The *Dynabook* Project:

An Engineering Approach To Research and Development of an Educational Innovation

Inverness Research

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Introduction

In 2003, Alan Schoenfeld and Hugh Burkhardt advocated for an engineering-based approach to research and development in education, and yet in the ten years since, relatively few examples have been put forward of work that manifests such an approach – when in fact, many would argue that it is even more relevant today. For example, the current administration is advocating for the creation of an Advanced Research Projects Agency for Education (ARPA-ED) because of a wide recognition of the *under*-investment in learning technology research, development, and innovation. Their goal is to allow innovation to transform instruction and learning opportunities in ways that are apace with how it has transformed communication, business, finance, travel, and defense:

> *[Research and development] accounts for only 0.2 percent of total national K-12 expenditures, [whereas most] knowledge-intensive sectors of the economy invest 10-20 percent of sales in R&D, and even mature industries devote 2 percent of sales to R&D. Too little innovation has deprived teachers of the tools and strategies they need to provide all students the skills they must acquire. Innovations in other fields, however, promise to make a surge of innovation in education easier, as education entrepreneurs leverage the [information technology] revolution already underway in other sectors.*[1]

An engineering-based approach to innovation has long been more appropriate and effective than experimental design for producing tools and resources that education actually needs. Engineering-based approaches provide more understanding about how and why to design an innovation for particular contexts, whereas randomized controlled

[1] http://www.ed.gov/sites/default/files/arpa-ed-background.pdf

studies measure just a single causal factor with extraordinary certainty. Projects that over-rely on a single causal factor tend to be educationally ineffective and/or not sustainable in real-world contexts.

The following paper describes a project, *Dynabook: A Digital Resource and Preservice Model for Developing TPCK,* as an exemplar of an educational innovation that integrated research, development, and practice, and was brought to fruition through an engineering approach. The Dynabook resource itself is multi-faceted and the team has written several articles that detail the features and functions of the resource. This paper focuses on the engineering design of the project itself and describes the research and development process.

Background

Dynabook

In 2009, the National Science Foundation funded the *Dynabook: A Digital Resource and Preservice Model for Developing TPCK* project through its Discovery Research K-12 program. Dynabook project leaders and NSF recognized that digital textbooks would soon be a primary instructional resource, and seized the opportunity to pursue the development of an innovation deliberately and thoughtfully – not to simply recreate a textbook in a digital format. Prior to Dynabook, there were no well-designed, well-organized digital instructional resources for preservice programs that were also aligned with the Common Core standards in mathematics.

The original purpose of the Dynabook project was to design a dynamic and adaptable resource for middle school mathematics teaching that would incorporate key elements of two frameworks – the Universal Design for Learning (UDL) framework and the Technological Pedagogical Content Knowledge (TPCK) framework. To achieve this goal, the Dynabook project assembled a multidisciplinary team with expertise in these two frameworks, as well as in technology development: SRI International in Menlo Park, CA; CAST (the Center for Applied Special Technology) in Wakefield, MA; San Francisco and San Diego State Universities in California as organizational partners; and mathematicians, computer scientists, teacher educators, and learning scientists as individual partners. At its core, Dynabook is now a digital resource to help teacher educators engage their students (who are middle school mathematics teacher candidates) in cognitively demanding proportional reasoning. It helps teachers to use an appropriate pedagogy when teaching proportional reasoning, and to collect and consider evidence of their students' understanding of proportionality.

The nature of innovation

It is neither a surprise nor an accident that SRI (the lead partner on the Dynabook project) would advance an educational innovation as the focus of this project. The desire to explore innovation in an R&D context, provide exemplars for it, and consider the value creation of such an effort is perfectly aligned with SRI's *raison d'etre* – their goal is to address a real need and not simply innovate for the sake of innovating. SRI's CEO Curt Carlson argues that successful innovations come from creating value (through new products, processes, services, etc.) by working with the intended customer or audience (Carlson & Wilmot, 2006). To get a sense of how Dynabook is an innovation, we refer to additional recent perspectives from the business and management fields.

Jointly funded by the Danish and Finnish governments, the *New Nature of Innovation* study (2009) was conducted for the OECD's (Organization for Economic Cooperation and Development) Committee for Industry, Innovation, and Entrepreneurship (CIIE) and promoted fresh perspectives on innovation that are well-aligned with how the Dynabook team approached their work:

> *"It represents four significant philosophical departures. From a traditional "firm centric view" of innovation, this study moves us to a "personalized, co-created view" of innovation… Secondly, it demonstrates the institutional interdependencies in innovation processes where specialized skills are sourced [from different organizations]. Thirdly, innovation is seen not as episodic but interactive, iterative and continuous. Finally, this is a call for democratizing innovation. Consumers, not just institutions, will have their share of voice in the innovation process. Collaborative capacity will be critical for innovation. This is a bold and timely departure from the traditional view.*

-C.K. Prahalad, Paul and Ruth McCracken Distinguished University Professor Ross School of Business, University of Michigan

José Santos, Professor of Practice in Global Management at INSEAD[2], one of the world's most prominent business schools, went on to say, "The value creation potential of such co-innovation is unparalleled in history." These statements also resonate with the approach the Dynabook team followed. The Dynabook resource was co-created by a project team that included education researchers, practitioners, and technologists. The expertise was spread across organizations, with contributions made by numerous individuals within each. In addition, as the project team revised their design, using evidence gathered in demonstration contexts as a guide, they brought in potential users of the Dynabook resource – expert teacher educators from around the world. As such, the Dynabook project exemplifies the boundary-spanning character of contemporary innovation, guided by two key drivers. The first such driver involves the user directly in the innovation process, co-creating value with potential customers and tapping the knowledge of potential users (von Hippel, 2005). The second driver involves using dispersed collaborative networks and partnerships (Govindarajan & Trimble, 2010). The Dynabook team consistently relied on its partnerships and networks to ensure that they had a realistic understanding of how and why the resource could be tailored and customized by potential users.

[2] INSEAD was formerly an acronym for the French "Institute Europeen d'Administration des Affaires"

As one of the Dynabook co-PIs said:

> *"… We don't see how we could stop thinking about how the Dynabook can and should be used. It seems to us that innovation is about fully imagining a new technology and its practical uses. Consider an analogy to Web 2.0 – yes, the technology is interesting but what is really interesting is what user communities can really do with it. We expect the power of Dynabook will come very much from its flexible adaptation by user communities".*

Inverness Research

Inverness Research[3] is an education evaluation firm that was contracted to study and document the potential of the Dynabook project. Initially, we focused our attention on addressing the guiding Dynabook program evaluation questions: "what is the potential of the Dynabook to transform teacher educators' understanding and practice? And to what extent and in what ways is the Dynabook innovation addressing important and broadly felt needs, and poised for potentially transformative impact?" In addition to providing formative and summative evaluation, we began to realize how innovative the Dynabook project was in its approach to research and development. As our work evolved, our focus shifted to documenting the full range of contributions that accrued from the Dynabook project. For this, we assisted the project in identifying and sharing key findings about their critical design principles and features that can be of value to the broader field. This report is a product of Inverness' attempts to distill and share the project's approach and lessons learned with the broader field.

This case study

In the case study that follows, we discuss how the Dynabook project was designed in line with an engineering mode, including iterative phases of development with multi-faceted feedback cycles. We articulate the key steps of an engineering approach and describe how the Dynabook project illustrated each step. Ultimately, the case study presents implications for the future of Dynabook and the broader relevance of the engineering paradigm.

[3] See www.inverness-research.org for more information.

An Engineering Approach
To Research and Development

Several theorists and practitioners have argued that educational research and development would be more useful to practitioners and to policymakers if it involved an engineering approach, which they also note is important in fields to which education is sometimes compared, such as medicine. They argue that educational research "would be more useful if its structure and organization were better linked to the practical needs of the education system" (Burkhardt & Schoenfeld, 2003). A fundamental question is: How does one refine ideas and materials so that they are robust across a wide range of contexts of implementation? To answer this, Burkhardt and Schoenfeld (2003) propose an adaptation of the "engineering approach" common to other applied fields. They contrast the engineering approach to the humanities approach and the science approach. In the humanities approach, researchers observe with the intention of building understanding and knowledge but are not required to carry out any empirical testing. The science approach also includes observation and analysis in order to better understand phenomena but the resulting assertions must be subject to empirical testing. The engineering approach to research is concerned with "practical impact" and developing high quality solutions to practical problems (Burkhardt & Schoenfeld, 2003, p.5). It has been described as "the use of existing knowledge in experimental development to produce new or substantially improved materials, devices, products, and processes, including design and construction" (Higher Education Research Funding Council, 1999, p. 4). It is also conceived of as a practice that "combines imaginative design and empirical testing of the products and processes in development and in evaluation" (ibid). The engineering approach to research focuses on "the processes that link the development of good ideas and insights, the development of tools and structures for implementation, and the enabling of robust implementation in realistic practice" (ibid).

Figure 1
Comparison of R& D capacities and commitments typically found in the fields of engineering and education

"Typical" Engineering Research and Development	"Typical" Educational Research and Development
Multiple successive stages of design, testing	Limited number of iterative stages
Long, deliberate, iterative development process	Idiosyncratic, indeterminate, or vague development process
Assemblage and testing of components	Holistic design, often changing many things at once
Careful study of and learning from prototypes	Minimal use of prototypes
Summative evaluation conducted after many testing and revision cycles	Often proceeds quickly to summative evaluation
Scale up done slowly and after extensive development	Lacks an established discipline or approach to scaling up
Seeks to produce future working versions, more complete than the last	Seeks to produce publishable knowledge
Seeks insight into effective, valuable, and practical design	Seeks significant statistical differences in outcomes

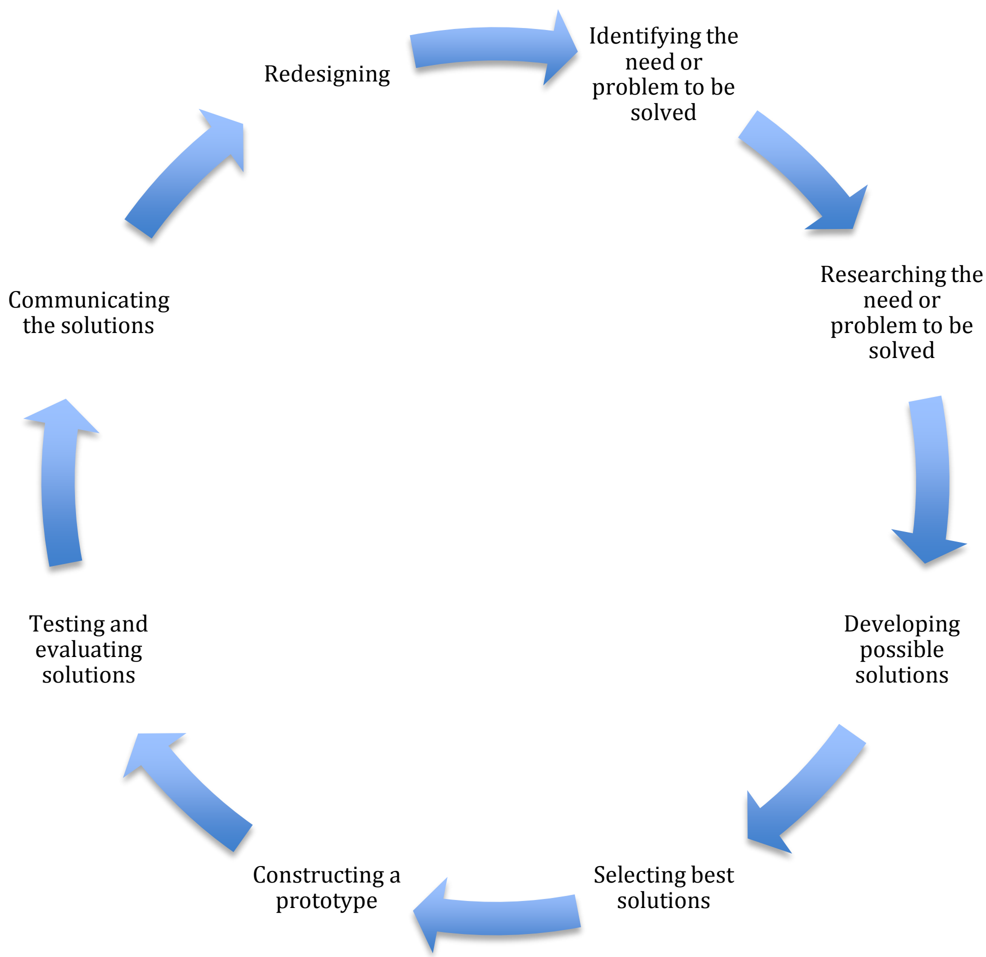
While the above discussion and figure sets up a forced extreme dichotomy between typical education research and engineering research and development, it is intended to illustrate ways in which the two can be different.

An Engineering Model

There is no one single model for "the" engineering approach to research and development but rather several different models involving four to ten basic steps such as design, develop, test and evaluate, and redesign, in an iterative cyclical manner. Outlined below is one useful model set forth by the Massachusetts Science and Technology/Engineering Curriculum and modified by the Center for Adaptive Optics (2007). First, we describe the features of the model; then we describe how the Dynabook project exemplified each.

Features of the engineering approach

- Identifying the need or problem to be addressed
- Researching the need or problem to be addressed
- Developing possible solutions
- Selecting the best possible solution
- Constructing a prototype
- Testing and evaluating the solutions
- Communicating the solutions
- Redesigning (continual iterative cycles of research and development)



In practice, the approach is not as linear as it might appear here: usually, those employing an engineering approach participate in the different features iteratively as new information is gathered and considered. Below we discuss how the Dynabook project manifested each of the above features.

Identifying the need or problem to be addressed

- Identification and clarification of the design problem to be solved or the challenge to be addressed
- Specification and prioritization of requirements and constraints to better define the need or problem
- Specification of the desired goals and outcomes
- Assembling the appropriate team/collaborative approach
- Understanding the context

This feature involves becoming clear about the intended outcomes, goals, and vision for the project, as well as the constraints and context within which it exists. Often goals are stated in terms of multiple dimensions to be optimized or minimized, and some dimensions of the design are often given higher priority.

The Dynabook team had a shared goal of developing an innovative technology-based resource incorporating the principles of Technological Pedagogical and Content Knowledge (TPACK) and Universal Design for Learning (UDL; Rose & Meyer, 2000). The team hoped that this resource could help to improve the mathematics knowledge and pedagogical skills of pre-service mathematics teaching candidates. The Dynabook project was informed by the project leaders' awareness that digital textbooks were being developed and would become a booming industry within education. They also recognized that initial efforts were likely to be weak in terms of full exploitation of the capabilities of technology; more likely digital textbooks would be still very much like paper texts in form and function. The group recognized this potential and decided to create a digital text that was more than a book on a computer – a resource that would leverage the unique affordances of a digital environment to provide coherence and connectedness among words and representations. And importantly, a digital text that would address an enduring unmet need to help prospective middle school teachers understand middle school mathematics and why it emphasizes the concept of proportionality as a central thread, so that the teachers may, in turn, help their students understand. All of this would require cycles of investigation, testing, and refinement.

Dynabook leaders originally envisioned the project as a four-year effort. Their consistent and persistent responsiveness to feedback was foreshadowed when they addressed the questions and suggestions of the NSF program officer in charge of the grant. They re-scoped the project to fit a three-year time frame with each year planned as follows: Year 1 would be focused on design and development, as well as usability testing, to prepare for pilot testing in Year 2; Year 3 would provide for a second year of pilot testing. In addition, the project changed its course from requiring preservice teachers to use the Dynabook for several weeks, and focused instead on shorter (six hours and up) blocks of usage that would emphasize and highlight the variety of ways in which the resource could be used. The leaders also planned to highlight the particular skills and expertise of each partner on the multidisciplinary design team: SRI would focus on issues associated with lesson content and facilitating instruction; CAST would focus on UDL; the university partners would focus on maintaining authenticity; and technical design and development would be under the purview of both SRI and CAST in a joint effort.

The Dynabook project leaders also indicated what would become a steadfast parameter: to never focus strictly on development in absence of context. In his reply to the program officer's questions, Roschelle wrote:

> *"… we could agree to make this a development-only project, emphasizing 'design and build' but not test [a suggestion made by the program officer]… We propose an alternate means… We do so because we agree that the NSF community does care about the 'test' in the 'design, develop, and test' cycle and hence, it would not be prudent to pursue innovation without rich contextual feedback. Keep in mind that we really don't have 'test' in mind, but innovation in the context of use. And we need to maintain rich connections to a context of use in order to pursue meaningful innovation for those contexts… Innovation comes from recognizing and fulfilling unmet needs in conversation with a user community… We believe the true value of an electronic resource is how it flexibly adapts to different kinds of uses."* (Roschelle, 2009)

Specification of the desired goals and outcomes

At the project kick-off meeting, all project partners participated in an activity whereby they developed personas (Cooper, 2004) and use scenarios to help specify the design challenge and guide the initial development of the Dynabook resource. The value of developing personas is that they provide a common reference point for team members and can improve communication and understanding of various audiences' attributes, needs, and contexts. Developing scenarios allowed each team member to think about a particular situation and how one might interact with the Dynabook in that situation.

Assembling the appropriate team

The proportionality Dynabook project is a collaboration between two California state universities (San Francisco State University and San Diego State University), SRI International, CAST, and Inverness Research. The project design team recognized the substantive, yet fruitful differences between the two CSU campuses. Rather than trying to create parallel experiences at both universities, the project refocused its efforts to capitalize on these differences, to better understand how Dynabook could be developed for and useful in different contexts:

> *"Across these experiences, we expect to gain insights that we still believe could be usefully organized into a framework that could inform the field about the ways in which digital resources could support new forms of preservice development for middle school math teachers."* (Roschelle, 2009).

At the project kick-off meeting at SRI in October of 2009, the PI stated:

> *"All of you are co-designers… not people who build and then test. We are going to design this together and pool our diverse perspectives on what it should be and have a somewhat structured design process".*

The project leaders set an example and a standard for the rest of the Dynabook project that most, if not all partners appreciated and supported. Early on, one partner said:

> *"Considering how large the team is, I think the project is going amazingly well… [The project leader] sets a great vision, which keeps everyone focused on the end result, with a real desire to work together (no individual agendas). There is redundancy among teams (many people working on content, some of whom work on design; some designers work with programming, etc.), which could be problematic but seems to work to our advantage – no group is working in isolation, and all are aware of what the other groups are doing. The team's willingness to change course after the last advisory board meeting [is telling]. I've been in other situations where teams don't want to change what they've been working on, despite the feedback. Again, the leadership made this easy for team members to embrace."*

A different design team member also spoke of the value of having intentional redundancy in members across project sub-teams:

> *"Dynamic groups were formed occasionally, on purpose, and representatives from different organizations have been working together in the design, development, and research process – so various insights from different specialties have been applied, and it has made the Dynabook content and supports very coherent."*

Dynabook is a project that spans many content areas including teacher professional development in general and special education, proportionality, technology-supported instruction, university class instruction, as well as research and development. Professional staff from all organizations contributed to each of the project activities, including collaboration around project goals, math content, feature and interaction design, and use scenarios. The same principles applied to the Dynabook's research efforts. There were both individual contributions as well as collaboration applied to the definition of research questions, instrument design, data collection, analysis, and interpretation/conceptualization in reporting the findings. The resulting multi-organizational research effort was conducted in the tradition of a mixed methods design-based project (Brown, 1992; Creswell, & Plano Clark, 2007), drawing on multiple types of data collection strategies.

Researching the need or problem to be addressed

- Examination of current theory and practice
- Examination the current state of the issue and current solutions
- Exploration of other options via the internet, articles, library, interviews, etc.

Engineering as a systematic process of research and development seeks to build and improve upon what is known to work. An engineering design process or approach will draw upon all the available scientific theory, pre-existing models, evaluation of previous experiments, and existing products and practices.

In "informed exploration" phases, the Dynabook project explicitly sought to interpret, within a specific context, learnings from the broader literature and team experience relating to TPACK, UDL, and specific needs of pre-service programs, and integrate these into the evolving Dynabook approach. These data led to scenarios of user needs, contents, design, and use models that were produced in the initial prototypes. In this way, in addition to UDL and TPACK, a focus on the additive to multiplicative learning progression (Lobato, Ellis, Charles and Zbiek, 2010) rose to prominence in the Dynabook approach, as did considerations of the "implied reader" (Weinberg & Wiesner, 2011) in mathematics texts. An "implied reader" is an idealization of the typical reader and their preconceptions and experiences reading mathematics text, which the development team would address. By conceptualizing an implied reader, the team sought to focus on the activities of the user in context, rather than the abstract capabilities of the technology in the lab.

Developing possible solutions

- Brainstorm possible solutions
- Articulate various possible solutions
- Identify design tensions

Here researchers and project designers begin to imagine solutions that would address the problem or challenge. Some of these solutions are holistic; others only addressed part of the problem. (By analogy, one might conceive the form of the vehicle to be designed; other engineers might simply think about optimizing the design of the transmission.) In Dynabook, this involved the entire team negotiating between the constraints of CAST's evolving technology platform (what is easy, what is difficult, what is impossible) and the perceived important needs of the university instructors and candidates, even while inclining in the directions suggested by the theory emerging from the informed exploration phase and integrating feedback from formative testing.

In the initial design enactment phase of the Dynabook, prototypes of the resource were presented to groups of teacher candidates on both campuses, as well as to advisory board members with expertise in math, teacher education, technology supported instruction, and UDL. The feedback they provided was consistent and initially difficult to hear. There were some good ideas in the Dynabook about the project's purpose, using technology, ratio, multiple representations, UDL, and drawing connections, but problems limited the prototype's potential and impact. One important message heard was that there was too simply too much content in Dynabook. Further, the reliance on the style and structure (and to a certain extent, content) of existing textbooks was limiting and gave the impression of a linear textbook. It also was not dynamic enough for a 21st century web application. It did not take sufficient advantage of a web-based resource, did not use video sufficiently, and did not go far enough in adherence to UDL principles. This feedback led the Dynabook team to reformulate their concept of a Dynabook (it's not about content, for example). For example, the team restructured the Dynabook to have multiple pathways through the content, and activities based on interactive lessons, challenging problems, or videos of student thinking. Indeed, many of the use scenarios originally contemplated were scrapped entirely. This process is consistent with the underpinnings of design research where co-designers must be able to listen to and accept fairly significant criticisms and act on them to improve the approach and its use (Collins, Joseph & Bielaczyc, 2004).

Over the course of several design cycles, the Dynabook team iteratively produced more than five distinct and different prototypes of the resource, which were then tested in university settings and then further refined. The next section briefly describes the design tensions that appeared during these design research or action research cycles and how those tensions were addressed.

<u>Identify design tensions</u>

The design tensions framework (Tatar, 2007) accounts for the process of organizing and providing a rationale for decisions. Unlike a more typical problem-solution approach, this framework allows design teams to focus on elements that must be resolved through compromise, a process that often leads to more innovative solutions (Lara-Meloy et. al, 2012). The team's attentiveness to all of the partners and stakeholders, and the feedback loop, surfaced design tensions and helped the team make them productive.

In fact, as the team reflected on what they were trying to create and why, they also revealed added dimensions of 'need.' While many projects might be satisfied with their initial definition or articulation of the need they are attempting to address, the Dynabook project continued to peel back the layers of their conception of need, and determine whether there were additional or more nuanced needs to guide their work. As they interacted with and reflected on the prototype Dynabook resource, the needs became simultaneously more textured and concrete. Hence understanding the "need" was as iterative as (and parallel to) the development of the resource itself.

Inverness determined that documenting emerging design tensions would be helpful to both the Dynabook research and development project and other audiences interested in pursuing similar work. Because the members of the design team were diverse and highly specialized, Inverness asked each lead partner and member of the development team to respond individually to the following questions:

1) Based on your role and the work you've been doing on the Dynabook team, what have been some of the design tensions and key decision-points that you've faced, and what was the outcome? How did that decision influence the Dynabook?
2) What have you learned from this process (the collaboration, this effort to create a digital text) that you would want others to know, who might take on a similar endeavor? What advice would you give them?

Below we describe four key design tensions that were raised early on and would be revisited throughout the project.

- **Book versus mash-up**

Early on, the team wrestled with particular issues associated with a digital book. Some team members were concerned about being able to create a resource that would be competitive with what is already available on the Internet or in learning management system (LMS) tools such as Blackboard or on publishers' websites. In addition, many on the design team felt that the "book" metaphor was limiting, in that it implied a linear progression through pages, rather than a dynamic, expressive medium, in which users could actually participate. Yet, a few partners were concerned about jettisoning the metaphor altogether. One said:

> *"I fear that if we ditch the entire book metaphor, we lose inherent organizers like a table of contents, a logical path for progression, and the genre that most college students are still accustomed to using."*

In response to the above concerns, the design team began to focus less on the "book" and more on the activity and experience of using the resource, and emphasized the social dialogic aspect of the tool and its quality pedagogical content. Indeed, the team started to see the potential of the Dynabook as optimizing a "mash-up" of resources already available – but helping the user to experience these resources in coherent, useful ways. The language to describe Dynabook shifted from "book" to "resource" or "tool" (and has shifted even further since, to "lab").

- **Digital native versus digital naive**

When the Dynabook project was being planned, the team believed that the latest generation of teacher candidates would be digital natives, having grown up with technology. Through additional conversations with teacher educators and observations of university classes, it became clear that the team actually could *not* presuppose a high level of sophistication with technology among teacher candidates. As one team member said:

> *"University undergraduates aren't digitally native enough to just 'get it'. And just because they might take the time to figure out the ins and outs of high interest, high technology (texting, Facebook, Twitter, etc.), this doesn't necessarily translate into them having a high persistence in figuring out novel*

> *technologies to gain content knowledge that they aren't convinced they need in the first place."*

Similarly, another said:

> *"It is important to get to know and understand the future users of the product you are developing. While that may seem intuitive, there is a difference between thinking you know your end-user and really getting to know them. I would advise a development team to talk with the end users, observe them, and allow them to be a continual part of the development team."*

- **Interconnectedness versus completeness (navigation and orientation)**

Originally, the Dynabook was conceived of as being framed by a Concept Map that teacher educators could use to navigate the Dynabook. Yet, in practice, Concept Maps were deemed to be too complex and abstract for teacher candidates to understand.

One design team member said:

> *"A key design tension (perhaps the key design tension) pitted interconnectedness (with its concomitant completeness requirement) of the implemented items against the richness of the individual items. From a theoretical and rhetorical perspective we had, from the beginning, we leaned very heavily in the direction of interconnectedness - with concept maps, tours, cross-linking parallelism, etc. high on the priority list."*

The team determined that it was more urgent to have a few elements completely and richly realized:

> *"While the team still recognized the importance of connection-making tasks, it chose to reconceptualize "connection-making" to understand how its benefits might be captured in richer (and hence more 'localized') tasks."*

- **Designing for familiar behaviors versus cuing and supporting new behaviors**

The Dynabook project began by using the technology infrastructure created by CAST. However, the team realized there are fundamental differences in how readers read and interpret written words or text (such as when reading a novel) and how Dynabook users would encounter and interpret mathematics. Through Dynabook, the team hoped to cue users to engage in a variety of activities (such as using an interactive applet, writing a script to solve a problem, creating an animation that would accompany a solution, drawing from other online resources, etc.) to support the textual information. Therefore, the team had to carefully design and test various means to cue users to navigate among and engage in interactives as they read text.

Ultimately, surfacing and addressing design tensions allowed the team to clarify its goals, priorities, and approaches, resulting in a more interactive, personalized resource that supports teacher educators in *creating*, rather than simply *using* textbooks or online videos and resources (Lara-Meloy, et. al, 2012).

Selecting the best possible solutions

- Determine, using simple analysis, which solution(s) best meet(s) the original requirements

Very often designers will try to instantiate a design concept by creating a very rough mechanical analog – a draft prototype. In testing this very rough initial creation the designer seeks to show that the concept is viable. No effort is made at this point to argue that the model that is produced is in anyway the model that will work in the real world. (The Wright Brothers in flying at Kittihawk produced a draft airplane that was a compelling proof of concept, if not a commercially viable aircraft.)

Dynabook's second design enactment phase set out to solve design problems suggested by teacher, partner, and advisor feedback, and formulated in terms of revision to the theory of operation. The theory driver in this case was an extension of UDL, positing the need for "multiple ways in" to the Dynabook content. The change to the current "matrixed" design (most easily visible on the Dynabook homepage) from the initially linear model represents exactly the kind of negotiated solution that is characteristic of a design enactment phase.

During "implementation research" (or "pilot") phases, augmentations and revisions of the technology, content, and planned lessons were completed and then employed over multiple class sessions on partner campuses. Qualitative and quantitative data collected during these sessions served the purpose of informing the next iterative design of the Dynabook content and software, as well as the in-class and out-of-class use-models, and the planned instructional activities within university classes themselves. These data also provided information about variation in contexts of the pre-service programs and the backgrounds, skills, and interests of the pre-service populations served in both campuses. Further, these Dynabook pilots provided opportunities to examine in detail the extent and manner in which the central theoretical constructs of TPACK and UDL, modeled throughout Dynabook, resonated with the candidates in these pre-service methods classes.

As one San Francisco State teacher educator said:

> *"This is important because as the tool is put to use in real learning environments, innovative uses and applications may surface… In addition, rather than focus on outcomes in testing students' knowledge of proportional reasoning, it is important to consider changes in the learning process. This would help in the ongoing development of the tool to become an instrument that fosters deeper learning and understanding."*

Constructing prototypes

- Model the selected solution(s) in two and three dimensions

In this engineering stage, the prototype is taken from a draft to a "minimally viable product" with core and essential features that can be tested. Using the technology development expertise of CAST and SRI, both teams collaborated to build a Dynabook prototype, adapting an existing CAST platform. A revised prototype was the result of each design research phase; therefore, a series of prototypes evolved through the life of the project.

Testing and evaluating the solutions

- Does it work?
- Does it meet the original design constraints?

Eventually, an engineering team begins to construct simple but valid prototypes of the ideas that seem most promising. These prototypes are then tested in more or less laboratory settings (e.g., for cars, wind tunnels) and/or in a few carefully selected real world settings, so that engineers may learn the extent to which their conceptions and theory are achievable. The engineers then study the prototypes with the express purpose of validating their continued feasibility and with the purpose of improving the prototypes in the next iteration.

The Dynabook use data came from classes conducted at the two partner universities. Because the Dynabook is an integrated development effort, with the technology and the content and the pedagogy evolving simultaneously, each pilot was different from the previous along all three dimensions. As a consequence, each data collection focused on an activity that was being tried out for the "first time:" a first time for a particular sequence of activities on either campus, a first time presenting the material and organizing the class, a first time for a new or redesigned feature, and even a first time for the data collection protocols. This is approach is distinct from studying a well-established curriculum sequence and activities. The research team studied 10 different class sessions on two campuses. This translated into 10 different lessons, different feature sets and 10 different sets of content and instructional emphases. In line with Eric Hamilton's (2012) perspective, the Dynabook project tolerated its own novice steps in order to make it to the expert level. Hamilton lauded the idea of granting permission to be incremental in the service of being transformative.

Like the design of Dynabook itself, researchers from all partner institutions contributed to the development of the research questions, data collection instruments, as well as to the collection, analysis and interpretation of the findings. Across partners, the resulting research efforts and lessons learned spanned a range of research topics including teacher preparation, technology-supported instruction in mathematics pedagogy, as well as use of the Dynabook in pre-service teacher preparation classes.

Communicating the solutions

- Make an engineering presentation that includes a discussion of how the solution(s) best meet(s) the needs of the initial problem, opportunity, or need
- Multiple sources of feedback

Once an idea has been shaped through repeated testing into a product that appears to work in real conditions, the innovation is ready for the next phase of testing which involves more diverse settings and naturalistic usage. Here the designers discover whether or not users who are not familiar with the product can use it successfully, and what kinds of supports and training are needed. In this process the designers discover all the unforeseen pitfalls and problems that earlier tests have not uncovered. And they begin, also, to have a sense of the key dimensions that will ultimately affect the marketability of the product.

For the Dynabook project, this step of communicating the solution(s) involved the project sharing and communicating about recent versions of the Dynabook resource and the associated research. In addition, a hallmark of the Dynabook project is the leaders' determined effort to collect and process feedback from a variety of sources – from the early conception of the project, through the prototyping and research phases, and through today. The extent to which and how the Dynabook project communicated their potential solutions and solicited feedback from different informants – including the university partners, the project's advisory board, the evaluators, a consultant network of teacher educators, and partners at other Cal State campuses – is in itself an innovation.

<u>Multiple sources of feedback</u>

University partners
The university partners of the Dynabook project were consistently seeking out opportunities to test the Dynabook in their own and in other faculty members' classrooms. They talked with other graduate students and faculty in their departments to gather additional perspectives on the use and potential value of Dynabook. The interviews they conducted and the conversations they shared with their own students (who are teacher candidates) helped inform all revisions of the Dynabook resource.

Advisory Board
The Dynabook project's very intentional and constructive use of their advisory board was well designed, and can serve as a model for other projects. Not only did they assemble a dedicated group of professionals with a wide range of relevant expertise, the Dynabook project leaders set up the annual face-to-face advisory board meetings to maximize the advisors' ability to provide useful input and feedback. The project team took the preparation for advisory board meetings seriously. They had several planning meetings

around each advisor board meeting, in order to discuss what the project most needed feedback on – and what was most relevant to share with the advisors in order to prompt such feedback. They sent the advisors sufficient information (in the form of video clips, papers, questions, agendas, and personal messages) in advance, to prepare them to discuss critical issues and raise germane questions. The actual face-to-face meetings themselves involved the project spending a limited time providing updates for the advisors, allowing the advisors to talk amongst themselves, and engage in a critical feedback session (with no project personnel present) facilitated by Inverness Research in the role of evaluator. Overall, the Dynabook project team provided clear goals for the advisors and their tasks, numerous structures and adequate time for the advisors to grapple with key questions and challenges, and several mechanisms to capture the advisors' concerns and revisit or review them iteratively over the course of the project.

Evaluators and the Teacher Educator Network (TEN)
Another innovation associated with the Dynabook project was the cultivation and maintenance of a network of consultants who provided additional feedback on the Dynabook resource. Inverness has previously recruited and relied on consultant networks to provide comments, criticism, and advice on other projects. For the Dynabook project, Inverness recruited a group of teacher educators from around the United States and Singapore[4]. At the beginning of the project, this group completed a preliminary assessment of teacher educators' needs and interests; the group was surveyed regarding their background, assignments, colleagues, departments, students, and pedagogical needs. Later, as the Dynabook evolved, each member of this network individually completed a tour of Dynabook, a series of assignments (to orient them to the Dynabook's various features), and an independent written review. The review addressed their general reactions, their assessment of specific functions, and how they could or might use Dynabook in their classes. In fall 2011, twenty-nine TEN members participated in the tour, assignment, and review (see the appendix for more information on the Teacher Educator Network and their reviews of the Dynabook.) The Dynabook project team carefully considered what the TEN members reported, in terms of their needs and their opinions regarding the Dynabook resource.

Other university partners
In addition to the teacher educators from San Francisco State and San Diego State, a faculty member from San Jose State also tested the Dynabook resource with her class, attempting new assignment structures and providing feedback – all of which was considered as the Dynabook project team planned for expanding their work to other campuses.

For any project, much less a three-year endeavor, the Dynabook leaders ensured that they solicited feedback and input from as many stakeholders as possible in a very short amount of time. More importantly, they listened to and respected that feedback.

[4] Singapore has a progressive national mathematics curriculum that focuses on conceptual understanding and problem solving. Singapore's students are consistently among the top-ranked in proficiency on international mathematics assessments. Individuals from Singapore's Ministry of Education have previously collaborated with members of the Dynabook team.

One design team member described the benefits of the feedback loops inherent in the Dynabook project:

> *"The advisory meeting, focus group interviews, and ongoing feedback from the university professors have been a great help and a key factor in making decisions and prioritizing the content and features to implement. Based on the feedback from the field, the instructional designers and programmers were able to come up with viable solutions, leveraging the flexible digital environment. Then, it was vetted with the entire team again. This kind of iterative process and frequent communication with partners from the field really worked out well in this project. I think that this has influenced the Dynabook to be more practical and prevented us from creating an 'ideal' but theoretical prototype in isolation."*

Redesigning (cycles of research and development)

- Overhaul the solution(s) based on information gathered during the tests and presentation
- Continue to revisit design tensions

Based on feedback gathered from multiple sources and through constantly revisiting design tensions and priorities, engineering projects continually iterated upon and improved their innovation. Further, each prototype must represent progress and advancement along multiple dimensions – it must be more complete, easier to use, and the value-added must be more evident and easier to access. Much of the Dynabook project's work that has been presented above continues to this day and will continue into the future. Even after five versions of the Dynabook resource, revisions are still being made in response to the feedback and input of different stakeholder groups. Dynabook is now poised to broaden its iterative design cycles to include new locations and contexts. When the lead technologist was asked what advice he would give to others interested in engaging in similar work, he said:

> *"…Resist the urge to 'get things done' at the expense of thorough design, as the gains that might be made by rushing to start can be lost when rushed designs have to later be re-designed and re-implemented. Identify a design process and stick it out. That said, do not be afraid to throw things out that are not working. Dynabook has greatly benefited from its course corrections and has done an admirable job of being responsive to early user feedback. And yet on the other hand, do not make a course correction every time some individual team member has a new idea or some individual user has a piece of unique feedback. Have a strong vetting process in place for suggested changes to design, great or small."*

Appropriately, the lead technologist played an important role in asking *how* the next cycle should be different and *why*.

Summary of the Case

Many education design efforts are embedded within an experimental paradigm, where one takes a design, implements it, and tests its impact, gathering data on whether the design "worked" or "didn't work," with the user as an outcome rather than an input. While this approach can validate causal claims, it rarely provides insight into what exactly worked or didn't work, much less *why*. In contrast, early Dynabook research was in service of gathering insight into the needs of and value to the user, in order to continue to evolve simultaneously the conception and design of the product.

As the conception of the product became clearer, a shift from testing the concept to testing a prototype gradually occurred. Ironically, a premature effort to test an innovation "at scale" before its theory of operation is well understood can undermine the quality of the innovation, thus reducing its chances of spreading and surviving. The slow and deliberate approach of the Dynabook project means it is more likely to have produced a robust innovation that will succeed in the real world and, perhaps, endure longer. To iterate on prototypes, the Dynabook project used a co-design approach. For this approach, the project brought together a multidisciplinary and multi-institutional team, implemented prototypes in real contexts, sought the feedback of multiple stakeholders through several design cycles, and *carefully considered that feedback*.

Conclusion

Through a collaborative approach that emphasized short-term cycles of design experiments (design, development, and testing), and heavily involved the perspectives of education practitioners, the Dynabook project has found a productive interaction or interplay between mathematics education and special education perspectives that encourages educators to listen to and consider carefully learners' mathematical thinking, along with a means for doing so.

1) <u>Implications for the Future: Further Refinement and Dissemination</u>

Sustaining the very same approach this paper has described, the Dynabook project is now primed to further its engineering-based approach by continuing to refining the resource, implementing it in different settings, and learning how it interacts with other systems. The engineering approach will continue; now it will be focused on engineering scale-up and broadening the reach of the project, focused on creating an improvement community around and growing the Dynabook resource itself. Rather than disseminating a final static product, the Dynabook project will be using an engineering-based approach in dissemination – the project will broaden the product's use and learn new lessons that will influence additional improvements, and the design, refinement, and dissemination will all be linked.

2) The Relevance of the Engineering Paradigm

In education, there is a more effective paradigm for approaching research and development of innovation than the controlled experiment that is so often promoted. As early as 1972, Parlett and Hamilton wrote of the dangers of relying on experimental designs that originated in psychology and used large randomized samples to understand and measure the effectiveness of an educational innovation. They argued that these designs sought only objective numerical data and failed to address the concerns of the participants and users because they were deemed too subjective or anecdotal. They concluded:

> *These points suggest that applying the [experimental design] paradigm to the study of innovation is often a cumbersome and inadequate procedure… it falls short of its own tacit claims to be controlled, exact, and unambiguous. Rarely, if ever, can educational programs be subject to strict enough control to meet the design's requirements. Innovations, in particular, are vulnerable to manifold extraneous influences.*

Instead they advocated for studying educational innovation in terms of how it operates in context, how it is influenced by school situations, and how intellectual tasks and learning experiences are most affected. Of this socio-anthropological paradigm they wrote:

> *…aims to discover and document what it is like to be participating in the scheme as a teacher or pupil; and, in addition, to discern and discuss the innovation's most significant features, recurring concomitants and critical processes. In short it seeks to illuminate a complex array of questions.*

Understanding how an educational innovation is adapted in particular contexts by potential users is a critical piece of the engineering-based approach to research and development. In contrast to fields such as medicine and electronics product development, education has not typically embraced an engineering approach to the research and development of innovative products, processes, and tools. We argue that the approach the Dynabook project has taken resembles the careful, iterative design cycles and testing that takes place in more engineering-oriented fields, is more attentive to the complexities of context, and is therefore, a more effective approach to research and development of an innovation than is often seen in education.

The fact that other research and development teams around the country are, simultaneously, creating educational innovations using portable digital formats such as tablets, has further implications. The type of resource that the Dynabook project represents is part of a new wave of innovation in which multiple innovators are working in multiple domains on a general problem in a field. There is likely to be considerable synergy, with many solutions surfacing that have features that are both distinctive and similar. However, the Dynabook project is unique among many of these efforts in that it has managed to remain true to and incorporate qualities aligned with cognitive research on how people learn, while still pushing the envelope of technological innovation, to create a product that practitioners find useful and valuable.

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Appendix

About the Teacher Educator Network

The Dynabook project is a collaboration of researchers, educators, and technologists from five different institutions of higher education and research, development, and evaluation non-profits. The design and testing process produced rich design tensions, which contributed to the evolution of the design of the application and its pilot use in teacher education methods classes. The team developed a common goal building a Dynabook that could reach its goals of an improved dynamic curriculum activity ecosystem. As described above, we had some indications of promise. It appeared that the Dynabook activities were engaging for most candidates, stimulated some self-reflection about math, student needs, and pedagogy. Taken together, the qualitative and quantitative data indicated some promise that continued development in this direction might be promising and that wider adoption might be worth exploring. However, members of the Dynabook team are not a representative sample of potential users of the Dynabook in math methods classes. The team began the project with the idea that technology could play a role in improved outcomes for candidates and their students alike, and set about to design a tool and instructional activities to test them. The use of the Dynabook in pre-service education required a significant amount of additional work for partner teacher educators from the team to design and implement classroom activities that would make use of the Dynabook in productive ways. As such, it was not at all clear that there would be broader interest in such a resource among teacher educators. Further, this issue of broader application is a crux of much criticism of the reliability and validity of design research (Onwuegbuzie & Johnson, 2006; Shavelson, Phillips, Towne & Feuer, 2003).

In order to address this issue, evaluators from Inverness Research recruited a sample of teacher educators around the country, to form a Teacher Educator Network (TEN). At the beginning of the project, this group completed a preliminary assessment of teacher educators' needs and interests; the group was surveyed regarding their background, assignments, colleagues, departments, students, and pedagogical needs. Later, as the Dynabook evolved, each member of this network individually completed a tour of Dynabook, a series of assignments (to orient them to the Dynabook's various features), and an independent written review. The review addressed their general reactions, their assessment of specific functions, and how they could or might use Dynabook in their classes. In fall 2011, twenty-nine TEN members participated in the tour, assignment, and review. Overall, they reported that the approach had promise, and were positive about Dynabook's features, content, and potential uses. For example, 89% agreed or strongly agreed that they would be likely to show Dynabook to their students, 85% agreed or strongly agreed that they would be able to use Dynabook in their class, and 63% agreed or strongly agreed that they would be likely to have their students use Dynabook. Respondents were also favorable about Dynabook's content, about its utility in demonstrating UDL principles, and its utility in demonstrating the use of technology in teaching. For example, 96% agreed or strongly agreed that the problems in Dynabook are helpful, 78% agreed or strongly agreed that Dynabook fosters critical thinking, and 74%

each, respectively, agreed or strongly agreed that that the UDL information in Dynabook is useful, and that using Dynabook fosters learning about how to use technology in learning (see table below).

TEN Reviewer responses to Dynabook

Statements	**Disagree strongly**	**Disagree**	**Mixed**	**Agree**	**Agree st**	***Agree or agre strongly***	**Disagree strongly**
I would be likely to show Dynabook To my students.	0%	0%	11%	56%	33%	*89%*	0%
I would be able to use Dynabook in my work.	0%	4%	4%	44%	41%	*85%*	0%
I would be likely to have my students use Dynabook.	0%	4%	26%	41%	22%	*63%*	0%
The problems in the Dynabook are helpful	0%	4%	0%	56%	41%	*96%*	0%
Using Dynabook fosters critical thinking	0%	7%	15%	41%	37%	*78%*	0%
The Universal Design for Learning (UDL) information in Dynabook is useful	0%	0%	7%	41%	33%	*74%*	0%
Using Dynabook fosters learning about how to use technology in teaching	0%	4%	19%	37%	37%	*74%*	0%

These findings paralleled those from the TEN reviewers' open-ended responses. As one reviewer stated: "The methodologies in terms of the integration of UDL, case-based learning, technology-enhanced learning and problem-based tasks are well-aligned with the content of my methods courses." Another reviewer noted: "I have been looking for effective ways to integrate technology into my courses, but thus far, everything has fallen short. This looks to be the deepest and most effective use I've seen yet. Looking at a problem and then looking at different students' interpretations was quite revealing. This could help my students learn to be better teachers. We don't have these kinds of situations available to us in the university classrooms."

The research team also gained valuable insight from the TEN reviewers about how they might use Dynabook in their teaching practices. Respondents saw potential in Dynabook's use as supplementary to the methods and materials they were already using. For example, as discussed previously, reviewers reported that they would be likely to show Dynabook to their students or use Dynabook in their work. However, only 33% agreed or strongly agreed that they would be likely to use Dynabook on its own. This theme is supported by open-ended responses, which show that reviewers were inclined to see Dynabook as a supplement to their traditional teaching methods and materials. Some comments from reviewers, when asked: "For what purposes would you use Dynabook?," and "How else can you imagine using Dynabook?" included: "I could imagine supplementing my course with some of the problems and cases…," and "seems like a great tool for self-study." Another reviewer noted: "It could also be used for practicing problem-solving as homework or as a tutorial, (and) also as a review for elementary and middle school teachers."

The Teacher Educator Network also provided valuable insight regarding which features they liked, and which they felt could be improved upon. Reviewers liked and most frequently used Dynabook's video cases and visual tools, such as the ratio bar. For example, 86% responded that that they watched the videos to some or great extent. This said, reviewers also most frequently experienced "bugs" when using the visual tools like the ratio bar and white board features. This feedback paralleled the information gained form our observations of pre-service teachers' use of Dynabook. Reviewers also indicated that navigating Dynabook could be confusing, particularly following the sequence of assignments. For example, 79% agreed or strongly agreed that they sometimes got confused about where to go next or what to do, and only 34% agreed or strongly agreed that Dynabook felt intuitive. As one responder noted: "I found the interface very unintuitive, and it took me a while to get used to it." As a team of researchers, gaining this outside perspective on Dynabook was useful in confirming data we received from other sources, such as our pilots of Dynabook in pre-service teacher classes. It was also useful in understanding how a broader potential audience, such as teacher educators, perceived Dynabook's usefulness.

In summary, as evident through the previous discussion, the lessons learned through and about Dynabook cut across multiple areas of research focus, with several important lessons learned in each area. The project gathered valuable information about Dynabook's potential, purpose, use, content, features, as well as information about the pool of people who were involved in the pilot test.