Fostering Human Development Through Engineering and Technology Education

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Fostering Human Development Through Engineering and Technology Education (ETE) is a collaborative work offered to students, scholars, researchers, decision-makers, curriculum developers, and educators interested in the rich learning opportunities afforded by engineering and technology education. This book provides perspective about the roles ETE might uniquely play in applying contemporary pedagogical practices to enhance students’ intellectual, cognitive, and social skills in the service of promoting equitable and sustainable human development.

Education about engineering and technology has become an imperative for all people due to the exponential rate of technological change, the impact of globalization on culture and economy, and the essential contributions engineering and technology make in addressing global and environmental challenges. Many of today’s students wish to use their education to influence the future, and school-based engineering and technology education programs meet the needs of these “millennial students” who are civic-minded, team-oriented, and want to make a difference. Therefore, support has been rapidly increasing for the establishment of school-based engineering and technology education (ETE) programs in many countries across the globe.

Chapters in this book provide discussion about dimensions of learning: capabilities, concepts and skills for third millennial learners; culturally relevant learning through ETE; and the promise of new pedagogies such as gaming and other project-based learning approaches in our digitally connected world. The author team includes renowned educational theorists, cognitive scientists, scientists and engineers, instructional designers, expert practitioners, and researchers who have coalesced best practice and contemporary thought from seven countries.
Fostering Human Development Through Engineering and Technology Education
Technology Education has gone through a lot of changes in the past decades. It has developed from a craft oriented school subject to a learning area in which the meaning of technology as an important part of our contemporary culture is explored, both by the learning of theoretical concepts and through practical activities. This development has been accompanied by educational research. The output of research studies is published mostly as articles in scholarly Technology Education and Science Education journals. There is a need, however, for more than that. The field still lacks an international book series that is entirely dedicated to Technology Education. The *International Technology Education Studies* aim at providing the opportunity to publish more extensive texts than in journal articles, or to publish coherent collections of articles/chapters that focus on a certain theme. In this book series monographs and edited volumes will be published. The books will be peer reviewed in order to assure the quality of the texts.
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INTRODUCTION

Human Development and Engineering and Technology Education

HUMAN DEVELOPMENT

The future of engineering and technology education (ETE) and its role in general education strongly depend on how educators, researchers, stakeholders and the general public conceptualize and understand the role of ETE in developing students’ broad intellectual competencies, talents, knowledge and skills that will enable them to enjoy long, fulfilling, and creative lives, and contribute meaningfully to society and the economy. Alkira (2002) articulated that the term ‘human development’ we have used in the title of this chapter is multidimensional and suggested a set of dimensions, including basic human functional capabilities, axiological categories, dimensions of well-being, universal human values, quality of life domains, universal psychological needs and basic human needs. Maslow, in his well-known book Motivation and Personality (1954) suggested a hierarchy of human needs including self-actualization, esteem, love and belonging, safety needs, and physiological needs. Max-Neef (1991) developed the Human Scale Development, which is defined as “focused and based on the satisfaction of fundamental human needs, on the generation of growing levels of self-reliance, and on the construction of organic articulations of people with nature and technology, of global processes with local activity, of the personal with the social, of planning with autonomy, and of civil society with the state” (Max-Neef, 1991, p. 8). This author classifies fundamental human needs as subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom. Each of these needs is also defined according to four existential categories of being, having, doing and interacting, and from these dimensions, a 36-cell matrix is developed. For example, the need for understanding means:

- Being equipped with critical capacity, curiosity and intuition
- Having things such as literature, teachers, policies and educational
- Doing actions such as analyzing, studying, mediating and investigating
- Interacting with others, for example in the family, school, university and community

The dimensions of human development sketched above provide us with a broad perspective of the role of education in general, and ETE in particular, in developing individuals and promoting their well-being and quality of life. This view was adopted, for instance, in the Human Development Reports of the United Nation Development Program (UNDP) in the years 1990 to 1996. As our era is characterized by rapid socio-economic changes that are breaking down old social frameworks and workplace characteristics, today, more than in the past, ETE should shift its focus from teaching
specific knowledge and skills to fostering students’ higher intellectual competencies, such as critical thinking, creativity, problem solving, independent learning and teamwork, as shown in the next section.

**A PERSPECTIVE ON ENGINEERING AND TECHNOLOGY EDUCATION**

In the past, technology education was often identified with teaching crafts, skills oriented at the traditional industry’s needs, or vocational education for low-achieving students. It is hoped that the term engineering and technology education would help in clarifying to learners, educators and the general public that the study of ETE is rigorous, will support the education of all learners regardless of career path, and appropriate as a new, fundamental subject for study in our schools.

The American Engineers Council for Professional Development (ECPD) defines engineering as “The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property.” Technology is a broader term, and more difficult to define. Marc de Vries (2005) describes technology as “the human activity that transforms the natural environment to make it fit better with human needs, thereby using various kinds of information and knowledge, various kinds of natural (material, energy) and cultural resources (money, social relationships, etc.).” In summary, although the terms engineering and technology are not the same, the border between them is not precisely defined.

To demonstrate our view about the term ‘engineering and technology,’ let us consider the following example:

Residents living in a high-rise building complain that during rush hour, around 8:00 a.m., they have to wait too long for the elevator. A technical solution to this problem could be, for instance, improving the elevator control program or mechanical system, replacing the elevator with a faster one, or adding elevators to the building. Engineering and technology, however, is not just about technical issues but also about human needs and behavior. These are the basic considerations in choosing how many elevators are needed in a building and how large to make them so people would feel they had enough space. Therefore, a more sophisticated solution to the elevator problem mentioned above would be to change not just the elevator’s parameters but also the residents’ elevator use habits. For example, consider the possibility that residents could call the elevator using personal electronic means such as a magnetic card or even their smartphones. Families using the elevator infrequently during rush hour (pensioners, for example) could get a significant reduction in their monthly building maintenance fee. The proposed solution could work well in one building but fail in another, depending on social and cultural factors. Moreover, using personal electronic means for calling an elevator might involve an
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ethical problem because this enables the system to accumulate information on residents’ movements in and out of the building.

This example shows that engineering and technology education is about fostering students’ knowledge, aptitudes and skills related to addressing scientific, technical and social-cultural dimensions in the process of design, problem solving or inventing new artifacts and technological systems. In addition to the individual development and career-related imperatives, ETE experiences can be very valuable pedagogically for students in providing an effective way of reinforcing mathematics, science, social science and language skills by mobilizing ‘engineering thinking’ and ‘technological thinking’ as a way of engaging young people in addressing design challenges in social contexts that are personally meaningful to them.

ENGINEERING AND TECHNOLOGY EDUCATION AND FOSTERING LEARNING COMPETENCES

As we have seen, the most important challenge to ETE is the transition from teaching specific knowledge and skills to fostering students’ higher-order capabilities such as critical thinking, creativity and problem solving. Unfortunately, we feel that this point has not been stressed enough in the past. While teachers and scholars in mathematics and science education often claim that the major objective of teaching these subjects in school is to develop students’ thinking skills, beyond teaching useful knowledge, it can hardly be said that engineering and technology educators frequently underscore this objective. Do mathematics and science education have better tools to promote meaningful learning and develop students’ critical and creative thinking than does ETE? We don’t think so. For example, Brandt (1998), in his book *Powerful Learning* articulates that people learn well when:

– “what they learn is personally meaningful to them;
– what they learn is challenging and they accept the challenge;
– what they learn is appropriate for their developmental level;
– they can learn in their own way, have choices, and feel in control;
– they use what they already know as they construct new knowledge;
– they have opportunities for social interaction; and
– they receive helpful feedback.”

We believe that all the seven characteristics mentioned above of a powerful learning environment are at the heart of engineering and technology education. This makes this field one of the best educational environments for fostering learning in school, as is explored throughout this book.

OBJECTIVES AND STRUCTURE OF THE BOOK

Over the past three decades, we have witnessed a significant increase in the amount of discussion and writing on issues such as the rationale, objectives, contents and methods of technology and/or engineering education. This has been expressed, for example, in the *International Technology Education Series* of books by Sense Publishers, within which this book is published, as well as in periodicals such as
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the International Journal of Technology and Design Education and Technology and Design Education-an International Journal. Series of conferences, such as PATT, CRIPT, ASEE, ITEA, and TERC, which take place globally, have also played an important role in presenting research and fostering discussion among scholars in the ETE community. Yet, we feel that a need exists to further accelerate discussion and writing about the role of ETE in developing students’ cognitive, social and personal skills, and the methods or impediments in achieving this end. Towards this aim, this book was designed to comprise four main parts, each including three to five chapters, as described below.

The first part of the book, entitled ‘Dimensions of Learning – A Theoretical Framework’ includes chapters by Christian D. Schunn & Eli M. Silk, John R. Dakers, Moshe Barak, and Scott D. Johnson, Raymond Dixon, Jenny Daugherty & Oenardi Lawanto. In these chapters, the authors review a range of theories and conceptual issues relating to learning and cognition particularly appropriate for supporting learning in the context of ETE, for example, distributed cognition, cognitive apprenticeship, activity theory, self-regulated learning and the question of learning transfer.

The next part of the book is about the ‘Dimensions of Human Development – Competences, Knowledge and Skills.’ It includes chapters by Marc de Vries, John Williams, David Barlex, John M. Ritz & Johnny J. Moye, and Thomas Liao. These chapters discuss issues such as the basic concepts that constitute the discipline of engineering and technology education, fostering learners’ dispositions ‘to do’ and thereby reducing the gap between abilities and actions, promoting creativity in the technology classroom, developing self-efficacy, goals, interests, values-motivation and skills related to technological design, and decision-making.

Part three of the book takes us to the ‘Cultural Dimensions’ of ETE. The authors Jacques Ginestié, Linda Rae Markert and Karl M. Kapp refer to subjects such as the teaching-training process concerned with the transmission of tools, artifacts and knowledge, an examination of the extent to which cultural orientation influences our capacity as individuals to become technologically literate, and questions dealing with how ETE is influenced by the third millennial culture and how this culture is influenced by technology.

The last part of the book contains three chapters addressing ‘Pedagogical Dimensions’ by David Crismon, Michael Hacker & Jim Kiggens, and Evangeline S. Pianfetti & George Reese. In these chapters, the authors bring into light some of the unique capabilities related to using design tasks in project-based learning environments, show how playing and developing educational games are instructional strategies that could add to the teaching and learning of contemporary engineering and technology education, and reveal ways in which computer technologies such as simulation, video and the Internet could be used to reshape the instruction of ETE and bring the curriculum closer to the active life of the mind.

CONCLUDING REMARKS

Since the contributors to this book are of different backgrounds and minds, they evidently do not share exactly the same meanings of the terms ‘human development’
and ‘engineering and technology education.’ In this sense, the book is an attempt to highlight and explore the contribution of engineering and technology education to human development from multiple perspectives, and in this way encourage further discussion, research and writing on the objectives, methods and outcomes of teaching engineering and technology education in P-12 schooling.

The editors of this work would like to express their profound thanks to the author team for their important and original contributions to this book. The authors represent a group of outstanding educators and researchers in Engineering and Technology Education who have provided visionary and consistent leadership to this field of endeavor that is poised for explosive growth. The willingness and seriousness of purpose with which each of the authors approached the development of their chapter is characteristic of the way they have approached their professional efforts. Our years of collaboration with these individuals have been personally and professionally rewarding for us.

We are grateful for the opportunity to work with and learn from such an able and visionary group of engineering and technology educators and researchers and hope that our combined work, as expressed in the following chapters, will prompt further exemplary reform efforts in the educational field that we hold so dear.

Sincerely,
Moshe Barak and Michael Hacker

REFERENCES


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1. LEARNING THEORIES FOR ENGINEERING AND TECHNOLOGY EDUCATION

INTRODUCTION

Optimizing technical systems depends on scientifically grounded models of system performance. Similarly, the development of engineering and technology education systems fruitfully builds upon relevant learning theories. Engineering and technology involve complex skills and concepts embedded in rich contexts. We review learning theories particularly appropriate for supporting learning of such complex concepts in rich contexts, drawing heavily on information processing, distributed cognition and cognitive apprenticeship.

OVERVIEW

The goal of this chapter is to articulate ways in which contemporary learning theories drawn from the learning sciences can enhance Engineering and Technology Education (ETE). We believe that ETE has much to gain by grounding research, instructional innovation and evaluation in existing theoretical frameworks. Connecting to theory helps guide instructional designers in the construction of learning environments that are likely to be effective as they build on the scientific work encapsulated in well-established learning theories and they are also then able to contribute further to what is known in ETE disciplines by refining and expanding on those theories.

But connecting to learning sciences theory is difficult for many experienced engineers and engineering/technology educators who seek involvement in education research, but who were not trained in a social science such as psychology or education (Borrego, 2007). To that end, this chapter intends to explore a number of contemporary learning theories that could serve to ground ETE research, design and evaluation. Although we cannot possibly cover all such learning theories, the ones we have chosen may be particularly useful to the work of ETE in which students must learn complex skills and concepts and to use those concepts adaptively in rich contexts.

The chapter is organized around the following two questions:
– Goals: What is ETE as something to be learned?
– Theories: What are some currently influential learning theories that could be applied to ETE?
In thinking about learning theories that may be relevant for ETE, it is important to be explicit about the outcomes that educators would like to see in their students. There are two dimensions to consider with respect to ETE. The first dimension is that ETE naturally involves elements of science, technology, engineering and mathematics (STEM). While technology and engineering elements are clearly the most central, they inevitably draw upon science and mathematics at various points, and the design of effective ETE environments should take those connections into account.

Second, there is the question of what fundamental form the elements to be learned take. Since the days of behaviorist learning theories, it has been clear that competent activity in a domain consists of many individual components, each of which must be acquired and developed through experience (Thorndike, 1913) —addition and multiplication, for example, are separate math skills, each requiring their own practice. This need for decomposition of learning goals and practice on the components continues to receive theoretical and empirical support (Singley & Anderson, 1989; Anderson, Bothell, Byrne & Lebiere, 2004). However, developments in education, cognitive psychology and neuroscience after the days of behaviorism have shown that there is more to learn than just skills (or stimulus-response associations in the language of behaviorism) and further that different kinds of learning involve different methods. For example, procedures and concepts rely on different brain areas for learning (Knowlton, Mangels & Squire, 1996); procedures become less introspectable with practice whereas concepts become more introspectable; and procedures are most robust but least flexible when automatized whereas reasoning is generally more flexible but requires conscious control (Anderson, Fincham & Douglass, 1997). Both are important for developing expertise in a domain.

In engineering terms, solving a problem in a domain involves a complex system requiring many skills, concepts and other competencies rather than just a simple list of skills. Here is a division that was first developed in mathematics education (Kilpatrick, Swafford & Findell, 2001) that could be applied productively to ETE. Success appears to require all five elements:

- **Procedural fluency**—skill in carrying out procedures flexibly, accurately, efficiently and appropriately. This would include the use of tools, models and mathematics in technology/engineering problem-solving.

- **Conceptual understanding**—explicit comprehension of relevant concepts from engineering, technology, science and mathematics, understanding what possible operations are available and why they work, and an understanding of the relationships between concepts and operations.

- **Strategic competence**—ability to formulate, represent and solve complex STEM problems.

- **Adaptive reasoning**—capacity for logical thought, reflection, explanation and justification.

- **Productive disposition**—habitual inclination to see STEM as sensible, useful and worthwhile, coupled with a belief in diligence and one’s own ability to solve technology or engineering problems.
A strong ETE curriculum will help students make progress at all five levels. Thus, it is important to consider each of these elements and learning theories that describe their acquisition. In the sections that follow, we will describe more concrete actions that ETE designers can use to develop more effective learning environments for each element.

ENGINEERING AND TECHNOLOGY EDUCATION LEARNING THEORIES

There are several broad theories of learning to consider that highlight some of the major outcomes from the learning sciences. Within each broad learning theory, there are more detailed theories of particular factors that influence learning, but here we focus only on the broad theories and the key distinctions they raise for the ETE teacher and designer.

One can roughly organize the components to be learned from more micro components (a large number of small pieces to be learned that are each executed quickly in time during problem-solving) to more macro components (a smaller number of larger pieces to be learned that are applied more pervasively during problem-solving). For example, there are many simple procedures to learn, each of which might only take a second to execute, whereas there are a few productive dispositions that need to be active through a potentially multiple-week-long process of solving a complex engineering problem. Similarly, one can organize learning theories in terms of having a more micro (short time scale focus on micro features of behavior) vs. macro (longer time scale focus on macro features of behavior) perspective (see Figure 1). This difference is more heuristic/approximate than absolute in that all of the theories make some contact with all of the components. However, a clear point of emphasis exists within each theory.

![Figure 1. Micro to macro organization of learning theories and components of competent behavior in ETE.](image-url)

INFORMATION PROCESSING (COGNITIVE) THEORIES OF LEARNING

One of the key insights of Information Processing theory is that complex tasks must be decomposed into informational components that are encoded, stored and processed, and fundamental cognitive limitations exist at each step that influence performance and learning. The mind, like a computer, does not have infinite capacity. A general flow of information is shown in Figure 2.
**Attention Issues**

The problem-solver, especially in more complex engineering and technology settings, sits in a rich environment with all kinds of sensory signals impinging on his/her body (sights and sounds most importantly, but also smell, touch, temperature, pain and hunger). Well-practiced, automatic skills can make some use of much of this information, but more conscious, deliberate problem-solving depends on using information in working memory. The problem-solver actively selects which information to encode into working memory via an attentional filter: only information that is attended is moved initially to working memory, and only a very small bandwidth of information that is perceived can be attended. The mind appears to attend to locations and modalities one at a time, but can switch rapidly between locations and modalities (Wickens & McCarley, 2008).

Novices often do not know what information to attend in a complex environment, and so the instructional designer and teacher must support the learner in attending to the right features at the right time. This might involve simplifying the environment to remove less relevant features, making critical features more salient, or bringing features closer together that must be encoded immediately to solve a problem (Wickens, 2008; van Merrienboer & Sweller, 2005). But note that learners will have trouble moving from a very simplified learning environment to the real performance environment if the information found in the simplified environment is perceptually different from the real environment and different information encoding skills are required.

Simply pointing out critical features to encode by itself can produce large speedups in learning because feature noticing can be subtle. For example, the skill of chicken sexing (determine a day-old chick’s sex by visual inspection) used to take thousands of hours to perfect, but was later learned in a matter of a few hours once learners were explicitly told which features were important to encode (Biederman & Shiffrar, 1987). Closer to ETE, Kellman, Massey and Son (2010) found that training middle and high school students in mathematics classes to recognize patterns and fluently extract meaningful perceptual structures in mathematics problems greatly improved equation solving performance and solving novel problems.
**Working Memory Issues**

Moving information into attention is a first step, but not the last one in terms of information processing. In addition to limitations on how much can be attended at once, working memory is extremely limited in capacity—approximately four independent visual/spatial items and four independent verbal/acoustical items (Baddeley, 2003). Thus, as problem-solvers attend to new things, old things are lost from working memory; they must be mentally rehearsed (or reexamined to re-encode them) to be kept in working memory over time.

With experience, problem-solvers can ‘chunk’ combinations of information so that these familiar combinations only consume one item, effectively increasing working memory capacity in that familiar situation—for example, a chess expert can remember a whole board because sets of pieces can be grouped into familiar chunks, but a chess novice is stuck thinking about each piece on its own (Chase & Simon, 1973). Similarly, complex devices to a novice are overwhelming to remember because the novice cannot encode the subsystems of the device in terms of familiar groupings (Moss, Kotovsky & Cagan, 2006).

This severe capacity limitation on working memory has a number of implications for the instructional designer or teacher, especially because reflection by the learner on the task or situation, thought to be useful for learning, also relies on this same limited working memory capacity (van Merrienboer & Sweller, 2005). First, it is important to think through how many components the task being performed requires for a problem-solver to consider simultaneously in working memory (called the intrinsic cognitive load). It is important not to overwhelm the learner, taking into account the chunks that a learner is likely to already have. The peak cognitive load moment in a task is when errors are most likely to occur (Carpenter, Just and Shell, 1990). Addressing this issue might involve using familiar situations when first introducing procedures/tasks having a higher intrinsic load.

Second, it is important to find and reduce additional features of the learning situation that might be adding to working memory requirements (called the extrinsic cognitive load). For example, cluttered displays often imply that learners must keep track of where key information is being kept. Somewhat counter-intuitively, giving learners a very specific result to compute in an example produces a higher cognitive load than just asking students to compute a variety of results in the same situation because the specific goal must be stored in working memory (van Merrienboer & Sweller, 2005)—as a result, the specific goal situation produces more errors and reduces learning. Similarly, initially studying examples that show the solution process produces better learning outcomes than having students immediately solve problems on their own because the cognitive load of solving problems is higher than that associated with studying worked examples.

**Consolidation/Fluid Fact Retrieval**

As noted above, the working memory requirements of a situation are reduced when the problem-solvers can encode the situation in terms of larger familiar chunks. Where do these chunks come from? The chunks reside in long-term memory,
which has essentially unlimited capacity (i.e., it never gets ‘full’), but information is stored relatively slowly in working memory through a process called consolidation. In addition, problems may occur in retrieving the right chunks at the right time (i.e., stored information can get lost in the sea).

Expert performance involves having rapid access to relevant long-term memory chunks and this rapid access is built up gradually through repeated exposure. Here there is no free lunch, no cognitive shortcut (Anderson & Schunn, 2000). Rather, a relatively simple relationship exists by which each exposure slowly increases the probability of retrieving the information later and decreases the rate at which information is forgotten. There is one important caveat: studying information repeatedly spread out over time, rather than cramming, can have a large effect on how quickly information is forgotten (Pavlik & Anderson, 2005). So, for foundational information that is to be used in subsequent units or courses, it is very useful to revisit that information repeatedly at multiple points in the curriculum, spaced out over time.

Proceduralization

Chunking and storage in long-term memory is what happens to facts or memories for particular task arrangements and outcomes. A different kind of learning happens with skills. Here, information moves from being represented as facts to being represented as actions, a process called proceduralization. As a simple example, learning to drive a car begins with being told or reading about the steps involved. Students might be able to recite what the steps are, but they cannot actually consistently execute the steps until they have practiced the steps repeatedly. Over time, with enough practice, a problem-solver might actually lose the ability to recite the steps involved verbally because he or she no longer relies on that form of knowledge.

Similar to consolidation, proceduralization is a slow learning process with no magic bullets other than finding ways for students to more consistently practice only relevant steps. If a problem-solver wants to become fast and accurate at a procedure, hours of practice are required. Interestingly, there does not appear to be any point at which improvements stop with practice: even after thousands of hours of practice, people appear to keep getting faster with increasing practice, although of course the amount of improvement with each hour of practice diminishes (Anderson, Fincham & Douglass, 1997).

Proceduralization reduces working memory requirements because elements of the procedure do not need to be represented in working memory. Proceduralization does not by itself automatize the skill in that the skill, when first proceduralized, depends on explicit goals found in working memory and can be easily stopped or adapted through metacognitive reflection. However, with enough practice, the skills become automatic in the sense that they do not require any attentional resources to start the procedure, but they also cannot be easily stopped or adapted. For example, adults automatically read words as soon as they appear and cannot prevent themselves from reading the words. Sometimes problem-solvers need to complete multiple skills simultaneously; this dual task activity becomes more feasible when at least one of the skills has been practiced to the point of automaticity.
Prior Knowledge/Misconceptions

The previous analysis gives the sense of knowledge elements in isolation, each practiced in isolation. However, there are connections, particularly with respect to concepts. Cognitive research has found that one of the strongest predictors of how well a student is likely to learn something is how the new learning is related to what the student already knows and how their prior knowledge is organized (National Research Council, 1999, 2007). If the concepts to be learned and the way they are organized match neatly with a learner’s pre-existing knowledge base, then the learning is likely to be smooth and rapid. However, in science and engineering, students often lack relevant conceptual frameworks or have frameworks that are not developed enough to support new learning adequately. If students cannot relate new information to a meaningful framework, they will probably resort to memorizing terms that will be quickly forgotten or that will remain in isolation, unable to be connected to other knowledge or applied when relevant.

ETE, including supporting science education, often extends everyday understanding to new levels that cannot be seen directly or experienced in everyday life. For example, much of biology and chemistry involves learning about entities and processes at a microscopic level. In biology, many students correctly associate properties like breathing, growth and reproduction with living organisms, but their understanding of these properties is based on their everyday experience. They understand something like breathing as taking air in and out through one’s mouth or nose, and the need to do so is self-evidently obvious. This is correct as far as it goes, but a scientific understanding delves much deeper and explains these properties in terms of exchanges of gases that are required at the cellular level for cells to engage in the metabolic processes that support life. The way a person, a fish and a tree “breathe” may appear quite different on the surface, but the processes of cellular respiration unify and explain the common need to exchange gases and help us understand how different groups of organisms meet that need (see Chapter 5 for a more detailed discussion of the transfer of conceptual knowledge). To make sense of this, students must add new levels of concepts and explanatory systems to their understanding of the natural world and then work out how those levels are connected to their pre-existing views of the world (Smith, Maclin, Grosslight & Davis, 1997).

While some elements of ETE involve concepts very foreign to students, some concepts are misleadingly familiar to students. Through everyday informal interaction in the world, students sometimes develop misconceptions of how the natural and man-made world around them actually works. For example, in physics, most students have very serious misconceptions that are in direct opposition to Newton’s Laws; students strongly believe that a table does not push up on a book sitting on it and they strongly believe that objects stay in motion only because a force continues to be applied to it (Clement, 1982). Because these informal understandings have been developed through years of experience, they are incredibly resistant to change through instruction. Instruction that ignores these misconceptions tends to fade quickly, leaving only the misconceptions in the learner’s head, whereas instruction that evokes and directly attacks these misconceptions has significantly improved student learning (Hammer & Elby, 2003; Kim & Pak, 2002).
Because these connections and reparation of existing knowledge are so crucial to learning, teaching and learning strategies that involve sense-making by the students have often been found to be especially effective. For example, encouraging students to self-explain during reading (i.e., monitor whether they understand what was read, make connections between paragraphs or between text and diagrams, make predictions and provide explanations for the provided information) can lead to great improvements in understanding the text, in retaining the material and afterwards the ability to apply the information later in new contexts (Chi et al., 1989). See Chapter 5 for a broader analysis of factors that influence this kind of learning.

Cognitive Task Analysis

Practice is the key to expert performance. But it is critically important that time be devoted to practicing all critical skills in the goal task. The benefits of practice are very specific to the particular skills that were practiced. For this reason, it is important to do a cognitive task analysis of the steps involved in completing a task. Note the term ‘cognitive’ in cognitive task analysis. A non-cognitive task analysis involves analyzing the external steps involved in completing a task. A cognitive analysis includes the mental steps required in the task, including mental calculations and retrievals from long-term memory.

A cognitive task analysis can be difficult to complete, especially by experts who have proceduralized many elements of the task, thereby losing the ability to articulate the procedures they execute verbally. So, one cannot simply interview experts to determine required skills. Instead, one must observe experts at work, perhaps having them give a think-aloud protocol that offers some access to the contents of verbal working memory (Ericsson & Simon, 1983). From this trace of external actions and contents of verbal working memory, one must infer the steps taken by the problem-solver.

Why is it worth the effort to do a cognitive task analysis? First, it clarifies what skills and concepts must be practiced, which makes it clearer as to what kinds of practice tasks should be assigned to ensure that all components skills and concepts receive some practice. Different problems can involve different subsets of skill application. As a simple example, different subtraction problems may or may not involve particular borrowing steps.

Second, the cognitive task analysis creates some opportunities for improving the efficiency of learning with intelligent learning systems that track student performance at the cognitive components level. Solving problems can take considerable learning time. If a given student has already made considerable progress on skills A, B, C but not skills D, E, less efficient use of learning time would be made to present more problems involving A, B, C or A, B, E and more efficient use of learning time to present problems involving just D, E. Cognitive tutors that present problems in exactly this way (in addition to providing immediate feedback on which cognitive steps were incorrectly completed) can take students to the same learning outcomes in much less time (Anderson, Corbett, Koedinger and Pelletier, 1995).

Third, important transfer across tasks can happen at the level of shared cognitive components. So, learners can be given simplified learning tasks (to simplify
attentional demands, to reduce working memory requirements and to focus time on unlearned elements) but still transfer to real tasks if the tasks share important cognitive components. For example, Klahr and Carver (1988) conducted a cognitive task analysis of program debugging skills. They then explicitly taught these skills to students, which they quickly mastered and practiced. Then, in a test of transferring these skills to a completely different task that should have shared important cognitive elements of debugging, Klahr and Carver found that students were much better at debugging errors in written instructions, such as arranging items, following map routes, or allocating resources.

Summary of Information Processing

From an information processing point of view, it is important to determine the information that students need to be processing, considering perceptual encoding, working memory, and long-term conceptual and skill components. Further, this analysis must examine both eventual fluent problem-solving and the learning environment. Learning takes place through accurate focus on and practice with the critical elements. Given the frequent complexity of ETE, it is easy to overlook critical skills or concepts without a careful cognitive task analysis conducted by the designer of the ETE learning environment.

DISTRIBUTED COGNITION LEARNING THEORIES

Information processing theories place a strong emphasis on the mental workings of individual minds. Distributed cognition generalizes the information processing theory framework to include the physical environment around the learner, including interactions with other problem-solvers. As noted in the previous section, cognitive load is a key bottleneck to complex problem-solving and learning. External tools and other problem-solvers in the environment can be used to share the load. For example, in a plane cockpit, the pilot uses dials to help remember the state the plane is in, uses the co-pilot to help run through check-lists before take-off, and even uses simple perceptual features of dials and indicators to compute simple computations about whether to change the plane’s speed (Hutchins, 1995).

This distributed extension of information processing applies to ETE in a number of different ways. First, engineering and technological problem-solving tend to involve working with complex external environments and groups of individuals working together, rather than individuals working alone or doing purely mental calculations. Thus, it is not necessary for ETE learners to be able to do complex tasks purely in their heads because it is unlikely that they will encounter that performance standard later.

Second, problem-based learning is often implemented as group-work. By assigning different individuals different roles (including monitoring overall performance or learning of individuals), the overwhelming complexity of many ETE learning tasks becomes manageable. However, it is important that the tasks be divided such that the cognitive load is decreased rather than increased. In tightly coupled tasks...
distributed across individuals, each problem-solver has the additional challenge of having to keep track of their partner’s task state as well as their own task state. Such distribution increases rather than decreases each learner’s cognitive load. It is better to have multiple learners work on more independent tasks or have them attend to the same task state but perhaps from different perspectives (Prince, 2004).

Third, engineers and technologists use thinking tools, often called models, that distribute thinking in another way and this requires an additional strand for learning. Models are tools or formalisms that represent aspects of some external situation for a particular purpose. Common examples from ETE include graphs, equations, physical prototypes, computer-aided design models and design analysis tools. A given situation could be represented by any and all of these examples (Gainsburg, 2006). Each representational tool has strengths and weaknesses. Which model or combination of models should be used at any given time depends upon the problem-solver’s purposes. Even within a given type of model (e.g., physical prototype), there are choices as to which features to include and which to exclude (e.g., color, moving parts, structural strength).

This last element is a critical component of strategic competence (one of the key components from Figure 1)—the ability to formulate, represent and solve complex STEM problems. Complex ill-defined problems (as frequently occurs in engineering and technology problem-solving) can move from being nearly unsolvable to trivial through the selection of the appropriate representational tools (Kaplan & Simon, 1990).

But modeling, as a skill, can be a challenge to learners. Students initially do not see models as representational—standing for something else—but rather just things on their own, serving no greater purpose. Further, students are usually given models rather than being allowed to modify and strategically select models, thereby under-cutting the development of strategic competence.

Models & Modeling Perspective and Model-Eliciting Activities

In the mathematics education and engineering education communities, a new general approach to instruction is developing called the models & modeling perspective (M&M; Lesh & Doerr, 2003), focusing on the complexities and benefits of models as a particular kind of distributed cognition. Whereas the information processing theoretical perspective often led to careful arrangements of problem-solving activity, the M&M perspective has advocated a different sort of instructional activity exemplified by model-eliciting activities (MEAs; Hamilton et al., 2008). MEAs are a form of problem-based learning well matched to ETE in which the problem-solvers are asked to produce conceptual tools for constructing, describing, or explaining meaningful situations. This process of developing such a conceptual tool typically involves a series of express-test-and-revise cycles. The iterative model development process helps students both to develop more sophisticated ways of understanding important conceptual ideas and to acquire a productive disposition toward thinking about their own ideas or models of situations as tools—useful and adaptable for solving real problems (Lesh & Lehrer, 2003).
MEAs have been developed for K-12 and undergraduate mathematics, technology and engineering education (e.g., http://modelsandmodeling.net). A number of well-defined principles for developing MEAs exist (Lesh et al., 2000). In addition, MEAs are typically contextualized around a problem where students have to sort through a wide range of quantitative data and develop a procedure or process for a client. For example, the Nano Roughness MEA (Moore & Diefes-Dux, 2004) challenges students to quantify the roughness of nanoscale materials that a biomedical company is considering to use for artificial hip joints. One principle of MEAs is the Model-Construction Principle—that the problem requires students to create a mathematical model of the situation. In the Nano Roughness MEA, students examine atomic force microscope (AFM) images that provide quantitative data on the surface height of materials and use this information to generate their own procedures for quantifying roughness, of which there are many possibilities.

MEAs can result in a form of local conceptual development in which students make progress in a particular situation with the specific tools available in a way that parallels larger developmental processes of more general conceptual structures (Lesh & Harel, 2003). Thus, MEAs provide students with opportunities to develop their ways of thinking about central conceptual ideas within realistic problem-solving contexts.

We have begun to explore in our own work with robotics technology classes in middle schools how the M&M perspective and MEAs can provide a sound theoretical basis for improved learning (Silk et al., 2010). For example, we provide middle-school aged students with the case of a robotics team that programs synchronized dancing Lego robots. The fictional team receives different dance routines from fans via the Internet. The problem is to program these various dance routines in a way that different sized robots will dance in synchrony. The students’ task is to develop a script that the fictional team can use to program robots for these arbitrary scripts quickly and accurately. Since the situation is open-ended, the students must develop their own physical and mathematical models to determine how different robotics moves vary across different sized robots and then use these models to develop the script. Here, students are thinking about specific proportional relationships in the problem, and through a model refinement process, they may further improve their mathematical concept of proportionality or their robotics concept of proportional control.

COGNITIVE APPRENTICESHIP LEARNING THEORIES

All areas of professional education, including engineering and technology education, have had a long history of apprenticeship approaches to learning. At school, students were meant to learn the underlying principles and most fundamental skills/knowledge (writing, mathematics, science), and then through internships, co-op experiences, or on-the-job training, learn the ‘real’ skills of the discipline. Even instruction that was intended for all children, rather than just the next generation of a particular profession, has been influenced somewhat by applying lessons from apprenticeship learning to instruction.
Traditional Apprenticeship Learning

Analysis of learning in traditional apprenticeship situations noticed important common instructional features. One important feature is that much early apprenticeship learning involves observation by the apprentice of more expert performance, rather than immediately having the learner engage in problem-solving, read about problem-solving, or hear lectures about problem-solving (Lave, 1988).

The second important feature is the expert provides many supports for the learner during problem-solving, called scaffolds. For example, the expert may provide hints or do parts of the task, leaving the first or last pieces for the learner. Gradually over time, these scaffolds are removed, a process called fading (Vygotsky, 1978). A number of intelligent computer tutoring systems have successfully used this scaffolding and fading approach to speed up learning (Renkl, Atkinson & Grosse, 2004), including of engineering materials (Reisslein, Sullivan & Reisslein, 2007).

From such apprenticeship experiences related to ETE, students develop a productive disposition towards STEM (the last key component listed in Figure 1). Because they see performance of STEM in action, the usefulness of STEM components is made very persuasively. Observation of a diligent expert provides a good model for work ethics in STEM. Finally, the scaffolding and fading help to ensure that students develop and maintain high self-efficacy about their own ability to solve STEM problems.

Cognitive Apprenticeship Learning

Although apprenticeship learning does produce expert performance, the path is often quite slow, and the learning that results can be somewhat fragile or specific to the particular learning environment of training (Suchman, 1987). This last element was particularly troubling for applications to school environments, which could not be made like work environments for large numbers of students. Information processing theorists examined apprenticeship learning and proposed a hybrid theory called Cognitive Apprenticeship that was meant to speed up and make the transfer from schooling to other settings more robust (Collins, Brown & Holum, 1991).

One element of cognitive apprenticeship is that the expert tries to make all aspects of the task visible to the learners, which further supports the learner’s ability to engage in more adaptive reasoning across settings (the fourth key component from Figure 1). In traditional apprenticeship, it is up to the learner to figure out which features to encode and what steps are going on. For ETE, in which many steps are mental and abstract, traditional apprenticeship leaves the learner with a huge inference task. To make aspects of the task more visible to the learner, an instructor might think aloud during problem-solving. For example, in mathematics instruction, Schoenfeld (1987) found it particularly useful to show students the heuristics that mathematicians use for selecting among possible problem-solving steps rather than just the formal steps found in particular algorithms. In addition, an instructor might ask learners to alternate between being a critic or guide and a learner or doer receiving critical comments. Reciprocal teaching is an approach that has used this element of cognitive
apprenticeship to great effect in reading instruction (Palinscar & Brown, 1984) and physics instruction (Reif, 1999).

A second element of cognitive apprenticeship is the importance of varying situations such that transfer to new situations will become more likely. Preferably this varying of situations is done by gradually increasing the complexity of the tasks and the diversity of the skills and concepts required to complete the task. That is, rather than simply working on complete problems as they come and providing scaffolding for the students, the order of selected problems is chosen purposefully with respect to complexity and diversity of skills and concepts (Collins, Brown & Holm, 1991).

However, the sequencing of problems does not mean instruction should begin with micro-problems that are completely divorced from real problem situations because the students will then lose the connection between what they are learning and the situations to which these skills and concepts should apply. Instead, instruction should go from global to local so problem-solvers can see the relevance. That is, a full problem can be introduced, but then instruction can transition to solving components of the larger problem. This issue of global/local is particularly applicable to problem-based learning approaches used in ETE. Rich problems can be attempted and yet students can practice critical component skills in effective order by supporting the transition from the larger problem to the component sub-problems.

For example, in our synchronized dancing robots problem described earlier, we can present the larger synchronized robots problem to students at the very beginning of a long sequence of lessons and then help the students break down the larger program into components, such as linear distance, linear speed, turn amount and turn speed. Each of these components can be divided further into measurement and programming tasks. But the students ‘see’ the larger problem at the very beginning, rather than beginning the unit with a discussion of measuring linear distances with robots, which the students see as an odd task out of context. There is now emerging evidence that providing a greater ‘need-to-know’ enhances learning in STEM (Mehalik, Doppelt & Schunn, 2008).

Overall, cognitive apprenticeship approaches support the development of adaptive reasoning in problem-solvers by encouraging students to reflect on the skills and strategies involved in solving larger, more complex problems.

CONCLUSION

Successful problem-solving in engineering and technology settings requires attending to five larger elements in the problem-solver: procedural fluency, conceptual understanding, strategic competence, adaptive reasoning and productive disposition. These five elements are not developed quickly and easily, and learning environments must be carefully organized across years of instruction to meet this challenge.

Given the complexity of what must be learned, it is not surprising that a range of learning theories must be used to explain how this learning happens and what environmental features best support it. As a rough heuristic, we have organized the learning goals from more micro elements to more macro elements, and have then
shown how different learning theories connect to these elements. But the mapping is certainly complex and much research remains to be done. In the meanwhile, we strongly encourage active sense-making by the reader in terms of trying to apply the contents of this chapter to their own ETE setting.

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2. ACTIVITY THEORY AS A PEDAGOGICAL FRAMEWORK FOR THE DELIVERY OF TECHNOLOGY EDUCATION

INTRODUCTION

As I write this chapter I occasionally look out over a field full of sheep tending their spring lambs. It is a pleasant day and the sheep spend their time grazing or resting as the lambs explore their new environment. Yesterday it rained. There was no appreciable difference in the sheep’s behaviour. They did not take shelter nor did they construct any form of shelter from the rain. They just continued to act as sheep do, come rain or shine. They exist in this particular field because the farmer decided that they should. Their ability to move beyond the boundaries of the field in question is restricted by a stone dyke that was constructed by human beings sometime in the past. The sheep have no agency, there is no considered meaning directing their actions, they do not purposefully alter their environment in order to shape it according to their needs and desires. Indeed, they have no cultural heritage that defines them, they simply form part of what might be described as the natural world. The particular sheep that I am describing are domestic sheep (Ovis aries). Their behaviour or observed activities are innate. This is true for most non-human animal species. Some animals such as primates are known to act, in a very limited way, with intent and, in some cases, even use technologies to assist in some of their endeavours. Domestic animals such as the sheep described above are bred specifically for their wool and for food production. They are to all intents and purposes a technology. They form part of a system known as agriculture. It is through a subset of agriculture that a community of human beings known as farmers cultivate livestock. Unlike the primitive and quasi-natural existence of the sheep described above, this process of cultivation is deeply infused with meaning and purpose and intentionality, and it is these traits that motivate human beings towards goal-orientated action that manifests itself in the form of their labour.

Traditionally, in scientific terms, the actions of the farmer in relation to the sheep can be understood by observing and interpreting their collective interactions. This is traditional anthropology. However, this affords only a very limited understanding. We may merely conclude from our observations ‘what it is’ the farmer is doing and ‘how it is’ that the farmer is acting, and whether these actions conform to acceptable levels of animal husbandry based upon socially acceptable, historically established conventions. What we miss in this analysis is the meaning and the purpose that motivate the farmer’s action at that particular time. These can be many and varied, and may change depending upon a number of circumstances that are unlikely to be
revealed by observation alone. The farmer will have a number of goals in cultivating sheep depending upon circumstances and cultural influences. A farmer may cultivate sheep on a small scale only and perhaps only for personal use, whereas the farmer who cultivates the sheep that I am observing appears to do so for commercial reasons and therefore does so more intensively. In this case, the most prominent goal motivating the farmer in a capitalist culture is to make a profit. Conversely, the goal of the small-scale farmer may be to lead an independent and sustainable lifestyle. However, the object of the activity with which both farmers are engaged, as distinct from their individual goals, is to produce food and wool. Whilst the goal of profit-making particularly is not directly related to the object of producing food and wool, it is nevertheless contingent.

Another significant and important factor associated with the activity of producing food and wool is the division of labour. My ability to eat my lamb cutlet tonight whilst keeping warm by wearing my wool sweater will be dependent upon a number of related activities involving a number of other human beings. The lambs have to be sheared. They have to be transported from the farm to the slaughterhouse; they have to be slaughtered, which may also involve some religious ceremony (e.g., kosher slaughter). They have to be butchered; they have to be sold; they have to be cooked. All of these processes are culturally determined, rule-driven and involve a variety of communities that require a division of labour, rendering them social in that the object of their collective activity, as distinct from their individual goals, is to produce food or woollen-based artefacts. Finally, and importantly, activities need to be mediated by technology and/or technique. In the case described above, mediation may include shearing tools, trucks, slaughterhouses, shops, stoves, etc.

A SHORT DISCUSSION RELATING TO ACTIVITY THEORY

Marxist Origins

Activity theory has never, until only very recently, been considered in anything but a theoretical sense as opposed to an applied or practical format. It follows, and is predicated upon, Marxist thinking. In more recent times, theorists have begun to research and analyse activity theory within more practical contexts, and have produced some innovative and interesting perspectives in terms of education and business (see, for example, Cole et al., 1997; Engeström et al., 1999; Kaptelinin and Nardi, 2006). However, in order to better understand activity theory, it is important to have a grasp of its philosophical heritage.

Marx (1954) argues that the thing that defines human beings from all other animals is that the purpose and intention of all human activity is directed towards the transformation of the natural world in order to accommodate human needs. In virtually all other animal species, actions are considered to be undertaken in harmony with nature and are, to a large extent, innate. Animals may kill other animals or alter their environment in some way (beavers building dams or birds constructing nests, for example), but they do so in such a way that their actions have little lasting impact upon the balance of the natural world. If we were able to imagine a world in
which human beings had never existed, we might well conclude that it would take a very different form in which ‘Nature’ had evolved in Her own terms. A balanced and sustainable ecological system would have been preserved (discounting catastrophic incidences such as meteor intrusions or extreme earthquakes, etc.). However, this has not been the case, and human beings, who also form part of nature (albeit in oppositional form), have, in evolutionary terms, constantly attempted to dominate and control ‘Nature,’ forming an imbalanced and less sustainable ecological system in the process. In so doing, they have changed the way that they interact with the world and with themselves: in today’s digital world, we act very differently from the way in which our ancestral forebears acted 100 years ago in their industrialised world, and they, in turn, acted very differently from those who lived in medieval times. Important to the development of these cultural and social alterations in human activity is the application of technology and technique. In order to discover and change their world and as a consequence, themselves, human beings have to be actively involved, and, for Marx, that activity is made manifest in their labour:

“Labour is, in the first place, a process in which both man and Nature participate and in which man of his own accord starts, regulates and controls the material re-actions between himself and Nature. He opposes himself to Nature as one of her own forces, setting in motion arms and legs, head and hands, the natural forces of his body, in order to appropriate Nature’s productions in a form adapted to his own wants. By thus acting on the external world and changing it, he at the same time changes his own nature. He develops his slumbering powers and compels them to act in obedience to his sway. We are not now dealing with those primitive instinctive forms of labour that remind us of the mere animal. An immeasurable interval of time separates the state of things in which a man brings his labour-power to market for sale as a commodity, from the state in which human labour was still in its first instinctive stage. We presuppose labour in a form that stamps it as exclusively human” (Marx. 1954: 173–174).

Whilst this paragraph clearly presages Marx’s famous distinction between ‘use value’ and ‘exchange value,’ it is the concept of object-orientated activity where human actions are directed towards the external world, as alluded to by Marx above, that form the inspiration for the formation of Leont’ev’s concept of Activity Theory. Considered by most to be the founding father of Activity Theory, Leont’ev was a member of the cultural historical school led by Vygotsky. Influenced by Marx, Vygotsky and his followers studied the “object-orientated action mediated by cultural tools and signs” (Engeström and Meitinnen, 1999: 4). Essentially, object-oriented action is any purposeful interaction between the subject and the object that brings about some mutual transformation. In its most basic form, this relationship can be demonstrated as seen in Figure 1.

\[ S \leftrightarrow O \]

*Figure 1. Subject – object relationship.*
In Figure 1, S represents the individual or collective human subject and O the object of the subject’s activity. In Activity Theory, the subject and object cannot be considered independently but must be considered in the form of their relationship. For this relationship to exist, it must be imbued with meaning and purpose.

“A basic or, as is sometimes said, a constituting characteristic of activity is objectivity (or rather ‘object orientedness’). Properly, the concept of its object (Gegenstand) is already implicitly contained in the very concept of activity. The expression ‘objectless activity’ is devoid of any meaning. Activity may seem objectless, but scientific investigation of activity necessarily requires discovering its object. Thus the object of activity is twofold: first, in its independent existence as subordinating to itself and transforming the activity of the subject; second, as an image of the object, as a product of its property of psychological reflection that is realised as an activity of the subject and cannot exist otherwise” (Leont’ev, 1978 in Kaptelinin and Nardi. 2006: 137).

Human activities are always directed towards their objects, and the objects of their activity will have some impact upon humans (hence, the two-directional arrow between the subject and object in Figure 1 above). “When people design, learn or sell, they design, learn or sell something. Their dreams, emotions and feelings are also directed toward something in the world” (Kaptelinin and Nardi, 2006: 66). It is this interaction between the subject and the object that gives rise to motivation and desire. “Human beings and objects are bound together in a collusion in which the objects take on a certain density, an emotional value – what might be called a ‘presence’” (Baudrillard, 2005: 14). Objects can be considered to be material like a car or a house, or they can take on an ideal form such as an aspiration or a thought. However, this distinction can tend to cause some confusion. In order to address this, I will use the term ‘object’ as meaning the object of activity and not a physical object. In other words, the object of human activity is motivated towards fulfilling some individual or social need and these needs are developed and changed over time. Activity cannot thus be reduced to either the subject or the object unilaterally; it is the subject-object relationship that determines how both the subject and the object develop (Kaptelinin and Nardi, 2006: 66).

Vygotsky’s unit of analysis in this respect centred upon the mediating tools that intervened in object-orientated actions (Vygotsky, 1978). These tools can take material form, psychological form or any combination thereof. Moreover, these tools, in whatever form, will influence the outcome of the subject/object relationship. Vygotsky’s triadic model of mediation is shown in Figure 2.

In order for the subject to interact with the object of activity to achieve some transformational goal-orientated outcome, some form(s) of mediation must be incorporated. So, if the subject, say a carpenter, wants to join two pieces of wood together (the purpose of which constitutes the object of the activity), she must use several tools, some of which may be her carpentry knowledge (psychological tools) and a hammer and nails together with selected pieces of wood (material tools) in order to realise that outcome. However, it is virtually impossible that the actual object of the activity will be simply to join two pieces of wood together, devoid of any meaning.
There will be a reason for the carpenter’s actions and they will be imbued with meaning for her. Otherwise, the activity would be random, purposeless, spontaneous and impulsive. If human beings acted in such a way, there would be no coherent structure to the world: actions would be devoid of meaning. It is much more likely that the object of the activity will have significant meaning associated with the activity such as creating an artefact, and the reason for creating the artefact will be further imbued with meaning. These multi-stable meanings will vary across space, time and participants. Like our farmers before, the carpenter may be motivated by money, or the development of higher level carpentry skills, or both. In order to better understand the object of a subject’s activity, Vygotsky analysed the cultural tools that mediated the activity. Vygotsky’s triadic model tended, however, to favour individual action. Leont’ev wanted to extend the analysis in order to consider collective activity as well as individual action. To this end, he made a distinction between the concept of individual action and collective activity.

Actions, for Leont’ev, are goal-orientated and individual in nature. Activity, on the other hand, is collective and social, and has, as a central feature, the division of labour. In a now famous passage (to those who read activity theory in any depth) describing a primitive hunt, Leont’ev distinguishes between activity and action:

“A beater, for example, taking part in a primeval collective hunt was stimulated by a need for food or, perhaps, a need for clothing, which the skin of the dead animal would meet for him. At what, however, was his activity directly aimed? It may have been directed, for example, at frightening a heard of animals and sending them towards other hunters, hiding in ambush. That, properly speaking, is what should be the result of the activity of this man. And the activity of this individual member of the hunt ends with that. The rest is completed by the other members. This result, i.e., the frightening of game, etc. understandably does not in itself and may not, lead to satisfaction of the beater’s need for food, or the skin of the animal. What the processes of his activity were directed to did not, consequently, coincide with what stimulated them, i.e., did not coincide with the motive of his activity; the two were divided from one another in this instance. Processes, the object and motive of which do not coincide with one another, we shall call ‘actions’. We can say, for example, that the beater’s activity is the hunt and the frightening of the game his action” (Leont’ev, 1981: 210).
Activity as a whole is composed of complex multi-stabilities that are set within relative or particular narratives. In other words, there are no activities that are immutable and universal in nature. Activities in this sense are collective and contextual. Activities are not typically directed towards their motives. Rather, they comprise units of activity that are purposeful and meaningful to the particular subject(s) involved at that particular time and in that particular space. They are thus formed by predetermined local and relative actions, or in other words, they are socially and culturally determined, each having its own goal (the division of labour) and it is that object that forms the motivation for the subject’s particular action.

To summarise, “Activity theory begins with the idea of a purposeful subject. Only living things have needs. These needs can be met by acting in the world, by bringing together the subject’s need and an object. When a need meets its object, the object becomes a motive and directs the subject’s activity. For humans, needs are, in significant measure, culturally shaped. The most fundamental notion of activity theory is the motivated activity of a subject enacted in culturally meaningful ways” (Kaptelinin and Nardi, 2006: 199). Considered in a classroom context, the motivating factors that form a need to learn about design, for example, would involve a multitude of goal-orientated actions undertaken by a number of participants across time and space who all contribute in some culturally meaningful way, thus acting intentionally towards some tangible outcome that serves, in some fashion, to facilitate learning about design (or just learning). So a school designed by architects and constructed using materials fabricated by others will offer a curriculum designed by policy-makers that will be delivered by teachers to young people. All of these multifarious goal-orientated actions are intended to combine in order to form a culturally meaningful activity called learning.

The Use of Tools, Intentionality and Systems

Drawing directly from Marx and Engels, Leont’ev introduces two mutually dependent mediating aspects relating to the subject-object activity involved in the Marxian concept of labour (Engeström and Meittinen, 1999):

“The first is the use and making of tools. ‘Labour’, Engels said, ‘begins with the making of tools’. The second feature of the labour process is that it is performed in conditions of joint, collective activity, so that man (sic) functions in this process not only in a certain relationship with nature but also to other people, members of a given society. Only through a relation with other people does man (sic) relate to nature itself, which means that labour appears from the very beginning as a process mediated by tools (in the broad sense) and at the same time mediated socially” (Leont’ev, 1981: 208).

For Leont’ev then, human cultural and social development cannot be considered only in terms of individual actions upon the objects of Nature. A collective activity system is constituted by not only individual human actions, but by all of Natures objects acting together, material as well as organic, human as well as animal. These multi-stable activity relationships combine to form what Latour (2005) describes
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as ‘Actor Network Theory’, or to what Delueze & Guattari (1988) refers to as an ‘assemblage’. Collective activity can only exist in a culture guided by purposeful intention. Or as Miettinen (1999) puts it:

“A gradual breaking of the direct, immediate, impulse based relation to the objects of the environment. With cultural development – characterised by communication and the construction and use of tools – a specifically human type of consciousness emerged. [Such a consciousness] also implies the capability if imagining and planning what the future may hold; that is, intentionality” (Miettinen, 1999).

Miettinen also noted that only humans can “take the initiative in the construction of new assemblies of humans and materials” (in Kapteijn and Nardi, 2006: 200). Technologies do not have needs, motives or intentions. They are, however, tied to a task that has varying degrees of meaning to a human. A technology, in this sense, is “something-in-order-to” (Heidegger, 1962). It is through the intentional use of technology as ‘something-in-order-to-serve-some-human-need’ that significantly assists in the formation of a given culture. It is then through the continued development of technology that the (re)-formation of any given culture continues to develop and change over time.

To recap, Activity Theory is more concerned with the analysis of a given activity system. The system under analysis may include many ‘actors’: human, non-human and technological. A technological system, whether a simple lever or a complex machine, has no inherent intentionality: this can only be designated or given by the designer, the fabricator and ultimately, the user of the technology. Technological systems can thus only be understood in terms of their designated purpose considered in conjunction with the interaction of human beings, and this designation is open to constant interpretation and reinterpretation. A car, for example, is simply a concatenation of inert materials that have been fabricated and subsequently assembled together in order to form what we have come to know as a car. However, without the inclusion of a human ‘actor’ as the user or the observer, the car is essentially meaningless. It does nothing independently, it has no independent conscious intention, it awaits its crucial vital dynamic component: it is only the human being who has any purpose and intentionality in her association with the car and the environment. These human purposes and intentions are multi-stable. Whilst many will argue that the primary function of a car is to get from A to B, Activity Theory helps bring to light the intention of the human-technology relationship. A suicide bomber has a different purpose and intention for a car than a commuter has, for example. The object of their respective activity is quite different, as will be the subsequent outcome.

Human activity can be analysed in similar terms. It is the purpose and intention motivating those involved in any activity that serves to reveal the meaning that lies behind any given activity. Activity Theory is not concerned with individual participants per se. Rather, it is concerned with revealing the meaning behind the actions of the participants. It does this by exploring the purpose or intent that participants or subjects in a given activity system, such as a classroom, have towards the object of their activity, in order that they might achieve some meaningful outcome by transforming the object of activity into a new outcome. Considered in reverse,
Activity Theory can help reveal the underlying meaning and hence the motivation of the subjects in the classroom setting. This is a fundamentally different approach to analysing classroom practice because it does not consider the teacher separately from the pupils. Nor does it separate the subject content or the assessment procedures. It considers the activity only in terms of the participants, and it is this classroom context that I now wish to consider in greater detail. It is important to highlight that I am presenting this analysis in a philosophical context. I have not undertaken any empirical research personally but have used other data, including empirical studies, to inform my arguments.

ACTIVITY THEORY CONSIDERED IN A TECHNOLOGY EDUCATION SETTING: A PHILOSOPHICAL EXPLORATION.

There is now a considerable corpus of research into contemporary pedagogy, curriculum development and the concept of knowledge, as well as the purpose of technology education. I do not intend to challenge or support any of this research in this chapter. Activity Theory, whilst recognising the importance of these on-going discussions, is more interested in meanings, intentions and motivations as agentive processes rather than as hierarchically imposed goals.

Goals may be the properties of the teacher by way of schools as institutions but not necessarily the properties of the pupils in the classroom. In this sense, “the institutional goals [ ] are part of a larger culture… but not the goals of individual subjects” (Kaptelinin and Nardi, 2006: 205).

Using the theoretical tools underlying the concept of Activity Theory, teachers can reform their pedagogy to create a more constructive learning environment that is less goal-driven, as suggested above. These new intellectual tools enable a more contextualised and authentic learning experience in technology education.

“Education provides new ‘tools of the intellect’, to be sure. But without contexts of use, these tools appear to ‘rust’ and fall into disuse” (Cole, 1990: 106).

Building upon the previous discussion, I will now offer what I consider to be several flawed models for delivering technology education, culminating in one that utilises Activity Theory to enhance classroom practice. I have discussed the subject-object relationship above. I now offer this in a technology education classroom context.

Figure 3 illustrates that the subject acts upon an object in order to achieve some desired outcome. The model shown in Figure 3 forms a crude template for a teacher’s goal-driven actions upon a technology education class. This model, I will argue, forms the dominant orthodoxy of teaching practice in schools today where the teacher is considered to be the expert and the student the passive learner. In this model, the technology teacher (perceived as the subject and separate from the object) will act upon the class (perceived as the object and separate from the subject) by teaching the class in order to [insert outcome]. However, this model is flawed in several respects.

First, it considers the class as being some material homogeneous entity rather than as a heterogeneous group, which suggests that the class, or year group, must move together as a single collective unit as directed by the teacher.
Second, it suggests a passive learning environment. The class (perceived as the object) is acted upon by the teacher (perceived as the subject). The way in which the class is thus modified is brought about by the actions of the teacher onto the class, in order to achieve some goal-orientated outcome designed by the teacher (or curriculum). In other words, the learners’ needs are prescribed by others.

Third, it is a very restrictive model for the development of creativity through design, for example. The outcome is controlled and designed by the teacher, the class has no agency in the process; their needs are again prescribed by others.

Fourth, the process is linear and unidirectional.

Finally, the class (perceived as the object) in this model must constantly look back to the teacher (perceived as the subject and separate) in order to seek direction and thereby know how to achieve the prescribed outcome ahead of them (represented by the dashed arrow in Figure 3). Whilst the class looks back, the orientation is still unidirectional: from the subject (teacher) through the object towards some outcome.

The teacher (subject) and the class (object) are thus seen to be distinctly separate components in this activity system. The teacher (subject) unilaterally directs the class (object) towards an outcome, preconceived by the teacher (and others who set the exam criteria and design the curriculum).

The Significance of Mediation

Remember that activity theory recognizes that in all activity, the relationship between the subject and the object is always mediated by tools. It is as a result of this mediation that the outcome will be shaped, one way or the other. If the teacher (perceived as the subject) needs to get her class (perceived as the object) to pass an exam in design, for example (the outcome), she will have to make some serious decisions as to how she might purposefully undertake this task. She will have to consider what resources she might employ: books about design; design tools like pencils, paper, CAD, etc.; her own expertise and experience; some concept for the students to work around. It is these tools that mediate between the subject and the object. This is illustrated in Figure 4.
The subject (perceived as the teacher) and the class (perceived as the object) are thus mediated by tools, which, in this case are provided by the teacher (or the school) for the class to use in order to engage in an action. The object of this will be to achieve some desired outcome decided by the teacher, who, in turn, is guided by those who set exams as well as policy-makers, head teachers and curriculum developers, etc. So, if, for example, the teacher wants to get the whole class to pass the design exam, she must consider the meditational tools that she will use in order to achieve this. Options might include, at one end of the spectrum, the teacher making available several authentic situated design tasks that she thinks will help motivate the class to work towards developing a better understanding of the concept of design, also passing the exam. At the other end of the spectrum she might simply get the class to practice past exam scenarios until they are able to pass all the required elements. It is important at this stage to remind ourselves of the distinction between action and activity: action is goal-driven and individual in nature whereas activity is collective and social in nature (Leont’ev, 1981). This reveals two distinct classroom dynamics. One is action, the dominant orthodoxy in which the teacher (perceived as subject) attempts to transform the class (perceived as the object) into passing an exam. This is individual in relation to the teacher who is goal-driven and passive to a large extent on the part of the class. The second variation follows a very similar model but does allow some agency on the part of the pupils.

This model is essentially behaviourist in form. The teacher (perceived as the subject) is trying to shape and thus change the behaviour of the class (perceived as the object) in order to have the class achieve the desired outcome as stipulated by the system. The class has little (or no) agency in this model, even in the one in which the teacher uses situated learning concepts because it is she who selects them independently of the pupils. It is Piaget, a constructivist, who offers us an enhanced model. He argued that children develop their understanding of the world by interacting with it and constructing meaning from it as a result of this reflection. This is illustrated in Figure 5.

![Figure 5. Teacher directed model of instruction.](image-url)
The model represented in Figure 6 is not meant to depict the large corpus of work and theory developed by Piaget. It does, however, represent my interpretation of a constructivist model of teaching. Furthermore, it brings to light the fact that the model cannot work if the object is the class. In this case the class would have to be a homogeneous mass, so to speak. Given, however, that any class is a heterogeneous collection of individuals with different needs and wants, different purposes and intentions, the models discussed thus far can work only if the object is taken to be an individual. In this case, the teacher can lead the class towards a common outcome only if she adjusts the mediational tools to take account of every individual in the class.

It is Vygotsky, a social constructivist, who changes the model to one in which socio-cultural and historical considerations are taken into account. This is represented in the model seen in Figure 7.

This model, based upon Vygotsky’s, resolves four of the five flaws outlined earlier. The learner in this model is no longer passive but takes an active role alongside the teacher and the classmates. The arrows indicate a more dialogic model in which this active role enables a more collaborative and thus creative learning environment in which participants have the freedom to test out individual and collective ideas. These ideas consequently allow the participants to begin to look forward by enabling them to try out new and innovative design ideas that do not require (at least initially) any reference to previous ideas. This is in line with Kimbell and Perry’s (2001) notion of creative environments where technology education classes are “packed with opportunities to explore and exploit designerly hunches” (p. 8). The one flaw this model does not resolve is the one related to heterogeneity. It still considers the class(object)
as homogeneous as is the case in all the previous models. In light of this, it can only consider the individual separately, albeit within the structure of the class. This, however, brings to light the clarion call that resonates with all student teachers (as well as in-service teachers): they simply cannot teach 20 or more pupils individually.

Activity theory enables us to consider a way to overcome this problem. If we consider a technology education class as an activity system rather than as a series of actions undertaken by the teacher in order to achieve prescribed goals, we become less concerned with the individuals. Rather, we are concerned with revealing the meaning(s) behind the actions of the participants. If the activity in the class is technology education, then the participants or actors in that activity are collectively the teacher, the students and the materials; together they constitute the subject of the activity. The object of the activity is no longer the class, seen as some material homogeneous mass. Instead the object becomes the design of [insert that which is to be designed] in order to transforming procedural and conceptual knowledge development into an outcome that will satisfy some human need. Some examples may help to clarify this.

The subject (now teacher and students) may wish to transform the design of a chair (object of their activity) in order to learn more about product design (outcome).
The mediational tools required for this will be constituted by looking back to historical, pre-existing materials, data, methodologies and techniques (tools). These will inform the student and the teacher how to transform the concept of a pre-existing chair into some novel form, and in so doing, learn about product design (outcome). Moreover, as the tools used in mediation will be socio-cultural, these will serve to shape the design of the new chair. If the mediational tools comprise, for example, things like chairs, techniques, materials, tools like saws and hammers, methodologies and influences that are culturally Chinese, then the new design will reflect this, whereas if the mediational tools are culturally European medieval, that is what will be reflected. It is the mediational tools that shape the outcome. Mediation will thus be constituted by looking back to historical pre-existing, socio-cultural data, both material- and knowledge based, and this will help to inform the student and the teacher in the transformation of the object into some novel design.

Although the activity of designing a chair requires the subjects to look back, it also, however, facilitates looking forward into the unknown – a novel chair design; new methods of fabrication, new use of materials. The outcome in this scenario may include the production of an artefact in the form of a chair; the development of psychomotor skills related to the construction of the chair; the development of skills associated with designing a chair, etc. The activity allows, moreover, for the development of conceptual knowledge. It is the tools used in mediating the activity as well as the collective teacher/class subject that will enable this development to occur. Given that the activity is designing and producing a new chair, each participant in the activity has agency. It is this collective activity that changes the pedagogical dynamics of the class structure. Rather than the teacher differentiating the activity for each child based upon perceived ability (unidirectional), the child, as an active agent in the activity, determines her own involvement (bidirectional). She does this in association with the teacher and her peers. The emphasis is no longer directed towards the individual but to the activity (see Figure 8).

It is significant to note that in the example given above, there are no clear and absolute ‘correct’ outcomes or solutions to the problem. Moreover, there is a great potential for spontaneous learning to take place. The participants’ design and construction is subject to discussion with teachers and fellow students (and others, if involved in the activity, such as experienced chair designers, for example). In this model, not all students have to design or make the same thing. Indeed, they may only design or make, or be part of a design group, construction group or both: understanding about the division of labour. This forms the basis of an interpretation of the activity that is founded upon the students’ experience to date and a reinterpretation through discussion and interaction with others. This model facilitates wider group participation, which, in turn, encourages broader discussion. An activity led by the teacher alone has a limited referential field of experience, whereas, an activity that involves 20 or 30 participants widens this field considerably and consequently the potential for creative activity.

By utilizing this new form of pedagogy informed by Activity Theory, teachers are no longer considered to be experts in some specific subject domain, depositing pre-established information into the minds of the young (a form of enculturation that is
closer to indoctrination). Rather, they become proficient in facilitating learning about culturally meaningful activities that are considered useful to the learners (a form of enculturation that is liberating). The outcomes of the participants’ activity are no longer limited: a chair might become a stool or a bench or even a coat rack. The activity is constantly negotiated and renegotiated between the participants. If the collective meaning behind the activity is restricted to passing examinations only, then the participants can easily work collectively towards that goal. However, under

Figure 8. Pedagogical model influenced by activity theory.
these circumstances they may conceive their participation in education as being somewhat reductive. If, on the other hand, their collective intention is directed towards learning something that is infused with meaning for them, their intentions will be motivated towards that end. In this latter case, the process is thus no longer school-based, abstract and exam-orientated having only a momentary impact on the participants. Instead, the activity system becomes socio-culturally significant with more enduring patterns of interaction. "It is this projection from the object to the outcome that, no matter how vaguely envisioned, functions as the motive of [the] activity and gives broader meaning to [the participants] actions" (Engeström, 1999: 31).

CONCLUSIONS
Activity theory teaches us that the quality of learning is determined by the nature of students' activity. Interaction with physical and intellectual tools (mediation) is central to learning. The outcomes of learning are not just about acquiring existing knowledge and skills, important though that is, but it must also be about developing students’ intellectual skills (as seen in Figure 8). Whereas the development of existing knowledge and skills (using woodworking tools or understanding the properties of timber, for example), does involve an expert-apprenticeship form of pedagogy, and the knowledge developed is essentially value-neutral (a saw is for sawing, hardwoods are classified for us) and risk aversive. The development of intellectual tools requires a more collaborative and explorative approach. No one, not even the teacher, has authority over this type of knowledge. It tends to be value-laden and risk-laden: Is that a good design? Is that the best material? Is that method of production sustainable? These types of questions can only be encouraged in a pedagogical framework such as the one represented in Figure 8. Activity theory offers us a pedagogical framework to enable the development of these intellectual skills that, I would argue, are distinctly lacking in the delivery of technology education.

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