DESIGN AS AN OBJECT-TO-THINK-WITH: SEMIOTIC POTENTIAL EMERGES THROUGH COLLABORATIVE REFLECTIVE CONVERSATION WITH MATERIAL

Dragan Trninic
University of California, Berkeley
trninic@berkeley.edu

Daniel L. Reinholz
University of California, Berkeley
reinholz@berkeley.edu

Mark Howison
Lawrence Berkeley National Laboratory
mhowison@lbl.gov

Dor Abrahamson
University of California, Berkeley
dor@berkeley.edu

We chart a historical analysis of a collaborative design-based research project investigating the emergence of mathematical meaning from embodied interaction with a technological tracking-system supporting the learning of proportionality. Recounting iterative cycles of a conceptually critical perceptual feedback element, we articulate three interconnected images of research-based designers: (a) Janus the two-headed keeper of passageways who sees artifacts alternately as a student would or as an expert would; (b) an investigator searching to explicate design decisions coherently in light of learning-sciences theory; and (c) a reflective practitioner who embraces tradeoffs and is open to constructive criticism and to implementing radical changes to design and theory. Ultimately, we posit, we as researchers are continuously developing professional vision for our own design even as the design changes.

Introduction

Design-based research (DBR), a fast evolving major approach to the investigation of human learning, is still nascent. Accordingly, whereas the approach has led to important ontological innovation and “humble theory” (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; diSessa & Cobb, 2004), it still receives formative criticism as methodologically volatile (Kelly, 2004), under-theorized (Abrahamson, 2009), and rhetorically inchoate (Puntambekar & Sandoval, 2009). In this paper, we—a DBR team investigating mathematics learning by developing and implementing innovative instructional technology—reflect on milestones in an evolving project in an attempt to respond productively to some of these constructive observations.

We view our team-based design processes through the same theoretical models of learning that have been applied to students and teachers engaged in collaborative problem solving, particularly in open-ended construction-based learning (e.g., Blikstein, 2008). Several philosophical, cognitive, and practical dispositions converge in our analysis: (1) an epistemological perspective on knowledge as emerging from learners’ explorative, highly divergent, yet possibly guided goal-based interaction with materials bearing semiotic potential (Bartolini Bussi & Mariotti, 2008; Lakatos, 1976); (2) a pedagogical commitment to constructionist learning in which bricolage antecedes hypothesis (Papert, 1996); (3) a methodological technique of collaborative qualitative microgenetic analysis (Schoenfeld, Smith, & Arcavi, 1991); and (4) a coherent view of designers as reflective learners (Schön, 1992). Engaging this reflexive analysis, we bear in mind the methodological limitations of introspection, moreover *group* introspection, and the exacerbating factor of professional capital at stake and the consequent vulnerability of practitioners revealing the meandering, backtracking, abductive processes underlying their products. Nonetheless, we are committed to a view of insight as emerging from previous dedication, creativity, hard work, and collaboration (Sawyer, 2007).

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Thus, to the extent that we can contribute to design theory by studying design, we wish to shift the investigation focus from design *product* to design *process*.

In sum, designers are learners just as much as their product consumers, the students, are. Whereas students engage in problems supporting content learning, designers engage in projects where interesting problems relating to epistemology, cognition, pedagogy, and design emerge. For designers, these problems are the semiotic potential of the evolving designs. And yet this potential can be availed of only in a collaborative culture of discourse. Just as teachers identify "teachable moments" bearing potential learning gains for students, so designers ought to identify "researchable moments" within their own design process that appear to bear potential learning gains for other designers and theoreticians—ontological innovations for the practice of design-based research. Similarly, just as classroom discussion is critical for students to avail of the semiotic potential of pedagogical artifacts, we submit, so design-team discussion is critical for researchers to avail of the theoretical potential of design decisions as revealing issues of cognition and instruction as well as design principles (cf. Edelson, 2002).

This paper is built as a reflective recounting of our collaborative design process in building instructional materials for the Kinemathics project, which centers on tapping Grade 4-6 students' physical action and embodied reasoning as a means of scaffolding their mathematization of proportionality (Abrahamson & Howison, 2010). The process involved numerous iterations of innovative technology. Whereas the iterations implemented superficially similar interactive affordances, reflecting on implications of nuanced differences among the iterations drove us to reconsider our foundational conjecture pertaining to the function of embodied artifacts in mathematical learning.

Background and Theoretical Framework

Beyond Historical Revisionism: Toward Dynamic Coherence of Project, Process, and Product

Reflecting on our mathematics background, the authors note one characteristic shared by mathematical proofs and design reports: the disproportionate emphasis on the product, which is often positioned as if it appeared *ex nihilo*. Initial attempts at problem solving, however relevant to consequent refinement or reorientation of the study, are oftentimes relegated to "just pilot talk" or, in the worst-case scenario, ignored wholesale or even ignominiously cashiered as unprofessional. In short, *historical revisionism*—reading onto the beginning of a process that which emerged only at its end—serves, by and large, as the normative modus operandi.

Yet it is precisely those early forays and bold conjectures that unshackle innovative design of extant unsatisfactory precedents, mark the unique character of the project, and lend functional coherence to the evolving group ethos and orientation—a coherence that enables the researchers to marshal and contain numerous local product oscillations typical in iterated development cycles of design-based research. If this historical process remains opaque, we submit, then the grounding of new theory may also remain opaque. We further submit that rendering the design process more transparent, and thus allowing a broad range of DBR practitioners operating in diverse domains to learn from one another's design decisions, is a crucial step towards developing DBR as a rigorous pan-project methodology.

Design 'Seeing' as an Emergent Process: Conversations With Material and Semiotic Potential

In his analysis of design, Donald Schön posits that the activity of design is necessarily *knowing-in-action* (1992)—that is, design acumen is implicit or procedural—and that, therefore, designers may gain best access to their professional knowledge when put in the actual mode of designing. Furthermore, due to limited information-processing capacity, designers cannot, in advance of implementing a particular “move,” consider all the consequences and qualities that may eventually be considered relevant to its evaluation. The immediate corollary is that some design decisions emerge organically through the designer’s conversation with the material of a design situation; that is, the designer analyzes the design material, plans and executes the design move, then reflects on the (oftentimes unintended) consequences of this move—a process Schön refers to as *seeing-moving-seeing*. The term “seeing” can be interpreted as sense-making: “in all this ‘seeing,’ the designer not only visually registers information but also constructs its meaning—identifies patterns and gives them meaning beyond themselves” (p. 133).

The clarity of Schön’s construct of seeing-moving-seeing notwithstanding, we found the work of Maria Alessandra Mariotti and collaborators (Bartolini Bussi & Mariotti, 2008) particularly useful in helping us better understand what a researcher *sees* when engaged in reflective design (cf. Abrahamson, 2009). Mariotti approaches issues of knowledge construction by examining epistemological and cognitive virtues of goal-oriented guided interaction with pedagogical artifacts—the artifact’s *semiotic potential*. She distinguishes between *personal meanings*—constructed meanings arising in the individual from using the artifact as a means of accomplishing the prescribed task, and *mathematical meanings*—meanings that an expert recognizes as mathematical when observing the student’s use of the artifact. Thus, cultural pedagogical artifacts, such as a compass, an abacus, or a geometry module, may offer valuable semiotic potential with respect to particular educational goals: by taking advantage of its semiotic affordance, the teacher utilizes the artifact to occasion opportunities for students to develop personal meaning into mathematical meanings that constitute the didactical goals.

We believe that Mariotti et al.’s theoretical constructs are applicable in arenas beyond teacher–artifact interaction. That is, we posit that one thing designers strive to *see* through collaborative conversation with an evolving design artifact is precisely the artifact’s semiotic potential—both project-specific and practice-general—in terms of issues akin to foreseeable learning trajectories based on implementing this potential. We thus propose to imagine the design artifact as a gateway between personal and mathematical meanings. Like Janus—the two-headed Roman deity of gateways, passages, beginnings and endings (the mythological as well as etymological epistemic *jani*tor)—designers approach their work with one face turned towards personal meanings and the other turned towards mathematical meanings, constantly striving to reconcile the two; designers construct the gateway–artifact and constantly modify and prune its corridors so as to optimize its wanderers’ learning trajectories.

In the following sections, having introduced our study’s orientation, objectives, and thesis, we present a design narrative consisting of vignettes of researchable moments that we view as indicative of the design process as a conversation wherein the emerging artifacts’ semiotic-cum-theoretical potentials are elicited; we then interpret the narrative through our theoretical lenses.

Research Context: An Embodied-Design Study of Presymbolic Proportional Reasoning

The study we report on is a subpart of *Action-Before-Concept* (*ABC*), a cluster of cross-disciplinary studies centered around questions respecting relations between procedural and conceptual knowledge, ultimately focused on the procedural–conceptual relation in mathematics instruction. ABC, writ large, is an inquiry into cultural precedence for pedagogical practice within explicitly embodied domains, wherein procedures are initially learned on trust yet subsequently—only toward perfecting the procedures toward mastery and further dissemination—are interpreted by experts as embodying disciplinary knowledge.

The particular study we report on is *Kinemathics: Kinetically Induced Mathematics* (Abrahamson & Howison, 2010), an investigation into how students operating interactive mathematical artifacts develop the emerging tacit, embodied, sensori-motor coupling with the device into mathematical meanings. Specifically, Kinemathics puts forth and pursues the bold conjecture that some mathematical concepts are difficult because ordinary life does not offer *physical* opportunities to develop multi-modal dynamical images by which to simulate these concepts *mentally*. Our approach is to devise tools and activities geared to induce in students physical experiences that are initially of little if any mathematical context yet gradually are seen as mathematical by having students appropriate strategically available disciplinary instruments as epistemic–discursive means of enhancing their inquiry and communication (see Abrahamson, 2009, for an outline and demonstration of this DBR meta-rationale).

Ultimately, this paper will focus on the evolution of a particular feedback element. At this point, however, we will build context for the subsequent discussion by overviewing the design's history through the perspective of its key artifact, the *Mathematics Imagery Trainer* (MIT).

The original MIT, MIT1, was implemented as a mechanical device using pulley wheels with 4'' and 6'' diameters to effect a 2:3 ratio in movement of the attached ropes. The student holds handles attached at the ends of the ropes, and the researcher cranks a lever to raise and lower the ropes at a steady rate (see Figure 1a). MIT1 was limited, particularly insofar that its somewhat cumbersome mechanism allowed for the student to experience only a single ratio, a structural constraint liable to limit the ultimate semiotic potential of generalizing the phenomenon of proportion (Janus frowned). These perceived limitations impelled us to redesign MIT2 in an attempt to increase the design's mathematical flexibility, performance precision, electronic module interactivity, and dissemination potential.

a. b. c.

Figure 1. (a) MIT1: researcher cranking the device, student holding on; (b) MIT2: student's incorrect performance turns the screen red; (c) correct performance turns the screen green

In our second iteration, MIT2, we leveraged the high-resolution infrared camera available in the inexpensive Nintendo Wii remote to perform motion tracking of students' hands, similar to work by Johnny Lee (http://johnnylee.net/projects/wii/). The Wii remote is a standard Bluetooth device, with several open-source libraries available to access it through Java or C#. An array of 84 infrared (940nm) LEDs aligned with the camera provides out light (source), and 3M 3000X high-gain reflective tape attached to a tennis ball allows effective motion capture at distances as far as 12 feet. In use, infrared rays emanate from the MIT2, reflect off tape covering tennis balls held by the student, and are then sensed, interpreted, and visually represented on a large display in the form of two crosshair symbols (trackers). The display is calibrated so as to continuously position the crosshairs at the actual physical height of each hand in an attempt to enhance the embodied experience of virtual remote manipulation. Advanced MIT2 prototypes provide visual feedback of the student's performance on a green–red gradient, a design feature we discuss in the following section (see Figures 1b and 1c; source and sensors are three feet left of the monitor).

MIT2 is our current technological vanguard, being successfully utilized in a study with Grade 4-6 participants. Analyses of twenty-one videotaped task-based interview sessions, in which individual or paired students worked with MIT2, suggests that participants struggled productively with canonical issues inherent to rational numbers, as evidenced by a succession of insights grounded in the embodied nature of the artifact. Namely, students first brought to bear naïve additive reasoning yet eventually assimilated the system's unexpected behavior as a new type of equivalence class that builds multiplicative structures upon additive reasoning. In our analysis of students' reasoning, we view mathematics learning as making connections between complementary mathematizations rather than progressive decontextualization. In this view, the MIT-induced embodied artifact of ambidextrous motion *is* proportionality, yet tacit proportionality initially unconnected, undisciplined: it needs to be reflected upon, signified in standard mathematical inscriptions, and substantiated and elaborated through explicit solution procedures. We detail our preliminary findings elsewhere (Reinholz, Trninic, Howison, & Abrahamson, 2010, in these same PME-NA32 proceedings; also see http://www.tinyurl.com/edrl-mit for a video overview).

Researchable Moments: The Trajectory of "Green"

Our decision to forsake MIT1 and re-embody our design in MIT2, and in particular our shift to an electronic medium, introduced both a wealth of opportunities and, concomitantly, a slew of new design challenges. Namely, whereas in MIT1 students were initially passive participants hanging onto the pullies, MIT2 required students to immediately take agency, and so a question emerged as to how this agency should be framed, elicited, and guided. That is, what were students to *do* in MIT2? What would be their task, how would they accomplish it, and what form of feedback might they receive on the quality of this performance? Our initial response was to create electronic "targets"—two circular symbols that move up and down the monitor screen at preset rates; we would task participants with tracking these targets by remotely manipulating two virtual crosshair symbols (trackers), thus constituting a digital analogue of MIT1's rope tautness.

Once the development of the MIT2 program and user interface had progressed to a point that we could present it to a larger circle of researchers, we were prepared to reengage issues of feedback engineering and optimization, particularly with respect to orienting young students towards task completion. Critical to this collaborative reflection was the question of how to optimize the task such that students could best avail of the technological affordances of this innovative design through exploring its embodied problem space. We had already considered implementing on the monitor a symbol-based feedback mechanism in the format of "2:x". Namely, "2" would remain constant while x varied according to the height of the participant's right hand as detected in the instrument's sensory field. However, the discussion session strongly suggested to us critical limitations of the "2:x" solution as a performance feedback: in addition to electronic calibration challenges of determining and displaying x, a selection of alphanumerical feedback was perceived as prematurely mathematizing students' essentially embodied activity—the group opined that students should be given ample "free range" opportunity to explore and discover quantitative properties of the novel situation initially unfettered by potential arithmetic encumbrance and biases invoked by symbolical mediation. Having debated the plausibility of various feedback types, ranging from purely numerical outputs to graphical animations such as growing flowers, it was suggested that color-based feedback might offer an adequate solution. In particular, the color green was suggested due to its positive cultural signification. Thence, the color red was selected in binary contradistinction to indicate poor performance. Finally, a color gradient between green and red would indicate intermediate performance. Yet, still a question remained: How exactly would the color feedback be implemented? Herein lay the rub.

Having established the green-to-red gradient as our feedback sign, we discussed the plausibility of coloring the targets *themselves* as feedback rather than presenting the colors as standalone signs. A dissenting group member suggested the alternative option of flooding the entire background with the feedback color. An evaluation of this suggestion, which was ultimately endorsed, led us to look anew at the very utility and purpose of incorporating targets in our design, in light of our intention to use color feedback. We concluded that the targets were now redundant and ultimately unwieldy. Specifically, participants' exploration would be limited by the requirement to track moving targets. In contrast, we wanted to provide students with an opportunity to move the trackers freely, without the restrictions introduced by moving targets. Furthermore, to our surprise, we recognized that green, initially conceptualized as *feedback*, could in fact serve as a *goal* onto its own (analogously, urban drivers might deliberately attempt to effect a "25 mph" radar feedback). We thus decided to remove the trackers from the design entirely and implement the green/red background as the primary goal-cum-feedback element. Students' task thus became, somewhat enigmatically, to "make the screen green."

A routine of our design team is to simultaneously track changes implemented to the design and articulate these changes in terms both of their apparent improvement on earlier versions and their implications for subsequent iteration of development and implementation. So doing, we strive to cohere with the learning-sciences constructs guiding our research. However, attempting to make sense of an ostensibly simple question—"What is green?"—proved unexpectedly challenging. Our initial definition of green as a feedback indicating appropriate interface actions, namely "correct" hand-to-hand ratio, seemed incomplete. A subsequent two-week email flurry following the adoption of green feedback evidences dogged pursuit of one recurring question: "What *is* green?" Gradually we came to reason as follows: to a participant, green would initially constitute an objective; then green would serve as the performance feedback in attempting to achieve the same objective; and would ultimately give rise to an equivalence class—a collection of hand-location pairs that the student would perceive as "the same" by virtue of their common effect on the screen. Given appropriate guidance within this context, we surmised, the semiotic potential of green could be cultivated into notions of proportion and reformulated numerically.

The green quandary settled, we faced a dilemma: having abolished the targets, would our design still enable learning processes consistent with the ultra-radical-constructivist version of our action-before-concept conjecture? That is, we worried that by having designated green as the students' goal-cum-feedback, students would not occasion opportunity initially to engage "meaninglessly" with the MIT. We had reasoned that MIT1 provided students with such passive participation, and this passivity cohered with our embodiment thesis; in contrast, MIT2 rushed students to a highly prescribed activity. Ultimately, we resolved this dilemma by modifying the ABC theoretical framework: rather than strive for completely meaningless activity—a design objective at odds with the Vygotskian thesis that complements our constructivist commitments—we start from an activity whose *performance* objective is prescribed and demands immediate agency, yet whose disciplinary *semiotic* implication is initially covert.

Discussion and Implications for Design

The episode above captures much of what we mean by “recognizing semiotic potential through collaborative conversation with material”: by implementing green feedback and reflecting on it, our research team could recognize in the design hitherto latent potentials as well as constraints. In particular, identifying emergent incongruence between the design and our theoretical commitments drove us to consider, and then implement, modification in our theory—a form, if you will, of productive cognitive dissonance. This is a particular advantage of working in the DBR approach: the seeing-moving-seeing cycles provide ample opportunities for both illuminating the design’s semiotic potential and reflecting on underlying and emerging theory.

Furthermore, inasmuch as the discussion helps other designers understand and improve their own processes, the episode would indicate the importance of avoiding historical revisionism in reporting design decisions as well as the value of persevering in making sense of intuitive design decisions (Abrahamson, 2009). Note that it is *not* the case that we introduced green feedback in order to replace the targets—claiming this would constitute historical revisionism and obscure the dynamic interactive nature of our collaborative design process. Rather, deciding to use green feedback led us to reflect in depth on the targets’ semiotic potential within the protean context of the evolving artifact, which in turn led to their removal from the design and our consequent focus on making sense of “green.” Thus a seemingly minor design decision resulted in drastic changes in both the semiotic potential of the resulting artifact and, consequently, the emerging theory.

The analysis of our shared design history, presented in this paper, portrays DBR practice as a complex, emergent system, with small sparks gathering together over time, multiple dead ends, and the constant reinterpretation of previous ideas (Sawyer, 2007). Our navigation of this maze, in particular the moment-to-moment contextual shifts framing the evolving artifact, yielded three images of design-based researchers: (a) Janus the two-headed keeper of passageways who sees artifacts alternately as a student would or as an expert would and strives to facilitate cognitive entries into, and safe passages through, these learning corridors; (b) an investigator doggedly searching to explicate design decisions and elements coherently in light of learning-sciences theory; and (c) a reflective practitioner who embraces tradeoffs as rules of the game, logs all design decisions, shares deliberations with colleagues, and is open to constructive criticism and the possibility of implementing radical changes to both design and theory. We have found the above images, which emerged from this study, helpful in structuring our project and, so doing, allowing us to constantly revisit (and frequently revise) our theoretical framework in productive ways. Though design-based research may follow divergent paths, it is not a random walk.

In closing, we wish to underscore the critical role of vigorous reflection and respectful challenge within the collaborative progress of a design team. Expressed within a collegial atmosphere, genuine dissent encourages divergent thinking and thus creativity (Nemeth, 2009). This cognitive and epistemic plurality, coupled with dogged insistence on systemic coherence, enabled us to pursue divergent research directions, including emergent issues of apparently nugatory significance that consequently proved crucial in advancing our theoretical understanding of students’ reasoning. Moreover, by engaging these materials as a group, a wide range of the artifacts’ semiotic potentials were broadcast, simulating some of the design’s interpretive diversity as we entered our empirical site and engaged our study participants. Note, though, that we do not restrict collaboration to the oral medium: indeed, the very activity of co-authoring and revising this text served to push our collective underdeveloped intuitions beyond the realm of “stygian shades” (Vygotsky, 1978) and towards articulated discursive coherence.

Ultimately, we as researchers are recursively developing professional vision for our own evolving design.

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