Review of Frameworks, Models, and Methods for Elementary Engineering Case Studies

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Abstract

Although robotics has been identified as a promising way to increase STEM interest and also teach science concepts (Brophy, Portsmore, Klein, & Rogers, 2008), there is no research of student use of robotics in a sustained program. More research is needed to understand how to teach engineering to students as their cognitive, motor, and social skills develop (Crismond & Adams, 2012; Penner, Giles, Lehrer, & Schauble, 1997; Roth, 1996). The studies that do exist show promising results for short term robotics programs in middle and high school (Hynes, 2007; Sullivan, 2008). The goal of this review is to determine the most relevant theoretical frameworks, engineering design process models, and methodologies that can be used or modified in a cross-sectional, microgenetic case study of elementary robotics students in the context of established K-6 elementary robotics curriculum (Heffernan, 2013). The aim is to optimize the curriculum and, more generally, to optimize the teaching of engineering taking elementary age student development into account.

Introduction

Although robotics has been identified as a promising way to increase STEM interest and also to teach science concepts (Brophy et al., 2008), there is no extant research of student use of robotics in a sustained elementary program. The studies that do exist show promising results for short term robotics programs in middle and high school (Hynes, 2007; Sullivan, 2008). Many of these studies use design, engineering, or robotics as a way to teach science concepts (Adamchuk et al., 2012; McGrath, Lowes, McKay, Sayres, & Lin, 2012; Williams, Ma, Lai, Prejean, & Ford, 2007). Design is defined as "to plan and make (something) for a specific use or purpose" ("Design - Definition and More from the Free Merriam-Webster Dictionary," n.d.). Examples of this broadest category of design could include architecture, engineering, or even crafts such as knitting. The case studies that exist typically measure time spent in the different phases of a design process model (Crismond & Adams, 2012; Crismond, 2001; McRobbie, Stein, & Ginns, 2001; Outterside, 1993; Roden, 1997). Engineering is a subset of design that is commonly defined as the application of math and science to create something new to address a human need (Brophy et al., 2008). Robotics, as used in school settings, is a further subset of engineering where students design, build, and program robots for specific tasks. Robots are typically defined as machines that can accomplish intelligent, complex tasks in an autonomous fashion. Robotics is a particularly rich design domain because it contains an integrated blend of collaborative learning, engineering, programming, problem solving, and technology (Gura, 2011). The goal of this review is to determine the most relevant theoretical frameworks, design process models, and methodologies that can be used or modified in a cross sectional, microgenetic case study of elementary robotics students. An additional goal is to examine related and relevant research in design, engineering education, educational robotics, and causal reasoning.

The research questions for the case study are: 1) how do grade K to grade 6 elementary students' robotics engineering skills and processes change over time in terms of construction and programming techniques, (2) what changes in their techniques and processes can be seen that impact their ability to realize their design ideas? Answers to these questions will enable teachers to improve their robotics-based elementary engineering instruction.

Literature Review Methodology

Over the past three to four years, I have collected and read many papers on engineering and robotics education in preparation for my own research questions: 1) how do grade K to grade 6 elementary students' robotics engineering skills and processes change over time in terms of construction and programming techniques and 2) specifically, what changes in their techniques and processes can be seen over time that impact their ability to realize their design ideas? This list grew over time by using the citations in read papers to find more papers. I also compared my list with a robotics literature review (Benitti, 2012) and three currently unpublished robotics literature reviews (Carberry, Klassner, Schafer, & Varnado, 2014; Sullivan, 2013; Torok, 2012). I crosschecked references for all papers noting any that were cited frequently or seemed important. I also retrieved and read every paper listed on the Tufts Center of Engineering Education and Outreach (CEEO) website ("CEEO: Home," n.d.). Reading the robotics papers also led me to a series of papers that discuss the broader topic of research on the processes of design, engineering education, developmental psychology, and causal reasoning. This review focuses on theoretical frameworks, engineering design models, research methodologies, and previous research that could inform a longitudinal case study on elementary robotics. Table 1 summarizes the papers. Note that the author column contains a code that indicates if the document has relevant theoretical frameworks (F), models (MD), methodologies (MT), or focuses on causal reasoning (CR).

Table 1 - Paper Summary

Authors	Citations	Title	Type	Domain	Framework	Age	Goal	Conclusion
Baynes, 1994 (F)	11	Designerly play	Theoretical	Design	Paper provides several theoretical frameworks for the design process: Jean Piaget, John Gabriel (play), and David Cohen & Stephen A MacKeith (imagination).	0 to adult	Map out in detail the relationship between the play models of Gabriel and Cohen & MacKeith to aspects of design.	The ability to design is common and important to all children.
Bers, Bers, Flannery, Kazakoff, & Sullivan 2014 (F, MD, MT)	New	Computational thinking and tinkering: Exploration of an early childhood robotics curriculum	Mixed Methods	Robotics, Programming	Constructivism, constructionism, Positive Technological Development (PTD)	K	Better understanding what worked and what did not in terms of programming in their TangibleK environment.	K students were able to program successfully. However, the difficulty of some parts (such as sensors, if not, and building) suggested some curriculum changes.
Bers 2008 (F)	49	Blocks to robots: learning with technology in the early childhood classroom	Theoretical	Robotics	Provides thorough theoretical review of Constructivism, constructionism, Positive Technological Development (PTD)	Early Childhood PK-2	Make the case for and give examples of early childhood robotics	Students need early experiences with technologies such as robotics to be producers and not just consumers of technology
Buchanan & Sobel 2011 (CR)	9	Mechanism-Based Causal Reasoning in Young Children: Knowledge of Causal	Causal Reasoning	Science	Covariation research	Ages 3 and 4	Unpack the importance of causal mechanisms in causal reasoning in young children	It appears that knowledge of the underlying causal mechanism is important for developing a causal model (not just covariation).

Case 1991 (F)	540	The mind's staircase: Exploring the conceptual underpinnings of children's thought and knowledge	Theoretical and studies	Child development	Neo-Piagetian, constructivist	Lifespan	Reconcile and update Piagetian theory to fix issues found in empirical research	Case produced a 4 (now 5) stage model that parallels Piaget's with different names and foci: sensorimotor, inter-relational, dimensional, and vectorial. Within each stage, there are 3 sub-stages (the same for each stage). Focus is broader than logico-mathematical, more flexible, and with more of a role for education.
Crismond, 2001 (MD, MT)	71	Learning and using science ideas when doing investigate-and-redesign tasks: A study of naive, novice, and expert designers doing constrained and scaffolded design work	Case study	Design	Cognitive Design Framework (Leonard, Dufresne, Gerace, and Mestre)	Mixed	How can design be used to apply science concepts and process skills?	Experts used science concepts and general principles in a redesign task while novices did not.

Crismond & Adams, 2012 (F)	18	The informed design teaching and learning matrix	Theoretical review; scholarship of integration study	Design and specifically engineering design	Constructivist, social constructivist, constructionist (implied)	K-16	Create a rubric that shows how novice and expert designers handle the following design tasks: understand the challenge, build knowledge, generate ideas, represent ideas, weigh options and make decisions, test ideas, conduct experiments, troubleshoot, revise/iterate, reflect on process.	They also delineate learning goals and teaching strategies for each step in the design process. They consider them design strategies and not explicitly a design process model as one dimension of a Design Pedagogical Content Knowledge (PCK).
Demetriou, Efklides, & Shayer, 2005 (F)	72	Neo-Piagetian theories of cognitive development: Implications and applications for education	Theoretical and studies	Child development	Neo-Piagetian, constructivist	Lifespan	Answer question of how neo-Piagetian theory can have a positive impact on education.	A constructivist approach should be taken to education with more flexible model than Piaget.
Fleer, 1999 (MD, MT)	22	The science of technology: Young children working technologically	Case study	Design/Technology	Anning; Solomon & Hall (design and technology education)	Ages 5-11	Characterize relationship between design ideas and actual products	Drawings and ideas exceeded young students capabilities so they mostly worked with 3D models. Design and evaluate phases occurred throughout the design process.
Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005 (MD)	55	Design-based science and real-world problem-solving	Quantitative study	Design (Design Based Science – DBS)	Designerly Play (Baynes), problem solving and inquiry (constructivism)	Grade 9	Science knowledge and transfer when using DBS	Transfer did occur using DBS

Fuson 1976 (CR)	8	Piagetian Stages in Causality: Children's Answers to" Why?"	Review	Child development	Constructivist	Ages 0-14	Explain Piaget's views on causality	Progression from realism to objectivity to reciprocity to relativity (all between 3 and 11). Artifacts of realism in child (and adult) thinking: magical thinking/participation, animism, artificialism (everything is for man), and finalism (everything has an explanation, any explanation). Divided CR into 3 stages Precausality 1 before 5 Precausality 2 -5-6 to 11, still animistic, artificialism, etc. True Causality - 11 + (begins at 7-8) contains things such as deduction, condensation, generation, spatial explanations

Jonassen & Ionas, 2008 (CR)	57	Designing effective supports for causal reasoning	Framework	General cognition	Aristotle/Hume	Lifespan	Present model of causal reasoning and present a number of methods to support the development of causal reasoning	Classifies causal reasoning as: predictions, inferences, implications, and explanations as enabling causal relationships. All four of these support CR by problem solving and conceptual change. Need both covariance and causal mechanisms to have true causal reasoning. Tools to teach/support CR: influence diagrams, questioning, simulations, expert systems, causal modeling tools, system modeling tools
Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, 2003 (F, MD)	364	Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting Learning by Design (TM) into practice	Descriptive with some data	Design/Engineering	Problem based learning and Case Based Reasoning	Middle School	The goal is to help students be creative collaborative design with a strong knowledge of how to use science to aid in design.	A key focus is on how to create the collaboration. Uses a situated learning approach but also designed in transfer from the start. Student data was positive but there were challenges in terms of teachers.

Kuhn, Black, Keselman, & Kaplan, 2000 (CR)	268	The development of cognitive skills to support inquiry learning	Quantitative	Science	Constructivism	Middle School	Test an intervention to provide students with a standard model of multivariable causality in the context of inquiry learning.	Author argues that multivariable causal inference (MCI) is an important but ignored part of the scientific method. Children (and adults) seem to have a non-normative model of MCI such that they are neither additive nor consistent. Results showed some improvements for an intervention.
Kuhn & Dean, 2004 (CR)	67	Connecting Scientific Reasoning and Causal Reasoning	Framework, Quantitative	Science	Constructivism (implied)	Preadolescent to Adult	Merge best of multivariable causal inference (MCI) and scientific reasoning (SR) research	MCI has focused on college students and covariance. SR has been multiage, developmental, microgenetic, and in the context of science. Children and even adults do not possess scientific models of cause and effect. In their study, prediction errors were directly correlated to the validity of their causality model for the specific domain.
Kuhn, Schauble, & Garcia-Mlia, 1992 (CR)	248	Cross Domain Development of Scientific Reasoning	Qualitative, microgenetic	Science	Constructivism (implied)	Grades 4-6	Does structured practice help development of scientific reasoning (SR) and does it transfer to different domains?	Authors see the process of as two-fold, one of theory creation and then verification. To succeed, subjects must be able to realize that their existing theory could be wrong and not be subject to bias such as interpreting only data that supports their theory.

Kuhn, 2007 (CR)	35	Reasoning about multiple variables: Control of variables is not the only challenge	Mixed methods	Science	Constructivism (implied)	Grade 4	Goal was to improve multivariable causal inference (MCI) by helping students learn about control of variables (COV).	Study of multivariable causality on fourth graders. Authors argue that (MCI) is an important but ignored part of the scientific method. Children (and adults) seem to have a non-normative model of MCI such that they are neither additive nor consistent. Results showed some improvements for the fourth graders but were still mixed. Focus Even though subjects could sometimes isolate out different causal and non-causal variables, they could not necessarily apply their knowledge to the situation. This lack of transfer could be because of the lack of a mental model of causality.
Legare, Gelman, & Wellman, 2010 (CR)	73	Inconsistency with prior knowledge triggers children's causal explanatory reasoning	Mixed methods	Science/technology	None specified	PK	Are causal explanations motivations by consistent or inconsistent results?	Children as young as 3 develop causal reasoning. Exposure to inconsistent cause and effect phenomenon cause explanations more than exposure to consistent phenomenon. Furthermore, explanations themselves may help develop causal reasoning.

Leonard & Derry, 2011 (F, MD, MT)	4	"What's the Science Behind It?" The Interaction of Engineering and Science Goals, Knowledge, and Practices in a Design-Based Science Activity	Qualitative	Engineering	Constructivist, social constructivist, constructionist, pragmatist, modeling, activity theory, sociocultural theory	Middle School	The goal is to help students be creative collaborative design with a strong knowledge of how to use science to aid in design.	Results showed that simple science models alone were not sufficient to enable the design task. Their conclusion is that thoughtful scaffolding is required to use engineering to teach science concepts. A pure scientific approach obscures the reality of actual system performance. A purely technological approach deprives studies of scientific concepts that will enable better solutions.
Levy & Mioduser, 2010 (MT)	2	Approaching Complexity Through Planful Play: Kindergarten Children's Strategies in Constructing an Autonomous Robot's Behavior	Qualitative	Robotics, programming	Constructionist	K	Understand the level of complexity young child could get to programming robots	Children could explain to a certain level then used strategies to prune or fuse complexity to a simpler level.
Martinez & Stager (F, MD)	2013	Invent To Learn: Making, Tinkering, and Engineering in the Classroom	NA	Design	Constructivist, constructionist, pragmatist	All ages	Gives rationale for and ideas for using tinkering and makerspaces in education.	Good review of theoretical frameworks and engineering design models. They use simplified TMI model: think, make, and improve.

McRobbie, Stein, & Ginns, 2001 (MD, MT)	24	Exploring designerly thinking of students as novice designers	Case study	Design	Not specified	Preservice teachers	Help teachers understand the design processes actually followed by students.	Students and novice designers do not follow the ideal design models that have been developed. System of modeling design actions could be used in my research.
Mehalik, Doplet, & Schunn, 2008 (MD)	72	Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction	Quantitative	Design/engineering	Constructivist (implied), systems design	Grade 8	Science concept learning	Students using the systems design approach showed significant gains compared to the scripted inquiry approach, especially low achieving African-American students.
Piaget & Inhelder (F)	1969	The psychology of the child	Theoretical	Child development	Constructivist	Ages 0-14	Understand the stages and processes of children's cognitive development	Children have set stages of cognitive development that built on previous stages depending on a combination of experience and biological readiness.
Outterside, 1993 (MT)	10	The emergence of design ability: The early years	Case study	Design	Design modeling (Baynes), multiple intelligence theory, constructivism (implicit)	Ages 2-4	Understand very young children's' design processes especially the interactions between perceiving, imagining, and modeling.	Children come to school with lots of experience and processes in place for design. Awareness of the processes and interactions between imaging and modeling is often implicit and should be made explicit in school.
Penner, Giles, Lehrer, & Schauble, 1997 (MD, MT)	122	Building functional models: Designing an elbow	Quantitative	Design	Modeling, constructivist (implied)	Grades 1-2	Model construction and model revision	Modeling can be taught and developed even for grade 1 and grade 2 children.

Portsmore, 2011 (MT)	0	AC 2011-1780: First Grade Students Planning And Artifact Construction While Working On An Engineering Design Problem	Mixed methods	Design	Constructivist, constructionist (implied)	Grade 1	Can first graders use planning in the design process?	First graders were able to use drawings to create successful designs in some circumstances. However, many first graders also succeeded even though their designs did not match their final product.
Puntambekar & Kolodner, 2005 (MD, MT)	24	Distributed Scaffolding: Helping Students Learn Science from Design	Mixed methods	Design	Bruner, social constructivist	Middle school	Find methods to help middle school teachers teach science using design. Teach students science concepts and processes.	Students need distributed scaffolding to fully use science process and content in the context of design based science activities.
Roden, 1997 (MD, MT)	14	Young children's problem-solving in design and technology: towards a taxonomy of strategies	Qualitative, longitudinal	Design with technology	Constructivist, social constructivist, situated cognition	Reception – year 2 (UK)	Come up with a taxonomy of problem solving strategies for early elementary students.	Came up with a preliminary taxonomy of problem solving process: personalization, identification of needs, practice, negotiation and reposing the task, focusing down, identifying difficulties, talking themselves through sub-tasks, and tackling obstacles, Praise, encouragement and seeking reassurance, sharing and cooperating, pretend panic and persistence, and showing and evaluating

Roden, 1999 (MD, MT)	19	How children's problem solving strategies develop at Key Stage 1	Qualitative, longitudinal	Design with technology	Constructivist, social constructivist, situated cognition	Reception – year 2 (UK)	See what strategies identified in the preliminary taxonomy decline or increase over time	They did find that strategies changed over time with some declining, some increasing, some changing in different ways, and a new one emerging (practice and planning).
Roth, 1996 (F, MD, MT)	127	Art and Artifact of Children's Designing: A Situated Cognition Perspective	Qualitative (ethnographic)	Design	Situated cognition	Grades 4 and 5	What is the nature of design artifacts from a situated cognition perspective? Can teaching be improved from such an analysis?	Artifacts are not ontologically stable. - Students will use whatever materials and processes they discover which may not match the teacher's intentions, Movements spread throughout classrooms so much that it is difficult to figure out individual performance, even though artifacts are named by students to belong to individuals or teams.

Schauble, Klopfer, & Raghavan, 1991 (CR)	329	Students' transition from an engineering model to a science model of experimentation	Mixed methods	Science	Constructivist (implied), Pragmatism (Dewey)	Grades 5, 6	Does setting up children to use either an engineering or scientific approach result in better causal reasoning?	When verifying cause and effect, children tend to use an engineering model, that is, manipulating variables to produce a desired or optimal outcome. However, science is more about understanding relationships among variables, can also be used for indeterminacy and non-causal variables, and is more systematic. Study found that students do move to a more scientific approach over time with enough exposure.
Schunn, 2009 (MD)	11	How Kids Learn Engineering: The Cognitive Science Perspective	Review	Engineering	Constructivist (implied)	K-16	Increase STEM pipeline, teach engineering as valuable in and of itself, teach science concepts	Gives practical tips and methods for teaching engineering
Siegler & Crowley, 1991 (MT)	595	The microgenetic method: A direct means for studying cognitive development.	Methodology	Research	Constructivist	Lifespan	Give rationale for and explain microgenetic analysis.	Looking closely and setting up experiences so that cognitive change can be seen and analyzed is the only way to really how understand how it occurs.
Sullivan, 2008 (MT)	35	Robotics and science literacy: Thinking skills, science process skills and systems understanding	Mixed methods	Robotics	Constructivist (implied), mediated learning, inquiry	Middle School	Thinking skills, science process skills, systems understanding	Robotics instruction, with proper pedagogy, can increase content knowledge, thinking skills, and science process skills, and systems understanding,

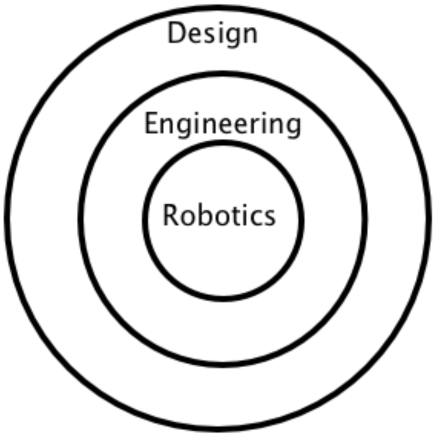
Sullivan, 2011 (F, MT)	7	Serious and playful inquiry: Epistemological aspects of collaborative creativity	Qualitative – microgenetic analysis	Robotics	Dialogism, constructivist (implied)	Grade 6	Gain a better understanding of how creative collaboration works	4 things allowed creative collaboration to emerge: open-ended, goal-oriented task; teacher modeling of inquiry; environment and tools that allowed for both seriousness and play, and tools and environment that allowed a "shared understanding achieved through tool-mediated, communicative, and cognitive interaction".
Svarovsky, 2011 (F)	1	Exploring Complex Engineering Learning Over Time with Epistemic Network Analysis	Mixed methods including Epistemic Network Analysis	Digital Zoo online engineering experience	Epistemic frame analysis, constructivist (implied)	Middle school girls	Develop engineering ways of thinking and not just science concepts and engineering design skills	Client focus and notebook reflection were 3 Digital Zoo activities that especially developed engineering ways of thinking.
Welch, 1999 (MD, MT)	45	Analyzing the Tacit Strategies of Novice Designers	Case study	Design	Extant design process models	Grade 7	Understanding actual design strategies of novice designers	Novice designers do not follow a model/expected design strategy but used a serial approach (not considering multiple possible designs first and evaluating them). Evaluation occurred much more than the models predicted.
Young, 2011 (F)	12	Development and causality: Neo-Piagetian perspectives	Theoretical	Child development	Neo-Piagetian, constructivist	Lifespan	Attempt to synthesize neo-Piagetian, cognitive science, affective, systems theory, and other models.	Author attempted broad integration and explanation of a wide range of developmental psychology.

K. B. Wendell & Lee, 2010 (MT)	6	Elementary students' learning of materials science practices through instruction based on engineering design tasks	Case study	Engineering	Situated learning, social constructionist	Grade 3	Science Content specifically materials science/engineering	Engineering based activity increased content understanding especially through the use of engineering workbooks.
Wood, 2007 (F)	114	Yardsticks: Children in the Classroom, ages 4-14	Theoretical	Child development	Constructivist	Ages 4-14	Delineate characteristics of different ages and the implications for teachers	Teachers need to be aware of child development and adjust curriculum and classroom management accordingly.

KEY: F=Framework, MD=Model, MT=Methodology, CR=Causal Reasoning

Review of the Literature

In this section of the paper, relevant framework, models, and methodologies for an case study of elementary robotics are examined. There can be overlap between definitions of frameworks and models. For this study, I am only interested in design or engineering process models: specific delineations of the stages of design that subjects use when tackling a design task. For the purposes of this paper, we define theoretical frameworks as overall theoretical lenses in which to view cognitive or other processes related to design. Engineering design is considered a subject of the more general category of design. For example, architecture is an example of design that is not engineering design. Robotics is a further subset of engineering design.



Theoretical Frameworks

What are the most relevant theoretical frameworks that can be used or modified for a case study of elementary robotics students? In this section, I look for common elements in the theoretical frameworks and propose a theoretical framework for my own research questions and curriculum.

The learning theories of constructivism (Piaget & Inhelder, 1969), constructionism (Bers, 2008; Martinez & Stager, 2013; Papert, 1993), and social constructivism (Vygotsky, 1978) all provide a framework to support the teaching of 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 effectively in groups to do so (social constructivism).

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) developed a taxonomy of children's creative play imaginings such as animistic (pretending an inanimate object is alive) and inventing people (such as imaginary friends). Baynes 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 by seeing how different design aspects and categories are used more or less over time.

In a longitudinal or cross-sectional study with a strong focus on cognition, existing cognitive benchmarks are obvious frameworks in which to measure development in the specific domain of focus. Piaget's constructivist theory defines four stages of cognitive development: sensorimotor (0 to 2), pre-operational (2 to 7), concrete operational (7 to 11), and formal operational (11 and up) (Piaget & Inhelder, 1969). In a longitudinal or cross-sectional study of K-6 children, students transition from the pre-operational, intuitive thought substage (between grades K and 2) to concrete operational (grades 2 to grade 5) and finally to formal operational (grade 6). Piaget notes that ages are "average and approximate" (Piaget & Inhelder, 1969, p. 3).

The development characteristics relevant to an elementary robotics longitudinal study are listed below.

1. Pre-operational, intuitive thought (K to grade 2)
    a. Egocentric – can only see their own point of view,
    b. Primitive reasoning – wanting to and starting to understand the "why" of things,
    c. Children know they have much knowledge but don't know how they acquired it,
    d. Key cognitive characteristics:
        i. Centration – only focusing on one aspect or cause of a situation,

        ii. Irreversibility – children can not mentally reverse a sequence of events,

2. Concrete operational (Grade 2 to grade 5)
    a. Start solving problems logically but only with concrete objects,
    b. Inductive reasoning from cases to a general principle,
    c. Trial and error problem solving,
    d. Key cognitive characteristics (for concrete objects):
        i. Seriation – the ability to sort objects by different characteristics,
        ii. Conservation – even if an object's appearance changes, the quantity remains constant,
        iii. Transitivity for concrete objects – just as in mathematics, if A < B and B < C, the A <C, for example,
        iv. Reversibility – the ability to mentally reverse a sequence of events or operations, specifically, objects that are modified can be returned to their original state,
        v. Conservation – an object can change appearance but still has the same quantity,
        vi. Classification – the ability to name sets (and subsets) based on objects' characteristics,
        vii. Decentering – the ability to take in multiple aspects of a problem,
3. Formal operational (Grade 6)

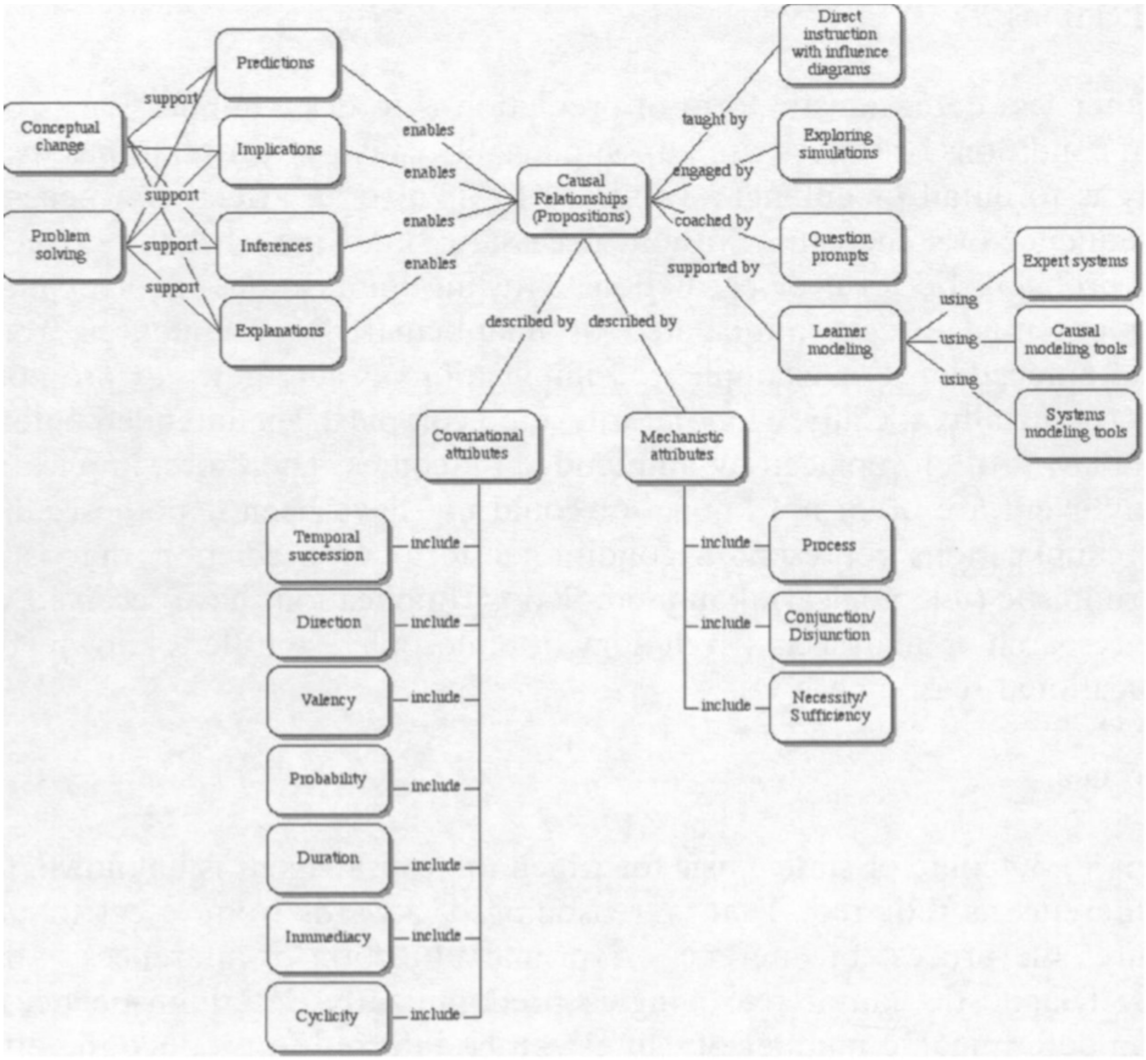
a. Deductive reasoning from a general principle to specific cases,
b. Logical and systemic problem solving,
c. Key cognitive characteristics:
    i. Abstract thought – all the operations developed in previous stages can be done mentally without reference to concrete objects,
    ii. Metacognition – the ability to reflect on cognition itself.

Neo-Piagetian researchers have modified Piagetian theory to address issues that developed. Namely, data showed that there was wide individual variation in the stages and that the structures Piaget claimed were not turning out to be as universal as Piaget had claimed (Bidell & Fischer, 1992; Case, 1991; Young, 2011). This resulted in a variety of modifications to Piaget. Bidell & Fischer (1992) in their skills theory see cognitive development as more of a web than a liner stage model so that different children take different paths through the web. They also point out that active instruction and learning in domain specific areas *is* cognitive development; one cannot just wait for brain development to occur. Bidell & Fischer (1992) also point out the need for development sequences in different domains. This latter point reveals the possibility for the identification of a learning progression for engineering for children (Krajcik, 2011).

The modification of universal structures to domain specific structures was also delineated by Case (1991) with his notion of Central Cognitive Structures (CCS) and Demetriou, Gustafsson, Efklides, & Platsidou (1992) Specialized Structural Systems. Case's work, in particular, seems to have relevance for elementary engineering research. There is a progression from stage to stage as children move from sensorimotor, to interrelational, to dimensional, to vectorial with each stage having its own executive control structures in addition to the domain specific structures. Sensorimotor (1 to 18 months), like Piaget's sensorimotor stage, is centered on direct perceptions and actions such as seeing and grasping. Case conceives of the interrelational stage as being characterized by the addition of representational thought. For example, children can draw a picture or use words to stand for physical objects, feelings, and concepts. In the dimensional stage, general relationships between two things can be established such as a number line. Finally, in the vectorial stage, many to many relationships can be established through things like abstract formulas that stand for the relationships. Case (1991) talks about progressing, within each stage, from one operation at a time, to two, and to more than two, and finally integrating the operations. This theory could shed light on the increasing ability of elementary students to plan and to project out the effects of their design decisions, which involve causal reasoning.

Piaget defined a progression of causality from magical-phenomenalist (also called realism) to an eventual scientific viewpoint (Fuson, 1976; Piaget & Inhelder, 1969). Infants do not have a delimitation of self and the outside world, attribute cause to the temporal proximity of events, and attribute the event to them without consideration of physical proximity. From three to eleven, a progression of causality occurs from realism to objectivity, reciprocity, and relativity (Fuson, 1976). In the realism stage, perceptions and feelings are directly experienced (real) without additional thought or mental representation and without a notion of self and other. In the objectivity stage, there is an understanding of self and other. With reciprocity, the child places equal value on the views of him or her and other. With relativity, the child perceives the relationships between different objects. In early stages of causal reasoning, children may give animistic, finalistic, participatory, and artificial explanations of phenomenon. An example of animism from robotics is when children attribute causation in robots or machines to an anthropomorphic conception of machine itself (Mioduser, Levy, & Talis, 2007). Finalistic explanations are the result of the belief that everything has an explanation and any explanation suffices regardless of its plausibility. Participatory explanations result from children's belief that they participate causally in natural phenomenon and are sometimes seen with associated magical thinking. Finally, artificial explanations attribute causality to its benefit to humans.

Jonassen & Ionas (2008) provide a complex model (see below) of causal reasoning and then suggest different ways to support the learning of causal reasoning. In this model, problem solving and conceptual change support predictions, inferences, explanations, and implications, which, in turn, enable causal reasoning. They see causal reasoning being engaged by direct instruction, simulations, question prompts, and learner modeling. Causal reasoning can be described using mechanism based or covariance based information. Engineering education provides problem solving affordances for learning causal reasoning. All four enablers of causal reasoning in this model are part of engineering - predictions, inferences, explanations, and implications - but predicting the performance of a system, subsystem, or program is most relevant to the pilot study. However, prediction is defined in terms of either scientific method, namely hypothesis, or forecasting events such as weather or economic performance (Jonassen & Ionas, 2008).



How does causal reasoning operate in the domain of engineering? Though engineering in particular and design in general centers around the prediction of how a design, process, or software program will actually function in the physical world, I was unable to locate any research on causality in the context of engineering. Casual reasoning or causal inference research typically centers on *a posteriori evaluation* of data to determine causes. However, in engineers make *a priori* predictions of the performance of their designed systems. The predictions may be augmented with simulations, models, and prototypes. In the context of LEGO robotics, students would normally be expected to design and then built with a prediction in mind and subsequently evaluate the actual performance. Since prediction is usually associated with science, I use the term mental projection to describe this cognitive skill in the domain of engineering. As will be shown, the ability to mentally project the impact of design decisions turned out to be an important difference between the second and sixth grade students.

While the literature on causal reasoning does not consider the domain of engineering, there are some principles and findings that may benefit the study of causal reasoning in the context of engineering. Kuhn, Schauble, & Garcia-Mlia (1992) found that successful causal reasoning depends on: 1) students being able to realize that their existing theory could be wrong and 2) students refrain from only including data that supports their theories. Furthermore, self-directed practice alone was sufficient to cause gains in scientific and causal reasoning. Finally, the authors suggest that the development of scientific reasoning, of which causal reasoning is an important component, is gradual and continuous and not a discrete developmental milestone like conservation.

Kuhn (2007) studied fourth grade students who received instruction in the control of variables (COV) strategy for understanding cause and effect. Even when they had mastered the COV strategy, students did not necessarily apply it to the domain under study. She suggests that curriculum is needed to help students apply COV and other scientific reasoning skills. Engineering education could be one such domain.

Legare, Gelman, & Wellman (2010) found in their study of preschool children, that inconsistent (rather than consistent) conditions triggered explanations which, in turn, triggered causal reasoning. The evaluation phase of engineering is rife with results that differ from the predicted outcome and therefore provides a rich experience for improving causal reasoning.

Schauble, Klopfer, & Raghavan (1991) distinguish engineering and scientific approaches to science by students. In their view, engineering approaches tend to involve making things to demonstrate causality while a scientific approach involves determining exact relationships between variables. The scientific approach therefore can determine causal, non-causal, and indeterminate variables while the engineering approach to science allows only the determination of causal variables by providing optimal solution to a design problem without exposing the underlying causal and quantitative relationships. Note that engineering is not considered non-optimal in general but only non-optimal as a way to do determine causal relationships.

Kuhn & Dean (2004) report that research on causality is split into two camps. Multivariate inference (MVI) researchers look at how college students attribute causes from multiple variables based on data. Scientific Reasoning (SR) researchers look at how children in general use knowledge of underlying mechanisms to attribute cause in the scientific realm. Kuhn & Dean (2004) argue that both approaches have merit, that research can be combined, and that causal reasoning should combine both data and underlying mechanisms. Buchanan & Sobel (2011) showed marked jumps in causal reasoning from age three to age four in experiments centered around changing battery and light configurations, which demonstrated that causal reasoning does have developmental characteristics. Their experiments also showed that this cognitive developmental was domain specific and not general. Finally, the children needed to see and understand the underlying causal mechanism to successfully determine cause and effect.

Though Piaget and the neo-Piagetians provide a theoretical framework for cognition, an open-ended, hands-on task such building a robot for a specific purpose also contains social, affective, and physical aspects not explained by a constructivist framework. Wood (2007) in his book Yardsticks: Children in the Classroom Ages 4-14 provides a broad framework for each age based on the work of Arnold Gesell, Jean Piaget, Erik Erikson and his own experience as an educator. For each age, Wood lists physical, social-emotional, language, and cognitive characteristics. Sample characteristics for five years old are from each category are: "focus visually on objects close at hand", "dependent on authority but also have trouble seeing things from another's viewpoint", "think out loud – that is, they talk their thoughts", and "like to copy and repeat activities" (Wood, 2007, pp. 62–63). Wood's yardsticks could provide additional explanatory power for the non-cognitive aspects of the robotic engineering tasks.

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 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 shown next.

- 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 (Bers, Flannery, Kazakoff, & Sullivan, 2014; Sullivan, 2008) and the actual use of computer programming to instantiate big ideas (Papert, 2000).
- "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 design, engineering design, causal reasoning, and robotics comes out of constructivist, social constructivist, and constructionist frameworks. A constructionist/constructivist framework best informs my own research questions on the EEC curriculum. The goal is to use the constructionist/constructivist theoretical framework to developmentally inform curriculum, instruction, and assessment as students move through an elementary robotics based engineering curriculum.

Design Process Models

One way to determine changes over time in children's engineering skills is to measure their use of various stages defined by engineering design process models. What are the most relevant design process models that can be used or modified for a longitudinal case study of elementary robotics students that seeks to delineate both the strengths and challenges of students at different ages in elementary school as they tackle open-ended engineering challenges? Even if the research focus is on strengths and challenges at different ages, characterization of these in the context of where they occur in a design process model may provide additional insights. One typical engineering design process model is shown below (Portsmore, 2011).

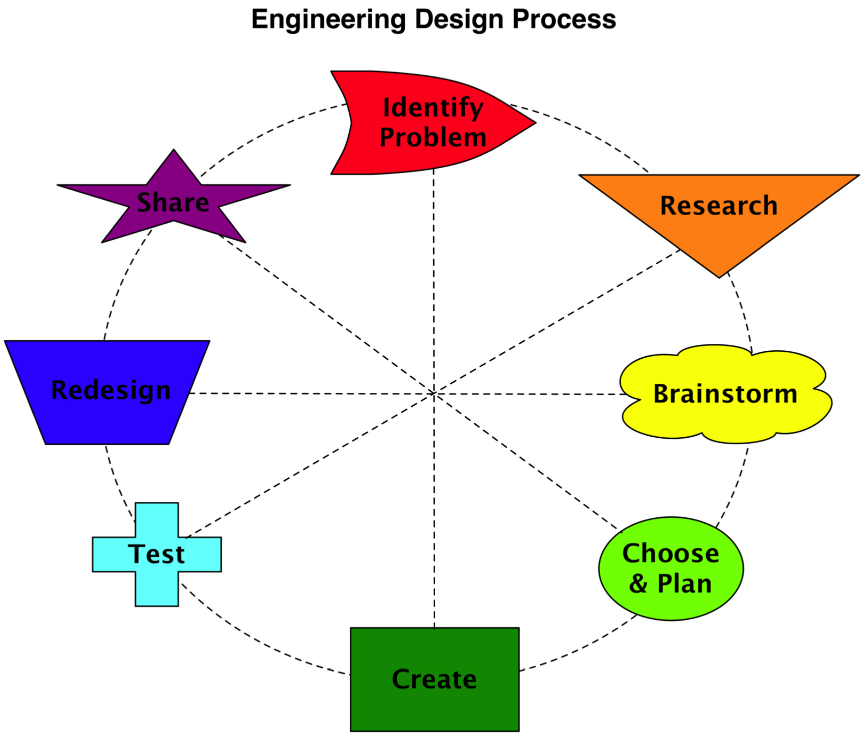


Figure 1 - Engineering Design Process Model - Dr. Merredith Portsmore, Tufts CEEO

Note the connecting lines across the circle, which indicate that the flow in the process may not be linear around the circle. This is an improvement on more linear models such as Mehalik, Doplet, & Schunn (2008). Welch (1999) points out that studies show that linear, rational, deterministic design process models may not actually be followed by designers and even less so by novice designers. Other models such as Resnick (2007) and Boehm (Martinez & Stager, 2013) spiral, which indicates that the process can repeat itself with the next iteration of the project.

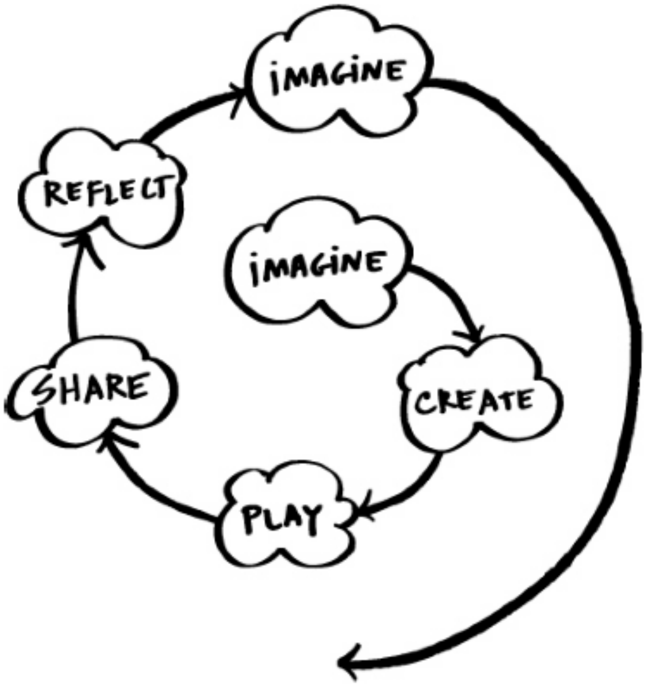


Figure 1: The kindergarten approach to learning

Models vary according to the domain of interest with Boehm being very formal and applicable to large engineering projects and Resnick geared towards early childhood projects. Resnick's model is also more general, that is, it applies to learning in general as well as the design process. In other cases, the model is essentially the same but some of the steps have different names. This can be seen in the Learning By Design Cycle (Kolodner et al., 2003; Puntambekar & Kolodner, 2005). Because the educational goal is learning science using design, this model, like that of Apedoe, Reynolds, Ellefson, & Schunn (2008) (see below) and Fortus et al. (2005) incorporates science inquiry into the model.

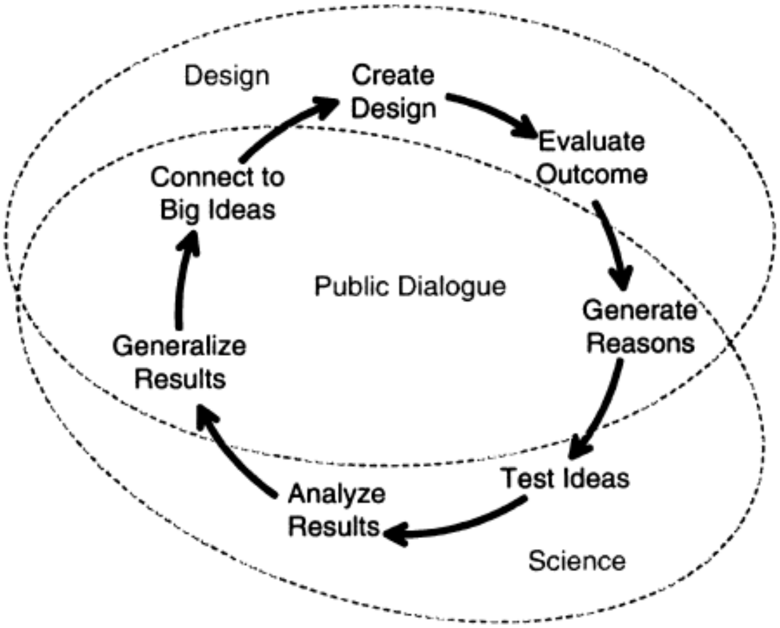


Fig. 2 Learning Cycle

Models also vary with the number of steps and complexity. Martinez & Stager (2013) have a simple three-step model they call TMI: Think, Make, Improve. The steps delineated in other models are subsumed into one of the three steps of the TMI model. Bers, Flannery, Kazakoff, & Sullivan (2014) use another child friendly variation in robotics studies of kindergarten students.

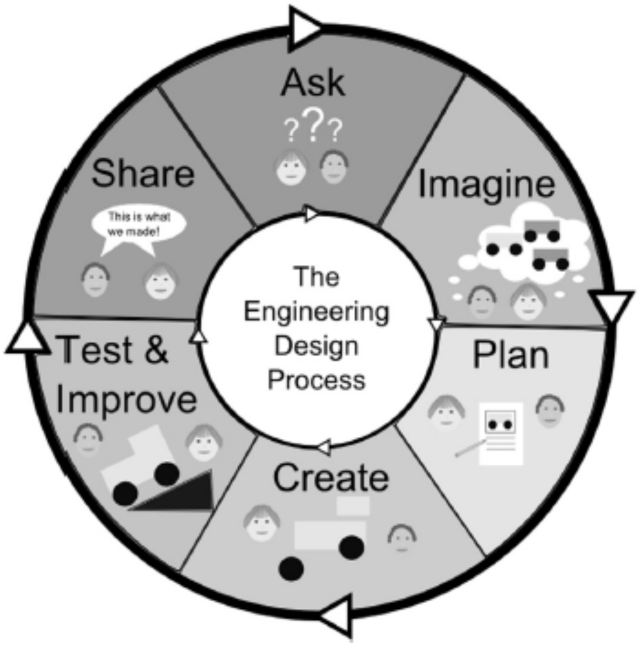


Fig. 4. An illustration of the engineering design process.

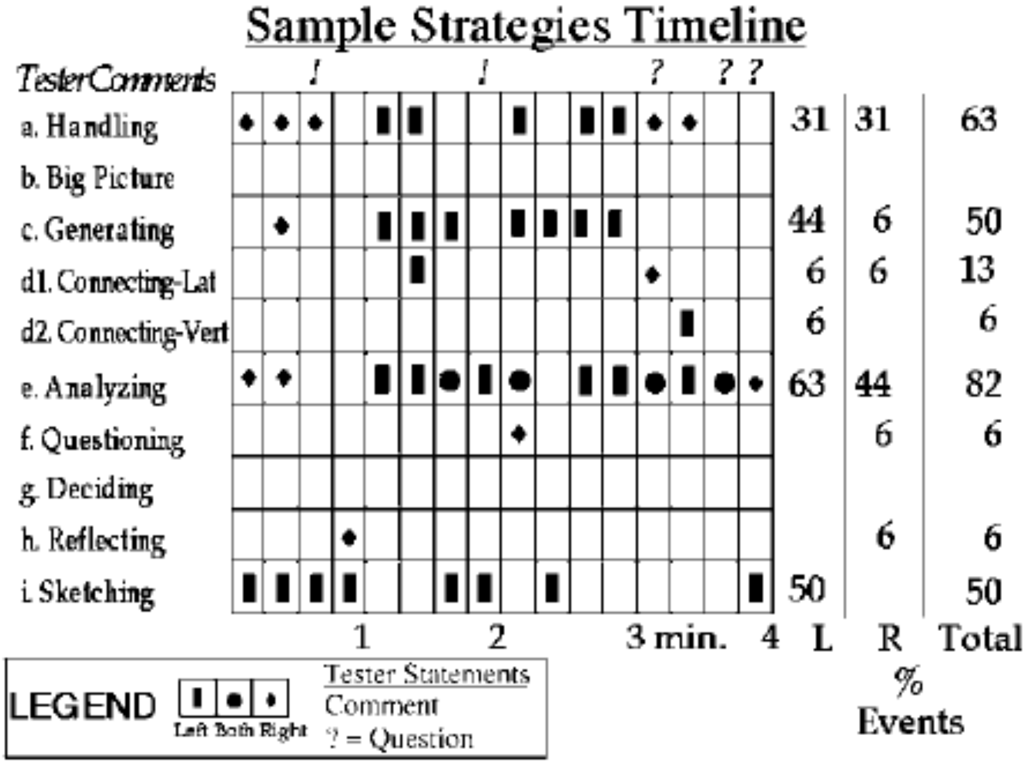
Crismond & Adams (2012) reviewed the existing design process models and attempt to synthesis extant models into a parsimonious and widely applicable model. Note that they do not explicitly label these strategies a design process model because they want them to fit into extant design process models with different numbers of steps (D. Crismond, personal communication, March 16, 2014). They define these nine parsimonious design strategies as part of their larger Informed Design Teaching and Learning Matrix.

1. Understand the Challenge
2. Build Knowledge
3. Generate Ideas
4. Represent Ideas
5. Weigh Options & Make Decisions

6. Conduct Experiments
7. Troubleshoot
8. Revise/Iterate
9. Reflect on Process

For each strategy row, the authors have a rubric consisting of columns for novice and informed designers. They also created columns of learning goals and teaching strategies. For example, for the design strategies Understand the Challenge", novice designers "Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve" while informed designers "Delay making design decisions in order to explore, comprehend and frame the problem better" (Crismond & Adams, 2012, p. 748). The matrix could be a lens in which to classify and measure student design strategies as they progress through school. Furthermore, a mapping could be made from the matrix back to Piaget and explain why novice designers of a certain age may not be yet capable of being informed designers due to a lack of the required cognitive skill.

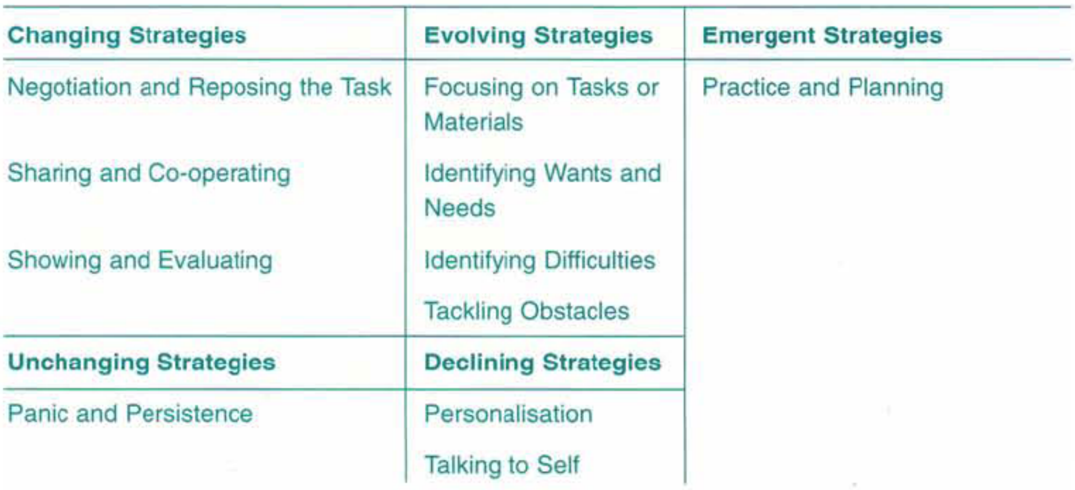
Other related models are not strictly design process models. Crismond (2001) compares novice and expert high school and adult designers as they tried to redesign some common household tools. Each teams' activities was coded and analyzed in terms of a cognitive model Crismond calls the Cognitive Design Framework (CDF). In the CDF, there are three pillars with these horizontal bases: design space, process skills, and content knowledge. Each pillar goes from the concrete level to the abstract level vertically. His thesis was that expert designers make connections both between the three pillars and also vertically from concrete to abstract. The CDF suggested a design process model with these design activities: handling materials, big picture thinking, generating ideas, making vertical CDF connections, making horizontal CDF connections, analyzing, suggesting solutions, questioning, deciding, sketching, and reflecting. The study then analyzed and compared how much time each expert and novice teams spend in each design activity.



Crismond found that only the expert designers used general principles and used connections to science concepts to help their design process. Crismond (2001) concludes that teachers must scaffold design tasks for this reason. Crismond's methodology and design activity model for a redesign task could be a useful basis for study of elementary student design processes and should apply to design (rather than redesign) tasks with modifications and simplifications. However, the focus would not be on making connections between science concepts and the design tasks as much as the strengths and challenges students face at different ages in realizing their design ideas.

Roden (1999) looked at changes in the design process from infant school to primary school in Great Britain over a period of two years with a focus on collaborative problem solving strategies. This study is important for my own research questions since it the only longitudinal design study I have encountered. He classified the collaborative problem solving strategies students used 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. Roden (1999) showed that these strategies do change over time and he suggests that teachers need to understand them and help children make them explicit.

Table 1: Strategy variation over Key Stage 1



Changing Strategies	Evolving Strategies	Emergent Strategies
Negotiation and Reposing the Task	Focusing on Tasks or Materials	Practice and Planning
Sharing and Co-operating	Identifying Wants and Needs	
Showing and Evaluating	Identifying Difficulties	
	Tackling Obstacles	
Unchanging Strategies	**Declining Strategies**	
Panic and Persistence	Personalisation	
	Talking to Self	

This study is important to my own research questions because it did show changes over relatively short longitudinal time frames. The strategies Roden identified are a mix of cognitive, social, and affective strategies. To reduce the amount of confounding variables, my own plan is to focus primarily on cognitive milestones as they relate to design tasks.

Tinkering is an alternate way of approaching the design process.

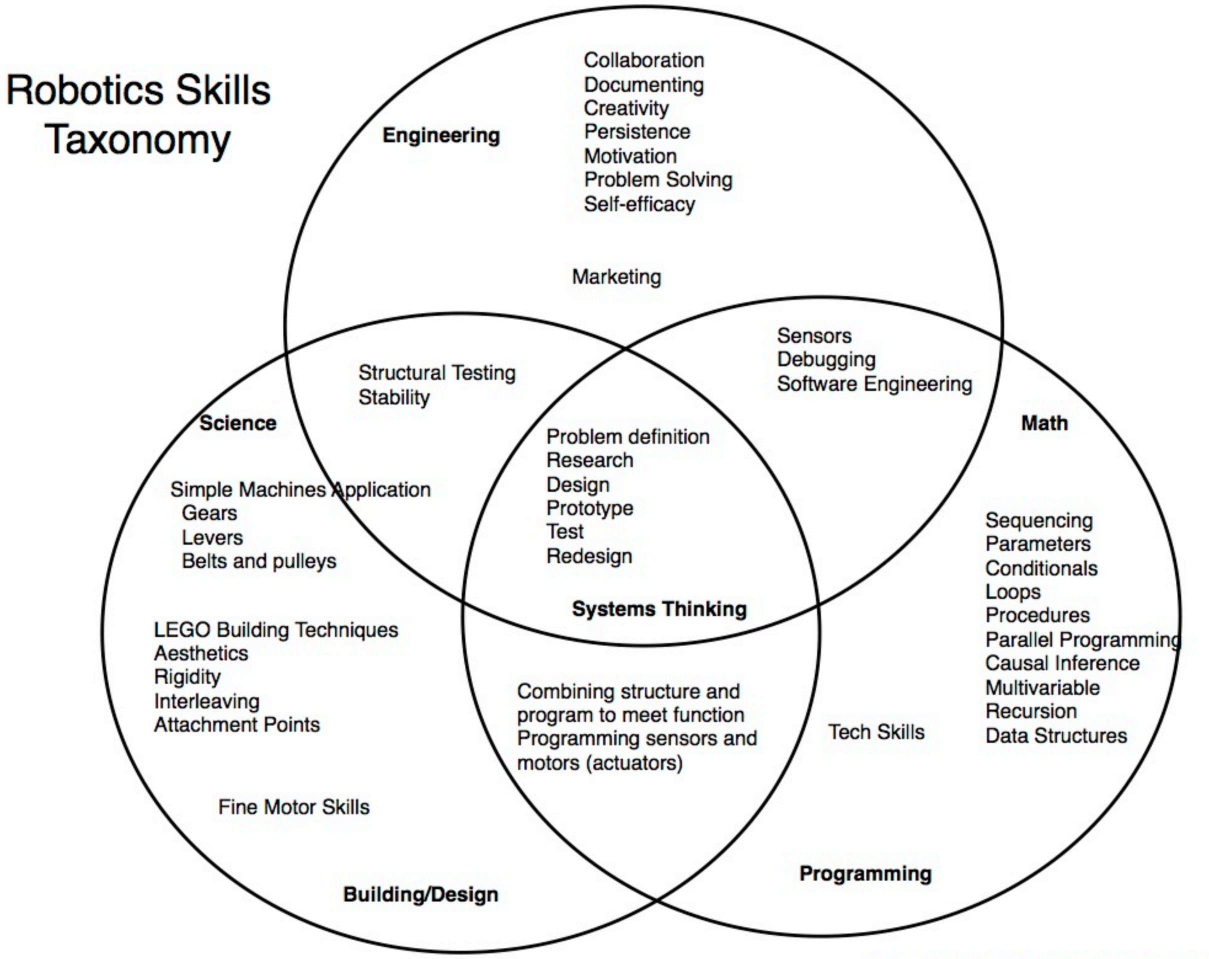
Resnick & Rosenbaum (2013) define tinkering as follows.

> We see tinkering as a valid and valuable style of working, characterized by a playful, exploratory, iterative style of engaging with a problem or project. When people are tinkering, they are constantly trying out ideas, making adjustments and refinements, then experimenting with new possibilities, over and over and over. (page 164)

Tinkering is a bottom-up approach as opposed to the top-down approaches of the design process models examined previously. Tinkerers, also known as bricoleurs, may not have a plan at all or may only have a general idea and may begin the design process by "messing around with the materials" (Resnick & Rosenbaum, 2013, p. 165). This is significant in any case study of design that attempts to classify activities into a formal design process model because some students may be tinkerers and may not fit into a defined design process model.

In a semi-structured clinical interview setting such as the one planned for the case study, a design process taxonomy based on observable behaviors (visually and with a talk-aloud protocol) may prove the most useful for measuring how engineering processes change over time: planning, researching, building, rebuilding, programing, reprogramming, testing, reflecting. The distinction between building and rebuilding and between programming and reprogramming is germane to this study because the study seeks to identify the difficult parts of each session.

A general taxonomy that categories children's robotics building and programming skills and processes may also prove useful for this study. Though complex, it provides a broad view of robotics skills students need when thinking about coding schemes for observable behaviors.



John Heffernan http://www.kidsengine

Other models focus on the surrounding culture and environment where design takes place have a situated cognition (Roth, 1996) or social constructionist perspective (Leonard & Derry, 2011). While social and environmental factors are important and interesting, our focus in on individual cognition changes over time. Now that theoretical framework and design process models have been examined for applicability for a case study of elementary robotics, we turn to a review of relevant methodologies.

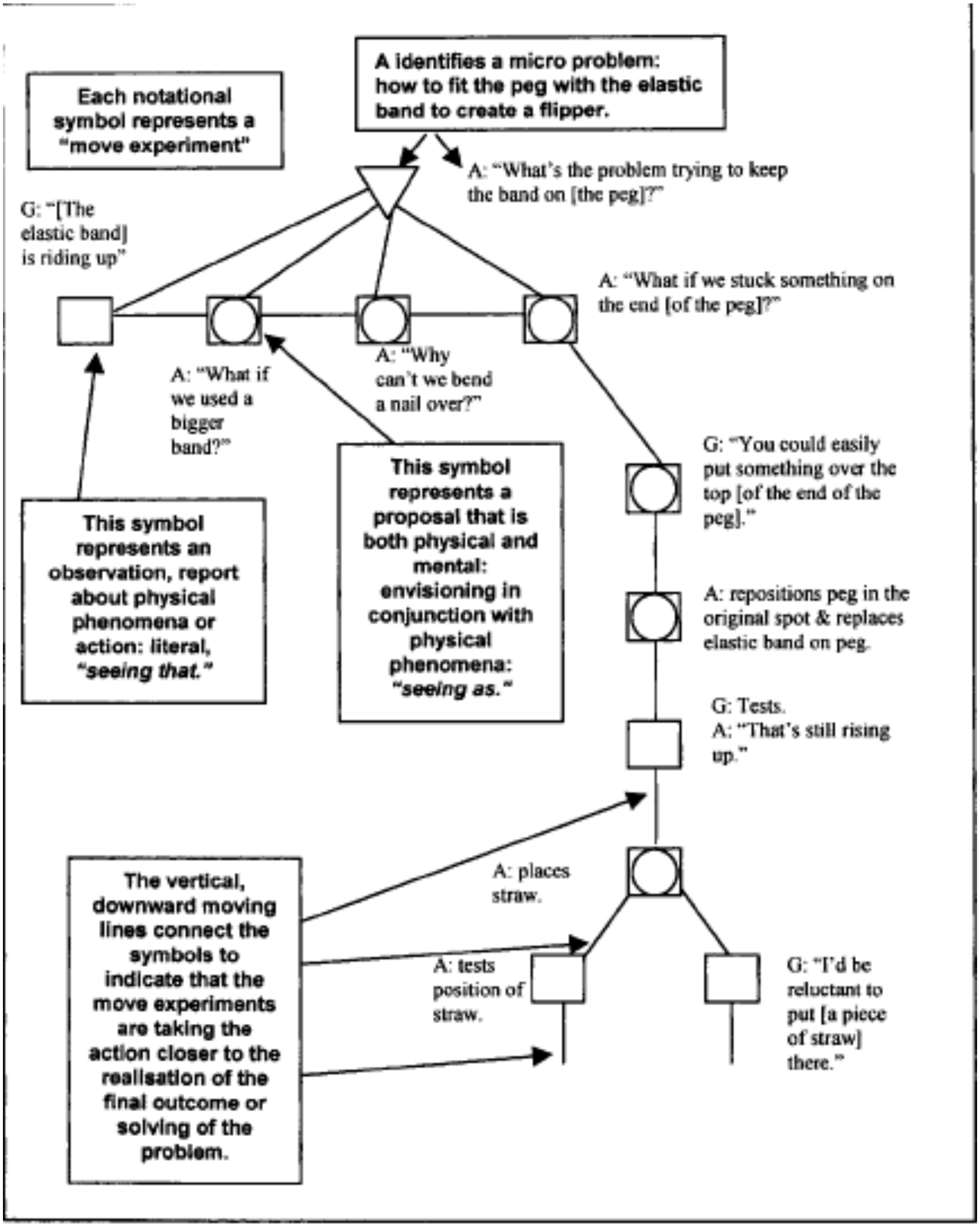
Methodologies

This section addresses the questions:

- What are the most relevant methodologies that can be used or modified for a case study of elementary robotics students that seeks to delineate both the strengths and challenges of students at different ages in elementary school as they tackle open-ended engineering challenges?
- What are the gaps in the existing research of elementary robotics?

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 using pre and post tests. Of greater relevance for my own research questions are case studies that seek to undercover design and engineering processes and development.

Some 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. This case study resulted in a methodology of mapping the evolution of design using connectors and symbols to map out the design and problem solving processes dyads used by analyzing their discourse.



The researchers found a three level hierarchy of problems that learners solved: macro (high level), meso (intermediate), and micro (small, specific). They concluded that novice teachers did not follow the idealized practices found in engineering design process models. Also, "without intervention by the teacher at appropriate times, deeper and more extensive learning about the natural world, about design processes or about knowledge itself at a world knowledge level will not necessarily occur (McRobbie et al., 2001, p. 111). The methodology of mapping out problem solving processes used in this could be a basis for my own research. However, it would need to be modified to work with individual students by examining their building and programming moves and utterances.

Fleer (1999) conducted a case study of design processes for elementary aged children (kindergarten and a combined grade 5/6 class) in terms of how their intended designs relate to what they actually built. In the study, students designed and built cubbies (hiding spaces). A macro, meso, and micro taxonomy of problems in this case study was used as a way to analyze student processes (McRobbie et al., 2001; Roth, 1996).

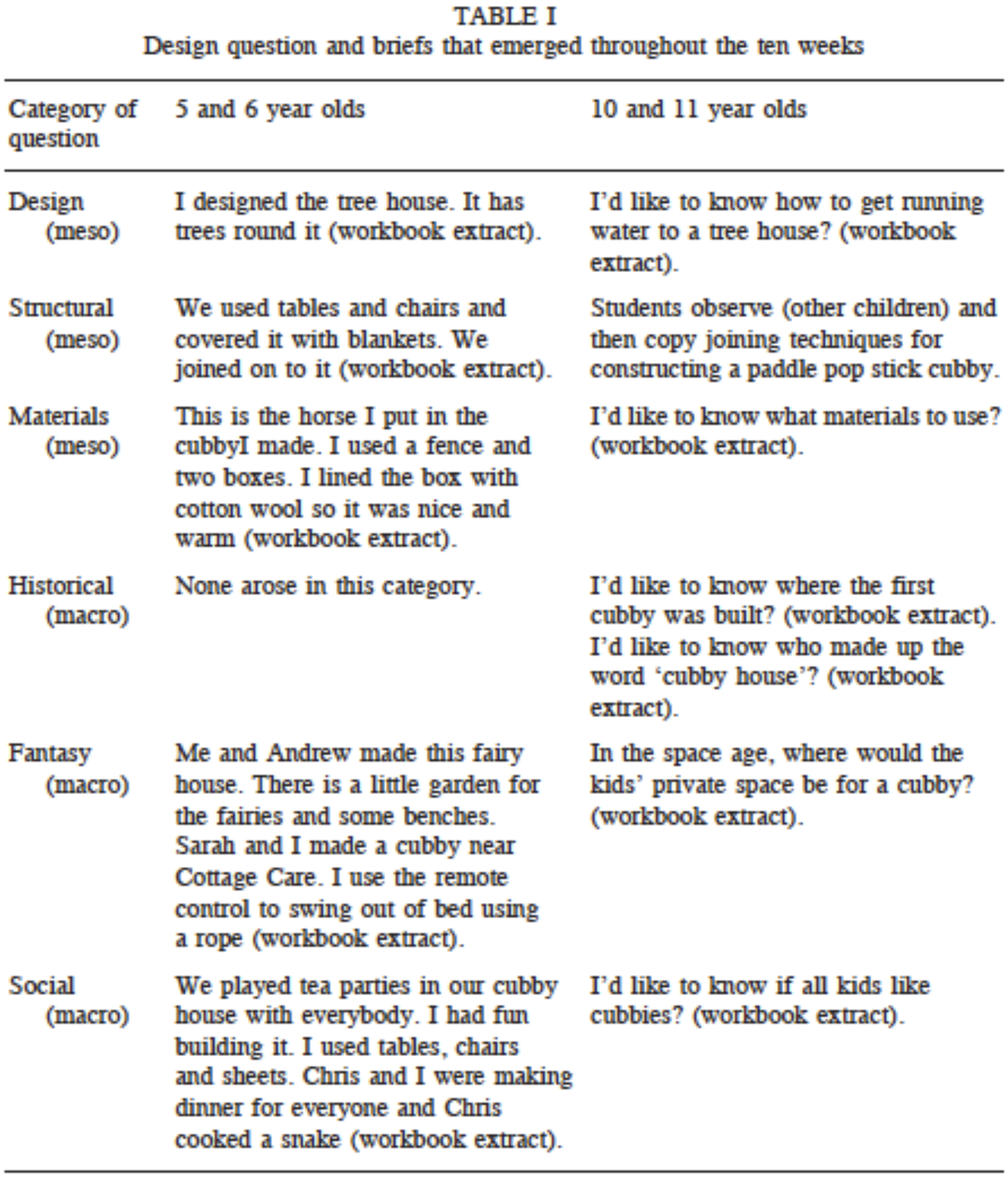


TABLE I
Design question and briefs that emerged throughout the ten weeks

Category of question	5 and 6 year olds	10 and 11 year olds
Design (meso)	I designed the tree house. It has trees round it (workbook extract).	I'd like to know how to get running water to a tree house? (workbook extract).
Structural (meso)	We used tables and chairs and covered it with blankets. We joined on to it (workbook extract).	Students observe (other children) and then copy joining techniques for constructing a paddle pop stick cubby.
Materials (meso)	This is the horse I put in the cubbyI made. I used a fence and two boxes. I lined the box with cotton wool so it was nice and warm (workbook extract).	I'd like to know what materials to use? (workbook extract).
Historical (macro)	None arose in this category.	I'd like to know where the first cubby was built? (workbook extract). I'd like to know who made up the word 'cubby house'? (workbook extract).
Fantasy (macro)	Me and Andrew made this fairy house. There is a little garden for the fairies and some benches. Sarah and I made a cubby near Cottage Care. I use the remote control to swing out of bed using a rope (workbook extract).	In the space age, where would the kids' private space be for a cubby? (workbook extract).
Social (macro)	We played tea parties in our cubby house with everybody. I had fun building it. I used tables, chairs and sheets. Chris and I were making dinner for everyone and Chris cooked a snake (workbook extract).	I'd like to know if all kids like cubbies? (workbook extract).

The methodology used in this study was not fully defined but it appears that drawings, interviews, and videos were examined for commonalities. 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. Play was an integral part of the kindergarten students' design activities.

The younger children especially showed a preference for using 3-D models (i.e., the actual materials) to solve design problems rather than drawings. Fleer also noted the importance of "tacit doing knowledge", that is, children expressed knowledge by acting on materials rather than discourse or drawings. It will be useful for own purposes to ensure that opportunities for preplanning and post make drawings be provided in elementary design research since in my other research I have not requested drawings. A similar overall approach could be used in the longitudinal case study, the differences being the domain (robotics rather than cubbies) and the additional grades studied.

Welch (1999) studied grade 7 students untrained in design working in single sex dyads on a design task. He coded their dialogue, analyzed it, and compared it to an idealized design process.

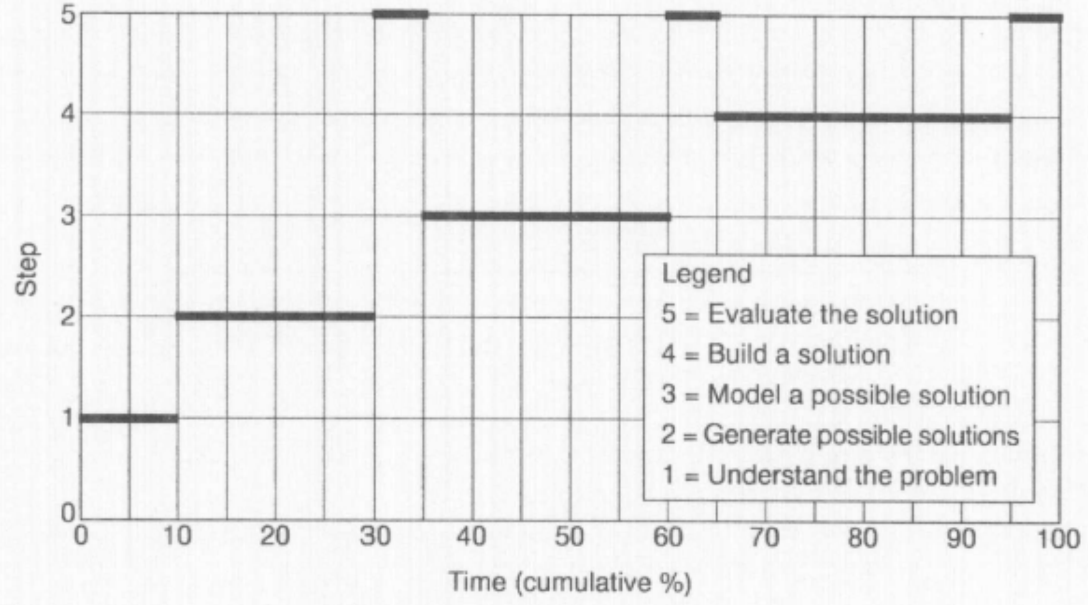


FIG. 3. Map of the five-step theoretical design process used in this study.

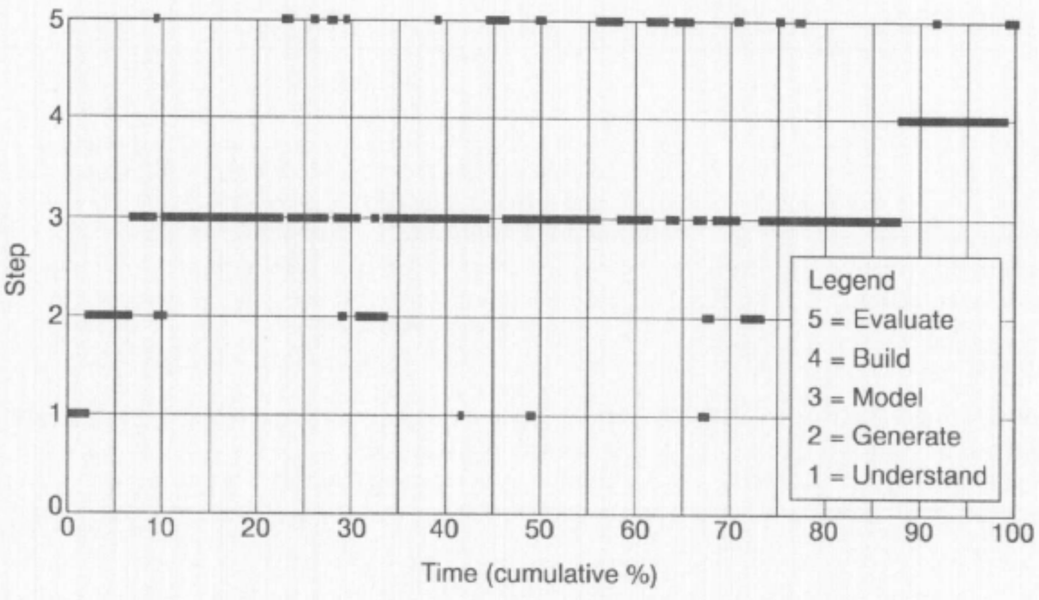


FIG. 2. The strategy used by dyad 5.

He found that students did not follow an idealized design process. They evaluated their design much more frequently that the model would predict, tried one idea at a time instead of evaluating alternatives, and preferred 3-dimensional materials to 2-dimensional sketches. Welch used a variation of grounded theory to produce codes for the study by first using codes for known design activities and then adding those induced by grounded coding theory. The major categories for the codes were: 1) understand the problem, 2) generate possible solutions, 3) model, 4) build, and 5) evaluate. These general categories and/or the method used to generate the codes could be utilized in my own research with younger students.

Portsmore (2011) looked at preplanning for grade one students and found that even first grade students could sometimes use effective preplanning in a design task with familiar materials. She used a one to one clinical interview with a precisely defined design task which was to retrieve a set of keys on a key ring from a tall container using a set collection of materials (such as tape, magnets, spoons, and pipe cleaners) with a twenty-minute time limit. Portsmore provided a very precise and structured task with concise rubrics for drawings of their plans and for their completed student designs. The combination of a controlled environment that enables precise rubrics and quantitative analysis suggests that something along the same lines could be used in longitudinal or cross-sectional study across the elementary grades. Many first graders were able to plan ahead successful designs and materials choices in the familiar and constrained domain. However, they did not necessarily build what they drew indicating that first graders may not have used these drawings as planning as adults would. This once again reinforces the importance of including drawings as artifacts in my own research. The results of this research seem to indicate the planning, which can be considering a formal or concrete operation (depending if the physical materials are on hand) can occur with younger children with familiar materials and tasks that are not too cognitively demanding (Gardner & Rogoff, 1990). Penner, Giles, Lehrer, & Schauble (1997) showed that even first graders could use models in a design task, seemingly ahead of established cognitive milestones.

Wendell & Lee (2010) studied the use of design as way to improve materials science concepts. Although their exploratory case study focused on performance gains, their methodology and rationale for using a case study may have relevance for design case studies. They used a combination of examining and scoring artifacts and semi-structured clinical interviews. Sullivan's (2011) microgenetic videotape analysis of a robotics task also may provide guidance in unpacking creative solutions in open-ended engineering challenges. Microgenetic analysis (Siegler & Crowley, 1991; Siegler, 2006) focuses in detail on cognitive changes and could help pinpoint important cognitive events in the videotape analysis of elementary engineering subjects. Microgenetic analysis research, in general, is characterized by:

1. The density of observations is high compared to the rate of cognitive change,
2. Activity is observed during periods of change,
3. Observations are intensely analyzed both quantitatively and qualitatively.

A combination of microgenetic analysis and a cross-sectional study (where different students of different ages do the same task) is planned for the pilot study to unpack the developmental engineering processes and strategies of elementary aged students over time.

Conclusion

In my current collection of about 200 papers on design, engineering, and robotics, I was only able to find three longitudinal studies. Roden's (1997, 1999) early study tried to broadly induce cognitive, affective, and social problem solving strategies at two points in early childhood. Fleer (1999) did some early, cross sectional work on characterizing the relationship between design and the artifacts actually produced in a design problem at ages five and eleven. English, Hudson, & Dawes (2013) are doing a longitudinal study of middle school students simple machine based designs. However, they are not looking at how students change over time but are more interested in the complete educational systems of teachers, students, and materials. 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 (Crismond & Adams, 2012; Penner et al., 1997; Roth, 1996). A microgenetic, cross-sectional study of elementary design processes would fill in important gap in the research base to help elementary teachers provide the appropriate scaffolding at each rapidly development stage of school age children's' development.

This review has identified the most relevant frameworks, design process models, and methodologies that could be used for such a study. A pilot study is underway to analyze videotape of two elementary students of different ages as they complete an open-ended robotics-based engineering challenge. Through a combination of talk-aloud (Sullivan, 2008), direct observation, and semi-structured clinical interview (Piaget & Inhelder, 1969), various coding schemes based on the ones described here will be tried and possibly modified to characterize student's engineering processes over time with particular focus identifying on the challenging aspects at different ages. Once these are identified, difficulties will be tied back to the matching development milestones provided by the theoretical frameworks of Piaget and others to better inform instruction and curriculum design for elementary engineering in a developmentally appropriate way. The literature does not provide guidance nor is it clear on how to identify strengths at different ages besides subjective, inductive analysis. A more systemic approach for identifying strengths may emerge from the pilot study. Levy & Mioduser (2010) showed that complex and advanced cognition can occur in young children's interpretation of robot rules and behaviors, likewise, similar understandings need to be uncovered for the construction and programming of robots.

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