The boxes along the top and bottom of the screen are the available concepts, and the menu on the right side of the screen displays the options for the labeled links. The circles labeled "Photosynthesis" and "Solar Energy" represent active nodes connected by an unlabeled link.

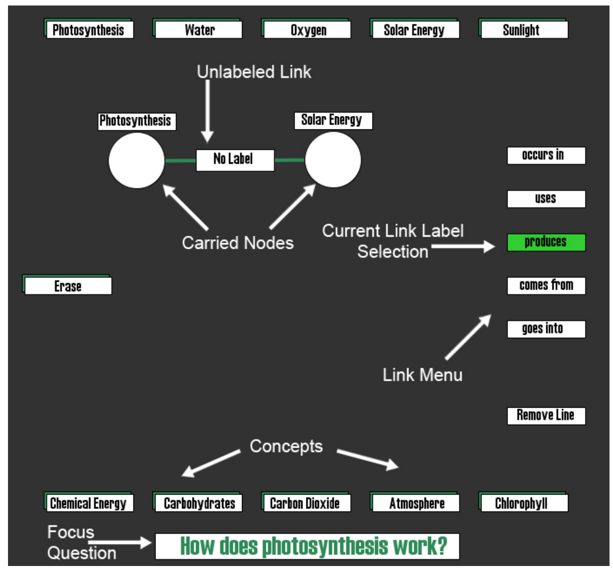


**Fig. 2. Annotated Screen Display**

*2) Tangible Pucks*

To interact with the projected image, we designed three fiducial marked objects, called pucks, for use on the tabletop surface. Fig. 4 shows two "event" puck objects. These two pucks are designed so that the underside of each carries one and a half fiducial symbols. The whole fiducial on the underside of each puck acts as a unique identifier and allows the camera to track the puck's movement and associate display elements with its position. When the two pucks are brought together, the two half-fiducials on their underside combine to form a whole fiducial and can be used to trigger a system event [16]. The "event" pucks are designed so that there is a clearly signaled, unique way to form this connection. One puck has a sharp arrow point on it, while the other has a corresponding V shape. A third coaster-shaped puck is marked with a single fiducial on its underside and a foam flower on the top.

**Fig. 3. Fiducial marked "event" pucks.**

*C. Interaction*

The four activities required for concept map creation process can be broken into two basic forms of user-system interaction: a *real-time object identification and tracking* focused paradigm that allows the user to create concept nodes, move them around in a "drag and drop" manner, and signal task completion, and an *event-based* paradigm that uses rotation and physical connections between the pucks to create and edit the labeled links.

*1) Creating and Moving Nodes*

By placing a puck on top of one of the concept boxes on the upper or lower edges of the screen, a digital node containing that concept is created. The node is displayed as a white circle with a labeled box sitting above it when it is being "carried" by the puck. The circle is obscured by the puck and the label is displayed above the puck so it is visible. Both "event" pucks can carry nodes at the same time, but only one node can exist for each concept. While carrying a node, the puck must be moved along the table surface to drag the node to the desired location. When the user picks the puck up off the tabletop, a carried node is "dropped" onto the field and displayed as a green circle with a white label in the center. A node can be picked up again by placing the puck on top of its location on the field. Fig. 5 shows a dropped node on the left and a carried node on the right. A carried node can be erased by dragging it to the "Erase" box in the middle of the left side of the screen or by dragging it to a different concept box to create a node for that concept.

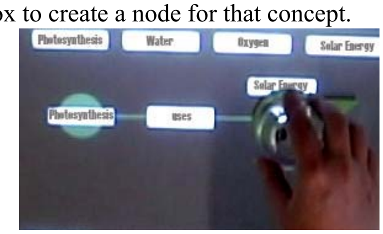


**Fig. 4. Dropped and carried nodes.**

*2) Creating and Labeling Links*

When both event pucks are carrying a node and they are brought together to form the third fiducial on the underside of the pucks, a link is created between them. This interaction exemplifies the *thinking through doing* theme discussed above. Rather than using generic mouse clicks or keyboard input to create a link in a GUI environment, the physical act of bringing the two nodes together reinforces the mental act of creating a relationship between them. The form of the pucks with their V-shaped connection makes the link creation mechanism visible, physically representing one of the problem constraints. Once the link has been created, each puck has a distinct function related to setting the label. One puck turns the right-side menu on by being rotated to the appropriate position. The second puck can be rotated to scroll through the available labels. This behavior connects to the *performativity* theme, using asymmetric, bimanual functions to expand the range of physical actions that are used for interaction. In Fig. 3 above, the shaded rectangle indicates which label is currently selected. When the menu puck is rotated to the "off" position again, the selected label is applied to the link and the menu goes away. The link label menu also allows the user to remove the link entirely by selecting the "Remove Line" option at the bottom of the menu.

*3) Concept Map Completion*

When the user has completed their map, they signal this completion by placing the flower object on the screen. When the system recognizes this object, it writes the completed map to a text file. Fig. 6 below shows a user created map in its final stage. The creation of the text file representing the user's map is the first step in the possible development of a system that analyzes and scores the created maps as a means of creating a preliminary user model.

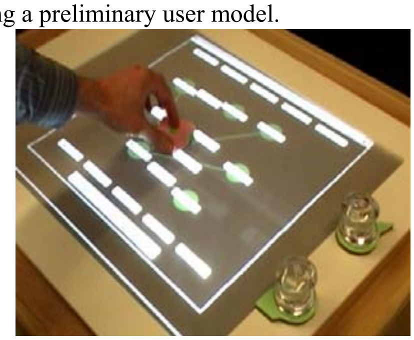

**Fig. 5. A completed map.**

## VI. USER STUDY METHODS

To investigate the *ease* and *effectiveness* of this prototype system, we conducted an informal user study consisting of a think aloud task followed by unstructured interviews and subsequent concept map analysis. All data collected was qualitative. The study participants used the system to create a map related to the focus question. The participants were two graduate students familiar with interactive technology and its analysis. In separate sessions, each participant was shown the basic elements of interacting with the system by picking up nodes, creating and setting links and moving the map around. Then they were asked to create a concept map relating to the focus question . They were encouraged to "think-aloud" as they were constructing their maps. Following their map building period, we asked them a series of questions about their experience. Their interaction with the table and the interview were video taped and all the participant comments were transcribed. We also analyzed their final concept maps in comparison with an expertly produced map.

In reviewing the video tape and transcribed think aloud comments and interview content, we looked for several different measures of ease of use and effectiveness. For *ease of use*, we focused on the think-aloud comments of the participants regarding how they were using the interface. We also looked at their physical interaction with the system to identify places where they hesitated or made errors in using it. For *effectiveness*, we considered comments by the participants discussing their understanding of the concepts and link labels available to them and looked at the final maps they generated to assess their accuracy.

## VII. RESULTS

In this section, we discuss two known technical issues with the system, as well as the results of the user study.

### A. Technical Issues

Going into the user studies, there were two known technical aspects of the system that had the possibility to cause problems. First, the object tracking was slow. Once a concept was picked up, the puck had to be moved fairly slowly and steadily, or the system lost track of it and would drop the concept onto the field. When this happened, it could easily be picked back up again, but it made for a stuttering kind of progress across the field until users got used to the speed at which they could safely move. A laptop with more processing speed would improve system response.

Larger fiducial markers on the pucks would also improve the tracking accuracy, but this would also aggravate the second known problem, which was that the available active zone of the table was small. This was due to a combination of a wide-angle camera lens causing recognition problems around the edges and the low height of the table, which had been originally designed for use by children. Because of the size of the interaction space, it was unlikely that users would produce very complex maps using all the available concepts; there would not have been space for them all to be placed. Despite these known technical limitations, the system performed adequately and allowed us to investigate the basic usability of the system in order to inform future designs

### B. Ease of Use

To evaluate ease of use we looked at how the study participants made use of the pucks, where they encountered difficulties or problems in moving nodes around and setting up links, and what they said about the usability of the system.

#### 1) Creating and Dragging Nodes

Both of the participants quickly recognized that they could not drag nodes as fast as they wanted to, but they adjusted to this limitation rapidly. Being able to quickly backtrack and pick up dropped nodes made the occasional outpacing of the system response fairly unproblematic. One of the participants dealt with the slowness humorously, saying "Come with me, Carbon Dioxide" encouragingly after dropping the node and having to go back and move it more slowly to where he wanted it.

#### 2) Creating Links

The link creation mechanism of bringing the two pucks together occasioned both positive and negative responses. One participant said:

"I did like the fact that they interlocked…I felt like that was a really useful constraint. It made it fairly obvious that these two things were going to fit together, and they were going to create a line that way."

However, that same person also said:

"I almost felt like I wanted to be able to have the puck on something, and because it was on that thing, by choosing something else it would draw the line automatically....that would facilitate not having to drag everything quite so much."

This suggestion would mean that every time two nodes were carried simultaneously, a link would automatically be created between them. The participant who suggested this was never observed to pick up two nodes at the same time unless he wanted to create a link, so this makes sense. However, the other participant occasionally used both pucks to move two nodes at a time in order to move the entire map around rapidly. In that case, drawing a link between the two carried nodes would have been inappropriate.

One of the participants was also observed fitting the two pucks together when one was carrying a node and the other was not. When reminded that both had to have nodes in order to create a link, he responded "Oh right thank you...I was hoping to drag it to that thing", and indicated a concept box at the top of the screen. He seemed to want to be able to create a link by bringing the pucks together and then dragging one puck up to the concept to create a node attached to the link. Other approaches to link creation, such as the one attempted by this user, may make sense to the users. However, the interlocking puck strategy of link creation was observed to be largely understood and followed.

#### 3) Using the Link Label Menu

The activation of the link label menu was one significant source of difficulty of use. The menu was turned on by rotating the menu puck to the correct position, and then had to be rotated to the opposite position to turn the menu off and set the link label in place. However, the menu puck was also rotated by the participants to get it to line up with the other puck and create a new link, so it was hard to leave it in one position and know what state it was in. One person commented:

"I noticed sometimes, when I was at the right angle, the menu would already appear as soon as I connected them. Which actually, I didn't mind. I figured you were going to have a menu anyway, so it might as well pop up."

The other participant made a related suggestion, saying:

"I didn't like that I had to bring out two [nodes] that I just thought might be related, and then look at what kind of relations are available and then decide if I wanted to keep these two in a line."

At one point, after building a small map, this participant placed the pucks on two already-connected nodes and turned on the label menu, saying "I gotta open this up so I can see my other options." He clearly felt that not having the link options visible at all times made it harder to use the system. This connects to the idea of epistemic versus pragmatic action discussed in the *thinking through doing* theme. The lack of visibility of the menu forced the participant to switch from actions which accomplished the task, such as moving nodes and selecting link labels, to actions which changed the nature of the task, by making the labels visible. While such switching between action types can be a way of encouraging reflection on the activity and helping the cognitive process, here it is seen as a distraction.

The use of the other puck to scroll through the menu options caused no observable problems and occasioned no comments. Both participants remarked, however, that they had trouble telling which puck controlled the scrolling and which controlled turning the menu on and off. There were labels on the pucks underneath the knobs, but they were perhaps too hard to read. Both participants suggested using different colors or dramatically different shapes to distinguish the objects and their functions.

### C. *Effectiveness*

In looking at the effectiveness of the system, we were interested in seeing how well users felt that they could express their knowledge about the target domain. The concepts and link labels pre-coded into the interface were based on a synthesis of internet resources, including wikipedia pages and concept maps on photosynthesis retrieved via google image search. Fig. 7 shows a complex map representing an "expert" level answer to the question which uses all available nodes and labeled links. While we did not expect any individual user to produce such a complex map, it gives an idea of the variety of relationships that can be expressed within the system. Below we discuss the factors that hindered the study participants from effectively representing their knowledge to the system.

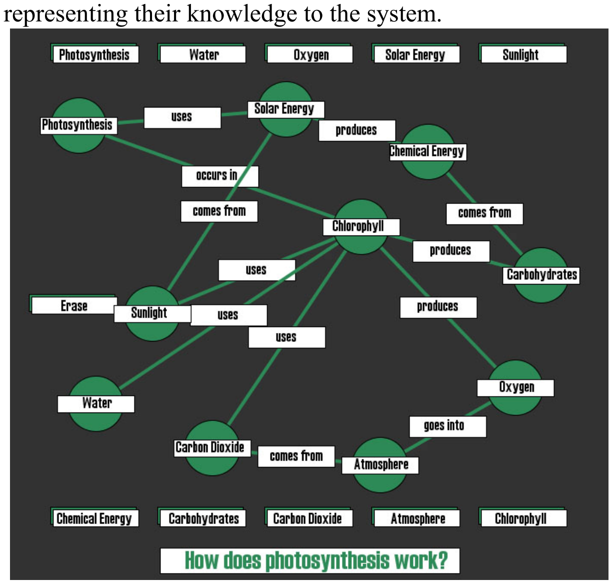


**Fig. 6. An "expert" map showing possible connections.**

#### 1) *Limited Interaction Space*

The limited size of the interaction space had a negative impact on the system's effectiveness. Once there were five or six nodes on the field, it became difficult to add new nodes without causing it to feel overcrowded. Although it was possible to drag a carried node through an already constructed map, both users avoided this and instead dragged new nodes around the outside of the existing structure. Given the necessarily slow movement speed, this could be a lengthy process and probably contributed to a resistance to add new nodes. The link menu's occasional presence on the right side of the screen further restricted the display size. Neither user placed more than six of the ten nodes before finishing.

#### 2) *Directionality of Links*

A second effectiveness concern was induced through observation and comparison to expert maps. The relationships in the TCM system were lacking in explicit directionality, and it was observed that directionality was implicitly understood by the two users in different ways. This is problematic for digital assessment related to subsequent user modeling. In most concept maps, lines between nodes include arrows on one end, indicating which direction the relationship is intended to be read in. Some concept maps are intended to be read from top to bottom, in which case arrows may be omitted. The TCM system does not include directionality in its links. One of the participants noticed this and carefully set up his map so that the correct statements were made by reading from left to right (See Fig. 8).

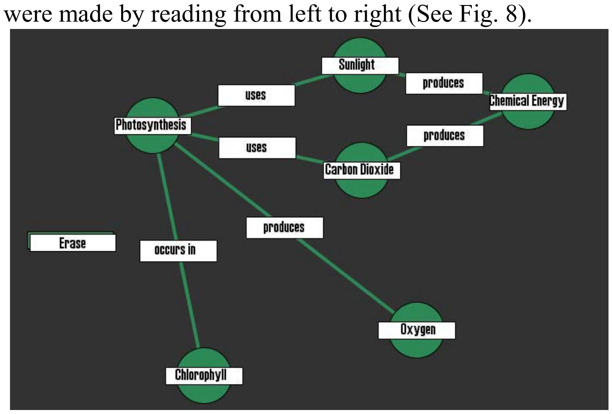


**Fig. 7. Map created by participant 1.**

The other participant did not talk about directionality at all while constructing the map, and when asked about it at the end of the session, said that he had not thought about it. (See Fig. 9) When it was pointed out that there was ambiguity in, for instance, the relationship *uses* connecting *Sunlight* and *Photosynthesis*, the participant replied that he intended *Photosynthesis uses Sunlight*. However, the most natural reading would be *Sunlight uses Photosynthesis* when reading left-to-right or top-to-bottom.

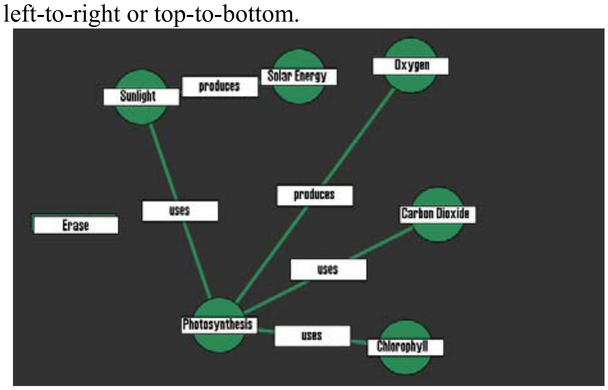


**Fig. 8. Map created by participant 2.**

#### 3) *Pre-determined Content*

By far, the biggest issue with the system turned out to be the limitations introduced by the pre-determined content. Both participants commented on multiple occasions that they were unhappy with the concepts and link choices available to them. One participant said "I recognize all the words but I don't know how they go together," and later "I want to say things but the words aren't there." The other remarked "Some of these words are kind of weird…they're not the ones I necessarily would have used." At the end of the interaction, the first participant reiterated his comments:

"The elements and the types of relations....they wouldn't be derived from the ego-centric point of view that I would be thinking of. So I had to figure out what I could say with what was there to figure out what I'd want to say about photosynthesis in a kind of perspective that I didn't start with because I figured that was not what was wanted...something else was wanted."

This is a problematic statement in terms of the effectiveness of the system. Clearly, the users are having trouble expressing their understanding of photosynthesis within the confines of the pre-coded content. It is therefore hard to argue that the system is accurately capturing the state of their current knowledge in any meaningful way. As noted above, giving students a set of concepts to work with is a common technique, but typically the relationships are not given. The link labels were observed to cause the most confusion for the participants. While trying to set up a link between Photosynthesis and Sunlight, one participant said "It's like this whole "uses" or "comes from"...does it use sunlight or does it come from sunlight?". Finding a way to allow users to enter their own link labels would make this system more effective.

## VIII. DISCUSSION

Results from the user study provide information and insight for recommendations for a second iteration of this system design.

### *A. Ease of Use Recommendations*

In terms of ease of use, there was a clear distinction between the more event based interactions and those requiring tracking. The creation of links by bringing the pucks together and the placement of the flower object to signal completion were largely successful. Technically, the system performed these actions reliably and quickly and the participants learned and retained the behaviors well. Scrolling through the menu options by rotating one of the pucks also proved to be a robust and easily learned action. These were the actions that made the greatest use of the *performative* and *thinking through doing* affordances of the tangible system.

Actions involving tracking the movement of the pucks were more problematic. The drag-and-drop paradigm of picking up concepts from the edge of the screen and moving them into position as nodes was slow and unreliable and inhibited the creation of complex maps. Conceptually, this interaction model was more suited to a GUI environment and did not take advantage of the ways in which a tabletop system is different from a desktop screen. Any redesign of the system should aim to minimize the amount of tracking and make better use of the more robust and physical actions like rotation and bringing the pucks together. Increasing the distinctiveness of the pucks is also a clear imperative, so that their different functions are more clearly signaled to the users. This will take better advantage of the *kinesthetic* component of motor memory to facilitate learning the system functions.

### *B. Effectiveness Recommendations*

On the effectiveness side of things, the most important change to make would be to implement a way for users to input their own labels for the links, giving them more control over the knowledge that they are representing to the system. This increases the *expressive* power of the learning activity, as per Marshall's framework, and increases the potential accuracy of the user model generated based on the analysis of the maps. It will complicate the assessment and scoring process, however, since the user-generated content will have more variation than pre-determined content. It's possible that a hybrid solution could be found, perhaps one that increases the number of available labels, providing for greater expressivity but still being computationally tractable. A way must also be found to include directionality in the lines, so that any potential ambiguity in the user's maps is removed.

### *C. New Design Requirements*

With these considerations in mind, we are considering a new interaction model that would eliminate the screen based concept boxes in favor of moveable physical objects representing each of the concepts. That is, instead of using one of two event pucks to pickup and move around the node "sunlight", users would simply place the "sunlight" puck wherever they wanted it. This would both free up screen real estate around the edges and eliminate the slow tracking element of dragging the nodes to the right place. It also increases the representational power of the physical objects used to interact with the system. Each concept object could have one whole fiducial element on it and two half-fiducials. One of those halves would be pointed like an arrow, the other shaped like a V, as with the pucks in the current implementation. By bringing two concepts together, a link would be created as before, but directionality could be signaled by which puck's arrow head was used. The physical design of the representation thus constrains the link creation task and supports the user's conceptualization of directionality between the two nodes. Fig. 10 below shows a mock-up of the new design for event pucks and shows how the different connection options could signal directionality through physical structure.

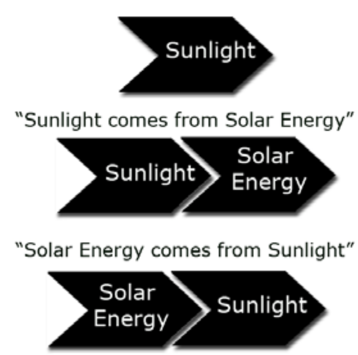


**Fig. 9. Mock-up of new pucks.**

## IX. CONCLUSION

This paper presented a tabletop system for eliciting concept maps representing prior knowledge about a subject area, with the goal of using these maps to construct a user model for an adaptive learning system. We examined some of the ways in which the elements of tangible interaction support this task by helping users organize and structure their knowledge about a domain. The small sample size of the user study discussed here makes it unwise to draw generalizations from the study. However, even a small amount of feedback was very helpful in gaining insight into the mapping task and the ways in which the implemented design did and did not support it. The elements of the interaction with the table which afforded for epistemic as well as pragmatic action proved most successful. For example, in bringing the pucks together to create a link between nodes, a portion of the mental task of establishing a relationship is offloaded to a physical task where the constraints of the pucks' forms guide and support the user's behaviour. This points at the potential for tangible interfaces to support learning and mental activity via physical manipulations designed to serve as cognitive scaffolding for the task at hand.

## X. Future Work

A second iteration of the system would take into account this preliminary feedback on the prototype and make changes to the interaction design as outlined above. We would also like to implement a feedback mechanism that evaluates the user's completed knowledge map and gives them a rating as to how complete or accurate the system thinks the map is. This would be a very simple implementation of the other two adaptive system components, inferential and efferential, in that it attempts to interpret the user's actions and provide a response to it.

The long-term validation plan for this system would be to undertake a mixed method analysis to explore the two dimensions of *ease of use* and *effectiveness* as discussed in Section 3. This would include conducting further qualitative investigations such as the ones described in this paper, as well as gathering numerical data such as time to completion and the scores of the concept maps generated by the users. Ideally, for at least a small set of the users, we would be able to administer a more traditional test of domain knowledge, which we could compare to the concept maps scores as a way of validating whether a high score on the concept map creation actually correlated with a good understanding of the domain.

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