CHAPTER 11

Design-Based Biotechnological Learning

Distinct Knowledge Forms Supporting Technology and Science Conceptual Understanding

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1 Introduction

> The information given in such a process [education] is meant to be absorbed into the life of the mind itself, and a boy leaving school with a memory full of facts is thereby no more educated than one who leaves table with his hands full of food is thereby fed. (Collingwood, 1924, p. 316)

In his characterization of concepts, Collingwood claims that they "… are not things lying about in the world, ready-made, like blackberries, for some sedulous *micher* to find; they are things that man makes … by an act of practical thinking" (1942, p. 48, para. 7.22). The context of conceptual learning as presented in this chapter reflects the act of practical thinking in which students will engage through technological and engineering design based learning (T/E DBL), and specifically technology and science concepts addressed in design based biotechnical learning (DBBL). Furthermore, as a mode of learning, T/E DBL is naturally integrative where science, technology, engineering, and mathematics (STEM) are utilized in a transdisciplinary manner during the co-occurrence of disciplinary practices selectively employed by the learner while they are engaged in the design of a technological solution.

The specific T/E DBL focus in this chapter centers on the conceptual learning that occurs when students engage in the design of biotechnical systems. Design Based Biotechnical Learning (DBBL) is a scenario-based instructional strategy that situates the learner in an overt need for using both biological and technological knowledge to arrive at a plausible artifact proposal (design solution). Biotechnical design scenarios immerse students in authentic Problem Scenarios (ProbScens) designed in a manner that ensures continuity of learning across sequenced experiences, where each experience provides the conceptual understandings necessary for successful engagement in subsequent experiences (Dewey, 1938, p. 27). Dewey's principle of continuity serves as a basic pedagogical tenant of DBBL and is essential to designing instruction

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that achieves targeted design based conceptual learning outcomes. It is the intentional connecting of content, concepts, and practices across sequenced designerly learning experiences that develops in learners the critical thinking habit of mind required in the design of biotechnical systems. Set within this instructional framework, the goal of this chapter is to explicate the designerly approach to technology and science conceptual learning that students encounter through DBBL and demonstrate the ways in which it leads to their recognition and adoption of a new and distinct way of coming to know – a designerly way of learning. The two main constructs around which the chapter is organized are: (1) design as a unique knowledge form, and (2) conceptual understanding achieved through design based biotechnical learning. As a prelude to knowledge forms and conceptual learning in DBBL, the chapter opens with a discussion of the goal of education and the underlying premise of learning within that goal.

2 Education Writ Large

Schooling has as its overarching goal the preparation of individuals who possess general literacy across a broad range of disciplines. Specifically, general literacy in the humanities (reading, writing, history, arts, etc.), maths (arithmetic, geometry, algebra, etc.), sciences (biology, physics, chemistry, etc.), and technologies (physical, biological, informational). Achieving such general literacy includes acquiring a basic level of knowledge (content, conceptual, practice) in each discipline, where "integration toward a discrete area of knowing has as its ultimate aim the educational objective of enhancing the individual's capacity to function in his environment in the broadest sense" (Fox, 1981, p. 38). The outcome of schooling is therefore intended to result in individuals capable, at a minimum, of utilizing their acquired knowledge in addressing the problems they are confronted with in everyday life. However, evidence indicates that schooling is not adequately preparing individuals with such sufficient levels of general literacy. National and international efforts to counter this issue have resulted in major revisions of education standards across the STEM (science, technology, engineering, mathematics) disciplines, along with promoting fundamental changes to schooling that challenge long-held pedagogical paradigms. These changes are evidenced in the growing global emphasis on K-12 STEM education and the wholesale attempt to provoke what is perceived as a new pedagogical paradigm in schooling – one where integrative technological/engineering design based learning (T/E DBL) and the centrality of

question-posing plays an increasingly prominent role in the education of all students.

3 Historical

The focus on STEM education today is not new – it is only newly important. This is equally true for using integrative, T/E DBL approaches when teaching STEM disciplines – it is not new. This approach can be traced back more than two thousand years to the early philosophers Socrates, Plato, and Aristotle (Frankena, 1965). To this day the Socratic method, developed in the latter half of the 5th century BC, remains a common pedagogical strategy in education where questioning is employed as an instructional tool for prompting learner use of conceptual knowledge in route to development of deeper understanding. Plato championed the question-posing pedagogy of his mentor Socrates by using it to prepare students enrolled in his Academy, considered the first institution of higher education in the Western world. Aristotle, a graduate of the Academy, later extended the questioning strategies of his predecessors by challenging students to go beyond merely conveying conceptual knowledge. Aristotle recognized students developed their conceptual capacity, their habits-of-mind, best through completion of projects where the mind would be informed by the hand as a direct result of engagement in authentic, concrete experiences (Frankena, 1965). Developing the mind through experiences of the hand thus became a graduation requirement whereby students demonstrated the extent to which they had gained deep conceptual understanding of a subject. Engaging learners today in T/E DBL has the same goal of using concrete experiences of the hand to develop the mental capacity of the mind.

These early philosophers, like many of their counterparts today, were mathematicians, scientists, and inventors who recognized that in order to acquire and truly understand both conceptual and practical forms of STEM knowledge, they must be experienced in authentically integrative ways. Contemporary European pedagogues such as Pestalozzi and Froebel, and their Western counterparts such as Parker and Dewey continued promotion of this learning philosophy, which today can be recognized as the pedagogical foundation underpinning technology and engineering education (Herschbach, 2009). Of significance to the integrative, designerly pedagogy followed by these early educators is adherence to a transdisciplinary approach to learning where contrived disciplinary boundaries do not exist. Conversely, schooling today, unlike its earlier predecessor, is charged with preparing the masses, which

has resulted in an evolution in education toward an efficiency model of siloed mono-disciplinary teaching.

4 Contemporary

Globally throughout the past century, real and/or perceived threats to national competitiveness and security were driving forces behind major educational reform movements. Although these threats were outside of education, providing solutions was placed on the shoulders of schooling. Reacting to the lack of general literacy in science, mathematics, and technology (SMT) in the late 1980s, education revised disciplinary standards to teach these subjects using an integrative SMT approach. Many countries recognized this was an opportunity to reorganize their technology education/design standards to achieve parity with the core subjects and to teach cross disciplinary concepts such as scientific inquiry through design based learning (National Research Council, 1996; Cross, 1980, p. 202). The "E" gained a position in the late 1990s when the National Science Foundation introduced STEM as the acronym representing science, technology, engineering, and mathematics. Their intent was to promote STEM as a concept for transdisciplinary approaches to teaching and learning. As an educational reform movement, the concept of STEM education was meant to usurp the traditional siloed disciplinary approach with one that immersed students in educational experiences where STEM disciplines were naturally integrated within authentic, relevant learning scenarios. On a global scale arguably the most impactful result of STEM education reform within schooling has been the growing recognition that T/E DBL is a pedagogy that inherently promotes conceptual knowledge acquisition across disciplines and questioning in all phases of design which naturally imposes the need for higher order thinking skills.

Internationally, technology programs (Design & Technology, Technology Education, Technology and Engineering Education, etc.) have for several decades been focused on preparing learners to be technologically literate. Beginning in the 1980s parallels in program development among countries is recognized in their common increased emphasis on design based learning and concerted efforts to focus more on teaching conceptual knowledge (knowing) rather than the traditional practice knowledge (doing) (Cross, 1980; Savage & Sterry, 1990; AAAS/SfAA, 1989; ITEA, 1996). Working to remain aligned with other core school subjects, design based learning programs organized themselves similar to the way other general education subjects were teaching core concepts and methods of inquiry. Likewise, core subjects, specifically science,

began incorporating technology education into their programs and using design based learning as a pedagogical strategy to improve the teaching and learning of their respective disciplinary content (National Research Council, 1996).

Technological literacy includes understanding science in the same way that science literacy includes understanding technology. The close relationship between these two disciplines is significant as a potential alliance for promoting reciprocative literacy development. The newly revised U.S. K-12 science education standards (NGSS Lead States, 2013) intentionally capitalized on this relationship by overtly incorporating two specific engineering practices (#1 defining problems and #6 designing solutions) as part of the eight practices to be learned in science. Inclusion of engineering practices was an explicit attempt at improving the "doing" of science that was missing in the 1996 version (National Research Council, 1996). The previous standards were intent on having students learn how to "do" inquiry, but classroom instruction instead focused on teaching the procedures followed in the scientific method for setting up experimental investigations. Including engineering practices in the 2013 Next Generation Science Standards (NGSS) was a strategy to more directly address the practice (doing) of scientific inquiry. Implied is the belief by the science education community that design (T/E) will improve both the teaching and learning of science concepts and practices.

Although well intended, embedding engineering design as a means of improving the teaching and learning of science is to a large extent more of the same – a continued promotion of the scientific method supported now through engineering activities. The NGSS are clear in stating they do not teach engineering design, nor do they acknowledge design based learning as a fundamentally different means of knowledge acquisition. However, the growing body of evidence indicates knowledge acquisition through T/E DBL is a profoundly different way of learning, of coming to know, and one which imposes markedly different cognitive demands on learners. For example, designerly ways of learning inherently present learners with the need for synthesizing disciplinary knowledge and the necessity of critical thinking skills for sense-making prior to design decision-making. The distinction between disciplinary ways of knowing resides in the forms of disciplinary knowledge acquired, the language of those disciplines, and how understanding (learning) is communicated through that language. The form of knowledge acquired and graphical language used in T/E DBL promotes different cognitive processes and requires different abilities on the part of the learner. These characteristics set T/E DBL firmly apart from other disciplines in its unique knowledge form which Hirst (1967) theorized is that "distinctive way through which our

material world experiences become structured and communicated by use of accepted public symbols".

Schooling is the means through which literate populations are prepared. Furthermore, literacies developed in the humanities, sciences, maths, and technologies all reflect different forms of knowledge, each with a distinct way of coming to know, inclusive of a language unique unto that knowledge form. The close alliance between technology and science inherent to T/E DBL, as well as their distinctly different forms of knowledge, languages and methods of learning, is important for technology and/or science educators to understand when preparing and implementing design based learning instruction. These educators should recognize that effective T/E DBL instruction "must be designed to enhance and to develop students' intrinsic cognitive processes and abilities" (Cross, 1982, p. 222). Such instruction will take into account that a student's ability to demonstrate different forms of acquired knowledge (e.g. technology and science) is largely dependent on the various disciplinary languages they can employ when conveying their knowledge. Specifically, the forms of knowledge and respective disciplinary languages acquired through T/E DBL broadens a student's ability to both communicate their cognitive (inner) thoughts and convey their level of conceptual understanding to others. Given both technology and science are utilized extensively in T/E DBL, and that their forms of knowledge call for distinctly different modes of information processing (Gagné, Wagner, Golas, & Keller, 2004), further discussion of knowledge, its forms, language, and modes of learning is warranted.

5 Knowledge: Forms, Language, and Learning

5.1 *Forms*

Preparing literate populations views liberal education as an initiation into what are seen as seven distinct forms of knowledge: human science, mathematics, physical science, history, literature (fine arts), religion, and philosophy (Hirst, 1965, p. 131). Hirst posits a distinct knowledge forms meets the following criteria: (1) a set of concepts central to the form; (2) a distinctive logical structure; (3) a set of distinctive expressions, testable against experience in a way that provides particular truth criteria; and (4) particular techniques and skills for exploring experience, which give the form its distinctive method. In his seminal essay *Liberal Education and the Nature of Knowledge* (1965), Hirst characterized a discrete form of knowledge as one reflecting a distinctive way through which our material world experiences become structured and are then communicated using accepted public symbols. Furthermore, different

from a discipline which represents an organized field of knowledge, a form of knowledge embodies a unique class of propositions that when tested present a coherent class distinct from others, regardless of whether they are elementary (practical) or technical knowledge. Simply stated, the various forms of knowledge afford the individual characteristically unique ways in which to structure and understand their world experiences.

It has long been argued (Fox, 1981) that T/E DBL is a distinct mode of knowing and thinking associated with and driven by the action-based (minds-on, hands-on) designerly way of knowing which functions parallel to and in support of the other discrete forms of knowledge as posited by Hirst. Specifically, designerly knowing and thinking are recognized constituents of a knowledge form unique to T/E DBL, with its own distinct language and thought-structuring tools used in organizing material world experiences and culminating in the generation of new understandings within the knowledge domains inherent to the designed solution. The language used to communicate within a given knowledge form therefore serves as a unique currency for cognitive reflection and thought-structuring within that form, which in T/E DBL constitutes a discrete pathway for coming to know – the designerly way of knowing.

5.2 *Design Language*

Learning theorists such as Bruner (1966) recognized there were other language norms/symbol systems beyond verbal language that were used as tools for structuring an individual's reality. Furthermore, in referring to the mechanisms by which the human mind used symbolry to organize the various inchoate manifestations of experience into a functional vernacular, Bantock (1967) acknowledged this as a capacity affording humans the ability to develop multiple modes of symbolic language for use in communicating their inner (cognitive) concepts of the world. Likewise, De Bono (1967) theorized that this multitude of symbolic systems was necessary in order for the human to move beyond, or not be restricted by, only a verbal-based language system and therefore possessing latitude in their cognitive function concurrent with developing psychological breadth. At the risk of over compression, it is reasonable to assert that the literature surrounding language development supports the view that the language of T/E DBL serves as a medium for both thinking (cognition) and expression of thought (artifact proposal). Moreover, one where the symbolry of design based learning is the conceptual language used in sense making, understanding, and communicating one's designerly experiences.

The ability to examine an inner idea or concept outside of the mind in some tangible form that is communicable to another individual is by its very nature the designerly process through which we develop greater understanding.

Moreover, a designerly approach to knowledge acquisition necessitates synthesis of information accompanied by the capacity to utilize the cognitive processes of symbolic representation through which understanding is achieved. In the context of T/E DBL, this cognitive interplay between mental and symbolic representation actually requires the use of languages across multiple knowledge forms, humanities and physical sciences in particular, to both conceive of and to then communicate plausible design solutions (artifact proposals). The practical nature of designing artifact proposals often approaches the solving of problems using prototypes as concrete elements of possible solutions. To the uninformed, this outward manifestation of the cognitive processes used in generating the concrete prototype might lead to the naïve assumption that only lower order thinking was required to do so. This naïve perspective might then lead to the misperception that all practical, action-based problem solving is relegated to lower levels of thinking (procedural and declarative). To the contrary, unlike other methods of learning T/E DBL naturally imposes on the learner a full spectrum of cognitive demands, from concrete to abstract, and requires them to communicate that thinking largely through the symbolry of design knowledge (the language of sketches, drawings, diagrams, etc.) which in and of itself reflects the learner's level of conceptual understanding. The symbolry of T/E DBL are designerly tools for communicating information not feasible through verbal, written, or numerical languages alone. The designerly mode of knowledge acquisition calls for synthesis and true integration of all disciplines involved in producing artifact proposals, and for "extending learning in several forms of knowledge" (Fox, 1981, p. 35). Adhering to Hirst's theory on knowledge forms, demonstration of learning (knowledge acquired) would then constitute the individual's ability to structure and communicate their understanding of the knowledge acquired using accepted public symbols unique unto a given form.

5.3 *Design Learning*

The languages (symbolry) of the various knowledge forms provide the cognitive scaffolding necessary for learning and meaning making to occur. In his scientific account of learning by the individual, Pea (2004) proposes there are two primary axes around which to organize the theoretical perspectives on the scaffolding processes of learning: social (natural) and technological (artificial). The social axis involves the socially interactive responsiveness of the learner contingent on their needs, which provides them with the resources enabling them "to do more than he or she alone" (p. 429). This closely aligns with the works of Vygotsky (1978) regarding the social foundations of an individual's higher mental function, specifically the zone of proximal development (ZPD),

as the mechanism whereby critical thinking is developed in the individual via another more capable individual; i.e., "... problem solving under adult guidance or in collaboration with more able peers" (p. 86). Scaffolding along the technological axis focuses on learning that occurs during the design of artifacts (Pea, 2004), which Vygotsky contends provides the artificial (technological) interactive responsiveness as the equally necessary counterpart to the natural (social) interactive responsiveness that are collectively required for human development. "Humankind is reshaped through the dialectic, or 'conversation' of reciprocal influences. Our productive activities change the world, thereby changing the ways in which the world changes us" (Pea, 1987, p. 93). Pea contend it is within these two axes that the majority of theoretical and research contributions have been made toward human learning and education. With respect to design based learning, such contributions substantiate cognitive functional accounts afforded by the symbolry language of design (technological and/or engineering) for enculturating the learner in a unique mode of thinking, learning, and coming to know about their material world experiences.

Recognizing technological/engineering design as a discrete knowledge form, with its own distinct mode of learning, is critical for those preparing instruction that intentionally scaffolds learning across all inherent knowledge forms. Within the pedagogical context of T/E DBL, an investigation of scaffolding by Puntambekar and Kolodner (2005) focused on learning through the lens of the scientific method. Their research was intended to better "understand the kinds of support that students need to learn science successfully from design activities" (p. 185). The underlying assumption was that the designerly way of knowing was the same, or equated to, the scientific way of knowing. This perspective views the design component as providing the scaffolding needed only to better learn the targeted science. Not focused on is design as its own distinct form of knowledge for learning targeted technology and engineering concepts, inclusive of the unique cognitive demands this approach to knowledge acquisition imposes on the learner when confronted by the need-to-know during artifact proposal creation. Throughout the phases of design, designerly questions associated with an ongoing need-to-know obligates the learner to draw on their resident knowledge (convergent thinking), prompting them to envision beyond what they currently know (divergent thinking) working within a set of criteria/parameters/constraints. This oscillation in thinking culminates in a synthesis of what they have come to know in order to generate a plausible and satisficing way forward (Wells, 2016b). Educationally, this results in learners possessing an increased understanding regarding the targeted conceptual outcomes for the instructional task at hand; i.e., learning the technological,

scientific, or mathematic concepts and practices as they co-occur during the design task.

In this section the case was made for establishing design, specifically technological and engineering, as a discrete knowledge form. It meets the four criteria of a form set forth by Hirst, utilizing a symbolry language exclusive to design, and immersing learners in the design method of knowledge acquisition as a patently unique way of coming to know. Furthermore, the distinctions between knowledge forms provides the pedagogical premise for using T/E DBL to teach both technology and science concepts while adhering to their respective knowledge forms, which is critical for maintaining fidelity of disciplinary practice. However, ensuring educator recognition of the distinctions between technology and science knowledge forms, their explicit differences in methods of knowledge acquisition, is essential for designing instruction that appropriately considers targeted technology and science conceptual outcomes during the co-occurrence of knowledge forms.

5.4 *Co-Occurrence of Technology and Science Knowledge Forms*

In 21st century K-12 schooling, the two disciplines arguably most prominent in leading STEM education reform are science and technology, with the former largely capitalizing on the disciplinary practices of the latter. The reason science exploits design (technological/engineering) lies in the fundamental differences between their disciplinary knowledge forms, methods of knowledge acquisition, and targeted learning outcomes. Science education deems science to be "the pursuit of explanations of the natural world, and technology and engineering [design] are means of accommodating human needs, intellectual curiosity and aspirations" (NGSS, 2013, appendix H, p. 2). Too often the scientific method (practice) is equated to the design method and suggesting that both could be seen as the "product of common core cognitive process and management of pragmatic complicating conditions" (Ferrell & Hooker, 2013, p. 701). This perception implies the methods followed in both science and design require the same core cognitive processes and that they both approach the management of complicating conditions in a similarly pragmatic way. Galle and Kroes (2014) however provide a convincing argument that such is not the case, making clear that both science and design are socially institutionalized disciplines, wherein scientists and designers respectively are socially institutionalized practitioners, and whose disciplinary practices reflect different kinds of intelligent action resulting in uniquely different outcomes (products).

Science can be defined as "the kind of intelligent action that consists of forming a novel, non-trivial, and well-supported belief about some part of the world (e.g., natural, artificial, social), for the purpose of better understanding

[that world]", where novel refers to the "discovery of new facts, predictions, explanations of facts" (Galle & Kroes, 2014, p. 220). The scientific method of learning is focused on discovering rules to follow, and where the outcome is theory generation as an expression of a held belief (hypothesis as the cognitive artifact). The outcome (product) is thus the expression of the belief formed, where such action is referred to as scientific theory generation, and which in science education equates to hypothesis testing. In contrast, an artifact proposal (design solution) would be an outcome reflecting the intelligent action called design (Galle & Kroes, 2014), where the product (artifact) may be, as Hilpinen defines it (Stanford online, 2011) "... an object that has intentionally been made or produced for a certain purpose" and which may include both material entities and non-material entities (such as pieces of music or organizations), but they are NOT mental states such as ideas which we do not make or produce.

An idea *expressed* as a product with purpose, concrete or abstract, is what *becomes* an artifact. One does not "make" a theory in the design sense of making a tangible/practical artifact. Given a science theory is not a tangible artifact (considered an abstract, conceptual artifact), it therefore does not fit the definition of design (or design proposal) given it is not something made, but rather conceived of. Furthermore, in the case when the scientist engages in design (e.g., designing measurement instruments) they are engaging in an instance of intelligent design action which is ascribed exclusively to design, and more specifically the preparation of an artifact proposal. The artifact proposal is primarily a product reflective of design symbolry language, and as such can be seen as having characteristics in common with cognitive artifacts as produced in science. However, the outcomes (that which is produced) of artifact proposals and scientific theory are fundamentally different. The distinctions being that a science "theory is a *cognitive-descriptive* artefact, whereas an artefact proposal is a *practical-descriptive* artefact" (Galle & Kroes, 2014, p. 223). During technology/engineering (T/E) DBL when design (T/E) and science intelligent actions are co-occurring, cognitive-descriptive and practical-descriptive artifacts are both typical culminating learning co-outcomes. Moreover, achieving each learning outcome requires a distinctly different kind of intelligent action resulting in unique ways in which an individual comes to know something, both conceptually and pragmatically. Furthermore, such differing intelligent actions often take place while engaged in other actions, as is the case when the student designer uses scientific methods (data collection, analysis, etc.) for investigating different material properties to determine which material best meets the design requirements of function, behavior, or structure. This is characteristic of an instance of co-occurrence of disciplinary practices (Galle &

Kroes, 2014) where design action is at times a necessary precursor to science action, the same as science actions at times are necessary to support design action needs. These combinations of intelligent actions are viewed as either "design in a science context" (need a widget to measure, test, manipulate something, etc.) or "science in a design context" (need byproducts from the bioconversion of dextrose) where the overall desired outcomes in each approach are different. Effective T/E DBL instruction will account for both contexts, design and science, to intentionally capitalize on the co-occurrence of different kinds of intelligent action, as well as anticipate instances where there is pure design or pure science action (no co-occurrence). Of particular importance for educators is recognizing design as a unique knowledge form that engages learners in a design method of learning where the co-occurrence of practices, content, and concepts of both design (technology/engineering) and science is an inherent characteristic of the type of problem solving leaners engage in through design based learning.

6 Design to Understand: Pedagogical Paradigm Shift

Pedagogically, regardless of subject, the fundamental goal of teaching is learning that leads to deep understanding. Core subjects such as science and mathematics have long enjoyed being broadly valued for their teaching of conceptual understanding. In contrast, the field of technology education (TE, TEE, D&T, etc.) has historically focused almost exclusively on promoting the value of its practices (making, doing). Much less attention has been given to the value of design (T/E) based learning for its unique way of coming to know requiring synthesis and higher order thinking that guides learners in achieving conceptual understanding. As a unique designerly way of both pragmatically and cognitively coming to know, the T/E DBL approach to learning facilitates the development of conceptual understanding largely through pattern synthesis – an ability to synthesize patterns recognized among STEM disciplines and utilizing the resulting transdisciplinary understanding for design decision-making. As espoused by Cross some decades ago, the field of technology education must take ownership and justify that design is an established knowledge form with a unique designerly way of knowing. One that develops in learners "a wide range of abilities in nonverbal thought and communication," promotes their "cognitive development in the concrete iconic modes of cognition," and cultivates their "innate abilities in solving real-world, ill-defined problems" (Cross, 1982, p. 226). Traditionally, K-12 schooling has promoted literacy development through the two education areas of the humanities and sciences both

reflecting discrete knowledge forms (Hirst, 1965). Each knowledge form has its own method for learning which employs a unique grouping of intelligent actions that learners are to use as a heuristic to guide their knowledge acquisition. The Knowledge Acquisition Heuristic (KAH) taught to learners in the humanities is a group of intelligent actions they will employ when engaging in the interpretive, hermeneutic method, and in the sciences, are those intelligent actions learners will know to employ when engaged in the scientific method. The escalation of STEM education reform over the past several decades has given rise to design, technological and engineering specifically, as a third area of education literacy and promoting design as a knowledge form, inclusive of its own distinct knowledge acquisition heuristic. In T/E design, where the primary educational goal is now one that has learners design to achieve understanding, the KAH is that group of intelligent actions learners will know to employ when engaged in the design method.

Accepting design as a distinct knowledge form calls for a paradigm shift that recognizes understanding to be the primary learning outcome of design where solving ill-structured design problems, tame or wicked, is the pedagogical framework within which learners design to understand (Wells, 2016a). A logical step toward this acceptance entails a pedagogical paradigm shift to (a) recognize design as a unique knowledge form, (b) distinguish problem solving in science from that in design (T/E), (c) intentionally teach, with disciplinary fidelity, inherent co-occurring disciplinary concepts, and (d) unpack the instructional strategies used in guiding learners through phases of design toward conceptual understanding. Biotechnology is a content area within the field of technology education that is well suited for explicating the elements of just such a pedagogical paradigm shift where conceptual understanding is the primary learning outcome of design.

6.1 *Biotechnology in Technology Education*

The fundamental goal of curricula covered in Technology Education (TE) is the preparation of learners who are technologically literate. There is general recognition in standards addressing technological literacy across multiple countries (US, UK, AU, NZ, KO, etc.) that all technological activity can be seen as occurring within three mutually interdependent contexts: physical, informational, and biological (ITEA, 1996). The content and practices of the physical and informational contexts are those with which the field has historically been most familiar, and therefore almost exclusively those addressed in the classroom through technology education curricula. As a result, integration of other disciplines such as science and mathematics as advocated for today within STEM education reform occurs largely through only the physical and

informational contexts. Thus, learners engaged in T/E DBL come to view integration from a narrowed disciplinary perspective, thereby limiting their range of experiences and potential gains in conceptual understanding of STEM connections. Design Based Biotechnical Learning (DBBL) incorporates all three technological contexts and provides learners with experiences that allow them to recognize and use a much broader and more complete spectrum of conceptual connections among the STEM disciplines.

Technology taught within the biological context has, for several decades been addressed by many countries through the incorporation of biotechnology into their national standards and curricula (Australian Education Council, 1994; Ministry of Education (NZ), 1994; Jones, 1997; Smith, 1988; ITEA, 2000; Korean Institute of Curriculum and Instruction, 2002; Ferguson, 2009). Curricula in all these countries similarly define biotechnology as "any technique that uses living organisms, or parts of organisms, to make or modify products, improve plants or animals, or to develop microorganisms for specific purposes" (OTA, 1984; FCCSET, 1993; Wells, 1994; ITEA, 2000). In this definition *any technique* refers to the breadth of micro/macro practices involved in biotechnical processes, *uses living organisms or parts of organisms* emphasizes the requirement that an entire organism or some part of it must be used, and *make or modify* characterizes biotechnology as a tool utilized within the context of human technological endeavors (Wells, 1996). Operationally, biotechnical systems are therefore those where biological components are used symbiotically with technological components. Pedagogically, educators must therefore recognize that in addition to those concepts addressed in the physical and informational technologies, the problems uniquely encountered in the design of biotechnical systems will impose on learners the need to grasp additional concepts associated with the biological sciences (plant, animal, microbial, biochemical, etc.).

In a Design Based Biotechnical Learning™ (DBBL) approach, distinct disciplinary concepts arise when students engage in discrete science and design (T/E) problems inherent to the co-occurrence of design and science intelligent actions. Specifically, pedagogies that take into account the co-occurrence of design and science intelligent actions during design based learning bring to light critical distinctions in the types of intellectual and cognitive demands imposed on learners engaged in generating solutions to designerly problems. Design and science are both processes that involve reasoning, deductive and abductive respectively, and the ways in which practitioners in these fields come to terms with specific disciplinary challenges confronting them are referred to as design or science problems. The fundamental distinction between scientific and design problems centers on the disciplinary nature of those problem

types, each of which imposes different intellectual and cognitive demands. Science is a mind-to-world fit (addressing a perceived misfit between how we are conceiving the world and the world as it truly is), whereas design is a world-to-mind fit (attempting to mold or modify the world to our conceptual view of it through artifact proposals). For example, science is characterized as analytical, deductive, and singularly focused on a specific outcome. Science problems call for convergent thinking, with the collection and analysis of data performed to establish a truth regarding a natural phenomenon. In contrast, design is characterized as constructive, and creates new knowledge and conceptual understandings resulting from the cognitive demands imposed by the design of a plausible, satisficing solution. Design problems call for the synthesis of information and the need to go beyond convergent thinking [what I know] to employ divergent thinking [what I need to know] in order to create that which does not yet exist. Design and science both depend on learners/practitioners having an operating level of content knowledge, which precedes the ability for divergent thinking. However, as Galle and Kroes (2014) aptly point out, "Despite whatever superficial similarities there may be between the symbolic artefacts produced by scientists and by designers, there is one all-important difference that sets them apart: scientists concern themselves with what exists, designers with what does not exist" (p. 224). To teach science and design (T/E) content, practices, and concepts intentionally, the DBBL pedagogy fully embraces this difference by capitalizing on the natural co-occurrence of design and science problems that impose on learners the need to employ discrete design Knowledge Acquisition Heuristics (KAH) and associated intelligent actions reflective of STEM disciplinary practices.

6.2 *Design Based Biotechnical Learning*

As the name implies, Design Based Biotechnical Learning™ (DBBL) is used for teaching content, practice, and concepts inherent to and imposed by the design of a biotechnical system. Specifically, as a pedagogical approach, DBBL is intent on engaging students in T/E design as a means through which they achieve deep understanding of targeted technology and science concepts – students design to understand. Ensuring engagement with the targeted concepts calls for instructional strategies that will intentionally present students with the need-to-know those concepts throughout the various phases of T/E design. As a pedagogical framework, the PIRPOSAL model (Wells, 2016b) (Figure 11.1) presents T/E design as phases of engagement through which a student progresses when responding to a design challenge. This pedagogical model depicts the intelligent actions of T/E designers and represents the unique Knowledge Acquisition Heuristic (KAH) they use in thinking and working

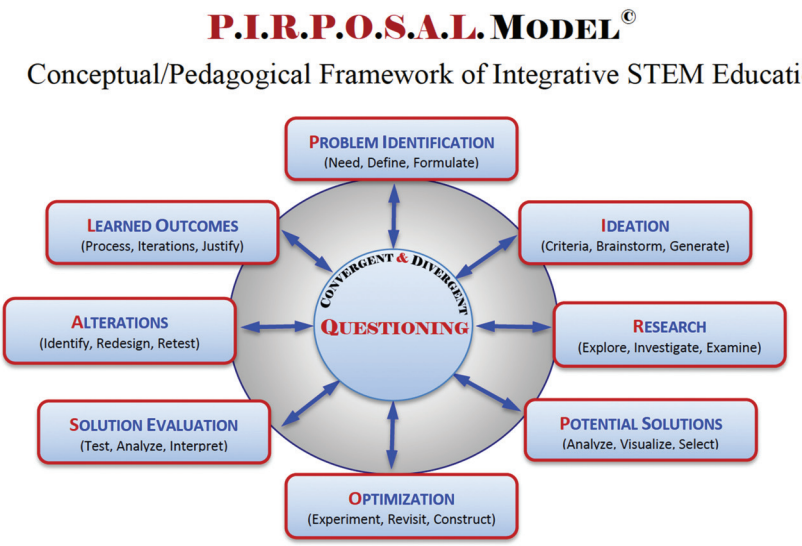

FIGURE 11.1 PIRPOSAL pedagogical model (from Wells, 2015)

toward an acceptable design solution. In T/E design, a KAH is not a series of steps one follows. Instead, it is a grouping of intelligent actions one employs as a heuristic for responding to design problems. The PIRPOSAL model recognizes the centrality of questioning for imposing on learners the full spectrum of cognitive demands (declarative, procedural, schematic, strategic) while engaged in T/E design, biotechnical or otherwise. Pedagogically, what is driving achievement of targeted learning outcomes (pragmatic and conceptual understanding) is the learner's need-to-know when confronted by questions within any given phase of design. The well-informed educator capitalizes on these cognitive demands in developing their instructional strategies to guide student learning within each phase of design with the intent of promoting them as the KAH they would use when later confronted with novel design challenges. Learners engaged in previous DBBL efficacy studies (Wells, 2016a) evidenced significant gains in conceptual understanding through engagement in DBBL Problem Scenarios requiring the designerly approach to knowledge acquisition.

Problem Scenarios (ProbScens) are biotechnical design challenges organized around eight biotechnology knowledge areas (Wells, 1994) and which comprise the units in the DBBL Teaching Guide (Wells, 2019). ProbScens present learners with open-ended, ill-defined, ill-structured, tame and wicked design problems requiring biotechnical solutions to meet human needs. Biotechnical systems are typically those designed to meet human, social needs. The context for all Problem Scenarios is therefore design that focuses on a

human, social need and avoids the perception that the challenge is an activity focused only on individual or personal needs. The human need serves as the underlying context and rationale driving the design challenge and requires the construction of a working biotechnical prototype as a proof of concept (artifact proposal). The requirement to make a working prototype for the expressed purpose of addressing a human need provides the authentic relevance that motivates students to learn new design (T/E) and science concepts, or to alter their current conceptions when confronted by the cognitive dissonance arising from incomplete conceptions or misconceptions they often recognize during testing and iterations. In line with Deweyan philosophy, instruction must ensure there is continuity of experience such that the preceding experience provides the knowledge leading to understandings necessary for successful engagement in the subsequent experience (Dewey, 1938, p. 27). Moreover, continuity of concrete (hands-on) experiences is what Dewey contends engages the learner in specific cognitive experiences (minds-on) such that they cumulatively clarify the abstract knowledge needed to achieve understanding. Continuity of experience is integral to the design of every ProbScen, with each implemented similarly following the eight phases of the PIRPOSAL model (Wells, 2016b). Explaining the potential of DBBL to promote conceptual learning is communicated best using excerpts from several different biotechnical design challenges. As such, the chapter continues with a select series of Problem Scenarios used to present examples of conceptual learning as achieved through the eight phases of design depicted in the PIRPOSAL model.

7 Conceptual Understanding – DBBL Imposed Cognitive Demands

As a way of illustrating how imposed cognitive demands inherent to DBBL promote STEM conceptual understanding, a sequenced series of ProbScens are used to demonstrate cognitive-descriptive (science) and practical-descriptive (design) artifact proposals prepared as co-outcomes reflecting different conceptual knowledge learners acquire within a given phase of design. Excerpts from three Problem Scenarios will provide continuity examples of the DBBL instructional approach for promoting T/E design and science conceptual understanding. All three ProbScens address authentic global renewable energy needs as identified by the Engineering Grand Challenges (NAE, 2020) within the Sustainability Theme[1] and implemented sequentially to intentionally scaffold concepts and skills across challenges. ProbScens 3D (algae photobioreactor), 4A (ethanol bioreactor), and 4C (microbial fuel cell) will be used to

illustrate the co-occurrence of conceptual learning in science (cell morphology, metabolism, bioconversion, etc.) and in T/E design (predictive analysis, iteration, optimization, etc.) inherent to a series of design challenges addressing the overarching context of renewable energy.

7.1 *Context for Sequenced Problem Scenarios*

The growing global demand for alternative energy sources provides the authentic human need addressed through this series of ProbScens. Many resources are available for use in connecting students to the very real human need for accessible energy sources. As one example, the Gates video featuring energy crises in developing countries is particularly relevant for connecting these ProbScens[2] and provides the context underpinning this sequence ProbScen design challenges.

7.2 *Sequenced Problem Scenarios*

7.2.1 3D Photobioreactor

The artifact proposal learners are to design in ProbScen 3D is a photobioreactor that utilizes the potential of algae for producing oil as an alternative energy source. Photobioreactor designs fall into two broad categories, coil and fence, and prototypes can be relatively easy to construct. However, as the first in this series of biotechnical design challenges, ProbScen 3D introduces learners to DBBL by focusing on designing a working prototype of only the pump subsystem, which must circulate the algae throughout the system without damaging the organism. The main instructional goal is that of introducing learners to the grouping of intelligent design actions in the KAH (PIRPOSAL phases of design) and becoming accustomed to preparing artifact proposals, both cognitive and practical descriptive, as a means of learning the inherent technology and science.

7.2.2 4A Ethanol Bioreactor

The second ProbScen is similar to the first in using a microbe to produce an alternative fuel, but the organism and bioprocesses are different. As in the previous ProbScen, this biotechnical challenge must take into consideration biological characteristics such as the morphology of the organism used in order to design an appropriate bioreactor. However, the ethanol bioreactor imposes the need-to-know more about how the organism converts organic waste into useful bi-products, as well as the use of immobilization techniques and the concept of porosity for maintaining separation of product from reactants.

7.2.3 4C Microbial Fuel Cell

The third ProbScen continues building on previously learned concepts as scaffolding for promoting the higher order cognition necessary for addressing the novel and more complex microbial fuel cell design challenge. Specifically, the anaerobic bioprocessing of organic waste, reduction and oxidation mechanisms, concentration gradients, electrodes, and electrical circuits all present learners with new concepts and impose on them different cognitive demands for synthesizing information needed in designing a functional MFC.

7.3 *Inherent Biotechnical Concepts*

The sequence of teaching episodes connecting all three ProbScens target multiple STEM concepts as specific learning outcomes learners are to demonstrate in the course of preparing a working artifact proposal (prototype). Table 11.1 lists the main co-occurring science and technology concepts inherent to one or more of these ProbScens that learners are expected to demonstrate, both formatively and summitively, as a result of working to achieve a satisficing biotechnical design solution.

All of the concepts listed in Table 11.1 align with the U.S. National Assessment of Educational Progress science, technology and engineering literacy,

TABLE 11.1 Sampling of main co-occurring science and technology concepts targeted

	ProbScen 3D	ProbScen 4A	ProbScen 4C	
✓ Science concepts				**× T/E concepts**
Biological systems	✓ & ×	✓ & ×	✓ & ×	Technical Systems
Morphology	✓ & ×	✓ & ×	×	Iteration
Bioprocessing	✓ & ×	✓ & ×	✓ & ×	Optimization
Metabolism	✓ & ×	✓ & ×	✓ & ×	Predictive Analysis
Biochemical conversion	✓ & ×	✓ & ×	✓ & ×	Prototyping
Volume (liquid or gas)	✓	✓	✓ & ×	Electric circuit
Flow (liquid or gas)	✓	✓	✓	Current/voltage/power
Porosity		✓	✓ & ×	Conductivity
Concentration gradient		✓ & ×	✓ & ×	Anode/cathode
Reduction/oxidation		✓ & ×	×	Electrode

and mathematics exams used to evaluate what students at various grade levels should be able to demonstrate in each of these subject areas.[3]

7.4 *MFC – Illustration of Imposed Cognitive Demand*

Chapter length does not allow for illustrating the full extent of cognitive demands imposed on students in this series of ProbScens. However, the Microbial Fuel Cell (MFC) can provide a brief illustration of how the need-to-know in biotechnical design confronts students with having to demonstrate conceptual understanding in response to an imposed cognitive demand in developing a plausible working artifact proposal (prototype).

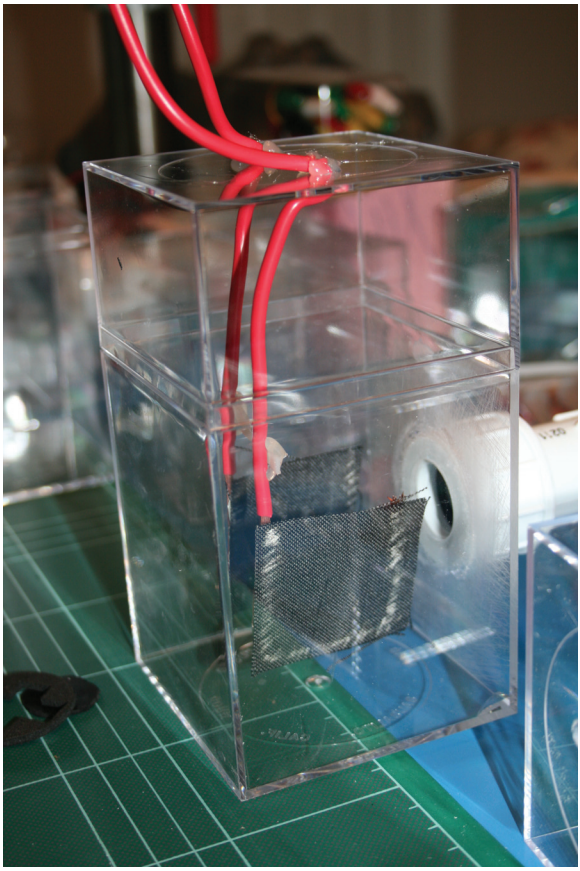

FIGURE 11.2
MFC electrode design

One of the key technical components of the MFC is the electrode located in the anode chamber (Figure 11.2). As benthic microbes in the anode chamber break down organic waste via reduction/oxidation (redox), they release free electrons outside their cellular membranes. The purpose of the electrode is

to provide a carbon substrate on which to generate a microbial film, accrue a sufficient number of free electrons on the carbon substrate, and then conduct those electrons from the electrode through the electric circuit to power a load. Designing the electrode and ensuring proper function within the MFC requires learners to engage in appropriate science intelligent action as a necessary precursor to design intelligent action (science in a design context). At a minimum, learners must grasp the concepts of (a) redox for generating free electrons, (b) carbon as a substrate that will attract the electrons, and (c) a concentration gradient between the anode and cathode needed to draw electrons through the circuit. Proper function is determined through analysis of data collected over time demonstrating theorized potentials of the electrode as designed. Specifically, data analysis will evaluate the predicted capacity for

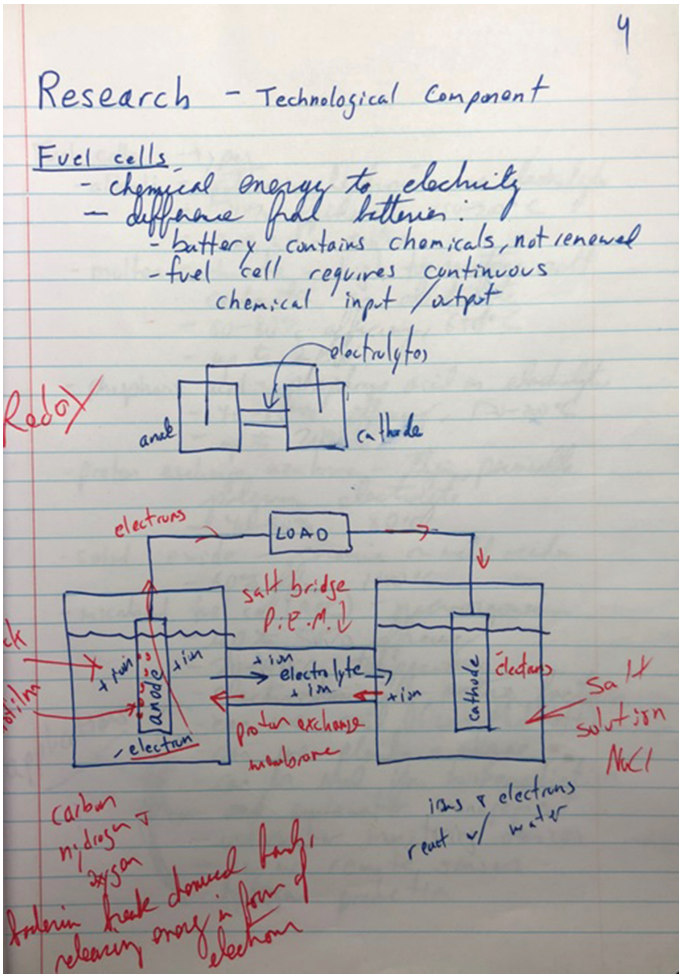

FIGURE 11.3
IEJ formative concept assessment

the surface area of carbon used for the electrode, the degree to which the adhesive between the carbon cloth and copper wire adequately conducts electrons, and whether or not a single electrode is sufficient to provide enough current to power the load. Preliminary science intelligent action determines the ideal outcomes as a precursor for electrode design, and utilizes scientific methods for data collection and analysis to evaluate the predicted performance in-situ. Predictive analysis, iteration, and optimization are ongoing design intelligent actions that occur while the learner makes improvements to the initial artifact proposal based on the necessary co-occurrence of science intelligent actions. Pedagogically, each of these intelligent actions result in artifact proposals (descriptive and practical) that together represent the achievement of culminating learning co-outcomes.

Several approaches to formative assessment of conceptual understanding are available, including Interactive Engineering Journals (IEJ) documenting design iterations, explanations learners give during gallery walks, and design modifications made in response to unforeseen issues arising during solution performance (Figure 11.3). Traditional content exams can serve as a summative assessment, but deep understanding revealed through verbal presentation and explanation of the prototype as designed and tested provides a more robust and thorough demonstration of true conceptual understandings.

7.5 *Implications for Designing to Understand*

Teaching through technological/engineering (T/E) design based learning prepares learners with a unique knowledge form distinct from all others and a distinct set of intelligent design actions used for knowledge acquisition. The design knowledge form is today gaining such recognition across core disciplines that those disciplines now incorporate it to teach their content and practices, and most often to the exclusion of those fundamental to technology education. As such, the fundamental epistemology of technology education is at risk of abdication to other disciplines. This epistemology, inclusive of content and practices, is unique in its capacity for preparing thinkers who achieve deep understanding through engagement in T/E design based learning. The designerly way of knowing is driven by the need-to-know during the creation of that which does not yet exist. This experiential approach provides the means for developing the type of higher order thinking ability that enables the learner to solve not only tame problems, but also the wicked ones that will most certainly confront the global community in the coming decades.

The realization of a true paradigm shift where conceptual understanding becomes the goal of designing will require several important changes within the technology education profession. Foremost would be a concerted effort by scholars in the field to conduct research documenting the validity of design as a pedagogy for promoting conceptual understanding as a learning outcome and the teaching strategies used to facilitate such instruction. Results from these research efforts would then serve as the basis to design and conduct the professional development needed to prepare K-12 educators in the pedagogy of design based learning where the goal is intentionally targeting conceptual understanding as the primary learning outcome. Logically, these efforts would then provide the foundation for assessment of those practices as a mechanism for evaluating the extent to which T/E DBL teaches concepts in a manner consistent with the evaluation of conceptual understanding conducted at both national and international levels.

Notes

1 See https://youtu.be/zwJ5E_EUUF4
2 See https://www.youtube.com/watch?v=xraThzKoXU8&feature=youtu.be
3 See https://nces.ed.gov/nationsreportcard/

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