16 Using the Past to Make Innovators

W. Bernard Carlson

It was a quiet afternoon at the workshop that brought most of the authors of this volume together, and the participants, who came from a variety of backgrounds, had been thoughtfully discussing various aspects of the innovation process. The organizers probably figured that the conference would come off without any problems.

But then came the fireworks. Humera Fasihuddin presented an overview of the University Innovation Fellows program, which trains students to act as advocates for innovation and entrepreneurship on college campuses across the United States.[1] Humera's talk was followed by comments from several students who reported firsthand on their experiences as Fellows. Student after student testified that administrators were hostile to introducing entrepreneurship programs and that faculty really did not have anything to offer students in terms of teaching them to be innovators. For students to succeed, they simply needed the opportunity to unleash their creative powers.

After about the fifth student, Maryann Feldman and I finally interrupted. "Wait a minute," we said. "We're both professors and have been working for years at our universities to create programs that foster innovation. You can't accuse all of us of neglecting student entrepreneurship. Some of us have devoted our careers to understanding the innovation process and teaching students to be innovators." Fortunately, both Humera and the students heard us, and the afternoon concluded with a fruitful exchange of views about what the students felt they needed and what we, as scholars, could teach them.

Nevertheless, I came away with a renewed awareness that many people do not appreciate what history can teach us about invention and

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

innovation. Great inventions, it is commonly assumed, come only to incredibly smart people like James Watt, Nikola Tesla, or Steve Jobs; these individuals possessed exceptional mental abilities that allowed them to do the extraordinary. Many people tend to think of invention as a mysterious, unknowable activity. As much as we would like to characterize the brain as a computer, we cannot fathom how humans are able to create beautiful paintings, amazing scientific theories, or inventions that revolutionize daily life.

If you regard invention and innovation as the products of genius, luck, or mystery, it is easy to conclude that innovation cannot be taught: you are either born to be the next Thomas Edison, or you are not. Invention—like all creative acts—is not something that you can teach; you can nurture and inspire the next Elon Musk, but you cannot reduce invention to ten easy lessons. To teach invention, then, is to teach the unteachable.

Despite these popular notions, my colleagues and I at the School of Engineering and Applied Science at the University of Virginia (UVa) have been working to teach the unteachable to students for thirty years. We have approached invention as a process that can be analyzed, using historical cases to create a robust notion of how inventors work. Moreover, we have distilled principles and techniques to teach students how to be innovators. This is why I had such a visceral reaction to what the University Innovation Fellows were saying at the workshop.

Our experience with invention and innovation at UVa Engineering has intertwined research and teaching. In this chapter, I first recount how our research on inventors evolved. I then explain how we used our research findings to shape courses and programs to make innovators. And I close by reporting on some of the outcomes we have achieved and comment on whether what we have learned at UVa can be transferred to other programs.

Building a Cognitive Framework of Invention

Much of my professional life has been devoted to studying such major inventors as Thomas Edison, Alexander Graham Bell, and Nikola Tesla. Inspired by historian Thomas P. Hughes, I decided to study inventors because they often left substantial source material (notebooks, letters, testimony, and artifacts). And because nonacademic audiences are interested in inventors, you can use inventors to talk about a variety of social and ethical

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

issues concerning technology with students, engineers, business leaders, and the public.[2]

I have stayed with inventors for so long because they raise hard questions about the nature of technological change:

- How do we make sense of both individual actions and social forces in history? Do such individuals as Napoleon or Edison "make" history, or are they merely the representatives of various interests?
- Do ideas just exist "out there" in some platonic realm waiting to be discovered or invented by individuals? Or are ideas generally constructed by individuals and groups out of the cultural raw materials available at a given time?
- What kinds of knowledge and skills are involved in creating new technological artifacts? Can we characterize the nonscientific knowledge and skills involved in this creative work?

I began studying inventors in the 1980s by examining Elihu Thomson, a contemporary of Edison. Along with inventing a successful arc-lighting system and doing pioneering work with alternating current, Thomson was significant because, unlike other late nineteenth-century inventors who generally worked alone, he spent his career in a large company, General Electric. This gave me the opportunity to look at how the organizational environment affects the innovation process. Thomson's career showed that innovation is a social process not only in the sense that it involves the interplay of individuals and groups, but also because effective innovation requires the coproduction of technological artifacts, corporate structure, and markets.[3]

But as I read through Thomson's letter books, filled with the memos he wrote to vice presidents and plant engineers, I realized that while I was learning a lot about how he moved his inventions through the company, I wasn't learning as much about how he conceived of his inventions. Thomson viewed dictating letters as being one step removed from the creative work on the benchtop, and I came to agree with him. The research question then became how to get closer to the point of knowledge and artifact production.

To investigate more closely what inventors did at the benchtop, I started a new research project with my colleague Michael Gorman. Gorman is a cognitive psychologist who had been conducting simulations of how people

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

solve scientific problems, and he welcomed the idea of using historical materials to investigate how people developed new technology.[4] Together we looked at the history of the telephone because of the availability of substantial archival materials on Alexander Graham Bell, Elisha Gray, and Thomas Edison.[5]

We undertook a fine-grained examination of work at the inventor's benchtop. We found we could borrow some ideas from the laboratory ethnographies produced by sociologists of science Bruno Latour, Steve Woolgar, and others, and we were encouraged by Peter Galison's study of experimental methods in physics.[6] However, with the exception of a brief study of Leonardo's sketches by Bert S. Hall and Hughes's ideas about the style and methods of inventors, we could not find much from the history of technology that could help us with this investigation.[7] Hence, we turned to a field with which Gorman was familiar, namely, cognitive science.

A dominant issue in cognitive science at the time was the tension between mental models and heuristics. Some major figures in the field—such as Philip Johnson-Laird—believed the key to understanding how people think was to comprehend the meta-ideas, or categories, by which they processed information, or what cognitive scientists call mental models. Other researchers—such as John Anderson and Herbert Simon—argued that cognition is much more about the strategies or procedures that an individual employs in thinking. These strategies and procedures are called heuristics.[8]

We decided to explore how inventors might use both mental models and heuristics in their work. Why privilege one concept over the other? We also sought to find a way to pay attention to the specific objects an inventor manipulates on the benchtop.[9] After all, it seemed possible that inventors might supplement their organizing ideas (mental models) with specific mechanisms, circuits, or materials with which they were familiar.[10] To pay attention to these "building blocks," we introduced mechanical representations as a third category for analysis. Inventors often begin an investigation of a mental model by borrowing components or devices from other projects since they are familiar with how those components perform. Edison, for example, took the drum cylinder he had used on the phonograph and covered it with a photographic emulsion to transform it into a key component of the kinetoscope, his motion-picture device.

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

With these three categories in mind—mental models, heuristics, and mechanical representations—we set out to study the notebooks, sketches, models, patents, testimony, and correspondence of our three inventors. We hoped that by tracing how Bell, Gray, and Edison each worked on the telephone, we could gain insight into the interplay of ideas and objects (mental models and mechanical representations) as well as the thoughts and actions (mental models and heuristics). By comparing three inventors, we hoped to produce generalizations about how inventors worked, generalizations that could be tested further through case studies of other inventors and technologists.

Gorman and I always saw our investigation as alternating between the theoretical categories and the historical evidence. As we learned more about how our inventors worked, we refined our notions of what constituted a mental model, a heuristic, or a mechanical representation. We were not interested in merely taking an established theory off the shelf and testing it with new cases; rather, we wanted to shape our categories as we worked with the sources.

Creating a Mapping Technique

As we started to study the primary sources, Gorman and I quickly realized that verbal accounts of the invention process (such as patent testimony or recollections) did not always square with the visual and physical sources (notebooks, sketches, and artifacts) produced in working on an invention. Verbal accounts of the invention process typically were created years later when an inventor was seeking to prove that he or she was the first to invent something. Adhering to the popular notion of a eureka moment, inventors often collapse the long process of trial and error into a single clairvoyant moment of insight.

If we were going to get close to what our inventors thought and did at the benchtop, we needed to create techniques for analyzing the visual as well as the written materials. Given the volume of sketches (dozens for Bell and hundreds for Edison) and the diversity of sources (especially with Gray), we decided to develop a computer-based system for organizing and storing the visual sources.

At this point, Gorman and I took advantage of the fact that we teach undergraduate engineering students at UVa. We turned to our best students

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

for help. Over a seven-year period (1989–1996), they worked with us to devise techniques for analyzing the visual materials used by our inventors. Together we created a mapping technique for the invention process.[11]

One way to understand our mapping technique is to think about the workspaces of inventors and artists. If we look around an artist's studio or an inventor's laboratory, what do we find? Both creative spaces are crammed with models, sketches, and notes as well as machines or paintings in various stages of development.[12] Using all these resources, an artist or inventor is trying to merge abstract ideas in the mind with objects in the real world. On the one hand, an inventor may have an idea for an invention and struggle with how to build a device to realize that idea. On the other hand, an inventor may experiment with a device to see what new ideas it produces. An inventor may move from idea to object and vice versa. Invention, in short, is about merging mental models and mechanical representations.

While it is easy for us to picture an inventor tinkering with a device on the benchtop, this is not the only way that he or she can mingle ideas and objects. He or she can do the same with a variety of substitutes; rather than make a full-scale version of a device, an inventor might use a prototype, sketch, a series of calculations, computer simulations, or even a written description. The advantage of these substitutes is that they often can be generated more quickly and manipulated differently than the full-size device. Edison, for example, filled notebooks with hundreds of sketches because drawing frequently allowed him to determine whether a device would work, thereby allowing him to avoid the cost and hassle of building each version that he envisioned. Substitutes that stand in place of the fully developed invention—such as prototypes, sketches, calculations, and written descriptions—are *representations* of an invention.

Invention, then, can be considered an activity in which inventors use a variety of representations to merge an abstract idea in the mind with material objects that exist out in the world. One way to sort through these representations is to create a map. Suppose you allow each permutation of an invention—each prototype, model, sketch, or experiment—to be a box on a map. This "box" can be a piece of paper, a square drawn on a computer, or a Post-it on the wall; it doesn't matter. In our case, we scanned all three inventors' sketches into the computer and then cut-and-pasted them into the boxes on the map. It was critical for us also to stay close to the visual

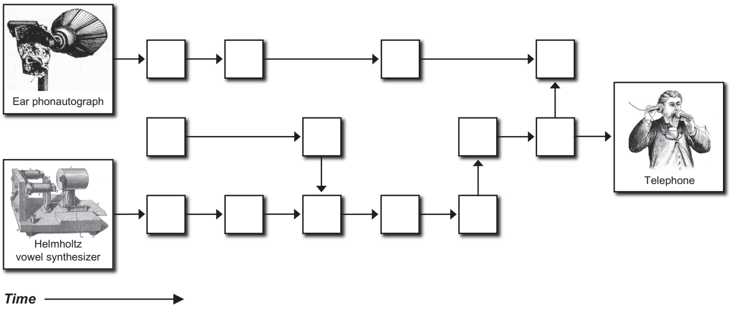
Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

Like artists, inventors engage in a series of activities that facilitate creativity. Both artists and inventors use a variety of representations—sketches, models, written descriptions—to merge an abstract idea in the mind with material objects that exist out in the world.

Each ***box*** is a sketch, model, or test—a representation

Each ***row*** shows a different idea or line of thinking

Each ***arrow*** shows how one representation can lead to another



An inventor may have several lines of investigation going at any time, and s/he may move an idea or device from one line to another.

For example, Alexander Graham Bell's notebooks, patents, and court depositions show that between 1872 and 1876 his telephone emerged from working on an ear phonautograph and a variation on Helmholtz's device for artificially producing vowel sounds.

Figure 16.1
Mapping the invention process.

materials and not reduce the sketches to verbal descriptions. We frequently gained insights by placing several sketches side by side on a map to look for similarities and differences.

Once you have the boxes, you can then place them in chronological sequence. In figure 16.1, for example, time moves horizontally from left to right. Arraying the representations in chronological order allows you to look for cause and effect. In some cases, one sketch prompts an inventor to produce another sketch or model, and you can capture these connections by drawing arrows between the boxes. You can also arrange the boxes in different rows, with each row representing a line of investigation or particular invention. Inventors frequently pursue several lines of investigation simultaneously and may move an idea or device from one line to another. For instance, when Edison was working on the telephone in 1877 and 1878, he was simultaneously investigating his quadruplex telegraph as well as the phonograph.[13] In fact, a key part of creativity is the ability or willingness to move ideas and objects from one line to another—to mix things up in unexpected ways.

Gorman and I worked on these maps with our students for seven years. It took such a long time because we developed multiple maps for each individual inventor. To cope with the more than five hundred telephone

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

sketches produced by Edison and his team at Menlo Park, we ultimately created eighteen large maps, each with dozens of boxes and arrows.

What Did We Find Out?

Using the maps, we looked for patterns in the ways that Bell, Edison, and Gray thought about and worked on the telephone. The maps suggested several aspects of the invention process:

1. Different inventors have different kinds of mental models. While Bell was guided by analogies (e.g., make the transmitter like the human ear), Edison tended to work in terms of a functional principle (use variable resistance to convert sound waves into electric current waves).
2. Different inventors use different heuristics. Bell, for instance, worked in a very incremental and methodical fashion; he often had to test each possible variation of his basic design on the benchtop. In contrast, Edison often varied several parameters at once and did not conduct as many benchtop experiments, because sketching allowed him to determine if a particular design would work.
3. We found it fascinating that while Edison generally worked “bottom up,” manipulating mechanical representations on the benchtop in order to formulate his mental model, Bell worked “top down,” starting with a mental model that he then tested on the benchtop.

Teaching Innovation

As we discerned patterns in our maps, we were determined to draw on our research to teach our engineering students how to invent. Both Gorman and I began moving ideas from our research into our teaching.

Gorman, for instance, teamed up with a colleague in mechanical engineering, Larry G. Richards, to offer a course on invention and design. In early versions of this course, students constructed their own telegraph and telephone systems.[14] Their course had a profound impact on one student, Evan Edwards, who, together with his brother Eric, invented an auto-injector for medicines. After graduating, the two of them launched a company to develop this product.[15]

I transferred ideas from our research to the communications course I was teaching to first-year engineering students. Since the 1930s, UVa Engineering

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

has had a tradition of teaching writing and speaking as part of the school's curriculum. Rather than have engineering students learn writing in classes offered by the College of Arts and Sciences, the Engineering School instead has its own faculty who teach communications, ethics, history, and the social sciences as they relate to engineering.

For me, the challenge in teaching first-year communications was to show my students how writing and speaking were integral to engineering practice. Although I initially had the students study Edison's career for inspiration, I quickly realized the potential of having the students imitate Edison—to try their hand at invention. I took seriously the fundamental results of our research—that invention is the interplay of ideas and objects and that inventors mix up ideas and objects by using a variety of representations. To get objects into the classroom, I began having students build kits, first a pendulum clock and then a robot car.[16] For the representations, I had them sketch ideas in notebooks, write technical descriptions, and ultimately draft a patent application. Whenever possible, I encouraged them to borrow from their mathematics and computer science classes to consider how to represent inventions in terms of equations or computer simulations. Through this teaching, I came to agree with the great cognitive scientist Herbert Simon, who insisted, "Solving a problem simply means representing it so as to make the solution transparent." I went on to articulate a philosophy of engineering-as-representation.[17] This philosophical approach now forms the basis of how we teach communications in the first-year engineering program.

Adding Context to the Cognitive Framework

During the early 2000s, I continued to mull over what Gorman and I had learned about the invention process. In particular, I was not happy with the fact that our cognitive framework did not take into account the social, economic, or cultural context in which inventors work. How might larger, external forces be included in this cognitive framework?

Attempts to understand the process of invention and innovation frequently follow a so-called linear model from ideas to manufacturing to adoption. Engineering textbooks reproduce this ideal to students in block diagram models (figure 16.2).[18] They suggest that inventors move through a specific sequence with no false starts or backtracking. The linear model embodies several dichotomies:

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

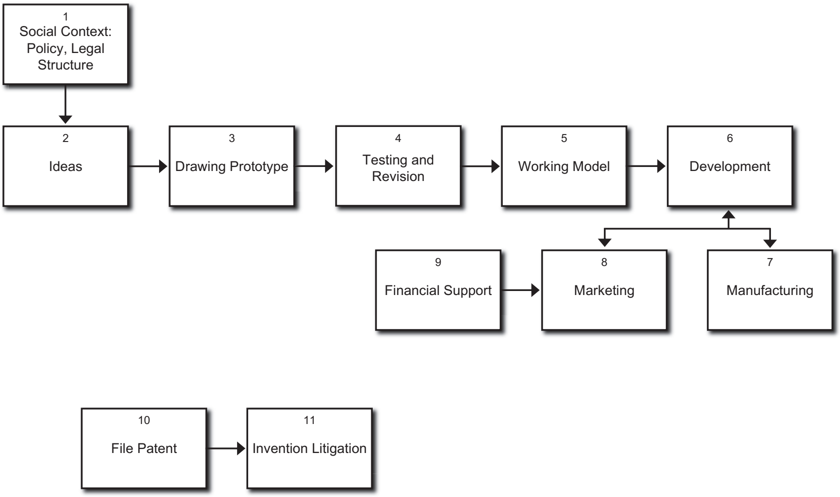


Figure 16.2
Invention as a linear process.

- It assumes that *ideas* come before *devices*, yet some inventors work closely with devices first and in so doing generate new ideas.
- *Social* factors appear only at the *beginning* and *end* of the model, yet inventors may be influenced by all sorts of external factors throughout their work.
- The model draws a distinction between the *technical* work that occurs in the middle steps and *marketing*, which comes at the end. But inventors are often doing both technical and marketing work at the same time.

While a linear model may be useful for introducing students to design, it is problematic for understanding how inventors actually work. For scholars intent on understanding the details of the invention process, using this sort of one-size-fits-all prescriptive model can seem like jamming a square peg into a round hole.[19]

I wondered if it would be possible to build on the work that Gorman and I had already done to create a more robust model that would soften these dichotomies; recognize how inventors are influenced by a variety of ideas, resources, and people; and highlight their day-to-day activities. Would it be

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

possible to generate a nonlinear model of the invention process that would capture the ways that invention is social and cultural?

Rethinking Invention as a Process

I began by reconsidering what it means to say that invention is a process (figure 16.3). Like other processes, invention has both inputs and outputs. In terms of inputs, what does an inventor use in the course of his or her work? Besides tangible resources (money, tools, and materials), he or she also relies on other individuals to provide help with such essential tasks as model building, patenting, manufacturing, and marketing. And an inventor draws on a range of intangible resources, including preexisting knowledge (of both science and other fields), needs seen in the marketplace, legal expertise (patents, regulations, and contracts), and emotional support and encouragement. Inventors may also be influenced by public events (such as wars or business conditions) or their personal situation (love, marriage, health, emotional depression), and so these should be included as inputs. To highlight that invention is an iterative process, there could just as easily be a loop back from the outputs to society, back to the original inputs.

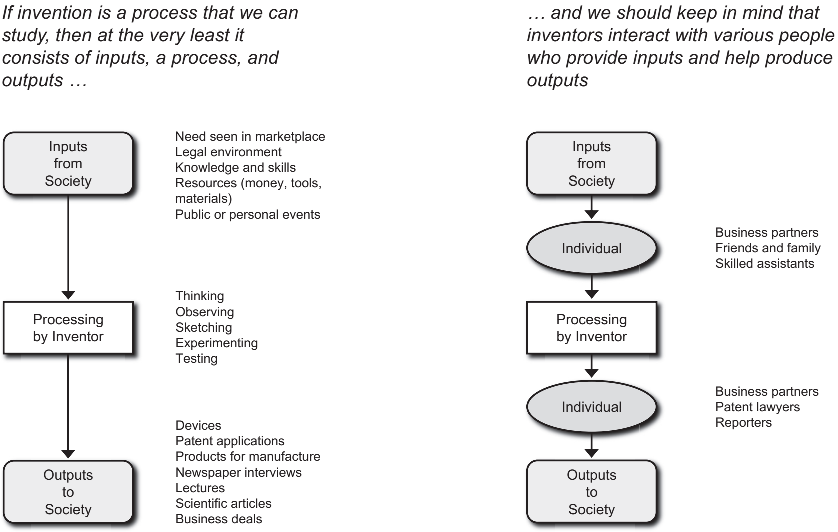


Figure 16.3

Invention as a social process.

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

In terms of outputs, we expect inventors to produce devices and patent applications, but they also need to promote their creations. Hence, the outputs from the invention process should include interviews, lectures, and publications. And since inventors may sell or license their creations, we should also list business deals.

While inventors can bring some resources into the creative process on their own (for instance, they can read the technical literature or study needs in the marketplace), these inputs and outputs often come into the invention process through interactions with other people. These individuals can include business partners, skilled assistants, family and friends, patent lawyers, and newspaper reporters. All of these intermediaries affect how ideas, resources, and results flow in and out of the invention process.

By considering the inputs and outputs to the invention process and by highlighting the individuals with whom inventors interact, I was placing the cognitive work of invention into a social context. Including an inventor's relationships in the diagram allowed me to show how inventors draw on their social environment and, at the same time, how they seek to shape it.

An Inventor's Flow

As I articulated invention as inputs-process-outputs, I soon realized that what Gorman and I had worked out in our research on the invention of the telephone was all the stuff that belonged in the middle, in the process box on figure 16.3. We had been mapping the activities by which an inventor gets an idea out of his head, refines it through multiple representations, and realizes it on the laboratory bench.

But as I looked with fresh eyes at our invention maps, I was reminded of how Tesla described his feelings in 1882 after he had envisioned his new AC motor using a rotating magnetic field. "For a while," Tesla recalled fondly,

> I gave myself up entirely to the intense enjoyment of picturing machines and devising new forms. It was a mental state of happiness about as complete as I have ever known in life. Ideas came in an uninterrupted stream and the only difficulty I had was to hold them fast. The pieces of apparatus I conceived were to me absolutely real and tangible in every detail, even to the minutest marks and signs of wear. I delighted in imagining the motors constantly running, for in this way they presented to the mind's eye a more fascinating sight. When natural inclination develops into passionate desire, one advances toward his goal in seven-league boots.[20]

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

What I had not yet appreciated was that invention is not just a process but a *state of mind*.

Like other creative people, inventors intentionally strive to generate a steady stream of ideas and representations, to study them, and to shape these ideas into meaningful inventions. Psychologist Mihaly Csikszentmihalyi calls this effort to generate a steady stream of ideas the "flow" of creativity.[21] Taken as a whole, mapping the various representations used by inventors gives us a visual picture of the flow of their work.

In looking at an inventor's flow, it is important to consider short-term versus long-term goals. Immersed in the creative process, an inventor may not be worried about the ultimate version of an invention but may simply be thinking about how she moves from one representation to the next. Being in the flow means being focused on the immediate opportunities and open to new possibilities as they present themselves. Along the way, inventors may change their mind about the ultimate goal, or the goal may only become clear by doing, by being in the flow. Hence, while it would be tempting to create a map of the invention process in which everything funnels into what we know as the final version, we should instead strive to include the ideas and devices that went nowhere, the false starts, and the wrong turns.

Combining Process and Flow

I now brought these two perspectives—input/output and flow—together on a single page (figure 16.4). I let the process move vertically down the page, with the inputs at the top and the outputs at the bottom. Meanwhile, I had the inventor's flow move horizontally across the page.

This diagram allows us to follow how ideas and resources affect an inventor's flow as well as how prototypes and other products then move out from the inventor's workshop into society. For instance, an inventor may learn about an idea on his own. In this case, we would draw a line and arrow from the idea box down to the sketch or experiment box that it affects. In other cases, an inventor learns about an idea from an individual, such as a friend, business partner, or assistant. In these situations, we add an oval showing the person's name.

In organizing the inputs and outputs depicted in figure 16.4, it is important to arrange them by how they are experienced by the inventor, rather

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

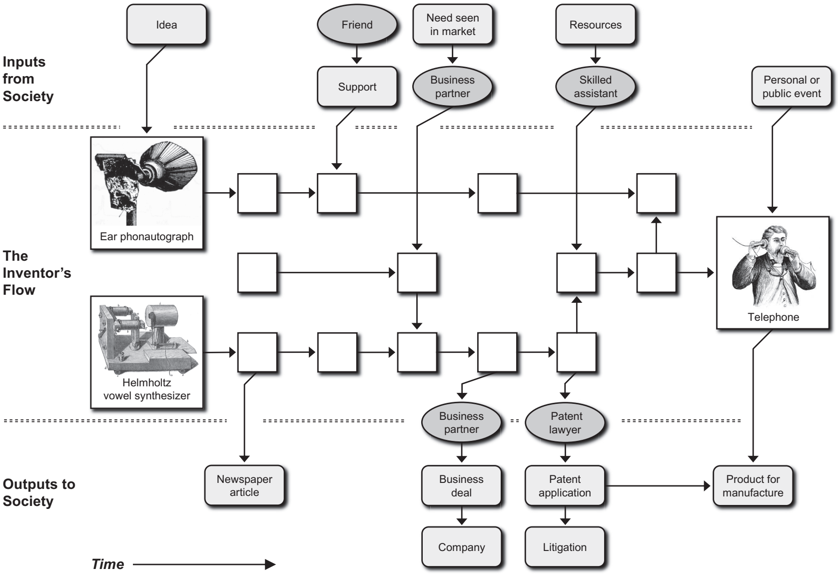


Figure 16.4
Invention as a flow process.

than by some sequence embedded in the model. This is the major advantage of the mapping technique over the old linear model. For example, the inputs—ideas, encouragement, needs, resources, and events—should be placed in the order by which historical sources indicate they affected the invention flow. In situations where a version of an invention is reported in a newspaper or written up in a patent application, we can connect a box in the flow that indicates outputs. Rather than squeezing the historical materials into the model, the model and diagrams are modified to reflect what the inventor is actually doing.

Yet we should be clear that the story portrayed in the historian's flow process model can be very different than the one an inventor might tell about how she came to create a particular device. It is important to recognize that inventors may edit the flow process down to a simple narrative to secure strong patents and to suggest that there was a logical progression in their thought processes. Moreover, an inventor may simply not be able to reconstruct all the twists and turns he took on the way to a particular outcome. Edison, for instance, introduced hundreds of sketches of the telephone as evidence in patent litigation in the late 1870s, but in testifying

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

he was hard-pressed to explain how he moved through this entire corpus of work.[22]

What Did This New Model Capture?

The flow model helps us capture three aspects of the invention process:

- The people, ideas, and resources that shape an inventor's work
- The activities that inventors use to develop new inventions (thinking, sketching, experimenting, and testing)
- The results of the invention process (patents, prototypes, processes, products, and publicity)

It is important to note that this model is not intended to be restrictive. No "one size" fits all inventors. Indeed, the point of the model is to draw out the unique and special qualities of each inventor. The model serves to help us ask consistent questions across different episodes of invention. It should help us discern both the social and the cognitive dimensions of creativity.

This model permits us to capture more of the details of the invention process and allows us to construct richer narratives of how inventors combine ideas and objects and merge the technical with the social. It also helps us to understand not only successful inventions but also the dead ends and ideas that fail. But, above all, this new model should enlarge our vision of what invention is and challenge us to better understand how people can create remarkable technology that changes the world.

The Entrepreneurial Turn in Research and Teaching

I found this new model of innovation as a nonlinear flow process to be enormously helpful in understanding how Nikola Tesla worked, but perhaps even more so in my approach to teaching innovation.[23] One of the most powerful features of the model is that it reveals the intellectual and social work required to convert a benchtop device into a commercial product. Left on their own, inventors often prefer to concentrate on the flow, on moving from sketch, to model, to new experiment; recall the sublime pleasure that Tesla felt as he imagined a stream of new electric motors. In the diagram for the model, inventors want to keep moving in a horizontal direction. When the time comes to convert a benchtop device into a

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

commercial product, however, the inventor must change direction; rather than put his or her energy into generating new variations, he or she has to work on connecting an invention with the wider world via publicity, business deals, or manufacturing. Often these connections cannot be made by the inventor alone but require the assistance of partners and patent lawyers. On the diagram, the movement of an invention from the benchtop to the marketplace means making a turn from the horizontal to the vertical. Hence, the diagram shows major decisions—where the technical gets connected to the social—as a *turn*.

This entrepreneurial turn brings into crisp focus the importance of partnerships in technological creativity. Careful observers will notice that partnerships combining technical skills with business acumen are scattered across the history of technology. In the case of Tesla and his AC motor, he needed the help of his business partners, Charles Peck and Alfred Brown, to know which motor ideas to patent, demonstrate in public lectures, and ultimately sell to George Westinghouse.[24]

The notion of an entrepreneurial turn also had powerful implications for teaching innovation. Several key ingredients are required to bring innovations into the world:

- There must be creative people—inventors, designers, engineers, and scientists—who are allowed to generate ideas and prototypes. The British lovingly call these creative types "boffins."
- The boffins must be protected from external distractions so they can be in the flow. This may mean giving them their own resources and space in an organization.
- At the same time, there must be individuals—the entrepreneurs—who can select the most promising variations from the flow and move them out into the world.

These three ingredients became, first, the kernel of a new course, and then a new technology entrepreneurship program at UVa.

In a new class, "Engineers as Entrepreneurs," I guided students as they explored the habits and practices required to place themselves in a creative flow: how to observe the world; represent it in words, sketches, and simulations; and generate innovations. My students had to understand that at times engineers—like artists or musicians—must fully immerse themselves in a technically rich stream of activities. This is the existential pleasure of

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

working in a lab or design studio.[25] At the same time, I challenged them to pay attention to what customers and other stakeholders might need or want by conducting interviews and market research. Altogether, they would have to use their technical expertise to understand the flow of ideas in the laboratory and draw out those ideas that might be used to satisfy the needs of customers.

"Engineers as Entrepreneurs" was well received by UVa students and caught the attention of both the dean of engineering and engineering alumni who wanted to promote innovation within the school. Working as venture capitalists in Silicon Valley and elsewhere, several alumni had learned that the most important people to meet from a potential start-up were not the "suits" (the MBAs), but rather the boffins, the engineers. Indeed, these alumni had become convinced that the most promising future start-ups would not be led by MBAs who employed engineers, but rather by engineers who knew enough about entrepreneurship to run their own enterprises.

With guidance and financial support from these alumni, we launched UVa's Technology Entrepreneurship Program (TEP) in 2010. TEP provides courses and activities that allow faculty, staff, and students to develop as entrepreneurs and innovators.[26] The program offers at least six undergraduate courses every year that cumulatively attract three hundred students. Students take these classes as part of their engineering major or in pursuit of a minor in entrepreneurship. In these courses, we teach customer discovery and employ Steve Blank's Business Model Canvas.[27] In most classes, students work in teams and practice pitching their ideas to investors and entrepreneurs from the local region. TEP also provides a variety of cocurricular activities to help aspiring entrepreneurs. Through a program called Works in Progress, students meet outside of class to brainstorm, form teams, and network with local entrepreneurs. To support our entrepreneurial students, we have two dedicated workspaces in the engineering school complex, and alumni have endowed several funds that support student projects.

Three core ideas underlie these courses and activities. First, we believe that technology entrepreneurship is different from the entrepreneurship taught in business schools. Entrepreneurship programs in business schools tend to emphasize demand-pull innovations: find an untapped market and then create a product or service that satisfies that market. In contrast, we believe the breakthrough technologies that alter everyday life are often supply-push

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

innovations that start at the laboratory benchtop and then move to the marketplace. Using the flow model of innovation, we are training engineers how to spot the most promising ideas percolating in labs—what one UVa alumni entrepreneur, Robert S. Capon, calls the “noble asset.” We then guide the students as they write patent applications, develop business plans, and work to launch ventures around these assets.

Second, it is critical to teach students about customer discovery. All too frequently, engineering students will come up with an innovation in the laboratory that is really cool to them but totally unrelated to a customer need. We show students how to talk to real customers, insisting that they not mention their idea but rather focus on the problems and wishes the customers might have. In fact, we tell our most promising student entrepreneurs that they really don’t know what the market will be until they have spoken to at least one hundred potential customers. It is only through this process that students are able to construct a market that fits their innovation. Not surprisingly, customer discovery often prompts our student entrepreneurs to redesign their inventions or to move their laboratory research in new directions. Customer discovery is at the heart of the National Science Foundation’s I-Corps program, and in 2017, we secured funding for an I-Corps program to train UVa faculty and graduate student to be entrepreneurs.[28]

The third big idea guiding TEP is that entrepreneurs need a community around them.[29] Popular mythology often depicts entrepreneurs, like inventors, as solitary individuals who work alone. However, as the flow model reminds us, inventors rely on a variety of people—friends, family, assistants, investors, and entrepreneurs—to be creative. In the same way, we have found that entrepreneurs do not work alone but rather need to interact with other entrepreneurs who provide ideas, guidance, and motivation. Across history, at the heart of the most innovative economies, you will find communities of entrepreneurs—whether it be Amsterdam’s coffeehouses in the seventeenth century, Philadelphia textile mills in the nineteenth century, Detroit machine shops in the early twentieth century, or Silicon Valley in the late twentieth century. In each of these places, entrepreneurs gathered to share and support one another.[30]

By drawing on history and listening to our students, we are nurturing a community of entrepreneurs. We help students who are just learning about entrepreneurship, but we also go out of our way to mentor those young

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

entrepreneurs who are ready to launch an enterprise. We create opportunities for these founders to meet regularly so they can learn from each other, and we provide our founders with dedicated work space.[31] Whenever possible, we encourage cross-disciplinary teams to form by working with students from the business, policy, and humanities arenas. We are especially proud that our founders frequently place highly in entrepreneurship competitions; for the past several years, our student teams have finished first in UVa events, including the E-Cup and the Darden Business Plan Competition. In 2016, Contraline, a student team whose members had invented a new contraceptive for men, placed second in the Atlantic Coast Conference's InVenture Prize. Another student team, Agrospheres, won the 2016 Collegiate Inventors Competition and took top place in the 2017 InVenture Competition. Agrospheres has since raised $750,000 to support development for using nanospheres to deliver pesticides precisely and safely to crops. And in 2018, Ashwinraj Karthikeyan not only won the ACC Inventure Competition again for UVa but also received the $50,000 Pike Prize for Engineering Entrepreneurship. Karthikeyan has developed a new bandage for treating diabetic foot ulcers and he will be deploying it in India.[32]

Conclusion

How should innovators be trained? Can you use the past to teach the supposedly unteachable? What we have learned is that invention and innovation are not simply about genius, luck, or confidence. By studying Edison, Tesla, and Bell, you can find patterns in the ways they thought and worked. Using these patterns, you can formulate a framework that suggests insights to teach students. If you want students to be innovative, they need to know that invention is the interplay of ideas and objects. Students can learn and practice using different representations—notes, sketches, prototypes, and simulations—to move ideas from the mind's eye into the material world. We can help them understand that inventors seek to be in a creative flow, striving to learn from each representation and to keep generating new variations. And student innovators can master the entrepreneurial turn—what it takes to recognize the most promising idea in a creative flow and to guide it from the laboratory bench to the end user. The past can be used to create curricula for innovation and entrepreneurship.

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

Our experience in researching and teaching innovation and entrepreneurship at UVa offers several lessons for faculty and administrators who are creating similar programs at their institutions. First and foremost, there is a body of knowledge and a set of skills that can be taught and that improve the chances of students successfully converting an idea into a product. This knowledge and these skills can be introduced in formal courses, but more importantly, you need to create opportunities and spaces outside the classroom where students can practice, practice, practice. As we often remind our students, Roland H. Macy failed four times before he came up with a winning formula for his New York department store. Is it not better for entrepreneurs to fumble a few times during their student years, before they face the vicissitudes of the real world?

To ensure that practice leads to results, students need guidance, mentoring, and resources. Students cannot teach students to be entrepreneurs and innovators; they need to learn from both scholars of entrepreneurship as well as experienced entrepreneurs. An effective entrepreneurship program does not assume that students will automatically “get it” and keep coming back for more. Administrators and faculty must be committed to helping individual students connect what they learn in the entrepreneurship classroom with cocurricular activities. Because these connections are built one student at a time, a successful entrepreneurship program is labor-intensive and ultimately expensive. Our experience has taught us that you can have all sorts of competitions, guest speakers, and get-togethers promoting entrepreneurship, but students only become innovators by working closely with dedicated staff and faculty. It is about the relationships created, not the events.

But do programs emphasizing entrepreneurial knowledge, skill, and practice demonstrably increase innovation? To be sure, several UVa students have become full-fledged innovators; we are proud of Evan Edwards and his auto-injector, and we expect great things from student teams like Contraline and Agrospheres. I would suggest that it’s not simple to measure direct cause and effect, that “concept X, taught to Y number of students, resulted in an increase in innovation by Z percent.” What one sees when working with student innovators is much more subtle—a better notebook sketch here, a more persuasive rocket pitch there, or a student team coming together and gaining confidence in themselves. Ultimately, what we teach is a mindset, an attitude that change is possible. Our students know that

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

they can develop the skills needed to innovate. Innovation, at its heart, is about nurturing the human spirit and fostering a faith in progress. None of our students have gone on to become the next Nikola Tesla—yet—but we see signs that we are on the right track.

Notes

1. See Fasihuddin and Britos Cavagnaro (chapter 3) in this volume.

2. W. Bernard Carlson, "From Order to Messy Complexity: Thoughts on the Intellectual Journey of Thomas Parke Hughes," *Technology and Culture* 55, no. 4 (October 2014): 945–952.

3. W. Bernard Carlson, *Innovation as a Social Process: Elihu Thomson and the Rise of General Electric, 1870–1900* (New York: Cambridge University Press, 1991).

4. Michael E. Gorman, *Simulating Science: Heuristics, Mental Models, and Technoscientific Thinking* (Bloomington: Indiana University Press, 1992).

5. In addition, there was controversy associated with the case, as historians had already suggested that Gray, not Bell, might be the true inventor of the telephone. See David A. Hounshell, "Bell and Gray: Contrasts in Style, Politics, and Etiquette," *Proceedings of the IEEE* 64 (1976): 1305–1314; Seth Shulman, *The Telephone Gambit* (New York: W. W. Norton, 2008); and Bernard S. Finn, "Bell and Gray: Just a Coincidence?" *Technology and Culture* 50 (January 2009): 193–201.

6. Bruno Latour and Steven Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, 1986); Peter Galison, *How Experiments End* (Chicago: University of Chicago Press, 1992).

7. See Bert S. Hall and Ian Bates, "Leonardo, the Chiarvelle Clock, and Epicyclic Gearing: A Reply to Antonio Simoni," *Antiquitarian Horology* 9 (1976): 910–917. On the concepts of an inventor's style and method, see the following studies by Thomas P. Hughes: *Elmer Sperry: Inventor and Engineer* (Baltimore: Johns Hopkins University Press, 1971); "Edison's Method," in *Technology at the Turning Point*, ed. W. B. Pickett (San Francisco: San Francisco Press, 1977); and *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: Johns Hopkins University Press, 1983).

8. See Philip N. Johnson-Laird, *Mental Models* (Cambridge, MA: Harvard University Press, 1983); John R. Anderson, *The Architecture of Cognition* (Cambridge, MA: Harvard University Press, 1983). For a review of the cognitive science literature around the time that we launched this project, see Gorman, *Simulating Science*.

9. W. Bernard Carlson and Michael E. Gorman, "Understanding Invention as a Cognitive Process: The Case of Thomas Edison and Early Motion Pictures, 1888–1891," *Social Studies of Science* 20, no. 3 (August 1990): 387–430.

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

10. As Reese V. Jenkins observed, “Any creative technologist possesses a mental set of stock solutions from which he draws in addressing problems.” See Jenkins, “Elements of Style: Continuities in Edison’s Thinking,” *Annals of the New York Academy of Sciences* 424, no. 1 (May 1984): 153.

11. Critical to this effort was Matthew M. Mehalik, who worked closely with Gorman and me all through his undergraduate years and subsequently earned his PhD in systems engineering at UVa with Gorman as his dissertation advisor.

12. See McManus and MacDonald (chapter 4) in this volume.

13. In the cognitive science literature on creativity and discovery, the collection of multiple lines of investigation is called a network of enterprises. See Howard E. Gruber and Katja Bodeker, *Creativity, Psychology, and the History of Science*, Boston Studies in the Philosophy of Science, vol. 245 (Dordrecht, Netherlands: Springer, 2005), 22–24, 52–57, and 89–104.

14. Michael E. Gorman and J. Kirby Robinson, “Using History to Teach Invention and Design: The Case of the Telephone,” *Science and Education* 7, no. 2 (1998): 173–201.

15. “Taking Their Best Shot: Kaléo Makes Big Strides in Auto-Injectors,” Lemelson Foundation, 24 June 2015, accessed 1 September 2017, http://www.lemelson.org/resources/success-stories/Kaleo.

16. W. Bernard Carlson and Karin Peterson, “Making Clocks: A First-Year Course Integrating Professional Communications with an Introduction to Engineering,” *Proceedings of the American Society for Engineering Education,* CD-ROM, 1996.

17. See Herbert A. Simon, *The Sciences of the Artificial*, 3rd ed. (Cambridge, MA: MIT Press, 1996), 132, and W. Bernard Carlson, “Toward a Philosophy of Engineering: The Fundamental Role of Representation,” *Proceedings of the American Society for Engineering Education*, CD-ROM, 2003.

18. When the Smithsonian Institution’s Lemelson Center for the Study of Invention and Innovation retained me as a consultant in 2006, I had an opportunity to revisit our cognitive framework. Shortly after its founding in 1995, the center had developed a linear model of the invention process that it used to generate questions and ideas about what sorts of materials it should collect to document the creative work of inventors. The Lemelson Center brought me in as a consultant not only because of my research on inventors but also because of my experience consulting with the R&D group at Corning. There I drew on the approach I had developed with Gorman to prepare a number of proprietary case studies of the innovation process. I captured my initial findings in a Lemelson Center white paper, “Understanding Invention and Innovation: A Documentary Study,” last updated 25 August 1998. As the center matured, so did its model of the invention process, especially as presented in Spark!Lab, its hands-on invention center for children aged 6–12 and their

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

families. Spark!Lab breaks the invention process into seven nonlinear steps: identify a problem or need (Think It); conduct research (Explore It); make sketches (Sketch It); build prototypes (Create It); test the invention (Try It); refine the invention (Tweak It); market the invention (Sell It). See "About Spark!Lab," Lemelson Center for the Study of Invention and Innovation, accessed 1 May 2018, https://invention.si.edu/about-sparklab.

19. As Eugene S. Ferguson observed in his study of design and technological creativity, "Block diagrams imply division of design into discrete segments, each of which can be 'processed' before one turns to the next." Eugene S. Ferguson, *Engineering and the Mind's Eye* (Cambridge, MA: MIT Press, 1992), 37.

20. Nikola Tesla, *My Inventions: The Autobiography of Nikola Tesla*, ed. Ben Johnston (Williston, VT: Hart Brothers, 1982), 65.

21. Mihaly Csikszentmihalyi, *Flow: The Psychology of Optimal Experience* (New York: Harper & Row, 1990).

22. Several inventors made this point during a Lemelson Center workshop on prototypes I helped organize in the fall of 2006. See W. Bernard Carlson, "Documenting Invention: Prototypes and Invention—An Inquiry into How Inventors Think and Communicate," 1 September 2007, accessed 1 September 2017, https://invention.si.edu/documenting-invention-prototypes-and-invention-inquiry-how-inventors-think-and-communicate.

23. While the flow model does not appear explicitly in my biography of Tesla, it particularly guided my thinking on how he evolved his plan in the 1890s for wirelessly broadcasting power through the earth. See W. Bernard Carlson, *Tesla: Inventor of the Electrical Age* (Princeton, NJ: Princeton University Press, 2013), especially chapters 10 through 15.

24. Carlson, *Tesla*, 76–105.

25. Samuel Florman, *The Existential Pleasures of Engineering*, 2nd ed. (New York: St. Martin's Griffin, 1994).

26. "Entrepreneurship and Business," accessed 1 September 2017, https://engineering.virginia.edu/departments/engineering-and-society/entrepreneurship-and-business.

27. Steve Blank and Bob Dorf, *The Startup Owner's Manual: The Step-by-Step Guide for Building a Great Company* (Pescadero, CA: K&S Ranch Press, 2012); Alexander Osterwalder, *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers* (Hoboken, NJ: John Wiley, 2010); Alexander Osterwalder et al., *Value Proposition Design* (Hoboken, NJ: John Wiley, 2014).

28. See Arkilic (chapter 5) in this volume.

29. See Hintz (chapter 10) in this volume.

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021

30. See Feldman (chapter 6) in this volume.

31. Elizabeth P. Pyle and Alexander J. Zorychta, "The Social Mechanisms of Supporting Entrepreneurial Projects beyond the Classroom," *Proceedings of American Society for Engineering Education*, Columbus Meeting, 2017, paper no. 19983.

32. "Agrospheres Announces Close of Oversubscribed $750,000 Seed Round," 21 August 2017, accessed 1 September 2017, http://www.agrospheres.com/news/2017/8/21/agrospheres-announces-close-of-oversubscribed-750000-seed-round; Elizabeth Thiel Mather, "Major Wins Propel UVA Engineering Entrepreneurship Team to Future Business Success," 8 May 2018, accessed 9 September 2018, https://engineering.virginia.edu/news/2018/05/major-wins-propel-uva-engineering-entrepreneurship-team-future-business-success.

Downloaded from http://direct.mit.edu/books/book/chapter-pdf/270610/9780262352598_cdi.pdf by guest on 28 October 2021