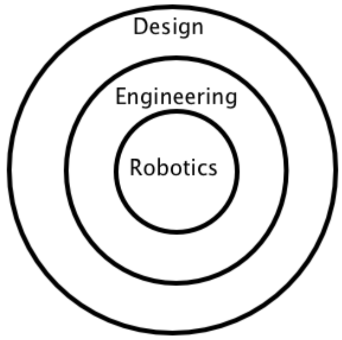
I then choose a smaller number of papers to review in detail based on the following criterion:

- Number of citations listed in Google Scholar (note that some of the papers do not list a number since they are conference papers) or seeming influence in the field,
- Relevance to my own research questions in terms of methodology, similar questions, age level of subjects, and similar theoretical outlook.

Review of the Literature

An examination of the table above reveals a taxonomy of design based science studies. First, design is the broadest category of a domain to teach science. Engineering is a subset of that. Architecture is an example of design that is not engineering. Robotics is a subset of engineering



Each study has its own methodology and age range. Methodologies range from quantitative (M. K. B. Wendell & Portsmore, 2011), mixed methods (Williams et al., 2007) to qualitative methods primarily case studies (Welch, 1999). Ages range from young children two to four (Outterside, 1993) to preservice teachers (McRobbie et al., 2001). Ten of twenty-six focus on middle school.

One educational goal is, by definition for this group of studies, science concepts and/or processes. Frequently, a second goal is also chosen such as problem-solving (Barak & Zadok, 2009), systems understanding (Sullivan, 2008), or motivation and interest (Nugent et al., 2010).

A few papers do not fit this model since they are reviews (Brophy et al., 2008; Schunn, 2009) or theoretical frameworks (Baynes, 1994).

Theoretical Frameworks

Designerly play (the elements of design that are found in children's play) has been identified as a fundamental component of childhood (Baynes, 1994). Baynes first reviews Piaget as a possible framework. Piaget's notion of development stages is attractive to Baynes but he feels that Piaget did not include enough of social component to fully describe designerly play. Gabriel (1970) classified play into five different types: sensory, emotional, identification, exploratory, and social. Cohen & MacKeith (1991) likewise developed a taxonomy of children's imaginings such as animistic and inventing people. Baynes then takes each taxonomy, gives design examples, and lists the design capabilities of each. For example an example of Gabriel's sensory play is sand and water table. A design aspect is "Exploration of the qualities and capacities of materials" and a design capability is "Ability to predict how materials will behave" (Baynes, 1994, p. 18). This framework could be useful in classifying the design trajectories of children over time.

The learning theories of constructivism (Applefield, Huber, & Moallem, 2000), constructionism (Papert, 1993), and social constructivism (Vygotsky, 1978) all provide a framework to support the teaching of science via design because: 1) children actively construct their knowledge in design projects (constructivism), they typically do so while building a physical model (constructionism), and they work in groups to do so (social constructivism).

A number of studies implicitly reference a constructivist framework (Penner et al., 1997; Schunn, 2009). Others reference design frameworks (Outterside, 1993; Welch, 1999). Some reference learning theories derived from constructivist principles such as situated cognition (Roth, 1996; M. K. B. Wendell & Portsmore, 2011), multiple intelligence theory (Perova et al., 2008), or project based learning (Barak & Zadok, 2009).

The Elementary Engineering Curriculum (EEC) (Heffernan, 2013) uses a mediated learning approach (Suomala & Alajaaski, 2002), which combines teacher instruction, structured activities, and open ended engineering challenges. Students generally work in dyads to help develop collaboration and communication skills (The Partnership for 21st Century Skills, 2002). Constructionism (Papert, 1993) is the theoretical framework that best reflects this approach. Bers defines constructionism as "a constructivist approach to developing and evaluating educational programs that make use of technologies with the purpose of learning" (Bers, 2008, p. 13). The key connectors between constructionism and the EEC are:

- The construction of artifacts as way to explore big ideas; "children … construct powerful ideas through firsthand experience" (Martinez & Stager, 2013, p. 18),
- Social aspects are important but not central as in social constructivism,

- The use of programming and computers has a rich history intertwined with constructionism both in terms of the value of debugging as a process and the actual use of computer programming to instantiate big ideas,
- "Constructionist learning environments allow for different epistemological styles, or ways of knowing, to flourish." (Bers, 2008, p. 19)
- The use of the engineering design process gives children a balance of scaffolding and open-endedness that provides a "constructionist learning environment" (Bers, 2008, p. 17),
- There is a focus on students documenting their own designs and processes and sharing out with a larger community, which provide a vehicle for reflecting on learning, an important tenet of constructionism (Bers, 2008).

In summary, the extant research on teaching science via design comes out of constructivist, social constructivist, and constructionist frameworks. More specifically a constructionist framework best informs my own research questions and curriculum.

Discussion

Studies have investigated different aspects of design and engineering as a means of teaching science concepts and process skills (Puntambekar & Kolodner, 2005), engineering (Hynes, 2007), problem solving (Fortus et al., 2005), and systems thinking (Sullivan, 2008). These studies have been of limited duration, have focused on older children, and have looked at the overall educational efficacy of the intervention.

Other studies have examined the novice design processes of learners in different contexts, ages, and have used different learning and process models. McRobbie, Stein, & Ginns (2001) analyzed the novice design practices of preservice teachers. They found that novice teachers did not follow the idealized practices found in engineering design process models. Roden (1999) looked at changes in the design process from infant school to primary school in Great Britain over a period of two years. He classified the collaborative problem solving strategies as: personalization, identification of wants and needs, negotiation and reposing the task, focusing on the task, tools, and materials, practice and planning, identifying difficulties, talking self through problems, tackling obstacles, sharing and cooperating, panic or persistence, showing and evaluating.

Each strategy was judged as: declining, emerging, developing, and changing over time. The study showed that these strategies do change over time and he suggests that teachers need to understand them and help children make them explicit. The methodologies, design cycle models, and strategy taxonomies in these two studies could be useful starting points for a study of elementary student design processes.

Crismond (2001) compares novice and expert high school and adult designers as they tried to redesign some common household tools. Each teams' activities was coded and analyzed in terms of an idealized design process model. Crismond found the teams did not follow the idealized model. Furthermore, only the expert designers used general principles and used connections to science concepts to help their design process. Crismond concludes that teachers must scaffold design tasks for this reason. Novice designers in the study did not follow the idealized design model but evaluated much more frequently. Also, students must have knowledge of and/or tinker with materials before starting their design task. Crismond's methodology and design cycle model for a redesign task could be a useful basis for study of elementary student design processes and should apply to design tasks.

Fleer (1999) looked at design processes for 5 and 11 years olds in terms of how their intended designs relate to what they actually built. She found that drawings were not always used. However, post-make drawings, especially by the older students provided good documentation of design choices. Older students still engaged in fantasy play associated with the design task but in a more subdued and socially acceptable way. They showed a preference for using 3-D models (i.e., the actual materials) to solve design problems. It will be useful for own purposes to ensure that opportunities for preplanning and post make drawings be provided in elementary design research.

Portsmore (2011) looked at preplanning for grade 1 students and found that even first grade students could sometimes used effective preplanning in a design task with familiar materials. Portsmore provides a very precise and structured task with concise rubrics for evaluated student designs.

Welch (1999) studied grade 7 students in a design task, coded what they were doing, and compared that to an idealized design process. He found that students did not follow an idealized design process. The evaluated their design much more frequently, tried one idea at a time instead of evaluating alternatives, and preferred 3 dimensional materials over 2 dimensional sketches.

K-12 robotics engineering, which typically uses design challenges, has been identified as a promising and effective way to incorporate engineering into K12 (Brophy et al., 2008). Multiple studies have pointed out the need for teacher scaffolding in the design process especially as a way to link to science concepts (Crismond, 2001; McRobbie et al., 2001; Puntambekar & Kolodner, 2005). However, elementary children's design processes are not well understood.

Conclusion

Common themes and important results emerged in the research on student processes of design in the context of teaching science.

- Students and novice designers do not follow ideal models of design process (Crismond, 2001; Fleer, 1999; McRobbie et al., 2001; Welch, 1999).
- Evaluation occurs in an ongoing manner not as one point in the design cycle

(Crismond, 2001; Fleer, 1999; Welch, 1999).

- Subjects showed a preference for 3 dimensional (rather than 2 dimensional) modeling especially for novices (Fleer, 1999).
- Possible solutions tend to be developed serially rather than evaluated in parallel up front as indicated in ideal engineering and design process models (Welch, 1999).
- Students must have knowledge of and/or tinker with materials (Baynes, 1994; Crismond, 2001; Portsmore, 2011).
- Teachers must provide careful scaffolding in design task or connections to science will not be understood (Barak & Zadok, 2009; Leonard & Derry, 2011; Outterside, 1993; Puntambekar & Kolodner, 2005).
- Experts were able to generalize and conceptualize much more than novices and hence transfer knowledge much more than novices (Crismond, 2001).
- There should be clear and limited links to science and engineering concepts (Crismond, 2001; Hynes et al., 2010; Leonard & Derry, 2011; Puntambekar & Kolodner, 2005)

The studies themselves also showed commonalities.

- Studies use the same or similar constructivist frameworks.
- In general, studies have a strong focus on group processes.

The studies uniformly use a constructivist, constructionist, and social constructivist approach. The studies vary in the age group studied, study methodologies, and the secondary goals of the instruction apart from the science focus. The studies report positive results but differ in their recommendations for instruction strategies. However, common themes are providing appropriate scaffolding to connect the design tasks to specific science concepts and processes. The vast majority of extant studies are short-term treatments of a few weeks. More research is needed examine and better understand how to teach engineering to students especially at the elementary level and, more specifically, how students design processes change over time (Penner et al., 1997; Roth, 1996). A longitudinal study of elementary design processes would fill in important gap in the research base.

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