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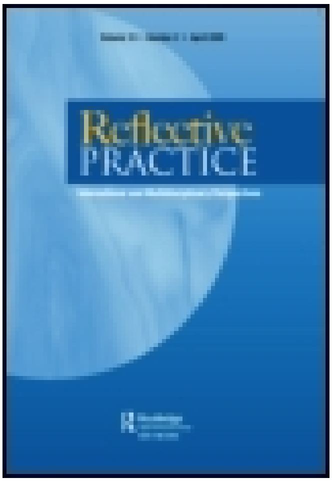

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Interfacing practices: domain theory emerges via collaborative reflection

Dor Abrahamson[a] & Kiera Chase[a]
[a] Graduate School of Education, University of California, Berkeley, 4649 Tolman Hall, Berkeley, 94720-1670 USA

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Interfacing practices: domain theory emerges via collaborative reflection

Dor Abrahamson* and Kiera Chase

Graduate School of Education, University of California, Berkeley, 4649 Tolman Hall, Berkeley, 94720-1670 USA

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Can reflective practice help an interdisciplinary team collaborate? When a new team begins negotiating their working process toward achieving project deliverables, members implicitly bring diverse professional practices to the table. Once minimal common ground has been established, members specify what they each need from the other in order to implement their respective expertise. This process of imposing mutual constraints results in adjusted workflow protocols that may modify participants' regular course of action yet are vital for facilitating the collaboration. Yet, we argue, this discursive process of negotiating collaboration protocols in interdisciplinary projects may result in more than just surface reconfiguration of local practices. The negotiation may yield an articulated reification of implicit know-how in the form of new theoretical constructs bearing potential impact beyond the local context of the project. We support the argument by presenting and analyzing archived records gathered from an interdisciplinary project, in which educational researchers and technology engineers collaborated in creating new instructional media for young mathematics students. In the course of struggling to formulate a mutually coherent workflow, the team 'stepped back' to formulate new goals that would address their coordination challenges. In turn, these goals implicated a new theoretical architecture that we present.

Keywords: algebra; boundary object; collaboration; design research; technology; transparency

Introduction

What does collaborative reflective practice look like? How is it motivated and what might it achieve? When collaborating experts from different domains of practice encounter a communication impasse, how should they proceed? How do interdisciplinary teams bootstrap themselves out of confusion toward achieving project deliverables? Can this local procedural achievement bear global disciplinary impact?

From the work of Donald Schön (1983), we know that effective practitioners advance their expertise by reflecting on their actions in situated contexts of practice. Such reflection can involve multiple fellow practitioners reflecting together on phenomena they observe in familiar situations, such as colleagues discussing problems of instruction. But what does reflective practice look like when collaborating practitioners share little or no professional history and only an inchoate future? In such

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*Corresponding author. Email: dor@berkeley.edu cases, how is joint reflection instigated, what does it draw on, how does it enfold and what does it generate? This paper reports on a case study of collaborative reflection that was motivated by communication breakdown in an interdisciplinary design team.

In what follows, we begin by citing prior work on this research problem of interdisciplinary collaboration. Next, we present the background and objectives of the particular interdisciplinary collaboration that is the case study of this paper. Drawing on minutes from the interdisciplinary team's meetings, we then reconstruct a narrative of how the team's collaborative reflection not only paved a pragmatic work plan but also yielded innovative theoretical constructs with far-reaching potential beyond the project.

Expanding research on reflective practice to the case of collaboration

In his seminal work, *The Reflective Practitioner: How Professionals Think in Action*, Donald Schön (1983) wrote the following on a particular 'meta-practice' exercised routinely by skilled practitioners:

> The practitioner allows himself to experience surprise, puzzlement, or confusion in a situation which he finds uncertain or unique. He reflects on the phenomenon before him, and on the prior understandings which have been implicit in his behaviour. He carries out an experiment which serves to generate both a new understanding of the phenomenon and a change in the situation. (p. 68)

Appreciating both the utility and interest of this form of adaptive expertise, Schön was concerned with developing theoretical models for documenting, explaining and propagating the systematic process by which effective practitioners' respond *in situ* to problems that emerge in the course of enacting their practice.

A particular setting for Schön's studies of reflective practice was the architect's studio. Design studios are auspicious spaces for investigating reflective practice, because therein the goal structures in question are concrete (i.e. models of architectural structures) in flux (i.e. the architect iteratively evaluates and modifies the objects), informed by authentic needs (i.e. the models will actually be constructed in full scale) and in negotiation with the public (i.e. stakeholders weigh in on the plans). Ethnographers of professional practice operating in the architect's design studio thus have access both to the material artifacts that focalize the practice and the process through which these artifacts evolve. In particular, Schön studied what he viewed as the ongoing 'conversation' between the architectural designer and the evolving models. More generally, Schön observed, as practitioners come to acknowledge and ponder their own implicit conceptualizations that frame their intuitive treatment of situations, these conceptualizations may change and, in turn, the practitioner may adapt the situation.

> In a good process of design, … conversation with the situation is reflective. In answer to the situation's back-talk, the designer reflects-in-action on the construction of the problem, the strategies of action, or the model of the phenomena, which have been implicit in his moves. (Schön, 1983, p. 79)

Like Schön, we are interested in better understanding and describing reflective practice, but our particular focus is on cases of *collaborative* reflective practice, where human speech supplements an artifact's back-talk. We submit that a helpful entry into the process of collaborative reflective practice is to examine the particular case of interdisciplinary projects; as diverse professionals convene on a joint project, they must establish routines of reflective practice even as they explore routines of collaboration. As such, the contribution of collective reflection is more starkly highlighted for our scrutiny.

Like Schön, we also find the designer's studio to be an auspicious setting for ethnographic study of professional practice, but our particular research site is an *educational* designer's studio, where new instructional materials and activities are envisioned, engineered, produced and field-tested. We further submit that a helpful entry into educational designers' reflective practice is the special case of design-based researchers. *Design-based research* is a practice-oriented approach to investigate the complexity of educational process. As they iteratively develop, implement and evaluate theory-based pedagogical resources, such as interactive technological artifacts for learning mathematics content, design-based researchers encounter and hone emergent questions germane to the disciplinary field of the learning sciences. In the course of addressing these questions, design-based researchers may develop new constructs – *ontological innovations* (diSessa & Cobb, 2004) that generalize beyond the study.

However, unlike Schön, reflective practice is not the mainstay of our professional interest. Although reflective practice is a familiar work ethos in our own laboratory, it is not necessarily a phenomenon of focal inquiry in our field studies. We are design-based researchers who usually generate pedagogical artifacts, educational theory and design frameworks, and not ethnographical studies of professional practice. Moreover, unlike Schön, we are offering an ethnographic study not of others but of ourselves. That is, we are offering a self-study, an ethnography of our own design-based research practice. In a sense, the following study is a post-facto reflection-*on*-action of reflection-*in*-action.

In summary, our objective for this paper is as follows. Schön has written extensively on how a practitioner engages individually in reflecting on their actions as well as how organizations operate as learning systems. This study intersects and elaborates on Schön's work by examining how reflection works in the case of collaborating individuals from different organizations who are attempting to make sense together of their yet-to-be-established work process. Building on a case self-study, we will argue that from the struggle to create viable collaboration routines new ontological structures may emerge that not only facilitate team coordination but also carry forward to change disciplinary perspectives on practice.

Teaming interdisciplinary practitioners: beliefs, boundary objects and beyond

When collaborating team members arrive from different disciplines, they may bear different conceptualizations of the project objectives, structures and processes. Yet many of these conceptualizations may be unarticulated organizational knowledge and orientations implicit to their respective routines. As the teams initially confer, their interdisciplinary differences might manifest as mere idiosyncratic uses of language. However, when the rubber hits the road – when concrete plans are to lay down project objectives and pave systematic and timely project process – the teams might be compelled to acknowledge and unpack the semantic vagueness of their respective jargon. At times, the teams might come to realize that their disparate terms ultimately refer to the same stuff in the world – the same ontological entities. For example, two international chefs from across the Atlantic might discover that their dispute over adding either cilantro or coriander into the broth was simply a happy matter of translation. In these felicitous instances the collaborators form a Rosetta Stone to facilitate their co-reference, even gallantly adopting each other's 'dialect'. At other times, however, attempts to resolve communication breakdowns are lost in translation, as it dawns on the teams that they are each speaking about something completely different. For example, collaborating mathematics-education researchers might realize that their most fundamental epistemological frameworks are incorrigibly disparate (Artigue, Cerulli, Haspekian, & Maracci, 2009). What happens then? Is incompatibility of fundamental perspectives a deal breaker for productive collaboration on a joint project?

One working solution is to realize that absolute consensus among project personnel is not necessarily required for managing successful co-production. Members of effective teams need not understand each other's expertise let alone agree with each other's positions, process and inferences. These facets of individual practice may remain obscure and entirely inscrutable to individual team members, because their collaborative activity is distributed over artifacts, people and time (Hutchins, 1995). Furthermore, when different stakeholders contribute to the development and maintenance of a joint project, they might be able to do so even in the absence of any direct interaction. The project then constitutes a *boundary object*:

> Boundary objects are objects which are both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual-site use. They may be abstract or concrete. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation. The creation and management of boundary objects is key in developing and maintaining coherence across intersecting social worlds. (Star & Griesemer, 1989, p. 393)

The notion of a boundary object and the literature around it focus on its function as just that – an entity created ad hoc to enable the interfacing of misaligned practices. Note that the boundary object per se is not expected to contribute back to either of the teaming practices – only to serve *in situ* as a mutually coherent 'portal' between worlds apart. Yet, we submit, even though boundary objects are locally functional interfaces built ad hoc for particular joint projects, they might nevertheless serve as far more than Rosetta Stones – they might be keystones, valuable and generative new resources that transform the attending disciplinary practices moving forward to other projects.

We believe that generative boundary objects are born via collaborative reflective practice, in which teaming practitioners may first become conscious of implicit principles underlying and guiding their situated decision making. By hence explicitly negotiating new protocols for coordinated process, the heterogeneous team may unwittingly lay foundations for a practical theory of practice, such as a novel pedagogical framework for designing instructional activities.

We are not the first to argue that interdisciplinary collaborating practitioners may co-develop boundary objects as ad hoc coordination solutions tailored to a specific project. Fischer and colleagues (Fischer, 2000; Fischer & Ostwald, 2005) propose to view heterogeneous design teams as communities of interest characterized by a *symmetry of ignorance* (Rittel, 1984). Both sides bring expertise that is vital for the completion of the project, and yet each side approaches the other's discipline with similar levels of naivety and neither team possesses the full breadth of knowledge to solve the problem independently. Fischer argues this symmetry of ignorance presents a powerful advantage in design. The process of negotiating different perspectives can disclose hidden aspects of design problems invisible to either group on their own, thus creating opportunities for learning (Fischer, 2000; Fischer & Ostwald, 2005).

A key to productive, creative interdisciplinary collaboration is in devising viable systems for communication (Mamykina, Candy, & Edmonds, 2002) that allow the two groups to negotiate and reach shared understandings (Resnick, 1991) despite their differences. Communication barriers, however, are inevitable when different communities of practice come together with their different knowledge bases and specialized languages (Fischer & Ostwald, 2005). Fischer argues that productive forms of negotiation arise via collaborative interactions with co-developed *externalizations* (from Bruner, 1996) that serve as boundary objects (Star, 1989). As boundary objects, these hybrid externalizations afford shared reference (Stahl, 2006), thus mobilizing process pragmatics, even as the teams maintain non-overlapping interpretations of the objects' significance (Akkerman & Bakker, 2011; Star, 1989, 2010; Star & Griesemer, 1989).

In particular, design artifacts (e.g. prototypes, plans) frequently serve as boundary objects (Bergman, Lyytinen, & Mark, 2007), providing a means to index unshared domain-specific terms and conceptualizations to publically shared elements of the perceptual field (Koschmann, LeBaron, Goodwin, & Feltovich, 2011). Sharing specific referents in joint perceptual fields – even while retaining distinct subjective senses and languages for these referents – allows participating researchers operating from within different knowledge systems to productively engage in practices that require cooperation. For example, this implicit 'looseness' in co-reference to objects in the joint perceptual field has been implicated as crucial in enabling initial pedagogical discourse around conceptual content between instructors and learners (Newman, Griffin, & Cole, 1989).

Airing dirty laundry as an intellectual ethos of design-based researchers

This paper is about an interdisciplinary collaborative design process from which emerged articulations of hitherto implicit pedagogical models. The diverse team comprised designers and programmers engaged in the collaborative process of creating educational-technology materials for young people to develop deep conceptual understanding of mathematical content, particularly algebra. The design process extended from the initial envisioning of educational solutions through to production and pilot implementation of prototypes, and finally to the analysis of video data collected in these experimental sessions. We argue that the pedagogical framework resulting from this collaboration emerged as a response to internal communication breakdowns. The breakdowns shifted the conversation to deliberate joint reflection on implicit epistemological positions underlying apparently disparate perspectives on the collaborative work process. As such, the design process itself inadvertently became part of what we were developing (Bergman et al., 2007). It is thus, we maintain, that frameworks and theory can sprout from the relatively mundane activity of managing and distributing roles in the co-production of a complex product among teaming members of diverse expertise.

Once such reflections are complete, they should be publicized to fellow practitioners and other stakeholders (Schön, 1983), which is what we are doing here. Sharing design deliberations can be of great value to educational researchers, because it advocates and legitimizes continual refinement or even rewriting of theoretical models for teaching and learning vis-à-vis ongoing discourse with practice. This is so much so that the design-based approach to educational research is explicitly and uniquely based on its practitioners' commitment to reflect publically on their implicit assumptions that did *not* bear out (Collins, 1992; Edelson, 2002).

Design-based researchers often share their process only when it has reached a significant milestone, and this usually involves insights from analyzing at least pilot data from implementing their design products. Yet, as Schön emphasizes, reflective practitioners may occasion opportunities to acknowledge and articulate principles underlying their expert practice *even prior* to implementing new design products and gathering empirical data on the effects of these products. For example, designers of instructional materials might explicate their implicit epistemological, cognitive and pedagogical assumptions by reflecting on their decision-making process in considering the ever-ramifying tree of design alternatives.

Surprisingly, therefore, academic publications that offer case studies of emerging design processes are quite scarce. With the exception of some essays in *Educational Designer* (e.g. Yerushalmy, 2013) and occasional journal articles or chapters (e.g. Abrahamson, 2009a; Barab et al., 2007), and despite general agreement over the importance of fostering reflective designers (Tracey, Hutchinson, & Grzebyk, 2014), design-based researchers rarely report on 'the making of' their instructional products. Our search through the archives of *Reflective Practice* going back a decade was equally unsuccessful in yielding reports on the reflective practice of designers, save the following near hit.

Merz (2002) describes the role of reflection in the ongoing evolution of a research design – a reflection that she conducted even as the post-intervention data analysis was still progressing. This process was characterized by a dialectic tuning of her investigative methods to insights that emerged for her in the data corpus. In particular, she chronicles her own paradigm shift from positivism to constructivism as a personal solution to a productive struggle. To wit, the structured process of data analysis occasioned for her opportunities to reflect on her implicit pedagogical and epistemological assumptions.

Our paper is similar to Merz (2002) in the sense that we, too, describe the process and product of reflecting on research methods, writ large. However, our reflection was: (a) collaborative rather than individual and in fact responded to emergent discourse problems; (b) occurred prior to the intervention, not after it, so that it was formative of the data we ultimately collected (cf. Vagle, 2010); (c) oriented on pedagogical design, not research design; and thus (d) contributed to the refinement of theory of learning.

Note that research design and design research are different activities. Granted, instructional materials employed in design-based research studies might be construed as part of the Materials reported on in the Methods section of research reports. Yet instructional design products might instead be conceptualized as far more than experimental instruments, because they embody the design-researchers' educational theory and pedagogical frameworks. These materials might evolve into serving an instructional role in school practice that far exceeds their methodological role in the empirical activity.

We thus report on an educational research team's collaborative reflection process through which an innovative pedagogical-design framework emerged. The team was reflecting on a breakdown in their ongoing problem-solving process of creating and refining materials and activities for educational purposes. We argue that the formulation of this framework was impelled by, and ultimately solved, internal communications problems – the framework created a network of shared, stable lexical referents that coalesced into a design architecture that shaped our process. In so doing, the emerging framework externalized into a coherent and generalizable form some of our key yet implicit assumptions. Prior to the collaboration, these assumptions were only latent to the decisions we made in building activity sequences. In a sense, reflecting on our practice enabled us to develop our know-how into know-that and, in so doing, to create a set of articulated criteria by which to evaluate the implementation of this know-how.

Setting the context: the 'giant steps for algebra' educational design project

This paper reflects on 'the making of' an educational design product, a technological activity for learning algebra. Here, we briefly sketch the background and objectives of the design project, and later sections will treat the design process. We begin with the design problem and continue with our domain analysis, proposed solution and pilot findings.

Learning algebra is described as progressing from arithmetic to algebra, with students' evolving meanings for the '=' sign playing an important role (Herscovics & Linchevski, 1996). When students first encounter algebraic propositions, such as '$3x + 14 = 5x + 6$', their implicit framing of these symbols is *operational*, because of a history of solving arithmetic problems such as '3 + 14 = __', where you operate on the left-hand expression and then fill in your solution on the right (Carpenter, Franke, & Levi, 2003). Yet, algebraic conceptualization of the '=' sign should be *relational*, as an equivalence between two expressions (Knuth, Stephens, McNeil, & Alibali, 2006).

The most common instructional methodology for fostering the *relational* treatment of algebraic equivalence is to use the *balance metaphor* (see Figure 1a). This metaphor invokes schemas implicit to the enactment of cultural practices involving a particular artifact, a twin-pan balance scale. The balance metaphor grounds the rationale of algebraic algorithms, such as 'Remove $3x$ from both sides of the equation'.

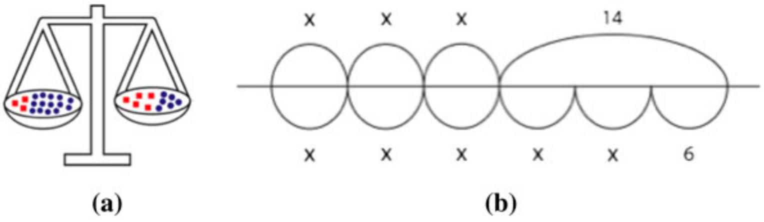

Figure 1. (a) Balance scale and (b) number-line instantiations of '$3x + 14 = 5x + 6$'.

However, students' persistent difficulty in *transitioning* from arithmetic to algebra suggests that the balance metaphor may not be the ideal method for building a relational understanding of equations (Jones, Inglis, Gilmore, & Evans, 2013). Moreover, the historical substitution of twin-pan scales with electronic scales may have rendered the metaphor inaccessible. We thus wondered, 'What alternative metaphor might facilitate students' passage from arithmetic to algebra?' Our search revealed that Dickinson and Eade (2004) tackled a similar problem. They used the number line as a diagrammatic form for modeling linear equations (see original work in Figure 1b.). Our design, 'Giant Steps for Algebra' (hence 'GS4A'), is based on this 'double-measuring-stick' model.

The number-line model for algebraic equivalence facilitates the offloading of intuitive schemes, such as naturalistic ambulatory motion, vis-à-vis the diagram's inherent logico-figural constraints. Problem solvers can thus focus on both qualitative and quantitative inferences while sustaining a sense of the solution steps; they are able to construct logical relations between variable and integer quantities directly by attending to spatial properties such as adjacency and containment.

In GS4A, a problem narrative describes how an agent performs two consecutive physical journeys that begin at the same point of departure and end at the same destination yet differ in progression. These journeys correspond to two equivalent algebraic expressions. For example, the algebraic proposition '$3x + 2 = 4x - 1$' is told as follows in an excerpt from an elaborate scenario:

> Starting from the port and walking straight along the only path, Egbert the Giant walked 3 giant steps and then another 2 meters. There, he buried some treasure. On the next day, Egbert wanted to bury more treasure in exactly the same place, but he was not sure where that place was. Setting off along the same path, he walked 4 giant steps and then, feeling he'd gone too far, he walked back one meter. Yes! He'd found the treasure! Your job is to tell your fellow elves exactly how many meters they need to walk from the docks to find the treasure.

We thus designed GS4A as an environment wherein students develop a notion of variable as a specific quantity: a numerical value that is consistent within a local situation. The specific value of the variable would initially be unknown to the student but could eventually be determined by triangulating available information about the Day-1 and Day-2 journeys. Figure 2 shows a number-line model of the above story.

One might construe this problem as presenting conceptual challenges for students – challenges that are inherent to the novelty of the algebra subject matter. Yet, what is the concept of algebra as expressed in this particular design (Abelson & diSessa, 1986)? Our observations of children working on this problem suggested

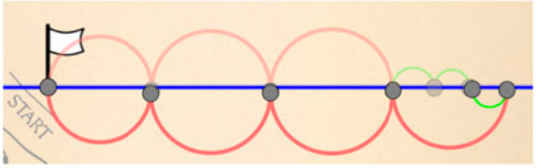

Figure 2. Application of the Dickinson and Eade (2004 #928) number-line algebra model in a virtual environment. The solution to '$3x + 2 = 4x - 1$' is visually tractable.

that it presents a *construction* problem – the problem of triangulating complementary depictive information. Successful construction, in turn, demanded of the students both structural precision and coordination, and these 'trivial' mechanical details surfaced as the stuff that algebra concepts are made of.

During early trials of the design, prior to the summer sessions, we used a variety of different modeling media. As we argue in Chase and Abrahamson (2013), when the students built a model from scratch, they understood its latent mathematical content better—it was more transparent to them. For example, students were more likely to understand the notion of a variable when they used paper and pencil to painstakingly scale up a drawing that depicted an unfolding sequence of giant steps, than when they were allowed to painlessly stretch an elastic ruler whose intervals scale up uniformly. Increasingly, the research team thus came to focus on the cognitive construct of subjective transparency (Meira, 1998). Enabling and enhancing the emergence of transparency became central to the redesign of GS4A, as we transitioned from low- to high-tech design solutions.

Our summer interns were to play a critical role in implementing the high-tech solution, and in fact had created a basic working interface in advance of their arrival as part of the interview process. Yet coming into the collaboration we did not foresee the complexities of facilitating this technological reimplementation. In particular, we wanted to create an interactive technological system that would emulate the human instructor's role in the tutorial interview, but we had not fully appreciated how much reflective effort would be required to articulate these tactics for our programmers. As we explain in the next section, our struggle to clarify what the technological system should accomplish turned out to be a struggle to articulate our underlying pedagogical beliefs and instructional methodology into what became a new type of design framework.

The emergence of a pedagogical framework from a design process

A fairly common practice in research teams is to keep minutes of regular meetings. Looking back, the minutes serve as documented insights on the empirical data toward writing up reports and publications. Looking forward, the minutes serve as action items that regulate individuals' prospective contributions to the collective effort. For this paper, we are using our bi-weekly minutes to reconstruct the project's design process, particularly to implicate events that we identify as milestones along the process. Whereas originally we did not conceive of the design process itself as the subject of a study, in retrospect the routine practice of taking minutes proved indispensable in enabling us to reconstruct the process.

The selected excerpts from our minutes that we present and interpret in this section will provide snapshot evidence for: (a) the educational researchers' struggle to articulate for the technology developers the underlying pedagogical rationale of the design; and (b) the evolution of a new pedagogical framework and, in particular, the emergence of the construct of Situated Intermediary Learning Objectives (SILOs). The narrative in this section will be interspersed with selected entries from the minutes of our team's meetings.

Note that at times the language of the following annotated transcriptions will be rather technical because the participants were discussing theory of learning. However, these passages will enable us to demonstrate how a new pedagogical framework emerged from the joint team's asymmetry of ignorance in the form of a workable boundary object upon which the heterogeneous experts could each index their respective practices. Furthermore, we envision that this boundary object bears the potential of living on beyond the specific project. Born as a conciliatory vehicle supporting a collaborative process, it might widely inform disciplinary practice.

Socialization: acculturating the interns into theory-oriented design practice

In late May 2013, two young scholars, both advanced undergraduate students in a technology-design program at a major Indian university, teamed up with the authors, a faculty member and a graduate student in the Special Education program in the Graduate School of Education, University of California, Berkeley. The interns had been carefully selected from a large pool of candidates on the basis of our evaluation of their prior work, email communications, assigned exercises and video interviews.

As we soon discovered, the interns came from an academic culture that was more product- than theory-oriented in comparison with our laboratory's praxis – their focus was more on design-for-use than design-for-research. To acculturate the interns into design-based research, we discussed some of the theoretical lenses that informed our initial design rationale and product. We find the following passage in our minutes:

> Whatever we build, we are guided by a theoretical construct that shapes what we do. Because we are scholars of education, we think about design from this perspective, we think about models for teaching and learning. (21 May 2013)

Citing John Dewey, the first author, Dor, then characterized conceptual development as an individual's reflective process of formalizing their experience – their guided passage from implicit know-*how* through to articulated know-*that*. The second author, Kiera, then cited two twin constructs prevalent in the Realistic Mathematics Education movement (Streefland, 1993 #930):

- *Model of*: a learner's naive way of schematizing an unfamiliar situation.
- *Model for*: over time, if students encounter multiple realistic situations that all can be modeled in a similar way, this leads to the emergence of a new form and category. Eventually, students can come to recognize an unfamiliar situation a priori as a case of this category.

Kiera also cited Gravemeijer (1999) who emphasizes the imperative of letting students' models emerge through their struggle to solve realistic problems: 'Students who work with these models will be encouraged to *(re)invent* the more formal mathematics' (p. 159, original italics). She explained that in GS4A we provide participants with media that enable them to generate models of the giant's journeys, with the intention that these local models will develop into general models for algebraic equivalence.

Finally, Dor introduced key tenets of Phenomenology and Enactivism in relation to perception, action and reasoning. From the *embodied-design* perspective, which Dor had been developing in his research, perceptual judgment and motor action are theorized as bearing seeds of mathematical concepts (Abrahamson, 2009b, 2014). For example, when students mark upon a medium a sequence of equidistant giant footprints, they are drawing on their tacit sensorimotor schemes for ambulatory motion. The distance *between* each two consecutive prints is then objectified by the student, as mediated by the instructor, as ‘a step’. This consensual sign structure – a word and its associated meaning – then facilitates the student-and-teacher co-enactment of the emerging cultural practice.

The first meeting was thus spent establishing a shared theoretical foundation for collaboration. The interns were then assigned a selection of video recordings from the project’s pilot data in order to practice the new theoretical ideas in the context of the design.

Up to this point in the narrative, the researchers were not so much coordinating with the technologists so much as indoctrinating them, so a negotiation of meaning had not yet begun. In the next section we describe how the technologists first made their own needs explicit, which led to the initial construction of a boundary object.

Getting to grips: cognitive task analysis in service of design query

The interns, who still needed some time to acculturate into the theory-laden discourse of the design-based research approach, were edging to demonstrate their programming mettle. To do so, they required of us a clear and finite set of action items couched in tractable form and adequate specificity, so that they could begin building the artificial tutor. That is, in order to delegate the facilitation of our experimental unit from human to silicon tutor, us human tutors have to spell out for our silicon compadres what it is we *do* when we tutor. Thus it was necessary to determine for our intern programmers in great detail what a student should know when first engaging in an activity and then after completing it, and, in addition, what the student should experience along the way that fosters the evolution from this not-knowing to knowing. For any instructor, these problems of knowledge assessment and activity facilitation are implicit to the attentive enactment of practice. However, programmers must necessarily cast all expert intuitive knowledge in the form of conditional actions that trigger output after computing input.

Researchers and programmers thus bear different conceptualizations of human knowledge. Yet this difference may reflect no more than the unique mundane pragmatics of two different professional activity structures; the difference need not reflect a terminal clash of vying epistemological commitments. If so, then achieving collaboration would mean coordinating activity structures more so than aligning epistemological commitments. In turn, this coordination would hinge on whether the researchers could operationalize and codify their implicit measures of knowledge. As such, negotiating competing perspectives on a pedagogical architecture bears the potential of fostering productive communication among collaborating parties whose implicit epistemological positions are, *and may remain,* grounded in different professional practices. This is precisely how boundary objects support collaborative practice.

In fact, what sparked our dialogue was Intern Vishesh’s question about designing the interface (28 May 2013). Specifically, Vishesh was planning a zooming functionality that would help students to manage the virtual construction of the giant’s journeys. Yet, as our transcriptions attest, Dor and Kiera worried lest Vishesh’s proposed functionality would interfere with students’ fledging cognitive structures for the target content of algebra. Specifically, zooming would uniformly change the screen sizes both of known quantities (meters) and variable quantities (giant step). We worried that the students would confuse two notions: (a) a known quantity (meter) that varies with screen size; and (b) a variable quantity (giant step) of indeterminate size. How facile might our audience be in navigating these proportional transformations in scale?

To support our concern, Kiera cited empirical data from the pilot trials, in which several participants who were modeling the giant's journey on the computer interface asked her, 'How big is a meter?' Reflecting on these data vis-à-vis, Vishesh's request for a decision on the zooming functionality, Kiera then said:

In a natural progression along their problem-solving process, the students should realize that:

(1) the problem is asking of them to determine how big a giant step is;
(2) the only measurement that they know is a meter; and
(3) the meter will help to figure out how big a giant step is.

And yet some students get stuck between #2 and #3, because they don't know the size of a meter in the virtual world.

The team decided that although the zooming functionality draws on culturally appropriate practices related to maps and would enable greater flexibility in constructing the diagram, it could potentially trade-off by impeding the students' development of the notion of a variable quantity. In addition, a zoom function would require a legend featuring the map's scale, and yet *this* feature could probably impede the students' development of the notion of a constant unit.

On reflection, we note that the set of three enumerated statements above marks the birth of the boundary object. It is the researchers' first attempt at unpacking for the programmers the students' knowledge-in-action as they engage the modeling problem. Thus the programmer's pragmatic query about a potential feature of the learning environment led to the researchers' cognitive task analysis of the target client's implicit knowledge structure.

Having articulated students' learning objectives, the researchers then turned to look at how the activity structure might foster these desirable learning objectives. The following section narrates the evolution of this line of reasoning through an expanded dialogue.

Designing knowledge: concepts as discovered rules of interaction

Students participating in the GS4S activity accomplish the embedded learning objectives through solving problems that emerge for them in the course of struggling with the task. As the design team worked to develop a work process, it became apparent to us that more specificity was required in explaining the relation between the students' activity flow and the learning objectives. The next shift in our conceptualization of learning was from thinking of the activity broadly as a case of problem solving to thinking of it specifically as a case of explorative modeling. We will briefly explain this distinction in terms of theoretical perspectives from the learning sciences.

Recall that the student first approaches the GS4A task without a trusted 'model for' algebraic situations – the student is still struggling to create a 'model of' the specific problem situation. Thus, initially the student shares with the instructor neither an understanding of what the problem demands nor how to solve it. Rather, the student attempts to build a diagram that 'tells the story' of the situation and only later inspects this diagram for clues by which to infer target information.

By design, the student's inferential process in solving the problem draws on cognitive operations serving the mathematical procedure that is the pedagogical goal of the instructional activity. For example, *seeing* the variable quantity as measurable by a known quantity (e.g. realizing that 1 step is equal to 3 meters; see Figure 2) would be an occasion for conceptual growth. It is a cognitive event that Peirce calls diagrammatic reasoning (Bakker & Hoffmann, 2005), Radford (2000) calls objectification, and Martin and Schwartz (2005) call distributed cognition. Importantly, our activity attempts to foster these cognitive events, in which students themselves construct solution procedures rather than instructors teaching the procedures. In enabling the student this agency, we were hoping to foster subjective transparency of the algebraic solution algorithm (Meira, 1998). That is, we were hoping for the students to see for themselves how algebra works.

We thus sought to characterize conceptual development as the noticing of logico-mathematical relations among diagrammatic elements of an evolving story model. That is, we came to realize that the set of learning objectives, cited above, is in fact a set of construction rules that the students figure out as they engage the particular challenges set before them. Our discussion minutes of 4 June 2013 include the following passage:

> In digital learning games, content/learning objectives are incorporated into the means of interaction. You have to figure out how to achieve the objectives, and in the process you are discovering the rules of the system that the designer wanted you to learn. Which brings us to ask the questions: What are the know-how features of GS4A? What are the impediments that participants encounter that they must overcome in order to achieve their goals?

Thus our thinking evolved from considering the students' in-coming tacit knowledge, for example, how a giant walks, to thinking about the students' instrumented actions of implementing this tacit knowledge in the virtual modeling environment. Through implementing this tacit knowledge, the students would come to notice diagrammatic relations that promote the solution of the problem. By developing these insights on learning, we were also responding to our technology experts' new queries concerning what functionalities to program into the interaction. We were beginning to realize that there is a relation between what the student has figured out – the set of learning objectives – and what the computer lets the student do. We realized that we should systematize a relation between interaction affordances and learning objectives.

Our research team was joined that day by a distinguished scholar of cognitive development, Jeanne Bamberger. She pushed us to articulate what it is that students know when they begin constructing a model of the story problem. Referring to the two journeys the giant takes, Dor replied, 'On both "days" the giant started and ended at the same point, but different stuff happened along the way'. Dor then continued, musing:

> But this is so far not math, it's only the story. What are these things that we know? They are so integral to how we work, and yet where is the algebra in here?! These are critical things – the instantiation of algebra within GS4A – and yet we don't have the language to express this.

In retrospect, we were at a critical juncture in the design-research process. On the one hand, our interns were asking which functionalities to program into the interface. On the other hand, the students who will be using this interface should ideally discover these functionalities themselves before we make the functionalities available to them. We realized that discovering the desired functionality is precisely the cognitive work that students should be doing. At the same time, these things that students figure out as they build the model and use it are not quite 'mathematics'. They are situated, intermediary learning objectives.

Having articulated a relation between interaction and learning in this specific environment, the team was ready to systematize this relation in the form of the activity's game mechanics. It is here that a new pedagogical architecture was founded.

A framework is born: Situated Intermediary Learning Objectives (SILOs)

By 11 June 2013, the research team was talking about features of the design and its implementation in terms of SILOs. The construct of SILOs enabled us to coordinate within a single linguistic nexus divergent aspects and objectives of our multidisciplinary tasks: (1) aspects of the target concept (algebra); (2) elements of the design (GS4A); and (3) observations of student behavior (in videotaped studies). We articulated the following three SILOs for the GS4A activity:

(1) *Consistent measures*. All variable units (giant steps) and all fixed units (meters) are respectively uniform in size both within and between expressions (days);
(2) *Equivalent expressions.* The two expressions (Day-1 and Day-2) are of identical magnitude – they share the 'start' and the 'end' points, so that they subtend precisely the same linear extent (even if the total distances traveled differ between days, e.g. when a giant oversteps and then goes back);
(3) *Shared frame of reference*. The variable quantity (giant steps) can be described in terms of the unit quantity (meters).

Articulating the SILOs increased the coherence and effectiveness of our work. The SILOs became a blueprint for the GS4A computer-based activity architecture. A user needs to demonstrate mastery over each of the SILOs in order to transition from their current interaction level to the next. At the next level, the functionality is instantiated automatically as a convenient shortcut that offloads the tedious mechanical work. That is, the computer system performs for students only what they have discovered themselves.

Once we had created game mechanics for implementing the SILO architecture, we were able to formulate a research design for evaluating the activity structure. In an experimental empirical study carried out after the summer work, we found that when students discover the SILOs they manifest greater learning gains than when they receive those functionalities ready-made (Abrahamson & Chase, 2015). Thus what began as an ad hoc boundary object for facilitating interdisciplinary collaboration in a design team evolved through collective reflection into a potentially powerful pedagogical architecture for designing educational technology.

Curiously, what we do with students is the opposite of classical scaffolding, because the computer system enacts for the learners what they have manifestly demonstrated that they *can* do, not what they *cannot* as yet do. We have therefore dubbed our pedagogical methodology 'reverse scaffolding' (Chase & Abrahamson, under review).

Conclusion

When an interdisciplinary collective of experts convenes on a joint project and struggles to build a mutually coherent activity plan, they should reflect together on their respective practices. Doing so may create opportunities to build boundary objects that not only facilitate the collaboration on the specific project but contribute widely to their respective practices.

Design is a journey; and the journey – how you travel, where you arrive – depends on your initial objectives, your companions and all that occurs along the way. Having arrived, one can look back and perhaps learn from understanding how one arrived there. We see non-trivial parallels between designers' creative journey as they build learning materials and students' learning journey as they engage those materials. Just as students tacitly apply their naïve know-how to their interactions with available media and only later reflect on the products of this application, so designers might not know what they know until they have built some object-to-think-with.

Thus demystification of design practice (Schön, 1983) begins from awareness that the creative process is tacitly informed by practical know-how – designers cannot predetermine principles of their own expertise prior to enacting this expertise and scrutinizing its products. Moreover, collaborative discourse plays an important role in articulating these tacit principles because it calls for language as a vehicle of negotiated coproduction (Wittgenstein, 1953). Such discourse is particularly conducive to the articulation of practice when the interlocutors have different, if complementary, knowledge bases and tasks, because the interlocutors require each other to make their knowledge explicit as a condition of effective collaboration. In that sense, teaming up for productive work is about negotiating a plurality of activity structures into a boundary object. Yet, this coordination artifact may prove to be a generative boundary object that lends rationale and structure beyond the local context of the particular project.

We hope to have demonstrated the utility of reflective design, at least for educational researchers who design for reflection. Expert educational researchers who cannot demystify their creative methodology limit their ultimate career impact to several instructional products, whereas an articulated effective methodology could scale up to bear colossal pedagogical impact. Our proposed reverse-scaffolding framework is enabling students to develop subjective transparency of algebra solution procedures (Abrahamson & Chase, under review). Days and further research will tell whether and how the framework bears out in other domains of mathematics and beyond to other STEM disciplines. Nevertheless, having shared our path with the community of educational researchers, we may now stand better chances of teaming up to serve future students.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Dor Abrahamson is an associate professor of Cognition and Development in the Graduate School of Education, University of California, Berkeley, USA, where he also directs the Embodied Design Research Laboratory. A member of faculty in the Education in

Mathematics, Science, and Technology graduate program, Dr. Abrahamson is a design-based researcher of cognition and instruction. He creates and evaluates systems for teaching and learning mathematical concepts and publishes on theory of learning and design frameworks.

Kiera Chase is a doctoral candidate in the Joint Doctoral Program in Special Education (San Francisco State University and University of California, Berkeley) with a designated emphasis in New Media. Her vision is to provide access to general education curriculum for diverse learners through differentiation and strong instructional design. Her doctoral dissertation focuses on the design and evaluation of a technologically enabled constructivist activity supporting young students learning the foundations of algebra.

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