

A Chapter from Phoebe's Field:

Using Narrative and Design to Communicate “How to Think Science”

M. McGrath, M. Vernon, K. Cennamo, and P.L. Newbill

Abstract

Phoebe's Field is a collaborative project involving university students, faculty and practitioners from design, science, technology and education. It is both a children's book and a proposal for an autonomous travelling science exhibition. The story is set amongst agricultural fields, which provide metaphors to connect Phoebe and “her pack” to the powerful concept of fields as used in science. Air, sound, temperature, water, earth, birds and bees become conduits to understanding fields as a type of invisible “glue” holding the universe together. The exhibit focuses on *electromagnetic fields* because of electromagnetism's close tie to the communication-centric technologies of contemporary culture.

Phoebe's Field responds to two problems in science education. The first is readying the student's “creative imagination” to meet the demands of science practice and, specifically, to harness creativity's role in discovery. The second is the declining population of students deciding to pursue careers in science and technology, and in particular, the longstanding dearth of young women opting for this path. We suspect a link between these two dilemmas. In response to the National Science Foundation's (NSF)¹ solicitation for new ways to teach science, we propose to teach kids how to “think science” like Einstein by leveraging design studio pedagogy to build upon proven research on informal science learning.

Phoebe's Field has been supported by two prior grants from the NSF including a Planning Grant, where the project team established:

- a set of science-based *Field Principles* to guide the exhibit design process
- exhibit design concepts for different types of fields
- a theoretical *Learning Framework* to guide instructional design (from a literature review)
- effective *Architectural Tactics* using this framework
- preliminary guidelines on using metaphor and analogy (from front-end interviews with middle school children age 9-12)
- and an effective process of collaboration, integrating university students, faculty, and practitioners from design, science, engineering and education.

The project is currently under review for construction and travel funding.

This paper will examine how a team of twelve architecture undergraduates participating in the Planning Grant engaged a complex task combining science learning with design. The team's role was to design a science education exhibit in which architecture was more than just the walls and vitrines to contain the exhibit: architecture was, as an “extra-spatial” environment, to *be* the actual exhibit. This task required that the undergraduates develop an operational understanding of science principles and learning frameworks. The team achieved this through comparing multiple and iterative design approaches together in studio, thereby developing an understanding of the limits and strengths of each. In this way *Parallel models* became a model for active science learning for the design team and for the proposed visitor experience to Phoebe's Field. As we will see, of particular interest was the use of narrative in the project, both as it communicated the aspirations of Phoebe's Field to team members and influenced the architecture of the proposed visitor experience.

Context

What does it mean to “think science” as Einstein did? Einstein's approach can be differentiated from how science is often taught today in two ways: his practice of visual thinking--using imagination to anticipate, structure and connect phenomena that might not be observable; and his place of work. Einstein did his work outside of a traditional setting: he took walks, rode a bike, had a job, and went sailing while making science. Schoolchildren learn the “scientific method” as a linear, rigorous experimental procedure performed in the controlled setting of a laboratory. The isolation of “external variables” places science outside of the day-to-day subjective happenings in life, and, therefore its perceived impact upon the world. Current research by the American Association of University Women (AAUW) and the Center for Children and Technology (CCT) indicates that the perceived lack of relevance is a large factor in children deciding in middle school (ages 9 to 12) not to pursue a career in science or mathematics. (AAUW, 2004; Brunner, 2006a)

As Thomas Kuhn discusses in the Historical Structure of Scientific Discovery, **creativity plays a pivotal role in discovery**. Paradigm changes in science often occur through scientists being able to see what others have overlooked before: “Discovering a new sort of phenomena is necessarily a complex process which involves recognizing both *that* something is and *what* it is. Observation and conceptualization, fact and the assimilation of fact to theory, are inseparably linked in the discovery of scientific novelty.” (Kuhn, 1962). Thomas Friedman suggests that it is this intellectual property—our “**creative imagination**”—that can and must now determine a society’s global competitiveness (Friedman, 2005, p. 469).

“A society that restricts imagination is unlikely to produce many Einsteins—no matter how many educated people it has. But a society that does not **stimulate imagination** when it comes to science and math won’t either—no matter how much freedom it has” (Friedman, 2007).

Scientific literacy, as defined by the National Science Education Standards, is about living more knowledgeably with an awareness of science in our world (NRC, 1996, p. 22). But scientific literacy is most often narrowly conceived as understanding concepts in certain codified ways, through mathematical equations, for example. The Phoebe’s Field project demonstrates more imaginative and relevant ways to connect science to our lives and to comprehend—**represent or model**—scientific ideas, in ways that are more accessible to more people.

Despite recent gains in physics degree conferrals for women, “physics has one of the lowest representations of women among undergraduate degree recipients of any of the science and engineering fields” (Mulvey & Nicholson, 2004, p. 12). **Drawing girls into physics widens the net for general scientific literacy**. Research suggests that girls at this age would invest in science if they could see *through* the science to its visibility and utility in their lives. (Brunner, 2006b)

Rather than use tools that enable them to merely transcend natural barriers, girls in essence are asking that tools enable them to become one with phenomena so they can understand them better from the inside out. They wanted to be active participants who could feel the transformations of data taking place. They wanted to see protons and electrons visualized...and to know how atoms come together and collide, and they wanted to be able to experience the collisions themselves in some way. (Brunner & Bennett, 2002).

Phoebe’s Field uses analogies of sound and wind fields to explain the more complex concept of electromagnetic fields, and invites visitors to become active components of the *fields* (as source, data point or interference, for example) – to have a **full-body, kinestheticⁱⁱ experience**. The objective of our work is to increase scientific literacy through building skills in acquiring knowledge rather than in accumulating facts. Being “**knowledgably skilful**” (Lave and Wenger, 1991) is the ability to apply fundamental concepts and practices learned within a particular domain to new problems and situations. (Lave and Wenger, 1991)]. As a description of **transference**--the goal of meaningful learning—it is not only one of the most difficult challenges to effect in situated cognition (Bereiter, 1997), but also to evaluate.

Scope and terminology

The 2005-2006 chapter of the project recounted here centers upon the experience of a group of architecture undergraduates participating in the NSF Planning Grant. The scope of this paper is the project’s contributions from design to informal learning.

In the Phoebe’s Field project we are investigating the transferability of lessons from “**designerly ways of knowing**” (Cross, 2001) to science learning through what we are calling “**active learning**.” Much of the existing research in transferring studio models to other disciplines is based on implementing design as probabilistic (best solution given the data). This has been termed “design thinking,” and views design as an engineering practice of needs-based problem solving. If design thinking works to expand the palette of inquiry; then “designerly knowing” would embody active learning. Glynn (1985) has suggested that “it is the epistemology of design that has inherited the task of developing the language of creativity, hypothesis innovation or invention that has proved so elusive to the philosophers of science.”

In design, active learning comes about through hands-on engagement: by drawing and making models and by an iterative dialogue of these artifacts with the material and situation. One might think of the artist Richard Serra’s lifelong conversation with steel, or, of a quote by a bio-engineer Drew Endy, “As a biological designer, until I can actually design something, I don’t understand it.” (Endy and Sagmeister, 2006, p. 103) The term *active* here is the collaboration of the mind and the hand in conducting experiments where abstract ideas and concrete material (or environmental forces) impact the solution, and, significantly, the problem at hand. These problems are “wicked”—where the question and answer develop together (Rittel and Webber, 1973). To understand a design experiment in this way means that knowing in design often happens through unknowing: listening to the situation and input from tools, mistakes and serendipity. Carlo Ginzburg (2003) finds an

analogous state in his research of history, “I believe that at decisive junctures in the research process one must allow oneself to be stupid--simply to **dwell in the state of not understanding**. That leaves one open to those chance occurrences from which unexpected discoveries spring.” A focus of our investigation concerns bringing designerly ways of knowing to science learning.

The Story of Design (2006)

Our experience as designers can serve as one “model” of the aim for kids to learn how to “think science.” The team of undergraduate architecture students at Arizona State University (ASU) demonstrates “designerly knowing” in practice. Because of principles and frameworks set-in place to support multidisciplinary collaboration in the Planning Grant, this experience is also a good example of an experiment in design. Of particular importance was the use of narrative in the project, both as it communicated the aspirations of Phoebe’s Field to new team members but also how it influenced the design outcomes.

In the spring of 2006, seventeen architecture studio students were presented with a brief to design a science exhibit in which the **exhibit is the architecture** (and vice versa). This opportunity to participate in a NSF Planning grant was one of three options put forward to a senior undergraduate research studio at ASU. The theme of the exhibit was to be “invisible fields”; its aim, to model alternative paths of learning using the physics of fields as the subject matter. A multidisciplinary team at Virginia Tech (VT) had begun the planning process the previous fall (2005). As the focus of Phoebe’s Field developed towards an “off the page” experience, Mitzi Vernon, the Principle Investigator and author of the children’s book, realized that architects should be added to the team. Margarita McGrath was invited to join as an architectural advisor, and in turn, she suggested inviting her studio to participate. The majority of the group, twelve students, opted to join the Phoebe’s Field project.

Field Principles as a Narrative Motif

The first challenge the undergraduates faced, perhaps more daunting than stimulating, was the science itself. The design students wrestled with the basic concepts behind the physics of fields, borrowing textbooks from their roommates, going home and talking to kids in the neighbourhood (learning about what the kids knew and didn’t know), and knocking on the doors of university faculty in the physics department. The question for the students that lay heavy on the table was “**how can we design an exhibit on science if we ourselves don’t understand it?**” What helped immensely in finding a place to begin designing was the set of seven *Field Principles* that the VT team had derived the previous semester. The *Field Principles* evolved out of the early planning process as a necessary way of focusing the collaborative and multidisciplinary design process and as an ever-present reminder of characteristics of scientific fields.

Fields Exist

Fields are Invisible but can be Detected and Measured

Fields are Three-Dimensional

Fields Pass through some Objects

Fields may be Blocked or Altered by some Objects

Fields are Created by Sources

Fields Map the Strength and Direction of Forces exerted by Sources

Schedule was the second challenge. The ASU students joined the team with less than eight weeks until the evaluation meeting with the Advisory Board in mid-April, the close of the Planning Grant. Although they hadn’t mastered the science, the team decided that the *Field Principles* gave them enough criteria to begin their work.

The *Field Principles* became a kind of program, analogous to a narrative “motif.” In this analogy a motif is the material--a list of characters and events--and imagery of which a story is made, minus the plot line or thread that makes it all come together in a meaningful way. A program in architecture is an explicit link to the use of a building--a list of spaces and functions. Just as characters might take on various roles in a story, spaces in an architectural program are often used in many ways. For example, a sanctuary might seat up to a thousand people on holy days and less than a hundred for an infant christening. The program would include that it serve both audiences well (everyone can hear and see on Easter Sunday; it doesn’t look empty on a Saturday morning ceremony).

Learning Frameworks as Subtext

Corresponding to the *Field Principles* “motif,” was a set of performance specificationsⁱⁱⁱ. The narrative analogy here is less clear, but perhaps “subtext” comes the closest to representing how these specifications played out in the design. Literary subtext is implicit content, often presented through metaphor, which is understood by the observer of the work as the story

unfolds. In Phoebe's Field the subtext came into the design criteria through a set of *Learning Frameworks* for informal science, which included approaches particularly relevant to fostering how girls experience science.

Conceptual Change Theory
Learner Motivation Research
Learning Games

The Nature of Science
Parallel Models

The first set includes proven practices from learning research. *Conceptual change* involves "re-conceptualizing" deeply rooted misconceptions through fostering cognitive disequilibrium. Inquiry is often motivated by indeterminate situations that provoke reasonable doubt (Dewey, 1963). Learning can also be initiated by putting a learner's current understandings in question. Disequilibrium plays a different role in research into *learner motivation*: it beckons attention (Keller, 1986). Once the learner is "present," motivation to learn comes into play: the content must have relevance in *their* world. Relevance is twofold, it could be a fit within a broader sociological context or an immediate situation—an opportunity to apply and test new knowledge. Learning games can provide relevancy and build confidence in children if done effectively, which, in the case of most girls, often involves providing social relevance through group games (as opposed to competitive).

The nature of science and the use of *parallel models* establish the character of the Phoebe's Field exhibit. This was transmitted to the design team through a definition of science and a mode of its communication: metaphors and models. The **nature of science** is a set of facts but also "a way of knowing." It is the latter that Phoebe's Field targets through modelling **a method of inquiry that embodies active learning**. Phoebe's Field cultivates *practices* of learning in science through scaffolding alternative modes of knowing. The exhibit invites visitors to get inside of the workings of what scientifically drives communication, using their whole bodies as active components of electromagnetic fields (as sources, data points or interference, for example). Metaphors and models transformed from words and images into spatial experiences become the building blocks of the exhibit experience.

Analogies help learners understand new concepts by comparing the new to something that is already understood (Duit, 1991). Albert Einstein's "thought experiments" (*Gedankenexperiment*) were visual experiments conducted through metaphor, using mental pictures and stories as tools to think about scientific phenomena. As a vocabulary of thinking, a model^{iv} – whether told as an analogy (riding a train through the universe) or constructed as a way to communicate to others (models of the solar system^v)--is a productive form of metaphor in science. By definition, as the root of metaphor is **to transfer**, metaphor returns us to the underlying aim of learning.

The very concept of field is simply a metaphor used to describe the similarities between a number of physical phenomena. No single example of a field can explain all the properties of fields. Models have limitations that prevent them from being the reality that they represent. For example, symbolic models (drawings) of fields typically only represent the three dimensions of a field in two dimensions. Thus models can introduce misconceptions, which add to pre-existing ones that learners bring to the learning experience. The use of multiple expressed models in parallel that serve as examples of the concept to be learned is one of the best ways both to correct misconceptions and promote concept learning (Harrison & Treagust, 2000). By experiencing parallel models of fields in Phoebe's Field, visitors are more likely to confront the limitations of their existing models and construct a meaningful knowledge structure into which information about other types of fields can be easily and effectively assimilated.

Story and Back-story

With motif and subtext established, the third frame for the project came from the story of Phoebe, and the back-stories from the autobiographical experiences of the story's author, Mitzi Vernon.

From the author's own history the students took her quest to learn to "think science" by harnessing the small "Einsteinian" part that exists in everyone.

I arrived at this work out of an earnest desire to teach myself something about difficult scientific concepts, which eluded me earlier in my education. After years of teaching, and working as an architect, I returned to graduate school to study product design in engineering, which made me realize that I had been using fundamental ideas without ever understanding their meaning or what they represented in physical terms. In fact, without being able to touch or see these ideas, I found myself lost in a myriad of still larger subjects such as electronics. Perhaps if teachers had painted

physics for me, I might have glided through mechanical analysis. $a^2 + b^2 = c^2$ might have been drawn for me, not as numbers in a right triangle, but as a relationship between gravity (the direction of “down”) and the horizon (the direction of “across”) as Jacob Bronowski (1973) suggested. So, I began to teach myself about sine waves and the Pythagorean Theorem with metaphors. I envisioned a way to use analogies in three-dimensional form to explain these intangible concepts to children. The metaphors grew into a collection of stories, which looks at abstract and scientific concepts and their intrinsic connections to each other and to us. Phoebe’s Field was not the original first story. In searching for a fundamental place to begin, atomic structure seemed logical at the time. But with new attention on field theory in the press, I wondered if fields might be a more essential place to start. Phoebe’s Field became that story. Fields, as a type of “glue” holding the universe together and as a base concept about space, are rich with cultural meaning and embedded metaphors. (Vernon, 2005)

From Phoebe’s story the students found context. The story is set in Meadows of Dan, an agricultural community situated amongst cultivated fields of sunflowers



Figure 1. Field metaphors from agriculture and mathematics.

and dormant fields overtaken by wildflowers. This metaphoric connection to fields as they occur in landscape was taken literally – the team sought to create an architecture of terrain rather than enclosure.

One passage in **Phoebe’s story**, where she works intensely on drawing a mayfly for a presentation in science class, became a touchstone for the ASU team. Here Phoebe, while carefully observing the mayfly through drawing, notices something happening to the grid paper of the *Rite-in-the-Rain*^{vi} field books that she uses. The grid becomes “goeey,” and suddenly the mayfly is set loose from the page.



The pencil, now heavy and commanding, suddenly began to stick! Phoebe was half awake with her cheek pressed against the notebook, with one eye opened glancing across the grid to her pencil. The pencil point had dissolved into the lines of the grid. She pulled, trying to release the pencil, but it was attached, and as she tugged, the grid followed the pencil—into the air above the notebook and deep into the page, *through* the book! Was she dreaming?

Fig. 2. The gooey grid. Image and excerpt from unpublished manuscript, Phoebe’s Field. Vernon, copyright 2005-08.

The magical transition from two to three dimensions became an inspiration for the team’s proposals. We can recognize this as Phoebe’s “down the rabbit’s hole” moment, an echo of Alice’s entrance into Wonderland through a rapid fall into a parallel universe where the ordinary is no longer ordinary. To an architect, this story is familiar in yet another way, as often the story of a building unfolds from intense observation of the setting at hand. Inspiration taken from this excerpt followed both formal and conceptual paths. Several schemes created a spatial experience to model this magical transition; others concentrated on scaffolding heightened observation of the ordinary world.

Architectural Proposals

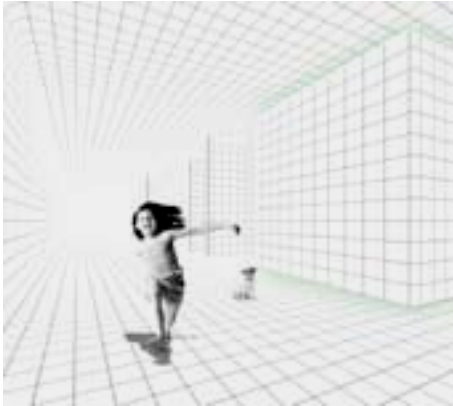


Fig. 3 **_nodes** A grid is overlaid onto the gallery space as a masking technique similar to that used in camouflage. Dave Bowen and Ian Wolfersteig.

Working in sub-groups, the team designed a total of seven schemes:

porcupine
_nodes
Infinity field

wind_board
edgeful_less

parallel_fields
modular

By designing the threshold of the exhibit—the opening of the story—as a “down the rabbit’s hole” experience the first set of schemes focused on priming the visitor for learning. Concerned that recounting Phoebe’s story would be artificial for the exhibit audience, these teams took the plot to heart but, rather than getting kids to re-enact sequences from the story, the designers made it inherent in how learners discover and explore the abstract science of fields. This was accomplished by studying moments from the narrative, specifically the transition into the gooey grid. The **porcupine** and **_nodes** schemes developed an architectural experience based on moving from a 2-d world into the extra-spatial. **Infinity field** (fig. 4) addressed the nature of the space itself. The role of architecture in these projects was to scaffold this experience in space—both in the design of the threshold and in the environment of the extra-spatial world within. The form of the architecture in all three began as a sheet of paper from the *Rite-in-the-Rain* field book. In the **porcupine** scheme the threshold was a tear in the paper, which led to a magical world on the underside of the page (fig. 5). **_Nodes** and **infinity field** used the gridded structure of the graph paper to connect to the original metaphor of a field.

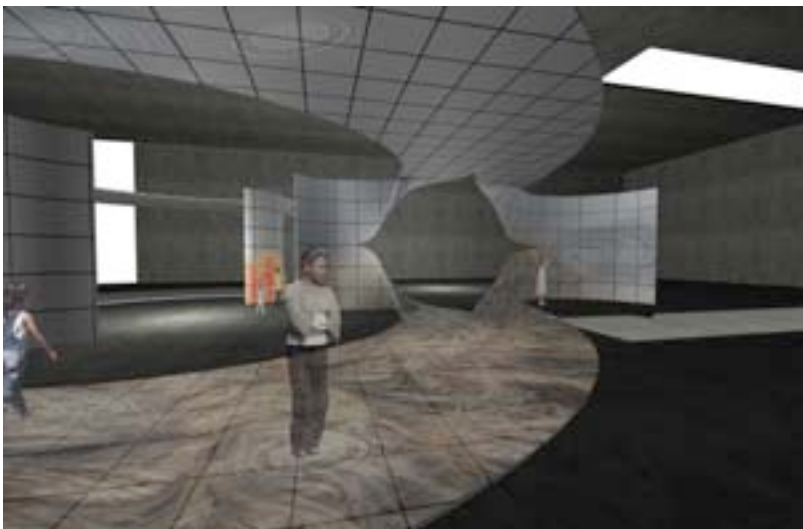
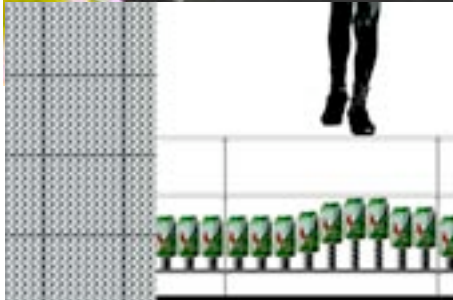


Fig. 4 (left) **Infinity Field**. The exhibits “live” in the shield’s skin. The skin assembly is a gridded datum of “smart” panels which responsively displays visitor interactions with various field phenomena. Oliver Rodrigo Romo.



Fig. 5 (right) **Porcupine**. The underside of the ceiling plane is lined with fibers that can sense various fields, for instance attracting towards or repelling away from a magnetic wand. By becoming the source, kids discover how they impact invisible fields. Joe David, Mark McCulloch, and Alissa Priebe.

The next pair of schemes, **wind_board** and **edgeful_less**, developed straight from the *Field Principles* and operated to transform the site (gallery in a science museum) into a spatial field. The **wind_board** (fig. 6) placed a piece of the exhibit on the exterior of the museum, with a monitor tracking the wind velocity mounted within the exhibit. The idea was that kids would create mental bridges between the two, thus blurring the boundaries between outside and inside. The **edgeful_less** (fig. 7) project took on the interior of the science museum. Deciding that the corners and the edges of the room were the most powerful shapers of enclosure, they worked on negating them. A menu of various tactics was created. One option was to multiply the number of edges in order to mitigate the singularity of the boundary. A second series of interventions worked to blur the edges through strategic lighting and the creation of continuity between planes.



The final two schemes focused on the *Learning Frameworks*. Their aim was to connect the exhibit experience to the day-to-day lives of the kids by creating concrete links between the exhibit and the outside world that the kids might re-experience. In this way the fieldtrip to the museum gains an after-life. Resonance was achieved through repurposing ordinary materials in extra-ordinary ways. The **parallel_fields** (fig. 8) project was constructed out of plastic drinking straws (thousands were stacked together to create paralexix surfaces) and soda cans; in the **modular** (fig. 9), standard construction components were employed.

Architectural Tactics

As the Planning Grant deadline drew near, the architecture team realized the necessity to shift their attention towards communicating their findings to diverse audiences: the project author and instigator, Mitzi Vernon; the VT design team; and to the project's Advisory Board of science, museum, and evaluation experts. Discussions led the team to two realizations. The first was the nature of their task as situated in a "Planning Grant" and, almost simultaneously, the second was recognizing the key role of the *Field Principles* and *Learning Frameworks* in their work. These realizations caused the team to move from talking explicitly about the seven projects that had developed in the studio to a set of *Architectural Tactics* that could be used by the next team of students in the funded-project design phase. Three concepts to "make invisible fields visible" were extracted from the design schemes to become a menu for transforming existing science museum galleries into a spatial field condition:

- Dissolve the boundaries of the exhibit.**
- Displace the ordinary (*Entfremdung*).**
- Distort the threshold between 2d/3d.**

The team developed a script that was plotted through this set of tactics, and "chaptered" by images taken from nature that corresponded with the main ideas of each project. Projects were shown as examples rather than solutions, telling a story as promised at the beginning of *Alice in Wonderland*, in images and words.

The use of the story

Alice was beginning to get very tired of sitting by her sister on the bank, and of having nothing to do: once or twice she had peeped into the book her sister was reading, but it had no pictures or conversations in it, "and what is the use of a book," thought Alice "without pictures or conversation?" (Carroll, 1869)

Fig. 6 -9 (from top to bottom). **Wind_board**, Shawn Nelson; **edgeful_less**, Danielle Jones and Shaun Salazar; **Parallel_Fields**, Stephanie Francis and Katie Scallon; **Modular**, Thomas Allen.



The emphasis in the design proposals on threshold resembles strategies in short storytelling. The storytelling device of a rupture, whether a passage through a rabbit hole, a looking glass, or a piece of grid paper illustrates a contract that the reader of these works makes with the author. Sarah Hardy (1993), in her article, “The Poetics of Immediacy: Oral Narrative and the Short Story” describes this as a pact to become listeners, “we [as readers] must agree at once to be present and to share the world of the story.” This call-to-be-present occurred in the concepts inspired by the gooey grid moment of Phoebe’s story, as these proposals made the experience inherent in how the kids discovered and explored the abstract science of fields.

Although one might have expected that the architecture team adopt Phoebe’s story more directly in the design of the exhibit, we discovered that they didn’t. The ASU team specifically chose *not* to do so: not one proposal to adapt Phoebe’s story into a learning game was made. Why was this so? Discussions with the design team revealed that they questioned both the meaningfulness of re-enacting a story and its ability to assist in transference. Cornelia Brunner, a member of the Advisory Board, put it aptly at the 2006 New York Advisory Board Meeting,

Narrative: the narrative structure here has to do with the experience itself, not with an outside story they may not know. Phoebe is an important icon because she says “girls are welcome here”, but she is just an image. The real story is in the experience itself, which is a group experience led up to by interesting, interactive investigations and followed up by more interesting interactive experiences, which can be group experiences, and which have conceptual assessments built in. The story, in other words, is in being part of an experience that deconstructs and provides a basis for understanding (at least metaphorically) a real-life phenomenon in which kids are genuinely interested, which is the mysterious ability to communicate sound, images and text across space and time...
(Brunner, 2006a)

The ASU students made their own story from the materials given to them—the *Field Principles, Learning Frameworks*, and Phoebe’s Story. The back-story behind the children’s book played a significant role in creating a common thread for the **collective** work of the team. In summary, the narrative of the children’s book **informed** the design in the following ways:

- **From the author’s own history** they took her quest to learn to “think science” by harnessing the small “Einsteinian” part that exists in everyone.
- **From the project’s beginnings they took its inspiration from nature** – sunflower fields, bees, and agricultural fields.
- **From the story of Phoebe, they took the threshold moment.**

As it turns out, this ability to weave an authentic story from multiple sources—models, metaphors and back-stories, is what we want the learners in Phoebe’s Field to be able to do, too.

Critical Finding

As designers, our “down the rabbit hole” experience dropped us into an unfamiliar domain of the physics of fields. Our “contextual information” was being skilfully knowledgeable in our domain of architecture, and thus being able to transfer ways of knowing to the task at hand. In design this happens by processing observations through transference, in our case through “re-presenting.” Our disciplinary knowing occurs through active learning: representing our observations by drawing, making models, and telling stories. Given the iterative nature of our work, each new artifact functions as a new model, frequently demanding that we revisit and reinterpret all that has come before it. A majority of our studio time was spent around a large table in the centre of the room with the thirteen of us (twelve students + faculty) discussing together the approaches of each sub-group and evaluating multiple iterations generated for each proposal. Through comparison, both of differing approaches and of subtle iterations within each proposal, we developed an understanding of the limits and strengths of each in meeting the aims of the exhibit. *Parallel models* became a model for active science learning for the design team *and* for the proposed exhibit experience for the visitor to Phoebe’s Field.

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Alissa Priebe, Stephanie Francis, Katie Scallon, and Thomas Allen. For a comprehensive view of the project please visit Phoebe's Field at <http://www.phoebesfield.org/>.

Endnotes

ⁱ NSF is an independent US government agency responsible for promoting science and engineering through funding research programs and education projects.

ⁱⁱ **Kinesthesia** is defined as “a sense mediated by receptors located in muscles, tendons, and joints and stimulated by bodily movements and tensions; *also*: sensory experience derived from this sense”(Merriam-Webster). Used here it refers to the participatory “hands-on” and spatial experience of visitors to Phoebe's Field.

ⁱⁱⁱ In architecture there are three kinds of **specifications**—proprietary, descriptive, and performance. Proprietary is self-evident, a specific manufacturer and product are named. A descriptive specification details the desired characteristics of what is required; a performance specification recounts the desired outcomes.

^{iv} A **model** is a “representation of an idea, an object, an event, a process, or a system” (Gilbert & Boulter, 1998, p. 53). The ability to manipulate and develop models is an important skill in science literacy because real scientists need these skills (Gilbert, 2004; Gilbert and Boulter, 1998, pp. 53-66).

^v A good example of **how models function in science learning** is how they are used to teach kids about planetary orbits. A typical physical model of a solar system has rigid bars connecting each planet to a central point near the sun on the model. A graphical model of the same phenomenon shows the planets in the same order, but illustrates the elliptical shapes of their orbits. A verbal explanation can explain the role of gravity in keeping the planets in their orbits. Any single one of these models might create misconceptions with the learners. Taken together, and with clear explanations of the limitations of each model, the learners are more likely to construct a mental model that most closely resembles the consensus model.

^{vi} **Rite-in-the-Rain** is a paper created specifically for writing field notes in all weather conditions. www.riteintherain.com

Reference List

AMERICAN ASSOCIATION OF UNIVERSITY WOMEN (AAUW). 2004. Under the microscope: a decade of gender equity projects in the sciences. Washington, DC: Author.

BEREITER, C. 1997. Situated cognition and how to overcome it. In: D. KIRSHNER and J. A. WHITSON, eds. Situated cognition: social, semiotic, and psychological perspectives. NJ: Erlbaum, pp. 281–300.

BRUNNER, C. 2006a. In: VERNON, M., et. al. Project book: planning Phoebe's field. Limited edition manuscript. Blacksburg, VA: Author.

BRUNNER, C. 2006b. On girls, boys and IT careers. Google Tech Talk. 6 April. [WWW] http://cct.edc.org/report_summary.asp?numPublicationId=220 (21 May 2007).

BRUNNER, C. and BENNETT, D.T. 2002. The feminization of technology. In: N. YELLAND and A. RUBIN, eds. Ghosts in the machine: women's voices of research with technology. New York: Peter Lang.

CARROLL, L. (pseudonym of Reverend Charles Lutwidge Dodgson) 1869. Alice's adventures in wonderland. Boston : Lee and Shepard. (Original work published in 1865).

CROSS, N. 2001. Designerly ways of knowing: design discipline verses design science. Design Issues, **17**, pp. 49-55. Boston: The MIT Press.

DEWEY, J. 1963. Experience & education, New York: Collier MacMillan. (Original work published in 1938).

DUIT, R. 1991. On the role of analogies and metaphors in learning science. Science Education, **75**(6), pp. 649-672.

ENDY, D. and SAGMEISTER, S. 2006. The Seed Salon: Endy and Sagmeister. SEED, **2** (2), pp. 99-103.

FRIEDMAN, T. 2007. China needs an Einstein. So do we. New York Times, April 27, p. A-27.

FRIEDMAN, T. 2005. The world is flat: a brief history of the twenty-first century. New York: Farrar, Straus, and Giroux.

GILBERT, J. K. 2004. Models and modeling: routes to more authentic science education. International Journal of Science and Mathematics Education, **2**, pp. 115-130.

-
- GILBERT, J. K., and BOULTER, C. J. 1998. Learning science through models and modeling. In: B.J. FRASER and TOBIN, K.G., eds. International handbook of science education. Dordrecht, Netherlands: Kluwer Academic Publishers, pp. 53-66.
- GINZBURG, C. and GUNDERSEN, T.R. 2003. On the dark side of history: Carlo Ginzburg talks to Trygve Riiser Gundersen. Eurozine. [WWW] <http://www.eurozine.com/articles/2003-07-11-ginzburg-en.html> (20 September 2007).
- GLYNN, S. 1985. Science and perception as design. Design Studies, **6** (3).
- HARDY, S. 1993. The poetics of immediacy: oral narrative and the short story, Style, fall. [WWW] http://findarticles.com/p/articles/mi_m2342/is_n3_v27/ai_15473855/pg_14 (20 May 2007).
- HARRISON, A. G., and TREAGUST, D. F. 2000. Learning about atoms, molecules, and chemical bonds: a case study of multiple-model use in grade 11 chemistry. Science Education, **84**(3), pp. 352-381.
- KELLER, J. 1987. Development and use of the ARCS model of instructional design. Journal of Instructional Development, **10** (3), pp. 2-10.
- KUHN, THOMAS S. 1962. Historic structure of scientific discovery. Science Magazine. June 1962, pp. 760-764. Washington, D.C: American Association for the Advancement of Science. Abridgement of: KUHN, THOMAS S. 1962. Anomaly and the emergence of scientific discoveries. Structure of scientific revolutions. Chicago: The University of Chicago Press.
- LAVE, J., AND WENGER, E. 1991. Situated learning: legitimate peripheral participation. New York: Cambridge University Press.
- MULVEY, P. J., and NICHOLSON, S. 2004. Enrollments and degrees report, **R-151.41**. College Park, MD: American Institute of Physics.
- NATIONAL RESEARCH COUNCIL (NRC). 1996. National science education standards. Washington, D.C.: National Academy Press.
- RITTEL, H. and WEBBER, M. 1973. Dilemmas in a general theory of planning. Policy Sciences, **4**, pp. 155-169. Amsterdam: Elsevier Scientific Publishing Company, Inc.
- VERNON, M. 2006. [WWW] <http://www.phoebesfield.org> (9 MAY 2007)