The Interface between Cognitive Science and Innovation

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1. Introduction

This paper addresses an observed shortcoming of university efforts towards innovation – particularly at land grant STEM-focused institutions. Specifically the observation is that considerably more effort has been expended on actions towards the realization and commercialization of ideas than has been invested in research on the actual ideation process, how it occurs in the minds of the ideators, as well as which conditions promote it. This hypothesis is borne out by comparing university investments in ideation research to funds appropriated for realization and commercialization.

The synthesis presented in this paper focuses on ideation and the mental factors that enable and enhance this process. The intent is to create a foundation and framework for a systematic research agenda into this critically important area. As such, the document represents an essential first step of a work-in-progress. Because of this focus, a description of the interface between cognitive science and innovation is necessary if we are to understand ideation – at least as it occurs in the technological/engineering world. Ultimately thereby we should be able to create more effective programs to help participants become more innovative. Following this introduction, the outline of the paper employs the following headings:

- The concept of innovation
- Cognitive science principles
- Metacognition
- Motivation
- Composite model for metal processes related to innovation
- Questions needing to be researched
- Summary

This author[1] and others[2, 3] including President Obama[4], have built case for the importance of innovation multiple times. Essentially this case is based on innovation's significance to modern economies[5, 6]. Governments; local, regional, and national; have pinned their hopes on innovation as a way towards prosperity. One outgrowth of such concerted attention was the enactment of the *America Competes Act*[7] in August of 2010. Most importantly in this respect, innovation enhances the rate of growth of our economy. Additionally, however, it has been argued that not only does technology and innovation impact the economic dimensions of our lives but also that it plays a critical role in affecting the quality of our lives. Because of this importance, probably hundreds of centers[11] are working to advance innovation for a variety of purposes, including, economic development, workforce development, efficiency and sustainability

But, like most propulsive forces, innovation also requires certain "factors" to be present in order for it to occur. Just like plants require water, food, and light; innovation necessarily requires capable people as its core resource. That is why this paper specifically addresses the innovation process and the people doing the innovating. Furthermore the intent is to look internally at what is going on in the minds of the innovators and not at the environments necessary to support them. It is the discipline of cognitive science that studies and explains the mind and how it operates – hence the focus of this paper. The goal of this examination is to yield thereby some insights that would be helpful to faculty in engineering and technology programs as they work to develop graduates with increased inclination for, and capability with, technological innovation[8]. To that end, this paper will specifically address the innovation—cognitive science connection/interface.

2. The Concept of Innovation

First, however, it would seem wise to stipulate the concept of innovation, and even more specifically, technological innovation since that is the primary focus of attention of engineers and technologists. Although probably hundreds of pages have been generated to describe what innovation is, for our purposes here, perhaps the one generated by O'Sullivan[9] will work as well as any:

> Innovation is the process of making changes, large and small, radical and incremental, to products, processes, and services that results in the introduction of something new for the organization that adds value to customers and contributes to the knowledge store of the organization. (p.5)

Because the focus of this paper is on engineers and technologists, and because their primary role is to design and work with technology, it follows that the central focus of this paper must necessarily be on technological innovation. This construct has been conceptualized by the author as the innovation spectrum shown in Figure 1.

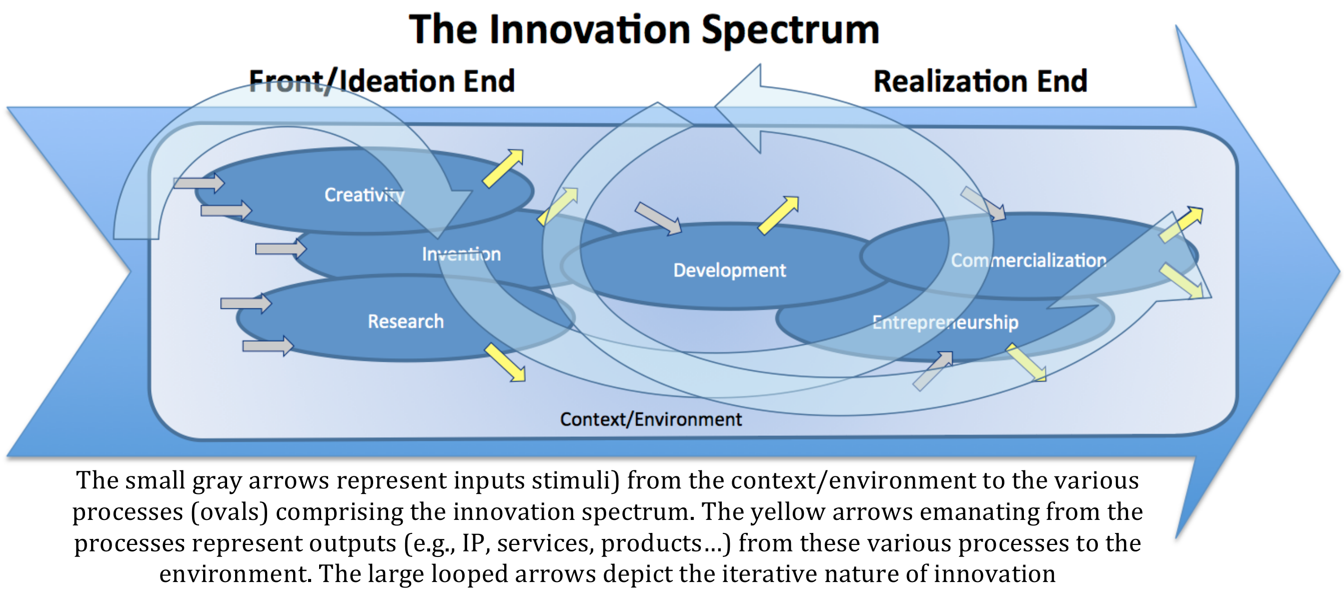

Figure 1 The Innovation Spectrum (Dyrenfurth)

Perusal of the proposed model for the innovation spectrum will evidence that it can be viewed as occurring in three stages as shown in Figure 2. These are (1) Ideation (involving creativity, invention, and research), (2) Development (involving refinement of and invention/innovation), and (3) Realization (involving commercialization or other forms of implementation and entrepreneurship).

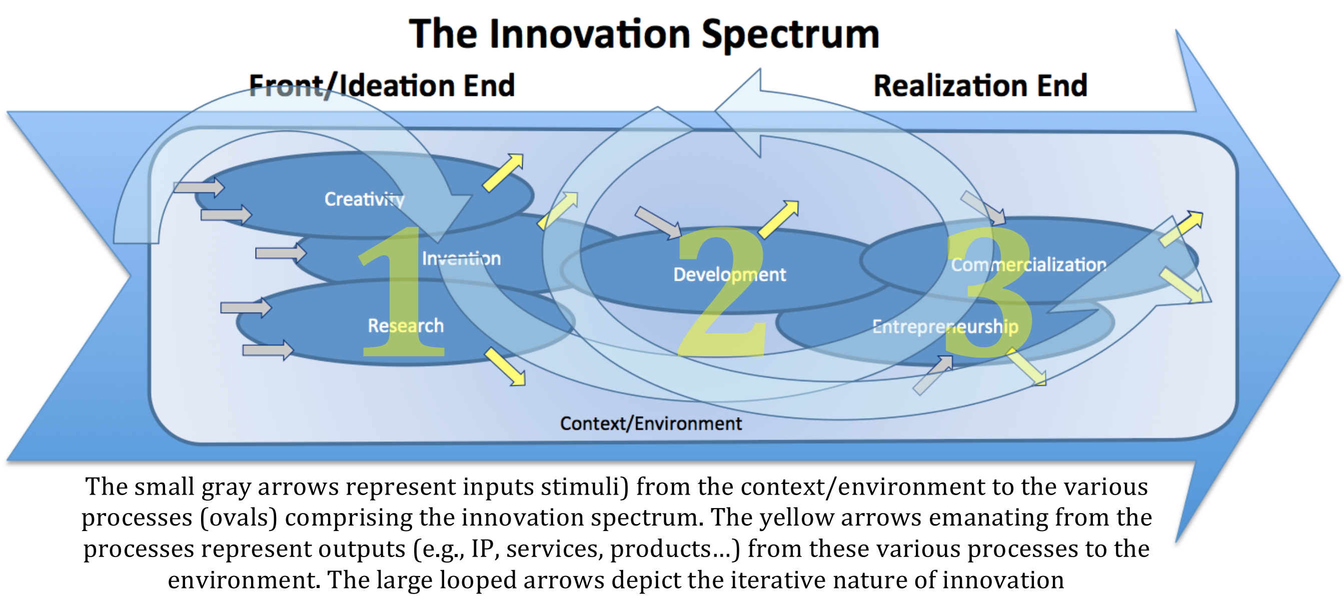

Figure 2. The Innovation Spectrum's Stages

The innovation spectrum's three phases of activity occur within an environment and therefore there are characteristic inputs and outputs (shown by small arrows) of each phase with this environment. The model also suggests the iterative/cyclical nature of technological innovation by its large looping ghost arrows.

But, while the model depicted in Figures 1 and 2 suggests how an innovation evolves and is subsequently commercialized or otherwise implemented, it does not show what happens in the mind of the innovator. The latter requires another perspective, i.e., one that looks penetratingly into the mind, both conscious and sub-conscious, of the person doing the innovating. To this end, Figure 3 was generated by the author to attempt to illustrate the complexities of innovation in the mind of the innovator. This model gradually evolved and was refined before, during and after the author participated in the CIRCLE invitational conference[10] on cognitive science in STEM Education (2014) held at Washington University in St. Louis and a subsequent one at Northwestern University a year later. The intent was to represent the mind of the innovator, and more to the point, his/her mental structures as generated by both formal and informal learnings. These activities, propelled by whatever goals motivated the individual, will have resulted in a set of understanding and capabilities situated in the three domains of learning that are conventionally used, namely the cognitive, affective and sensorimotor domains. The model further depicts these mental structures, understandings and capabilities being carried by the individual's needs, attitudes, learning styles and innate characteristics such a creativity, tolerance for ambiguity, fears, and the like.

Notably, the author recognized one of the major shortcomings of his initial model in that it did not depict any of the key processes (other than initial formal and informal learning) involved in the actual generation of an innovation or the processing of ideas leading to the generation of an innovation. For example the stimuli for ideation; such as observation, analogies from either the natural or human made world, systems theory, or other innovation tools such as the morphological box or contradiction analysis still need to be incorporated into the model. The author views the processing of ideas as the heart of cognitive science and this again pointed him to the central focus of this paper.

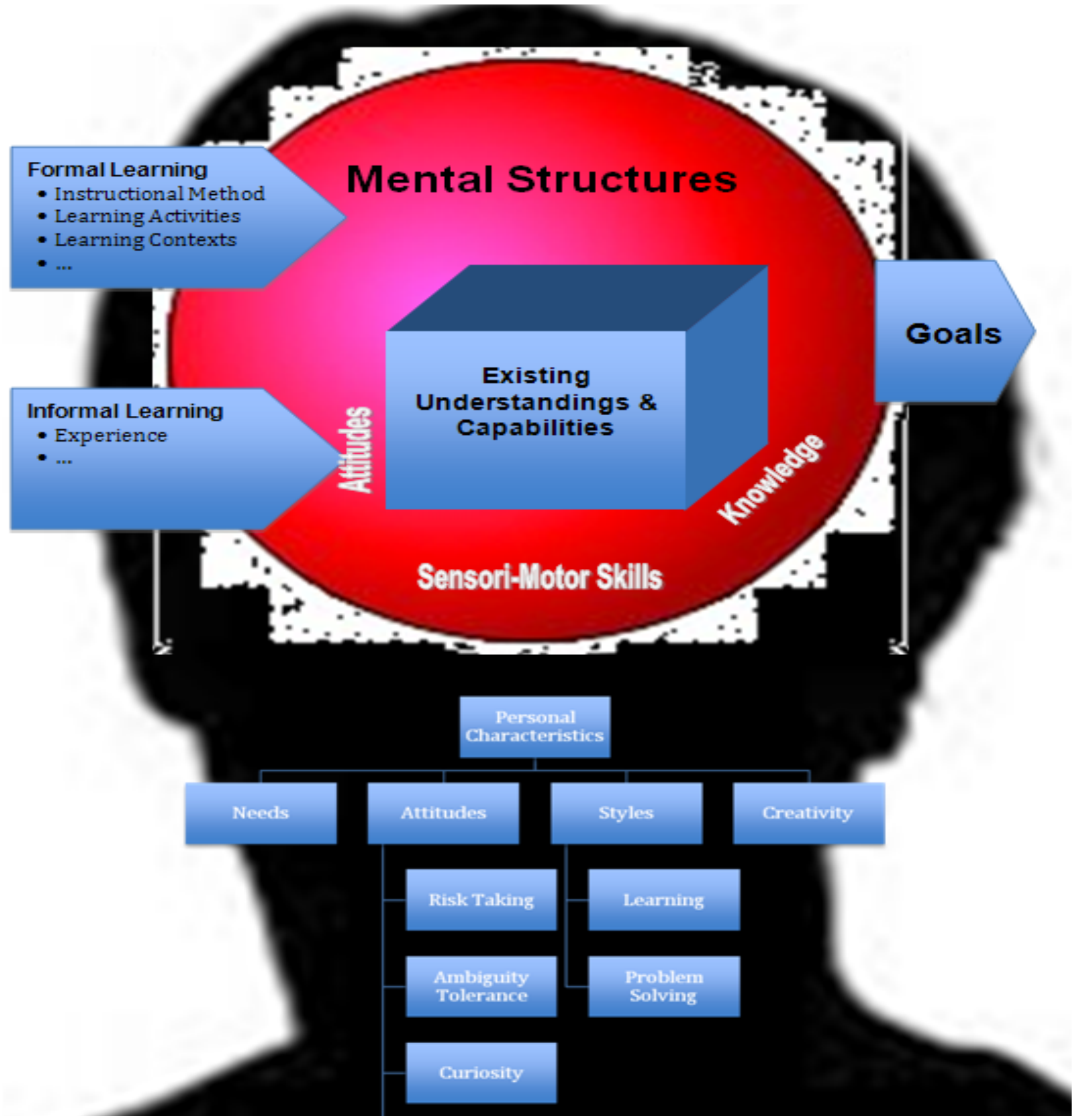

Figure 3. Initial Model for the Locus of Innovation

3. Principles of Cognitive Science

In an earlier paper[12] "The innovation – cognitive science interface: Implications for engineering & technology education" the author presented to European engineering educators that:

> Essentially cognitive science is the study of the mind, how it/we process information and/or stimuli, i.e., think, transform it, store and retain it, perceive it, reason, emote, and otherwise employ cognitive functions for a variety of purposes. For the purposes of this paper, our interest is how these topics affect not only our proclivity to innovate but also our capability to do so. In essence we are asking why do innovators see new patterns or connections or possibilities that others did not? Why are they able to solve problems in ways that were not visible to others? How do they do it? (p.4)

A systematic review of the scholarly literature reveals that the topic of ideation has received considerably less research effort than has realization and commercialization. The three major findings of this review will be highlighted by providing summaries of each: (1) the principles of cognitive science, (2) the concept and processes of metacognition, and (3) the motivations for innovation. Based on these findings the author then generated a composite model for metal processes involved in innovation. Both graphic and taxonomic descriptions of this composite model are presented in Section 6 of this paper.

The author's review of literature[27, 28, 29] describing the basic tenets of cognitive science resulted in his identification of ten concepts and/or principles, presented in Figure 4, that were central to the discipline. While the author is certain that these fundamental core elements do not encompass all of what cognitive scientists would maintain is the base of their discipline, it seems plausible that the ten concepts constitute at least a large part of the heart of the field.

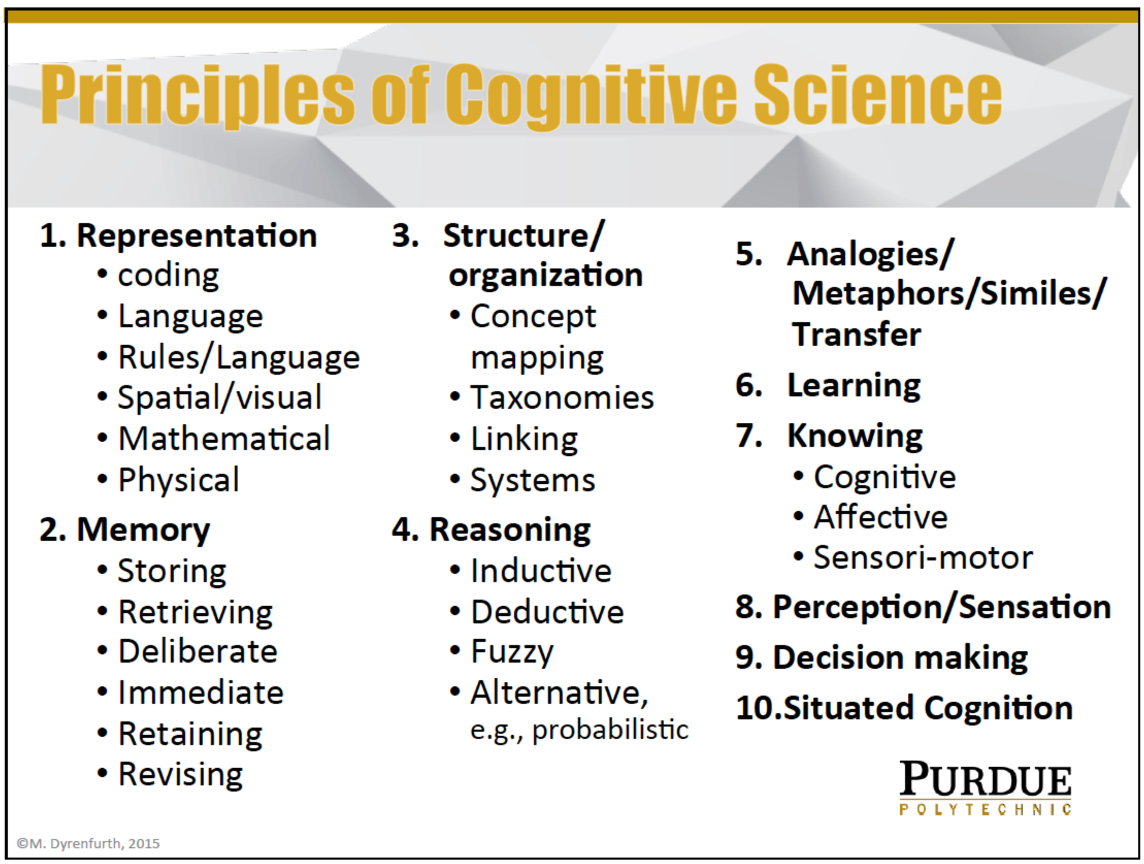

Figure 4. Principal Concepts of Cognitive Science

Engineering and technology education programs would be well advised to consider the potential of each of these phases and interactions for student learning activities. As prominent recent evidence of the need for attention to stimulating innovation by employing sophisticated educational methods that are inherently based on cognitive science principles, Bement, Dutta, and Patil[2], working pursuant to a commission from the National Academy of Engineering, have published a book entitled *Educate to Innovate: Factors That Influence Innovation: Based on Input from Innovators and Stakeholders*[2]. Similarly the National Research Council[30], *Educating the Engineer of 2020*[31], and Olson[32] have also spoken to the need for applying cognitive science and other sophisticated principles to the education of engineering and technology students.

For example, the following constitute a sample of effective practice furthering our students' propensity for, and capability with, technological innovation:

Phase 1 Ideation: In an introductory freshman class using creative brainstorming of how technological problems are addressed differently in various regions of the world.

Phase 2 Development: Implementing a vertically integrated capstone project that teams students from each year of the baccalaureate program on an industry-based problem. Senior students mentor junior ones to develop advanced skills.

Phase 3 Realization: Students work with entrepreneurs, for example in the university's technology park or incubator, in implementing an innovation

Interaction with Context:

- Students conduct a needs assessment to identify unmet societal needs in their community.
- Implementing EPICS[13] (Engineering Projects In Community Service) to address the identified need.
- Crowd sourcing and funding the implementation of a solution to the EPICs-identified need.

This paper focuses on ideation, i.e., the front end of the innovation continuum, as is highlighted in Figure 5 and which led the author to the field of cognitive science and its deep investigations into the processes of human cognition.

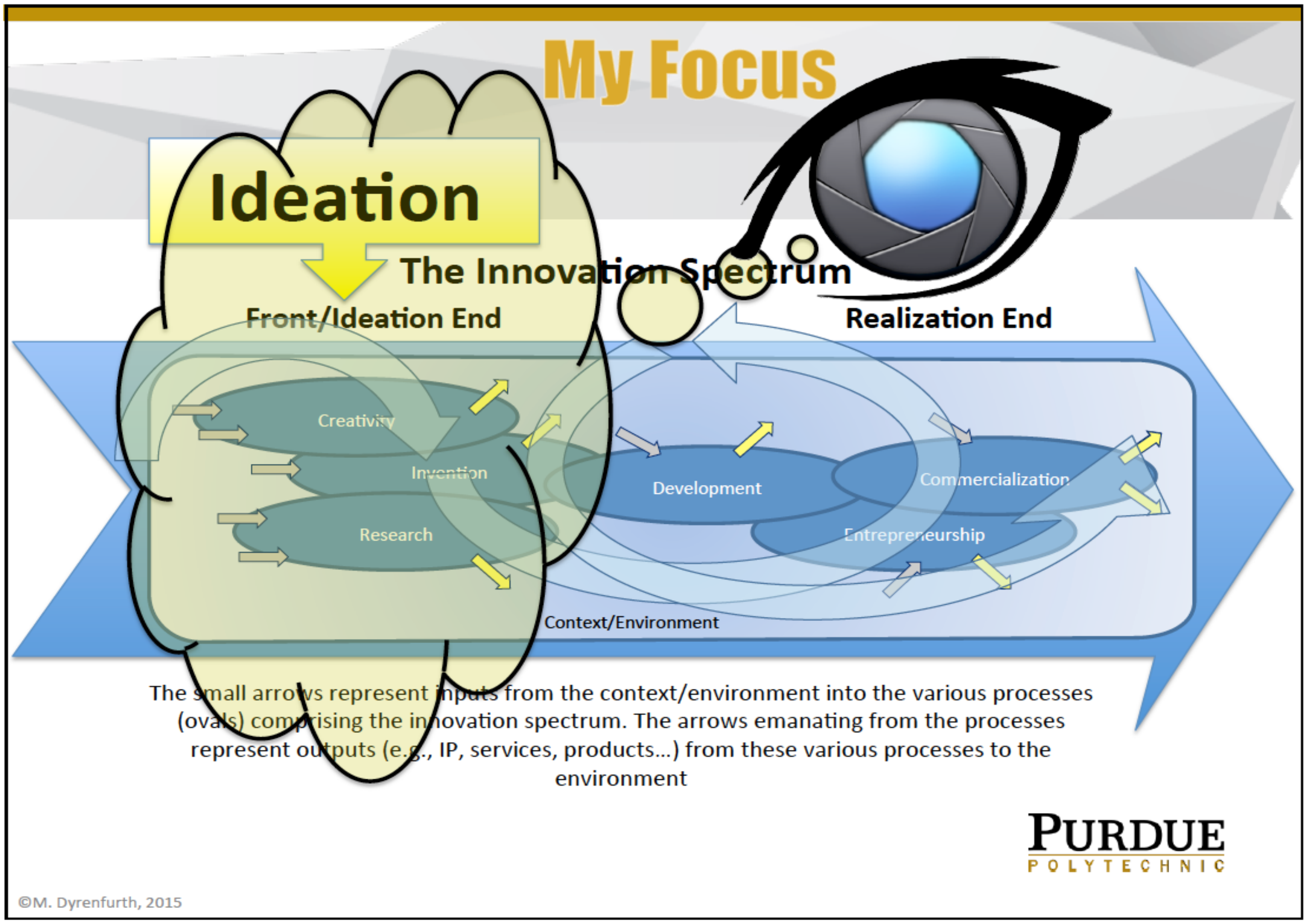

Figure 5. Ideation Focus of this Paper

So, how does cognitive science inform our understanding of ideation? Why can person A in a given situation generate a potential innovation while person B, perhaps even with a substantially similar background, cannot? Consideration of the concepts/principles presented in Figure 4 provides engineering and technology education researchers a framework for raising questions that might lead to fruitful investigations. The ten speculations listed below are initial examples of such research questions. Perhaps the innovator('s):

1. knowledge representation is more holistic, i.e., established as a system as contrasted to hundreds/thousands of discrete individual facts/ideas?
2. has a better memory and a larger/wider store of information to work with , or perhaps the innovator just has a better/quicker way of retrieving information?
3. organization/structure of knowledge lends itself better to pattern recognition so that the problem is better understood?

4. benefits from advanced reasoning capabilities?
5. is more adept and has a wider range of seeing analogies with similarities that provide a trigger for innovation?
6. has developed better learning habits that have yielded the larger store of knowledge referred to in question 1 (above)?
7. is more aware of their ‘knowing’ processes, i.e., metacognitive capabilities?
8. has evolved higher levels of perception/sensing enabling the recognition of cues that others miss?
9. is advantaged by better decision-making capabilities that evaluate information more effectively and/or that address a wider range of information?
10. situated cognition, i.e., learning/sensing, can interact with the environment better than others?

4. Metacognition

Certainly each of the ten cognitive science concepts/principles already highlighted in Figure 4 merit careful individual consideration by engineering and technology education researchers. This author intuits, however, that two of the concepts may play a more managing/executive role than the others. These two are Metacognition and Motivation. Each is dealt with in a separate section of this paper.

Metacognition refers to both metacognitive knowledge and metacognitive processes, i.e., executive functions, regulating one’s thinking.

1. Metacognitive knowledge[14]:
    - Declarative knowledge: refers to knowledge about oneself as a learner and about what factors can influence one's performance[15].
    - Procedural knowledge: refers to knowledge about doing things[15].
    - Conditional knowledge: refers to knowing when and why to use declarative and procedural knowledge[16, 17].
2. Metacognitive regulation or "regulation of cognition" contains three skills that are essential[14, 15].
    - Planning: the appropriate selection of strategies and the correct allocation of resources that affect task performance.

- Monitoring: one's awareness of comprehension & task performance
- Predicting the consequences of an action or event[18],
- Evaluating: appraising the final product of a task and the efficiency at which the task was performed.

3. Executive function

Each of these aspects of metacognition has promise for the framing of innovation-related research. Might it be, for example, that innovators possess higher levels of the three types of metacognitive knowledge and thus are better empowered to process the stimuli and problem-related knowledge they are presented with as well as tapping into the store of technological knowledge they have already amassed? Alternatively, or perhaps even concurrently, the effective innovator is more aware of, and adept with, the four metacognitive regulatory skills of Planning, Monitoring, Predicting, and Evaluating.

5. Motivation

Numerous researchers, psychologists, educators, and philosophers have worked on the concept of motivation. While there are many differences in the various theories they have evolved, there is also a central commonality. Specifically, regardless of the theory, it seems that motivation can well be considered as providing the fuel or energy propelling action of some kind. Building on the work of two of the prominent conceptualizers in this field, Maslow[19, 20] and Herzberg[21, 22], the author synthesized a combination, Lewin[23] force field-like model of motivation shown in Figure 6. Essentially the figure shows a horizontal blue bar which represents the innovator and three sets of forces acting on him or her: their own needs (for example as characterized by Maslow), a set of positive motivators (shown by the green arrow), and a set of de-motivators (shown by the brown arrow). Both of the latter derive from Herzberg's dual factor theory. Then, just as in free body diagram analysis, these forces act on the innovator in varying degrees and directions and their resultant is what will determine the strength, direction and longevity of the motivation propelling the innovator.

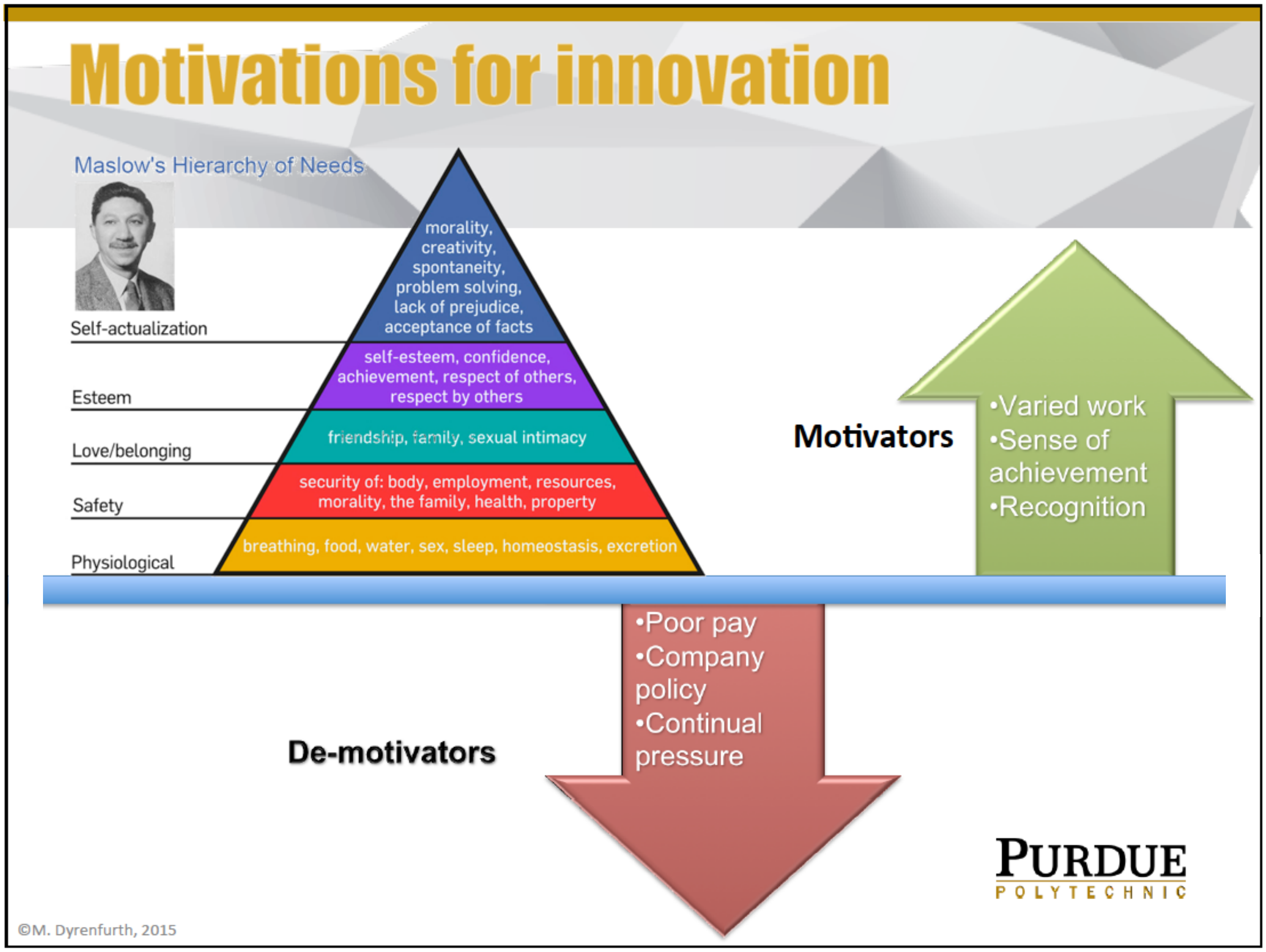

Figure 6. Synthesized Model of Motivation

Probably innovators are as varied in their motivations as humans can be. But, with the exception of the incidental innovator, i.e., the person who just happens to evolve a single innovation and then reverts to a life devoid of further innovation, the people who pursue a career of innovation, or at least become serial/multiple innovators, seem to have been motivated by one or more of the motivational forces depicted in Figure 6. Innovator biographies such as those written about Jobs, Gates, Edison, Ford, Watt and others have highlighted the drive for recognition, safety/necessity, financial reward, escape, self-esteem and responsibility as forces driving one or another innovator. While certainly corporate or university management can evolve systems to create one or more of these forces, the question of whether they will interact with the psyche of the individual(s) exposed to such forces is clearly up to the individual and not to the organization. In all likelihood, the individuals comprising the corporation, university or other entity housing them are so varied in their psyche that no single motivational strategy will be universally successful.

6. Proposed Composite Model of the Mental Processes Related to Innovation

Given the key topics presented in this paper so far, i.e., innovation, cognitive science, metacognition, motivation, the author felt a need to coalesce some of these concepts into a more unified model that would serve as a better tool for thinking about the why and how of innovation. This model of the mental processes affecting innovation is presented in Figure 7.

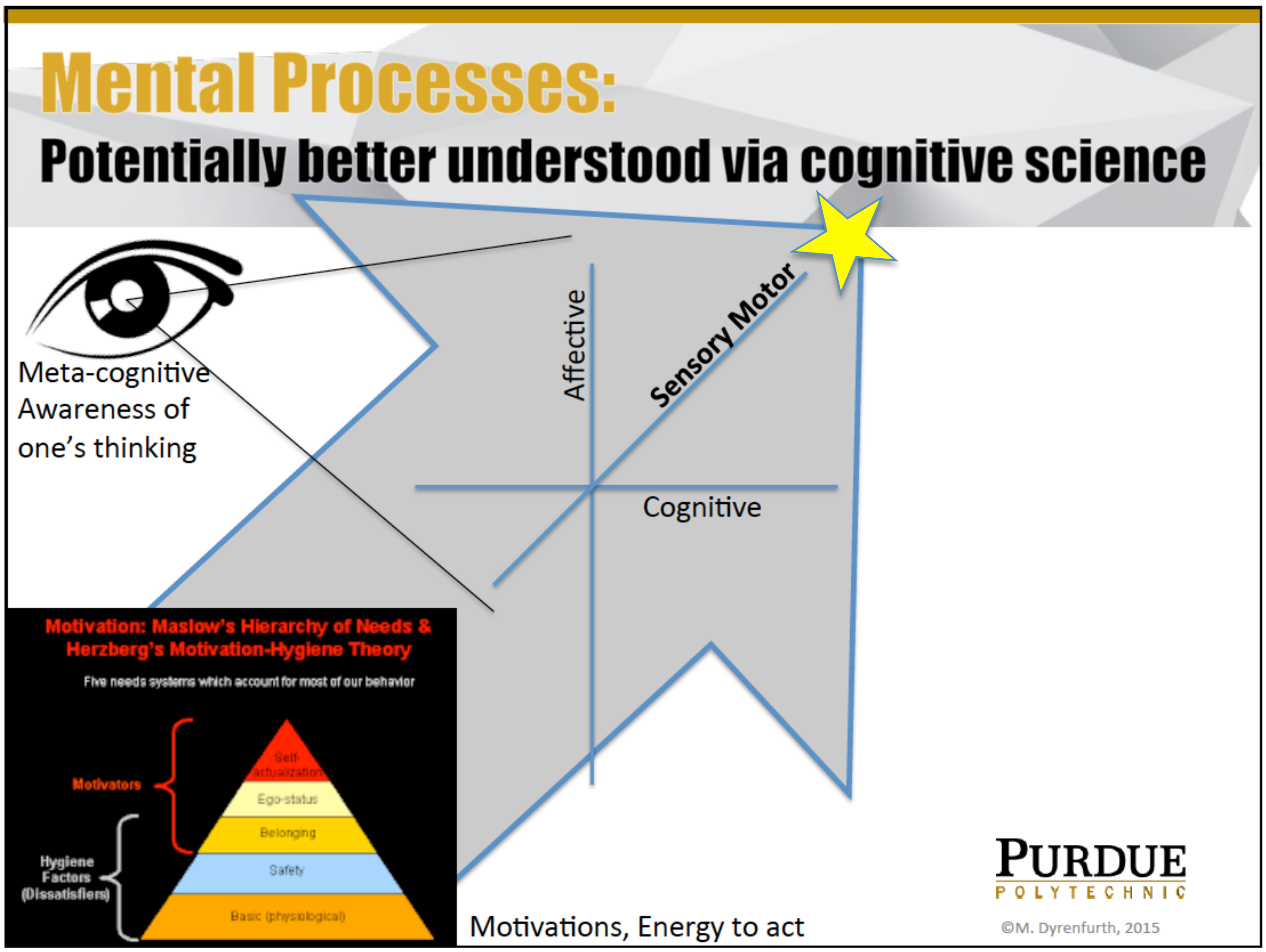

Figure 7. Model for the Mental Processes Situating Innovation

The author's model in Figure 7 shows motivation acting as the energy source [depicted by Maslow's hierarchy] for mental actions (i.e., thinking [depicted by the large gray arrow]) leading to innovation [depicted by the yellow star]. Metacognition serves to provide awareness and executive regulation [depicted by the eye] of these thinking actions. The innovator brings with him or her a set of knowledges, capabilities, sensory awarenesses, attitudes, interests and other psychological characteristics [depicted by three orthogonal axes in the center] that serve as the resource base for innovation. Combined, these all form a conceptual locus for the thinking that leads to the innovation.

7. Questions Needing to be Investigated

Arguably the least prevalent addressing of innovation has occurred in university research activity. In making this point, note, the author makes a distinction between entrepreneurially focused research and research focused specifically on the process of innovation and/or technological innovation[33]. Unfortunately, in the opinion of the author, the former has received much more attention than the latter, more important research area. Addressing this point in prior work[12] on this topic, at the European Society for Engineering Education annual conference in 2015, the author and a coauthor, J. Barnes, observed that:

> with the exception of entrepreneurially focused research and innovation research focused on economic development, the actual profile of university research focusing on the process of innovation and or technological innovation is nascent at best. (p.3)
>
> …
>
> there is too little actual research occurring with the focus on the process of technological innovation or even simply the process of innovation in any of its variants. Furthermore, the bulk of what the authors have seen is driven by an education perspective and situated primarily in the K-12 STEM education context. Now with at least Purdue University and Virginia Tech (Virginia Polytechnic Institute and State University) offering strong engineering education programs there are increased research reports about university level engineering and STEM education. But, this paper's authors would claim that the majority of these studies have employed an education or educational psychology perspective and not enough of attention has been paid to cognitive science and how it and its methodologies might further our understanding of who innovates, why, and how they go about it… (p.4)

There are some grounds, however, for optimism in this otherwise stark landscape in the growing body of research activity investigating the process of design thinking[23]. The author and Barnes went on to point out[12] in this regard, that:

> To the extent that these initiatives address technology and how the individual thinks about it as they design new artifacts, procedures, and generate solutions to problems, such research is directly aligned with the point of this paper. For example, Beckman and Barry in Innovation as a Learning Process: Embedding Design Thinking[25] cited Owen's[26] depiction of building and using knowledge by designers provides useful guidance to researchers seeking to apply cognitive science to design and innovation processes. (p. 3-4)

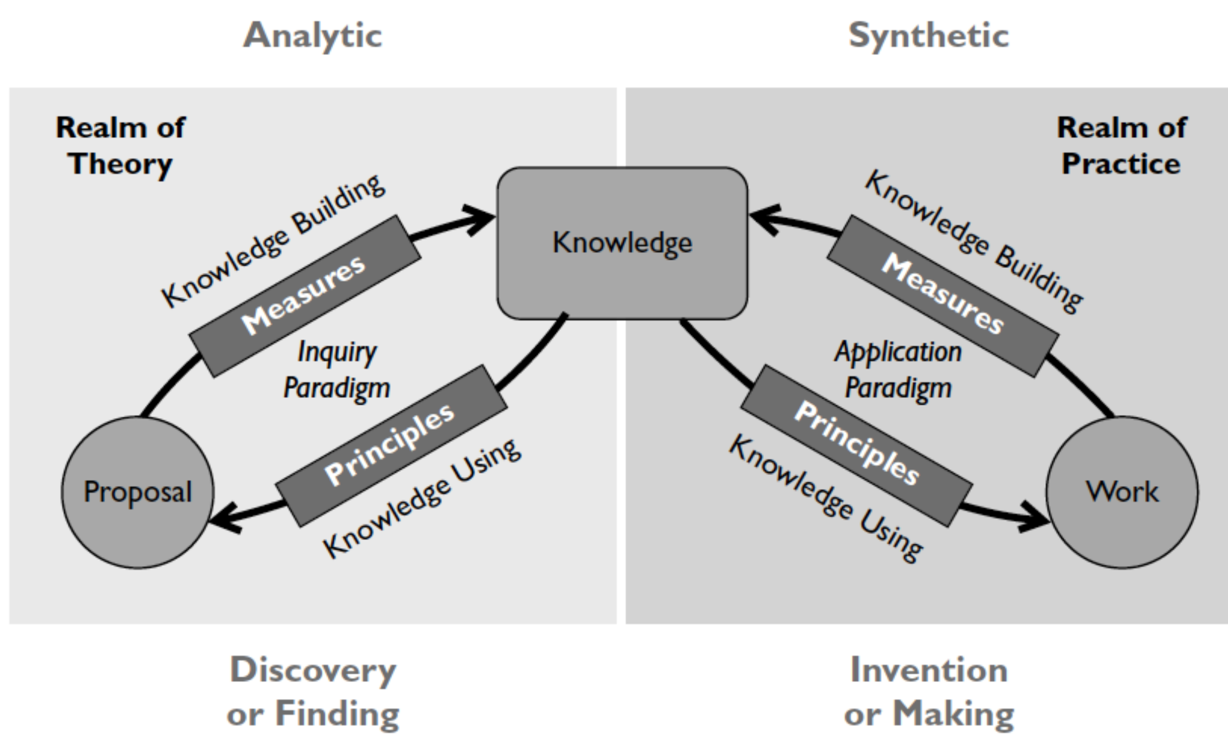

Figure 8. Owen's[26] Potential Framework for Guiding Innovation Research[26]

At this point, it is hoped that this author's has established a foundation for further empirical research. As illustrated in Figure 8's left-hand graphic, the paper presents a proposal and some key principles that should prove fruitful for further research. Despite the foundation established in this paper, some larger questions central to the interface of cognitive science with technological innovation have surfaced and are presented here with the hope of encouraging further research by engineering and technology education researchers. Such work should result in better understanding of the process of technological innovation and thereby ultimately enabling our ability to develop enhanced innovation capabilities in our students or workforce and hopefully even increase their propensity to innovate. The initial set of questions pertaining to cognitive science's interface with innovation and generated by the author's work are:

1. What affects our propensity to innovate?
2. What increases our capability for innovation?
3. How does our ability to represent in multiple modes impact our ability to innovate?
4. What is the relationship between memory and innovation capability?
5. Do our mental structures/organization of our knowledge affect our innovation capability?
6. Does skill with alternative modes of reasoning increase our capability for innovation?
7. What is the relationship between analogical thinking and innovation capability?
8. Does how we learn something affect our subsequent ability to use it innovatively?
9. What is the relationship between sensori-motor and kinesthetic sensitivity/skill and innovation capability?
10. How do affective levels/motivation affect the propensity/inclination to innovate?
11. Would learning activities intensively involving innovation strengthen either innovation capability or propensity?
12. What contribution might the decision sciences make to our understanding of innovation?
13. What is the relationship between metacognitive awareness and skills and innovation capability or propensity?

8. Summary

This paper began by presenting the construct of innovation and technological innovation and then overviewing cognitive and two of its central concepts: metacognition and motivation. Although a considerable amount of literature pertaining to these topics was referenced, the conclusion stated in the author's 2015 SEFI conference paper[12], still holds, i.e., that there remains a need to better understand the process of ideation and that the discipline of cognitive science offered much potential for research leading to improved understanding of innovation. Subsequently, and with reference to engineering and technology education the potential of employing the perspectives and methodologies of cognitive science was posited and at least some of the implications thereof were highlighted by generating a set of questions with potential to yield fruitful results. Much work, however, remains to further explore and detail the latter.

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