The 7 trans-disciplinary habits of mind: Extending the TPACK framework towards 21st Century Learning

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Abstract

In this article we examine the need for fostering transformative learning, emphasizing the roles that trans-disciplinary thinking and recent technologies can play in creating the transformative teaching and learning of the 21st century. We introduce the Technological, Pedagogical Content Knowledge (TPACK) framework as a starting point for discussing the special kinds of knowledge, skills, and understanding that teachers require in order to become effective classroom mediators of transformative learning experiences. Within this framework, we propose seven cognitive tools needed for success in the new millennium, and describe how teachers can repurpose digital technologies to use these cognitive tools. We explore the implications of these issues for research and practice.

> Today, the defining skills of the previous era—the "left brain" capabilities that powered the Information Age—are necessary but no longer sufficient. And the capabilities we once disdained or thought frivolous—the "right brain" qualities of inventiveness, empathy, joyfulness, and meaning—increasingly will determine who flourishes and who flounders. (Pink, 2005, p. 3).

In this paper, we argue that one key aspect to transformative learning, given the demands of the 21st century, is its *trans-disciplinary* nature. In our approach "trans-disciplinary" goes beyond inter-disciplinary, identifying deeper themes and habits of mind which cut across disciplinary boundaries and allow for greater creativity. In addition we argue that such a trans-disciplinary approach is greatly supported by the possibilities of digital technologies. We situate this new kind of learning, and the role of technology in facilitating this change, in the framework of Technological Pedagogical Content Knowledge (TPACK). Using the TPACK framework, we propose seven trans-disciplinary habits of mind (or cognitive tools) needed for success in the new millennium, and offer examples of how teachers have repurposed digital technologies to use these cognitive tools.

The role of technology in learning

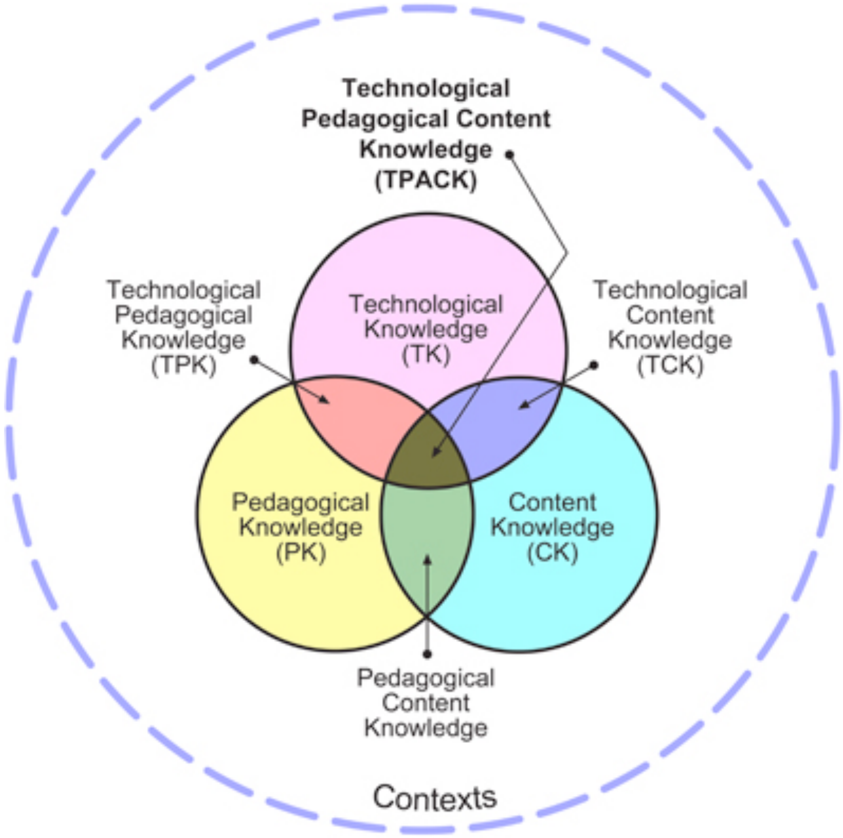
We live in exponential times – digital technologies have already transformed the way we work and play. From cell phones to websites, from YouTube videos to multiplayer games like World of Warcraft, technology is fundamentally changing how we humans interact with information and with each other. The future promises more of the same, given the ever-increasing pace of technological innovation.

It is no surprise that the ongoing discussion of technology and its role in education takes on even greater significance today. This rapid rate of change can be a big challenge for educators, as technologies become obsolete as quickly as they arrive. With increased pressure on teachers to learn new ways to integrate technology with their teaching, billions of dollars and countless hours have been spent on hardware, preparation and training. Despite this, technology integration still finds disappointing levels of penetration and success (Barron, Kemker, Harmes & Kalaydjian, 2003; Cuban, Kirkpatrick & Peck, 2001; Bauer & Kenton, 2005; Ertmer, 2005; Frank, Zhao & Boreman, 2004; Gulbahar, 2007; Keengwe, Onchwari & Wachira, 2008). A recent review of the research and scholarship on technology integration identified teacher knowledge as one of the key barriers for effective technology integration (Hew & Brush, 2007; Mishra & Koehler, 2006). Teachers must know more than the technical aspects of technology, and must understand that technology has affordances and constraints both for representing content and identifying pertinent teaching approaches (Harris, Mishra & Koehler. 2009). Recently, the *Technological Pedagogical Content Knowledge* (TPACK) framework (American Association of Colleges of Teacher Education, 2008; Koehler & Mishra; 2008; Mishra & Koehler, 2006) has developed as an integrated framework for teacher knowledge for effective technology integration.

The TPACK framework acknowledges that teaching is a highly complicated form of problem seeking and problem solving using flexible and integrated knowledge (Glaser, 1984; Putnam & Borko, 2000; Shulman, 1986, 1987). Teachers practice in a complex, dynamic environment (Leinhardt & Greeno, 1986; Spiro, Coulson, Feltovich, & Anderson, 1988; Spiro, Feltovich, Jacobson & Coulson, 1991) and must integrate knowledge of student thinking and learning, knowledge of the subject matter, and increasingly, knowledge of technology. At the intersection of pedagogy, content, and technology, is the very specialized brand of teacher knowledge represented by TPACK.

This TPACK framework describes these three components together as being a critical synthesis of knowledge used by the most effective teachers. *Content Knowledge (CK)* refers to the knowledge about the subject matter that is to be learned or taught, such as 8th grade mathematics, or 5th grade science (though we shall complicate this somewhat straightforward conceptualization later in this article). *Pedagogical Knowledge (PK)* refers to knowledge about the processes and practices or methods of teaching. It includes classroom management skills, teaching strategies, evaluation techniques, and the nature of target audience. *Technology Knowledge (TK)* refers to knowledge about both the standard technologies and more advanced technologies. It enables teachers to understand information technology, apply it properly for optimum learning, identify useful technologies, and continually adapt to changes in technology (Mishra & Koehler, 2006; Mishra & Koehler, 2008; Koehler & Mishra, 2008; Mishra & Koehler, 2009;

Koehler & Mishra, 2009; Harris, Mishra & Koehler, 2009).



The TPACK Framework (source: www.tpack.org)

As shown in the diagram above, each of these three core constructs interact with each other in important ways. At the heart of this framework is *Technological Pedagogical Content Knowledge* (TPACK), which emerges from the interaction of content, pedagogy, and technology knowledge. *The TPACK framework suggests that quality teaching requires developing a nuanced understanding of the complex interplays between three key sources of knowledge: technology, pedagogy, and content, and addresses how they play out in specific contexts* (Mishra & Koehler, 2006; Koehler & Mishra, 2008; 2009).

Over the past few years the TPACK framework has received a great deal of positive scholarly and research attention. For instance, the tpack.org wiki lists more than 15 dissertations, over 60 articles and conference presentations and symposia related to TPACK over the past two years (www.tpack.org). These include articles on implications of the framework on teacher professional development, instructional strategies for developing TPACK, and research on measuring changes in teacher's TPACK over time. The TPACK framework is also becoming an integral part of teacher education courses at universities and programs for teacher professional development in K12 schools (http://punya.educ.msu.edu/research/tpck/newsletter-archive/). In brief, the TPACK framework has become a key part of the discourse on educational technology use in relatively short period of time (given that the journal article introducing the construct was published just in 2006!).

There has been one key misconception about the framework that is important to discuss. The TPACK framework has often been described as being just about the integration of newer digital technologies. However, the TPACK framework is as applicable to older technologies such as the pencil as it is to the iPod. In fact the TPACK framework is neutral not just about technology but with respect to content and pedagogical goals as well. The TPACK framework offers little guidance about *what content to teach*, *which pedagogical approaches are useful*, and *what kinds of technologies* are worth using in teaching.

In some sense the breadth of its application is the framework's greatest limitation as well. *So the important question we need to ask ourselves as educators is what today's students need to know* (the "C" in the TPACK framework). This must come from outside the framework. Once we have identified these larger purposes and goals the TPACK framework can help us determine *how* to achieve them.

Living and learning in a changing world, an overview and a critique

The rapid evolution of technology is just one of the many changes that have the 21st century has brought to our lives. We live in a more competitive, yet more interdependent world. We confront multiple business, political, social, scientific, technological, health and environmental challenges that demand creative solutions in a complex world. Global economies driven by innovation and knowledge dictate that jobs of the future will require creative people who are life-long learners (Florida, 2002; Peck, 2005).

The scope of these changes clearly calls for a new form of learning, one that is receptive to this continually changing world. Certain skills and ways of thinking become more essential for students to master. Recently there have been a spate of books and reports that criticize the current goals and practices of schooling (Zhao, 2009; Keengwe, Onchwari & Wachira, 2008; Kozma, 2003, 2009). These authors argue that schooling needs to be fundamentally reconfigured to meet the demands of a changing world. As the

Partnership for 21st Century Skills states in their Mission Statement, "Every child in America needs 21st century knowledge skills to succeed as effective citizens, workers, and leaders in the 21st century." These skills and competencies may be defined somewhat differently but they share some common themes. There is an emphasis on higher order cognitive processes such as critical thinking and creative problem solving, along with traits such as curiosity, and adaptability. It is also suggested that students engage in technology rich learning contexts where they work collaboratively to solve complex, multi-disciplinary, open-ended problems.

Though there is little to disagree with in these recommendations, we argue that the issue of *what* is to be learned (or taught) is often given short thrift in most recommendations about 21st century learning skills. Most of them do not even mention content, and in the rare cases (Schofield & Davison, 2002; Russell & Abrams, 2004; Law, Pelgrum & Plomp, 2008) that content is noted, it is only in terms of traditional disciplinary content areas, such as reading or language arts, arts, mathematics, economics, science, geography, history, government and civics. As we argue below, it is problematic to ignore content or conceptualize it in traditional ways.

Why we cannot ignore content …

The standard way of considering content in schooling is as disciplinary knowledge. Gardner has argued that disciplinary thinking is perhaps the greatest invention of mankind, and that the teaching of disciplines is the most important and least-replaceable purpose of schooling (Gardner, 2006, 2007). How this content is conceptualized is also critical, in terms of how it is presented and how it is learned. Creativity, which is included in most of these lists of 21st century competencies, cannot occur without some domain within which it would be evaluated. This lack of emphasis on the *content* of what is being learned (or taught) suggests that creative and innovative thinking can occur in a vacuum -- but this is a fundamental misunderstanding. This is contrary to most current research and theory on creativity, which suggests a more complicated relationship between domain knowledge and general creativity. This research shows that creativity is both domain general and domain specific, existing in a transactional relationship between the two. As Plucker and Zabelina, (2009) write in a review of the research,

> A person who deals with domain general techniques and approaches to creativity will never scratch the surface of a problem, yet someone who focuses too tightly for long periods of time on a particular task is likely to experience functional fixedness…. [The] optimal condition for creative production is a flexible position somewhere between generality and specificity… with the individual moving between positions as the task or problem of the moment dictates (p. 9).

This means that creativity is inextricably tied to cultures of disciplines, to ways of knowing that are constrained by specific fields of study *as well as* broader ways of thinking that cut across different disciplinary frameworks.

… and why we need to rethink it?

However, standard disciplinary structures, around which school-curricula have been constructed, may not be as useful today as they were before. Disciplinary knowledge in the traditional sense is shifting beneath our feet. As educators we have to realize that *disciplines are continually changing,* and thus *the kinds of disciplinary knowledge our students need to develop are changing as well.* A strict adherence to standard core disciplinary structures is quite limiting to the kinds of learning that are of most importance to our students. Most of the jobs of the future will be "hyphenated jobs", (bio-mechanics, environmental-engineering, product-psychology, interactive-media-design) jobs at the intersection of two or more disciplines. Thereby, recommendations for the future of learning emphasize the importance of being able to creatively move across multiple disciplines, to cross-pollinate ideas from one field to another. This shift in disciplinary knowledge is rarely considered in designing the school curriculum or lessons in the classroom, but we argue that it should be. Research shows that students not only lack the ability to transfer academic knowledge across fields, they do not feel comfortable with applying knowledge gained in one field to another or to real situations (Wagner, 2008).

So although the overall goals of 21st century learning skills (analysis, creativity, collaboration, communication and use of new technologies) are commendable, we must focus on ways to interpret them in cross-disciplinary terms. We argue that higher order thinking skills such as creativity cannot be taught in a vacuum. Creativity emerges from habits of mind that cross disciplinary boundaries. What we need is a trans-disciplinary approach that both values the disciplines *and* looks across them for common patterns and strategies. Only this can lead to true transformational learning.

Transformative learning and Trans-disciplinary learning

As must be obvious, preparing students for this rapidly changing world presents a challenge to teachers and teacher educators alike. It requires us to rethink the goals of education, from a static transmission model to a trans-disciplinary transformative model of learning. *Transformative Learning Theory* (Mezirow, 1991; 1995; 2000) helps to address this challenge by requiring learners to rethink prior knowledge, even drastically transform their approach to a subject matter. Transformative learning theory expresses the universal challenge of teaching and learning as the most critical kind of knowledge transformation – a "paradigm shift" or a perspective transformation, in which a renovation of existing knowledge structures occurs (McGonigal, 2005). This is best defined by Mezirow (1991) who explains it as follows:

> The process of becoming critically aware of how and why our assumptions have come to constrain the way we perceive, understand, and feel about our world; changing these structures of habitual expectation to make possible a more inclusive, discriminating, and integrating perspective; and finally, making choices or otherwise acting upon these new understandings (p.167).

There are many ways in which transformative learning, or getting learners to question their assumptions and to see the world "anew", can be instantiated. We suggest trans-disciplinary knowledge—*i.e. knowledge that even as it emerges from disciplinary practices transcends them, is key to helping learners to think in a creative and flexible manner.* Trans-disciplinary knowledge helps students move beyond looking for one "correct" solution, towards a more realistic approach that integrates many forms of knowledge, solutions, viewpoints, or perspectives. In this age of information-plenty, the best way to help students adapt to changes in technology and society is to help them develop an adaptable array of knowledge and learning skills.

More specifically, trans-disciplinary approaches eschew traditional distinctions between art and science, applied and pure knowledge, cognition and action. This approach seeks to find commonalities between strategies and habits and thinking used by creative individuals in any discipline. This contrasts with most depictions of creative processes, which are often seen as markedly different in the sciences and the arts. In reality however, many scientists and engineers frequently use the arts as scientific tools, and insights of the artistic kind have paved the way for successive scientific discoveries and their practical applications.

Our work in this area builds on prior conceptual work done in this area by Robert and Michele Root-Bernstein (1996, 1999). They have extensively studied the value of trans-disciplinary learning through both historical and empirical research. This has led them to demonstrate that creative scientists and artists generally use a key set of cognitive skills that cut across disciplinary boundaries. As they write:

> … at the level of the creative process, scientists, artists, mathematicians, composers, writers, and sculptors use…what we call "tools for thinking," including emotional feelings, visual images, bodily sensations, reproducible patterns, and analogies. And all imaginative thinkers learn to translate ideas generated by these subjective thinking tools into public languages to express their insights, which can then give rise to new ideas in others' minds. [11]

Based on their work we propose a list of seven key trans-disciplinary thinking tools (i.e. cognitive skills), which encapsulate how creative people think effectively across a range of domains[1]. These seven habits of mind or cognitive tools are: *perceiving, patterning, abstracting, embodied thinking, modeling, play, and synthesizing.* Each of these is described in greater detail below. We assert that these seven cognitive "tools," or habits of mind, comprise a framework for trans-disciplinary creativity and can serve as the basis for the kinds of curricula that are essential for the "conceptual age" in which we live in today (Pink, 2006).

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[1] The Root-Bernstein's list 13 cognitive tools in their book. In our work (teaching and research) we have modified this list to come up with seven that we consider to be particularly significant.

Connecting TPACK to trans-disciplinary cognitive tools

We began this article with a description of the TPACK framework and suggested that a criticism of the framework was that it was it underspecified specific pedagogical and content goals. The preceding sections were devoted to developing an argument for transformational learning of a specific kind. Thus the "C" or content in the TPACK framework has a new flavor—moving from standard disciplinary structures to one that values trans-disciplinarity. Consistent with the TPACK framework, this change in how we conceptualize content has implications for both pedagogy *and* technology. As we had said in a paper introducing the TPACK framework, the three components (T, P, & C):

> "Teaching and learning with technology exist in a dynamic transactional relationship (Bruce, 1997; Dewey & Bentley, 1949; Rosenblatt, 1978) between the three components in our framework; a change in any one of the factors has to be 'compensated' by changes in the other two." (Mishra & Koehler, 2006, p. 1029).

In the next section we describe each of the trans-disciplinary cognitive skills and also offer examples of how each of these, as habits of mind, can be instantiated in a classroom context through the appropriate, TPACK driven, use of technology.

1. *Perceiving*: The cognitive tool of perception is critical to both the arts and the sciences. We envisage it as a two-layered process, requiring both observing and imaging. Observing is the first step to understanding anything and is a finely tuned skill based on intent focus on, attention to, and curiosity about information gathered through the five senses. For example, bacteriologists use their sense of smell to observe bacteria, or an ornithologist might identify bird species by sound. Inventors and mechanics cultivate hands-on experience with tools and machines - relying on a sense of "feel" to know how tightly a knob or mechanical part is screwed on. A higher level of observation calls for imaging, or the ability to evoke or bring to mind the impressions/sensations we observe, without the presence of external stimuli. Artists, scientists, mathematicians and engineers all have well-developed imaging skills and find them essential for the work they do.

Both observation and imaging can be honed with practice to improve the skill of perceiving, and teachers can design opportunities for students to develop these skills. For example, the website *Found Functions* combines photographs of curves found in nature with the graphs and functions associated with them. An activity of this nature pushes students to go beyond the "abstract" curves in their textbooks, and observe the "underlying mathematical reality" of objects in the world. A similar activity for younger kids might be to take digital photographs of geometric shapes in and around their classroom or home or the use of stop-motion animation to study an evolving phenomena. This type of exercise utilizes knowledge highlighted in the TPACK framework where the use of technology is inextricably linked to the needs of pedagogy and content. By using the technical affordances of a digital camera along with the students' own senses, the lesson moves them away from traditional means of observation and transforms their thinking towards sharper *perception* of the world around them.

2. *Patterning*: Creative practitioners are always involved in recognizing and creating patterns. Recognizing patterns involves identifying a repeating form or a plan in a seemingly arbitrary arrangement of things or processes. Recognizing is the analytical part of patterning, while forming is basically a creative act of constructing new patterns. For example, when architects study a landscape and then utilize the patterns they see to design a building they are both recognizing and creating patterns. Because there is a finite number of basic structures they can work with architects must rely on both their understanding of existing patterns, along with their own creativity, to produce something new. Innovative writers and poets also do this, relying on their knowledge of linguistic patterns and structures, with their own innovations, in order to dream up a new story, poem, or other form of writing (Root-Bernstein, 2003; Gardner, 1983).

   Teachers can help students develop Patterning skills in both the arts and sciences, since patterning skills are useful within and across domains. One example demonstrates how the TPACK framework might be used to develop patterns that combine both Math and Music, using a freely available DJ software called trakAxPC. This software lets users download music samples and copy and paste them into a mixer. Students can cut the music samples into smaller units of sound and arrange them. What makes this a compelling TPACK lesson is that students essentially manipulate the trakAxPC software to help them describe and explain fractions, ratios and percentages. By connecting musical concepts such as rhythm and tempo to mathematical concepts (ratios and percentages, etc), students can creatively find and build patterns. Patterns form a relationship between concepts (musical beats per minute and ratios) that belong to different disciplines (music and mathematics). They can and should be integrated, however, and the elements of TPACK in this lesson are just one example of the myriad possibilities of how technology, pedagogy and content can seamlessly combine to design learning environments that promote students' patterning skills.

3. *Abstracting*: Creative people use *Abstracting* in order to concentrate on one feature of a thing or process, in order to boil it down to basics and grasp its essence. Scientists, for example, may eliminate all superfluous traits from a physical situation (i.e. shape, size, color, texture, etc.) to key in on features of interest such as boiling point or mass. Another aspect of abstracting is the finding of analogies between seemingly disparate things. We may be more familiar with poets using analogical thinking but scientists do it as well. Newton's comparison of the moon to a ball thrown so hard that its descent misses the earth and passes into orbit is an analogy as well, and one that led to the theory of universal gravitation.

   Anytime we ask students to distill the meaning or fundamentals of an idea or thing, and to explain by way of comparison, we are asking them to use abstraction or analogy. A creative example of this is a challenge recently put out by a professor of mathematics for her students to write mathematical poetry and share it with the world (on the web). This task represents the unlikely (in traditional domain specific thinking) junction between mathematical truth and poetic expression. The act of writing creatively and deliberately about mathematical topics necessitates a deep understanding of both the math idea of choice and the traditional conventions of poetry. In order for students to retell a mathematical proof or idea in a new and different way, they must fully understand the main idea (to abstract) and then "translate" this essence through analogies and other rhetorical moves into rhyming verse. Sean Nash, a high school biology teacher has extended this to the domain of science as well and has written extensively (on his blog) about its pedagogical value. His students have written dozens of poems that they share with the world on their class site. This in turn has motivated others to do the same. By pairing the pedagogical and content factors to the attributes of a technology (in this case word processing and the web), the lesson shows us how technology, pedagogy and content are bound together towards a common goal of transformative teaching and learning, and in this case, to facilitating the trans-disciplinary skills of abstracting and analogizing.

4. *Embodied thinking*: involves two skills which generally feed into each other - *Kinesthetic Thinking* and *Empathizing*. Kinesthetic Thinking means thinking with the body, including the sensations of muscle, skin and sinew; and the feelings in the body of movement, balance, and tensions. For example, in his thought experiments, Einstein imagined himself as a photon, and described not only what he saw, but what he *felt in his body* (Root-Bernstein, 2003). Besides this trait of bodily thinking, an important element of embodied thinking is empathizing, or imagining oneself in another's position, walking in their shoes, or feeling what they might feel. Actors, poets, and novelists, for example frequently empathize with other people, animals, and characters in order to portray them in interesting ways. Individuals in the sciences must also sometimes apply empathetic thinking to understand other organisms, even non-living things and processes.

   There are a number of different ways for teachers to tap into Embodied Thinking in their students. In sports or dance, kinesthetic thinking is often taught through drill and practice. In the Arts, empathizing can be taught through acting in plays or situational re-enactments. The mathematician and game designer Scott Kim (with his colleagues) conducts a series of mathematical dance workshops (called Math Dance) that allow participants to play with ideas of pattern and symmetry, through music and physical movement. Technology, however, can easily engage embodied thinking to illustrate a number of concepts. For example, by using a tilted and time-infused version of the Cartesian coordinate system (a dynagraph) in a math applet created with Geometer's Sketchpad, teachers can demonstrate the properties of a mathematical function. In such an applet students drag the input point A along a horizontal axis, and the output responds by moving appropriately according to a certain rule or function. Students can *see* the function traced over time, and *feel* the tempo of it as the input is pulled along the axis. Students can watch the motions of such functions with the same curiosity they might direct toward human behavior, asking, "What will they do next? Why are they moving like that?" From a TPACK standpoint, this is simple but excellent way to fuse technology, pedagogy and content by taking the concept of a mathematical function and rendering it in a visceral/kinesthetic manner in light of the affordances of such interactive applets. The learning experience is transformed from static to tactile.

5. *Modeling*: To create a model is to represent something in real or theoretical terms in order to study its nature, composition or purpose. Artists create and draw on models often by preparing smaller views of a piece of art in advance of creating it. Scientists also employ basic models of things and processes. Modeling requires that we employ abstractions or analogies, and more importantly that we use the facility of *dimensional thinking*, that is our thinking with respect to space and time. Creative people think dimensionally when they change the scale of things, when they take two-dimensional information (blueprints, etc) and construct them in three dimensions; or vice-versa, when they plot things that occur in three dimensions into two dimensions. This can be either (or both) a scientific or an artistic aspect of thinking. In the arts, this is the very crux of drawing in perspective; similarly, engineers must constantly think dimensionally in order to

toggle between blueprints/plans and actual structures. Dimensional thinking, paired with abstractions and analogies, help create models of things or processes that explain the real world.

The advent of software tools such as Geometer's Sketchpad has changed the nature of mathematics as it is practiced (and taught). This and other similar computer programs allow students to experiment with shapes and form, making it easier to construct standard geometry proofs. In this regard, the software program merely emulates what was done earlier when learning geometry. However, the computer program does more than that. By allowing students to "mess" with geometrical constructions, it changes the nature of learning geometry itself – proofs by construction are a form of representation in mathematics that was not available prior to this technology. This is a fundamental shift in geometrical thinking, from an axiom-to-proof approach (which has been the foundation of Euclidian mathematics), to one that celebrates experimentation and hypothesis testing. Learners can model phenomena and geometrical constructions and their relationships dynamically, in real time.

As a part of the *Bits to Atoms* project at the University of Virginia, teachers use cheap, portable and light-weight die-cutting machines to teach mathematics and visualization to children as young as 2nd graders. Students can develop their 3-dimensional visualization skills by designing 2-D cutouts that are then die-cut and constructed into 3-D shapes. Examples that have been used include models that depict the Earth's major tectonic plates that designed to be cut out and assembled with the aid of a used tennis ball. These are explorations that combine the power of manipulating digital bits and bytes with the physicality of atoms.

6. *Deep Play* (or Transformational Play): Playing is something that we do just "for the fun of it". Simply put, "play" is using knowledge, body, mind and abilities for the pure enjoyment of using them. When imaginative or innovative people play with things or concepts or processes, they may open doors to new ways of thinking via unexpected breakthroughs. Play by its multimodal, open-ended nature expands the manner in which we deal with concepts and ideas, leading to transformational ways of thinking. Creative people in different disciplines all speak to the value of play. They play with distinctions, boundaries, unassailable truths and the limits of utility and it is through this play that they also transform. They transform both themselves and the object of play. We call this deep-play to distinguish it from everyday play, which can often be quite superficial. Deep play in contrast is creative, seeking to construct new ways of being in the world.

Play has traditionally not received much attention, as a pedagogical strategy, in the school curriculum. Mathematicians (as creative people in other disciplines) often describe their work as being akin to play. The playful aspect of mathematics can be revealed in many different ways. Through video games and simulations, through puzzles and interactive software students can engage and play with ideas, propose solutions and test them. In some way, many of the examples already provided above (from mathematical poetry to constructing die-cuts) can be seen as examples of play. The crucial difference to keep in mind is that the essence of play is its open-endedness and that needs to be considered when thinking of including play in the classroom.

7. *Synthesizing:* The final cognitive tool or habit of mind really ties together all of the previous tools/skills discussed above. Synthesizing entails putting multiple ways of knowing together into synthesize knowledge. When we fully understand something (a concept, or a proof) our feelings, senses, knowledge and experiences come together in a multi-faceted and cohesive kind of knowing. A person feels what they know and they know what they feel. For example, Einstein noted that when he sailed he felt and experienced mathematical equations occurring via the boat interacting with the wind and the water. The creative process is often described by artists, writers and scientists as coming together of the five senses and their emotions, interlaced into an aesthetic and intellectual experience which is difficult to dissect. When feeling and thinking work together, creative and

> intellectual processes are far more powerful and have been described as being "synesthetic."
>
> The act of synthesizing is difficult to describe. In this it is similar to Dewey's idea of an educative experience, where continuity of an individual's past interacts with the present situation to open up a person's access to future growth experiences. By bringing together the previous six habits of mind, synthesis allows for the development of deeper connections between subject matters, and points to future development. Thus, these ways of thinking (and the examples that go with each) are not completely independent of each other. Figuring out the mathematical equations underlying shapes in nature is as much a process of perception as it is one of construction. Writing a poem is as much about pattern forming as it is about abstraction. In this these six tools work together to develop a synthesis greater than the sum of its parts.

In essence, these seven cognitive tools, which emerge out of disciplinary practices and are yet universal in their application, are key to the kinds of transformative learning we seek to achieve. We would like to point out two main attributes that the descriptions and examples share.

First, most of the examples require educators to repurpose existing tools for pedagogical purposes. For instance using the die-cut printer for teaching solid geometry was not something the tool was designed for – but it does a wonderful job none-the-less. We have described this idea of "creative repurposing" in greater detail in other publications (Mishra & Koehler, 2009; Mishra, Koehler, & Kereluik 2009; Mishra & Koehler, 2003; 2005).

Second, the reader may have noted that all the examples provided are connected to mathematics. This choice should not in any way suggest that these seven cognitive tools are applicable just for this domain. Quite the contrary, as "*trans-disciplinary*" skills they can, and should, be applied across other domains. In each case, we shall see that the standard boundaries between art and science, engineering and music fall to the wayside, leading to a focus on deeper, trans-disciplinary themes.

One of the reasons for choosing mathematics is that mathematics is often seen as being a dry subject, restricted to formulaic (pun intended) problem solving strategies. What few students realize is that this dull conceptualization of mathematics is very different from how practicing mathematicians see it. Mathematicians often talk about elegance and parsimony when they speak of proofs. Most mathematicians are fascinated by symmetry and balance, which are essentially aesthetic ideas. Mathematics can be (and has been) the basis of many artistic endeavors: from the tessellations of M.C. Escher to the songs of Tom Lehrer; from the Op art of Bridget Riley to the impossible structures of Roger Penrose; from the geometric patterns of Islamic architecture to the three-dimensional geodesics of 60-atom carbon molecules. All of these go to show that mathematical sophistication and artistic representation, far from being divorced from each other, actually do go hand in hand.

To realize that many students do not get to explore this rich conceptualization of mathematical thinking is tragic, denying them access to some of mankind's greatest achievements. (One could easily replace mathematics with engineering, writing, or music and so on, and the argument would still hold true, though of course the examples would change.) We believe that it is through this emphasis on trans-disciplinary cognitive tools and intelligent uses of technology students can learn the true nature of any domain, and through that have the potential to be transformed in how they learn, how they view themselves, and their possible futures.

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