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REPORTS AND REFLECTIONS

Principled Practical Knowledge: Not a Bridge but a Ladder

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The much-lamented gap between theory and practice in education cannot be filled by practical knowledge alone or by explanatory knowledge alone. Principled practical knowledge (PPK) is a type of knowledge that has characteristics of both practical know-how and scientific theory. Like basic scientific theory, PPK meets standards of explanatory coherence. However, its main function is not explanation or prediction but practical guidance. PPK grows out of efforts to solve practical problems, but it requires additional effort invested in producing knowledge that goes beyond what is required for the task at hand yet not so far beyond as to be unusable by practitioners. The Wright brothers' construction of PPK to address problems of flight control is used as a model for building such knowledge in the learning sciences. Design-based research in the learning sciences may motivate research into basic theoretical questions, but it is unlikely to contribute directly to answering them. Extending design-based research to the creation of PPK can, however, increase the generalizability of knowledge produced through design work and provide a ladder leading to sometimes radical design improvement.

Although the local, situated character of educational design research is widely recognized, a number of learning scientists have considered how design work might contribute to more generalizable knowledge about learning (e.g., Brown, 1992;

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Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004; Design-Based Research Collective, 2003; diSessa & Cobb, 2004). In this article I discuss a kind of generalizable knowledge that can come out of design work but that is not presumed to contribute directly to the advancement of learning theory or any other basic theory. It is what I call *principled practical knowledge* (PPK).

Informally, PPK may be defined as *know-how combined with "know-why."* This definition is too loose for analytic purposes, however. PPK may be more precisely characterized as *explanatorily coherent practical knowledge.* Thus, the know-why, although not necessarily constituting a testable theory, meets standards of explanatory coherence—internal consistency as well as consistency with evidence and coherence with other explanatory propositions in the field (cf. Thagard, 2000).

I use the term *practical* in preference to *procedural* knowledge because the latter term is so closely tied to the familiar distinction between procedural and declarative knowledge. Principled practical knowledge is both procedural and declarative. It is knowledge of how to achieve practical objectives but it is also knowledge that can be communicated symbolically, argued about, combined with other propositions to form larger structures, and so on. Furthermore, PPK is not merely a description or codification of practice. Although it is created in the process of solving problems, it involves additional effort and it can play an active part in advancing the problem-solving or productive process.

NOT ALL CODIFIED PRACTICAL KNOWLEDGE IS PRINCIPLED

PPK is explicit rather than tacit knowledge (Nonaka & Takeuchi, 1995). As such it is accessible to the range of what Inhelder and Piaget (1958) called "formal operations": operations performed on propositions rather than operations performed by concrete action or its mental representations. But practical knowledge can be explicit without being principled. The typical food preparation recipe, for instance, represents explicit practical knowledge but not principled knowledge. It tells us what to do, but it seldom tells us why. This becomes important if we are interested in improving or simplifying a recipe. Virtually every risotto recipe instructs us to add liquid to the rice a little at a time, stirring until the liquid is almost gone before adding more liquid. But the vendor of a top-quality Italian rice recommends forgetting all that, just measuring the rice and liquid into a pot, slapping on the lid, and letting it cook for the suggested time. There are two possibilities for what this could mean:

1. The traditional method is obsolete; it was adapted to the uncontrolled conditions of a wood fire, on which cooking according to time could result

in burned or underdone rice; the temperature control afforded by modern cooktops makes the laborious traditional method no longer justified.

2. Something is in fact lost in abandoning the traditional method, but the loss is slight and the vendor hopes to attract more customers by making risotto easier to prepare.

Without principled knowledge we have no way of evaluating these alternatives except through empirical trials.

Some risotto writers claim that the traditional method is necessary in order to release and distribute starches that make the risotto creamy. This is a justification, but it falls short on the criterion of coherence. It is ad hoc, unrelated to more general principles of food chemistry, and it is unclear as to how it might or might not apply to other cases in which creaminess is desirable. It is an empirical generalization local in scope and unconnected with deeper levels of explanation. Everyday knowledge, as Vygotsky (1934/1962, p. 116) pointed out, is distinguished from scientific knowledge by its lack of system. PPK is systematic, coherent in a broad theoretical sense. It provides explanation, but unlike formal theoretical knowledge, its main purpose is not explanation or prediction but practical guidance.

THE EXPLANATORY FUNCTION OF PPK

In basic scientific research, explanation is typically an end in itself. A progressive research program, as defined by Lakatos (1970), is one that deals with anomalous findings and unexplained loose ends by building stronger and deeper explanations as opposed to adding theoretical patches to cover special cases. PPK aims at explanation as well, but only to a depth sufficient for its purposes. Zoologist and evolutionist E. O. Wilson (1998, p. 61) wrote that the human brain evolved "to survive in the world and only incidentally to understand it at a depth greater than is necessary to survive." PPK goes beyond what is necessary to survive—beyond requirements of the task at hand—but not far beyond. PPK goes to a depth that is sufficient for a field of practice to advance.

"Sufficient for a field of practice to advance": This phrase packs important implications. If knowledge is only sufficient for the task at hand, progress in a field will be slow and far from certain. It will be an evolutionary process coming about through accidental variations, through what Alfred North Whitehead called "the occasional happy thought" or, as has often been the case in contemporary education, through appropriating innovations from more progressive fields. Progress will be slow because in any established profession or occupation there will already be knowledge of what to do and how to do it sufficient for normal activities and contingencies (what is nowadays called "best practice"); but it will not necessarily be sufficient to produce desired outcomes, much less to extend the limits of what practice can achieve. *Best practice, evidence-based practice,* and *reflective practice* all refer to ways of making optimum use of know-how that already explicitly or implicitly exists. They are not the same, but they are compatible and can make a powerful combination. But it is not a combination that advances the frontiers of practical knowledge. In a word, it does not *invent.* In most fields of practice today—medicine, communications, agriculture, energy production, and so forth—invention is what moves them ahead, not only technological invention but also invention in strategies, methods, and organizing concepts. To the extent that education needs invention in order to advance, it needs PPK.

PPK ARISING FROM, AND PLAYING A PART IN, PROBLEM SOLVING

The phrase "theory into practice" implies a unidirectional and sequential process, with basic research and theory coming first. PPK, by contrast, does not adhere to this sequence but instead comes out of and develops simultaneously with efforts to achieve practical goals.

A classic example of PPK created in the course of solving a problem is the Wright brothers' solution of the problem of lateral control in an airplane (the following account is elaborated and documented in Bereiter, 2009). Because it is a story about design and because it is so rich in concrete detail, the Wright brothers' story has been mined for insights into the creative design process in the learning sciences (O'Neill, 2012) as well as in business management (Eppler, 2004) and creativity research (Crouch, 1992). Here, however, I consider it from the standpoint of problem definition and the construction of principled knowledge as part of the solution process. The immediate problem faced by the Wrights and their fellow pioneers of powered flight was the tendency of early airplanes to roll over and crash. Efforts by other airplane pioneers pursued greater lateral stability through the size, shape, and orientation of wings. It was known, for instance, that a dihedral configuration (wings sloping upward to form a shallow V) increased lateral stability. Yet these efforts were not sufficient, and experimental airplanes continued to crash. The Wright brothers, however, reconceptualized the problem as one of recovering balance when the wings begin to tip. They observed that gliding birds did this by changing the front-to-back angle of their wing tips. By a mechanism they called "wing-warping," the Wrights were able to achieve this effect. The mechanism enabled them to make continual small adjustments to lateral orientation, thus keeping the wings level. An unwanted consequence of tilting the wings, however, was that the airplane tended to swerve off course. The Wrights, although initially discouraged by this result, found that they could correct the fault by yoking a vertical rudder to the wing-warping mechanism. In solving the problem of lateral control, the Wrights produced principled knowledge, which they actually called a "theory." It was indeed know-how combined with know-why, and they patented and lectured on their invention as a theory. But it is important to appreciate that the theory did not precede practical problem solving, nor was it a natural emergent of the problem-solving process. The Wrights thought long and hard about it, observed birds in flight, and experimented with kites and gliders. But it was not theory for theory's sake; it was theory in the service of solving a practical problem. The theory did not constitute a solution in and of itself. There was still the matter of designing a mechanism that would produce the desired adjustment of the wing tips, a problem that was famously solved when Wilbur Wright noticed the effect of twisting a bicycle inner tube box. But it was principled knowledge that made the twisted box recognizable as suggesting wing-warping, the solution quickly arrived at by the brothers. There was no gap between theory and practice.

There was a gap between theory and practice, however, in the work of a contemporary of the Wrights, J. P. Langley, whose attempts at powered flight occurred close in time to their own. Langley was a highly respected physicist and astronomer who had done 15 years of research in aeronautics. He had done empirical research on lift and thrust and had formulated what came to be called "Langley's law," which served to convince people in advance of actual demonstration that powered flight was physically possible. His effort finally to translate theory into practice, however, was a complete failure. As explained by Anderson (2002, pp. 78–79),

> Langley made no experiments with piloted gliders to get the feel of the air. He ignored completely the important aspects of flight control. He attempted to launch Manly [his chief engineer] into the air on a powered machine without Manley's having one second of flight experience.

Although guided by the most sophisticated knowledge of aeronautics available at the time, Langley had produced a plane that was evidently structurally unsound and not navigable. His unfortunate experience illustrates what seems to be a common failing of the theory-first, practice-second approach. No one expects a theory to cover all aspects and contingencies of a real-life problem, but with the theory-first model, the theory's gaps can become practical failings.

Theory-first approaches with similarly disappointing results have had a part in the history of education. In the early 1960s, Piaget's theory was just beginning to make its way into North American education. The Genevan research provided ways of testing stages of cognitive development but had little to say about promoting growth from one stage to another. Efforts to apply the theory in early childhood education relied on giving children practice on the tasks used in assessment (Lavatelli, 1970). A limited application of Piagetian theory at best, it was further limited by the fact that educators did not understand the theory at a deep enough level to generate additional tasks and so were bound to the rather small set of procedures used in research. It was not until mathematics and science educators began to tackle known learning problems from a Piagetian perspective that PPK of a constructivist character began to be produced. And real pedagogical breakthroughs only began to appear in the late 1970s, when neo-Piagetian theory was developed that could lead to significant innovations in approach to learning problems (cf. Case, 1985).

The Piagetian theory-into-practice story is being replicated today in efforts to teach phonemic awareness. Research has established the importance of children's ability to perceive spoken words as composed of identifiable sounds and has provided ways to assess it (Blachman, 2000; Murray, 1998). But how to teach phonemic awareness? This is still mainly done by having children practice the tasks used to measure it. Again, theoretical knowledge is too shallow to support the generation of new and improved learning activities. Principled know-how and know-why need to be produced before much progress in this important instructional mission can be expected.

The Wright brothers' story has a further fascinating chapter. Wing-warping and the principled knowledge that lay behind it were developed by the Wrights in order to keep a plane level, to proceed some distance in a straight line, and to land safely. That was the modest goal airplane pioneers were aiming at and was the basis for prizes awarded at the time. But it turned out that the combination of wing-warping and a movable vertical rudder produced an airplane capable of doing something unheard of, namely making banked turns. It was the ability to make graceful banked turns with a short radius that astonished the aeronautics community and altered the course of airplane development. This is a dramatic illustration of the fact that PPK, like theoretical knowledge in general, can have implications and applications far beyond what the creators of the knowledge envisaged.

The most notable thing about the learning sciences, in the context of the present discussion, is that they have largely abandoned the theory-into-practice model and followed the Wright brothers in creating PPK on the way to solving real-life educational problems. When successful, such knowledge eliminates the gap between theory and practice.

PPK AND DOMAIN THEORY IN THE LEARNING SCIENCES

According to Edelson (2002), whereas the goal of ordinary design work is to create "a successful design product," design research has in addition "the goal of developing useful, generalizable theories" (p. 112). Besides theories and models internal to design as a form of practice, Edelson proposed that design research could also produce *domain theory,* which he characterized as "a theory about the world, not a theory about design per se" (p. 113). However, the examples he offered fall short of constituting a scientific theory, if by that we mean "a comprehensive explanation of some aspect of nature" (National Academy of Sciences and Institute of Medicine, 2008, p. 11). One theoretical result claimed by Edelson "describes the challenges facing students who are engaging in extended scientific investigations for the first time" (p. 113). This sounds less like a theoretical explanation than like something a theory is needed to explain. The same may be said of his second example, which is a model of reflective inquiry that "breaks the skills of reflective inquiry into three key components . . . : creating a record of progress, monitoring progress, and communicating process and results to others" (p. 114).

It is to be expected, of course, that design research will lead to new insights and new problem formulations. With further reflection it may also lead to new distinctions and new categories—what diSessa and Cobb (2004) called "ontological innovation" and to which Tsoukas (2009) attributed a powerful role in organizational knowledge creation. All of these have potential relevance to learning theory, helping it develop beyond where it can get by traditional experimental methods (Brown, 1992). Sandoval (2004), however, proposed that advances in learning theory may come about through refining conjectures about learning that are embodied in the design products themselves.

All designs may be said to embody ideas, but these ideas are not necessarily cognitive objects available for further development. Birds' nests embody structural ideas and ideas about materials, sometimes very complex ones, but they are not available to the bird for use in developing a theory or designing a better nest. The embodied conjectures discussed by Sandoval (2004), however, are explicit ideas drawn from prior theoretical knowledge. In the example discussed by Sandoval,

> the central conjecture is that conceptual and epistemic scaffolds for scientific inquiry should be integrated such that they can help students understand the epistemic goals of their inquiry (the kind of knowledge they are trying to construct) while providing conceptual guidance that supports students as they try to make sense of particular problems in specific domains. (p. 216)

This is practical knowledge, as I have been using the term, but it is not at this stage principled, let alone theoretical. However, synthesizing findings from various studies, Sandoval refined the conjecture into one that he called "theoretical": "The theoretical conjecture is that epistemological ideas constrain the space of possible investigative strategies one might employ during inquiry to those that satisfy knowledge-making goals, but that such epistemological constraints function in relation to disciplinary knowledge" (p. 216). What we have here is a coherent justification of the practical knowledge, hence, PPK. I would not call it theoretical. It explains why integrating conceptual and epistemic scaffolds is a promising idea, but it does not link up with any cognitive theory that might explain how epistemological ideas constrain investigative strategies, nor is it a testable theoretical proposition in its own right. Sandoval claimed that “the underlying theoretical conjecture . . . can be tested by examining whether predicted intervention outcomes occur” (p. 217), but any real-life application of the scaffolding ideas is unlikely to rule out alternative conjectures. What gets tested in design-based research is the practical knowledge, not its principled basis.

Besides reporting a series of refinements in scaffolding design, Sandoval (2004) also reported finding that students’ inquiry strategies did not mesh with their explicit beliefs about science as a discipline. This led him and his coinvestigators to launch a research program on students’ practical epistemologies. This is theory-building, explanation-seeking research that may in turn launch a new cycle of design research and PPK development.

In summary, Sandoval (2004) and, in less detailed form, Edelson (2002) appear to have been describing a three-stage process that consists of (a) a practical observation growing out of the design research experience; (b) a relatively limited and shallow but nevertheless plausible, coherent, and generalizable explanation of what has been observed; and (c) basic research aimed at integrating the results of Stage 2 into canonical theory (i.e., “a comprehensive explanation of some aspect of nature”; National Academy of Sciences and Institute of Medicine, 2008, p. 11). Stage 2 represents PPK, which is both a foundation for further design advances and a stimulus for theoretical research, but it cannot be expected to play a direct role in basic theory building.

PPK’S ROLE IN DESIGN-BASED RESEARCH

It is beyond the scope of this article to survey examples of PPK leading to advances in learning and teaching. The much-cited Bransford, Brown, and Cocking (1999) volume and subsequent publications from National Academies Press, along with the *Cambridge Handbook of the Learning Sciences* (Sawyer, 2006), provide numerous examples. If I were to pick one exemplar it would be the work of Robbie Case, since carried forward by his students (Case, 1985, 1992; Case & Okamoto, 1996). The key theoretical idea is central conceptual structures, which underlie and enable the kinds of learning that figure in educational objectives but which, Case believed, are teachable in their own right. For whole number arithmetic, the central conceptual structure can be represented by the number line. Intensive use of game-like activities designed to internalize the number line structure proved to be highly effective in boosting children’s subsequent performance in elementary arithmetic (Griffin, Case, & Siegler, 1994). The obvious next challenge was rational numbers, a domain in which failure tends to be the rule rather than the exception. I remember Case speculating about the nature of the conceptual structure underlying rational number understanding and experimenting with various representations such as dual number lines. His epiphany came while gazing at the little bar on a computer screen that indicates the progress of an operation—without any numbers! It is pure proportionality, and if the bar is quantified at all it is in terms of percent; yet it is immediately comprehensible. Joan Moss and Case (1999) worked out an approach to rational numbers that turned the conventional fractions-first approach on its head, starting with unquantified proportionality and then introducing percents, only later moving to fractions. The model for the underlying conceptual structure was not number lines but rather tubes or beakers of similar shape but dissimilar size that children could compare as to fullness (Moss, 2005). Children's intuitions about degrees of fullness served as the basis for a series of games and activities used to build up proportional reasoning, with the arithmetic of rational numbers coming later as a means of dealing more precisely with proportions. The effectiveness of the approach was remarkable.

I have singled out this example because it represents a radical flip, similar in kind if not in consequence to the Wright brothers' flip from focusing on stability to focusing on control. Most instructional advances brought about through learning science research stay within existing curriculum frameworks, introducing innovations in content or process: Consider such landmark examples as reciprocal teaching (Palincsar & Brown, 1984), Lampert's (1986) approach to teaching arithmetic algorithms, and Learning by Design (Kolodner, 2006). The Moss and Case example represents a more radical shift, a shift of problem definition from one that attempts (frequently with ill success) to build on children's intuitions about whole number quantities (Ni & Zhou, 2005) to one that builds on their intuitions about fullness. Such flips are bound to be uncommon, but they still fall within the range of what may come about through the pursuit of PPK.

PPK AND THE THEORY–PRACTICE GAP

The learning sciences as a whole may be taken as an effort to overcome the much-lamented gap between research and practice in education. A common metaphor for dealing with this gap is that of a bridge, as in *Bridging Theory and Practice in Teacher Education* (Gordon & O'Brien, 2006). As far back as the beginning of the 20th century, psychologists interested in education have been saying that education needs a bridging discipline similar to engineering, which spans the gap between basic physical science and manufacturing (cf. Dewey, 1900). Are the learning sciences that bridge, and if so where does PPK fit in?

Some insight into issues of gaps and bridges may be gained by examining something going on in a neighboring discipline, computer science. There is a theory–practice gap in computer science, with theory represented by people who create algorithms and practice represented by people who try to build things that actually work on computers that actually exist. Although the gap has existed for decades, resulting in sometimes troubled coexistence within departments, there is now emerging an effort to deal with the gap by creating a bridging discipline explicitly labeled *algorithm engineering* (Müller-Hannemann & Schirra, 2010).

At first glance, it appears that algorithm engineering maps well onto design-based research in the learning sciences. The algorithms coming from the theory side meet certain ideal criteria, but they come with no assurance that they will work in the messy conditions of real life. Algorithm engineers implement the algorithms under realistic conditions and carry out design-and-test iterations to achieve practical results, sometimes discovering actual theoretical errors, other times finding theoretically suboptimal algorithms that work better for real-life tasks with real-life parameters. If we substitute "educational strategies" for "algorithms" this sounds much like what learning scientists do in developing workable designs that draw on theoretical knowledge from the more basic behavioral sciences. However, closer analysis reveals important differences. The algorithms coming from theoretical computer science actually *do* work—mathematically. They produce intended results, just not necessarily results that can be achieved in real-life applications. The first steps in algorithm engineering, according to Chimani and Klein (2010), are to understand the theory-derived algorithm and try to implement in faithfully. This is very different from what the learning sciences get from theoretical work in cognitive science, for instance. We may get suggestive ideas and findings. In the extreme, we may get constraints (such as working memory constraints) that our designs must work within. But we do not get anything like algorithms, conceptual artifacts that work in a definite enough fashion that they can be implemented and adapted. In effect, learning scientists do what both theoretical computer scientists and algorithm engineers do. We produce ideal strategies that work under the optimal conditions found in experimental classrooms, where researchers and practitioners work closely together, and we test and modify the strategies in more typical real-world conditions.

Software engineering, too, must deal with real-world conditions such as those of business offices and technically unsophisticated office staffs, where usability issues become paramount. But that is not what algorithm engineering is about; that is the job for another subdiscipline, usability engineering (Holzinger, 2005). Algorithm engineering is concerned with filling a gap that exists *within* computer science, between ideal and real problem spaces. A comparable gap exists within the learning sciences, even though it is not institutionalized in the form of different professional roles. Something comparable to algorithm engineering needs to occur in design-based learning research in order to bring forth designs that are *capable* of working in real-life learning environments. I suggest that PPK belongs in that problem space. There is still the problem of adapting designs so that they actually do work with intended populations of teachers and learners, but, as with usability engineering, that is a different problem.

The literature on algorithm engineering is replete with references to it as a bridge. The learning sciences, however, need something more than a bridge. The problems we face are not of the well-structured type that can be solved by working backward from a theoretically specified goal; they call instead for a hill-climbing heuristic (Newell & Simon, 1972). We know or think we know which way is up, and we are prepared for the possibility that reaching a summit will only reveal another hill to be climbed (or sometimes that we climbed the wrong hill). Principled knowledge should not merely connect theory with practice but should enable the continual and occasionally radical improvement of practice. That is what the Wright brothers' principles of flight control did and what PPK in the learning sciences should be able to do.

INVESTING IN PPK

PPK sufficient to support progress requires an investment of effort over and above that required for coping with problems at hand. Investment in the creation of PPK is an investment in future problem solving, although it may also serve more immediate purposes if, as in the case of the Wright brothers, available knowledge is proving insufficient to solve the problem at hand. In competitive businesses, specific procedures may be guarded as trade secrets, but in publications and conferences competitors may freely share higher levels of PPK on the premise that progress in such knowledge will help advance the field. That is exactly what the Wright brothers did (Wright, Wright, Chanute, & McFarland, 2001), with the result that their wing-warping mechanism was quickly surpassed by other mechanisms that did the same job better. In a field like education, where hiding trade secrets has no legitimate place, collaboration in the advancement of PPK ought to be the norm.

Collaboration in the production of practical knowledge in education is hampered by well-known practical constraints associated with classroom walls, but these are being partly overcome by Web-based forums and resource repositories. Collaborative production of PPK, however, does not depend so much on improvements in communication as on the willingness of the relevant professionals to invest time and effort in it. Key players are teachers, researchers, and technology developers, preferably working together.

After 25 years of PPK development that has attempted to wed classroom practice, theory, and technology innovation related to knowledge building (Scardamalia & Bereiter, 2010), I conclude that many education authorities around the globe are interested in applying PPK but hardly any are willing to invest money in its production. Research funding by education authorities (as distinct from research funded by the likes of the National Science Foundation) remains essentially limited to Cronbach and Suppes's (1969) decision-oriented research, which amounts to testing known procedures. Considerable invention and problem solving may go into implementing an imported innovation, but the PPK that is developed in the process is PPK for change management, not the kind of PPK that can generate solutions to problems at the classroom level. Decision-oriented research plays a large role in medicine, too, as the daily news makes evident, but it is not what has produced the dramatic advances in medical care. Those have come about through advances in formal knowledge and in PPK grounded in such knowledge. The medical landscape is dotted by hospitals that make some investment in PPK over and above the funds spent directly on medical care. These hospitals play a vital role, along with research laboratories (public and private), in advancing the state of the art. Advances in educational know-how are likely to remain slow and uncertain until educational institutions follow suit and devote funds to supporting their role in the production of educational PPK.

REFERENCES

Anderson, J. D., Jr. (2002). *The airplane: A history of its technology*. Reston, VA: American Institute of Aeronautics and Astronautics.

Bereiter, C. (2009). Innovation in the absence of principled knowledge: The case of the Wright brothers. *Creativity and Innovation Management*, *18*(3), 234–241.

Blachman, B. (2000). Phonological awareness. In M. Kamil, P. Mosenthal, P. D. Pearson, & R. Barr (Eds.), *Handbook of reading research* (Vol. 3, pp. 483–502). Mahwah, NJ: Erlbaum.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academies Press.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences*, *2*, 141–178.

Case, R. (1985). A developmentally based approach to the problem of instructional design. In S. F. Chipman, J. W. Segal, & R. Glaser (Eds.), *Thinking and learning skills: Vol. 2. Research and open questions* (pp. 545–562). Hillsdale, NJ: Erlbaum.

Case, R. (Ed.). (1992). *The mind's staircase: Stages in the development of human intelligence*. Hillsdale, NJ: Erlbaum.

Case, R., & Okamoto, Y. (1996). The role of central conceptual structures in the development of children's thought. *Monographs of the Society for Research in Child Development, 61*(1–2, Serial No. 246).

Chimani, M., & Klein, K. (2010). Algorithm engineering: Concepts and practice. In T. Bartz-Beielstein, M. Chiarandini, L. Paquete, & M. Preuss (Eds.), *Experimental methods for the analysis of optimization algorithms* (pp. 131–158). New York, NY: Springer.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, *32*(1), 9–13.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *Journal of the Learning Sciences*, *13*, 15–42.

Cronbach, L. J., & Suppes, P. (Eds.). (1969). *Research for tomorrow's schools: Disciplined inquiry for education*. New York, NY: Macmillan.

Crouch, T. D. (1992). Why Wilbur and Orville? Some thoughts on the Wright Brothers and the process of invention. In R. J. Weber & D. N. Perkins (Eds.), *Inventive minds* (pp. 80–92). New York, NY: Oxford University Press.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*(1), 5–8.

Dewey, J. (1900). Psychology and social practice. *Psychological Review*, *7*, 105–124.

diSessa, A., & Cobb, P. (2004).Ontological innovation and the role of theory in design experiments. *Journal of the Learning Sciences*, *13*, 77–103.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences*, *11*, 105–121.

Eppler, M. (2004). *The Wright way: 7 problem solving principles from the Wright brothers that can make your business soar*. New York, NY: AMACOM.

Gordon, M., & O'Brien, T. V. (Eds.). (2006). *Bridging theory and practice in teacher education*. Rotterdam, The Netherlands: Sense.

Griffin, S. A., Case, R., & Siegler, R. S. (1994). Rightstart: Providing the central conceptual prerequisites for first formal learning of arithmetic to students at risk for school failure. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 25–49). Cambridge, MA: MIT Press.

Holzinger, A. (2005). Usability engineering methods for software developers. *Communications of the ACM*, *48*(1), 71–74.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York, NY: Basic Books.

Kolodner, J. L. (2006). Case-based reasoning. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 225–242). New York, NY: Cambridge University Press.

Lakatos, I. (1970). The methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds.), *Criticism and the growth of knowledge* (pp. 91–195). Cambridge, England: Cambridge University Press.

Lampert, M. (1986). Knowing, doing, and teaching multiplication. *Cognition and Instruction*, *3*(4), 305–342.

Lavatelli, C. (1970). *Piaget's theory applied to an early childhood curriculum*. Boston, MA: American Science and Engineering.

Moss, J. (2005). Pipes, tubes, and beakers: New approaches to teaching the rational-number system. In J. Bransford & S. Donovan (Eds.), *How children learn: History science and mathematics in the classroom* (pp. 309–350). Washington, DC: National Academies Press.

Moss, J., & Case, R. (1999). Developing children's understanding of rational numbers: A new model and an experimental curriculum. *Journal for Research in Mathematics Education*, *30*, 122–147.

Müller-Hannemann, M., & Schirra, J. (Eds.). (2010). *Algorithm engineering: Bridging the gap between algorithm theory and practice*. New York, NY: Springer.

Murray, B. A. (1998). Gaining alphabetic insight: Is phoneme manipulation skill or phoneme identity knowledge causal? *Journal of Educational Psychology*, *90*, 461–475.

National Academy of Sciences and Institute of Medicine. (2008). *Science, evolution, and creationism*. Washington, DC: National Academies Press.

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice Hall.

Ni, Y., & Zhou, Y-D. (2005). Teaching and learning fraction and rational numbers: The origins and implications of whole number bias. *Educational Psychologist*, *40*(1), 27–52.

Nonaka, I., & Takeuchi, H. (1995). *The knowledge creating company*. New York, NY: Oxford University Press.

O'Neill, D. K. (2012): Designs that fly: What the history of aeronautics tells us about the future of design-based research in education. *International Journal of Research & Method in Education*, *35*(2), 119–140.

Palincsar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction*, *1*, 117–175.

Sandoval, W. A. (2004). Developing learning theory by refining conjectures embodied in educational designs. *Educational Psychologist*, *39*(4), 213–223.

Sawyer, R. K. (Ed.). (2006). *Cambridge handbook of the learning sciences*. New York, NY: Cambridge University Press.

Scardamalia, M., & Bereiter, C. (2010). A brief history of knowledge building. *Canadian Journal of Learning and Technology, 36*(1). Retrieved from http://www.cjlt.ca/index.php/cjlt/article/view/574

Thagard, P. (2000). *Coherence in thought and action*. Cambridge, MA: MIT Press.

Tsoukas, H. (2009). A dialogical approach to the creation of new knowledge in organizations. *Organization Science*, *20*, 941–957.

Vygotsky, L. S. (1962). *Thought and language* (E. Haufmarm & G. Vakar, Eds. and Trans.). Cambridge, MA: MIT Press. (Original work published 1934).

Wilson, E. O. (1998). *Consilience: The unity of knowledge*. New York, NY: Knopf.

Wright, W., Wright, O., Chanute, O., & McFarland, M. W. (2001). *The papers of Wilbur and Orville Wright: Including the Chanute-Wright letters and other papers of Octave Chanute*. New York, NY: McGraw-Hill Professional.