

The Practice of Instructional Technology

Andrew S. Gibbons

Utah State University

Paper presented at AECT 2000, Annual International Conference of the Association for Educational Communications and Technology, Denver, CO, October, 2000. Comments and reactions are welcome at: gibbons@cc.usu.edu.

Learning the secret of flight from a bird was a good deal like learning the secret of magic from a magician. After you know the trick and what to look for, you can see things you didn't notice when you did not know exactly what to look for.

Orville Wright
(From Combs, 1979)

Neither could have mastered the problem alone. As inseparable as twins, they are indispensable to each other.

Bishop Milton Wright,
describing his sons
Wilbur and Orville.
(From Combs 1979)

We (in the sense of human beings) travel and explore the world, carrying with us some 'background books'. These need not accompany us physically; the point is that we travel with preconceived notions of the world, derived from our cultural tradition. In a very curious sense we travel knowing in advance what we are supposed to discover. In other words, the influence of these background books is such that, irrespective of what travelers discover and see, they will interpret and explain everything in terms of these books.

Umberto Eco (1998)

Section I: Science and Technology

Introduction and Purpose

This paper was begun with the purpose of clearly separating the worlds of science and technology so that apprentice technologists—specifically those studying instructional technology—could become aware of the customs, habits, expectations, and standards of the professional world they were entering. Historical bias sees science and technology as being closely joined. An unfortunate by-product of this closeness is that technology is seen by most as merely an applied branch of science.

If science and technology are inseparable, still this paper makes a distinction between the scientific and the technological *purposes of human activity*. This makes it possible to define separately the identity of the technological researcher, one that is clearly unique within the context of creating reliable human knowledge. The goal is to identify the implications of this for the practice of instructional technology and as a basis for framing research questions in that field.

What is Science?

Science is one of society's several disciplined methods for the production of shared community knowledge. For over 2000 years, scientists and philosophers of science have carried on an intense discussion, to which Kuhn's (1970) description of *The Structure of Scientific Revolutions* is a relatively recent and respected contribution. This discussion has over time exposed the practice of the scientist to public scrutiny and debate. This has aided the creation of traditions, rules, and methods—an extensive culture of research and reasoning—aimed at producing reliable, verifiable knowledge.

The development of the scientific standards for knowledge creation has not been without controversy. Constant public discussion of the methods of the scientist in schools and popular media (including a cable TV channel devoted to the subject) has established an idealized model in the minds of most people of how scientists approach the natural world to ask questions. This educational campaign for science has been conducted for so long and so effectively that some (mis)understanding of science and its main purposes and methods is quite general.

Kuhn and others argue that the scientific method as it exists in the understanding of millions of public minds is an idealized description of something that is in actuality more complex. Nobel Laureate Sir Peter Medawar (researcher in immunological tolerance) describes his view of the process: "What scientists do has never been the subject of a scientific...inquiry. It is no use looking to scientific 'papers', for they not merely conceal but actively misrepresent the reasoning

that goes into the work they describe". Describing what does happen, Medawar says, "Scientists are building explanatory structures, telling stories which are scrupulously tested to see if they are stories about real life." (quoted in Judson, 1987, pg 3).

Ziman (1978) describes a view of scientific knowledge that defies the traditional and familiar view. He maintains that, "the goal of science is a consensus of rational opinion over the widest possible field". In the early period when science itself was forming as a community of inquiry, a statement like this would have been rejected, but today it represents an acceptable view of a field that is constantly changing its own definition. Hull (1988) describes evolutionary science as a process itself subject to adaptation and selection, especially in subject-matter fields where direct experimentation is not possible. A single universally agreeable definition of scientific activity does not seem possible, because science is a diverse practice under constant questioning and self-critique by those who practice it across several fields and under different constraints (see also Feynman, 1999).

What is important to our present purpose is the extensive discussion of scientific processes, underway for centuries, that has resulted in a more or less educated public view of science. This discussion has been a community-building force for scientists and is especially pervasive in the culture of higher education, particularly in the processes of degree-granting and degree-seeking. This paper argues that a similar discussion is much needed among technologists.

Science and Technology

In the thinking of many, technology is a supporting or auxiliary activity for science—less glamorous and vaguely associated with blue collars and dirty hands. A book by Nobel Laureate Herbert Simon, *Sciences of the Artificial* (Simon, 1969), initiates a community dialogue on the subject of technology for technologists (*the* scientists of the artificial) and the public. Though Simon's book is roughly contemporary with Kuhn's, relatively few technologists and fewer non-technologists are thoroughly familiar with it. Discussion of the practices of technology has not had a wide audience. As a result, many technologists are more aware of the knowledge-creating practices and methods of scientists than they are of the corresponding practices and methods of the technologist. It is a matter for most technologists of not seeing the larger goal to which their work contributes.

Discussions of scientific versus technological practice are more than arguments over semantics and word definitions; they are an important part of culture-building that has progressed far for the scientist but not far for the technologist. In a world coming to be dominated by knowledge culture, technologists—a major group of society's creators of new knowledge—need to become more self-

aware of the foundations and principles of their practice. This can only take place through a discussion as lengthy, vigorous, and sustained as the one that science has enjoyed.

This paper defines technology in context with—but not subordinate to—science. Figure 1 relates science and technology to this context by showing science as an attempt to deduce and verify causes of observed effects, whereas technology is shown as an attempt to use known causal relationships through planned action to achieve specified effects.



Figure 1. Relationship between science and technology.

This suggests that science and technology are distinct modes of thinking and action rather than distinct professions or people. The same person can use these two modes of thinking at different times. The difference between the two is that one is analytic and one is synthetic: one (science) builds conceptual models from one set of constructs in order to explain observed effects (lightning, sunrise, rainfall), the other (technology) builds *different* causal models using a different set of constructs to describe how artifacts can be created. All scientists are technologists and all technologists are scientists. This duality of action modes is institutionalized in much of our society as a differentiation of professional categories, but the distinction is not true to nature, and both scientists and technologists engage in both modes of action in a constant interplay that is essential to both.

Figure 1 shows that both scientists and technologists attempt to build causal models. One popular image of technology assumes that the causal models used by technologists originate in scientific theories, making technology reliant on science for direction and substance, and making the direction of effect one-way—to technology from science. In fact, there is much historical evidence to indicate that technology stimulates science equally much, if not more. Technology historically invents its own causal models—models of energy and information transfer—in many cases before scientific causal models can be known to the technologist. Vincenti (1990) argues that there are several classes of technological knowledge that cannot be construed as scientific knowledge. In the absence of science to seed technological models and theories, technology proceeds ahead and not only invents its own causal models but also sets the stage for rudimentary scientific models. Later work is often necessary as science progresses to maintain the linkage between link scientific and technological causal models and theories so

that both practices can progress together more rapidly and with fewer blind alleys (Rheinberger, 1997). It is when science and technology are not in communication through causal model linkages that inefficiencies in knowledge creation occur.

The image of a one-way, science-to-technology relationship is therefore an oversimplification. Technology often provides a theory-building stimulus to science. The medical practices (technology) of rain forest tribes has led to pharmaceutical explorations resulting in new medicinal drugs (further technology) but has also led to exploration of new classes of drugs, particularly of the manner in which the classes affect the functions of the body (science).

The two-way relationship between science and technology finds expression in a more formal way in the language of general systems theory. Klir (1969) characterizes both scientific and technological research in terms of the same construct—the natural or artifactual system. Science and technology are described as different problems of systems. In the problem of science the challenge is to use known “fundamental system traits” as the beginning point in the determination of system traits that are not known. In the problem of technology the researcher is given a set of constraints and a goal—both partly expressed in the form of system traits—and is asked to use what is known about the effectuation of conceptual structures to design and create an artifact (which is a new system) that accomplishes the goal within the constraints. In the case of science a system is studied to determine its behavior and time-invariant relations; in the case of technology a new set of time-invariant relations is designed and created.

This distinction between scientific and technological activities is supported by Simon in his description of technological activity:

The thesis is that certain phenomena are "artificial" in a very specific sense: they are as they are only because of a system's being molded, by goals or purposes, to the environment in which it lives. (p. ix)

Simon concludes that it is difficult to support the claim that technology, which he defines as a prescriptive activity, falls within the purview of a descriptive science:

Sometimes these doubts are directed at the teleological character of artificial systems and the consequent difficulty of disentangling description from prescription. This seems to me not to be the real difficulty. The genuine problem is to show how empirical propositions can be made at all about systems that, given different circumstances, might be quite different than they are. (p. x)

Concerning technology as system creation, Simon explains:

As soon as we introduce 'synthesis' as well as 'artifice', we enter the realm of engineering. For 'synthetic' is often used in the broader sense of 'designed' or 'composed'. We speak of engineering as concerned with 'synthesis' while science is concerned with 'analysis'. (p. 7)

In moments of great enthusiasm, some proponents of science claim that the creation of new knowledge is the exclusive province of science and that all activities that create new knowledge are by definition scientific in nature. Simon, however, is clear in his view that technological pursuits produce and use types of knowledge that are uniquely technology-related.

...I thought I began to see in the problem of artificiality an explanation of the difficulty that has been experienced in filling engineering and other professions with empirical and theoretical substance distinct from the substance of their supporting sciences. Engineering, medicine, business, architecture, and painting are concerned not with the necessary but with the contingent—not only with how things are but with how they might be—in short with design. (p. xi)

Simon points out the essential difference that human goals and intentionality are a defining characteristic of technological activity and thinking:

If science is to encompass these objects and phenomena in which human purpose as well as natural law are embodied, it must have a means of relating these two disparate components. The character of these means and their implications for certain areas of knowledge—economics, psychology, and design in particular—are the central concern of this book. (p. 6)

He further explains:

These examples set the terms of our problem, for those things we call artifacts are not apart from nature.... At the same time, they are adapted to man's [mankind's] goals and purposes.... As man's aims change, so do his artifacts. (p. 6)

What Simon terms the "sciences of the artificial"—what this paper terms *the practice of technology*—is clearly a distinct set of practices, communicating with and sometimes drawing upon the findings of science, but more importantly pro-

ducing and using its own findings, theories, and principles and using methods and processes unique to its own aims.

There are at least five clear differences between scientific activity and thinking and technological activity and thinking:

1. The questions pursued by scientists and technologists are of fundamentally different types and forms.
2. These questions are pursued using knowledge-creating reasoning processes that are also fundamentally different.
3. The products of scientific and technological pursuits are substantially different.
4. The kinds of knowledge created by scientific and technological activities differ.
5. Science seeks dimension-less principles, while technology seeks theories by which the structures, dimensions, and proportions of artifacts can be determined.

What Is Technology?

Technology is defined here as *the structuring time and/or space in order to achieve a specified purpose within the bounds of given problem constraints and to the level of given problem criteria*. There are several important elements in this definition:

Structuring time and/or space:

The practice of technology is always associated with the design and creation of some kind of structure, including ones that are immaterial and not directly sensed (such as event structures). Humans create structurings of time and space by balancing and transforming opposing natural or human-made forces and information that are channeled and directed toward some purpose using a variety of materials. Many human artifacts consist of spatial material structures. A building stands mainly because of the forces transferred through its material structural members and their articulations. Building designers learn to use these forces, balancing and channeling their action through the structural members (Salvadori, 1980; Smith, 1992). Buildings are visible, but the energy and information by which they work are not. Designers of experiences and events (such as instructional designers) must also account for invisible forces applied and transferred through non-tangible *event* structures.

The greatest number of human artifacts are invisible, immaterial structurings of time and space, and many deal in the transfer and transformation of information impressed on energy. Spoken words—artifacts for communication—are temporal structures of atmospheric vibration. Artifacts can often be transformed into multiple forms: speech recognition software can convert the structural framework of a spoken word into electronic pulses. Other software can convert words into visible spatial vibrational signal patterns. Hand signals can also be used to convert the intention of a word into spatial motion. Many of the structures made by humans are momentary structurings of information. Time is an essential dimension of that structuring. Computers and the new “information society” depend on information structures constructed through dynamic electrical forces (electrical charges) over time.

To achieve specified purposes:

Intention is essential to technological activity. Intention directs the formation of plans and designs. Technology is more than just synthesis: it is synthesis toward a goal. As Simon describes it, “The engineer, and more generally the designer, is concerned with how things ought to be—how they ought to be in order to attain goals, and to function” (p. 7). In order to create plans for artifacts focused on the specific range of outcomes, designers require enormous amounts of knowledge, principles, and data of a specialized type. Instead of being descriptive, this knowledge is prescriptive and brings about the “ought to be” of which Simon speaks. (This “ought” should not be interpreted in the imperative but in the opportunistic sense.)

Within the bounds of given problem constraints:

Design problems always present themselves with constraints on allowable solutions. Constraints take the form of: (1) conditions in the environment; (2) existing knowledge boundaries; (3) practical realities of resources, materials, skill, logistics, and infrastructure; and (4) characteristics of the user. For design problems within institutions, constraints may also include design decisions that have been pre-made by the circumstances or goals of the larger organization and so may appear irrational from the designer’s point of view. This often requires the designer to seek out the larger issues and understand local problems within the larger organizational perspective.

To the level of given problem criteria:

Technological problems are almost always accompanied by a set of criteria

and priorities that an acceptable solution must meet. As long as the solution meets or exceeds the criteria, it is said to be "satisficing". Since most problems have more than one satisficing solution, a technological problem does not seek the one "right" solution but seeks as many acceptable solutions as possible within the available design time, space, and resources. Designers will frequently present multiple acceptable solutions for problems to a jury of users or clients for consideration. Beyond satisficing, however, some design problems involve optimizing or maximizing the solution. This involves producing a solution that exceeds all others on some combination of criteria.

Convergence

Technology specializes in working within a kind of "convergence zone" where conceptual artifacts (immaterial designed structures and architectures) must be given specific form with materials, information storage and processing mechanisms, and force-action transfer mechanisms. In this convergence zone, conceptual artifacts are linked with enacting artifacts so that the enacting artifacts express the intentions designed into the conceptual artifacts. In a discussion of the World Wide Web and Model-Centered Instruction, Gibbons and his associates (Gibbons, Lawless, Anderson, & Duffin, in press) describe this convergence zone in terms of instructional-strategic conceptual constructs meeting with and being operationalized by the programming constructs of a particular software tool.

This is the place where the designer's abstract instructional constructs and the concrete logic constructs supplied by the development tool come together to produce an actual product. At this point, the abstract event constructs are given expression—if possible—by the constructs supplied by the development tool.

Simon describes this convergence zone in more general terms as a key to technological activity:

I have shown that a science of artificial phenomena is always in imminent danger of dissolving and vanishing. The peculiar properties of the artifact lie on the thin interface between the natural laws within and the natural laws without. What can we say about it? What is there to study besides the boundary sciences—those that govern the means and the task environment?

The artificial world is centered precisely on this interface between the outer and inner environments; it is concerned with attaining goals by adapting the former to the latter. The proper study of those who are

concerned with the artificial is the way in which that adaptation of means to environments is brought about—and central to that is the process of design itself. The professional schools will reassume their professional responsibilities just to the degree that they can discover a science of design, a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process. (p. 131-2)

The Nature of Technological Knowledge

Vincenti, in his book *What Engineers Know and How They Know It* (1990), dwells on the important issue that technologists are knowledge producers just as are scientists. Vincenti proposes significant differences, however, in the nature of the knowledge produced:

Engineering knowledge, though pursued at great effort and expense in schools of Engineering, receives little attention from scholars in other disciplines. Most such people, when they pay heed to engineering at all, tend to think of it as applied science. Modern engineers are seen as taking over their knowledge from scientists and, by some occasionally dramatic but intellectually uninteresting process, using this knowledge to fashion material artifacts. From this point of view, studying the epistemology of science should automatically subsume the knowledge content of engineering. Engineers know from experience that this view is untrue, and in recent decades historians of technology have produced narrative and analytical evidence in the same direction. Since engineers tend not to be introspective, however, and philosophers and historians (with certain exceptions) have been limited in their technical expertise, the character of engineering knowledge as an epistemological species is only now being examined in detail....

What engineers do, however, depends on what they know, and my career as a research engineer and teacher has been spent producing and organizing knowledge that scientists for the most part do not address. (p. 3)

Vincenti describes the conclusions of recent historical reviews of technology related to the body of technological knowledge:

In the view developed by these historians, technology appears, not as derivative from science, but as an autonomous body of knowledge, identifiably different from scientific knowledge with which it interacts. (p. 3-4)

“Technological knowledge”, Vincenti points out, “in this view appears enormously rich and more interesting than it does as applied science” (p. 4). The existence of the body of uniquely technological knowledge is startling news to those who, as Vincenti describes, look at technology as the application of scientific knowledge. However, this news is especially important to technologists and has profound implications. It means that the pursuit of technology includes: (1) the application of knowledge to specific solutions, and (2) the study of the design process for arriving at solutions, but also (3) an organized and sustained research effort to create the specialized body of knowledge referred to by Simon and Vincenti that is involved in constructing designs and maximizing their utility and fit while minimizing impact.

Technological knowledge, according to Vincenti, falls into categories essential to framing technological problems, directing research, computing the play of forces within competing architectures, describing the behavior of artifact classes, and forming theories of operation. Doctoral students and professional researchers should be especially aware of these classes of technological knowledge because they are the leaders in creating it. Designers should also be aware of the kinds and extent of this knowledge in order to build state-of-the-art technological systems.

Illustrations of uniquely technological knowledge production are everywhere. Consider the following example from computer science—a field in which the science-technology issue has been under discussion for several years. In an article entitled, “ACM Turing Award Presented to Jim Gray of Microsoft Research” (Association for Computing Machinery, 1999), it is reported that Gray made “seminal contributions to database and transactional processing”. A *transaction* is defined as “the fundamental abstraction underlying database system concurrency control and failure recovery”. An interview with Gray contains a more detailed description of the accomplishment and how it came about. Beginning by describing his predecessors in database technology, Gray relates:

...they worked in an ad hoc way; they came to a problem and they solved it, they came to another one and they solved it, too. They could not spend much time on the general properties of these algorithms; they had product to ship. Another group worked at IBM and built the IMS database system that also solved these problems....

So there was quite a lot of ferment in this area. People were building systems that actually worked. But there wasn't much discussion about what the underlying theory was for why the systems worked and whether there were better ways of doing things. At IBM Research in San Jose, there

was a group of people, including myself, who owe their intellectual heritage to another Turing Award winner, Ted Codd. We were fairly academic in background and more interested in studying systems than actually building them. What I mean by that was we were in research and were particularly interested in making computer systems that were extremely easy to use. We believed that if a fairly formal theory was the basis of the system, then the system would have much simpler behavior than one with an ad hoc design. I think the success of the relational database has vindicated that approach. (p. 13-14).

As Gray describes the theory that led to the relational database idea, it becomes clear that it was distinctly technological—a theory of means and architectures expressed in a form that made it useful not for describing but for structuring purposes:

Q: What were the fundamental tenets of the theory?

*A: One was **that all of the data be represented in a relational form**. At the time, this was a pretty radical approach. (p. 14, emphasis added).*

Gray describes the creation of an entirely new architectural construct—the relational form of record structure—that has resulted in immense gains in computing power, economy, and data security for almost all database users. It has also stimulated research into distributed databases and data mining—problems that can now be expressed clearly and solvably in terms of Gray’s relational theory of architecture.

The point of this example is that a technologist is shown inventing a new abstraction of uniquely technological knowledge—an abstraction that can be applied in different ways to a multitude of design problems. What was created in this case was a *technological* principle to guide synthetic activity, *not a scientific* or descriptive one.

Examples of the creation and application of uniquely technological knowledge are found in the popular press but, ironically, mostly in publications devoted to science. This perpetuates the confusion of technology with science for both technologists and the public. It is, however, of more concern to technologists, who tend to be uncertain of their professional heritage of knowledge and of their calling as technologists. Advanced students in technological areas, unless their professional area can supply a firm expression of the role and activities of the technologist, can come to think of themselves as junior, or “wannabe” scientists. This self-image can be sustained by pressures from other academic departments in toward “scientific” framing of technological dissertations and theses. This mis-

appropriated self-image is damaging to technological research, especially to research in instructional technology.

Section II: Categories of Technological Knowledge Introduction

Vincenti argues, using a set of detailed historical case studies, that there are specialized and historically-supported categories of technological knowledge essential to the advance of any technology. Vincenti's is one of a growing number of books on technology that specialize in the knowledge-production views described here—books on power production and distribution, transportation, medicine, genetic engineering, factory design, automotive design, and many others.

Clearly, technological artifacts are produced daily without recourse to organized and research-based bodies of knowledge, and what is known at a given moment is what gets used. The progress of technology is marked by links between controllable causes and desired effects that allow intervention with greater precision to produce greater productivity and higher quality. The extent to which purpose is satisfied depends mainly on the quality and extent of technological knowledge that precedes and facilitates artifact creation. The knowledge base of a technology and its advancement as a technology are clearly linked (Richey, 1998; Seels & Richey, 1994).

The remainder of this paper discusses Vincenti's categories of technological knowledge and how they can be applied to instructional technology in general—using mainly two specific *instructional* technologies, web-based instruction (WBI) and computer-based instruction (CBI), to illustrate applications. The main goal is to reach a clearer definition of a wide range of appropriate research targets for the instructional technologist.

Classes of Technological Knowledge

Vincenti (1990) describes six classes of technological knowledge he found necessary to the evolution of aeronautical engineering designs. Here I will try to apply them to instructional technology. Vincenti's classes are (including my own extensions marked with an asterisk):

- *Fundamental design concepts*
 - *Operational principle*
 - *Normal configuration*

- *Criteria and specifications*
 - *Specifications*
 - *Standards (*)*
 - *Measures (*)*
 - *Criteria*
- *Theoretical tools*
 - *Mathematical models and theories*
 - *Intellectual concepts*
- *Quantitative data*
 - *Properties of things*
 - *Quantities required by formulas*
- *Practical considerations*
- *Design instrumentalities*

Each class suggests a family of essential and researchable technological questions. Each is described below, with examples of how it can be used within instructional technology to organize existing knowledge and generate new research.

Class: Fundamental design concepts

The class of fundamental design concepts consists of two sub-classes—*operational principle* and *normal configuration*. These subclasses are used to frame technological problems and their solutions at the most abstract level. They constitute the heart of technological explanations and represent one class of technological theories.

Sub-class: Operational Principle

The operational principle class of knowledge includes the essential characterization of “how the device works” (Vincenti, p. 208). It is a description of the *primitive forces* acting either in opposition or in harmony to produce the technology’s effect. In aviation, this includes an understanding of the balancing of basic, opposing forces that produces flight. This includes knowledge not just of *which* forces act but of *how they are seen as interacting* to produce flight.

Vincenti describes how statement of a new operational principle by Cayley in 1809 revolutionized and focused technological research on the construction of flying machines. The new principle was: “...to make a surface support a given weight by the application of power to the resistance of air”. This view expressed a balance of forces that would make flight possible. It “freed designers from the previous impractical notion of flapping wings” (Vincenti, p. 208). This principle

directed the research of the Wright Brothers toward certain types of solution.

The fixed-wing concept explored by the Wrights (an adjustable wing surface pulled or pushed through the air) predominates today, thanks to Cayley's framing of the operational principle. An independent line of research based on the same operational principle but a different normal configuration (see the section below) led to the helicopter. In rotary-wing aircraft, a wing is propelled through the air in a rotary direction rather than straight forward. But the underlying operating principle—the basic dynamic of forces—is the same. The flapping-wing, a different operating principle did eventually produce workable configurations, and today flapping-wing toys are common only in toy stores. This operational principle has not, like others, been scalable to larger constructions.

Nuland (1989) describes a long-standing tension between two opposing operational principles that see the purpose of medicine as being either "to treat human beings that happen to be sick" or "to treat sicknesses that occur in human beings" (p. 233). The subtle difference, Nuland notes, has great implications for the practices and training of the individual physician and the medical researcher. Nuland describes how an especially important new operational principle was discovered by John Hunter in the 18th century. Hunter expressed the problem of surgery as a "planned, controlled injury to the body which depends for its success on a predictable healing pattern" (p. 186). According to Nuland, this operational principle has continued to open up new, previously unconsidered avenues of practice and research to the present day, all of them based on Hunter's ability to see inflammation in the body as a sign of a self-correcting force at work rather than as a result of force applied to the body by sickness or injury.

Contrasting operational principles are not "right" or "wrong", they are simply different framings or structurings of force, information, and material useful for the solution of a technological problem. Several operational principles related to the same problem may produce much different yet satisfactory solutions. Operational principles are how we attack a larger problem to break it into smaller, solvable problems. They often require the re-expression of old problems in new terms that describe new balances of forces and lead to unexpected new solutions.

Vincenti's idea of an operational principle (inspired by Polya) corresponds with the idea of the internal/external "interface" described by Simon. The technologist must address:

- Identification of forces and/or information impinging from outside the artifact
- The nature, description, and conditionality of forces and information

- How forces and information are applied to the artifact
- How forces and information are distributed by substructures of the artifact
- How forces and information balance internally to the artifact
- How forces and information are exerted back into the environment.

These issues describe an economy of opposing and cooperating forces within a class of possible artifacts. They constitute one way that things can operate and define how an artifact operates through its internal organization on its outer environment.

Information and Force

Engineers study how the forces applied to the members of a structure are channeled through the structure until they meet and are balanced by opposing forces. Our modern digital technologies have led us also to consider the role of information as a kind of force that can be transmitted and transformed. Information is an important force in the operational principles of a range of digital and electronic artifacts. Genetic engineers also express operational principles that describe ways in which chemical energies and chemically-encoded information act together, sometimes through multiple chemical transformations, to produce biochemical outcomes that are structural artifacts.

The emerging field of structural genomics (Garber, 2000) takes advantage of the fact that “genes are merely blueprints for making proteins—versatile molecules that perform every vital function in our bodies” (p. 48). Through operational principles expressed in terms of information- and energy-transforming forces, this field seeks to bring about mass production of protein structures. That the problems involved are mainly technological is evidenced by a description of how structural genomics will transform the discovery of drugs from a chance exercise to a precision technology:

Today, the vast majority of drugs are still found by hit-and-miss methods, albeit on a massive scale. The world’s top pharmaceutical companies have sunk billions into automated systems that can synthesize and test hundreds of thousands of chemical compounds a week, hoping to turn up a few ‘hits’ against a protein target. (Most drugs on pharmacy shelves work by attaching to proteins, activating, or disabling them.) [Author’s Note: Notice this succinct expression of an operational concept.]

Structural genomics proposes turning traditional drug discovery on its head, putting protein structures first and using them to design drugs from

the ground up, a process known as 'rational drug design' or 'structure-based drug design'. Instead of relying on luck, with a three-dimensional structure as a starting point, chemists can use the details of its shape to create a chemical compound that fits precisely. The drugs that result should, in theory, be exquisitely specific, avoiding the side effects that often doom otherwise promising compounds to the pharmaceutical dustbin. (p. 48)

Accepting information as an element in the expression of operational principles makes clear the benefits of Vincenti's ideas for the technology of instruction. Operational principles related to both design and instruction can be expressed. This leads to the acknowledgement of at least two major bodies of theory for instructional technologists: (1) theories of instructional design, and (2) theories of instruction.

There are many current operational principles used to guide the design of instruction. Some are derived from learning (scientific) theory, some are derived from instructional theory, and some are derived from the reverse engineering of successful instructional products. Certain kinds of instructional research are aimed at the articulation or testing of an operational principle, though acknowledgement of this as distinctly technological research is seldom seen.

Operational Principle Links To Design Process

To embed constructs in designs, a designer works either from a personally-held operational principle or from a set of design rules that embody one or more operational principles. Formalized design processes most frequently specify the use of particular design constructs that link forward in a specified way from primitives (like tasks or objectives) to event and experience constructs (lessons, exercises, problems). This provides a tracing from training requirements to training experiences and media elements. The primitives—abstractions captured in the form of task, objective, or problem statements—are information structures that are transformed by mapping rules to experience constructs, which are also abstractions but which are mapped in turn to concrete media structures, including resources and the logic for administering them (Gibbons, Nelson & Richards, 2000).

The operational principles used during design in making construct transformations are intimately linked with the designer's personal theory commitments and determine the processes followed by the designer. A behaviorist designer who subscribes to the operant structure (Sd-->Rs-->Sr) should be expected to generate design constructs that generally conform to the theory. (For an interest-

ing opinion on how often this is the case, see Cook, 1998). Moreover, the design process will do whatever is necessary to derive those constructs. A cognitivist, working with different operational principles, will generate different kinds of constructs that are linked forward differently, and a different design process will be determined by the constructs and their linkages. A designer subscribing to no particular theoretical view or a view made up of bits and pieces of formal theories (probably the large majority of designers) will create constructs that represent whatever operational principles have been adopted by the designer, and the design processes will flow from those constructs.

Progress in any technological field depends partly on the specific operational principles available to the designer but even more on the fact that operational principles are published and consistently applied. Technological problems yield to broad variations in operational principle. For instance, the technological problem "elevate a human body through the gravitational field of earth" has been solved through the application of different operational principles: the "rocket" or the "repulsion" principle (push from behind), and the "airfoil" or "balloon" principle (lift from above). Neither of these is "right" but one will be of more value than the other under different problem constraints.

Operational principles constitute an essential type of technological knowledge used for the fabrication of designs and are only sometimes forward projections of classical descriptive scientific research.

Sub-class: Normal Configuration

Also within the class of *fundamental design concepts*, Vincenti describes a category of knowledge called the *normal configuration*. The normal configuration includes, "...the general shape and arrangement that are commonly agreed to best embody the operational principle" (p. 209). This knowledge is important because it defines an "envelope" within which a designer's solutions will fit while applying a given operational principle. The normal configuration for most (but by no means all) aircraft is "tail-aft, engine front, tractor, monoplane". The most common automobile configuration is "four-wheels, front-mounted engine, liquid-cooled". Several other less-visible configurations of automobile exist within the operational principle of the auto (for instance, three-wheels, rear engine, air-cooled).

A normal configuration can be considered a pattern that guides the exploration of further design options along specific *structural* lines within the scope of one operational principle. Normal configurations express a detailing of the operational principle that can in turn lead to an entire *class* of similar designs. Thus, one way of looking at a normal configuration is as a high-level design pattern in

which certain design decisions have been pre-made in a way that still leaves the designer a range of details to determine within the pattern. The value of recognizing the existence of operating principles and normal configurations is that they give the technologist a structural basis for systematically exploring the options for solution of classes of technological problems as well as single problems.

The expression of a normal configuration not only scaffolds a design but also gives clues that help define alternative solution configurations. The use of the categories "four-wheels, front-mounted engine, air-cooled" indicates higher-level category titles: "number of wheels", "engine placement", and "engine cooling". This in turn suggests other specific categories within those titles (two wheels, three wheels, five wheels, engine on top, engine to the side, etc.). Moreover, if the more general heading "traction type" is used in place of "number of wheels", new configurations of velocipede are defined that include the treaded snowmobile and the water-jet propelled jet ski. Modular configuration swapping of this type can act like a child's block puzzle, leading to interesting new solution possibilities that would otherwise not be considered. For general technological problem solving, Tsourikov (Garfinkel, 1999; Knowledge and Innovation Server™, n.d.) has developed an automated search engine that pairs problem structures with solution structures using abstracted and parameterized configuration descriptions for both. A similar tool is in principle possible for instructional problems.

The import of the normal configuration for technological research is that it constitutes a kind of technological hypothesis that can be tested, not in classical scientific research terms but in the terms of technological research. These hypotheses, once formed are in need of considerable testing through multiple instantiation and measurement against solution criteria. Testing of artifacts without reference to their operational principles and normal configurations adds little to the knowledge store of the technologist. Testing with reference to operational principles and normal configurations under well-specified conditions with success measured against well-specified criteria can add knowledge not only about the specific product tested but also of the higher-level design principles it embodies. Gray's experience in the discovery of the relational data base principle shows how a simple configurational structure can lead to the solution of many seemingly unrelated problems, can open huge new areas of research, and can create the basis for major progress in an entire industry. When John von Neumann wrote his first computer program (Knuth, 1996a) we can wonder whether he realized he was creating a new operational principle and normal configuration and where it might lead.

A common normal configuration for CBI today is "message-centered, sequential, frame-based logic". The advances of the last two decades in principles of

pedagogy are based on a new operational principle and represent normal configurations derived from it that include also “model-centered, non-sequenced, problem-based, coached”. This new normal configuration has led to a large family of different (on the surface) but very similar (in operating principle) individual products. Different normal configurations lead to much different product architectures, product behaviors, and product-provided experiences. Gibbons & Fairweather (2000) describe this change that is underway in the normal configuration of CBI: a shift in the basic “paradigm” of instruction from direct and message-centered to indirect and environment-centered (See also Hannafin et. al., 1997).

Both the operational principle and the normal configuration apply at many levels of design. Consider that a designed artifact is in actuality a conglomeration of sub-artifacts. An automobile artifact really consists of engine, chassis, drive train, and wheel artifacts designed to work together. For each of these sub-artifacts (artifacts in their own right) an operational principle and a normal configuration are implicit in the artifact’s design and were almost certainly explicit in the designer’s thinking. In the same manner, each of these sub-artifacts is itself composed of sub-artifacts. The engine sub-artifact subsumes a carburetor artifact, one with a particular operational principle and normal configuration. This decomposition continues down to the smallest designed component of the smallest sub-artifact. In terms of the architecture of CBI programs, it suggests a series of modular interfaces that may be exploited in the future to enhance the cost, interoperability, flexibility, and maintainability of products (see Gibbons, Nelson, & Richards, 2000).

The value for researchers and theorists in defining operating principles and normal configurations lies in systematically defining: (1) new areas of legitimate systematic research inquiry, and (2) new design practices. A designer need not confine designs to one normal configuration. A configuration should be picked that is appropriate to the design task. Two-wheel drive cars are designed for certain applications, and four-wheel drive cars are designed for others. In mature technologies, designers do specialize, and in many cases specialization centers on an individual component of a complex system—for example the brake system of a car, or even the master cylinder within a braking system. This does not mean, however, specializing in designs that follow one operational principle or one normal configuration. A good design exploits the modular interfaces that have been mentioned. These can represent opportunities for the design of individual components of content and instructional logic that employ unique operational concepts and normal configurations within themselves but interface in a standard way with other components. The principle of data hiding from the field of programming seems especially well suited to the problems of instructional

technology. One measure of the skill of a professional designer may be the range of operational principles and normal configurations with which the designer can work competently.

Over time, standard operating principles and configurations accumulate in every design field. These are used in the process Vincenti calls “normal technology”, a parallel process to Kuhn’s “normal science”. One task of technological research is the creation and testing of new operational principles and normal configurations. In some cases this can lead to a “revolutionary technology” phase. Formal research on operational principles and normal configurations consists of the search for new symmetries, channelings of force, and information structures that can be used as patterns for families of artifact designs: new structural patterns for the transmission of force or information, and new architectures.

One phase of formal research seeks to understand operating principles and normal configurations that have come into common use through serendipity or common usage by reverse engineering them—analyzing their internal and external dynamics. For just this purpose pharmaceutical researchers analyze the medicinal preparations of rain forest healers, hoping to find not just new drugs but new drug *classes*. Another phase of formal research into operational principles and normal configurations consists of extending known principles and configurations through systematic alteration studies, combinatorial testing, and substitution. The structural genimocs example cited earlier represents the transition of a technology from a probabilistic exercise to a new level of formalism dependent on new, more powerful operational concepts and normal configurations.

Vincenti summarizes the entire *fundamental design concept* class of technological knowledge in this way:

"The operational principle and the normal configuration provide a framework within which normal design takes place. To translate these concepts into a concrete design requires knowledge from the categories that follow."

Class: Criteria and specifications

Setting and reaching goals at measurable criterion levels is a central activity of technology. The *criteria and specifications* category of knowledge includes that knowledge necessary to specify designs for classes of artifacts, express artifact class standards, measure attainment of standards, and judge criterion-level performance. Though the rules for specifying criteria may appear uncomplicated, this category is the home of complex theoretical issues that give a technology its measurability and therefore its guarantees of performance and reliability. Without this kind of knowledge, a technology lacks the discipline to progress beyond a

rudimentary level. Determining what to measure and how to measure it is a major activity of science, and it is no less important to technology.

Subclass: Specifications

The category of *specification* knowledge includes those theories and principles that govern the expression of designs. According to Vincenti:

"The necessity for a bridge to carry traffic over a river has to be translated into specific span and loading requirements. For a given width of river, a given estimate of the amount of traffic, and a given description of the traffic (size of the vehicle, weight of vehicle, etc.) only certain minimum criteria and specifications for the bridge will serve the purpose." (p. 211)

Vincenti continues:

"To design a device embodying a given operational principal and normal configuration, the designer must have at some point specific requirements in terms of the hardware. That is to say, someone—the designer or somebody else—must translate the general, qualitative goals for the device into specific, quantitative goals couched in concrete technical terms." (p. 211)

Designs are expressed for many purposes, among them:

- To communicate a plan to design stakeholders (designer, client, fabricator, public, regulators)
- As a description of work solicited from an outside party, such as in a request for proposals
- As a general standard to be met by a family of artifacts.

Designs can be expressed at different levels of formality and detail. Designers tend to create specifications at the minimum level required to communicate design details to stakeholders. Architects, for instance, can work at levels from very abstract sketches to detailed and formal drawings to communicate information to design stakeholders (Robbins, 1994). The degree of design specification necessary depends on the history of prior communication and mutual understanding. Knowledge about how specifications are captured, expressed, and used is an important kind of shared knowledge among the workers and researchers of a particular technological field.

The body of knowledge for specifications includes, among other things, prin-

ciples for selecting the defining properties of an artifact to be used to create artifact categories. Several properties of steel were considered in the early 1900's as defining categories for steel applied to different uses during auto manufacture (Misa, 1995). In every technological field, maturation of the field is accompanied if not signalled by the development of more finely discriminated measurable product categories leading to improved quality standards. Rules also evolve for matching these more finely discriminated categories with specific instances of need.

The body of knowledge for specifications also includes professional standards for expressing designs. Design languages like the Unified Modeling Language (Booch, et al., 1999) and architectural specification languages like that proposed by Bass and his co-workers (Bass, Clements & Kazman, 1998) are representative of the ongoing search for languages in which to express software specifications. These guidelines for design expression have far-reaching implications, and design languages can become the basis for commercial product definition. They also become the basis for automated design systems. One of the future uses of UML will be no doubt for the automated production of software. Automated design systems based on a common language for design expression have become necessary in the computer chip industry as the design complexity of chips has exceeded human capacities.

In the field of instructional technology *Designers Edge*™ (Allen Communications, 1994), an instructional design system, uses specifications expressed in a standard form to support the evolution of designs that can be poured as data directly into popular authoring tools for the automated fabrication of computer-based instruction. Interest in automated design systems is an important sub-area of the instructional technology field (Merrill, 1999; Regian, 1999; Towne, 1999; Schank, 1998). New paradigms of instruction (Gibbons & Fairweather, 2000) present a fresh challenge in both the expression of design specifications and the evolution of design languages for use by designers. Research in this area is an important need.

A less obvious area of knowledge related to specifications is methods for validating the application of abstract theoretical ideas to the concrete media elements of artifacts that are intended to give expression to those abstractions. This is a particularly troublesome area for instructional technology because instructional designers create concrete artifacts, but they are only a means to an end and do not represent the *real* instructional product—which is the perishable and intangible *instructional experience*. Whereas in other fields, conceptual design abstractions tend to be expressed in concrete form, in instructional technology they must be linked through intermediary event and experiential structures that only then link with concrete media artifacts. Cook (1997), a participant in

the early days of programmed instruction, describes how many forms of programmed instruction intended to be expressions of radical behaviorist theory failed to achieve that application due to poorly-engineered theory-to-artifact linkages.

This concern is not limited to a particular learning theoretic viewpoint. As instructional theory of any kind is used, it must find expression through media artifacts fashioned by many hands, and abstract theoretical constructs must be linked to media and tool constructs (Gibbons, Nelson & Richards, 2000). Often in instruction name association to a theory is invoked, but examination of artifacts shows the linkage to be tenuous. It is often impossible to find substantive differences between instructional artifacts created using different theoretical bases. Instructional technologists should research principles and methodologies for ensuring and evaluating the soundness of the fit between theory constructs and design elements.

Subclass: Standards

Standards are a special class of specifications used as a benchmark for a class of artifacts. A standard expresses acceptable artifact qualities for a set of key quality indicators in a manner as quantitative and unmistakable as possible. A standard is a community-wide professional document that describes the minimum limits required for different classes of artifact, each given a specific class designation, to be acceptable to the community.

Standards allow artifacts to interoperate with other artifacts—especially those designed by other designers—in a safe, dependable, and predictable way. Organizations like Underwriters' Laboratories™ (UL) and the Society of Automotive Engineers™ (SAE) have been established to moderate standards in a wide range of technology products, each a class of artifacts. Because of this, consumers can buy standard-level transmission fluid and motor oil products with confidence in their consistency, safety, and basic quality, and electrical plugs on appliances can be expected to match the electrical receptacles in houses. Standard-setting is a requirement for the advance of industries founded on technologies, therefore, there are standards in all technological fields. Work on standards is not considered as interesting as other technological tasks, but the influence of standards boards is far-reaching, and technologists in any field feel the effects of standards often without knowing about the process by which the standards were set or who set them.

The steel industry experienced three periods of standard setting and upgrading in the last quarter of the nineteenth and the first quarter of the twentieth century, one for rail steel, one for armor plate, and one for construction steel for buildings. There is great current interest in standards with respect to

interoperable objects for instructional use over the World Wide Web (Wiley, 2000; Advanced Distance Learning Initiative, n.d.; Educational Object Economy, n.d.; Instructional Management System Project, n.d.). Though this is the most visible standards effort for instructional technologists, it is only one of a wide array of standards that impact designer work in terms of hardware, software, internet and Web standards, and accessibility.

A standard normally contains the following items of information, some of which are omitted from some specifications:

- Clear definitions of artifacts and artifact classes—A description of what artifacts are and are not covered by a particular section of the standard and terms that refer unambiguously to each class of artifact
- Clear definition of the key artifact properties and qualities: dimensions of the artifact to be measured
- Definition of measures to be used for artifact properties and qualities
- Definition of minimum/maximum (and sometimes optimum) values for key measurable dimensions of artifacts
- Interpretive rules for linking the measures to artifacts—Statements of limits of applicability, methods for making measurements
- Symbol systems used in expressing measures or artifact properties, references to other standards, etc.

Standards represent an important type of technological knowledge, not because they are a product of traditional research but because they represent the previously-accumulated and continuously-accumulating experience of a community of designers. Properly maintained, they become one of the important memory repositories of a technological field.

At key points in the maturation of technology, particularly following or during periods of rapid development and innovation, the proliferation of non-standard artifacts usually begins to make further progress of the field as a whole difficult. In such cases designers tend to lack guidance that would allow their artifacts to interface within the larger operational context. They find that continued designing without a community standard will be wasteful. At such times, designers representing key players in the developing technology's community come together to produce a standard. The goal of this effort is to define key measurable artifact qualities that promote safety, inter-operability, efficient use of public in-

frastructure, or user friendliness and give these qualities minimum standard values that henceforth sanctioned products must meet. Standards compliance sometimes grants the right to associate a product with a seal or symbol of the standard. This becomes a badge of confidence for suppliers and customers and becomes an important market factor.

Once a standard is set, it is maintained. On a regular basis the stakeholders in the standard come together to review and update it to be compatible with the latest developments in the field. In some areas of technology like aviation and construction, standards are also reviewed following major failures of the technology to ensure that design products will not fail in the same manner in the future. Standards that are important to safety and well-being of large numbers of persons become public codes and regulations, and an extensive literature on regulatory practice and its effects on technologies has grown up in many areas. Not only the nature of standards and the selection of measurable dimensions but the methods of evaluation deserve study in a technological field.

Standards can be proactive, defining desirable theoretic or aesthetic qualities to accelerate the progress of a field. Standards also have strategic value for cooperation and competition. The software industry has seen multiple instances where large cooperatives of stakeholders have come together to form a standard that promotes the progress of a technology. The World Wide Web is a technology for which this has been especially true, and numerous consortia and standardization organizations have formed around it. While standards represent an acceptable level of practice in a field, researchers should keep in mind that today's standard was yesterday's research and development project. Standards should never be allowed to restrict the free development and testing of new approaches and methods. It is in the interests of all—especially the continuing commercial enterprise—for new ideas to create an open, competitive environment. The software industry has been the scene of quite public warfare with standards as the weapon of choice between producing organizations who adopt, change, or try to control standards in order to strengthen their own competitive advantage.

Standard setting is an important area of design competence and knowledge because designers use standards and in many cases contribute to them. Of special interest to research in instructional technology is how to create standards that maximize beneficial effects while minimizing restrictive influences on current and future artifact designs. Designers should be particularly interested theories of standards and regulation in general, since standards are eventually unavoidable in any area of technology, and since bad standards or over-regulation can restrict progress.

Subclass: Measurement and Instrumentation

Vincenti, an aeronautical engineer whose field of technology is relatively mature, does not mention measures as an area of knowledge within criteria and specifications class of technological knowledge. Measures are a *sine qua non* for a mature engineering field like aeronautics. In a new technological field, measurement is an essential and fundamental class of knowledge that should be tended to as early as possible. Technologies must grow toward increasing precision of effect, predictability, and dependability. Measurement is both the vehicle and the test of that growth.

Frederick W. Taylor's history-changing innovations in the technology of tool steel were based on a rigorous, instrumented methodology for measuring temperatures and intervening in specific ways at key temperature-defined points. This method contrasted sharply with the prior dependence of craft masters on the glowing color of the metal as an indicator of when to take action (Misa, 1995).

A technology's artifacts are measured in order to assess standard compliance, mark improvement, identify design deficiencies, identify opportunities for improvement, and quantify productivity. Every technological area develops its own set of measures, measurement practices, measurements standards, and measuring instruments. The maturity of a technology is correlated with the degree to which it can objectively make observations and measurements.

In the history of medicine a main thread of progress has been the ability to measure momentary body states that lead to rational decision making and planning of therapies. Nuland (1989) describes how Rene Laennec, using a tube of rolled paper to listen to a patient's chest sounds, strengthened his profession's slow movement toward the use of objective measures—a movement that took nearly 100 years to complete. Before Laennec's invention of the crude paper (later wood) stethoscope, doctors relied largely on patient self-report and subjective, often pre-conceived judgments. To arrive at conclusions about disease they reasoned with insufficient data in terms of bad air, moral weakness, and the effects of unbalanced bodily humors. The stethoscope and other medical measuring instruments changed what doctors could hear, see, and feel and so changed the basis of their reasoning. Laennec was able to publish a work in which he identified and gave names to specific thoracic sounds. These in turn could be connected with disease conditions.

For any field, serious measures and their implementation is non-trivial (see Kuhn, 1977). In science and technology both, measurement of some kind lies at the source of verifiable knowledge and defines how any field can "know" something. Some of the most complicated technologies of this century—the Hubble

telescope, MRI scanning, and the GPS satellite system—are essentially measurement devices. Key technological measurement inventions of prior centuries have included the clock, the telescope, the microscope, and the musical measure. Crosby (1997) describes the awakening of western culture to a type of quantitative thinking essential to the scientific and technological revolutions that have occurred since then.

In most technological (and scientific) fields, the processes and tools for measurement become a sophisticated sub-specialty. There are principles for measurement that apply generally to all fields, and there are specialized instrumentations for every field. How a field's professionals have agreed to measure things in their area constitutes an important part of the field's knowledge. Though there is a huge and technical literature on measurements in education, instructional technology is a field almost entirely without useful or used measures, so research in this area offers many opportunities.

Research in measurement within a technological field includes many theoretical and conceptual as well as practical issues:

- Establishment of scales
- Definition of properties of interest to measurement
- Relation of scales to properties
- Construction and calibration of measurement instruments
- Algorithms for counting
- Creation of interpretive theory for measures
- Creation of measurement procedure standards
- Establishment of recording and reporting conventions

As measures accumulate for multiple artifacts of the same class, the data reflects on the soundness and utility of operational principles and normal configurations that those artifacts represent. It is through the process of applying measures to classes of artifacts that the technology advances and knowledge about artifact classes accumulates.

Subclass: Criteria

The specification of criteria that artifacts must satisfy is one of the distinguishing characteristics of technology as a practice distinct from science. Criteria express in general the decisive dimensions along which success quality will be measured for a specific artifact or artifact class. Along with the problem that guides almost every design project, there is an explicit statement of criteria that will be used to judge satisfactory performance.

Vincenti makes it clear that setting criteria is itself a complex process:

"Design criteria vary widely in perceptibility. Sometimes...the necessary quantities...are simple and obvious; they can be discerned at once and without much effort. In other cases...the criteria are not immediately clear; they have to be devised consciously and deliberately over some period. In still others...the criteria are obscure and require great effort over a protracted time." (pp. 211-2)

Criteria can exist for classes of artifacts as goals for designers to strive toward over long periods of research and design. As the Wright Brothers pursued the goal of powered flight, criteria dividing soaring and gliding from true powered flight were important to their success claims. Combs (1979) describes those criteria as involving distance flown, degree of control, and the conditions of wind and terrain under which the flight had to be taken. As flight technology advanced following the first demonstrations, new success criteria rose just ahead of the technology, leading research and development toward increasingly more capable flight artifacts.

Criteria imply the presumption that testing and judgment will take place, and this can occur at the level of artifact instances or of artifact classes. Criteria are most useful in a technological field because they describe the researchable problems that lie just beyond reach. Many technologists fail to realize that criteria themselves are also appropriate subjects of research.

Dealing with technological criteria consists of more than setting them, because with the setting there is implied a process for judging the outcome. Often for any technology this is a difficult thing to accomplish. Simon (1969) describes approaches to criterion judging that involve cost-benefit analysis, utility functions, and optimization measures. These kinds of tools require theoretic bases and mathematical tools for application, all of which are a legitimate part of a technology's knowledge base. Likewise at the meeting point of theoretical with practical concerns, technology fields need to concern themselves with issues of feasibility assessment, cost-function trade-off study, and measure efficiencies.

Class: Theoretical tools

Vincenti includes in the *theoretical tools* class of technological knowledge: (1) *mathematical models and theories* (including qualitative models) used in making design decisions, and (2) *intellectual concepts* for thinking about designs. This general class of knowledge contains the basic "vocabulary" of the technology; it is the beginning point from which the other classes of knowledge are derived and enables the expression of theories.

Subclass: Mathematical Models and Theories

Vincenti refers to this subclass of knowledge as a “body of mathematically structured theoretical knowledge” (p. 213). It is expected that theories in physical science be expressed in mathematical terms that represent essential relationships. However, mathematical models in technology have a somewhat different purpose than in science. Scientific math models can be used for prediction. Most often they are expressed in terms that are dimensionless and represent relationships that are true across several levels of scale, though every theory has its bounds of applicability. The formulas relating gravity and mass are expected to hold at the universe level, the galaxy level, and the solar system level.

Technological math models, in contrast, are created for the purpose of *assigning* dimension values or *testing* contemplated values. Once a dimension of one element of an artifactual system is determined (for instance, the piston diameter of a steam engine), a mathematical model can be used to determine the dimensional range that other elements of the system must possess in order to function properly (meaning within criterion bounds). These calculations are expressed in and are restricted to certain units: inches, centimeters, pounds, liters, etc.. This difference in the use of mathematical models between science and technology is described by Layton (1992) and Kroes (1992).

Computer Science, whose intellectual leaders have included mathematicians like Boole, von Neumann, and Knuth, use specialized mathematics as a tool in generating algorithms (Knuth, 1996b), computer language features (Sethi, 1996), and computer designs (Tinder, 2000).

Technological fields vary in their ability to express theory mathematically. Many mature technological fields, such as engineering, have succeeded in doing so. Butler (1998) supplies hundreds of computational formulas for everything from *air conditioning* to *yield stresses* in a building structure. These formulas guide building designers into computations that will lead to safe, durable, servicable structures.

Given the profusion of mathematical models in mature technological areas, the lack of such models for instructional technologists might be cause for concern and could be interpreted as a sign of relative technological immaturity. Probably the most important reason for the lack of mathematical models related to instruction is the lack of consistent, reliable measures and measurable quantities.

One of the most firmly established technological theories related to human instruction is the mathematically-stated law of practice (Newell & Rosenbloom, 1981):

"There exists a ubiquitous quantitative law of practice: it appears to follow a power law; that is, plotting the logarithm of time to perform a task against the logarithm of the trial number always yields a straight line, more or less. We shall refer to this law variously as the log-log linear law or the power law of practice" (p. 2).

Newell and Rosenbloom trace the knowledge of this law back to the early part of the 20th century, and though they give numerous examples of its applicability to a wide range of learning types, they observe that "it is hardly mentioned as an interesting or important regularity in any of the modern cognitive psychology texts" (p. 2). The law of practice is a technological theory because it reliably predicts the effects of intentional artifactual intervention into human learning processes.

Attempts have been made to introduce formulaic manipulations into instructional theory, generally relying on highly structural views of instructional process and content combined with qualitative rules (Merrill, 1994). Anderson (1993) and others have proposed structuring metaphors that allow instructional equations to be expressed in the form of "if...then..." statements (Wenger, 1987). At higher levels of organization, attempts have also been made to introduce standard elements that increase the computability of instruction (Gibbons, Bunderson, Olsen & Robertson, 1995; Reigeluth, 1999a; Gibbons, Nelson & Richards, 1999).

Intelligent tutoring systems (ITS) researchers explore the use of expert rules as a computable basis for just-in-time instructional design. The expert's rules are quantities or qualities ("ifs") related through rules to specific instructional actions ("thens").

"If the number of omission errors becomes greater than three, then invoke the coaching message".

Even when a quantity is not expressed in an expert rule, we assume that the quantity is "one" and the rule is still qualitative by being binary:

"If the response given is not the expected response, increase the error index by one and move to the next item".

Intelligent tutoring system researchers have been recently trying to speak in familiar terms with designers and to produce tools that allow the average designer to experiment with rule-governed instruction. The Air Force Research Laboratory (Regian, 1999) has developed portable expert routines that bring formulaic computation into instructional products designed by a large audience of

designers. Shank, (1998) is engaged in a project to produce authoring systems that embody his principles and his computational engines for instructional control over instruction that selects the most important story structure and content at a given moment during instruction.

The average designer might also become aware of the quality-and quantity-connected rules they already use without realizing it as they design traditional products. These rules come from multiple sources—research, experience, peer practices, habits based on introspection, copied designs, and even informed guesses—and comprise part of the designer’s personal instructional theory. However, for this category of technological knowledge to advance, designers must begin to make explicit and test those rules. Mathematically-expressed theories and systems expressed as non-mathematical production rule systems are possible for instructional technology. Their spread depends on a willingness in designers to see their products in new, architectural terms. Steps along that road will require more clear expression of the intellectual concepts (see the next section) that represent key structural components of more rigorous instructional theories. Reigeluth (1983, 1999b) has been a leader in promoting a theoretic mindset to instructional technologists. Early emphasis on technological theory-building for instructional design was expressed by Bruner (1966) and others (see, for instance, Hilgard, 1964), but these calls came at a time when instructional (technological) theories were normally confused with learning (scientific) theories.

Scientific Theory and Technological Theory

A short discussion is necessary at this point to clarify the term “theory” as it is being used here and to relate the familiar idea of *scientific theory* to the relatively new one of *technological theory*. The goal of science is theory-building and verification. In science, theories are explanatory tools in an emerging unified and orderly description of phenomena. A scientific theory describes how things happen. This description is given in terms of constructs that are hypothesized by the theory to exist. The theory describes either mathematically or propositionally how the constructs interact to produce observable phenomena. The scientists applies one or more theories to explain observed phenomena and strives to be able to predict them by replicating required conditions. For a scientist a theory is tentative and subject to experimentation to establish its credibility. In principle, theories emerge and are tested, following which they are either sustained or modified.

The proper goal of technology should also be theory-building and verification. But technological theory does not fit the traditional, scientific, mold. In technology, theory is defined as a description of how things *can be made* to produce

a targeted outcome. Technological theories are theories of control, influence, and effectuation; they are theories of channeling and directing force through mechanism and theories of creating, storing, applying and applying information to the channeling process. They are theories of transformations: force-to-force, force-to-information, information-to-force, and information-to-information. Technological theories express beliefs about how force and information can be transmitted and transformed through some material or event medium in order to reach a desired end state.

During design, technologists apply one or more existing theories of force and information transfer and transformation to create an artifact conception—a structural dynamic—and then apply additional theories of material, mechanism, measurement, form, and action to link from this abstract artifact conception through successive stages of transmission and transformation to the desired criterion of form, functionality, and materiality. Design consists not in creating an explanation or a prediction but in creating plans—designs—for artifacts that channel force and/or information for a particular end.

Technological theory and scientific theory interact in a way that enables each to provide the seed for the other. That means that scientific and technological theories must be expressible in forms that link with each other at key points. It is useful to think of technological theory in terms of pivotal points in a natural or artificial process (described by scientific theory) at which deliberate, goal-directed intervention is planned for the purpose of deflecting, transforming, transmitting, including, decoding, storing, impressing, or releasing force or information. In this view, electricity is just controlled lightning, the computer is just a machine for converting electrical pulse patterns into other electrical pulse patterns, and concrete is just a stone that has been formed in a specific place with a specific shape.

Frederick W. Taylor's research into the technology of steel manufacture has already been mentioned (Misa, 1995). It made possible durable steel tools that could be used in the high-speed shaping and working of other steels without breaking. This resulted in the ability to produce harder steel products at higher rates. Taylor's innovation consisted of: (1) using pyrometers (high-temperature thermometers) to measure the temperature of the steel batch at any given moment, and (2) using these measurements to define pivotal points in the steel-making process at which to make interventions that diverted the path of the material formation at the microscopic level in a prescribed way that produced an expected criterion outcome.

Taylor performed a systematic search for steel secrets for 10 years, testing numerous technological hypotheses. Earlier craft-oriented wisdom rejected systematic exploration and relied on subjective time-tested measures of metal color

(that it turns out were unreliable and varied with the degree of light in the room) rather than on objective temperature measures applied in a consistent manner to determine the state of the steel batch. Taylor discovered through his well-measured researches that heating the steel to specific temperatures and by quenching or otherwise treating the steel at specific time-temperature intervention points using specific chemicals allowed him to produce with precision much more resilient steel: that is, much more steel, and much stronger steel both.

What Taylor discovered was not just one recipe for steel but a theory of fabrication that produced a family of steel recipes. The theory described not just *ad hoc* but principled and deliberate manipulations. These later were linked with a scientific theory of materials, and that linkage opened up principles to guide a proliferation of recipes that continues to this day. With this science link, product qualities could be described in terms of the natural processes taking place within the steel as it cooled. Once a desired pattern was chosen, a new recipe could be generated using technological theory: the conceptual framework that prescribed the diversion and channeling of natural forces.

Technological-prescriptive theory conceived in these terms interfaces with scientific-descriptive theory because both are expressed in terms of natural process. Through this relationship a working technological methodology discovered through serendipity or systematic exploration (for instance healing through rain forest medicinal preparations) can present a challenge for explanation to science. Likewise, the existence of a scientific theory presents a challenge to technology to bring natural processes and forces under control if there is a worthwhile and desirable goal that can be accomplished by doing so. However, doing so is a non-trivial activity that entails the creation of additional technological theory.

Hughes (1983) describes a systematic view of technology as a collection of subsystems, each of which can be advanced or retarded in its progress, creating a reverse salient: the inability of one technology to integrate with others due to lack of progress. We could apply the same concept to describe the relationship between technological and scientific theory, defining as a reverse salient any area in which either scientific theory or technological theory had not matched advances in the other, causing a lag in technological or scientific knowledge.

Scientific and technological knowledge can advance jointly or independently. Moreover, science and technology can interact through linked theories, regardless of the truth and validity of the theories on either side. Over the period of time when the theory of balanced bodily humors was current as one explanation of health and sickness, a corresponding theory of treatment prescribed interventions that included redistributing the humors (through cupping, tilting, etc.) or eliminating them from the body (through bleeding, purging, etc.). Here a scientific theory (of bodily humors) that we know was incorrect in its details was ca-

pable of giving rise to a linked technology (of therapies). Moreover, at the time, as competing theories arose, the humorist technology was able to contribute improvements in technique back to the scientific theory of body humors. This apparently successful mutual contribution between science and technology lent stability to a (now superseded) system of belief and practice that we see as primitive and sometimes brutal.

We no longer subscribe to the theory of humors in the form it was expressed during that period. Today when we bleed a patient or perform any of several seemingly equally violent interventions (tilting, purging, etc.) it is for different, theoretical reasons even though the act itself is basically the same. Similarly, as previously described, John Hunter, a physician and naturalist in 18th century London was able to form a theory of "controlled injury". In this theory human-afflicted injury was proposed to intervene in natural bodily processes to remove or alter a destructive source, following which the body's natural healing mechanisms could perform the restoration to health. Today we call this "controlled injury" surgery, and it is still conceived in its modern form as an intervention at specific, measured points that deflects, controls, and otherwise takes advantage of natural processes (Nuland, 1989).

Several types of theory are important to technology. These theories to explain how things can be made to work. The list below is suggestive of the range of technological theories needed but is by no means complete:

- Theories of sequence/process—algorithm theory
- Theories of feedback—Cybernetic theory and Heuristic theory
- Theories of measurement
- Theories of structural dynamics, force transfer, and force distribution
- Theories of force-information transformations
- Theories of search
- Theories of information
- Theories of materials
- Theories of storage
- Theories of valuation
- Optimization theories
- Theories of goals and goal decomposition
- Systems theory

These theories and others constitute appropriate research areas relative to specific technological areas, such as instructional technology.

Technological theories are expressed in terms of constructs that represent states, actions, and goals (Simon, 1981). States can be linked with actions through contingency formulas: if/then/else, when/then/else, while/then/else,

until/then/else (see Reigeluth, 1983, 1999b; Merrill, 1994).

The design process can be considered theory-based to the extent that theories are used in defining and selecting among alternatives. To the extent that some other basis is used for selection, the design becomes experience-based at best and ultimately *ad hoc*. This is an especially strong temptation to technologists, who tend to enjoy making and using more than theorizing. However, technologists, whether researchers (producers) or designers (consumers) of technological knowledge, should become aware of the important role of theory in technological practice. A beginning point would be the evolution of basic understandings, conventions and standards for theory expression. This leads us to the category of technological knowledge that Vincenti calls *intellectual concepts*.

Subclass: Intellectual Concepts

Vincenti's intellectual concepts are the building blocks for all of the other types of technological knowledge. Intellectual concepts as defined by Vincenti constitute the terms of design and design thinking. The intellectual concepts possessed by a designer are the constructs used by a designer to conceive designs: the conceptual components of design. They supply both the outcome ("then") portion of design rules and the conditional ("if") portion. Intellectual concepts are the terms of instructional formulas and the *vocabulary* of instructional theories. Designers in any field share a culture of intellectual concepts. An *arch* is a specific, concrete thing, but the *concept of arch* is a designer's intellectual concept, as are the architect's concepts of *load bearing wall* and *space*. These concepts are basic design building blocks.

Intellectual concepts provide the set of reusable conceptual structures (constructs) that designers can share and use among themselves. Crosby (1997) describes how the intellectual concepts of *staff*, *note*, and *measure* led during the period from 900 AD to 1600 AD to systems of musical notation. The history of Western music is in this way bound up in the history of its evolving intellectual concepts. This simple set of intellectual concepts has been the means of expressing and sharing increasingly varied, complex, and interesting music over the past four hundred years that was unattainable before the invention of those concepts. Instructional designers are often eager to get to the "hands-on" part of a project. They want to begin creating product and are often impatient with detailed concerns about the inner structural composition of their products. For this reason designers often find the sophistication of their designs limited in the same way the musical monks of the middle ages were limited.

Designs created without adequate attention to inner structure (expressed in terms of intellectual concepts) find products messy to create and maintain beyond a certain size and degree of complexity. Moreover, the quality of such prod-

ucts is often uneven and unsatisfying. Designs that are deliberate in their use of inner conceptual structures have no guarantee of being inherently better, but such designs employ larger patterns and structures that were not before attainable, and they can employ more articulated and subtle interactions and effects. The product, being better designed structurally, is often also easier to construct and maintain, and the product tends to be of more even quality throughout (Bass, Clements & Kazman, 1998).

Robbins (1994), shows how different types of architectural sketch, drawing, plan, elevation, and model become part of the conceptual language in which designs are expressed and evolve over time. This common language allows architectural teams to work together to create designs, allows designs to be inspected and evaluated, and suggests and encourages the construction of ever richer and more sophisticated designs. Berliner (1994) describes a similar unwritten language used by jazz improvisationists to create rich variations of highly structured designs at the moment of performance.

CBI designers are experiencing an avalanche of new intellectual concepts from new instructional *normal configurations* (paradigms) that are ill-matched with existing CBI tool structures (Gibbons, Lawless, Anderson & Duffin, in press; Gibbons & Fairweather, 2000). This same problem is aggravated for Web-based instruction, whose conceptual tool structures are hardly as mature. Finding the missing tool concepts will depend on the realization that the appropriate order of design is instructional constructs first, tool constructs second. Designers will come to expect tools over time to adapt to their designs, rather than vice versa. As David Liddle (1996) sums up regarding software development tools in general:

"Software design is the act of determining the user's experience with a piece of software. It has nothing to do with how the code works inside, or how big or small the code is. The designer's task is to specify completely and unambiguously the users whole experience.... The most important thing to design properly is the user's conceptual model. Everything else should be subordinate to making that model clear, obvious, and substantial. That is almost exactly the opposite of how most software is designed." (Liddle, p. 30)

The intellectual concepts (design constructs) of a technological field come from many sources: everyday practice and usage, designer intuition and invention, designer folklore swapped at the water cooler, R&D literature, project experience, cookbooks, team problem solving, and theoretical writing. Some categories of technological knowledge, like specifications, standards, and measures,

seek to stabilize knowledge within a field. Intellectual concepts, in contrast, are an important cutting edge where it is important that there be constant change and growth balancing with stability. Revolutionary periods of scientific research are said by Kuhn (1970) to alternate with periods of relative stability. We can see the intellectual concepts of a field as the crux of instability and change when it occurs.

Research in instructional technology should emphasize the analysis of anomalies as strongly as it seeks statistically homogeneous results through standard research methodology. These anomalies are the clues that lead to new intellectual concepts. Schrage, in *Serious Play* (2000), describes how prototyping as a method of research encourages the discovery and exploitation of anomalies.

Class: Quantitative Data

In the *quantitative data* class of technological knowledge Vincenti places data on the properties of things and quantities required by formulas. During design, data is used as the basis for making individual decisions. An enormous amount of data is needed. The more mature the technology, the more vital is the role of data in decision making and the more voluminous the body of data required.

The vast amount of data required during design is made up of several types:

- Materials properties
- Data on standard manufacturing processes for production
- Scientific data describing processes occurring in systems
- Data on operational conditions in the physical world of artifact use
- Data on the specific contexts that will host artifacts
- Data on the human user, its strengths and limitations
- Data on human and system performance criteria
- Data on law-related physical constants
- Data for formula computations (qualitative/ quantitative)
- Data on safety factors and safety margins and failure factors
- Data on acceptable standards for the artifact class

An aeronautical engineer may look up the strength properties of a type of steel in a materials table and see not only limits of stress but the manner in which the material breaks down. An anaesthetist trying to determine the amount of anaesthetic of a particular type for a specific patient of given body weight to achieve a given the depth and length of anesthesia finds data to guide such decisions summarized in charts and graphs. A computer chip designer must know the thermal and electrical properties of not only individual components but the

properties of interfaces between components of different types. A large-scale CBI designer needs to know the instructional properties and the average cost of producing the logic and multimedia resources for a particular type of strategic program unit. All of this data is found through systematic research.

When the Wright brothers began their quest for controlled powered flight, they gathered data of previous researches from every known source. Wilbur, writing for both of the brothers, said in a letter addressed to the Smithsonian Institution, "I wish to avail myself of all that is already known, and then if possible add my mite..." (Combs, p. 50). After examining the data and comparing it to their own careful studies, the Wrights reached the conclusion that:

"Thousands of men had thought about flying machines, and a few had even built machines which they called flying machines, but these machines were guilty of almost everything except flying. Thousands of pages had been written on the so-called science of flying, but for the most part the ideas set forth, like the designs for machines, were mere speculations and probably ninety percent false. Consequently, those who tried to study the science of aerodynamics knew not what to believe and what not to believe. Things which seemed reasonable were very often found to be untrue, and things which seemed unreasonable were sometimes true..." (p. 53-54).

Without the detailed and accurate data they needed, the Wrights were powerless to move ahead toward their goal of flying. By using error-filled data, they would not only fail, but they would subject themselves to mortal danger. Combs describes the experimentation necessary for the Wright Brothers to create accurate and sufficient data, first with a kite model, then with small and increasingly larger gliders. Only after gathering an extensive body of data on non-powered modes of flight was it possible to attempt powered flight.

How sufficient is the data now available to help a CBI designer determine the minimum number of problems to present during principle instruction? What graphs summarize the best size and complexity of a practice problem, given skill complexity, skill newness, and the characteristics of the learner? What chart summarizes the average relative cognitive load associated with a particular selection and spatial arrangement of CBI event controls—a cognitive load value that can serve as a defining intervention point just as did the temperatures of Taylor's steel? The absence of CBI properties and performance charts and tables does not indicate that the data is not needed for use during instructional design and delivery for decision making. Rather it shows that the sophistication of product designs has not yet advanced to the point of precision where the moment-to-moment activity of the instruction requires collections of data to inform its deci-

sions.

The field of the aviation-related simulations is perhaps the one area of CBI in which substantial data on the operating characteristics of a computer-based instruction system *have* been gathered. Extensive ergonomic studies have been conducted to determine the effects of session lengths, task demands, and simulator characteristics related to learning and learner performance. Many CBI designers find these studies to be tedious and detailed, and most CBI designers are not even aware of this body of literature. But the design of sophisticated aircraft simulation systems would be impossible without it.

As the amount and quality of the technological knowledge in other categories on Vincenti's list of knowledge types grows, the need for bodies of engineering data will become evident, and studies will gather the data that reveals the topology of human-CBI/WBI interactions over a wide range of variations, particularly in environment-based event structures. We will then see the appearance of the CBI designer's engineering fact and data book much as the early 20th century saw the publication by Carnegie Steel of a rudimentary but expanding (over the years) fact book for architectural designers on structural steel options (Misa, 1995). Designs can then be based on data rather than guesses and personal preferences.

Class: Practical considerations

In the *practical considerations* category of technological knowledge Vincenti places, "an array of less sharply defined considerations that frequently do not lend themselves to theorizing, tabulation, or programming into a computer" (p. 217). He continues, "such considerations are mostly learned upon the job rather than in school or from books; they tend to be carried around, sometimes more or less unconsciously, in designer's minds. Frequently they are hard to find written down" (p. 217). We can consider this class of knowledge as rules that designers have learned to follow—rightly or wrongly—from teachers, experience, books, peers, reverse engineering of other products, or from personal discovery.

Vincenti notes that this type of knowledge is pervasive not only in relation to design but in relation to production and operation of the technology as well. Williams (1991) provides an excellent (and rare) example of this sort of knowledge in the *Circuit Designer's Companion*. According to Williams his book is written "with the intention of bringing together and tying up some of the loose ends of analogue and digital circuit design, those parts that are never mentioned in the textbooks and rarely admitted elsewhere". (p. 1). Williams' book is filled with principles that describe a special class of knowledge that relates theoretical principles to real world application. If the book's content was condensed into simple statements, one might be: "Though the theory says *this*, in the real world

the fact of the matter is *that*, so you have to apply the following principle as a *remedy*." Another might be: "In real circuits there are <temperature, radiation, grounding, component variability, signal timing, etc.> effects, therefore you must apply the following principle to correct for that".

For example, Williams describes the practical implications of the aluminum chassis on circuit grounding:

"Aluminum is used throughout the electronics industry as a light, strong and highly conductive chassis material—only silver, copper and gold have a higher conductivity. You would expect an aluminum chassis to exhibit a decently low bulk resistance, and so it does and is very suitable as a conductive ground as a result. Unfortunately, another property of aluminum (which is useful in other contexts) is that it oxidizes very readily on its surface, to the extent that real-life samples of aluminum are covered by a thin surface film of aluminum oxide (Al_2O_3). Aluminum oxide is an insulator. In fact, it is such a good insulator that anodized aluminum, on which a thick coating of oxide is deliberately grown by chemical treatment, is used for insulating washers on heatsinks.

"The practical consequence of this quality of aluminum oxide is that the contact resistance of two sheets of aluminum joined together is unpredictably high. Actual electrical contact will only be made where the oxide film is breached. Therefore, whenever you want to maintain continuity through a chassis made of separate pieces of aluminum, you must ensure that the plates are tightly bonded together, preferably with welding or by fixings which incorporate shakeproof serrated washers to actively dig into the surface" (p. 6).

This example, picked because of its content familiarity to most readers is a relatively non-technical example: one of literally hundreds, many of which are expressed in mathematical terms. This type of knowledge comprises much of the so-called fuzzy logic that adds up to human judgment. In reality it is knowledge about the interface between the conceptual world of abstractions and the real world of materials and their articulations with each other.

In the absence of a mature CBI technology in which Vincenti's other categories of knowledge are more complete and disciplined, the practical considerations knowledge has become a kind of catch-all category. A CBI designer's product is often more a product of personal judgment, pattern following, and estimation using homely rules than anything. The relative emptiness of most of the other knowledge categories where CBI is concerned leads us to suspect that under present conditions much of CBI design takes place in the hands of a vast army of CBI and Web developers on the basis of homely rules rather than on the basis of

Careful, informed, measured engineering. For this reason, some rightly claim that CBI design (and instructional design in general) is an art as much as it is a craft or an engineering pursuit. The emergence of a mature technology for CBI will displace to a great extent designers' knowledge from this *practical considerations* category into the other categories we have been describing in this section. But as long as conceptual knowledge must be interfaced with real world materials and concrete artifacts, this category will still always hold some of the type of knowledge that Williams' book exemplifies.

Class: Design instrumentalities

In the class of *design instrumentalities* knowledge Vincenti includes knowledge to guide decisions regarding the design process itself. This includes an awareness by the designer of what to do, when to do it, how to do it, how to break roadblocks, what tools to use, and how to use them. Vincenti points out the importance of "ways of thinking", the paths of reasoning or mental processes that lead to useful design steps and designs. The method by which a designer does problem solving is an important body of knowledge.

How do designers create designs? How should they create designs? How do CBI designers work? What would be the benefit if designers were more aware of their design processes? To what extent have sequenced design models used extensively in instructional and CBI design in the past aided or retarded awareness of other design options and choice points? What are the alternative views of the design process?

There is an increasing interest in how designers create designs in many fields (Jones, 1980; Petroski, 1994; Winograd, 1996). Studies of the design inspired by interest in artificial intelligence are developing knowledge about design processes (see, Hinrichs, 1992). In addition, publications that report sociological studies of the design and technological evolution process are revealing how designers actually design as opposed to how textbooks have idealized the process (Bucciarelli, 1994; Kidder, 1981; Pool, 1997). Vincenti's book is an example of a study of technological knowledge-accumulating processes for aeronautical engineering. Design studies in all fields are broadening our view of how everyday human decision and action processes are technological in nature.

We should emphasize also in this class knowledge of *tools* and *tool principles* as they interface with and influence the design process. Tools are essential to the growth of a technology as amplifiers of force and information and strongly influence designs (Gibbons, Lawless, Anderson & Duffin, in press). Technology is an act of using tools for further tool-building, and productivity is the goal. Tools are of different kinds: (1) tools that support design of artifacts, (2) tools that support production of artifacts, and (3) tools used in research. Tools may be physical or

conceptual. The classes of knowledge described here constitute one set of tools technologists may use. Much research is needed to determine relative tool values and to identify tools for designers that will accelerate the testing and application of new technological principles and with more shallow learning curves, less attention to the demands of the tool itself, and increased productivity (see Gibbons & Fairweather, 2000).

Conclusion

Applying technology can be seen as a repeating cycle of steps that draw upon the classes of technological knowledge Vincenti describes:

1. Breaking a design goal into sub-goals
 - Requires intellectual concepts that describe artifacts and their qualities
2. Searching for alternative paths that lead to sub-goal satisfaction
 - Requires measures to identify intervention points
 - Requires operational principles/normal configurations to define intervention structures
 - Requires theories to define intervention actions
 - Requires specifications and standards to guide search
3. Judging among alternative paths and selection of one
 - Requires data to guide judgment and selection
4. Review of progress toward solution
 - Requires criteria against which to measure completion
5. Selection of a new goal or sub-goal

This extended description of technological knowledge categories from another design field is intended to help CBI/WBI designers and instructional design theorists in general to realize the nature of the diverse bodies of knowledge used by instructional designers. These knowledge categories suggest a set of tasks for CBI theorists, researchers, designers, and tool makers to improve the level and content of our discourse.

References

Advanced Distance Learning Initiative (n.d.). (www.adlnet.org).

Allen Communications (1994). *Designer's Edge* TM. Salt Lake City, UT.

Anderson, J. R. (1993). *Rules of the Mind*. Hillsdale, NJ: Lawrence Erlbaum Asso-

ciates.

- Association for Computing Machinery (1999). ACM Turing Award Presented to Jim Gray of Microsoft Research. *ACM Member Net* (Supplement to the Communications of the ACM), 42(6), June, 1999, pp. 1, 13-14.
- Bass, L., Clements, P. & Kazman, R. (1998). *Software Architecture in Practice*. Reading, MA: Addison-Wesley.
- Berliner, P. F. (1994). *Thinking in Jazz: The Infinite Art of Improvisation*. Chicago, IL: University of Chicago Press.
- Booch, G., Rumbaugh, J. & Jacobsen, I. (1999). *The Unified Modeling Language User Guide*. Reading, MA: Addison-Wesley.
- Bruner, J. S. (1964). *Toward A Theory of Instruction*. Cambridge, MA: Harvard University Press.
- Bucciarelli, L. L. (1994). *Designing Engineers*. Cambridge, MA: MIT Press.
- Butler, R. B. (1998). *Standard Handbook of Architectural Engineering*. New York: McGraw-Hill.
- Combs, H. (1979). *Kill Devil Hill: Discovering the Secrets of the Wright Brothers*. Englewood, CO: TernStyle Press, Ltd.
- Cook, D. A. (1997). Behavioral Analysis as a Basis for Instructional Design. In C. R. Dills and A. J. Romiszowski (Eds.), *Instructional Development Paradigms*. Englewood Cliffs, NJ: Educational Technology Publications.
- Crosby, A. W. (1997). *The Measure of Reality*. Cambridge, UK: Cambridge University Press.
- Eco, U. (1998). *Serendipities: Language and Lunacy*. New York: Orion.
- Educational Object Economy (n.d.). (eoe.org)
- Feynman, R. P. (1999). *The Pleasure of Finding Things Out*. Cambridge, MA: Helix Books.
- Garber, K. (2000). The Next Wave of the Genomics Business. *Technology Review*,

104(4), 47-56.

- Garfinkel, S. (1999). Genius Minus Perspiration. *Technology Review*, 102(5), 32-33.
- Gibbons, A. S., Bunderson, C. V., Olsen, J. B. & Robertson, J. (1995). Work Models: Still Beyond Instructional Objectives. *Machine-Mediated Learning*, 5(3&4), 221-236.
- Gibbons, A. S. & Fairweather, P. G. (2000). Computer-Based Instruction. In S. Tobias and J. D. Fletcher, *Training and Retraining: A Handbook for Business, Industry, Government, and Military*. New York: Macmillan Reference.
- Gibbons, A. S., Lawless, K., Anderson, T. A. & Duffin, J. R. (2000). The Web and Model-Centered Instruction. In B. Khan (Ed.), *Web-Based Training*. Englewood Cliffs, NJ: Educational Technology Publications.
- Gibbons, A.S., Nelson, J. & Richards, R. (1999). Model-Centered Analysis Process (MCAP): A Pre-Design Analysis Method Based on Theory and Derived Criteria. Center for Human-Systems Simulation Technical Report, Idaho Falls, ID, Idaho National Engineering and Environmental Laboratory, Summer,1999.
- Gibbons, A. S., Nelson, J. & Richards, R. (2000). The Nature and Origin of Instructional Objects. In D. Wiley (Ed.), *Instructional Objects*. Association for Educational Communications and Technology.
- Hannafin, M. J., Hannafin, K. M., Land, S. M. & Oliver, K. (1997). Grounded Practice and the Design of Constructivist Learning Environments. *Educational Technology Research and Development*, 45(3), 101-117.
- Hilgard, E. R. (1964). *Theories of Learning and Instruction: The Sixty Sixth Yearbook of the National Society for the Study of Education*. Chicago: University of Chicago Press.
- Hinrichs, T. R. (1992). *Problem Solving in Open Worlds: A Case Study in Design*. Hillsdale, NJ: Erlbaum.
- Hughes, T. P. (1983). *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore, MD: Johns Hopkins University Press.

- Hull, D. L. (1988). *Science As a Process: An Evolutionary Account of the Social and Conceptual Development of Science*. Chicago: University of Chicago Press.
- Instructional Management Systems Project (n.d.). (www.imsproject.org).
- Jones, J. C. (1980). *Design Methods (2nd ed.)*. New York: Van Nostrand Reinhold.
- Judson, H. F. (1987). *The Search for Solutions*. Baltimore, MD: Johns Hopkins Press.
- Kidder, T. (1981). *The Soul of a New Machine*. Boston: Little, Brown.
- Klir, G. J. (1969). *An approach to general systems theory*. New York: Van Nostrand Reinhold.
- Knowledge and Innovation Server™ (n.d.). Increase Engineering Productivity Through Access To Technocal Knowledge. (www.invention-machine.com/products/demo_knis/Dknis_1.htm)
- Knuth, D. E. (1996a). Von Neumann's First Computer Program. In D. E. Knuth, *Selected Papers on Computer Science*. Cambridge, UK: Cambridge University Press.
- Knuth, D. E. (1996b). Computer Science and Its Relation To Mathematics. In D. E. Knuth, *Selected Papers on Computer Science*. Cambridge, UK: Cambridge University Press.
- Kroes, P. (1992). On the Role of Designing in Engineering Theories: Pambour's Theory of the Steam Engine. In P. Kroes & M. Bakker (Eds.), *Technological Development and Science in the Industrial Age: New Perspectives in the Science-Technology Relationship*. Boston, MA: Kullwer Academic Publishers.
- Kuhn, T. S. (1970). *The Structure of Scientific Revolutions (2nd ed.)*. Chicago: University of Chicago Press.
- Kuhn, T. S. (1977). The Function of Measurement in Modern Physical Science. In T. S. Kuhn, *The Essential Tension: Selected Studies in Scientific Tradition and Change*. Chicago, IL: University of Chicago Press.

- Layton, Jr., E. T. (1992). Escape from the Jail of Shape: Dimensionality and Engineering Science. In P. Kroes & M. Bakker (Eds.), *Technological Development and Science in the Industrial Age: New Perspectives in the Science-Technology Relationship*. Boston, MA: Kullwer Academic Publishers.
- Liddle, D. (1996). Design of the Conceptual Model. In T. Winograd (Ed.), *Bringing Design to Software*. Reading, MA: Addison-Wesley.
- Merrill, M. D. (1994). *Instructional Design Theory*. Englewood Cliffs, NJ: Educational Technology Publications.
- Merrill, M. D. (1999). Instructional Transaction Theory (ITT): Instructional Design Based on Knowledge Objects. In C. M. Reigeluth (Ed.), *Instructional-Design Theories and Models, Vol. II: A New Paradigm of Instructional Theory*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Misa, T. J. (1995). *A Nation of Steel: The Making of Modern America, 1865-1925*. Baltimore, MD: Johns Hopkins University Press.
- Newell, A. & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Nuland, S. B. (1989). *Doctors: The Biography of Medicine*. New York: Vintage.
- Petroski, H. (1994). *The Evolution of Useful Things*. New York: Vintage.
- Petroski, H. (2000). Making Headlines. *American Scientist*, 88(3), 206-209.
- Pool, R. (1997). *Beyond Engineering: How Society Shapes Technology*. Oxford, UK: Oxford University Press.
- Reigeluth, C. M. (1983). *Instructional-Design Theories and Models: An Overview of Their Current Status*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Reigeluth, C. M. (1999a). The Elaboration Theory: Guidance for Scope and Sequence Decisions. In C. M. Reigeluth (Ed.) *Instructional-Design Theories and Models, Vol. II: A New Paradigm of Instructional Theory*. Mahwah, NJ: Lawrence Erlbaum Associates.

- Reigeluth, C. M. (1999b). *Instructional-Design Theories and Models, Vol. II: A New Paradigm of Instructional Theory*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Regian, J. W. & Fleming, J. (1999). DATAGUIDES (Deployable Agents for Training, Aiding, and Guidance). In A. K. Noor, *Advanced Training Technology and Learning Environments (NASA/CP-1999-209339)*, Hampton, VA: NASA Langley Research Center.
- Rheinberger, H. (1997). *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube*. Stanford, CA: Stanford University Press.
- Richey, R. (1998). The Pursuit of Usable Knowledge in Instructional Technology. *Educational Technology Research and Development*, 46(4), 7-22.
- Robbins, E. (1994). *Why Architects Draw*. Cambridge, MA: MIT Press.
- Salvadori, M. (1980). *Why Buildings Stand Up*. New York: W. W. Norton.
- Schank, R. C. (1998). *Inside Multi-Media Case Based Instruction*. Mahwah, NJ: Erlbaum.
- Schrage, M. (2000). *Serious Play: How the World's Best Companies Simulate to Innovate*. Boston, MA: Harvard Business School Press.
- Seels, B. B. & Richey, R. C. (1994). *Instructional Technology: The Definition and Domains of the Field*. Washington, D.C.: Association for Educational Communications and Technology.
- Sethi, R. (1996). *Programming Languages: Concepts and Structures* (2nd ed.). Reading, MA: Addison-Wesley.
- Simon, H. A. (1969). *Sciences of the Artificial, (2nd ed.)*. Cambridge, MA: MIT Press.
- Smith, H. C. (1992). *The Illustrated Guide to Aerodynamics* (2nd Edition). New York: Tab Books/McGraw-Hill.
- Tinder, R. F. (2000). *Engineering Digital Design* (2nd ed.). San Diego, CA: Academic Press.

- Towne, D. M. (1999). Generating and Delivering Diagnostic Instruction. In A. K. Noor, *Advanced Training Technology and Learning Environments (NASA/CP-1999-209339)*, Hampton, VA: NASA Langley Research Center.
- Vincenti, W. G. (1990). *What Engineers Know and How They Know It: Analytical Studies From Aeronautical History*. Baltimore: Johns Hopkins University Press.
- Wailoo, K. (1997). *Drawing Blood: Technology and Disease Identity in Twentieth Century America*. Baltimore: Johns Hopkins University Press.
- Wenger, E. (1987). *Artificial Intelligence and Tutoring Systems: Computational and Cognitive Approaches to the Communication of Knowledge*. Los Altos, CA: Morgan Kaufman.
- Wiley, D. (2000). *The Instructional Use of Learning Objects*. Bloomington, IN: Association for Educational Communications and Technology. (<http://wiley.ed.usu.edu/book/>)
- Williams, T. (1991). *The Circuit Designer's Companion*. Oxford, UK: Newnes.
- Winograd, T. (1996). *Bringing Design to Software*. Reading, MA: Addison-Wesley.
- Ziman, J., 1978, *Reliable Knowledge*. Cambridge, UK: Cambridge University Press.