Teaching Innovation and Economic Content to Materials Science and Engineering Students: Innovation for Materials Intensive Technologies and Industries

Dr. Robert A Heard, Carnegie Mellon University

Dr. Heard holds a Teaching Professor in the Materials Science and Engineering Department at Carnegie Mellon University. Past work includes activities as an industrial consultant, entrepreneur/president of two companies, and vice president positions in several engineering companies. His experience lies largely in the development and application of specialized new technologies and business opportunities, having significant international business and project experience. He has served on the Board of Directors of the AIST, worked on several committees in professional societies, and is a member of AIST, ASM, TMS, Sigma Xi and ASEE. He has authored 28 technical papers on a wide range of activities in materials science, including education, innovation management, environmental issues, nano-materials, steelmaking, casting, plasma and alternate iron technologies and authored a book on the Horizontal Continuous Casting of Steel.

Dr. J F Whitacre, Carnegie Mellon Univerisity

Professor Whitacre started his career at the Jet Propulsion Laboratory, where he worked on energy technologies ranging from functional materials to systems engineering. In 2007 he accepted a professorship at Carnegie Mellon University, where he develops materials for energy storage and performs economic/environmental impact assessment for a range of technologies. His work resulted in the conception of a novel sodium-ion battery based on low-cost materials and manufacturing techniques. In 2008 he founded Aquion Energy, a company that has since grown to manufacture fully scaled energy storage devices. While maintaining his professor post, he also serves as the Chief Technology Officer for Aquion.

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Abstract

Three years ago, the school of Engineering at Carnegie Mellon University implemented "Teaching Innovation" as an initiative of the Dean's office. Subsequently a course, "Invention and Innovation in Materials Intensive Technologies" was developed and offered as an elective suitable for fulfilling requirements in both the Material Science and Engineering and the Engineering and Public Policy programs. We have completed the second offering of this content to students drawn primarily from the senior undergraduate student population. We note that in the cohort of science and engineering students, few have been exposed to more than a cursory look at business operation, product development or commercialization strategy; thus this course fulfills a need in the practice of how to operationalize innovative change.

With all products being comprised of materials, innovative changes in material selection, processing, and material properties can be felt in almost every business sector. Many innovations claimed at the product level are in fact traceable to or made possible by innovation in materials. Few, if any other engineering disciplines have such a wide influence. This course is unique as it has been constructed specifically to dissect the commonly accepted interpretation of innovation and re-assemble the process with materials and the materials business in mind.

Throughout this document we will refer to the term "materials innovation" as a catch-all term for innovations of materials and material systems, process innovations that are essential to materials manufacturing, and business practice changes within the framework of the materials industries. In delivering this course to our students, we wish to have our engineering students consider and be able to understand the complexities that arise as a result of invention and the issues that arise during commercialization of the innovation. The topic scope is constrained to materials and material intensive industries as there are significant differences when innovating materials as opposed to products.[1] Innovation of products can also be dependent on the innovations arising from materials either through new functionality or improved properties and performance. On innovation, a report by Royal Academy of Engineering offered that the long cycles of innovation we now experience maybe a result of the incremental innovation practices of the past century.[2] We endeavor to remove these constraints by educating future engineers and scientists in the theory and practice of innovation with a particular focus on materials.

Background

While generally innovation is associated with products, materials themselves either provide functional, mechanical or aesthetic attributes to these products. Materials can be viewed as a starting point or as a pool that must be used to support the innovation process. To this point, we emphasize that for materials, invention is associated with, but different than innovation. Although materials undergo improvement in performance (functionality and properties) in a seemingly continuous incremental process, seldom do we observe radical innovation. Invention, which may occur frequently in materials, must become part of a product construct or service, and find application through commercialization for innovation to occur. This incorporation dependency erects the largest barrier to innovation process that involves new materials and derives from the fact that materials enter the production stream early in the supply chain and in many cases find themselves in critical applications.

Figure 1 attempts to illustrate the spheres of technical influence and business influence we use to explain the materials innovation process in this course. For this paper, we endeavor to show that innovation in materials comes from a combination of business and technical acumen through feedback loops that inform near-term and long-term decisions. For the sake of clarity, we have excluded the forward and feedback loops that exist between many of these domains but have indicated with the red and blue arrow that there is extensive bi-directional transfer of information necessary between the technical and business spheres. Invention can occur in business that changes technology; or in technology so that it changes the business; or in both, and the materials industry has provided many cases and examples of each scenario.

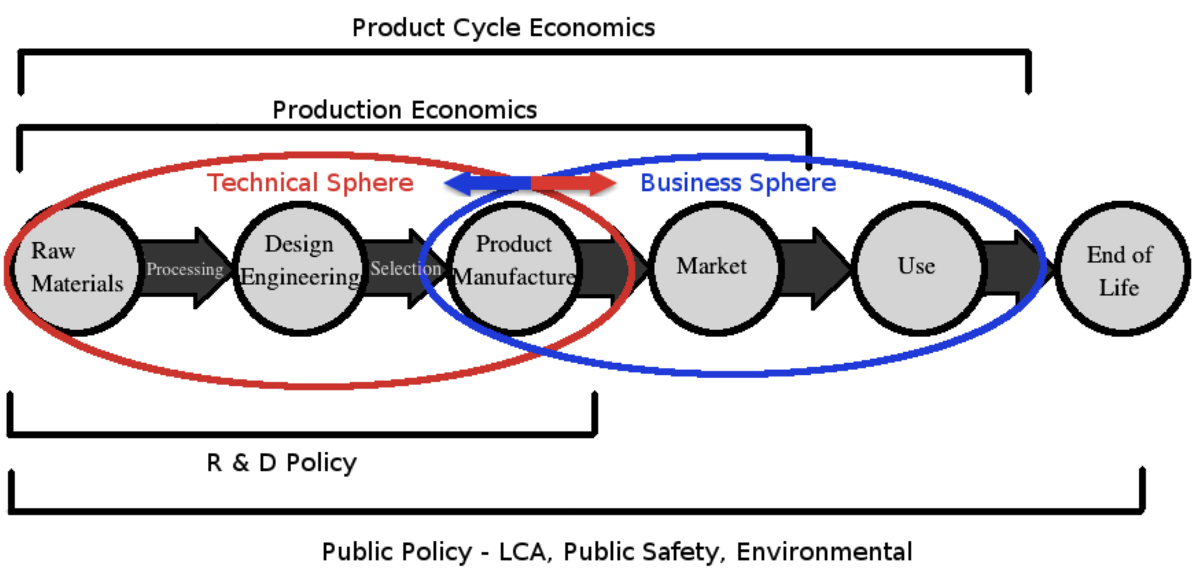

Figure 1. Simplified Structure of Materials Innovation Realm

Innovations originating in technology find their roots in the sciences or engineering disciplines. These innovations come from the technical sphere and require access to deep understanding in materials science or engineering. If radical innovation is observed, it is often associated with functionality discoveries in materials or new processes for materials, whereas incremental innovation may be often associated with material performance or process improvements (e.g. mechanical, physical or aesthetic). Christensen used the disc drive industry as an example of this radical change brought on by increased digital storage capacities.[3]

In the business sphere, materials are found at the two extreme ends of the market spectrum. Materials are incorporated into everyday products thus suffer from commodity status (being inexpensive and substitutable). At the other end, materials may be considered as specialty materials, usually rare, and with special properties that prevent substitution. For commodity materials, business innovations built around process improvements influencing the supply and value chains are critical. Some examples of how business innovation can transform the materials industry is the emergence of the steel mini-mill, the rapid cost-down of poly silicon based solar cells, and the increased use of carbon composites in the aerospace industry. For rare and controlled materials, business cases are more difficult to find but examples exist that connect the rarity or market scarcity to high costs associated with extraction or capital investment.

Both the technical and the business spheres are influenced greatly by policy; governmental, public, or private. The success of a materials innovation therefore must include consideration of the market and all business factors related to processes of manufacture, use, and disposal. Factors can include design, sustainability, life cycle responsibilities, and market cycle economics.

Course Format

In this course, information on relevant innovation topics is delivered by traditional lecture, class discussion, and through readings. The learning strategy keys on the operationalization of the gained knowledge. In our approach, each topic is presented in a lecture or a series of lectures. Students then receive assignments consisting of two parts, the first asks them to reflect on and explain the implications of the topic within the framework of innovation in materials or material intensive industries. This ensures the students have completed the suggested readings and have understood the content of the lecture(s). The second portion of an assignment asks the student to operationalize the knowledge of their selected learning on their “project” topic. For this portion, students are also asked at the beginning of the course to identify a material, a material intensive product (product whose manufacturing or performance is dominated by a material) or a material process that they wish to innovate and are able to discuss throughout the semester. We will refer to this as the student “project,” although it is continually built upon as an imaginative case study.

Instructions and example investor pitch presentations are provided in class, and the student will use the framework and direction provided to encase his or her “project.” As each project is focused on an innovation, the pitch can be focused toward venture funding or as a corporate request for general investment funds to support the growth of the innovation. By having to propose growth in return for investment, we can see how the student interprets the impact of the technology on business chains and on the market, and the student must articulate this clearly and succinctly in order to achieve the funding goal.

Course Content

To build this course we have assumed that the students are coming from either, Engineering and Public Policy with some basic understanding of the economic impact of technology in social context (technology business) or from the Engineering College, having background and knowledge in materials and material processing. Our ambition therefore is to provide a combination of these backgrounds while extending their knowledge of how new materials or processes find useful application. The course can be generalized into three sections: Background of Innovation; Innovation of Materials and Materials Processes; and Factors and Policies Influencing Materials Innovation.

Background of Innovation

The course begins with an introduction to invention at a generic level. The primary focus is to illustrate the dependence of invention and innovation on the community of knowledge at large. The process and influence of societal innovation resulting from materials development and technical innovation in materials are discussed through the science era and into the modern research era. Modern day invention methodology and the transformation to innovation from invention is then explained as innovation models in light of the TRACES and Project Hindsight reports which have close association with advanced materials development work.[4, 5]

Innovation of Materials and Materials Processes

The uniqueness of materials innovation lies with the facts that materials come early in the supply chain and either have a broad application as a commodity or they possess a highly specialized degree of performance that we wish to exploit. This creates two classifications for materials, 1) commodity materials that have a broad base of uses and applications, and 2) specialty materials that have limited use but provide properties for market domination and exclusion. These two extreme classifications of material usage are also related closely to incremental and radical innovation. Existing products that substitute materials or use improved materials are incrementally improved and thus categorized with incremental innovation. Materials that are developed and exhibit completely new performance attributes are often the basis for new technologies and thus often are considered enablers of radical innovation.

Materials however, seldom find their use as a stand-alone consumer product. For commodity materials, the supply chain and value chain are heavily dependent on the product cycle of a downstream customer that is servicing the end user marketplace. A similar situation often exists for advanced or specialty materials producers. Because these materials find themselves as part of a product they are dependent on product cycles and market conditions of a downstream company. While students learn that the basics of product planning and the innovation cycle that establishes incumbent and emerging companies in the marketplace, the intent is to have student understand that these downstream market influences greatly influence the upstream material supply and value chains of a materials producer.

Factors and Policies Influencing Materials Innovation

Materials do not move easily from invention to the marketplace and thus can take several decades.[1] Furthermore, once in use, a technological innovation is subject to diffusion pressures as copies or similar competing products appear. Several factors influence the rate at which technologies diffuse, these being the presence of enabling technologies, intellectual property control, investment environment, and market demand to mention a few.

The market success of an innovation is largely influenced by the learning curve associated with the speed of product or process introduction and commercialization. For materials, the learning curve relating to processing changes is a major factor in the economics of production. Intellectual property control ranges from knowledge control in the form of trade secrets through formal patent protection. The pros and cons of these options are discussed as they relate to what in a material or process can be protected. Lastly, investment into innovation through research and development activities can originate from governmental agencies, private sources or even crowds.

The business of materials and new product development is influenced through feedback from the marketplace. While material producers have been held responsible by governmental regulations in the past, the new business environment is seeing more pressures exerted by stakeholders and market demand for green design and sustainability. These factors are providing new direction and opportunities for innovation as they place constraints on material selection and processing options while requiring new investment and innovation to remain competitive in the greening marketplace.

Evaluation of Learning

Although it is common for assessment methods in innovation studies to be based upon attitude, communication skills, participation, and interaction of student team projects, we have chosen to evaluate the learning on an individual student basis. Our intent is not to teach creativity for innovation, but to have students recognize how materials are a source of innovative change, and learn how to influence and predict the impact that the material or material processing innovation will have on business and/or society.

The reading and comprehension of basic knowledge is evaluated by a traditional assignment method. For the evaluation of the project, students build and present their pitch decks at two times during the course to obtain feedback used to enhance the pedagogical value of the evaluation process. With the first pitch at mid-term, the presentation evaluates the ability of the student to recognize and understand the actual material – technology connection of the innovation. Can they identify the impact and influencing variables, and do they understanding the key value drivers of their innovation. A preliminary market analysis is required along with some supply and value chain content. For the final presentation, a significantly more robust analysis of these topics requires intellectual property planning, policy assessment, risk assessment, sustainability considerations, and a more complete financial assessment of the value proposition. Conceptually, the two presentations are depicted as a "first contact" pitch to possible funders, and then the deeper "follow on" pitch that has more detail. Table 1 lists the evaluated content for the two presentations and provides comments on the expectations.

Table 1: Learning Outcomes Evaluated by Mid Term and Final Pitch Presentations

	Mid Term Evaluation	**Final Evaluation**	**Learning Goals Evaluated**
Basic Description	Basic description of the technology: how complete was it?	Basic description of the technology.	• Evaluation of depth of study. • Mid term pitch is emphasized because the same technology is carried through to Final
	Basic description of the technology: how compelling was it?		
Market and Business Definition	Market analysis: how complete/clear was it?	Market analysis: was there a quantitative market assessment that was compelling?	• Can the student comprehend and estimate the market for the material innovation? • Can they operationalize the innovation by selecting a commercialization concept? • In Final pitch, this evaluates the understanding of IP protection strategies and possible policy influences either promotional or detrimental to innovation.
	Market analysis: how compelling was it?	Production cost down and future technical plans - was it clear and believable?	
		IP strategy: is there a defined plan?	
		Policy analysis and suggestions: were they clear and compelling - did they increase the viability of the company?	
Supply Chain and Value Chain	Supply chain analysis: How complete/clear was it?	Supply chain analysis: is the position of the company in the supply chain well described?	• Does the student have an understanding of material supply and value chain for the material and can the student anticipate possible impacts of the innovation to material flows and market values? • Does the Final pitch include consideration of the material demand changes in view of sustainability (corporate and material supply) and evaluate the risk exposure along the supply and value chains.
	Supply chain analysis: how compelling was it?	Value chain analysis: is there a clear description of where the venture is on the value chain?	
		Sustainability: is the proposed venture sustainable, and was this communicated clearly?	
		Risk assessment: does the content capture risks where applicable?	
Ability to Value	Value proposition: how complete/clear was it?	Value proposition: Does the company valuation and the funding ask make sense for the investor?	• Can the student reason out and estimate the value of the innovation and fit the innovation into real world economic model?
	Value proposition: how compelling was it?		
Overall Effort and Interest in the Innovation Process	What do you think this proposed venture/idea is worth, in Millions?	What do you think this proposed venture/idea is worth, in Millions?	• Did the student to work through validation models? • Provides a measure of the student's effort to participate and desire to express the aggregate knowledge.
	Would you invest in this venture at the asked value	Would you invest in this venture at the asked value?	

For evaluation, a “crowd sourced” method is used whereby everyone in the class completes an online questionnaire as the presentations are given. This evaluation process of these projects is completely anonymous and the data is captured and tabulated. Any outlying data can be easily recognized and eliminated so the analyses of the responses does not carry any significant biases. The results of the evaluation are available in near real time. The students react well to this approach and report that they end up thinking more critically about their work and how it is seen through the eyes of their peers.

Summary

We have established “Invention and Innovation in Materials Intensive Technologies” directed toward students from both the Material Science and Engineering and the Engineering and Public Policy programs at Carnegie Mellon University. This is a course that is uniquely constructed to dissect the commonly accepted interpretation of innovation and reconstruct it in a form focused on materials and the materials business. Learning outcomes for students taking the course are: a recognition of how materials are a source of innovative change; a knowledge of invention and innovation process for materials; and an understanding of how material or material processing innovations may impact business and society. In addition to traditional evaluation of a students’ knowledge, we have established an unique, individual assessment method using “crowd sourced” evaluation of a students’ ability to apply the knowledge gained from the course.

References

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