2. Operant Probes for Scientific Research through Interaction Design

2.1 Introduction

A persistent issue in education research is the question of what its relevance is to actual educational practice. Burkhardt and Schoenfeld argue that "part of the reason is that the traditions of educational research are not themselves strongly aligned with effective models linking research and practice" (2003). Shepard, in her AERA Presidential Address, called for the field to develop methodologies that embrace "dilemmas of practice." (Shepard, 2000) Leaders in the field call for "usable knowledge" (Lagemann, 2002) using these methods.

Knowledge is usually communicated through media (text and images), but knowledge also lives in and is communicated by designed functional artifacts (Cross, 1999). Modern computing makes it easy to share not just bits that represent words but also bits that represent interactive artifacts (i.e. software). Fishman et al. call for design knowledge to make software that is cognitively oriented, scalable and sustainable (Fishman et al., 2004). This work posits that developing this knowledge base is promoted by targeting the design of "usable artifacts". These are research artifacts that can cross the chasm into practice or be adapted by practitioners. I explore the potential of such artifacts to promote research and illustrate the opportunity for a new type of situated research artifact, the operant probe.

2.2 Design-based Research in Education

Education is fundamentally a design endeavor. Adopting Simon's definition of design, "transformation of existing conditions into preferred ones" (Simon, 1969), all facets of education are design: e.g. teaching improves conditions of learners' minds; better instruction improves conditions of teaching; better technology and research improves instruction; better public policy improves all of the above.

To help close the gap between research and practice, education researchers in the early 90s began "design-based experiments" wherein they would iteratively and reflectively prototype interventions in classrooms (Brown, 1992; Collins, 1992). This grew into the Design-based Research methodology and movement, The Design-based Research Collective (Design-Based Research Collective, 2003). However there are numerous conceptions and splinter methodologies and terminologies. Two excellent surveys are those of Mor & Winters and Wang & Hannafin (Mor & Winters, 2007; Wang & Hannafin, 2005) and the book Educational Design Research compiles critical essays (van den Akker, Gravemeijer, McKenney, & Nieveen, 2006b). Howley contrasts these conceptions of design within the field of education with design more generally (Howley, 2010). To stay above the terminological morass, I will use her term DBRE to indicate the cluster of design-based research methods in education.

DBRE is motivated by the observation that the direct application of theory is not sufficient to solve the complicated problems of education (van den Akker,

Gravemeijer, & Nieveen, 2006a). Instead researchers situate themselves within the context of use and iteratively intervene by reflecting on the situation. These well-documented reflections and iterations form the basis of "humble theories", which are domain-specific and pragmatic for the activity of design (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003).

DBRE adds an important methodology that was missing from the toolbox of education research (Collins, Joseph, & Bielaczyc, 2004). However since the debut of DBRE in 1992, modern computing has opened new opportunities for situated interventions. The field of Human Computer Interaction has made greater progress in understanding how to build usable computing systems. I will switch to the lens of HCI to articulate this emerging research paradigm and then return to how it can address some of the remaining gaps in the methodological toolbox of education researchers.

2.3 Scientific Research Through Interaction Design

Interactive computing systems have the potential to improve the quality of education while lowering its costs. The field of human computer interaction has developed to address the considerable complexities in making systems that people can and want to use. Further, the field of HCI, like many applied sciences, has also grappled with the gap between research and practice (Buie et al., 2010).

Because the term "design" is so frustratingly polysemous, I situate this work in a particular framework of "research through design" (J. Zimmerman et al., 2007). RtD describes much of HCI research and draws from Frayling's distinctions between research *into*, *through*, and *for* art and design (Frayling, 1993). Research through Design defines (i) a model of interaction design research that benefits both research and practice communities and (ii) a set of criteria for evaluating the quality of an interaction design research contribution.

A distinction of RtD from other design methods is the conception of the artifact itself as a research outcome. The artifacts, in transforming the world from its current state to a preferred state, serve as exemplars for HCI design practitioners. While the artifacts themselves communicate design knowledge and facilitate extension of the ideas therein, RtD contributions also describe their process in detail to support practitioners in making similar insights in their own design work. As illustrated in Figure 2-1, through this process the interaction designer can synthesize the knowledge from multiple modes of inquiry into an artifact that passes easily into practice.

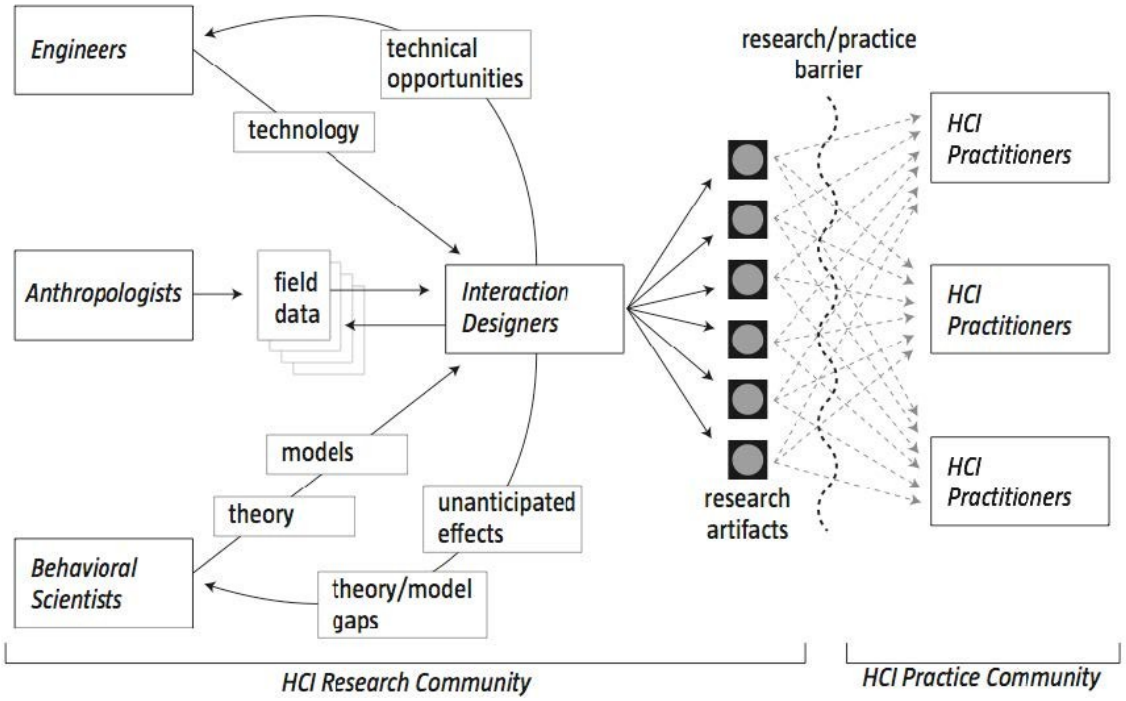

Figure 2-1 Pathways and deliverables between and among HCI researchers and practitioners (from Zimmerman et al. 2007)

RtD distinguishes research activities from practice, in part, by the goal "to make the *right* thing: a product that transforms the world from its current state to a preferred state." They differentiate research artifacts from design practice artifacts in two important ways:

First, the intent going into the research is to produce knowledge for the research and practice communities, not to make a commercially viable product. To this end, we expect research projects that take this research through design approach will ignore or de-emphasize perspectives in framing the problem, such as the detailed economics associated with manufacturability and distribution, the integration of the product into a product line, the effect of the product on a company's identity, etc. In this way design researchers focus on making the right things, while design practitioners focus on making commercially successful things.

This distinction between the *right* and the *commercially viable* highlights an important issue in education research, distinct from HCI practice. While researchers are generally concerned with what is right and good for learners, the communities that produce the products in the educational marketplace are concerned with what creates a perceived value for which the consumer will provide money (or attention for advertising, etc.). In education, this often means that commercial products are adopted that may be viable but not beneficial to learning outcomes, or at least not as beneficial as some *right* but less viable research artifact. However, the public and philanthropic funding of education provides an opportunity to make systems that

are both *right* and also *viable* through non-commercial means of distribution and funding.

A second distinction of the education domain is that the most common practitioners, teachers, do not design technologies. While they design experiences of how technologies will be used in their courses, and may re-appropriate technology in creative and inventive ways, they do not and can not be expected to design the technologies themselves. Participatory design methods like co-design draw in education practitioners as actors in the design process (Roschelle & Penuel, 2006), but at some point the system is made and deployed to practitioners who will have nothing to do with its design.

The difficulty in translating research into practice is a great challenge to the education research enterprise. There is a growing literature of "usable knowledge" in the form of practice guides, etc. However not all basic knowledge can take these forms. We also need "usable artifacts" that operationalize this knowledge into a usable form. By designing interactive usable artifacts, we can bring that knowledge into practice and help to inform the practical constraints of existing scientific knowledge and opportunities to advance it. Within the frame of Research through Design, I call this approach Scientific Research through Interaction Design.

2.4 Operant probe as research artifact

Interactive software systems are an ideal form for operationalizing knowledge in education. They can shape the behaviors of learners and mediate their interactions with learning materials, peers and facilitators. Further, recent advances in computing afford software applications that (i) cost little to develop, deploy and scale; and (ii) provide instrumentation to collect data and run controlled experiments on live systems in natural contexts.

The costs of building web-based software systems are lower than ever. Software standards like HTML5 have driven down the costs of developing for a wide audience. Open-source operating systems and application stacks have driven down the costs of software infrastructure. Commoditization of computing has driven down the costs of hardware infrastructure. Today, one lone developer can make a web-based application, integrated with other services, and serve it to millions of users. The costs to develop and run such systems are miniscule compared to the value they can create. For example, Instagram was recently purchased for $1 billion and had only 13 employees. Projecting falling prices of server resources, a researcher could leave all their software systems running online the rest of their careers for less than the cost of a conference trip.

Further, these systems can be used by people in real natural settings. Today software is constantly adapting to users and the objectives of its designers. For example, Google monitors everything its users do and make inferences to update their designs. These are small hypotheses about how a change to the product (e.g. autocompletion of search queries) can improve some desired outcome (such as speed to find a satisfactory search result). Often a hypothesis is tested through an A/B test which randomly assigns some users to one variant of the system. In this

way Google can develop its theories of its specific product and general theories of user behavior.

The software then is an artifact which operates on the user's environment (e.g. web browser) to achieve an outcome (e.g. fast search) and also probes that environment for data to improve the product's design and more general theories. Let us name this type of artifact an "operant probe". As an outcome of Research Through Interaction Design, an operant probe creates a new space that is both research and practice (Figure 2-2). Research from different modes of inquiry can be brought together to influence the design of an operant probe. The probe, operating in real world contexts, can then influence the learning experience. This influence can be experimentally manipulated to test theories, both humble and robust. Finally, all the data from its use can be used to model the outcomes and mechanisms. With these features, I offer a formal definition:

> ***Operant probe (n): an* in vivo *research apparatus that operationalizes theoretical constructs and collects data by which to both evaluate its effects and model the mechanisms.***

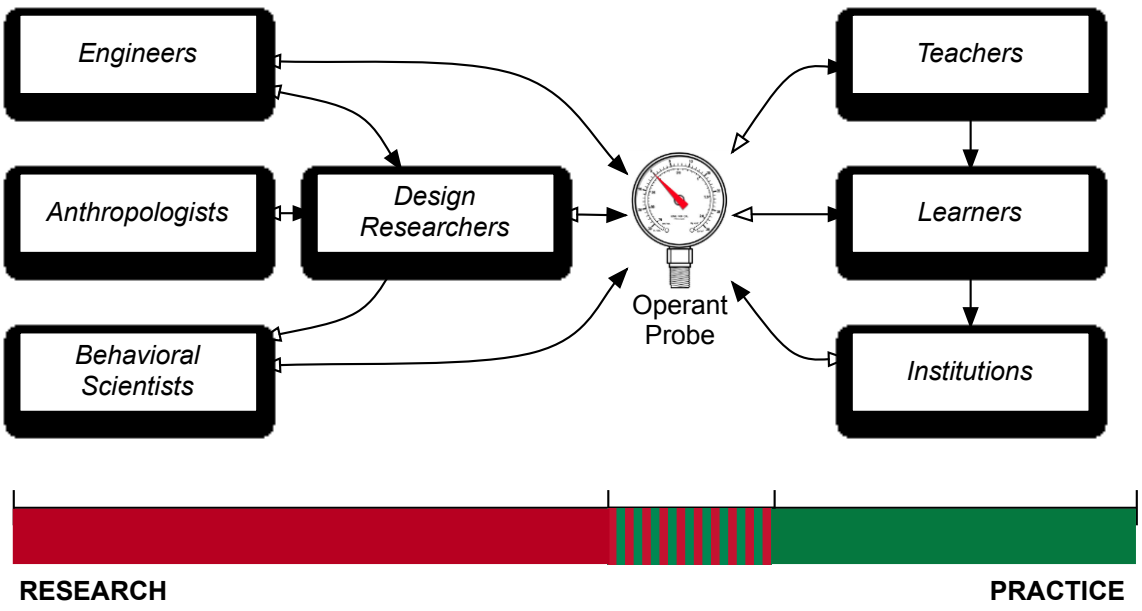

Figure 2-2 Relationship of Operant Probes to communities and contexts

Operant probes are not new to education but there should be more. Intelligent Tutoring Systems make a large class of operant probes. The Cognitive Tutor product from Carnegie Learning could be described as the most successful operant probe in education, operating in thousands of schools and providing millions of data points to improve the product and scientific theories of learning with intelligent tutors. From cognitive tutors a whole field has emerged with variations and enabled exploration and quantitative evaluation of new designs and scientific ideas . Games for learning are a growing class of operant probes, using interaction data to improve the design

of the game and sometimes to contribute back to theory. Khan Academy is a popular system that uses interaction data extensively to drive their design, though they haven't yet engaged any scientific research community.

The operant probe concept fits well into the "iterated in vivo experimentation" methodology (E. Walker, 2010). Walker explains that such experiments, "use a design-based research process to create an intervention, deploy the intervention using an in vivo experiment, and then interpret the effects through a design-based lens, may be a more effective way of theory building than executing an in vivo experiment in isolation." In such experiments, the intervention may be chiefly or entirely an operant probe. So in some sense, "operant probe" is a name for the artifact used in this methodology. But moreover, the design of operant probes is to produce systems that function as well outside the research activity because they are designed to have apparent value to their users and fit easily into their existing behaviors and constraints. Once in place, a well conceived and designed operant probe needs only minimal intervention in order to provide value to users and researchers.

2.5 Value for Research

Operant probes have specific affordances to the practice of research through design. The requirements of a software system to be considered an operant probe are listed in the first column of Table 2-1, with their benefits to research practice and validity.

Table 2-1 Benefits of operant probes to research practice and validity

Requirement	Practical Benefit	Relevant Validity
Low cost and high fidelity of distribution in lab and real-world	high deployability	External and Ecological validity
Consistency of intervention, ease of replication	high replicability	External validity
Operationalization of theory	high specificity	External validity
Instrumentation to provide data to model its use and context	high resolution of data	Internal and External validity
Controlled manipulation of its design within and between deployments	high manipulability	Internal validity

Research framed with operant probes helps fill the gap between descriptive accretive science and interventionist case-based design by supporting endeavors that are both interventionists and accretive. New classes of operant probes can provide learning scientists with new opportunities for real-world impact and new funding sources. They can provide design-based researchers with new tools for building on scientific approaches and rigorously evaluating their designs in many contexts without their active participation. I argue that the design and deployment

of new operant probes can improve outcomes, validate the practical import of basic theory, and generate new research questions.

To advance research, probes must fit into their targeted contexts, provide conditions to validate or invalidate research hypotheses, and provide data to inform the selection of competing models explaining the outcomes. Below I survey the prevailing challenges for design-based research in education to highlight the opportunity for operant probes.

2.6 Problems in education research

In the couple decades since the introduction of design-based research in education, challenges in the paradigm have been articulated by an array of researchers. Operant probes provide an opportunity to address some of these problems in education research. This section quotes heavily from other authors to convey the tone of the critiques and variety of voices.

2.6.1 Ill-defined methodologies

One challenge in design-based research is that the methodologies are so shaky. This is not due to any lack of definitions and procedures; in fact there exists a surplus of distinct frameworks and terms (Wang & Hannafin, 2005). This focus on process has led to research that is over-methodologized and under-conceptualized (Dede, 2004).

Operant probes as a design and research activity fit with existing methodologies instead of seeking to supplant them. As an interface between different communities, they have a face in each that can be engaged with and evaluated per the existing norms of those communities without having to invent new evaluation methods.

2.6.2 Design principles have little traction

Design-based researchers extract principles from their design activities. These are modeled after the design patterns of architecture and software development (Mor & Winters, 2007). Some frameworks advocate a hierarchy of patterns as design principles: General Cognitive Principles such as *self-regulation*, Metaprinciples such as "promote autonomy and lifelong learning", Pragmatic Pedagogical Principles such as "Encourage monitoring", and Specific Principles such as "Multiple, diverse opportunities for students to reflect on their ideas and create representations of their views" (Bell, Hoadley, & Linn, 2004; Linn, Davis, & Eylon, 2004).

While these principles could be useful to a designer employing them, there is little evidence that education technology designers refer to such principles. Technology designers, like other designers, generally learn from examples, not abstract principles (Cross, 1999). Fortunately, unlike in architecture, in education technology the design artifacts are increasingly easy to share. Operant probes serve as highly visible design examples to learn from and iterate upon.

2.6.3 Split competencies and interests

Designing systems that are 1) rigorously grounded in theory and 2) are appealing

in messy real world contexts requires two distinct competencies. Dede describes the consequences (Dede, 2004):

[…] much DBR lacks a strong theoretical foundation and does not attempt to generate findings important for the refinement and evolution of theory. Part of this shortfall may be that the skills of creative designers and the attributes of rigorous scholars have limited overlap. Effective DBR groups have a complex "cognitive ecology" with contradictory tensions: freewheeling, "whatever works" innovation versus controlled, principled variation. People fascinated by artifacts also are often tempted to start with a predetermined "solution" and seek educational problems to which it can be applied, a strategy that frequently leads to under-conceptualized research.

In my experience in education technology for design, there are more than just two categories. Psychologists, technologists, interaction designers, visual designers, ethnographers, teacher liaisons, and others all play a role in the development of successful technologies for learning. While there have been attempts to engage technologists as collaborators in research (Slotta & Aleahmad, 2009), it is a difficult social challenge. Operant probes provide a productive interface and artifact with which to engage.

2.6.4 Difficulty of modeling across layers of complexity

The design of technology for education requires multiple distinct competencies, and research to support these different aspects requires different models. DiSessa and Cobb explain the gap between these layers (diSessa & Cobb, 2004):

We introduce the phrase "managing the gap" to name the issue that is behind the failure of most frameworks for action to achieve what we would like accomplished. The "gap" arises from the fact that instruction is the result of many sorts of complex, interacting elements. Instruction depends on the values of the participants; it depends on technological infrastructure; it depends on the nature of classroom discourse; it depends on practicalities such as available time. We also want to make instruction both depend on and serve to test theory. And yet, in order to see and assess the impact of underlying theory, we must cleanly separate it from the myriad of other issues that we handle, as best we can, in the management of trade-offs among the multiple constraints impinging on instruction. In the ideal case, then, pedagogical strategies and conjectures are separated by a carefully considered and articulated gap from the theory or theories that explain or motivate them. A well-managed gap separates the implications of a particular theoretical claim from other claims and also from atheoretical aspects of design. Attention and effort are necessary to perform this management.

To take a noneducational example, there can be no doubt that there is science in the design of airplanes. However, the shape of a Boeing 747 aircraft does not follow in a direct and simple way from any of this science. Neither does the shape of the aircraft, as a whole, directly test elements of the underlying theory. With sufficient care (corresponding to managing the gap between design and theory), however, a failure attributable to the shape of the aircraft might implicate a failure of a theory of

strength of materials, not just to a careless mistake, a failure to anticipate transient loads, or a poor choice of materials.

An operant probe is like the aircraft. Similarly, it is a specific operationalization of an underlying theory (or theories), and a failure to affect the desired outcome could be due to any number of factors that do not directly test the theory. However, those success conditions and effect sizes do inform the relative significance of theoretical predictions, ease of operationalization, etc. The pursuit of successful operant probes helps illuminate these factors. The iteration of probe designs by different communities can help isolate the features that contribute to that success.

2.6.5 Expense of collection, management and analysis of data from context

Much of the *in situ* data for design-based research comes from observing the physical environment. While these methods can facilitate the discovery of important subtle issues, they are expensive in time and resources. Collins et al. describe the prevalence of unmanageable data (Collins et al., 2004):

Design researchers usually end up collecting large amounts of data, such as video records of the intervention and outputs of the students' work, in order to understand what is happening in detail. Hence, they usually are swamped with data, and given the data reduction problems, there is usually not enough time or resources to analyze much of the data collected. It also takes resources to collect so much data, and so design experiments tend to be large endeavors with many different participants, all of whose work needs to be coordinated. All these factors make design experiments difficult to carry out and the conclusions uncertain.

Operant probes automatically collect their own data through logging of their operation. Additional data can be cheaply and reliably related to the recorded data. Keeping with the airplane metaphor, operant probes each have a black box recorder.

2.6.6 Failure to scale

Educational innovations can be difficult to scale to more users. This is often because the innovation is transformed in new contexts, sometimes losing the essential productive aspect or even becoming "lethal mutations" (Brown, 1992). Traditional design-based research requires working intimately with these contexts to manifest the innovation as intended. Operant probes, as Web-enabled software artifacts, have can be manifest in new environments with high fidelity to their original designs.

When innovations that worked in a limited context are scaled up to more contexts, they often fail. Large randomized controlled trials, such as those advocated by the IES What Works Clearinghouse, find null results so often that some researchers think that What *Doesn't* Work would be a more accurate description (Schoenfeld, 2006). A common reason for the failure to find effects is that the intervention is not implemented correctly in the schools. Teachers often resist these top-down changes to their practice and reject them, even those who had signed up for the study. Instead, operant probes are designed for adoption by practitioners and randomized

controlled trials can take place within systems that are already integrated into practice. Ideal operant probes fit easily into new contexts without much researcher intervention. Imagine an airplane that can be duplicated without cost and modified like clay.

2.6.7 Difficulty of reproducing studies

Due in part to scaling issues, experiments in technology design are difficult to replicate. This limits their contributions to generalizable knowledge.

DiSessa & Cobb content that "design research will not be particularly progressive in the long run if the motivation for conducting experiments is restricted to that of producing domain specific instructional theories" (diSessa & Cobb, 2004). To test the generality of principles and design decisions requires testing concrete enactments of them in other contexts.

The story of the designing the first supersonic jet (Phillips, 2006) helps to illustrate how operant probes can help:

In the period immediately following the end of World War 2 the US military, in conjunction with the agency that was the forerunner of NASA, set out on a project to design a plane that could regularly (and safely) fly faster than sound. Not only was it desired to produce a workable product (the X-1 plane), it was also desired to understand the physics – the aerodynamic principles – of flying at speeds greater than Mach 1. In essence, then, the participants were involved in an early piece of design research. The situation was alleviated by the use of two planes, one for pushing as hard as possible, the other for slower testing. Maybe there is a moral here for design researchers, and their funders.

The operant probe, as an easily replicable and deployable artifact, can be used in multiple settings for multiple purposes. In one, designers can move fast to optimize its operation (the plane pushing as hard as possible). With copies (forks) of the probe, researchers can move slowly to maximize utility of the probe to understand what is going on and what can be learned more generally with confidence before changing it again. When the designers have innovated something interesting to the researchers, they can move on to that version to investigate.

2.6.8 Limited duration of studies

Design-based research in education often requires the active participation of researchers in the context. By putting this design effort into developing systems that can be deployed cheaply to many other contexts, the marginal cost of additional time for a study is greatly reduced. A researcher can let the system persist and check in on it just periodically. This facilitates more longitudinal research that looks at changes over months and years. The systems can even follow participants through multiple learning contexts.

2.6.9 Control of variables

Perhaps the foremost challenge to design-based research in education is the lack of control of variables. Dede describes it poetically (Dede, 2004):

The queasiness about DBR felt by many scholars conservative in their research methods stems from the realization that in DBR studies many variables are deliberately and appropriately not controlled, the "treatment" may evolve considerably over time, and even the research methodologies utilized may shift to fit the morphing intervention. Further, to aid with interpretation under these difficult circumstances, in DBR large qualitative and quantitative datasets of various types are often collected by many different participants, introducing substantial problems of alignment, coordination, and analysis. To a methodologist steeped in traditional Campbell and Stanley research strategies, this combination of challenges may seem less a promising new approach to scholarship than a type of study conceived in hell as Sisyphus-like torture for investigators.

With operant probes, the system itself is a well-controlled variable, due to its reliability of replication. Evaluating a design in whole however confounds many variables that make up the design. As a way around this, features of the system can be selectively ablated to determine which are important to the outcome variables. The scale of operation allows these sorts of experiments.

2.7 Limitations

Operant probes offer many benefits, but only for situations in which they fit. Not all settings would allow an operant probe study. One strong reason would be the privacy of the subjects. The benefits of operant probes are largely in the remote collection of data. The limitations that different contexts pose on data collection can limit the viability of a probe. For example, federal law places strict requirements on how schools store and release grade information. In light of the benefits of mining these data, these restrictions may be lessened.

Another limitation of the operant probe is in the requirement that it be desirable in the context. This is much easier said than done. Educational games offer a clear example of a desirable probe. What other systems can be made that are desirable? That question will drive research in the design of probes.

Finally, there are new types of limits to the control and data collection. Operant probes take some features of the lab out into real world, such as control of design and collection of data. However the remote nature of use, while providing other benefits, limits the data and control to only what takes place inside or with the system. There is no way of controlling or even knowing exactly where and under what circumstances users are interacting with the system. The system can also them such questions or operate a virtual laboratory though a web camera, but such solutions trade off on the authenticity of the learning experience.

2.8 Design process

There are many methods for developing such probes, whether called probes or intentionally following any method at all. Because probes must fit into a user's real world experiences, the most productive design framework would be user experience design. User-centered design is a perspective and set of design methods to help designers products that their target population *can use*. User experience design builds on user-centered design and expands the scope to methods for designing products that the target population *wants to use*.

A necessary step in designing an operant probe is selecting a goal for which to design. Researchers often approach the design process with a problem frame in mind, for which they are designing a solution. Without questioning this frame, they proceed to iterate towards better solutions within that frame. Many other problems and many other frames to the same problem are often ignored. Mapping out the opportunities can lead the researcher to discover new ways of looking at the context and where operant probes could be most successful. As part of user experience design, sketching user experiences can help to create this map (*Sketching User Experiences: Getting the Design Right and the Right Design*, 2007).

User experience design has some limitations for education research, principally that it looks to the user as the source of data for design decisions. It does not always ask the user directly, for they might not know what they really want, but it does try to extract the design knowledge from the user. However in education, many important design principles are secret from both the designer and the user. For example, there is a whole class of "desirable difficulties" in the learning process that improve long-term retention of the learned material (Bjork, 1994). For example, running counter to the training and intuitions of graphic designers, making fonts hard to read can be desirable because the difficulty leads learners to better retain the information (Diemand-Yauman, Oppenheimer, & Vaughan, 2011). Decades of education psychology research have illuminated the processes of learning and many results counter our human intuitions. Indeed, these counterintuitive findings are perhaps the most important to implement in usable artifacts because they run so counter to the dominant practices. In the following chapter I discuss how to integrate theoretical knowledge of learning into the user experience design process.

2.9 Evaluating an operant probe contribution

For an operant probe to be a research contribution, there must be clear criteria by which to evaluate it. Like other Research Through Interaction Design artifacts, operant probes should be judged by Process, Invention, Relevance and Extensibility. Quoting from Zimmerman, Forlizzi and Evenson: For process, "interaction design researchers must provide enough detail that the process they employed can be reproduced. In addition, they must provide a rationale for their selection of the specific methods they employed." For invention, "Interaction design researchers must demonstrate that they have produced a novel integration of various subject matters to address a specific situation. In doing so, an extensive literature review must be performed that situates the work and details the aspects that demonstrate

how their contribution advances the current state of the art in the research community." For relevance, interaction designers "must articulate the preferred state their design attempts to achieve and provide support for why the community should consider this state to be preferred." "The final criterion for judging successful design research is extensibility. Extensibility is defined as the ability to build on the resulting outcomes of the interaction design research: either employing the process in a future design problem, or understanding and leveraging the knowledge created by the resulting artifacts. Extensibility means that the design research has been described and documented in a way that the community can leverage the knowledge derived from the work."

In addition to the above criteria for all RtD, operant probes must satisfy three more criteria: Acceptance, Insight, Scalability and Effectiveness. Acceptance is the evidence that the operant probe artifact is desired in its target context, such that it will be accepted by the stakeholders and would be used independent of a research activity. Insight is the production of some generalizable knowledge through the operation and evaluation of the probe. For example, practical limitations to the operationalization of some theoretical construct or lab-based results. Insights can also lead to generalizable knowledge; for example, by raising new testable hypotheses. Scalability is evidence that the system can easily scale to more users and contexts. For example, a highly desirable system might be one where the researcher pays to have all student essays graded with detailed feedback and annotations. The costs of such a design prohibit scaling up. This can also be conceived as the marginal cost of additional use within and between contexts. Effectiveness is evidence that the operant probe operates on the context to achieve a desired outcome. This includes not just whether there is an effect but how great it is (e.g. effect size measure such as Cohen's d). This allows both comparing the effects of a probe in multiple settings and assessing whether the probe is worthy of the resources it requires.

2.10 Conclusion

The inability to translate research into practice threatens the enterprise of education research and stagnates the practice of education. The methods of Design-Based Research in Education help to develop this *usable knowledge* for practice. Modern computing is creating a new opportunity to create *usable artifacts* that carry over research knowledge and engage researchers directly in the real world environments of practice.

Operant probes are a type of research artifact that are usable directly in practice and allow researchers to test hypotheses and models in vivo with relatively high experimental rigor. Research through Design provides part of a design frame by which to create and evaluate usable artifacts. I've extended RtD into Scientific Research through Interaction Design as a frame by which to create and evaluate operant probes in particular. In the next chapter I will explore methods for mapping opportunities for operant probes and in the following two chapters I document the design and evaluation of two probes designed to exploit found opportunities.