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Designs that fly: what the history of aeronautics tells us about the future of design-based research in education

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For almost two decades, there has been growing interest in what design-based research (DBR) can contribute to both educational practice and theory. Since its introduction into the literature, this orientation to educational research has repeatedly been likened to aeronautical engineering as a way to clarify its nature and argue its potential. This paper critically examines for the first time how the aeronautics analogy both strengthens and hampers thinking about educational research and design. Three cases from the history of aeronautical engineering are used to highlight similarities and differences between the two fields, and lessons are drawn from the development of aeronautics that may help DBR to fulfil its long-term potential. Principally, it is argued that design researchers must report the failure of designs much more frequently and in a more informative way, and that a critical audience for informative reports of design failure is indispensable to the progress of educational design research.

Keywords: design-based research; analogy; aeronautics; history

Introduction

When I ask a roomful of student teachers to develop ideas for empirical research projects (as I often have), many of their responses take the same form: quasi-experiments comparing the efficacy of one curriculum, style of teaching, or set of teaching resources to another. To them, the experiment is not just the gold standard for research – it practically defines what research is.

Experimental comparisons are a worthwhile way to address some of the questions that concern educators. However, even distinguished psychologists have noted weaknesses in experiments as a road to knowledge. Reviewing a collection of creative and competently performed experiments, Allen Newell, one of the founders of cognitive science, declared that in the experimental paradigm,

> … clarity is never achieved. Matters simply become muddier and muddier as we go down through time. Thus, far from providing the rungs of a ladder by which psychology gradually climbs to clarity, this [approach] … leads rather to an ever increasing pile of issues, which we weary of or become diverted from, but never really settle. (Newell 1973, 288–9)

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Such concerns, along with the lack of ecological validity in lab experiments and the difficulty of transferring findings from the lab to the classroom, famously led a dyed-in-the-wool experimental psychologist named Ann Brown to take up a new form of educational research that her colleague Allan Collins had termed 'design experiments' (Brown 1992; Collins 1992). This orientation to educational research has since won many adherents, including both practitioners and career researchers (Vanderlinde and van Braak 2010), though not all of them necessarily agree on what it is. As Phillips and Dolle (2006) note, design research takes a host of forms that at best bear a family resemblance due to some shared features:

- partnerships between researchers and practitioners to design innovations for teaching and learning (e.g. curriculum, software);
- trials of these innovations in 'real' classrooms;
- data collection on both the learning outcomes and processes of teaching and learning;
- data analysis aimed at understanding both whether and *how* the innovation works (or fails);
- design revision and further trials informed by this analysis.

While design-based research (DBR) often involves qualitative data collection and analysis, it is clearly based on an analogy to engineering (Bell 2004; Hjalmarson and Lesh 2008; Middleton et al. 2008). Indeed, while scholars from a wide array of traditions are now involved in it, the basic drive behind DBR is to fashion education into a rigorous design science (Glaser 1976; Collins 1992; Collins, Joseph, and Bielaczyc 2004). The desire for a tight, explicit and determinative body of educational knowledge, approaching that of engineering, remains clear in recent publications (e.g. Clarke and Dede, 2009).

As desirable as such knowledge may be, DBR's current practitioners (including me) must admit that it is a problematic way to do research, requiring a range of skills not common among educational researchers (Vanderlinde and van Braak 2010). DBR's teething pains have been discussed in several special issues of education research journals (Design-Based Research Collective 2003; Dede 2004; Sandoval 2004), as well as a recent handbook (Kelly, Lesh, and Baek 2008). Together, this chorus of voices makes clear that if you are really thinking as a design-based researcher, you regularly wonder what you are up to.

In the face of such uncertainty, design-based researchers have relied either explicitly or implicitly on analogies to clarify and inspire their work, as other educational researchers have found useful to do (Pirrie and Macleod 2010). As mentioned, advocates of DBR are universally enamored of engineering, but the most enduring of the analogies used for DBR is that of *aeronautical* engineering specifically. In their influential 1992 publications, both Brown and Collins explained the idea of educational design research by analogy to aeronautics (Brown 1992; Collins 1992). In her opening paragraph, Brown (1992) explained:

> In my current work, I conduct what Collins (in press) refers to as design experiments, modeled on the procedures of design sciences such as aeronautics .... (141)

Publications have continued to play upon the aeronautics analogy over the years (Collins, Joseph, and Bielaczyc 2004; Phillips 2006; Phillips and Dolle 2006;

Schoenfeld 2006). Fourteen years after Brown's seminal piece, Alan Schoenfeld, a former president of the American Educational Research Association, began a chapter about design research with a lengthy paragraph about early aeronautics (Schoenfeld 2006).

I would not claim that educational design researchers are always pondering aeronautics somewhere in the backs of their heads, but the repeated use of the analogy over such a long span of time shows that it frames the design research enterprise in an important way. Analogies can be powerful aids to thinking (Gentner and Jeziorski 1979; Gentner and Stevens 1983), channelling thought in particular directions and shaping how the 'target' domain (here education research) is seen. Part of why analogies are intellectually useful is that they can raise the salience of features in the target domain that are otherwise downplayed or ignored. Below, using three cases from the history of aeronautical engineering, I examine the similarities and differences that this mature design science bears to the developing tradition of educational DBR. From these cases and related literature in education, I draw three lessons for educational researchers about where the DBR agenda is likely to take them, and discuss what will be necessary to do justice to these lessons.

What is design?

Design is a deep subject that has been explored by scholars in many fields (e.g. architecture, fashion, computer science), to whose work I cannot do justice in this article. However, I will briefly explain what I believe most educational design researchers mean by the term. Most educational design researchers follow Herbert Simon's seminal work in observing that what separates design from other creative processes is the aim to achieve particular, preconceived objectives (Simon 1969). Also prominent in design researchers' thinking is the notion that design is constrained by trade-offs, in which the attempt to achieve one end often comes at the cost of another or entails undesirable side effects (Simon 1969; MacLean, Young, and Moran 1989; Hjalmarson and Lesh 2008). The designer's main job is thus to optimize for desired effects, while minimizing undesired ones.

Optimization is where the aeronautics analogy starts to show its relevance to education, because this task demands a working understanding of the elements of a system and how they interact (Glaser 1976). In both education and aeronautics, our understanding of the system we are designing within is never entirely complete. Due to the incomplete understanding upon which educational design stands, failure can be highly instructive. Under the right conditions, the failures of particular designs should help designers to appreciate flaws in the ideas upon which they are based (Sandoval 2004). This premise underlies the claim that educational design research can make contributions both to educational practice (through useful new designs) and theory (through the testing and improvement of embodied theories, and the explanation of outcomes). It is this promise of 'killing two birds with one stone' that continues to draw people to DBR, despite the fact that it is more difficult to carry out and report than a typical lab experiment or intervention study (Vanderlinde and van Braak 2010).

Theories as heuristics for design

As in aeronautics, the value of theory for design in education is largely heuristic (Glaser 1976; Nathan 1998). Over decades, scholars of learning have constructed explanations of how people accomplish skilled performance, and why some conditions are more supportive than others are to the development of skill (Bransford, Brown, and Cocking 2000; Sawyer 2005). However, this body of theory is not complete enough to dictate educational design. The same is true in aeronautics, even though aircraft designers have a body of theory to guide them that is arguably superior to any in education. Newtonian mechanics and fluid dynamics have, for their purposes, more impressive explanatory and predictive power than Vygotsky's (1978) sociocultural theory, and a greater range of application than Anderson's ACT theory of cognition (Anderson 1993; Anderson et al. 2004) or Mayer's (2005) theory of multimedia learning. Nonetheless, there is a lot of creative work involved when aircraft are designed (Sutter and Spenser 2007). Vincenti (1990) quotes a British engineer speaking to the Royal Aeronautical Society:

> Aeroplanes are not designed by science, but by art in spite of some pretence and humbug to the contrary. I do not mean to suggest for one moment that engineering can do without science, on the contrary, it stands on scientific foundations, but there is a big gap which has to be bridged by the art of the engineer. (4)

Similarly, in education, bodies of theory may point toward new possibilities for design, but they are not complete and predictive enough to inform *all* the decisions that make up a full-fledged design for learning in a specific setting, like a high-school social studies classroom or physics lab. Once one has followed theoretical inspiration as far as it goes in education, there is still a gap to be bridged between the science and the art, to use Vincenti's phrase.

In the following sections, I share three historical cases that help illuminate other, previously unexplored ways in which the aeronautics analogy does and does not map to design research in education.

Case 1: the Pregnant Guppy

In Brown and Collins' influential 1992 publications (Brown 1992; Collins 1992) about design research, the aeronautics analogy served more than one purpose. On the one hand, it helped to explain a novel concept, but it also served a rhetorical purpose: to lend legitimacy to educational research for an audience intolerant of 'soft science'. With regard to this rhetorical purpose, though, the analogy is deceptive; for when aeronautical engineering is conducted in a way much akin to what is done in education, it has a 'seat-of-the-pants' quality of which most readers would not be aware. This quality is captured well in the story of the Pregnant Guppy.

The Pregnant Guppy (Figure 1) is an airplane designed and built by Aero Spacelines, a small company created to cope with a peculiar problem of the Apollo space program. Building the hardware to get men to the moon was a job too big for any one aerospace company, so the three stages of the Saturn V moon rocket had to be built in far-flung facilities and integrated at the launch site. As a result, large rocket stages (up to 33 feet in diameter) had to be transported from manufacturing sites in California and Washington states to the launch site in Florida. Most bridges in the USA provided just over 14 feet of clearance, so the only way to ship the stages initially was through the Panama Canal. This 'took 15 days and ... the parts arrived banged up and corroded from the weather' (Tripp 2002, 34). The Pregnant Guppy was the design solution to this problem.

Figure 1. The Pregnant Guppy (NASA 2009).

Like educators, aerospace engineers are inveterate pragmatists. The design process for the Guppy was as pragmatic as one could imagine. Aero Spacelines started with war surplus Stratocruisers and Stratotankers, then the longest aircraft in the world. Two planes were pieced together to create one long enough to carry a Saturn V stage, then test-flown. When the result did not crash, a bulkier fuselage was built around the original one, with enough girth to hold a Saturn stage. Finally, when *that* did not crash, the original, inner fuselage was cut away. Tripp (2002) describes the first time the Guppy went up with a full payload:

> . . . the landing gear was retracted, but the ship could climb no faster than the hilly ground was rising in front of it . . . . An awed and expectant silence prevailed in the cockpit, even as the engines and propellers churned away at their noisiest level.
>
> The town of Boron loomed dead ahead. It looked as if the Guppy's crew would clean it out if they didn't turn, but a turn might sink them back into the ground . . . .
>
> To this day some crew members swear that the burning of fuel . . . was the only reason the Guppy finally managed to climb. They say a string of skeletons from jackrabbits that died of pure fright runs from Mojave to Boron. After that flight the engineers and pilots agreed to decrease the plane's maximum weight by 8000 pounds ... . (31)

The story of the Pregnant Guppy captures a sense of risk that is generally absent in reports of educational design experiments, for reasons I will explore later. However, while none have yet died of fright, my experience suggests that educational design researchers also fear that a new design will 'crash'. A new technology might fail at an inopportune moment, wasting a precious class period. New activity structures might prove impractical, or new teaching materials uninterpretable. Students and teachers might balk. Finally, in the messy environment of a real school, problems arise that no one can predict (Berliner 2002).

In a similar way, the highly pragmatic plan for the Guppy faced unexpected complications that the designers were not well equipped to understand and address. These problems were managed by Jack Conroy, a former USAF test pilot:

> When the first test flight revealed that retracting the flaps caused buffeting, Conroy hired Irv Culver, a well-known aerodynamicist, to design a fix to smooth the flow at the wing-fuselage juncture. . . . Since there was not nearly enough money to do a wind-tunnel test program, Irv took a model with silk strings attached and put it in front of a fan. Using cardboard and modeling putty, he came up with a shape that was then drawn and used.
>
> This was a classic example of how things got done at Aero Spacelines. An expression often used by designers describes this type of work: 'Build to fit. Draw to match. Paint to cover.' Conroy was fond of saying, 'It's amazing what you can do without paperwork . . . .

> On most aerospace projects, any of our planes would have taken three years'. (Tripp 2002, 34–5)

In fact, the Pregnant Guppy made its first payload flight for NASA only 1 year after its initial test flight. Without the plane, Tripp claims that NASA could never have gotten to the moon before the end of the 1960s.

Four features unite the story of the Guppy with educational design research as I have experienced it: high ambitions, limited budget, limited time and somewhat flexible standards. Aeronautics has matured greatly in the 50 years since the Guppy first flew, now employing processes of design and testing that are far slower, more methodical and supported by more mature analytical tools (Heppenheimer 1998; Sutter and Spenser 2007). However, these processes are also worlds apart from those in education today. While an academic audience might prefer for educational design research to be carried out in the methodical fashion of today's aeronautics, it is difficult to avoid the sense of urgency that comes from serving students and teachers whose satisfaction and learning rest in our hands. The combination of urgency and scarce resources pulls design experimenters toward an approach more like that of Aero Spacelines.

Cases from early aeronautics: some background

Aside from rare stories like the Guppy, one has to go back pretty far to find aeronautical design work that resembles current design work in education. In fact, due to the less predictive theory that designers must contend with in education, their design work bears more of a resemblance to the aeronautics of the early 1900s than that of the early 1960s. The advocates of DBR in education should ask themselves (but so far have not) what the design enterprise was like in aeronautics when aeronautical engineers' theories were more like those in education today. Equally important, *how* did the aeronauts begin to progress from 'seat-of-the-pants' work to the advanced design science that we know now? In the following sections, I address these questions by examining the exploits of some very different aviation pioneers: the famous Wright brothers, and a lesser-known Frenchman named Louis Bleriot. First however, some background is needed.

Americans are usually taught that the first flight by a human being took place at Kitty Hawk, North Carolina, on 17 December 1903. It was accomplished by the Wright brothers, with only a local lifeboat crew looking on (Hoffman 2003). According to aviation historians, however, the story is not as simple as that (Schneider 2003).

For hundreds of years, the field of aviation was occupied by daring but naïve innovators. Near the end of the nineteenth century, scientific authorities like Lord Kelvin continued to insist that manned flight was impossible (Hoffman 2003). Finally, in the early 1890s, Otto Lilienthal undertook successful experiments with manned gliders in Germany, based on careful study of the anatomy of birds. Aviation historian Gibbs-Smith (1970) declared Lilienthal 'the first man to fly practical heavier-than-air aircraft consistently and successfully' (80). Lilienthal's published work became the basis of some of the Wrights' first gliders. The Wrights also got early help from Samuel Langley (head of the Smithsonian) and Octave Chanute, a French-born Chicago engineer (Crouch 1981).

By the early 1900s, innovators like the Wrights, Louis Bleriot and Alberto Santos-Dumont had built airplanes that showed some promising performance, and they had nascent theories about lift and control. But their machines and the theories behind them were primitive by today's standards. Due to the immaturity of their theory, improving airplanes remained a lurching, grasping process in which the aeronauts followed theory as far as it would go, made up the rest as necessary to complete a testable design, then tried it and attempted to understand its performance. As I discuss in the next two sections, the methods that early aircraft designers followed were determined partly by the status of applicable theory at the time, partly by their own personal character as designers, and partly by the circumstances in which they worked. The influences working on educational design researchers are equally diverse, much as they might be encouraged to present their work as an entirely rational enterprise. The current editors of a journal strand on educational design research have decried that:

> Given the central role of the design-enact-analyze-revise cycle in descriptions of design research, there is a notable lack of reflection on methodologies for accomplishing that cycle in ways that can demonstrate that particular revisions are warranted from empirical analysis ... (Puntambekar and Sandoval 2009, 325)

What follows will help illuminate why accomplishing such analysis may be difficult for educational researchers at the moment.

Case 2: the Wright method

The Wright brothers were sons of a Dayton, Ohio, minister who made their living as bicycle mechanics. Neither completed high school, but they became brilliant self-taught engineers (Crouch 1981). Aviation historians have noted several ways in which the Wrights stood apart from their contemporaries. The first was how methodical their approach to the problem of flight was. They were among the first in history, for example, to construct and use a wind tunnel to test the lift generated by differently shaped airfoils (Gibbs-Smith 1970). While their financial resources were limited in comparison to many of their European contemporaries (see Case 3), the Wrights' more efficient methods of inquiry allowed them to make rapid progress.

The Wrights were also some of the first to have understood the necessity of controlling the roll of an aircraft (rotation around the longitudinal axis), in addition to its pitch and yaw (Crouch 1981). While Europeans sought to make airplanes inherently stable in the air, the Wrights realized that balancing an aircraft may need to be a constant effort – just like balancing a bike (Crouch 1981). Their unique solution to the problem of roll control was termed 'wing warping'. Cables running through the flexible wood-and-cloth wings of the Wright Flyer allowed the pilot to twist them during flight. This increased the lift of one wing and decreased that of the other, allowing the plane to roll left or right (Bereiter 2009). Today most aircraft use ailerons for the same purpose.

Rather unique as well was the Wrights' cautious, stepwise approach to refining their machines. The Wrights built unpowered, unmanned kites to test their ideas before building manned gliders, then full-scale, powered machines. This stepwise refinement is evident in Figures 2–4, which reveal the striking similarity of the basic layout of their aircraft at each phase of development. At every stage, the Wrights' designs featured a pair of main lifting wings in back, and an elevator for pitch control in the front. (To observers today, Wright Flyers appear to be flying backwards.) In Figures 3 and 4, we see the addition of a vertical rudder in the rear.

A final difference between the Wrights and their French contemporaries (particularly relevant to educational design researchers) lies in their appetite for publicity.

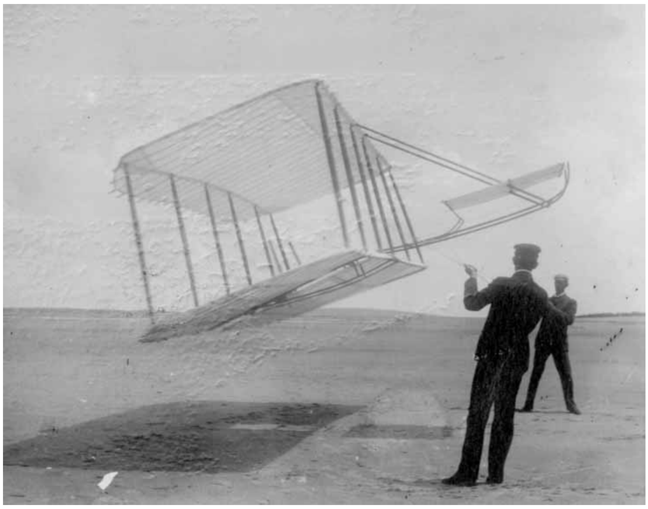

Figure 2. The Wright brothers testing a biplane kite at Kitty Hawk (Wright Brothers 1901).

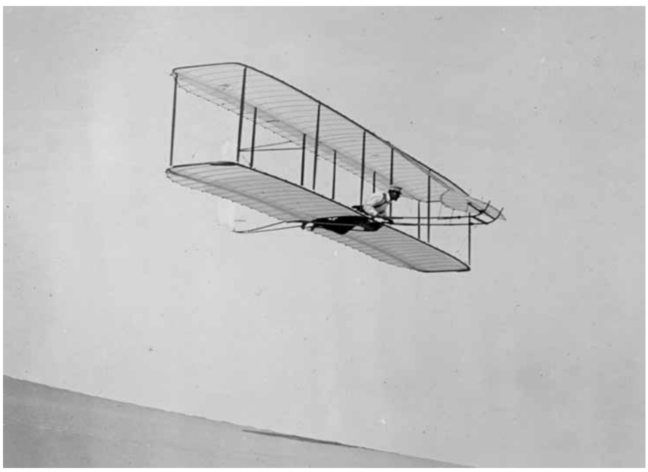

Figure 3. A Wright manned glider (Wright Brothers 1902).

The Wrights had none. After early assistance from Langley and Chanute, the Wrights largely kept to themselves (Crouch 1981). During the same period, Europeans like Gabriel Voisin, Henri Farman and Louis Bleriot tested their ideas by building full-scale, powered machines of comparatively primitive design, and risking their necks in them in full view of one another and the public (Josephy 1962). On a rare American trip, Henri Farman publicly gibed the Wrights, saying 'It is better for others to see what you are doing, and for you to see what they are doing, each improving by the mistakes of the other' (Roseberry 1972, 117).

Historians suggest that the Wrights' shyness stemmed from their desire to achieve a legal monopoly on the airplane, as Alexander Graham Bell had done with the telephone (Roseberry 1972; Shulman 2002; Hoffman 2003). It may have galled the Wrights to

Figure 4. A powered Wright Flyer (Anonymous 1909).

have fellow aviators doubt their achievements of 1903, but they were determined not to reveal the details of their invention until their patent rights were secure.

Even with a broad patent though, the Wrights' business did not thrive. After producing their first successful design and securing patents for it, they stuck to this basic configuration until surprisingly late, displaying a kind of fixedness in their thinking (Spenser 2008). By 1909, the Wrights' biplanes with their forward elevators and pusher propellers looked out of place in a field containing monoplanes and biplanes with superior 'tractor' configurations, in which the propeller pulls from ahead of the main wing, and the rudder and elevator trail behind. After years of ugly disputes over patent rights and the death of Wilbur Wright, the Wright Aeronautical Company was merged with rival Curtiss Aeroplane and Motor Company in 1929. The Wright Flyer became a proud piece of history, but nothing more.

Case 3: the Bleriot method

Like several of his fellow aviators in France, the Wrights' contemporary Louis Bleriot was a wealthy man. An engineer by training, he made his fortune by inventing and marketing a bright headlight for automobiles. Using this wealth, he embarked on a programme of design research into powered flight. He had the advantage of living in Paris, which was then considered the world capital of aviation. After years of witnessing flights in balloons and dirigibles, Parisians had grown accustomed to seeing brave aviators testing their rickety contraptions. *Issy les Moulineaux*, a makeshift airfield near the Eiffel tower where Bleriot and others experimented with airplanes, became a popular place to go for entertainment (Charlson 2005).

Aviation was not merely entertainment, but a fiercely nationalistic endeavor for the French. Between the Wrights' first flights in 1903 and their first public exhibitions of their machine in 1908, Frenchmen like Robert Esnault-Pelterie made crude copies of the Wright biplane, which did not fly (Gibbs-Smith 1970; Spenser 2008). This did not prove that the Wrights had not flown, but the demonstrations reassured French

Figure 5. The Bleriot V, a pusher monoplane with forward elevator and rudder (Bleriot 1907a).

aviators that they had not fallen behind the Americans – that the Wright brothers were *bluffeurs*.

Since available theory did not suggest a clear route to success and the Wrights' example appeared worthless, Bleriot developed a series of widely varying aircraft designs – each one not a scale model or unpowered kite (like the Wrights had earlier built), but a full-scale, powered machine that he piloted himself. It is difficult to appreciate just how different Bleriot's designs were from one another (and how different his approach was from the Wrights') without examining photographs of them. Between his model V (Figure 5) and model VI (Figure 6), Bleriot changed the number of lifting wings (from 1 to 2), moved the engine and propeller from the back to the front and changed both the shape and location of his control surfaces. Pursuing this antithesis of experimental science, Bleriot eventually settled on a single front lifting wing, forward propeller, and rear elevator and rudder (Figure 7). This is the shape of nearly every small airplane made today, and quite different from the Wright brothers' first successful design.

Bleriot's rapid shifting from one design configuration to another is described by Vincenti as 'radical design':

Figure 6. The Bleriot VI, a tractor monoplane with 'tandem' wings of nearly equal size fore and aft – after a hard landing (Bleriot 1907b).
Source: Gunston (1992).

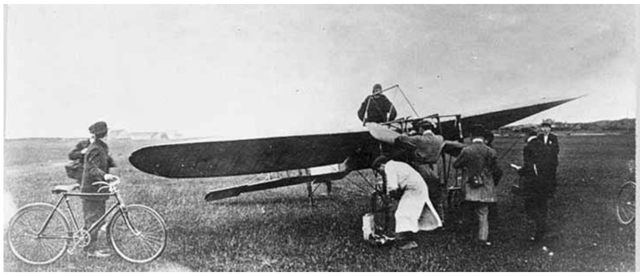

Figure 7. The Bleriot XI, a tractor monoplane with forward lifting wing, and rear rudder and elevator (Bain 2009).

> In radical design, how the device should be arranged or even how it works is largely unknown. The designer has never seen such a device before and has no presumption of success. The problem is to design something that will function well enough to warrant further development. (Vincenti 1990, 8)

Month after month, Bleriot and his French contemporaries watched one another power themselves into the air in machines that were barely in control at all. For a time Bleriot achieved quite limited success, and his crashes were so frequent that he earned the nickname 'prince of bad luck' (Charlson 2005). Fortunately, since his primitive craft flew low and slow, his injuries were minor.[1]

Finally, Wilbur Wright (with patent in hand) visited France and demonstrated his system of wing warping to Bleriot and his confreres. Bleriot immediately adopted wing warping for his Model XI, in which he gambled his life and won. In 1909, Bleriot became the first person to fly a heavier-than-air craft across the English Channel, claiming a prize of 1000 pounds from the London Daily Mail newspaper. This feat brought him instant fame and made his model XI the biggest-selling airplane in the world (Charlson 2005).

Vincenti argues that from the perspective of the aeronautics community as a whole, Bleriot's improvisational approach was productive:

> [Bleriot's] unsystematic efforts led to only modest achievement by 1908, but the body of experience and community of designers and fliers that resulted put the French in position to forge ahead rapidly once Wilbur Wright had shown them how truly successful flight could be accomplished. From the French work (mainly) came the engine-forward, tail-aft biplane (and occasionally monoplane) configuration that became normal in airplane design by the beginning of World War I. (Vincenti 1990, 243)

Considered from the perspective of educational DBR, Bleriot's experience illustrates the success that is possible in an under-theorized design field by integrating the results of methodical, stepwise work (here, wing warping) with bold, creative experimentation.

Where does the analogy map?

In the next two sections, I unpack several ways in which the aeronautics analogy does and does not map to design research in education. Both the mappings and the mismappings are instructive, raising some issues that have received no attention in the extensive literature on educational DBR.

Mapping 1: systematic variation is not everything

Clearly, systematic variation in design (like the Wrights did) can be helpful in speeding up progress on key sub-problems when a design requires new knowledge. Without their wind-tunnel work on airfoil shapes, the Wrights would have taken much longer to refine their craft. However Bleriot's ultimate success suggests that the Wrights' cautious approach alone is not sufficient to realize the potential for progress in an under-theorized design field. As Vincenti discusses, innovative design must occasionally preceed theoretical understanding. Thus, Vincenti describes design innovation as 'blind'. He explains:

> . . . any variation that leads to truly new knowledge . . . must be blind in the sense of going 'beyond the limits of foresight or prescience.' . . . 'blind' (in this sense) does not mean 'random' or 'unpremeditated' or 'unconstrained.' It simply denotes . . . that the outcome of the variation cannot be foreseen or predicted . . . . If it could, the knowledge obtained would not be new. (Vincenti 1990, 242)

Despite Newell's (1973) doubts about controlled experiments, there remains a powerful school of thought in education research (and a powerful political bloc) that takes them as the only route to valid knowledge (Kirschner, Sweller, and Clark 2006; Phillips and Dolle 2006). One problem with this approach from a design stance is that it requires exhaustive work to put each possible design variation on trial. Borrowing Jack Conroy's word, it involves a lot of 'paperwork'.

If education researchers are to take aeronautics as a model, they must realize that it did not depend exclusively on the incremental control-of-variables approach for its progress. Bleriot's riskier and more intuitive approach was equally essential. Thus, design progress in education must involve both 'the hare of intuitive design and the tortoise of cumulative science' (Koedinger 2002, 10).

Mapping 2: if at first you do not succeed, fail, fail again

In early aeronautics, it took a *lot* of carefully scrutinized failure to achieve success. In part, the number of failures needed is explained by the lack of good theory to direct observation during design trials. The early aeronauts at *Issy les Moulineaux* were in the unenviable position of trying to refine both their designs and their understanding of aerondynamics without the benefit of systematic observations by third-party observers. They must have done a great deal by the feel of the aircraft alone.

Similarly, teachers and educational researchers try new things every day. Like the early aviators, their attempts do not always succeed. Design-based researchers take the position that if educational innovators have not been able to learn what they might have from failure, it may be because they have not articulated the theoretical basis for their innovations clearly enough and have not studied the results carefully enough. However, educational researchers and teachers can take heart that unlike the early aeronauts, their efforts at theorizing can benefit from video recordings and detailed observations of design trials (Brown 1992; Sherin 2004; Zaritsky 2008). Thus, we have opportunities today that Bleriot never dreamed of – if only we can create a research culture that encourages taking advantage of them.

Mapping 3: openness aids advancement

Several historians have remarked on what a mistake it was, in retrospect, for Orville and Wilbur Wright to keep their work secret. Even in their day, when news travelled more slowly, maintaining this secrecy took a lot of resolve and occasional deceit (Shulman 2002). On the other side of the Atlantic, French aviators spent a lot more money and took great personal risks to accomplish only a few short hops (Gibbs-Smith 1970; Hoffman 2003). However, they did so publicly, and as soon as they understood the Wrights' approach to the problem of roll control, they quickly surpassed the Americans' efforts (Spenser 2008). In Vincenti's account, the reason the Wrights' revelation catalysed such success for the French was that they had always been open about their failures. Due to the culture of openness at *Issy les Moulineax*, the French aviators' repeated failure to build working airplanes built a strong community of designers who learned together.

In the field of education, we have traditions that produce Issy-like openness on a small scale. These include 'video clubs' (Sherin 2004) in which teachers share videotaped lessons and professional development systems involving 'intervisitation' of teachers to one another's classrooms (Stein and D'Amico 2002). How much more powerful could such openness be if it occurred on a large scale?

Where does the analogy not map?

Analogies are also instructive when they do not map. Several important differences separate education and aeronautics as fields of design and theory development. Attending to these differences provides insight not only into the limits of the aeronautics analogy for DBR, but also into critical aspects of DBR that need attention if it is to advance.

Mismapping 1: the ease of knowing when you have flown

As mentioned above, there are still arguments today about who was the 'first in flight' and what that means. If such arguments can take place in aeronautics, it is no surprise that more intense ones take place in education. With aircraft there are only a few key outcomes, all consensually agreed upon and (relative to outcomes in education) easily measured: altitude, distance, speed, acceleration, etc. With educational innovations, people care about myriad outcomes that are not easily measured, such as equity, depth of understanding and transfer of learning. Transfer alone has been described as 'a problem of Gordian proportions' (Alexander and Murphy 1999, 561) and Alexander and Murphy note that even in the pristine setting of the lab, there has been little evidence of subjects transferring learning to novel problems. Thus, despite advances in educational measurement, it is far less obvious when an educational design 'flies'. Proving the efficacy of a new design for learning will likely never be as straightforward as checking the telemetry on a rocket.

Mismapping 2: there are no wind tunnels for classroom innovations

The Wright brothers' success was partly due to their wind tunnel tests of small-scale wings. In aeronautics, tests on scale models can produce highly transferable basic knowledge (Vincenti 1990). In education however, problems are not so easily decomposed, and small-scale findings are not easily transferred to larger undertakings (Phillips and Dolle 2006). As a result, it can be a major challenge to identify, let alone *reproduce* the conditions that are needed to make an innovative design function at the level of a classroom, school and district (Clarke and Dede 2009). Thus, generalizability – almost a non-issue with aircraft – can be a monumental problem in education.

To make wind tunnel testing roughly parallel educational work, one would have to give each air molecule its own mind, intentions and motivations, and let it talk with all the other molecules.

Mismapping 3: sharing failure is difficult

Unlike the French aeronauts, educational design researchers today seem reticent to be seen at their worst, and rarely report failure *as* failure. There have been some noteworthy exceptions to this general rule. For example, Barab et al. (2001) reported on the teething pains of the Inquiry Learning Forum; Radinsky et al. (2001) wrote about the difficulty of negotiating and sustaining mutual-benefit partnerships between educators and corporate partners; and Polman (2006) reported the well-meaning failure of his research team to couple an adolescent's interest in rap music to his interest in history.

There may be other examples, but the small number of detailed reports on failed educational designs is wholly out of step with the reverence that design-based researchers profess for engineering, given the great importance placed on failure analysis in that field (Petroski 2006). Zaritsky (2008) has argued the importance of studying failures, and Koedinger (2002) went so far as to say that design researchers should be 'proud' of them. However, where failed designs are concerned, educational DBR appears to have its own version of psychology's 'file drawer problem' (Smart 1964; Rosenthal 1979) in which negative results are rarely published. Our literature appears to operate on the principle that 'bad news is no news'.

Experience from aeronautics is informative here, as it illustrates the tremendous potential that can be lost when failure is not reported in a design field where basic knowledge is under development. The many public hops and crashes at *Issy* laid the foundations for the French aviation community's future success. How much longer would this success have taken if the failures had been kept as secret as the Wright brothers kept their work? This question should be one of considerable urgency for educational design researchers, though currently they seem to be ignoring it.

Mismapping 4: the risks are not the researchers' alone

Part of the power of public failures at *Issy* stemmed from the fact that they were understood as brave sacrifices in the cause of science. Figure 8 shows a postcard of a little-known pilot named Legagneux, flying before an appreciative crowd at *Issy les Moulineaux* during qualifying trials for an air meet. The text of the postcard, in part, translates 'though he did not qualify, Legagneux finished the whole course, becoming popular by virtue of his courage and gaity'.

It is difficult to imagine such a public celebration of failure in education today, partly because in our field innovators risk more than their *own* pride and health – they risk the achievement of students, and potentially, the credibility of the educators and schools with whom they partner. This shared risk naturally makes failure a more sensitive issue in education, where there are expectations of 'certainty, security and safety' (Thomson and Gunter 2011, 27). While Bleriot and the Wrights got multiple opportunities to make their craft fly, and knew the risks they were taking, most children get only one chance at an education.

At the same time however, one can argue that the larger stakes of educational design trials make sharing and learning from failure more important. Every lesson plan is new at some point. The question is not whether one will fail somewhere, but whether what is

Figure 8. Legagneux flying at Issy les Moulineaux in 1909 reproduced with permission from the private collection of David Lam (M.C.F.L. 1910).

learned from that failure will benefit anyone besides the immediate witnesses. It is no doubt unpleasant to contemplate the loss of opportunities that we may cause students by our well-meaning failures to improve education; but in other fields, such as engineering and medicine, practitioners regularly report failures that cost *lives* (Gawande 2003; Petroski 2006). If these fields can produce a literature of honestly reported failures that entail far higher costs, should we not be able to report our failures? I would argue that we are ethically bound to do so.

Lessons for the progress of design research in education

Despite, and in some ways because of the mismappings discussed above, I claim that the aeronautics analogy has valuable lessons to offer design-based researchers in education.

Lesson 1: there is theoretical potential in radical design

Previous writers on educational DBR have not appeared to recognize how much might be learned from attempting to explain the success of 'radical' designs that do not follow already accepted theory. Though not all educational design is 'blind' in Vincenti's sense, if an innovation steps beyond what accepted theory would prescribe (like Bleriot's radical designs), there is both real danger of failure *and* the potential for substantial new learning and theory generation.

It is clear from the Wright and Bleriot cases that aviation would not be so advanced today if the Wright brothers' conservative model of engineering had been pursued exclusively. Bleriot's more improvisational approach proved essential to the advancement of aeronautics as a design science, and the complementarity between the 'tortoise of cumulative science and the hare of intuitive design' may be even stronger in education due to the lack of 'wind tunnels' for classroom innovations. Because the design space is larger in education than in aeronautics, educators will inevitably need more radical exploration to hit upon the strongest designs, then theorize about how they work.

Lesson 2: fail early, fail often and report it

While reproducibility is a central value in basic science (Bazerman 1988), it is problematic to adhere to in design fields like education because there are so many ways for the application of good ideas to be marred by poor implementation. In education as in aeronautics, one cannot *prove* that an idea will not work by implementing it badly, the way Robert Esnault-Pelterie appeared to have done with his copies of the Wright Flyer. It is therefore simple-minded for educators to think that a failure tells them 'don't try that again,' and a mistake to be skittish about failure if they are serious about improvement.

Despite the advantages that aeronautics has over education in its body of guiding theory, many first (even 51st) implementations of good aviation ideas were failures (Gibbs-Smith 1970). When testing innovations in a theory-impoverished design field, the mistake lies not in trying a failed idea more than once, but in not being prepared to learn from each failure. This may be even truer in education than it proved to be in aeronautics, since in education an idea that has clearly failed in one context may simply need to find its niche. The known sensitivity of educational innovations to context (Berliner 2002) is part of why design researchers continue to advocate the testing of new designs in widely varying settings (Brown 1992; Middleton et al. 2008).

Lesson 3: intuition has a legitimate place in DBR and in its reporting

Because the space of possible design solutions to a given problem is extremely large in education (Glaser 1976), educational design problems are by nature 'wicked' (Rittel and Webber 1973). When faced with a wicked problem and an under-constraining body of heuristic theory, one can choose to do one of two things: start with past designs and make incremental changes (like the Wrights) or make radical changes on a more intuitive basis (like Bleriot).

I do not use the word 'intuitive' in a derogatory sense here, for all intuitions are not created equal. Bleriot was one of the most experienced pilots of his day; so his intuitive 'feel' of an aircraft meant something. The need for highly qualified 'feel' is part of why the practice of educational design research demands a solid, trusting partnership between researchers and classroom teachers (Koedinger 2002). When done well, DBR problematizes the relationship between teachers and researchers, which is usually assumed to be dichotomous (Thomson and Gunter 2011). A seasoned teacher's understanding of what *might* work can help to blaze a trail through a massive design space when theory does not provide adequate direction. Ownership of the design and its underlying assumptions become joint between the teachers and researchers.

This depiction of the partnership between teachers and design-based researchers has an important, overlooked implication for how reviewers judge what is acceptable in the publication of design research. If they expect design conjectures to derive entirely from credentialed academic theory, the possibility of learning from radical design is ruled out in principle. Based on the foregoing cases, I would argue that educational design researchers cannot afford to be so principled. They must remember that as with the Pregnant Guppy, innovative design is sometimes built to fit, then drawn to match.

Discussion: a design researchers' Issy?

As I have shown, the science of human flight has inspired the high ambitions of educational design researchers from the beginning. However, educational design researchers seem reticent to recognize that they are in a stage of development with their work that is more akin to the aeronautics of the early 1900s than the early 2000s. I do not think it is at all wrong for education researchers to aspire to the example of aeronautical engineers; but in doing so they must remember that the problems of aeronautics are cleaner and more amenable to decomposition. As Labaree (1998) has written:

> . . . in looking for the silver lining in the cloud of problems surrounding the production of educational knowledge, we should not ignore the significance of the cloud itself. The characteristics of educational knowledge present researchers with both advantages and disadvantages. These elements do not cancel each other out, but instead, in combination, they define a universe of working possibilities and enduring dilemmas within which educational researchers have to forge their way. (11)

My examination of early aeronautics suggests that the route forward for the fledgling design science of education will inevitably involve radical design (like Bleriot's) and will rely even more than aeronautics did on the kind of openness displayed at *Issy les Moulineaux*. Indeed, the history of aeronautical engineering may be of greatest aid to design researchers in sharpening their focus on the question of how failure should support progress. Because it is more difficult to know when an educational design 'flies', educational researchers need to think carefully about the characteristics that a design researchers' analogue to *Issy* would have.

To support the generation of new theory, failed educational designs must be shared and rigorously studied far more often than they currently are. This sharing need not necessarily take place in a journal, though publishing a design failure should ideally be as difficult and prestigious as publishing in a selective journal. Further, to support progress, each report on a failed educational design trial should have some features similar to a failed design in aeronautics. Below is an initial list of requisite features for an informative report of a failed educational design trial, based on lessons from aeronautics.

Feature 1: it should be plain that the design failed to achieve its goals

Because of the historical bias towards publishing success, design researchers appear to regularly re-cast their failures as successes. There is not necessarily any dishonesty in this practice, since many failures are partial rather than total, and a multifaceted educational project may produce positive outcomes other than those originally intended. However, focusing on unintended successes or inflating partial ones obscures the fact that the intended goals were *not* achieved, thus negating opportunities for understanding the nature of the failure and advancing knowledge.

Feature 2: it should explain why (according to the designers' understanding) the design **should** *have worked*

Reports of failure in the realm of educational design may not be published, in part, because they may simply be considered examples of *bad* design. Of course many bad curriculum designs exist, and it would not be informative for the design research community to learn all the sordid details of a design that failed because its creators had simply ignored prior work or disregarded relevant theory. Scholars have noted before that educational designers often claim allegiances to particular theories of learning without clarifying how these shaped a design (Conole et al. 2004). If a report of a failed educational design is to reveal the incompleteness of available theory (and make its extension possible), the theoretical inspiration behind the design needs to be made explicit, and the community must judge it to be adequate to its purpose.

Feature 3: it should clarify where the embodied conjectures were **not** *based on established theory*

Since, as discussed earlier, no body of educational theory is currently complete enough to dictate design, any report of a failed educational design trial should be forthright, reflective and unabashed about where design decisions were based on intuitive leaps, practitioners' suggestions, cost, simple convenience or guesswork – all of which regularly shape educational design, but seem taboo to discuss in publications. Rather than being stigmatized, these sources of inspiration should be looked upon (in the presence of other necessary features) as the possible seeds of future theory.

Feature 4: it should demonstrate that the implementation was good

In both aeronautics and education, good concepts can fail due to poor implementation. The literature on educational innovations (especially technological ones) is rife with articles concluding that such-and-such an innovation holds enormous promise, though in the reported case it did not prove out due to inadequate technology access, training, etc. These reports are not directly useful to theory improvement. If a report of failure is to aid the development of a design science, it must not be explainable as a function of such simple flaws. Therefore, reporters of failed educational designs should make a persuasive case that given the quality of the implementation, the design concept *should* have had a solid chance of success.

Feature 5: it should provide enough detail to allow the possibility of explaining the failure

To support Henri Farman's goal (mentioned above) that one designer and theorist 'can improve by the mistakes of another', a corpus of reports on failed educational design trials should provide sufficient detail for scholars and practitioners to generate their *own* novel theories about what is needed for success. It is fine if the designers offer their own explanation for a failure; but given the enormity of the educational design space, this alone is not enough. Instead, it is essential that design researchers provide sufficient and appropriate detail of an educational design trial to allow others to generate alternative explanations. In this way, the story of a failed design should serve as 'a place to begin inquiry rather than ... a place on which to fix pre-existing categories and meanings' (Gallagher 2011, 53). Without such interpretive openness in reports of failure, progress for educational design research will be severely handicapped.

The five criteria I have offered here are admittedly slippery. By framing them, I am placing considerable faith in the DBR community to develop and exercise a new kind of connoisseurship about reports of educational design failure. Like the emergence of other scholarly norms, the development of this connoisseurship is likely to be a complex and time-consuming process (Bazerman 1988; Fischer 2010); however, it is difficult to see how educational DBR can progress without it.

Conclusion

Although the concept of educational DBR has been with us since 1992, its proponents recognize that its practice remains in the early stages of development. This is precisely why more mature design sciences like aeronautics have important lessons to teach us. In the view I have advocated, the aeronautical engineering analogy has persisted in the

DBR literature for good reason – though a detailed examination of its merits, problems and implications is overdue. While educational design researchers may not 'build to fit, draw to match, and paint to cover' in precisely the way the engineers did at Aero Spacelines, those engineers and their predecessors have a lot to teach us about how to fly. Critically, the authors of educational DBR, their editors and audiences need to learn how to report and understand failures in ways that will advance knowledge. The development of a true educational design science is likely farther off than Collins and Brown expected, yet it remains a worthwhile aspiration.

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Note

1. Ironically, despite their more cautious approach, the first fatality in a powered aircraft took place in a Wright Flyer.

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