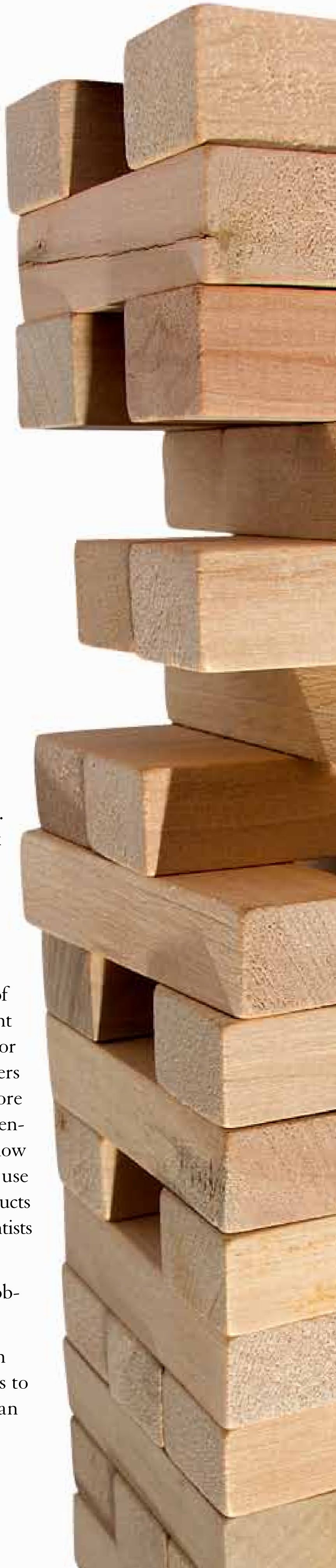
DESIGN PRACTICES AND MISCONCEPTIONS



A *Framework for K–12 Science Education* (NRC 2012) includes *engineering design,* formerly *technological design* (NRC 1996), alongside *scientific inquiry* in K–12 science instruction. Design challenges can include creating whirligigs or parachutes that descend a given distance as slowly as possible, building a model bridge or tower while learning about stability of structures, making a catapult that can hit a target with its projectile, and designing model cars powered by rubber bands, balloons, or fans so that they travel far or fast.

Some science educators may be dismayed at the prospect of including a whole new class of learning activities in their already crowded teaching calendar. Though some teachers may have taught engineering design tasks, few take engineering courses in college and fewer still are trained in effectively using design tasks with students. Such teaching know-how (i.e., pedagogical content knowledge) includes recognizing students' different design practices, knowing learning progressions and common beginners' misconceptions, and using effective teaching and assessment strategies.

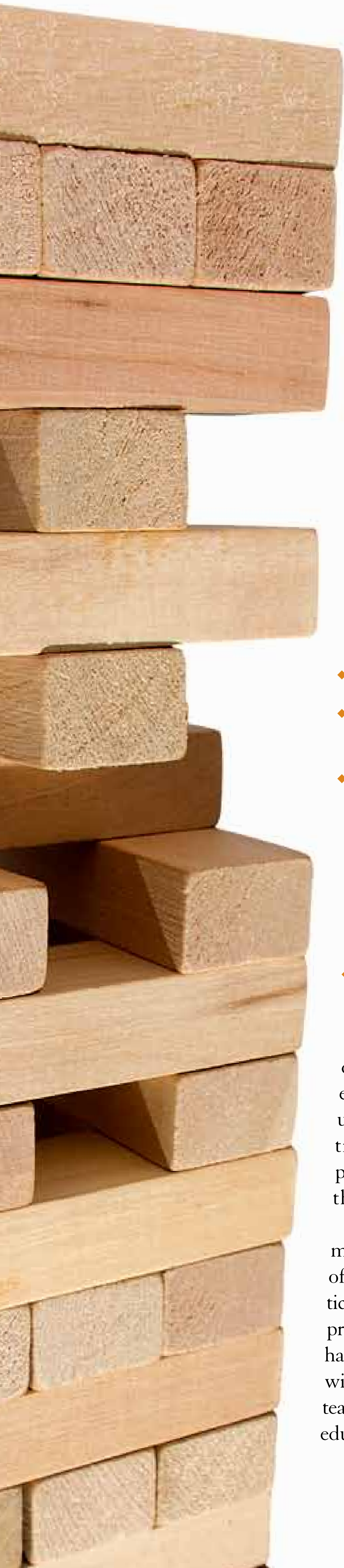
In this article, I describe beginner habits and misconceptions related to design practices (Figure 1, p.52). Once teachers are aware of these habits and misconceptions, they can more easily recognize them and work to remedy them through instruction. "The Informed Design Teaching and Learning Matrix" (Crismond and Adams 2012) provides more in-depth descriptions of the design practices, research on misconceptions, and teaching strategies for helping students become "informed designers" who can learn and use science, technology, engineering, and mathematics (STEM) ideas and practices while doing design challenges.

Background

A Framework for K–12 Science Education (NRC 2012) describes eight practices related to both scientific inquiry and engineering design (Figure 1). Inquiry and design share six of the practices, and two (i.e., numbers 1 and 6) describe practices that make inquiry and design quite different from one another.

Practitioners perform some of the same practices with different goals in mind (NRC 2012). For example, scientists and engineers both use simple models of more complex systems; however, scientists use them to understand how nature works, and engineers use them to understand how products or built systems work. Both scientists and engineers also

- research to understand problems better,
- argue from evidence when choosing which hypothesis to support or what design plan to build,



HELPING BEGINNERS IN ENGINEERING DESIGN

David Crismond

- conduct fair-test experiments,
- use mathematics to transform data,
- interpret test data to see if a hypothesis (science) or prediction about a prototype's performance (engineering) has been refuted or supported, and
- communicate results to others.

What practices make design and inquiry different from one another and unique as key STEM activities? Figure 2 (p. 53) compares the process models for these "big STEM tasks."

The following are habits and misconceptions related to seven of the *Framework's* eight practices. Each item begins with the practice, describes a related design habit or misconception, and ends with details about the habit and teaching techniques that can help educators address these issues.

Practice 1: Asking questions (in science) and defining problems (in engineering)

Habit or misconception: Beginning designers tend to treat design challenges as well-defined problems that they can immediately solve with a single correct answer rather than delaying their design decisions until they understand and frame the problem better.

Scientists observe and ask questions to frame the investigations they conduct. Likewise, engineers need to frame approaches to the ill-defined problems they face. But beginning designers often assume that design problems have a single "right" answer and think they are ready to solve it. Informed designers know that they need to explore the materials and try many possible approaches before committing to any particular solution.

Design teachers typically present new design tasks to their students via a *design brief* (GTRC 2004), which describes the problem situation and explains *what* an acceptable solution must do without clarifying *how.* The functions that the finished product needs to achieve are the design *criteria,* and the solution's limits are the design *constraints.*

Comprehending the design brief is different from framing the design problem. For example, students might read a design brief for model parachutes and summarize it: "We need to design a parachute that takes a long time to fall when we drop it from the top of a bookshelf." However, after students construct a basic parachute and explore how it works, they may reframe their understanding: "We need to build a model parachute that falls straight down with little swaying, has a canopy that inflates quickly and stays fully inflated while falling, and takes a long time to reach the ground when we drop it from the top

FIGURE 1

Practices for K–12 science classrooms (NRC 2012, p. 42).

Inquiry and design share the following practices:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, & communicating information

of a bookshelf." With specific behaviors in mind, students can adjust and optimize their designs until they achieve what they want. Teachers need to remind students to avoid premature decisions until they fully grasp the problem and can describe how they want it to behave.

Practice 2: Developing and using models

Habit or misconception: Beginning designers develop superficial ideas and models that do not help them investigate their designs and would not work if they built them.

Modeling is central to scientific inquiry and engineering design. The goal of modeling is similar for both disciplines: Create a device or system that is a simpler version of an existing device or system. Students can investigate the model to gain insights into the more complex system. Models can be physical, conceptual, or mathematical. In science, students can construct a terrarium to make predictions about a rain forest ecosystem. In engineering, they can build a prototype to learn more about a product and how it works (e.g., a model bookstand made of index cards and rubber bands, a model bridge made of straws and paper clips).

Students can model by sketching with pencil and paper or a computer-based drawing application (e.g., SketchUp, a free drawing program). Computer simulations model systems in nature or technology and can help students predict which plans will work well or poorly before they build them (Crismond, Howland, and Jonassen 2011).

Beginning designers often sketch design ideas that wouldn't work if they built them. *Rapid prototyping,* in which students build very rudimentary models with index cards, cardboard or Legos can help address this issue. Students can also benefit from a class discussion in which they assess the strengths and weaknesses of their models because, in both science and engineering, models are useful but imperfect representations of the phenomena or system under study.

Practice 3: Planning and carrying out investigations

Habit or misconception: Beginning designers run few if any tests on their prototypes, and when they do, they often devise confounded experiments in which they change two or more variables in the same test.

Design tasks provide many opportunities for students to plan and run fair-test experiments that serve their design efforts. These investigations help them learn about how the device works and can help them avoid haphazard or trial-and-error designing. Students select a single feature or variable from the device and decide what to measure and how to control all other variables. Just as scientists do, they then communicate trends in test data that may help them and others make better design decisions.

In their excitement to test a new design idea, students often change more than one variable in a given test. With model parachutes (see sidebar, p. 54), for instance, they can choose to investigate whether vent holes in the canopy improve performance. If students cut out a large vent hole and compare this chute to one with no hole, they will run a confounded experiment—since they are varying both the weight of the parachute and the use of vent holes. Helping students recognize a confounded experiment when testing a design is an important teachable moment in science.

Practice 4: Analyzing & interpreting data

Habit or misconception: Beginning designers tend to be unfocused when watching their prototype tests, and they need structure to effectively troubleshoot their designs.

In engineering design, building a prototype, testing it, and improving the design based on the tests is called an *iteration.* Iterative design is a cornerstone for students' design learning, especially when completed multiple times. For example, if students test a model car prototype, they may not notice that the wheels aren't turning or that it stops suddenly when it should be moving. Students who fail to notice such performance flaws think they saw a well-designed model car in action. In reality, the prototype needs troubleshooting to test whether the axles are aligned or the model has faulty bearings.

Students need instruction and practice to help them see problems in design, identify and determine the causes, and fix them. A four-step troubleshooting process (Crismond and Adams 2012) involves answering these questions:

1. What did you observe during the test? (observation)
2. What would you call the problem you saw? (diagnosis)

3. Why is this problem happening? (explanation)
4. How would you fix it? (remedy)

To help students troubleshoot effectively, have them do side-by-side or *paired tests* of a baseline versus new prototype. The National Science Foundation–funded City Technology materials (see "On the web") ask students to keep a troubleshooting notebook, where they document problems they notice and then try to remedy them using a three-step troubleshooting sequence: identify issue, explain, and fix. Such a notebook helps meet literacy goals while it provides evidence of student learning, chronicles the evolution of the design, and unveils students' understanding of how the device works.

FIGURE 2

Scientific inquiry and engineering design process model comparison.

A side-by-side comparison of process models for scientific inquiry and engineering design shows that certain practices are shared and others aren't.

Scientific inquiry	Engineering design
Observe and question	Grasp and frame problem
Research	Research
Generate hypotheses	Generate ideas
Use models and make predictions	Use models and build prototypes
Conduct experiments	Conduct experiments
Interpret data and iterate	Troubleshoot and iterate
Communicate	Communicate

Practice 6: Constructing explanations (for science) and designing solutions (for engineering)

Habit or misconception: Beginning designers can be reluctant to generate more than one solution to a design challenge.

Generating lots of ideas and selecting the best idea for further development is a trademark design thinking strategy. Though many techniques exist for helping people generate ideas, *brainstorming,* during which the aim is to generate lots of different ideas, may be the best known. Research shows that emphasizing *quantity* of ideas over the *quality* leads designers to produce more quantity *and* quality (Paulus, Kohn, and Arditti 2011).

Beginning designers sometimes resist requests to generate multiple solutions to a challenge, especially when working in an unfamiliar domain. Once students come up with an initial idea, they may ask, "Why should I brainstorm more when I already have an idea worth trying?" This habit, known as *idea fixation,* involves "the inability of designers to see new ways of using objects they are exposed to" and a "premature commitment to a particular design solution" (Gero 2011). Brainstorming can help designers avoid such fixation. If students can think of three or more viable solutions, then it is harder (although not impossible) for them to fixate on any single plan.

Practice 7: Engaging in argument from evidence

Habit or misconception: Beginning designers are often unaware of reasons for their design decisions, which can be a result of not weighing the pros and cons of each solution.

When teachers give students a design challenge and leave them to their own devices, they grab for materials and start building before they have well-formed ideas in mind (i.e., impulse designing). But teachers can channel such enthusiasm so that students make design decisions based on sound reasoning and big STEM ideas (i.e., informed design decisions).

When teachers ask students to describe the ideas they are considering, students tend to talk about the positives in the plans they like and the negatives in plans they don't. But teachers can help students review all design options, articulate the good and bad of each idea, and share this thinking with others. Though the objective of marketplace design is to sell products, the goal of classroom design activities is to get students to learn, explain how things work, and provide reasons for their choices. Teachers want to encourage students to explain both the pros and the cons of design ideas they consider.

Practice 8: Obtaining, evaluating and communicating information

Habit or misconception: Beginning designers sometimes skip conducting research before they design and may miss opportunities to communicate what they learn from doing design work.

Beginning designers sometimes confuse *designing* with *inventing.* Inventors go to the patent office with an idea they believe is novel and useful so that they can develop the idea and receive royalties on it. A civil engineer, however, doesn't have to invent a new kind of bridge every time a city needs a span built. Instead, he or she chooses from a collection of existing bridge types (e.g., arch, suspension, truss, trestle) and adapts one plan to meet the needs of the particular terrain and keep within budget. When faced with design challenges, beginning designers should conduct research to find out what other designers have created.

Students can research design in many ways. For example, they can investigate earlier versions of the product they are developing, write a product history to show how products evolve, or conduct focused internet searches, using appropriate search terms (Kimbell 1994). Teachers can have students regularly turn in a results table (Barlex and Wright 1998) to check for students' understanding of relevant STEM topics.

Informed design rubric

A rubric based on these misconceptions and the notion of informed design (Crismond and Adams 2012) is available online (see "On the web") to help teachers mark students' progress as they become familiar with engineering design practices. This Informed Design Rubric helps teachers assess student learning over one or more design activities, and even multiple years of instruction, and can be used to follow students' development of capability in design practices.

Conclusion

Including design among the short list of key practices that science teachers soon will be asked to address with students is challenging yet doable. There is much overlap between inquiry and design, and science teachers have seen design challenges in instructional materials before. Helping students to learn to design demands that teachers be aware of common starting points and preconceptions. By keeping habits of beginning designers in mind during instruction, teachers can sharpen their planning and interventions as they use more design activities in their science classes. ■

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On the web

City Technology materials: *www.citytechnology.org*

Design in the Classroom: *www.designintheclassroom.com/designTasks/parachute/index*

Informed design rubric: *www.nsta.org/highschool/connections.aspx*

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Model parachute design challenge.

Teachers and students can learn about the forces of gravity, air friction, and Newton's laws of motion while creating model parachutes out of coffee filters, masking tape, paper clips, and string. *Problem-Based Inquiry Science*'s "Diving Into Science" module (GTRC 2010) has students develop whirligigs and model parachutes, both of which are designed to take the longest possible time to fall a given distance. Watch a tutorial on the relevant science in the *Design in the Classroom* website (see "On the web"), which has videos showing classroom implementations of this and other design challenges.

The type of path that a model parachute travels (e.g., straight down, angled, or wavy) during descent is an important outcome for students to describe as they test different designs.