Making Design Pedagogical Content Knowledge Visible within Design Reviews

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Abstract:
Design pedagogical content knowledge (PCK) is the content-specific specialized teacher knowledge that connects the how (pedagogical knowledge) and what (content knowledge) of teaching design. In this study, we make visible the design PCK in three student design reviews: choreography, undergraduate industrial design, and mechanical engineering. We use cognitive apprenticeship and teaching-as-improvisation frameworks to characterize PK, and design judgment, design task strategies, and process management strategies to characterize CK. We identify and describe four patterns of design PCK: scaffolded articulation, driving for meaning and guidance, breaking the 4th wall to create a teaching moment, and "suggest don't tell". Theoretical implications of this work include translating theories of social learning to the context of design reviews and showing design-specific teaching approaches design coaches use to support and instruct students as learners of design. We summarize practical implications for design students, new design coaches, and more experienced design coaches.

Keywords: *pedagogical content knowledge, design thinking, cognitive apprenticeship, teaching as improvisation, conceptual knowledge, procedural knowledge, design reviews*

1. Introduction

Pedagogical content knowledge (PCK) is a framework for making visible the "craft knowledge" that guides teaching actions within a subject (Driel et al, 1998; Shulman, 1986; 1987). It is the integrated knowledge of the "how" and "what" to teach that represents teachers' accumulated wisdom in practice. For example, PCK includes content-specific knowledge of (1) student conceptions, preconceptions and misconceptions, (2) the difficulties students encounter and what makes these topics easy or difficult, (3) predicting what students will find interesting and motivating, and (4)

interpreting students' emerging and incomplete thinking (Ball, Thames & Phelps, 2005; Gess-Newsome, 1999; Grossman, 1990; Shulman, 1986, 1987). It also includes content-specific teaching strategies such as (1) examples to use to help students develop depth of understanding and make connections, (2) useful forms for representing ideas, and (3) knowing when to pose new questions or tasks to deepen students' understanding (Ball, Thames & Phelps, 2005; Davis, 2003; Driel, Verloop & Vos, 1998; Gess-Newsome, 1999; Magnusson et al, 1999; Shulman, 1986, 1987; Veal, Tippins & Bell, 1998).

Linking this idea of PCK to the context of teaching design, design PCK can be a framework for investigating and understanding teachers' practice-based knowledge that shapes teaching interactions with students. Here, *design PCK* is a design thinking specific version of pedagogical content knowledge that characterizes the ways teachers use teaching techniques to convey design thinking knowledge and help students develop as design thinkers. This idea of PCK may be particularly relevant for design. Because design may be characterized as a form of situated knowing (Cross, 2006; Dorst, 2004, 2006; Lawson & Dorst, 2009; Schön, 1993, 1995), design PCK provides a lens for studying situated approaches to design teaching. By integrating perspectives on the "how" and "what" of teaching and learning in a specific domain, a PCK lens provides a unique vantage point for linking research and practice agendas. This includes research on how people design and acquire design expertise, and the nature of design situations or environments (Dorst, 2004, 2006; Goel & Pirolli, 1992) with related instructional implications (Jonassen, 2000). It also includes the nature and structure of design teaching (Andjomshoaa, Islami & Mokhtabad-Amrei, 2011; Dym Agogino, Eris, Frey & Leifer, 2005; Schön, 1993, 1995), and the structure of design reviews (Goldschmidt, 2002, 2006; Oh, Ishizaki, Gross & Do, 2012).

Other studies articulate teaching strategies for design, but few investigate design PCK. Uluoğlu (2000) identified multiple strategies architecture instructors' use in design studios to convey knowledge to students such as interpretation, examples, analogies, scenarios, demonstrations, reminders, and evaluation. Goldschmidt (2006) identified similar strategies as well as using scenarios and precedents to help students develop a repertoire, and helping students develop skills for classifying problems into categories to facilitate retrieval for use in developing acceptable solutions. Hynes (2012) examined middle school engineering teachers' use of prototypes and iteration as a form of design PCK to help students clarify or identify new needs or imagine future versions. Dym et al (2005) also studied how to teach engineering design, focusing on deep inquiry through divergent and convergent questions. From a meta-synthesis of design cognition research, Crismond and Adams (2012) suggested design PCK could include knowledge of (1) how to structure and represent design thinking content, (2) typical design learning trajectories, including common misconceptions and difficulties students encounter, (3) common inefficient habits of mind, and (4) relevant learning goals and teaching strategies.

The DTRS 10 dataset (Adams & Siddiqui, 2013) provides multiple windows into the structure and nature of design reviews across contexts (choreography, entrepreneurship, industrial product design, mechanical engineering design, and service learning design) and emphasizing diverse principles such as aesthetics, science and technology, and

human-centered design. By taking a pedagogical content knowledge lens, we hope to *make visible the design pedagogical content knowledge coaches use in design reviews when guiding students to develop as design thinkers*. The goal of this exploratory study is to generate a broad perspective by investigating similarities and differences of design PCK across disciplines and review structures. By using the lens of pedagogical content knowledge we hope to provide an integrated view that links research on design thinking, design teaching strategies, and design student capabilities.

2. Three Complementary Lenses of Design PCK

For this study, we broadly define design PCK as design thinking specific teaching approaches coaches use that brings together the "how" and the "what" of design teaching. It is composed of design pedagogical knowledge (PK) and design content knowledge (CK). We use two pre-existing frameworks to characterize PK: *cognitive apprenticeship* and *teaching as improvisation.* These PK frameworks emphasize the social and constructivist nature of design teaching. The CK lens emphasizes the conceptual and procedural attributes of design thinking knowledge coaches seek to convey or develop in their students.

2.1 Cognitive Apprenticeship: characterizing PK as "making thinking visible"

Cognitive apprenticeship theory is situated within the learning sciences and emphasizes how humans learn in a social manner by observing senior members in one's community of practice (Collins, Brown & Holum, 1991; Lave & Wenger, 1992). Since cognitive activity is not visible by default, teachers of intellectual subjects need to practice "making thinking visible," or "the externalization of processes that are usually carried out internally... to bring these tacit processes into the open." (Collins et al, 1991, p. 6) In this way, the use of cognitive apprenticeship techniques is the practice of making one's metacognition visible to learners in one's community of practice. An expert's actions may seem mysterious to novice learners: why did a coach like or dislike an element of a student's design, or how would they go about the same task? By providing the underlying rationale and thinking behind an expert's decision making and judgment processes, cognitive apprenticeship techniques support student learning by helping them examine and develop their own decision making and judgment processes as junior practitioners in the field.

As shown later in Table 2, cognitive apprentice techniques include modeling (demonstrating a desired skill), scaffolding (allowing learners to finish a partially-completed job), coaching (watching students perform and providing feedback on the sidelines), and fading (encouraging students to tackle a project on their own with less and less guidance) (Collins, Brown, & Newman, 1987; Collins et al, 1991). These are concrete techniques that may be observed in coach-student interactions during a design review. As such, this framework provides a lens for noticing patterns of design PCK coaches' use in design reviews – both the teaching technique and the design thinking lesson being conveyed. It also fits within a tradition of design education as apprenticeship (Cross, 2006). While cognitive apprenticeship theory is not typically cited as a framework for understanding design thinking, teaching or learning, elements are

evident in the existing literature through calls for constructivist approaches to teaching (Andjomshoaa, Islami & Mokhtabad-Amrei, 2011), an emphasis on teacher modeling their design thinking values and strategies as a dialectical process with students (Goldschmidt, 2006; Oxman, 1999), and scaffolding divergent-convergent thinking combinations in design teaching (Dym et al., 2005; Cardoso, Eris & Badke-Schaub, 2014; Yilmaz & Daly, 2014; Wolmarans, 2014).

2.2 Teaching as improvisation: characterizing PK as adaptive

The second perspective, *teaching as improvisation*, is inspired by Goffman's (1956) idea of performance and builds on Sawyer's (2011) idea of adaptive teachers as skilled improvisers. Sawyer (2004) argues that teaching is analogous to improvisational acting: it is unpredictable, contingent upon interactions, and built from moment to moment but also draws upon an existing repertoire of pedagogical patterns (Borko & Livingston, 1989; Sawyer, 2004). Expert teachers, having considerable expertise and experience to draw from, are better at this kind of improvisation than novice teachers (Borko & Livingston, 1989; Sawyer, 2004).

Teaching as improvisation aligns with the "knowledge is emergent" mindset found in learner-centered and constructivist approaches to teaching (Brennan, 2013; Kang, Brian & Ricca, 2010). When there is no script to follow, students are allowed to be self-organizing – leading their own experiences and shaping the flow of a teaching interaction (Crossan, 1998; Sawyer, 2008). These kinds of loosely structured environments, which are similar to a design studio model, are effective for facilitating learners' development of inquiry skills (Sawyer, 2011). Similarly, if designing may be characterized as a flexible and iterative process (Adams, Atman & Turns, 2001; Radcliffe & Lee, 1989) with opportunistic deviations (Ball & Ormerod, 1995; Visser, 1990) and co-evolutionary cycles (Dorst & Cross, 2001), then it might be expected that design teaching would have similar features. In a study of expertise, Goldschmidt (2006) described the process of translating and conveying knowledge to students during design critiques as highly adaptive to the student and situation, rather than a place of teacher-directed synthesis or a consistent script. For example, the improvisation technique of the "Yes &" rule can facilitate shared understanding between students and teachers (Vass, Littleton, Miell & Jones, 2008), especially when a teacher lets go of a structure or script and instead uses guiding questions to focus students on concepts relevant to their situation (Kang, Brian & Ricca, 2010). In contrast, teachers may use the improvisation technique of "breaking the 4^{th} wall" (Kang, Brian & Ricca, 2010) or "denial" (silencing unexpected student ideas with soft dismissals) (Beghetto, 2009) to take control of the dialogue, providing structure to communicate a concept students may find difficult. These teaching techniques, along with others based on improvisation language, may be used as a lens to make visible aspects of design PCK that involve drawing on teaching repertoires to flexibly adapt to a situation.

2.3 Content knowledge: characterizing conceptual and procedural knowledge

From a PCK perspective (Shulman, 1986; 1987), facilitating design thinking competence rests on developing two inseparable knowledge types: conceptual and procedural knowledge (Anderson, 1976; Goldschmidt, 2006; Star, 2000). Conceptual knowledge refers to the knowledge of declarative concepts, facts, and principles that govern a

domain, and the relationships that lead to an integrated conceptual understanding of a domain of knowledge (Anderson, 1976). Procedural knowledge refers to the knowledge of how to perform or operate in a situation, and these procedures or action sequences may be simple or complex in nature (Anderson, 1976), and may be multi-faceted with attributes of routine competencies as well as intelligent performance (Star, 2000).

For design thinking, conceptual knowledge might include ideas about universal principles (Lidwell, Holden & Butler, 2003) or the ways disciplinary structures shape what knowledge is used to develop and judge design ideas. For example, Carvalho, Dong, and Maton (2009) identified substantive differences in the valuation of design knowledge across diverse disciplines (engineering, architecture, digital media, and fashion design) that went beyond simple dichotomies of art vs. science, quantitative vs. qualitative, and rational vs. reflective. Conceptual knowledge might also include the ways prior knowledge or precedent informs problem framings and solutions (Purcell, 2003), and how an understanding of the structure of design tasks can shape design activity (Goel & Pirolli, 1992) such as managing ambiguity (Cross, 2006; Lande & Leifer, 2010), negotiating different object worlds (Bucciarelli, 1996), abductive reasoning (Dorst & Lawson, 2009; Dorst, 2004), iteration (Adams, Atman & Turns, 2001), co-evolution (Dorst & Cross, 2001), and the different lenses designers use when designing (Daly, Adams & Bodner, 2012).

There are many perspectives on procedural knowledge in the design thinking community including design processes, design heuristics and methodologies, and social processes. For this study, we used a scholarship of integration effort that provides a framework for characterizing design PCK (Crismond & Adams, 2012) as design behaviors teachers can encourage (or discourage) in helping students learn to design. This *Informed Design Learning and Teaching Matrix* was based on a review of over 75 studies drawing from diverse communities. The Matrix describes a learning trajectory from "beginning designer" (that depicts assumptions about prior knowledge and skills of learners as they enter a learning progression) to "informed" designer (that depicts what learners are expected to know and do by the end of the progression). Here, an "informed designer" is one whose level of experience includes some formal training in design, and level of competence lies somewhere between that of the novice and expert designer. This midrange stage maps well to generic models of design expertise such as "advanced novice" (Dreyfus & Dreyfus, 2005) and "competent performer" (Dreyfus & Dreyfus, 1986) in ways of perceiving, interpreting, structuring, and solving complex problems (Lawson & Dorst, 2009). Compared to experts, informed designers' pattern matching skills would be less reliable, retrieval and use of learned ideas would be done less flexibly since those ideas would have fewer interconnections, and awarenesses would be more situation-dependent and wedded to the contexts in which there were originally experienced (Crismond & Adams, 2012). From the perspective of school-based design education, informed designing is a more developmentally appropriate learning goal than expertise, which would be a long-range learning goal.

The Matrix is written as a collection of nine contrasting statements of beginning versus informed designing related to key performance elements that make up effective design practice. For example, for the pattern of *Ignore vs. Balance Benefits and Tradeoffs*, beginning designers are prone to ignore complexity and trade-offs and make design decisions without weighing all options or attend only to pros of favored ideas or cons of lesser approaches. In contrast, informed designers use words and graphics to display and weigh both benefits and trade-offs before selecting a solution. For the pattern, *Haphazard or Linear vs. Managed & Iterative Designing*, beginners design in haphazard ways or do design steps once and in a linear manner. Informed designers do design in a managed way, improving on ideas iteratively through feedback and using strategies multiple times as needed, in any order.

3. Method

Our intent with this exploratory study was to find a language researchers and practitioners can use to start describing the broad landscape of design PCK used by coaches in design reviews. To overcome some of the challenges with studying content-specific approaches to teaching and lay a foundation for a practice-based theory of design PCK, we followed an approach similar to Ball et al (2005). This involved characterizing the "work of teaching" as observed in the moment-to-moment demands of design review situations: what coaches do when teaching design, and how what they do conveys or demands design reasoning, insight, understanding, and skill. This section summarizes our data selection, coding, and analysis processes.

3.1 Data selection

We used five considerations to select data from the complete dataset (Adams & Siddiqui, 2013). The first and most impactful consideration was **maximizing variation** across disciplines and review structures in order to create a language that could have fidelity across a wide range of design review contexts and structures. Our dataset includes mechanical engineering (ME) design reviews with both formal conceptual design and informal final design presentation formats frequently interrupted by coach questions, informal choreography (CHOR) discussions with a circle of multiple coaches taking turns to provide student feedback, and one-on-one industrial design (ID) reviews in a shared design studio space that included both early-stage and late-stage work. All contexts utilized speech, text, gestural, and artifact modalities.

The second factor shaping our data choices was the desire for **longitudinal perspectives** to ensure our language could describe the evolution of coach-student dynamics over time. Third was choosing to **focus on undergraduate learners** in order to see how coaches socialized novices into a relatively unfamiliar field of inquiry; this removed the graduate-level industrial design dataset from consideration. We also required **substantial coach-student dialogue** instead of one-way presentations, since our questions about design PCK center around how coaches respond to students in real-time; this removed the entrepreneurship dataset from consideration. Finally, because of our focus on design PCK we focused on **instructors as coaches** as compared to peers or stakeholders; this removed the service learning dataset from consideration. As a note, had there been more data points in the service learning dataset of the very rich advisor debrief conversations,

the service learning dataset would have met our criteria. Our final data subset is displayed in Table 1. Other DTRS 10 studies that compared the same datasets and emphasized student-teacher interactions include Yilmaz and Daly (2014), Mann and Tekmen-Araci (2014), and Purzer, Fila and Dick (2014).

Table 1. Design PCK data subset

Discipline (Learner level)	Longitudinal video subset	Learners	Coaching Dialogue	Structure
Choreographers (Seniors)	First, Second & Third (final) Review	Elena & Anita	Learners being reviewed as individuals	Group sessions with multiple coaches and working prototypes (performances)
Industrial Design (Juniors)	First, Second & "Looks Like" (Fourth) Review	Todd & Sheryl	Learners being reviewed as individuals	One-on-one sessions with sketches and prototypes
Mechanical Engineering (Seniors)	Conceptual Design Review & Final Design Review	Robot Fish Team	Learners being reviewed as a team	Formal and informal presentations with working prototypes

3.2 Coding process

Three lenses were used to capture relationships between the "how" (teaching technique) and the "what" (content) of the design pedagogical content knowledge coaches' use in design reviews. The teaching technique lenses are based on cognitive apprenticeship theory and a teaching as improvisation framework. The content knowledge lenses are comprised of conceptual and procedural knowledge frameworks. Each is described in the following sections.

Cognitive apprenticeship codes

As shown in Table 2, the cognitive apprenticeship codes describe teaching techniques masters (coaches) of a cognitive craft can use to "make their thinking visible" to their apprentices (students) (Collins, Brown, and Holum, 1991; Collins, Brown, and Newman, 1987). The framework was originally developed to describe the process of teaching reading, writing, and mathematics to younger children. We have made two modifications. First, the new code of *bounding* was added to reflect the tendency of adult learners to direct a teacher or coach as to how they want to learn a topic, in contrast to young children who may be less self-directed. Secondly, we excluded the concept of "fading" as it referred to the gradual withdrawal of other support techniques rather than describing a specific and distinctive support technique itself.

Many of these codes support observations across the dataset including "pressing" students to articulate their reasoning (Mann & Tekmen-Araci, 2014), scaffolding-modeling-coaching sequences as a form of feedback (Cardella et al, 2014) or suggesting modifications (McNair, Paretti & Groen, 2014), coaches modeling how to ask good questions (Cardoso, Eris & Badke-Schaub, 2014) or sharing linguistic routines with

students (Howard & Gray, 2014), and students *bounding* by asking questions of coaches (Cardoso, Eris & Badke-Schaub, 2014).

Table 2. Cognitive Apprenticeship codes. New codes indicated with (*).

CODE	DESCRIPTION
MODELING	Coach makes their thinking visible to the student, demonstrating the target task while thinking out loud about their process.
ARTICULATING	Student makes their thinking visible to the coach. This usually involves the student explaining and justifying their process to the coach so the coach can check the reasoning behind the student's performance. This code may be understood as a role reversal of *modeling*.
SCAFFOLDING	Coach makes their thinking about a student's performance visible to the student. This is usually done by directing the student towards a subset of the task as a suggested next step or as homework for the future. The coach may also partially complete the task to enable the student to pick it up at an easier point.
BOUNDING*	Student makes their thinking visible to the coach by directing the coach towards a subset of the problem they want guidance on. This code may be understood as a role reversal of *scaffolding*.
COACHING	Coach makes their thinking about a student's past performance visible to a student. This typically involves providing feedback on the student's performance on a target task. Note that coaching is a response to the student's past performance, whereas scaffolding is a direction for the student's future performance.
REFLECTING	Student compares their process to an expert's process.

Teaching as improvisation codes

The teaching as improvisation codes in Table 3 are based on Sawyer's (2004) framework and describe techniques teachers could use in loosely structured constructivist learning environments to facilitate learners' development of inquiry skills and individual creativity. Some techniques refer to instances in which the coach and student are working collaboratively, and some refer to instances in which they are not. For example, Sawyer (2004) notes that *breaking the 4th wall* can negatively impact a teacher-student dynamic whereas *Yes &* ("yes, and") is more likely to have a positive impact. Some techniques were not evident in our dataset, and these were deleted from the final code set (i.e., listen and remember, asking constraining questions, endowing, and playwriting).

Many of these codes support other observations in the broader dataset including "directed recommendation" or driving a student to focus down (Yilmaz & Daly, 2014), "noting negatives" or disagreeing with students (McNair, Paretti & Groen, 2014), and a code similar to breaking the 4th wall for when an individual interrupts the interaction dynamic (Sonalkar, Mabogunje & Leifer, 2014). Many researchers observed versions of a *Yes &* code: a form of collaborative interaction (Sonalkar, Mabogunje & Leifer, 2014), a coach responding on behalf of the student (Cardoso, Eris & Badke-Schaub, 2014) or finishing a student's sentence (Howard & Gray, 2014), a coach "noting positives" (McNair, Paretti & Groen, 2014), and a coach elaborating on a student's comments as a form of non-directional feedback (Yilmaz & Daly, 2014).

Table 3. Teaching as Improvisation codes.

CODE	DESCRIPTION
BREAKING THE 4TH WALL	When the coach breaks an interaction dynamic to communicate an important point to the student such as a concept or "ground rule" that has intrinsic value for the coach or the field of inquiry. *Breaking the 4th wall* can be a form of metacommunication as well as a means for the coach to settle a conversation at the end of its allotted time. This code typically is solely used by the coach (as expert) and can co-occur with *driving*, where the coach takes control of a conversation. If the coach breaks the fourth wall too often, the collaborative nature of the conversation may end.
DENIAL	*Denial* works as the opposite of the *Yes &* code, in which one person rejects what another has introduced into the dramatic frame. In a coaching scenario, this can be difficult for coaches to do, as they may not want students to feel like their contributions are not valued. While *denial* can be confrontational, abruptly switching focus from the student to the coach, it can also be subtle yet distinct from constructive revoicing.
DRIVING	While *driving*, the coach takes over the interaction, not letting others talk or contribute. To determine *driving*, the transcript must be read to determine pauses and the accompanying video must be observed to determine if there are corresponding physical cues (e.g., sufficient pause, body language, authoritative tone, etc.). While a student could drive, the coach's expertise is often the main reason for this kind of shift in conversation.
YES &	The coach has an affirmative reaction to a student's assertion or work, allowing a coach-student collaboration to emerge and flow. In these situations, the coach accepts a student's assertion as valid and revoices this to the student(s), often building on the assertion. A coach may also use a *Yes &* to encourage a student to continue elaborating or discussing design decisions. This code may also be used to signify when coaches are building off other coaches.

Content codes

The content codes make visible the design thinking knowledge coaches are encouraging with their students or exhibiting through their own actions during a design review conversation. As such, these codes represent implicit or explicit design teaching and learning goals enacted within a design review. The following sections summarize the kinds of conceptual and procedural concepts and strategies coaches conveyed in their teaching interactions with students.

Conceptual knowledge codes

Conceptual knowledge was defined as knowledge for *judging design decision* (see also Christensen & Ball, 2014) and is comparable to a frame of reference for making design decisions (Howard & Gray, 2014). These codes were generated bottom-up from the data using the constant comparison method (Glaser & Strauss, 1967; Ryan & Bernard, 2003), but complement other research findings (e.g., Carvalho, Dong & Marton, 2005; Goldschmidt, 2006). An intentional goal of this process was to identify concepts in ways that would support inclusion across all contexts. Most codes are subjective or negotiable in nature, and inform design requirements and design constraints. Many of these codes align with observations across the full dataset. This includes aesthetics (Christensen & Ball, 2014; Ferreira, Christiaans & Almendra, 2014; Mann & Tekmen-Araci, 2014), technical or feasibility issues (Christensen & Ball, 2014; Ferreira, Christiaans & Almendra, 2014), and originality or novelty (Christensen & Ball, 2014; Mann & Tekmen-Araci, 2014).

Table 4. Conceptual Knowledge codes.

CODES	DESCRIPTION
AESTHETIC	The way a design has artistic (e.g., visual, auditory, and sensory) appeal or embodies a sense of beauty. Sub-codes include: authenticity (embodies "realness" or authenticity to some idea), simplicity (clean, straightforward, or purity of form), and the aesthetics of form (shape or geometry, color, rhythm, texture, symmetry, contrast, repetition, organic, formal, negative space, variation, tension, juxtaposition, etc.)
COHERENCE	The way a design achieves coherence. Sub-codes include: coherence (embodies cohesion, integration, completeness, or inter-relationships in a system), essence (embodies a personality, philosophy, or has meaning), and passion (embodies the designer's passion).
(UN)PREDICTABILITY	The way a design creates drama or stimulates an unexpected, unpredictable, or counterintuitive experience. In the ID and CHOR context, this code served as an *aesthetic* principle; in the ME context the opposite of this code, predictability and certainty, served as a *feasibility* principle.
FEASIBILITY	The way a design is feasible or possible to achieve. Sub-codes include: easy to afford (cost effectiveness), easy to realize (easy to make, build, coach, perform, manufacture), technologically feasible (achieves technical performance within technological constraints), and feasible within the constraints of the human body.
INTERACTIVITY	The way users interact with or experience a design. Sub-codes include: ergonomic requirements, interactive (easy or practical to use, multi-functionality, adaptability to different situations), and enjoyable (fun, pleasurable, engaging).
NOVEL	The way a design is unique, evolutionary, opens up new markets or meets a future need.

Procedural knowledge codes

Procedural knowledge was characterized as task knowledge (generally applicable techniques or heuristics for accomplishing tasks) and process management knowledge (general approaches for directing one's solution process) (see also Goldschmidt et al, 2014). As shown in Table 5, the task knowledge codes are summarized first, followed by the five process management codes. Task knowledge codes were based on the *Informed Design Teaching and Learning Matrix* (Crismond & Adams, 2012) described earlier. These codes represent nine informed design behaviors as learning goals for students, contrasted with ineffective and inefficient design behaviors beginners are prone to exhibit. The framework was developed for the context of engineering and may emphasize technological investigations but does not prohibit the identification of aesthetic investigations. Process management codes were generated bottom-up from the data using the constant comparison method (Glaser & Strauss, 1967; Ryan & Bernard, 2003), and emphasize the various strategies designers use to manage time (see also Yilmaz & Daly, 2014) and scope, and preserve ambiguity. As with the conceptual knowledge codes, effort was taken to generate codes that could be applicable across contexts.

Table 5. Procedural Knowledge codes – task and process management.

TASK CODES	DESCRIPTION
PROBLEM FRAMING	Coach encourages and/or exhibits problem-framing behaviors to help the student comprehend important features of the problem (e.g., describing or stating how the design should function or behave, reframing an understanding of the problem based on early solution explorations, and delaying decisions until critical framings are grasped). The coach may discourage or counteract behaviors such as treating

	design as well-defined and prematurely attempting problem-solving.
DOING RESEARCH	Coach encourages and/or exhibits doing research behaviors to help the student learn about the problem or how the system works (e.g., information searches, case studies, user research, product dissection). The coach may discourage or counteract behaviors such as skipping doing research and building solutions immediately.
IDEA FLUENCY	Coach encourages and/or exhibits idea fluency behaviors to help the student work with lots of ideas (e.g., divergent thinking, brainstorming, metaphors, analogical reasoning, relaxing constraints to see in new ways). The coach may discourage or counteract behaviors such as working with few or just one idea, which they can get fixated or stuck on or may not want to discard or revise.
DEEP MODELING	Coach encourages and/or exhibits deep drawing or modeling to help the student inquire into how ideas work, function, or could be made (e.g., rapid and low fidelity prototyping, 2D and 3D drawing, modeling, gesturing, multiple representations). The coach may discourage or counteract behaviors such as superficial drawings or models that can't support inquiry or wouldn't work if built.
BALANCE TRADEOFFS	Coach encourages and/or exhibits strategies for helping students judge options and making decisions that acknowledge both benefits and tradeoffs (e.g., describe and attend to both pros and cons, articulating design values, making selections that take into account multiple criteria). The coach may discourage or counteract behaviors such as attending only to pros of favored ideas and cons of lesser approaches.
VALID EXPERIMENTS	Coach encourages and/or exhibits conducting valid experiments to help students substantiate design decisions (e.g., investigate and redesign cycles, gather advice from others, optimization studies). The coach may discourage or counteract behaviors such as doing few or no tests on prototypes, or running confounded experiments that cannot provide useful information.
FOCUSED DIAGNOSTICS	Coach encourages and/or exhibits focused diagnosis to help students identify and attend to problematic aspects, and propose ways to improve, fix, or build on them. The coach may discourage or counteract behaviors such as unfocused and non-empirical diagnoses of designs that cannot provide useful information for improvements or fixes.
ITERATIVE	Coach encourages and/or exhibits doing design in a managed way where ideas are improved iteratively through feedback (e.g., time to iterate, being open to revisit original intentions). The coach may discourage or counteract behaviors such as designing in haphazard ways where little learning gets done, or do design steps in a linear order. There are two variations of iteration: local or micro iterations thatand global or co-evolutionary iterations that bring solutions and problem framings into greater alignment.
REFLECTIVE	Coach encourages and/or exhibits reflective practice (e.g., listening to "situation's backtalk", keeping tabs or self-monitoring behavior, assessing the value or relevancy of design strategies, asking subjective questions). The coach may discourage or counteract behaviors such as tacit designing with little self-monitoring or not being open or willing to reflecting on past decisions.

PROCESS MANAGEMENT CODES	DESCRIPTION
COMPLEXITY MANAGEMENT	Coach encourages and/or exhibits strategies for managing complexity (e.g., scope of work, feasibility within a timeline) to help a student be successful in their process.
RISK MANAGEMENT	Coach encourages and/or exhibits strategies for anticipating and addressing risk (e.g., playing it safe, meeting deadlines, giving clients the illusion of choice, ways to communicate designs in a persuasive manner) to help a student be successful in their process.

TIME MANAGEMENT	Coach encourages and/or exhibits strategies for managing time to help students complete tasks successfully within a prescribed timeframe.
MULTIPLE PERSPECTIVES	Coach encourages and/or exhibits plurality of perspectives including disagreements and agreements to support students in developing their own perspective and a tolerance and appreciation for ambiguity.
SUGGEST DON'T TELL	Coach encourages students to exercise and develop design judgment under ambiguous circumstances. When coaches make suggestions they explicitly encourage students to make their own decision.

3.3 Analysis process

Tiago and Mel applied *a priori* teaching technique codes (Tables 2 and 3) to the data first, annotating paper transcripts while watching videos in their entirety and attending to visual cues and pauses. Based on video data, they modified the code set to the versions summarized in Tables 2 and 3 until the code sets and their application represented full agreement across both coders. This resulted in an extended codebook with examples of coaches' use of teaching techniques across the selected dataset, which is not provided in this paper. After a full-team discussion of the evolved *a priori* teaching technique codes, David and Robin generated the emergent conceptual knowledge code set (Table 4) and the emergent process management strategy codes (Table 5), and tested the *a priori* task strategy codes (Table 6) using a similar paper-based process. This resulted in an extensive codebook with examples of each code across the selected dataset, which was then discussed as a team and modified to improve clarity, accuracy, and simplicity. We performed our final coding on Dedoose, a web-based computer-assisted qualitative data analysis software (CAQDAS) tool that simplified the search for code applications and co-occurrences. Because we allowed overlapping codes, we were able to characterize interactions (co-occurrences) among teaching techniques and content knowledge to discern a broad array of design PCK patterns. After Dedoose coding concluded, the team collaboratively identified exemplars of codes and excerpts of potential design PCK patterns. We identified 31 notable excerpts: 5 of Todd, 6 of Sheryl, 6 of Anita, 10 of Elena, and 4 of the Robot Fish Team team. The results presented in the next section were drawn from this set of 31. The final decision for inclusion in this paper was based on the extent to which a design PCK pattern was representative across the dataset, illustrated similarities and differences associated with the review context or structure, and could be reliably supported with evidence.

Researcher's positionalities

Our personal histories as scholars and designers shaped our approach to this study in ways that are important to make transparent. We are all US-based, native-English speakers with extensive design review experience as students and coaches. We are all engineers and qualitative-focused engineering education researchers with strong relationships to the arts; Robin is a mixed-media artist, Tiago a musician, Mel a (deaf) dancer, and David a theatrical designer.

4. Making design PCK visible

PCK refers to the subject-matter specific teaching approaches to help students learn. We conceptualize design PCK as the use of teaching techniques (drawing from cognitive apprenticeship and teaching as improvisation coding schemes) to convey design knowledge (drawing from conceptual and procedural knowledge coding schemes). In

this section we illustrate the following patterns of design PCK observed across variations of contexts and design review structures:

- Scaffolding to help students articulate their reasoning or reflect on their decisions
- Driving for meaning and guidance – instructor and student-directed approaches
- Breaking the 4th wall to create a teaching moment
- Suggest don't tell to let the student figure it out

In describing these patterns, we use *italics* to signify the application of codes from Tables 2 through 5.

4.1 Scaffolding to help students articulate their reasoning or reflect

During design reviews students often explain or justify their reasoning or current understanding of an issue. This is an example of the cognitive apprenticeship technique of *articulating*, where the coach encourages the learner to explain and justify their process so the coach can check the reasoning behind their performance. We observed multiple instances of coaches using *scaffolding* to assist a learner in *articulating* their reasoning by directing them towards a focal point that is a subset of a larger task, such as: concerns regarding *coherence*, *usability*, or *feasibility* in *problem framing; deep modeling* how a solution works or could be made*; focused diagnostics* to troubleshoot solution performance; and *reflecting* on *time management* strategies. In some of these cases, the coach partially completed the task to enable the student to pick it up at an easier point. The following excerpts describe the ways coaches' *scaffolded articulation* to convey design concepts and strategies across the three contexts.

ME – What prevents the fish from taking a nose-down attitude?

Many examples of *scaffolded articulation* are evident in the ME conceptual and final design reviews through such phrases as "Hold on just a second…" and "I wanna go back just [a] second…" which serve to focus attention towards a specific area of inquiry. A short example is provided below. It occurred during the conceptual design review close to the 18:00 timestamp. This excerpt begins with the instructor, Nelson, using *scaffolding* to convey the design strategy of *focused diagnostics*, focusing students' attention on the technical performance (*feasibility*) in controlling the fish's movement in the water. Doug, a student on the team, responds by *articulating* how they used multiple preventative measures to ensure that the fish maintains a balanced position in the water: adjusting the moment on the caudal fin to balance the fish so the nose doesn't point down, and if the nose does point down the moment on the pectoral fins can correct for the center of gravity. The example concludes with the instructor acknowledging Doug's *articulation* and giving an indication to continue the presentation.

Nelson:	Hold on just a second. I wanna ask – I wanna go back just second. What prevents the fish from um taking a nose-down attitude when it's just going horizontal?
Doug:	We have two preventative measures. Ah, the caudal fin can adjust vertically along the back, so we can change that moment along there which, which would ideally balance so that would have no nose down. And even if you initialize it and it ends up having some form of nose down, the pectoral fins are in front of the moment, created by – or the center points or center of gravity so that create a moment.
Nelson:	All right, okay. (Yori continues on with her part of the presentation)

A more extensive example occurred during the whole class final debrief where the directed students to reflect on their experiences with *time management*. The instructor's *scaffolding* is expressed in the form of structured questions that guide the class to *articulate* and *reflect* on how and why they didn't stay on schedule. This example is described in depth in another section as an example of *breaking the 4th wall* to create a teaching moment, and illustrates the ways coaches combined multiple teaching techniques to convey design knowledge.

CHOR – What does the title have to do with your piece?

While many examples of *scaffolded articulating* occur in the ME context, in part due to the formal presentation structure that requires students to articulate the reasoning embodied in their designs, there were also examples in the other contexts. For choreography, *scaffolded articulation* was evident through coaches' questions such as "That's an interesting choice, why do you want to do that?" For example, during Anita's second design review one of the five coaches directs Anita's attention to the reasoning behind the title for her design, "Purlicue". The excerpt below, which occurs at the 14:00 timestamp, begins with Mia using *scaffolding* to draw attention to a potential lack of *coherence* between the meaning of the title and the *aesthetics* and *essence* of the hand gestures in the piece, as well as her sense of how the audience may experience the title (*interactivity*). Anita responds by asking Mia if she should "talk about it", and Mia encourages her to *articulate* her reasoning.

Mia:	When you told us your title you said what it meant and so I wondered what the title has to do with your piece. Because I'm just, okay, all right, so is it the tension, is it the spatial juxtaposition or the relationship, because students –.
Anita:	Would you like me to talk about it?
Mia:	Yeah, because I'm just gonna tell you, my students won't know what that means, and so they'll whip out their phones and they'll look up this word and then they're gonna see it at the dictionary and they'll just space the distance between their thumb and their forefinger and then they're gonna go, hmm. So I was just curious why you chose this title.
Anita:	I mean for me, like this, this idea that first of all there is a definition for this word and to me this was very gestural and articulate, like looking at the distance, you know, 'cause you have to be very precise and measuring that, and that has something to do with the hands and the hands are something that I'm working with. And I'm looking at the word purlicue and the way you write it and the way the letters are formed and the way you say it on your tongue is very – you know, it has that rounded flowy-ness to maybe that –
Mia:	Kind of feminine.
Anita:	Yeah, it sort of fits into the aesthetic that I have in my head for my piece. And so it sort of like, you look at it and it makes sense, and if you like were told to like look it up, it was like, oh, this is like a thing, you know, this is like a thing, this is a thing even though it doesn't – you don't use it, you know, you don't measure things in purlicues but it's a thing. So.

Anita explains how the intentionality of the title embodies a gestural *aesthetic* that emphasizes the use of the hand as form of measurement or precision, and the "rounded flowy-ness" of the word itself in terms of "the way the letters are formed and the way you say it on your tongue." Mia expands on this idea (using the improvisation technique of

Yes &) by connecting Anita's explanation to a feminine *aesthetic*. Anita uses *Yes &* to build on Mia's comment by connecting how this *aesthetic* has *coherence* with the *essence* of the idea "in my head for my piece. And so it sort of like, you look at it and it makes sense." She then *articulates* another aspect of her reasoning, emphasizing the *authenticity* of the concept, that "this is like a thing" even in you "don't measure things in purlicues."

ID – Now explain that…

In the ID context, *scaffolded articulating* often began with the instructor asking questions to focus students on design strategies of *problem framing* or *balancing trade-offs* to select among a group of alternative designs, *deep modeling* to think through ways a design could be made to achieve a particular goal, and *focused diagnostics* to troubleshoot design performance. Similar to the CHOR context, the informal one-on-one structure appeared to support combinations of *scaffolded articulating* with the teaching as improvisation technique of *Yes &*, where the coach affirms a learner's assertion or work, creating the conditions for coach-learner collaborative co-designing.

This example occurred during the first review around the 6:00 timestamp. It illustrates Gary using *scaffolded articulation* in combination with *Yes &* to focus Todd's attention on two inter-related tasks: picking his top five designs and imagining how one particular design could be made. It begins with Gary asking Todd to identify his top sketches: "if you had to pick say five or six, which would be the ones you want to develop?" Gary adds, emphasizing the strategy of *suggest don't tell*: "you're [Todd] the final decision-maker on this. I'm just here to…help you along if I can." Gary *models for* Todd ways to justify his top choices in terms of such principles as *novel* and *aesthetics* of simplicity and form: "keep it simple. Play up the forms. Look at what the competitors are out there. Do something unique." He also encourages *complexity management*, telling Todd to "keep in mind the more complex you're gonna be…you've got a week to do better line drawings and presentation boards and so we can then narrow that they'll pick the one." Todd's first choice is a "stacking idea" but notices that this isn't really a stacking idea but that it could be and that it "might look cool if they were all stacked." Gary affirms (*Yes &*) Todd's idea and restates the idea of stacking as an *aesthetic* choice that could create tension, while building on the idea in terms of other *aesthetic* choices such as using different materials and colors and being *novel*. Throughout this exchange, much of the reasoning being made visible is Gary's by *modeling* for Todd important design strategies and ways to judge designs.

This dynamic of Gary *driving* the conversation shifts when Todd presents a third option, based on the stacking concept. Here Gary *scaffolds* Todd to *articulate* how that design could be made: "No, now explain that. How would – what would use for mechanical, would this be Velcro or something, or what". Todd explains that that he's not sure he wants "all of them to be able to pull off" but maybe only the "big one, like that should be the one to pull off and sit on it." Gary again *scaffolds articulating* by asking Todd to *deep model* a *usability* issue: "Now keep in mind you pull it off, it's gonna – where's it gonna go? Is it gonna go down pretty much, stand on it." Todd explains that the piece

could then become a form of foot rest, but notes that "it's kind a rough idea" suggesting that he the details of the idea are not fully formed.

Discussion

This design PCK pattern of *scaffolding articulation* involves the coach directing the learner's attention to an aspect of their design or plan, encouraging the learner to articulate their reasoning for their decisions or engage in particular design strategies. This pattern was prevalent across all contexts and review phases in this dataset. Cardoso et al (2014) also observed the ways coaches helped students articulate their ideas and Cardella et al (2014) observed the ways the ME coach asked students questions to help them seem what was missing in their design or design process.

72% of the 47 instances of coaches asking students to *articulate* their reasoning involved *scaffolding*. Instances of *articulation* also frequently co-occurred with *modeling* where coaches made visible their own reasoning or shared examples from their own experience, with *Yes &* where students and coaches collaboratively co-design, and with *breaking the 4th wall* where the coach proactively guides students towards effective design practice. From a design PCK perspective, these combinations of techniques indicate content-specific teaching strategies coaches used to interpret students' emerging or incomplete thinking, provide examples to students to support deeper understanding, or guide the student towards a new task that may deepen students' learning.

From a design thinking perspective, this pattern creates opportunities for making visible the "how" and the "what" of design thinking: *scaffolding articulation* was frequently used to focus attention on issues of *aesthetics* and *feasibility* in relation to *problem framing*, *deep modeling*, *focused diagnostics*, *reflective practice*, and *time management*. While this pattern is not limited to this set of design thinking concepts, these findings indicate the kinds of knowledge coaches in this study were likely to stress with their students, which may also indicate the kinds of issues coaches' anticipate students may find difficult or the kinds of misconceptions or inefficient habits of mind coaches' try to counteract with their students.

From a learning perspective, focusing students' attention on potential design problems and supporting them in explaining their reasoning may help students reflect on their tacit knowing and make their evolving design knowledge visible and explicit (Crismond & Adams, 2012), and move beyond surface level understandings to inquire deeply into their own designs in more principled ways (Chi, Glaser & Farr, 1988). Similarly, scaffolding or limiting the field of view to a specific sub task may help learners navigate complexity (Dreyfus & Dreyfus, 1985).

Evidence of this pattern across contexts and review structures suggests that different review structures support different opportunities for *scaffolding articulation*. In the ME context, the formal presentation slides that detailed explicit design decisions appeared to provide an entry point for the coach to probe deeper into student's reasoning and scaffold further inquiry. In the ID and CHOR contexts, the multiple prototypes (dance movements, sketches, foam models) and informal structure provided entry points for coaches' to ask questions about decisions embodied in work-in-progress and help

students articulate and assess their own reasoning. In addition, the informal individualized reviews in the ID and CHOR contexts were more likely to combine *scaffolding articulation* with *Yes &* techniques of collaborative co-design.

4.2 Driving for meaning and guidance

We observed two forms of *driving* for meaning and guidance: coaches driving the conversation and students driving the conversation. The situation of coaches *driving* the conversation is derived from the teaching as improvisation code set, where a coach takes control of the interaction dynamic to help students see and consider options for addressing a problematic situation, either in the present or anticipated in the future. The situation of students *driving* the conversation is derived from the cognitive apprenticeship code set, where a student uses *bounding* to direct a coach towards a subset of the task, focusing attention on the student's desired next step. In this way, *bounding* is the role reversal of *scaffolding*: students explicitly seeking guidance from coaches via directed *coaching* and *modeling*.

In the selected dataset there were 19 examples of coaches *driving* and 19 examples of students *bounding*. In this section we provide examples of students *bounding* across all three contexts, and only two examples of coaches *driving*. While *bounding* was observed in all contexts, Sheryl in the ID context enacted over 80% of these. There was only one instance of *bounding* in the ME context, and the only examples of *bounding* in the CHOR context involved Anita, who had prior experience with designing choreography and this set of coaches. *Driving* was only observed in the ME and ID contexts, and often co-occurred with other techniques as part of pattern of "*breaking the 4th wall* to create a teaching moment", which is described in the next section.

ID – Student bounding: Do I need my prototype to function?

An illustrative example from the ID context occurred during the "looks like" review between Gary and Sheryl, where the focus is helping the student to develop a full-scale prototype that can communicate form and function such as *aesthetics*, *novelty*, and ease of use (*interactivity)*. Prior to this segment of the transcript, there was a high frequency of *Yes &* collaborative interaction with Sheryl describing aspects of her design and Gary building off of Sheryl to suggest options and ideas. Sheryl's final design is a multi-person and multi-functional "impromptu seating" that in its "open" configuration is a table with cushions and in its "closed" configuration is a large ottoman or coffee table. To achieve this transformation, Sheryl uses a telescoping rod that lifts and then locks the top in the "open" configuration. The design of this telescoping rod has been the focus of a large portion of the review session.

Around the 11:00 timestamp, Sheryl uses *bounding* to direct Gary's attention on scope of work expectations to request guidance on *managing complexity* on the extent to which her prototype should be fully functioning. As shown in the excerpt below, Gary *models* how he would reduce complexity by not making the prototype "too difficult". Gary supports Sheryl's idea for limiting complexity by only showing how the telescoping could rod move, but not providing a working model of the locking mechanism. To reduce the potential *risk* of breaking the prototype Gary encourages Sheryl to find a

buddy who can model the *usability* of the telescoping rod, so it communicates functionality: "it looks like it's functional but it really isn't."

Sheryl:	Mm-hmm. Um, I guess my last question then is when I do that, do I need to make it more of a prototype? So if I pick up the table, do I need a function for it to actually lock there?
Gary:	I wouldn't, that's too difficult. I would –
Sheryl:	Can I just not do that? *[Laughs]* Just say, "Look, it moves."
Gary:	I would say that. I'd say, "Listen," and you lift it up and someone puts in your four sections, someone like your, a demo -
Sheryl:	A buddy?
Gary:	Yeah, buddy to help you out on this and don't let anyone else touch this, watch this for me. So, it looks like it's functional but it really isn't, so you need to explain that –

The discussion then shifts from Sheryl's *bounding* to Gary *driving*, where he *coaches* Sheryl to *manage her time* on this aspect of her design, focusing on the telescoping rod design since he perceives the other pieces will be "relatively easy*"* to make *(feasibility)*. At the 20:00 timestamp, Gary *breaks the 4th wall* to *coach* Sheryl about how efforts to *manage complexity* should not conflict with fulfilling the purpose of the "looks like" prototype in communicating an authentic *aesthetic* of form and function: "But make sure, when it's finished it's the real materials and all of a sudden, it takes it out of ah somewhat real."

A similar conversation occurred with Todd although it did not involve *bounding*; rather, Gary used *driving* in combination with *scaffolding-modeling-coaching* techniques to guide Todd on ways to *manage complexity*, *risk*, and *time*. This illustrates how the same coach used different techniques to convey the same aspects of design knowledge, suggesting that coaches' shape or adapt their design review interactions based on perceived student needs or abilities.

CHOR – Student bounding: Can I ask a general question about the tempo of the piece?

An illustrative example from the CHOR context occurred during Anita's second review around the 25:00 timestamp when most of the coaches had completed their feedback turns. Anita's use of *bounding* sets in motion a combination of techniques with coaches working together (*Yes &)* to provide specific *coaching* and *modeling* of their reasoning about *aesthetic* choices that contribute to creating a *coherent* experience, while preserving ambiguity (*suggest don't tell*) by encouraging Anita to *reflect* – as the choreographer – on her choices and how they achieve her goals. As shown in the following excerpt, this begins with Anita using *bounding* to break the dynamic of the turn-taking review structure and direct coaches to providing feedback on the tempo (*aesthetics*) of her design: "Can I ask a general question about, for you, notice or feel anything about the tempo of the piece…it's lagging or it's just like for me, when I keep watching it I feel like it's…but I don't know how fresh eyes see it." Sophie uses *coaching*, to note that Anita's choice of tempo felt "like you were doing that on purpose", and Hannah concurs:

Sophie:	I felt like you were doing that on purpose.
Hannah:	Yeah.
Anita:	Okay.

Hannah: I think that's the thing.
Sophie: Stacy Joyce kinda did that thing, can you stay with something longer than what's comfortable –
Anita: Duration
Sophie: - that's what feels like you're doing to me, you're making me stay longer than I want to but they're so purposeful I mean so focused.
Hannah: That's sort of part of that why it feels ritual like.
Anita: Okay. So that's not boring.
Carol: Uh-uh.
Hannah: No, I'm staying engaged.
Anita: Okay.
Sophie: But it feels like you're doing something there with that choice.
Hannah: It's in a specific world and you're staying in that world, and so it feels okay, it doesn't feel to me like oh, this is boring or something. I don't know.
Sophie: As a choreographer yeah, yeah. It's not boring. As a choreography where you kind of have to – when you get like that you have to ask that question and my –
Anita: Yeah.
Sophie: This is my choreography and I can get tired watching this with what the choreography wants to do.
Anita: Yeah.
Sophie: Or does it, or does it really need something there.
Anita: Right. Okay, cool. Thank you.

Sophie continues *coaching* by making a connection between Anita's tempo and another choreographer's intentionality with staying "with something longer than what's comfortable." Anita uses *Yes &* to revoice this as "duration", and Sophie builds on this to explicitly speak to the *coherence* between the tempo and the purpose or *essence* of the design: "that's what feels like you're doing to me, you're making me stay longer than I want to but they're so purposeful…" Hannah uses *Yes &* to expand on this feeling of *coherence*, connecting Anita's choices with tempo to a "ritual like" *aesthetic* she is experiencing. Anita revoices what she heard from Hannah and Sophie, which appear to alleviate her concerns about tempo: "Okay. So that's not boring." Carol, Sophie, and Hannah respond with affirmations. Hannah and Sophie then *model* their reasoning, explaining how the intentionality experienced in the design makes it engaging. For example, Hannah emphasizes how the tempo provides *coherence* by linking a feeling of intentionality to her level of engagement: "It's in a specific world and you're staying in that world, and so it feels okay, it doesn't feel to me like oh, this is boring or something." The excerpt ends with Sophie *coaching* Anita to *reflect*, as a choreographer, to "ask that question" about "what the choreography wants to do…or does it really need something there." In other words, encouraging Anita to find and use her voice as a choreographer (*suggest don't tell*).

ME – Student bounding: We have a question

The excerpt below demonstrates the interplay between *bounding* (on the part of the students) and *modeling* (on the part of the instructor Nelson). It begins with Joshua using *bounding* to direct the instructor to provide feedback on ways to fabricate the PVC pipe that will house the motor and sensors that control the fish's movement in the water. Nelson responds by *modeling*, thinking out loud how he would either buy threaded caps or machine the PVC including the O-ring element. Similar to other examples, the

instructor *suggests but doesn't tell* students what to do, by identifying options (making or buying the part) and providing information on the relative difficulty associated with each option.

Joshua:	We have a question for like actual threading the PVC. Do we have the dies here or is that something you –
Nelson:	No, you can buy the threaded caps.
Joshua:	Oh, yeah.
Nelson:	The machining puts the O-ring in it.
Joshua:	Okay.
Nelson:	So you don't have to do it. Or you can make 'em if you wanted to. If you want to make really light ones, you can, you could actually turn 'em. They're not very hard. Since you got a machine plan for that O-ring, a slot, then you might want to just machine. It'd be – it, it would not be hard.

ME – Coach driving: You're gonna need an O-ring

This example illustrates the version of a coach *driving* for meaning and guidance. Most examples of this pattern involve the coach "*breaking the 4th wall* to create a teaching moment", a pattern described in the next section. In this example, the instructor uses *driving* in combination with *coaching-modeling-scaffolding* techniques to direct students' attention to an issue that will impact two *feasibility* issues: technical performance and what Nelson later refers to as "design for manufacturing".

The excerpt below begins approximately 19 minutes into the conceptual design review with the instructor taking control (*driving)* and *breaking the 4th wall* to *model focused diagnostics* on the design of the PVC tube that houses the electronic system: "Okay, back into the PVC tube…we're probably gonna need an O-ring seal…when you put that together." Yori affirms the instructor's point, but counters with an assertion that the seal is "already tight". The instructor uses *coaching* to repeatedly draw attention to his concern that the PVC tube needs to remain watertight (*feasibility*). Finally, he uses *scaffolding* ("You're gonna want to get it back apart, right?") to help students make a connection between the need for a watertight seal (*feasibility*) and the need to continually access the electronic system (*easy to realize*) to improve system performance. At this point, it is not clear if the students have internalized the instructors coaching.

Nelson:	Okay, back into the PVC tube that you put electronics in, we're probably gonna need an O-ring seal when we – it's when you put that together.
Yori:	Yeah it's are already tight.
Nelson:	You're gonna need an O-ring seal probably.
Yori:	We'll like with the cover, seal the end, the end, one end of the cover -
Nelson:	You're gonna want to get it back apart, right?
Joshua:	One end, yes.
Yori:	One, yes. We seal with one end, and then the other we can open.

Approximately three minutes later, the instructor *breaks the 4th wall* during Yori's description of how the PVC tube houses the electronic system to again *focus diagnostics* on the need for an O-ring: "Okay. So what I was saying is on that cap that's screwed on, you're probably gonna need an O-ring." Yori affirms this feedback and continues the presentation. The issue of the O-ring isn't revisited until the end of the presentation almost twenty minutes later.

Nelson: Yeah, I got, I got two concerns. One is the water tightness of the, ah, PVC. I think you need to make sure you got O-ring seals because you're gonna have to go in and out of that a number of times.
Joshua: Okay.
Nelson: And so using RTB or, ah, silicone. Ah, it won't be too, ah, efficient for you if you have to pull it off –
Joshua: Redo it.
Nelson: - and then go in there and then reseal it and wait for it to dry and then pull it off.
Joshua: Right.
Nelson: So I, I just, just use O-rings on the caps.
Joshua: Okay.
Nelson: Then you can just take it apart and do something, screw 'em back on and you're ready to go.

As shown above, Nelson takes control of the conversation (*driving*) and uses *denial* and *modeling* to help students make sense of his concerns about the *feasibility* of using silicone to maintain a watertight seal. He suggests students *iterate* by incorporating an O-ring that will allow continual and efficient access to the electronic system (*easy to realize*). Joshua appears to understand Nelson's coaching by finishing the instructor's statement of "it won't be too, ah, efficient for you if you have to pull it off" with "Redo it", suggesting that he accepts the need to *iterate* on the current design, which requires continually resealing the PVC tube with silicone.

ID – Coach driving: Always do something safe

There were multiple examples in the ID context in which Gary used *driving* in combination with *breaking the 4th wall* to encourage particular design thinking concepts and strategies. The following example illustrates the way Gary *coaches* and *models risk management* associated with client expectations such as including a safe design to give "the illusion of choice". This example occurred after the 4:00 timestamp in Todd's first design review. By this time Todd had presented most of his initial ideas as sketches, and Gary takes control (*driving)* to direct Todd's attention to strategies for selecting among a set of ideas. Gary *models* his reasoning for how he would select initial ideas within a *problem frame*, highlighting the importance of designing for the future *(novel)* to help the client imagine the "next level" of "traditional ottomans" and linking this to reasons why a customer would buy his "design versus what's already out there now" – such as *novelty*, *aesthetics* of form, and user experience (*interactivity*) by creating "a nice little surprise" (*unpredictability*).

Gary: So as the designer, ah, National wants you to come in and – this is what I perceive that they want you…If you were the designer from one of those other kinda traditional ottomans, what would the next level be? Especially with National coming in behind the first, first group, ah, they can't be a me, too. So what's gonna attract whatever you design, a customer from buying your design versus what's already out there now. So what would be the next level? So it's color. It's form. It's dynamics. It's like you said, to me that one where you pulled the leaf down and all of a sudden, you got, you got a neat little surprise.
Todd: Mm-hmm.
Gary: So that, that's what they're looking for, something, something new and exciting. Always do something safe. Um, *[clears throat]* 'cause sometimes you never know how, what people are, how, who you present to, but there's, there's a good reason for the safe, too, is

> what it does if you don't have the option – I call it the illusion of choice. If you don't have that option and they see all you're really extreme, they, they don't have anything that's gonna ground 'em to, to why, ah, why they like what you like. So – they like. So if you give them an option, you can fall back on this, but the, the goal as the designer. So the reason you invited us here, invited us to this project, we're working in innovation. This is where we feel, feel it's going next.

As shown above, Gary *breaks the 4th wall* to communicate a strategy for reducing *risk* and increasing the potential for Todd to gain the attention of the client: "always do something safe". He goes on to explain, *modeling* his design thinking and professional experience, with a strategy of creating "the illusion of choice" where the client sees variations in a designer's work from a "safe" design to the "really extreme". He explains that this helps the client make sense of a designer's body of work, to "ground 'em to, to why, ah, why they like what you like. So – they like." This provides opportunities for a designer to gain the client's attention as well as a safe alternative to fall back on if other alternatives are too far outside the client's perspective. He concludes with how this *risk management* strategy is essential when a designer is being asked to work "in innovation". Underlying this strategy appears to be an implicit aspect of Gary's experiential knowledge about how gaining a client's attention may involve managing the tension and ambiguities of *multiple perspectives* involved with helping a client gain a novel competitive edge (what Gary describes as a "me, too") while remaining consistent with a client's design perspective or brand. As a note, a similar conversation occurred with Sheryl.

Discussion

The design PCK pattern of *driving* for meaning and guidance took two forms: (1) coaches taking control of the review dynamic to help students make conceptual connections or see fallacies or limitations in their design thinking, and (2) students taking control to direct a coach towards a subset of the task and ask for situated guidance for a desired next step. For the version of coaches *driving*, the examples illustrate patterns evident across the selected dataset: a high co-occurrence of *driving* with techniques of *modeling* (making reasoning visible), *scaffolding* (directing attention to a problem and offering suggestions), and the design PCK pattern of "*breaking the 4th wall* to create a teaching moment" (such as offering strategies to help students manage risk and time). In the broader dataset, Howard and Gray (2014) and Cardoso et al (2014) observed coaches driving much of the complexity of the design review, and McDonnell (2014) observed Gary's "prescriptive instruction" as driving and modeling process management strategies.

From a design thinking perspective, *driving* was often used to encourage design strategies of *problem framing*, *doing research*, *deep modeling*, *focused diagnostics*, and *iteration* and to address issues of *feasibility, usability,* and *complexity, time and risk management.* For the version of students *bounding*, coaches typically responded by *modeling* their own reasoning or design perspective to convey conceptual knowledge of *aesthetics*, *coherence*, and *feasibility*, or procedural knowledge of *focused diagnostics*, *reflective practice*, and *complexity* and *risk management* strategies. For both cases, there was a high co-occurrence of this pattern with the design strategy of *suggest don't tell*.

From a design PCK perspective, the combination of *driving* or *bounding* with *modeling* and *breaking the 4th wall* techniques illustrate teaching strategies used to provide examples to students to support deeper understanding or guide a student towards a new task or new perspective to deep learning. From a design thinking perspective, students and coaches tended to emphasize similar concepts (*feasibility*) and procedures (*focused diagnostics*, and *complexity, time* and *risk management* strategies). These kinds of knowledge were experienced as shared points of concern that may represent fallacies or limitations in thinking, or as opportunities to deepen understanding such as making conceptual connections or broadening the space of alternatives for addressing problematic situations.

From a learning perspective, Sawyer (2004) notes that *driving*, along with *breaking the 4th wall* and *denial*, breaks a constructivist interaction structure and should be discouraged. However, instances of coach *driving* frequently co-occurred with coaches' encouraging students to make their own decisions (*suggest don't tell*). This suggests that while coaches took control of the conversation to proactively address student needs, they also encouraged students to take control of their own design decisions. Also, the technique of *bounding* is not part of the original cognitive apprenticeship literature; it was added to account for observations of students driving a design review conversation and to acknowledge the ways cognitive apprenticeship codes do not explicitly account for a broad range of learner roles.

The *driving* version of this pattern only occurred in the ID and ME contexts, which vary dramatically in their design review structures – the ID context was an informal one-on-one structure while the ME context was a formal group presentation. The turn taking structure of CHOR may be an implicit form of driving since the coaches took formal turns driving the conversation. The *bounding* version was most evident in the ID design context. We speculate that the context and structure of design review conversations as well as the characteristics of the student whose work is being reviewed may facilitate *bounding*. For example, the few instances of a student breaking the formal presentation structure in the ME context to direct a question towards the coach suggests that while students may have felt in control of the content of the presentation (defending their work) they may not have felt in control of the structure of the review or the roles of the individuals within that structure. Similarly, the turn taking structure in the CHOR reviews did not include an explicit "turn" for the students being reviewed. In comparison, the one-on-one informal design review structure in the ID context appeared to have no a set time or interaction structure – interactions flowed to an undefined end point when the student and coach concluded the conversation. This may have created a dynamic where both student and coach felt comfortable with breaking the interaction dynamic. In addition, the extent to which a student would drive a conversation may be related to a student's confidence, level of experience, or competency in being able to shift the dynamic and take agency in shaping the design review conversation. For example, most instances of *bounding* involved Sheryl from the ID context, whereas most instances of *driving* in the ID context involved Todd. The only instances of *bounding* in the CHOR

context involved Anita, who had completed two choreography projects with these coaches.

4.3 Breaking the 4th wall to create a teaching moment

Breaking the 4th wall is from the teaching as improvisation code set. It occurs when the coach breaks the dynamic of a coach-student interaction to communicate an important point such as a concept, ground rule, or strategy that has intrinsic value for the coach or the field of inquiry. This can take the form of a "teaching moment" if it is used in combination with other techniques such as *scaffolding*, *modeling*, and *coaching*. From a design PCK perspective, when coaches *break the 4th wall* they may be drawing on their experiences to proactively address learner's naïve conceptions or misconceptions, or ineffective habits and behaviors that may limit their ability to successful produce and persuasively communicate a final solution. The following examples illustrate the ways *breaking the 4th wall* was used as a situated teaching practice, opportunistically responding to a situation (the ID and CHOR example), and as an intentional practice, intentionally creating a teaching moment (the ME example).

CHOR – Ideas are generative, right?

This example occurred during Elena's second review, between the 13:00 and 17:00 timestamps, and early during Rachel's six-minute review turn, which occurred after Hannah's and Carol's review turns. Here, Rachel encourages Elena to engage in *reflective practice* and *co-evolution (iteration)*, *modeling* why iterations occur and how iterative reflective practice can support greater *coherence* between problem framings and solutions. It begins with Rachel *coaching* Elena on the *coherence* she enjoyed in the cast's performance regarding the *aesthetics* of the hand gestures: "I'm enjoying watching your dancers…I really liked your cast, like the way they are all together…a lot of these gestures that sort of have something to do with like the head or like things coming out of the head or like I'm really enjoying those."

As shown in the excerpt below, Rachel *breaks the 4th wall* to *coach* Elena on the benefits of stepping back to *reflect* on how her current design aligns with her intentions (*coherence* and *essence*), and to encourage Elena to let the design talk back to improve problem-solution alignments (*iterative co-evolution*). She *coaches* Elena that "you're in…your optional situation right now" and how Elena "started with an idea that generated movements…staging and everything" that makes up her current design. She *models* how the situation talks back (*reflective*), suggesting that the early framing and the current version may be out of alignment: "what happens is we work and then we create something and that thing speaks, and I don't think it's necessarily saying like straight your ideas that generated it." Rachel then uses *scaffolding* to focus Elena's attention on the lack of *coherence* she perceives between the problem framing and the current design: "I don't understand what you're trying to tell me and I don't go to the place you started from." In the process she articulates her philosophy as a coach (*modeling*) by explicitly communicating that she is "not advocating" for any particular solution (*suggest don't tell*), but rather encouraging Elena to take this moment to *reflect*, *iterate*, and be "generative". By *breaking the 4th wall*, Rachel is creating a "teachable moment" to help Elena develop as a design thinker that also encourages Elena's agency as a designer.

Rachel: I think you're in – you're your situation, your optional situation right now is that you started with an idea that generated movements and generated your staging and everything. Um, and I think that what happens is we work and then we create something and that thing speaks, and I don't think it's necessarily saying like straight your ideas that generated it. So for me, the optional situation, and then seeing women like half-dressed in underwear, I like I don't understand what you're trying to tell me and I don't go to the place that you started from. And I'm not advocating for you pushing your piece in the direction of the ideas you started from, because ideas are generative, right.

The review continues with Rachel encouraging *focused diagnosis* on a lack of *coherence* with the *essence* of the work: "because these ideas about pulling the clothes may not have anything to do with your ideas about worry, right?" She again encourages Elena to critically *reflect* – to be open to changing her initial "preconceived notions", listening to the way the design wants to evolve (*iterative co-evolution*), and making her own decision (*suggest don't tell*) to either "push it towards" the original idea or "follow the flow":

Rachel: But the piece is maybe calling for that to happen. So you just get to decide, like do I kinda stick and like, and like go into like I want it to be like this, and make changes and push it more towards an original idea or do you flow with like what is happening and go, you know, I can let go of some of my preconceived notions and follow the flow."

Rachel continues to *break the 4th wall* in combination with *modeling-coaching-scaffolding* techniques to encourage *focused diagnostic troubleshooting* on the ways the costumes may be interpreted that impact a sense of *coherence* and *authenticity* in the work. She offers suggestions to help Elena explore her intentions. The excerpt ends with Rachel *coaching* Elena to step back (*reflect*), this time to revisit the *aesthetic* intention (*essence*) of the costumes and how they may be experienced as either a theatrical dance outfit or an abstraction of the reality of being half-dressed (*interactivity*).

Rachel: It is interesting to have this elaborate top with the lacy bottoms. For me, right now, it's reading like a dance outfit. I don't see the like half-dressed thing. If they were wearing shoes and socks pulled up to the knees and like looked a little more like everything is there except the pants, I might go to that theatrical place. Right now I'm in a little more abstract zone. They're barefoot, they're in underwear and barefoot, like um so I just think it's tricky, you know, like what do we – like do you go the theatrical route, do you go whatever, like is there a way to like from here up make them up even more and they've got like the pearly necklace and some earrings and like a scarf, or like, you know, do you like really go crazy up here, um which is just more props and things that could turn into pillows or whatever, you know, and it's like maybe whoa, too much, but um, but yeah, I just kinda wonder about that a little bit."

Throughout this "teaching moment", Rachel *models* her own thinking on how *reflective practice* and *co-evolution* strategies can be difficult and somewhat counterintuitive, but are important aspects of design practice. She ends her review in a way that points to the co-evolution (*iteration*) decisions she thinks Elena needs to make: "So I think it's really hard to step away from your work and just ask it, you know, kinda like, well, what are you doing, already, work, and how can I help bring that to fruition. Because I think it – for me, I think it has a different title than, than how you've got it right now."

ID – Put this in scale

There were multiple examples in the ID context in which Gary *broke the 4th wall* to communicate design concepts and procedures that foreshadowed future concerns. Some of these are associated with other examples presented in this paper. For example, "Coach driving: Always do something safe" focused on *risk management*, and "Student bounding: Do I need my prototype to function?" focused on *complexity* and *time management*. The example below illustrates Gary *breaking the 4th wall* to direct Todd's attention, or *scaffold*, on the ways formalizing the ergonomics of a design (*interactivity*) can have unexpected consequences. This example starts around the 13:00 timestamp during Todd's first design review. As shown below, Gary encourages Todd to "put this in scale" before committing to his top design choices. This is the design strategy of *deep modeling* to inquire into how scaling up the dimensions to meet "ergonomic seating requirements" impact the *essence* of a solution. Gary uses *scaffolding* to direct Todd's attention to ergonomic standards such as seating heights and the process of translating a sketch into a dimensional model using rulers and tracing paper. He then *models* the importance of *deep modeling* early in the process as a way to examine the *coherence* between formalizing dimensions and retaining the *essence* of an initial idea: "'Cause you may lose the essence – design essence and what you're passionate about. Formalizing it may just all go away - ."

Gary: Well, I'd say, see, you've got by this Friday, you've got, you've gotta have – and, again, the next step from this is try to put this in scale.

Todd: Mm-hmm.

Gary: You know, 'cause this – may change all of a sudden, and when you really try to get a, a decent base to it in the – the size so the ergonomic seating requirements, then your height which needs to be from, you know, it could be 16 inches you know, they said 15 to – 15 to 20. So I mean, maybe find something in that range. So, I mean some of these may – again, the next thing you do is you, you, you put this in a format of somewhat of scale, even just doing a – taking your rule or whatever and, your tracing paper over it or transferring that. 'Cause you may lose the essence – design essence and what you're passionate about. Formalizing it may just all go away –

At the 14:00 time stamp, Gary *breaks the 4th wall* to *scaffold* a *time management* strategy of working on the "simple ones first, and the more complex ones later". In the process he repeats how the importance of *deep modeling* can help Todd "find out on your forms whether or not – it's something you wanna work with." Gary provides additional *scaffolding* on *time management* strategies such as giving "yourself a cutoff…a couple of hours" for each idea, and *modeling* on how the "secret of about good design is having a consistent body of time to focus". Gary emphasizes that this is "just a suggestion with your time" (*suggest don't tell*), and *models* his reasoning by explaining how the time cutoff can help Todd assess early in the process whether or not a design is "too complex" (*easy to make or build*), meets the "functional requirements", is *simple*, "still meet my *aesthetic* needs as a designer", and the needs of the client "to bring something exciting into the workplace" (*novel*).

Gary: And you may find out that, you know, in fact, what I would do is I would do the, the easy simple form ones first, and the more complex ones later, and that way – 'cause you're gonna find out on your forms whether or not - it's something you wanna work with.

Todd: Mm-hmm.

Gary: And what I would do, once you decide which ones you're working on, I would spend – give yourself a cutoff. Give yourself say a couple hours on one. This weekend's really important for you on this project, and once you get into – to me a secret of about good design is having a consistent body of time to focus, if things get broken up because of your class load and everything, and you're always stopping and starting –

Todd: Mm-hmm.

Gary: So this weekend is really important.

Gary: So, um, anyway, just suggestion with your time. But, ah, I would take one concept and spend two hours on it, and then just you're gonna find it out at the end of two hours as a, as a designer is this too complex. Have met the requirements? Is it no longer meeting requirements? It's gotta meet the functional requirements first. Keep it simple. Use as much upholstery as you can. Ah, and then this – the final thing is now after all of that, after I scale this down and I looked at this and thought about how this functions, does it still meet my aesthetic needs as a designer? ….So what you're gonna be bringing is excitement and in terms of color. Like art – functional art you can sit on.

After the 16:00 timestamp, Gary *breaks the 4th wall* to repeat his earlier guidance on "put this in scale" that started at the 4:00 timestamp: "put it 'em into height, width, function, and then as designers it still meets your aesthetic needs of, of being innovative." In this teaching moment Gary repeats his *coaching* on the use of *deep modeling* to inquire into the ways formalizing a design retains or loses *aesthetic* or *innovative* qualities. However, this time Gary adds a new emphasis on *iteration* and *reflective practice* as a process of listening to early designs at a time in the overall process where there are still opportunities for change: "And some you may find out you just got along you've gotta change it, which may lead even lead you a better solution, or you may say, listen now, this is wonderful thoroughbred, you know, horse I had designed, now it looks probably like a mule and (mm-hmm) a goat."

ME – So why did you not stay on schedule?

After the student teams completed their final presentations, the instructor engaged the entire class in a debrief session to help students connect attributes of their experience to attributes of professional design practice. This is similar to each individual team debrief in the final design reviews, but more extensive. This example begins around the 3:00 timestamp with Nelson *breaking the 4th wall* to ask a series of questions to direct students' attention to *time management* realities and strategies. The instructor's *scaffolding* is expressed in the form of structured questions that guide the class to *articulate* and *reflect* upon how and why they didn't stay on schedule. As students respond, Nelson uses *Yes &* to affirm students comments and revoice them in terms of *time* and *complexity management* strategies. This process, similar to a Socratic questioning, continues until the instructor shares his perspective, *modeling* a relationship between time management and good design practice and grounding this perspective in his experience in industry.

Nelson's *breaking the 4th wall* begins with drawing attention to the "schedules in the back of your book are red, right?" and then asking, "Why did you do that?" Doug (from the Robot Fish team) *articulates*: "It's very – the schedule's super idealistic, and it's very, very, very hard to keep up with." Nelson acknowledges but also pushes back on Doug's response, encouraging students to reflect on their time management issues: "Ah, that's a

relative point. From my point of view, it's easy to keep up with…Alright, so why did you not stay on schedule? I mean, really." One student, Mark, *articulates* the reason his team went off schedule and Nelson builds on this to *scaffold* deeper reflection on the relationship between *managing complexity* and adjusting or *iterating* on schedules:

Mark:	Well, I know our requirements were a little bit different. Most of our – the hardest part of our project was at the design part.
Nelson:	Yes.
Mark:	The actual building, assembly, and all that stuff, didn't take as long as anticipated, but the design took longer
Nelson:	Did you know that when you went behind schedule?
Mark:	Um, we –
Ellie:	We guessed.
Mark:	We realize as we were getting behind schedule that we were still in that part, and then the next part wouldn't probably take long.
Nelson:	Okay. So that's an – actually, a good reason. If you recognize the complexity of the different phases and you adjust for that, then that's a good idea.

Around the 5:00 timestamp, another student *articulates* reasons why her team got behind in their schedule: "I have to say it was reverse for us because designing wasn't as clear a problem….What happened was we got to the end, and we didn't know – we tried to force the machine to go faster, but you, there's really time constraint on that we didn't know camming was gonna take so long for us. And then actual testing for it, I think people don't put enough time or consideration into that, that it does take a while to put the circuit together. It's not gonna work on the first try. You do need a week or two weeks to really test everything." Again, Nelson uses *Yes &* to affirm and build on the student's reasoning to make visible the ways "we underestimate things…Especially things we haven't done before."

This combination of *scaffolding*, *articulating*, and *Yes &* techniques continues until the 6:00 timestamp, where Nelson *breaks the 4th wall* to *model* his perspective on the nature of professional mechanical engineering practice and the criticality of achieving technical performance (*feasibility*), being able to plan and maintain a schedule (*time management*), and staying within *cost*. He adds emphasis to this point by linking these capabilities to job security:

Nelson:	All right, so what – the three things – you're exactly right. The schedule went red. That's kind of important, and I didn't grade on your schedule being red, because I anticipated that and I want to make this point because I want to s- give you the best service I can for your next job. That's really where I'm going with this. An engineer has responsibilities for three things – in industry. One is technical performance. If you don't get technical performance, you don't have anything you're out of a job, right? That's the same way here. You had to have some minimum technical performance to continue. Secondly, what's – next most important is schedule, and thirdly, is cost. And schedule is the second most important thing because if we stay on schedule or, or ahead of schedule, you contain your costs. Costs are built on the schedule when you, when you lay it out, and if you go beyond the schedule, the costs ex-, ah, ah, go up, and things get really bad. Now in industry, they generally can accept technical performance and on-schedule and over cost to some degree. They can accept that. What they cannot accept is non-technical performance, and what they generally do not accept is going over schedule, because then you – go over schedule and you increase costs. And they usually allow you to do that

> once before they take you out of the equation. So that's a really important thing is just to stay on schedule. Now none of you stayed on schedule. Clear up until the end, essentially. So why did you not correct for that?

Nelson continues this process of *scaffolded articulation* with *Yes &* by asking: "When you saw it went red and you were red for three – two-thirds of the semester, if not longer, why did you not correct?" Kristen *articulates* how "trying to find the balance and time management between our other classes" can make it difficult "to get back on schedule", which Nelson acknowledges (*Yes &*) and then asks, "is that the same answer for everybody?" Chris *articulates* how "each step took exponentially more time and more effort…so now you have all of these components in every single one of those components needs to be purchased or manufactured…assembled. And it just got like bigger and bigger and bigger…harder and harder –." Nelson's completes Chris' sentence using a *Yes &:* "- harder and harder to catch up?" He affirms this experience by acknowledging how "once you get behind schedule, it gets exponentially harder to catch up. That is the norm." This dialogue continues, with Nelson emphasizing the ways problems can cascade and Kristen connecting this idea with her own experience of how "you find one problem, and then another one arises right as you solve that one." This style of interaction ends around the 11:00 timestamp when Nelson *breaks the 4th wall* again to explicitly communicate the intentional learning goal for this debrief:

> *Nelson:* Anybody else? Okay, so here's, here's the issue. When you're in industry, here – we did the way we did it here. And, of course, this is maybe the first time that you had to try and meet a schedule under difficult situations. But in industry, this would not be acceptable. If I was in industry and you were working for me as program manager, you'd only do this once, and then I would not allow you to be in that position again…
>
> So the thing you need to take away from this class, or just two things, one is the process we use, it's one that's generally used in industry everywhere, but with a PDR and CDR, now they call 'em different things, but they're generally used in industry.
>
> And the process we use – so it's a pretty robust process, mission statement, performance criteria, design criteria. It's a very robust process. So it automatically leads you to success – if you follow the process. But the other thing you have to take away from this is you must follow that process within the schedule. Because those are the two things that are going to get you in trouble. If you don't follow the process, you won't get technical performance. And if you don't stay within schedule, you'll be costing me money and I won't allow that to happen a second time.

The key messages conveyed through this *scaffolded* and co-constructed *Yes &, reflective practice* dialogue both ground Nelson's approach to creating an authentic experience for his students and his tacit knowledge regarding critical capabilities central to design practice - *time management*, *complexity management*, and meeting technical performance (*feasibility*) and *cost* requirements. In the process, he makes visible his reasoning for how the "process we use" is "robust" and "automatically leads you to success – if you follow the process." The consequences of not staying on schedule is that "you'll be costing me money and I won't allow that to happen again" and "I will get rid of you and get somebody else." The debrief session concludes with Nelson sharing one of his *time*

management strategies, one he used with the students: "never tell your team working for you what the true schedule is. Always put a buffer in it, and never tell them. Because it is human nature for them to overrun to some extent."

Discussion

This design PCK pattern of *breaking the 4th wall* to create a teaching moment illustrates the ways coaches seek to convey knowledge of design thinking concepts or strategies that for students may be unfamiliar, abstract, counterintuitive, conflict with prior beliefs or conceptions, or difficult to recognize as central to designing and therefore central to becoming a designer. This took the form of a "teaching moment" where coaches combined *breaking the 4th wall* with *scaffolding* (48% of co-occurrences), *modeling* (31% of co-occurrences), and *coaching* (18% of co-occurrences). As noted previously, this frequently co-occurred with coaches taking control of the conversation (d*riving*, 72% of co-occurrences). McDonnell (2014) observed this pattern as a willingness on Glen's part to demystify "knowing how to design" and be the authority in helping students make sense of their design choices and the design process itself.

From a design thinking perspective, coaches used *breaking the 4th wall* to convey or encourage *problem framing* in relation to design intentions such as *coherence* and *aesthetics*; *focused diagnostic* troubleshooting in relation to *aesthetic*, *feasibility*, and *usability* issues; *risk* and *time management* strategies; *iterative* and *reflective practice;* and a *suggest don't tell* perspective. These co-occurrences were evident across the selected dataset and suggest that coaches perceive these particular design thinking concepts and strategies as difficult for students to learn, understand, or use. As such, this pattern of design PCK may make visible a coach's prior knowledge regarding student misconceptions, inefficient habits of mind to which student's are prone, and difficulties students may encounter both in the moment and down the road after the design review has concluded. For example, when Rachel broke the 4th wall with Elena, she was drawing attention to the ways reflective practice and iteration can bring problem framings and solutions into greater alignment; a design thinking concept that students have difficulty understanding or valuing as effective practice (Adams & Fralick, 2010; Crismond & Adams, 2012).

We observed two forms of this design PCK pattern: situated and intentional. Just as designers use opportunistic and flexible strategies during design (Ball & Ormerod, 1995; Radcliffe & Lee, 1998; Visser, 1990), design coaches appear to be opportunistic and flexible in their approach to coaching. This provides evidence of the utility of the teaching as improvisation framework for characterizing design PCK during design reviews. Most of the observed *breaking the 4th wall* examples could be characterized as times when the coach was opportunistic and adaptive "in the moment" to provide *scaffolding*, *modeling* or *coaching* on a particular issue or planning process. In contrast, the ME example was an explicit and intentional effort on the part of the coach to communicate issues (via *modeling* and *scaffolded articulation*) that have intrinsic value for the coach and the coach's perception of the field of mechanical engineering design (e.g., *time management*, performance *feasibility*, and *cost*). Lande and Oplinger (2014) described this as a Socratic dialogue in which the coach "pulled along" the students to understand design concepts associated with time management. In terms of similarities

and differences across contexts, this pattern was evident and prominent across all contexts.

4.4 Suggest don't tell to let the student figure it out

One common coaching strategy across the contexts involved coaches encouraging students to make their own decision (*suggest don't tell*), by using *scaffolding* and *coaching* with *Yes &* to draw attention to potential misalignments between design intentions and design solutions, offer suggestions on ways to resolve these misalignments, and engage in collaborative design with students yet ultimately leave the decision with the student.

A unique aspect of this pattern occurs in the CHOR context where there are multiple coaches, each with a different subjective eye or perspective. In some cases the coaches may agree, using *Yes &* to expand upon and complement *multiple perspectives*. For example, Mia builds off of Carol's comments during Elena's first review to provide feedback on the linear progression in her piece: "Um, and just to piggyback what Carol was just saying about the sleep thing is that it's almost like they're dreaming about sleeping like they're going through their workday and like 'I wish we could go home and take a nap' and so if your piece is going to have a linear progression it would totally work". In other cases, coaches may use *Yes, but*, a derivative of *Yes &*, to provide a perspective others did not talk about. For example, during Anita's third review Rachel provides an alternative perspective that highlights how she focused on aspects that were different from the other coaches: "I just wanted to add that I realize that I haven't really haven't look(ed) at them as women at all…they're wearing leotards and all that stuff and so I don't look at them as women. I categorize them as dancers more…think of this as a form piece pretty strictly just to put that out there." Coaches may also use *No, but* to offer a conflicting perspective that can co-exist among multiple perspectives. As an example, during Anita's second review Sophie disagrees with the other coaches' interpretations and adds her own perspective: "I did, I did not see a secret. Just to put it out there, I was in a little more abstract place."

Overall, for this pattern of design PCK the use of *suggest don't tell* and *multiple perspectives* in combination with *scaffolding*, *coaching*, and variations of *Yes &* appeared to support coaches in guiding students to move forward while preserving ambiguity as they encouraged students to make their own decisions.

CHOR – Is it a subway?

A brief illustrative example of the ways coaches combined *suggest don't tell* with *scaffolding*, *multiple perspectives* and variations of *Yes &* to *focus diagnostics* on a problematic situation and offer suggestions occurred in Elena's first review around the 6:00 timestamp during Carol's turn. As shown in the excerpt below, Carol uses *coaching* with *Yes &* to affirm, "this clump, I love how it's evolving", and then *scaffolding* to direct Elena's attention to her confusion regarding the hands and *suggesting* that she "play around with different hands".

Carol: So it's like yes, I love this clump, I love how it's evolving – but it's like I don't get what that means so maybe a little more work on that. Um, play around with different hands, um, so what is it to you? Is it subway?
Elena: Yeah, it's subway.
Carol: Then maybe it's how their weight is…um how they're…
Hannah: They need to go on the subway.
Carol: Yeah, there you go.
Rachel: Like a loop your hand ends up more like this, than this. Like look at my wrist right, instead of this.
Hannah: Yeah, it's more round

Here, Carol is referring to a hand gesture that appears to be portraying the ways people hold onto the ceiling strap when standing in a bus or in a subway. When Carol asks, "is it a subway?" Elena affirms, "it's [a] subway". Carol then builds on this explanation to *focus diagnostics* on a problem she perceives around how the dancers are distributing their weight (*Yes, but*). Hannah expands on this adding her suggestion that "they need to go on the subway" (*Yes &*), and Rachel builds on Hannah's comment (*Yes &*) to help Elena see the link between an authentic *aesthetic* and the shape a hand takes when holding a strap to maintain balance when riding the subway: "Like a loop your hands up more like this (holds her hand up at an angle), than this (holds her hand up straight)." Hannah affirms, explaining that the shape of the hand "is more round" (*Yes &*).

After this collaborative *Yes &* dialogue, Carol uses *scaffolding* focus Elena's attention on the movements associated with "putting on the brake" in the subway and wonders (*suggests don't tell*) if Elena "could find other ways of that being stopped in your tracks kind of feeling, um, like what would happen if it was part of a turn and all of a sudden you stopped in the middle of the turn just to explore that you know, the brakes."

ID – He's gotta discover that

The focus of the fourth review in the ID context was to select the final idea and create a "looks like" model – a full-scale semi-functional prototype to communicate the design to the client. This is the last review before the final client presentation. This one-on-one review occurred at Todd's workstation, which was part of a long table of student workstations each with two monitors. It occurred between the 0:45 and 8:30 timestamps, and at moments includes Alek, a student sitting to the left of Todd. In this example, Todd *denies* Gary's feedback on the *feasibility* of his rotating ottoman design, and Gary *breaks the 4th wall* to create a "teaching moment" where he *models* the kinds of design thinking he wants Todd to develop and use - *valid testing* of design *feasibility* and *deep modeling* to inquire into how a design might work. While Gary could have simply told Todd the design wouldn't work and that he should do something else, he consistently *suggests but doesn't tell* Todd what to do, providing *scaffolding* to help Todd make his own decision based on informed reasoning. This is a notable change from previous reviews where Todd was less vocal in his interactions with Gary.

This example begins with Todd identifying his top choice, and noting that this design was the one the client felt was "more pure" (simple *aesthetic*) and *interactive* where they "want it to rotate. That's the thing they kept talking about". Todd shows Gary a 3D foam model of the design, an ottoman with three separate but independently moving

diagonal segments that allows the user to change the shape and direction of the seating area. Todd believes that a single axis will allow the segments to spin smoothly, however within the first minute of the conversation, Gary quickly *diagnoses* a *feasibility* issue:

Todd:	They want like, ah, what's gonna happen is this base is gonna be weighted. And it's gonna have basically a pole coming out of it, and these two pieces are gonna be lighter and they're gonna just kinda like fit on top of that hole that's coming out like this, right? And then that can spin on the axis.
Gary:	But keep in mind, though, if you have just one center axis, you sure you're not gonna have to have a second axis? Because what happens is this is going straight through here what can really – you're already locked in.
Todd:	Will I be?
Gary:	Well, what we'll see, get a pencil and ah, ah, see, that's what I'm thinking's gonna happen.

Gary notices that the segments are on different planes and will require more than just one axis of rotation. Todd asserts that because this "plane is perpendicular, so I can rotate it like anywhere." Gary uses *Yes, but* to acknowledge Todd's assertion while also rejecting his reasoning, and then *modeling* the strategies he would use to set up a *valid test* ("get a dowel rod and drill through all these and see what you think") to inquire into the ways the segments may or may not rotate when they are held together by a perpendicular central axis. While Gary doesn't seem to believe Todd's idea will work, he suggests that Todd "play with it" to determine what will really happen.

Todd:	This plane is perpendicular, so I can rotate it like anywhere.
Gary:	It's perpendicular to this. If you rotate it perpendicular to this piece.
Gary:	I would get a – actually, you know what – you've got pictures of this. I would get a dowel rod and drill through all these and see what you think.
Todd:	Okay.
Gary:	And play with it. I think what's gonna happen though is this is your, your point of axis rotating here.

Gary continues to encourage Todd to develop *valid experiments* and *deep models* so that he can develop an understanding of the *feasibility* of his design and *diagnose* the extent to which his design will perform as desired. Gary and Todd continue in a *Yes &* collaborative manner discussing manufacturing procedures, potential materials for this and other elements of his design, and Todd's ambitious goal of creating a working prototype. Around the 5:00 timestamp, Gary *breaks the 4th wall*, shifting the *Yes &* collaborative dynamic to offer procedural advice on managing time and complexity. Gary *suggests* bounding the scope of work (*complexity management*) to only illustrating the idea of the rotating function through either a foam model or CAD renderings, rather than making a working full-scale prototype: "don't overcomplicate yourself…it needs to be a 'looks like' it doesn't need to be a function…it's just you just need to do enough to show it, the function of it, ah, and again, you can do a small model, which you explain how this goes. But then you have your CAD renderings." He *models* his reasoning about *time* and *complexity management* by explaining how the effort of creating the working prototype "will take away from your schedule. It'll take away from your electronic presentation." In other words, he anticipates that the effort it would take for Todd to

create the working model would reduce the time Todd needs to create an effective presentation.

Around the 7:00 timestamp, the discussion returns to whether or not the rotating idea could work. This time the student sitting to the left of Todd, Alek, joins the review conversation and asserts that the rotating idea won't work: "It's not gonna spin with the dowel. Not with the angles." Todd disagrees, and Gary *breaks the 4th wall* to *suggest but not tell* Todd it won't work, "He's gotta discover that." He *coaches* Todd to experiment and figure it out for himself. Todd continues to explain his reasoning, "I don't know why it wouldn't. 'Cause like when I have it, I'm gonna have it where – where it originally was, which is this (showing this on the foam model)." Alek counters this reasoning by explaining to Todd that he can either have it sit flush or spin, "you can get one or the other" but not both. Gary follows up on this to *model* what would happen, using the small-scale foam model of the design. When Todd still has difficulty seeing the issue, he *breaks the 4th wall* to *suggest but not tell* Todd to experiment and figure it out for himself suggesting it will be an important learning experience: "you just need to go through it. This will be a good experience for you."

Gary:	Ah, and what you're gonna find out, maybe before your "looks like" model, you're not gonna – don't overcomplicate it, and it doesn't have to be functional. Say, you could show them on a small m-, a small model, ah, and that's what I would do. Make – you, you gotta get this thing done. I'd rather have it a better-looking model than one that gets – 'cause you're – just to get this right, it would be a nightmare.
Todd:	Yeah.
Gary:	And you don't have enough time. You've only got two weeks, two weeks only, and then you gotta be sharing the same equipment.

As shown, above, Gary *breaks the 4th wall* again to repeat his *modeling* of *time* and *complexity management* strategies, *suggesting* that Todd *reduce complexity* by creating the best looking model (rather than a working model) that he can build in the time available.

ME – You're putting a pretty large moment on that servo

This example occurs in the conceptual design review (CDR) and starts at the 10:00 timestamp. It is revisited at the 12:00 timestamp, the 27:00 timestamp, and also at the end of the presentation. Here, the instructor repeatedly draws attention to the *feasibility* and *coherence* of the sub-system that controls the movement of the fins on the robot fish, using a combination of *suggest don't tell* language such as "you might check that" and "intuition tells me it's not gonna work, but – go ahead" with *scaffolding-modeling-coaching* and other design PCK patterns (*breaking the 4th wall* to create a teaching moment, *driving* for meaning and guidance, *directed scaffolding*). In the process, he encourages the use of design strategies such as *deep modeling*, *conducting valid tests*, and *focused diagnostics* to assess *feasibility* (a watertight seal and the size of the moment on the servo arm) and *coherence* (the interrelatedness among parts that make up the system).

As background, the students had presented details on the design of the dorsal and pectoral fin sub components, focusing on the connections between the servo arm, the fins, and the solenoid. Nelson followed up on this discussion to ask for details about the ways the tail

is attached to the servo arm, the response time of the solenoid that drives the servo arm, and if the solenoid is waterproof. At the 9:00 timestamp, Neal (the student mainly responsible for the mechatronic aspects of the design) *articulates* how the dorsal fin is attached to the servo motor to turn the fin: "plastic servo arms, and again that goes to the coupler slot inside the cover plate. So it's gonna be a slot. And that's how the fin turn directly." At the 10:00 timestamp Nelson *breaks the 4th wall* to "hold on just a second" and *focuses diagnostics* on the "very large moment arm on that servo". He *models* his reasoning for why this may not be *feasible* and uses *scaffolding* to direct the students' attention to what may be creating this problem: "there's a – this large distance between that center pressure and the pivot point. What is that distance…If the center of pressure is the center of that pin, what is that moment arm?"

As shown below, Neal tells Nelson the length of the arm (1 inch), and Nelson translates this information into an assessment of *technical performance*, "you're putting a pretty large moment on that servo." Nelson continues to *scaffold* by directing the team to conduct *valid tests* to assess *feasibility* by asking, "we calculated that?" Neal responds with saying the team hasn't performed those analyses, and Nelson *suggests but doesn't tell* the team to *iterate* to improve *feasibility*: "you might want to think about moving the pivot point to the center of the pressure so that moment arm is reduced." Neal asks Nelson to "say that again", and Nelson responds by providing more detailed *modeling* of his reasoning, explaining how if the two screws are moved "to the center of pressure of the fin", then the "moment arm is significantly reduced." Neal acknowledges Nelson's explanation and Joshua encourages "moving on".

Neal:	Um, the length of the arm is about 1 inch.
Nelson:	One inch. So you're putting a pretty large moment on that servo. And we calculated that?
Neal:	Um, we haven't calculated it yet.
Nelson:	All right, so you might want to think about moving the pivot point to the center of pressure so that moment arm is reduced.
Neal:	Um, talking about moving the fins?
Nelson:	Pardon me?
Neal:	Ah, can you say that again?
Nelson:	If you move the – where the two screws are, to the center of pressure of the fin.
Doug:	Right here, right?
Nelson:	Yes.
Doug:	Those screws.
Nelson:	Then the moment arm is significantly reduced.
Neal:	Oh, okay. All right.
Joshua:	Um, moving on.

Before the 12:00 timestamp, Nelson *breaks the 4th wall* to ask another question about the servo arm. He *scaffolds* students to *articulate* the ways the different components of the servo arm system interact (*coherence*), in the process encouraging *deep modeling* to inquire into the *feasibility* of that approach. After Joshua confirms that the centerline for the servo and pivot rod is not the same, Nelson continues to *scaffold focused diagnostics* on the system integration (*coherence*) aspects of how the movement of one part (the servo arm) affects another part (the pivot rod). This becomes an interactive discussion

where the students use the presentation slide (on the wall) to *articulate* their model, while Nelson asks questions about the ways components are connected or move in relationship to each other (*coherence*). After a couple minutes of this back and forth discussion, Alissa asks, "We can pull up the coupler drawing in the actual package and show you his design 'cause he took that into consideration." Nelson affirms this suggestion and after looking at the drawings asks a clarifying question, "so that arm rise in the two bearings, one on top, one on bottom. Is that correct?" Neal affirms this, and Nelson revoices the issue and gives back control of the presentation to the students: "There's a slide. Okay. I've got it."

Around the 27:00 timestamp (below), when the students are describing how the fish performs in the water, Nelson *breaks the 4th wall* again to revisit the *feasibility* of the current servo arm design. In the process he *suggests but doesn't tell* them to assess the performance of this aspect of the design by saying "you might check that with the relative position". He encourages the team to *deep model* and conduct *valid tests*: "go through the kinematics of it to make sure it works, like in Solidworks to cycle it back and forth." Joshua and Neal respond by saying they did some of those tests, and Nelson appears to draw on his own experience to *suggest but not tell* them to revisit their tests: "Again, it looks – intuition tells me it's not gonna work, but – go ahead."

Nelson:	Okay back, back to the 48 then. Looking at that servo again, if this is an accurate representation, I don't think that moment arm's gonna, even in the slot's going to rotate that. You might check that –
Joshua:	Okay.
Nelson:	- with the relative position, and I realize the picture might not be accurate.
Joshua:	Okay.
Nelson:	But it looks like in an extreme location, I don't think it's going to work, but just check it to make sure.
Joshua:	Okay.
Nelson:	You know, go through the kinematics of it to make sure it works, like in Solidworks to cycle it back and forth.
Joshua:	Yeah, you did that.
Neal:	Yeah with the, with the, the small angle, the fin will be close to the shaft.
Nelson:	Again, it looks – intuition tells me it's not gonna work, but – go ahead.

At the end of the presentation, Nelson *breaks the 4th wall* again to summarize his two concerns with the current design – the "water tightness of the, ah, PVC" and "then you need to look at that thin drive because I think that's going to be a problem."

Discussion

The design PCK pattern of *suggest and don't tell to let the student figure it out* illustrates the ways coaches support multiple perspectives (both complementary and conflicting) and ambiguity by encouraging students to make their own informed decisions. This is evident in coaches' language of "play around with that", "he's gotta discover that", "you might check that", and even "it's not gonna work, but – go ahead".

The examples in this section illustrate the ways coaches used *suggest don't tell* to encourage self-expression and agency, as well as discovery and experimentation on issues of *feasibility*, *aesthetics*, and *coherence* through the design strategies of *problem*

framing, *deep modeling*, *conducting valid tests*, *focused diagnostics*, *reflection*, and *iteration*. There was also a high level of *suggest don't tell* co-occurring with *scaffolding-modeling-coaching* cognitive apprentice teaching techniques, *Yes &* improvisation teaching techniques, and other design PCK patterns (*breaking the 4th wall* to create a teaching moment, *driving* for meaning and guidance, *scaffolded articulation*). This suggests that coaches drew on a broad repertoire of teaching techniques and design PCK to help students see, express, judge, and reflect upon their design intentions in relation to their design solutions. In some cases coaches actively challenged a student's prior beliefs and conceptions, providing examples and other forms of scaffolding to help students understand the consequences of design decisions and imagine more effective alternatives.

From a design thinking perspective, designerly ways of knowing involve having a tolerance for ambiguity and the possibility of multiple solutions (Cross, 2006), managing and preserving ambiguity (Lande & Leifer, 2010), reasoning about uncertainty (Dym et al, 2005), and developing personalized stopping rules (Goel & Pirolli, 1992). In this way, coaches' use of *suggest don't tell* across the selected design reviews and contexts may be an indicator of a shared philosophy of design – *design as ambiguous* – that has intrinsic value for the coaches or field of design inquiry. As Goldschmidt (2006) notes in their study of architectural design studios, "we find it rare for instructors to explicitly state or prescribe specific design goals…Both students and instructors expect students to define their own goals, emphasize clear concepts ('leading ideas')…an implicit underlying premise calls for self-expression and rewards creative behavior." In addition, the frequent co-occurrence of *suggest don't tell* with *breaking the 4th wall*, may be an indicator of the precarious line coaches walk between encouraging students to make their own decisions and taking control to help students understand what they need to do successfully move forward. This observation aligns with Yilmaz and Daly's (2014) description of design coaching as giving students freedom to explore and come into their own design aesthetic while also providing enough guidance and mentorship to help them approach complex design tasks. It also aligns with observations of Glen helping students develop their own voice and design values (McDonnell, 2014) and introducing ambiguity to help students see differently (Cardella et al, 2014).

This pattern was evident in all contexts in the selected dataset, although it occurred more frequently and consistently across design reviews in the ID and CHOR contexts perhaps in part to the one-on-one or group-on-one informal interaction structure. Also, it was not evident in the ME final design review or final debrief, most likely because these reviews focused on presenting final work rather than seeking guidance or feedback.

5. Summary and Implications

We began this exploratory study with a goal of *making visible the design pedagogical content knowledge coaches' use in design reviews when guiding students to develop as design thinkers*. We combined theories of teaching, learning, and design thinking to investigate the similarities and differences of design PCK across disciplines, review structures, and learners. We identified four patterns of design PCK, which are

summarized in Table 6 as coaches' actions that link the "how" (repertoire of teaching techniques) and the "what" (learning goals and content knowledge) of teaching design.

Table 6. Observed Patterns of Design PCK

DESIGN PCK PATTERN	DESIGN THINKING SPECIFIC TEACHING KNOWLEDGE
SCAFFOLDING ARTICULATION - coach directs the learner's attention to an aspect of their design or plan, encouraging the learner to articulate their reasoning for their decisions or engage in particular design strategies	Teaching strategies: *articulation* and *scaffolding* in combination with *modeling*, *Yes &*, *breaking the 4th wall* Conceptual and procedural knowledge: *aesthetics* and *feasibility* in relation to *problem framing*, *deep modeling*, *focused diagnostics*, *reflective practice*, and *time management*
DRIVING FOR MEANING AND GUIDANCE - (1) coach takes control of the review dynamic to help students make conceptual connections or see fallacies or limitations in their design thinking, and (2) student takes control to direct a coach towards a subset of the task and ask for situated guidance for a desired next step	Teaching strategies (1): *driving* in combination with *modeling*, *scaffolding*, and "*breaking the 4th wall* to create a teaching moment" Teaching strategies (2): *bounding* in combination with *modeling* Conceptual and procedural knowledge (1): *problem framing*, *doing research*, *deep modeling*, *focused diagnostics*, *iteration* and *suggest don't tell* – to address issues of *feasibility, usability,* and *complexity, time and risk management* Conceptual and procedural knowledge (2): *focused diagnostics*, *reflective practice*, and *complexity* and *risk management* strategies – to address *aesthetics*, *coherence*, and *feasibility*
BREAKING THE 4TH WALL TO CREATE A TEACHING MOMENT - coach seeks to convey knowledge of design thinking concepts or strategies that for students may be unfamiliar, abstract, counterintuitive, conflict with prior beliefs or conceptions, or difficult to recognize as central to designing and therefore central to becoming a designer	Teaching strategies: *breaking the 4th wall* in combination with *scaffolding*, *modeling*, *coaching,* and d*riving* Conceptual and procedural knowledge: *problem framing* in relation to design intentions such as *coherence* and *aesthetics*; *focused diagnostic* troubleshooting in relation to *aesthetic*, *feasibility*, and *usability* issues; *risk* and *time management* strategies; *iterative* and *reflective practice;* and a *suggest don't tell* perspective
SUGGEST DON'T TELL TO LET THE STUDENT FIGURE IT OUT – coach supports multiple perspectives (both complementary and conflicting) and ambiguity by encouraging students to make their own informed decisions	Teaching strategies: *suggest don't tell* in combination with *scaffolding-modeling-coaching*, *Yes &*, and other design PCK patterns (*breaking the 4th wall* to create a teaching moment, *driving* for meaning and guidance, *scaffolding articulation*) Conceptual and procedural knowledge: encourage self-expression and agency, as well as discovery and experimentation on issues of *feasibility*, *aesthetics*, and *coherence* through the design strategies of *problem framing*, *deep modeling*, *conducting valid tests*, *focused diagnostics*, *reflection*, and *iteration*

5.1 Implications across contexts and review structures

In this section we summarize three observations across disciplinary contexts and review structures. The first observation is that while disciplinary context and review structures

varied, coaches shared a repertoire of teaching techniques, design thinking knowledge, and design PCK patterns. All coaches utilized the full complement of teaching codes, with the exception of explicit *driving* in the CHOR context, and encouraged the same task and project management strategies. They also held a common perspective or philosophy of design as managing and resolving ambiguity. This was demonstrated through using *suggest don't tell* to draw attention to problematic aspects of a design while encouraging students to experiment and make their own informed decision. This observation is comparable with the ways coaches used feedback to help students negotiate ambiguity the ME and ID contexts (Cardella et al, 2014), and the ways the ID coach encouraged students to develop their own voice and design values (McDonnell, 2014). It also aligns with features of designerly ways of knowing (Cross, 2006) and provides evidence of the utility of the Crismond and Adams (2012) matrix across disciplinary contexts. Also, all coaches strongly emphasized *focused diagnostics*. They appeared to anticipate or perceive that students would need considerable guidance with diagnosing their own designs as well as connecting features of design solutions back to earlier problem framings. This was also a troubleshooting lens coaches used to help students iterate on the *coherence* or alignment between a current solution and a problem framing. This is similar to the observation of "generative sensing" in which a coach begins with evaluating a student's design and then switches from deductive to abductive reasoning to sharpen or loosen up the problem frame (Dong, Garbuio & Lovallo, 2014). Finally, all four patterns of design PCK were observed across contexts and design review structures.

While coaches shared a repertoire, there were also disciplinary differences in what they emphasized, an observation others noted (Christensen & Ball, 2014; Yilmaz & Daly, 2014). For example, all codes for judging designs were present across all contexts and review structures, although emphases varied. The CHOR coaches emphasized *aesthetics* and to a lesser extent, *coherence* and *essence,* but also referenced *feasibility* to articulate concerns about the limitations of the human body or human movements. The ID coach emphasized *aesthetics*, *interactivity*, *novel* early in the process, and emphasized *feasibility* and to a lesser extent *interactivity* and *aesthetics*, later in the process. The ME coach primarily emphasized *feasibility,* but also referenced other issues including *aesthetics*. All coaches used the *coherence* code, but in different ways. In the ME context *coherence* referred to linking system complexities and producing a complete or integrated solution. In the CHOR and ID contexts, *coherence* referred to the aesthetic and material integration of form and function. In contrast, the *(un)predictability* code for judging designs had different meanings and disciplinary values. In the CHOR and ID contexts, students were encouraged to integrate *unpredictability* into their designs as an *aesthetic* principle of creating drama or surprise. In the ME context, the coach encouraged solutions that would be *predictable* as way to establish the *feasibility* of a solution. Finally, the ID and ME coaches were more likely than the CHOR coaches to emphasize *risk*, *time*, and *complexity management* strategies. For example, *time management* played a central part in the ME coach's debrief with students (see also Lande & Oplinger, 2014). Yilmaz and Daly (2014) observed that ME and ID coaches encouraged convergent thinking as one way to help students make decisions that allowed

them to finish their work on time, and McDonnell (2014) observed that the ID coach drew on his professional experience with unpredictability to mentor students on managing time, risk, and complexity.

The second observation is that coaches' repertoires may be a form of situated knowledge, an observation that is supported in prior research (Goldschmidt, 2006). Coaches flexibly applied their repertoires, modifying their approach as needed to suit an individual student's needs or the goals of a particular design review. For example, coaches encouraged students to use different task strategies over time. The CHOR coaches' emphasized *problem framing*, *focused diagnostics*, *iteration* and *reflection* relatively consistently across the different design reviews although the early emphasis on *problem framing* decreased over time. Similarly, the ID coach emphasized different strategies across students and design reviews, and the ME coach emphasized different strategies across design reviews with a notable increase in *reflective practice*. This supports other observations of coaches using different approaches in relation to student expertise or design grammar level (Ferreira, Christiaans & Almendra, 2014), tailoring feedback to the design review context (Cardella et al, 2014), and using opportunistic pedagogical teaching strategies to share their linguistic routines with students (Howard & Gray, 2014). Coaches also combined teaching techniques to help students' notice, understand, and develop design thinking capabilities. For the example in ME of "You're putting a pretty large moment on that servo", the coach used a variety of techniques to help students notice the issue of the moment on the servo arm – at times *modeling* his own reasoning, using *scaffolded articulation* to have students explain their reasoning, providing *coaching* on how the current solution may not perform well, and *breaking the 4th wall* to bring attention back to the original concern.

The third observation is there were similarities and differences in design review structures that appear to have different affordances for design PCK patterns:

- Formal presentations and informal individualized one-on-one settings appear to support *scaffolding articulation*, but create different opportunities for coaches to probe students' reasoning and scaffold further inquiry. In ME, students "perform" a presentation, making their reasoning explicit; in the ID and CHOR contexts, students informally discuss works-in-progress, where their reasoning is implicitly embodied in prototypes.
- Most instances of *driving for meaning and guidance* commonly co-occurred with a coach *modeling* their design knowledge and strategies. The *driving* version of this pattern frequently occurred in the informal one-on-one ID context, a few times in the ME formal presentation review, and implicitly as a turn-taking structure in the CHOR context. The *bounding* version was evident across the dataset, but was most prevalent in informal review structures and with students who appeared to have more self-confidence or design experience.
- The pattern of *breaking the 4th wall to create a teaching moment* was prevalent across all contexts and review structures. In most cases the coach created teaching moments opportunistically and in response to a situation. There was one extensive case of an intentional teaching moment in the ME context during the Socratic-style final design debrief (see Lande & Oplinger, 2014).

- The pattern of *suggest don't tell to let the student figure it out* was evident in all contexts, although it occurred more frequently and consistently across design reviews in the ID and CHOR context. This may be due in part to the one-on-one or group-on-one informal structure where there was a high level of collaborative interactions (*Yes &*), or reviews that emphasized work-in-progress. A unique feature of the turn-taking and multiple-coach structure in the CHOR context is that students were presented with (and had to resolve) complementary and conflicting coach feedback (*plurality*).

5.2 Implications for cognitive apprenticeship and teaching as improvisation frameworks

In this section we summarize implications regarding the frameworks used to characterize content-specific pedagogical knowledge. First, the prevalent use of teaching as improvisation techniques across the dataset provides substantial evidence for a new perspective of design coaching as a situated practice and experienced design coaches as skilled improvisers. Second, we modified coding frameworks to take into account the capabilities of adult learners and unique attributes of design reviews. We added a code to the cognitive apprenticeship framework for student *bounding*, where students direct coaches to model their own reasoning. This was observed as a role reversal of *scaffolding*, and provided a student-directed complement to the code of *driving* from the teaching as improvisation framework. This may reflect the tendency of adult learners to be more self-directed than pre-adult learners (Mezirow, 2000). This seems to be an important addition to the framework even though we did not observe students frequently asking questions of coaches (see also Cardoso, Eris & Badke-Schaub, 2014). While the technique *breaking the 4th wall* is often discouraged in the teaching as improvisation framework because it can break a constructivist coach-student dynamic (Sawyer, 2004), we observed coaches' frequent and effective use of this technique to provide just-in-time metacommunication teaching moments to help students manage their own process, critically evaluate their designs, and move forward with design decisions (see also McDonnell, 2014).

Table 7. Integrating cognitive apprenticeship and teaching as improvisation frameworks

	WHO MAKES IT VISIBLE?	WHOSE THINKING IS MADE VISIBLE?	WHOSE PRACTICE IS MADE VISIBLE?	VISIBLE TO WHOM?	WHO IS DRIVING?
BOUNDING	Learner	Learner	*sets boundaries*	Coach	Learner
SCAFFOLDING	Coach	Coach	*sets boundaries*	Learner	Coach
COACHING	Coach	Coach	Learner	Learner	Coach
MODELING	Coach	Coach	Coach	Learner	Coach
ARTICULATING	Learner	Learner	Learner	Coach	Learner or Coach
BREAK 4TH WALL	Coach	Coach	Coach	Learner	Coach
DENIAL	Coach	Coach	Learner (via coaching)	Learner	Coach or Learner
DRIVING	Coach	Coach	Coach (via modeling)	Learner	Coach or Learner (Bounding)
YES &	Coach and Learner	Coach and Learner	Coach and Learner	Coach and Learner	Coach and Learner

Third, by having these frameworks to co-exist as interacting coding schemes, we were able to provide richer characterizations of teaching technique repertoires that take into account the predictable and unpredictable aspects of design reviews. This links coach's repertoires as skilled improvisers with their repertoires for supporting cognitive and metacognitive development. Based on this, we imagined a combined framework, shown in Table 7, that illustrates how each technique makes visible either a coach's or a learner's thinking as well as who is driving the coach-learner interaction.

5.3 Implications for building a language of design PCK

Our intent with this exploratory study was to find a language that practitioners and researchers could use to build a foundation of design PCK used in design reviews. Underlying the four observed design PCK patterns are four sets of coding schemes that characterize the "work of teaching" (Ball et al., 2005) in the moment-to-moment demands of design review situations. Two of these coding schemes characterize concrete, observable, and recognizable teaching techniques (cognitive apprenticeship and teaching as improvisation); two characterize observable and recognizable design thinking content knowledge as conceptual knowledge guiding design judgment and as procedural knowledge guiding use of design strategies and process management. As a collection, these patterns and coding schemes provide a language for sharing, discussing, critiquing, and reflecting upon what happens during a design review and how to facilitate learning during a design review.

By focusing on concrete examples of teaching practice and providing a language for noticing, this study may help *design coaches* make sense of their own experiences in ways that support reflective practice, moving tacit experiences into the realm of explicit design PCK strategies. The coding scheme and design PCK patterns may also support collaborative learning and knowledge sharing as part of a larger community of practice, including helping coaches identify approaches to teaching design they may not have previously considered. Also, the integrated coding schemes may help coaches understand their practice as authentic professional practice embodying a diverse repertoire of design thinking knowledge, understandings of student capabilities, and relevant learning goals and teaching approaches – that foreshadow student needs with the deployment of just-in-time teaching as a situated practice. Finally, new coaches can use findings from this study to make sense of the expertise of others and to contribute to an evolving body of knowledge of design PCK.

By making visible aspects of design thinking knowledge, *students* may begin to understand design as a form of inquiry and authentic practice, rather than a method to follow. The findings may also help students recognize and make sense of their own effective or inefficient habits of mind and difficulties, and the ways coaches try to help them overcome these difficulties, enable their voice as a designer, or facilitate the success of their design projects. Including examples of *bounding* may provide a way for students to recognize and create opportunities to take control of a design review, just as the examples of *suggest don't tell* may provide a way for students to make sense of the complicated dynamic coaches experience when they seek to provide guidance while encouraging students to develop their own voice as designers.

Finally, this study has implications for *researchers* as a starting point for translating concrete design PCK patterns into a general language of PCK as content-specific knowledge of relevant learning goals and student capabilities and content-specific teaching strategies and ways to represent design thinking. Regarding content-specific knowledge of learning, the four design PCK patterns appear to represent coaches' efforts to interpret students emerging or incomplete thinking, and concerns regarding student fallacies, limitations in thinking, anticipated difficulties students may encounter, and inefficient habits of mind to which design students may be prone. The pattern of *suggest don't tell* illustrates a shared learning goal of navigating complexity and ambiguity as seen through coaches' efforts to help students develop their own voice and agency as designers – helping them see, express, judge, and reflect upon their design intentions and processes. Regarding content-specific knowledge of teaching, coaches in this study used strategies that emphasized (1) helping students make conceptual connections or see limitations in their thinking, (2) offering alternative language or examples to support deeper understanding, (3) drawing on prior experiences to proactively challenge prior beliefs, naïve conceptions or misconceptions, and inefficient behaviors, (4) knowing when to pose questions or a new task that may deepen learning, and (5) encouraging students to reflect on their tacit knowing and make their emerging design thinking knowledge visible and explicit.

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