



Exploration and Innovation in Creative Material Education

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 MRS, ASM, TMS, Sigma Xi and ASEE. He has authored 30+ 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.

Mr. Christiaan Job Nieman, Universidad de los Andes

Industrial Designer of The Hague University, with a Masters in Architecture from Universidad de Los Andes, with more than 15 years of experience as an independent designer in different fields from product design to architecture and urban design. He was a partner of Architectuurwerkplaats de Ruimte (2003-2004) and founding partner of the QENEP architecture & design office (2004-2008) based in The Netherlands.

He has been a teacher of Industrial Design since 1999 at the University of The Hague (1999-2008), the Pontificia Universidad Javeriana (2008-2012) and the Universidad de Los Andes in Bogotá (2009 onwards). Since 2015 he is a full-time assistant professor in the Faculty for Architecture and Design of the Universidad de Los Andes. He teaches Product Development, Sustainability, and a course in Design, Processes & Materials.

Christiaan Job Nieman's work as a designer is characterized by being directed towards sustainability at an environmental and social level. Reuse and repurposing of materials, Cradle to Cradle, and Biomimicry are his inspiration in the search for energetic, economic and social sustainability, but more than anything he designs with the purpose of finding simple solutions to complex problems. This all from the product scale to that of urban interventions, and from commercial proposals to bottom-up social innovation. He works mostly in a collaborative and collective way, seeking to apply the design in a multidisciplinary and participatory field where possible. Tends to seek action and intervention as a way of experimentation.

Exploration and Innovation in Creative Materials Science Education

Materials play a broad role in modern life yet with few exceptions, the only significant formal education in materials science is available within specialized post-secondary educational programs. Furthermore, even where available, students enrolled outside of engineering or technical programs may find limited opportunities to study materials science, or they may be hesitant to enroll in a materials science course because they feel intimidated by the potential technical analysis and explanations. As a result, in many institutions, schools outside of engineering colleges (design, architecture, business, fine arts etc.) often resort to offering their students a "light" coverage of materials from the perspective of their own discipline.

A student's technical knowledge of materials science, materials processes, and suitability for application can be segmented. There are:

- Those receiving formal education in materials science, in disciplines related to engineering, physics and chemistry
- Those that have achieved a good working knowledge of materials science by experience. By definition, most of this knowledge is contained in specific materials, processes and applications that would be common to the individual's use. There may be little knowledge of actual competitive materials. Knowledge of the need usually defines what material has found use and acceptance in fulfilling the need.
- Those with a need but a very limited knowledge of materials science. This level includes the non-expert who recognizes a need and applies a known, "proven" material as a solution. The solution is most often based on historical learning (by observation or recommendation) or after consideration of some limited information gleaned from current research (commonly the internet today).

Years ago, the Boyer report recognized that research and study boundaries at the undergraduate level were reinforced by the traditional departmental structures and one proposed remedy was the implementation of an interdisciplinary undergraduate educational paths that included independent research and thus supported a more independent and creative environment for learning [1]. Although this resonated with most educational institutes, adaptation has proven difficult. Such programs require sufficient resources to support student research, and the provision of equal opportunities in multiple disciplines [2]. At research universities, this also suggests the need for interdisciplinary research activities. According to Rhoten, this has proven to be an even more difficult challenge with most institutions treating interdisciplinary research as a trend instead of a comprehensive reform [3]. In a discipline such as materials science with broad applications in science and engineering, the resistance to true interdisciplinary structuring has resulted in materials science now being taught by materials scientists employed outside of the majors' department; in "materials-related" engineering and science departments [4] and in schools of computer science, design, architecture, and others.

Oxman has proposed and formatted the environment of the education system in terms of creativity [5]. Using Krebs cycle as a reference, Oxman presents the concept that there are many overlapping interests and much more entanglement of the creative disciplines. This entanglement had also been noticed by the authors, who were originally working independently toward novel

courses at their respective universities. Both were introducing new courses in materials science to an audience with material interests and material solution needs but with a lack of formal material knowledge. This led to the collaboration and the premise for publicizing this observation: that as materials science educators, we could help students outside of the materials science discipline understand more about materials and processes and ultimately be able to distribute their creativity synergy of any shared solutions and ideas across disciplines.

Students in disciplines that engage some level of materials understanding also represent a population that is creative and unbounded by preconceived (or taught) constraints and therefore can envision different applications, demands, and designs for materials. We feel that to engage these students, a more creative active learning space is needed that allows for exploration with materials. As such, lectures cover only the basic information pertaining to material families, common materials, basic properties and performance, and social and environmental issues. The remainder of the learning is achieved with active hands on exploration of materials concepts in a studio environs.

Studio style classes have found to be useful when teaching large engineering projects, in particular, studio work is noted to require "students to expand their knowledge in areas outside their knowledge base" [6]. This contrasts with the work in a more traditional engineering lab where, more typically, known concepts are reinforced by the experimental work. In studio work, assignments are sufficiently open-ended and student may follow many paths to a solution that is almost certainly not unique [7]. This concept is akin to Problem Based Learning (PBL) with the caveat that individual students define their own problem and work toward their own goal(s) in the studio.

Studio learning outside of engineering (art/design, architecture, drama, etc.) is often focused on teaching procedural skills (e.g., specific techniques, approaches, tools, and media) using concepts and ideas to establish the conditions, examples, and inspirations that spark creativity and exploration. Applying this to engineering subject matter requires a different approach where, in studio learning, Dinham considers a distinction between the educator as "controller-of-information" versus as "orchestrator"[8]. Taking lead from Dinham's general recommendations, the following guidelines listed by the Eberly Center were used to establish the practice [9]:

1. *Situating: Establish the exploratory experimental tasks within the context of the course and discipline, so that students see the relationship to other core concepts and practices*
2. *Modeling: The instructor models expert practice while describing and explaining each step of the process from planning (selecting materials/tools, organizing work space) through execution*
3. *Scaffolding: The instructor provides guidelines, steps, and parameters to structure student exploration. The student begins to conceptualize the task and begins planning.*
4. *Coaching: The instructor provides coaching and feedback while students engage in the exercise themselves. The student engages in the practice, asks questions, reflects on own practice in relation to expert practice*
5. *Fading: The instructor gradually decreases coaching and scaffolding, allowing students greater independence. The student operates with increasing independence in more and more complex situations (less structure, more choices/complications, etc.)*

6. *Self-Directed Learning: The instructor assists only when requested. The student practices the real thing alone or in groups*
7. *Generalizing: The instructor guides students from their own process to larger insights and useful generalizations. The student generalizes from own practice to larger principles, concepts, or interpretations [9]*

Tasks 1 and 2 above can be accomplished in a lecture format as either a focused mini - lecture or as part of the background on materials science. Moving to the studio, students will have the learning objectives clarified and the experimental task explained or demonstrated. Students then can reproduce the basic task while thinking about how they can evolve the material into their experience through manipulation, modification, or innovation, by providing creative changes that they judge will improve the performance or use. Unbounded from traditional science and engineering constraints, this allows a very free and open exploration of a material's possibilities.

Two Approaches Taking Materials Science to Non-Expert Students

1) Bringing Materials Science to the Design School Students

At the University of los Andes, materials science was introduced into the Design program with a specific focus on creativity. In "Diseño Materiales y Procesos" (Design, Material and Processes) students in the design class work with a simple traditional material to understand it's processing and eventual limitations. The design students are then requested to "innovate" the material by changing composition or process to evolve it for different or improved performance for a specific design purpose.

The course begins with students identifying the fabrication processes and connecting these to materials. Using photos of products, students are asked to find evidence of different manufacturing processes (for example welding joints, or injection lines). Students then research these processes and provide information about the process from literature or from the CES Edupack database. Early competences evaluated are still strongly design orientated, measuring a student's perceptual acuity (capacity to perceive value of what they present), textual communication skills (descriptions), and ability to provide visual communication (photography).

Having some knowledge of fabrication, students move on to produce a video report on a given fabrication process, and try to find or engage a company using this process so they can report on the actual processing technologies. This project looks to develop technological literacy, to expand but synthesize the students understanding of the fabrication processes, improve visual communication skills (video) and develop self-directed learning skills.

Having investigated fabrication processes relating to real world production of products, lectures in materials science are introduced to help facilitate students connect processing, to materials and the development of properties. Students begin this portion by searching for an innovative material of interest on the Internet or in print. Students then try to replicate the fabrication of this material or similar material, restricted only by the material and facilities at hand. During this exploratory studio work, students record all steps of fabrication and any notable properties, learning to frame a project and develop practical skills that incorporate flexibility and a capacity

for adaption. To be successful, students also must be able to create a vision of the material, a path to its fabrication and be able to describe any attributes achieved in the material.

Students, pairing up, select one or both materials they created, analyze the material characteristics and seek to find a design purpose for the original material(s). In a final stage, students are then asked to innovate their material further through experimentation toward this design goal. This activity stretches the student creativity and challenges their practical skills requiring the student to weigh the risks associated with the innovation and evaluate the possibilities failure (or success). The student will build upon their framing ability, practical skills, analysis and evaluation skills, and improved their visualization of how a material and a product is made.

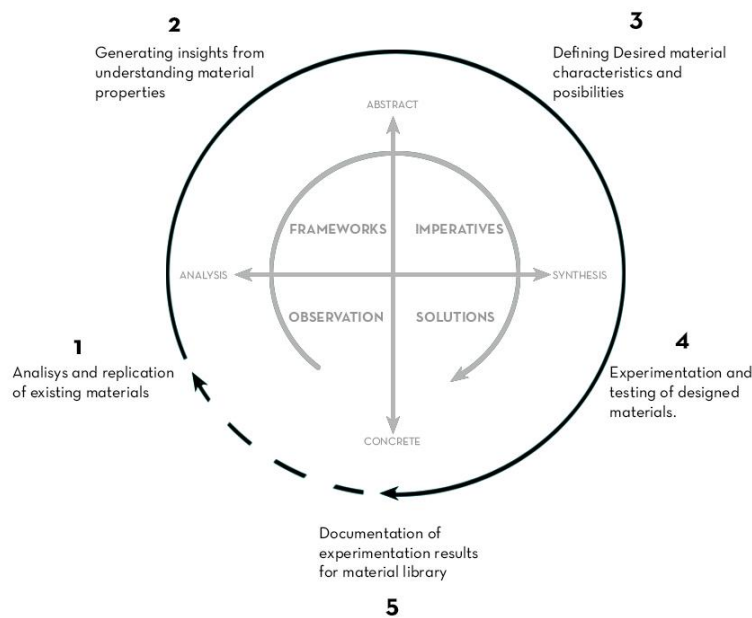


Figure 1. The material design process by students in Universidad de los Andes. Based on the model of the Innovation Process in *“Innovation as a Learning Process: EMBEDDING DESIGN THINKING”* by Beckman (in grey) [10].

Evaluation of Studio Work

In the Diseño, Materiales y Procesos course, it is the faculty from the school of Design that are evaluating the student work. Based on the innovation process modeled by Beckman and Barry [10], the same process the student use in other design courses, the process passes the steps of Observation, Frameworks, Imperatives and Solutions. To enable the iteration this process implies, the students deliver a document with their process and results. It is a common practice to use relatively simple templates that capture the essence of the design process learning objectives. These templates require photographic records of the process steps and the final material results, as well as textual descriptions and comments on the results and possible improvements. The

standardization of the template allows the course to build a database of the results that can become a material reference for other students. The students are evaluated on their ability to propose innovative experimentation, and their critical assessment of the result. Reaching the design goal is not part of the evaluation, as is the way the design process is planned and executed. The student's ability to describe the material result in sensory and technical attributes are judged. Sensorial attributes include finish, optical properties, form, texture, durability, perceived temperature, auditory and olfactory properties. Technical attributes include resistance to fire, UV degradation, temperature, chemical/corrosion and scratching along with considerations of weight and sustainability.

2) Bringing the Design School Students into Materials Science and Engineering

At Carnegie Mellon University, design students with the desire for deeper materials science knowledge select the class "Everyday Materials". In this class, design students are introduced to materials, product fabrication methods and properties. In a similar approach to that at the University of Los Andes, the design students experience hands-on materials processing and eventually are asked to apply their creativity to materials, changing composition or process to evolve it for different or improved performance for a specific design purpose.

The course begins with lectures that introduce materials and processing at the family level. The design students have some background in product design so therefore come to the class with a developed design approach to material selection. One learning goal of the course is to have the design student merge or supplement the design approach for material selection with the engineering approach. The first assignment is for the student to select a product that supports material fungibility and list out a design procedure they would apply to material selection. This forms a baseline for them as we work through the course. Eventually after having background lectures on material properties, process, sustainability and other material attributes, the students are asked to reflectively decide where and how these would fit in or modify their own method decision making process for material selection. A short written explanation was also taken as a response along with an updated/modified conceptual diagram to evaluate each of these learning advances. When developing this second list that incorporates the engineering considerations, the student internalizes the engineering process within their own decision structure. An example of this learning is summarized below in Figure 2, where the student has expanded their initial decision framework to a more complete analysis including the economics, life (material) cycle, physical attributes and impact on the planet following an instruction session on material sustainability. The depth of consideration and the recognition of the where and how materials knowledge changed, added to, or interacted with their existing decision framework was evaluated by a typical rubric for educational concept comprehension ranging from sophisticated to naïve.

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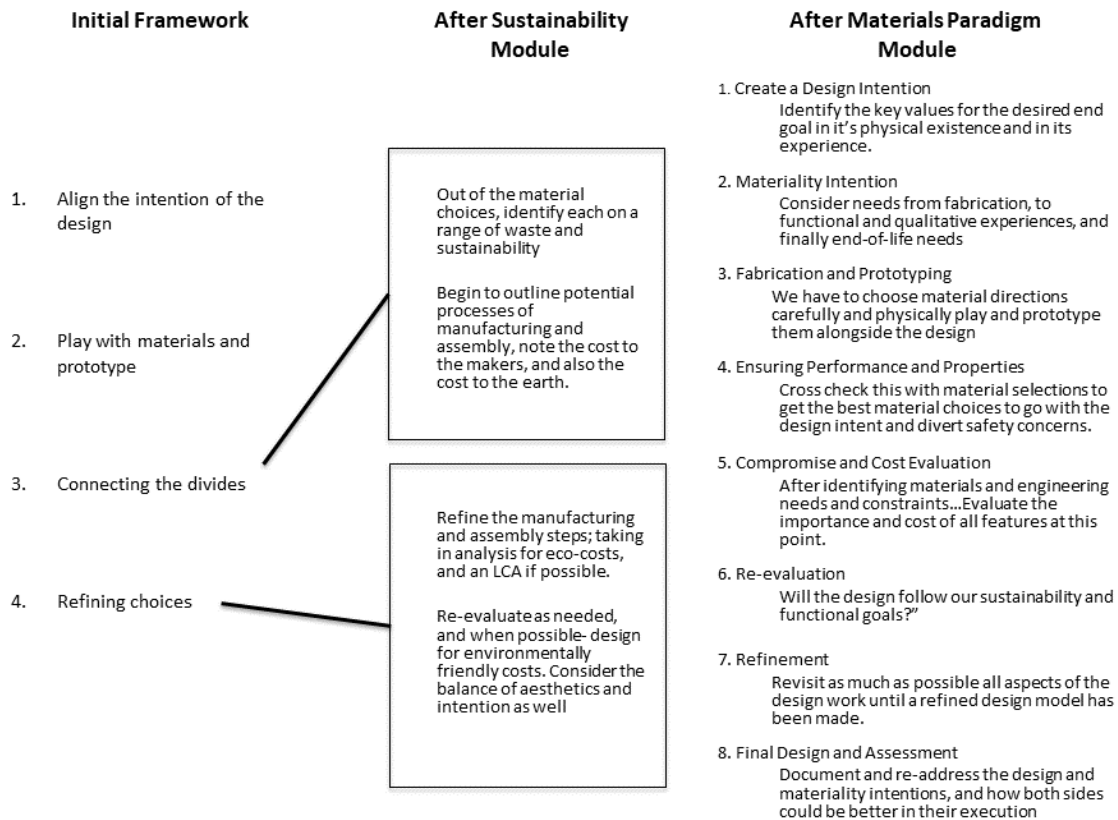


Figure 2 Example of a design students' decision framework expansion. Note how the student first incorporated concepts then was motivated to expand and rethink the entire process once lecture material on materials structure, properties and performance were introduced.

Following the early family-level look at materials and process, students begin their first studio work completing basic studio demos processing glasses, metals, ceramics and polymers while discussing and considering design applications for each. After the final demo studio, the students are asked to consider one material that they wish to consider for a design application. They are requested to search the Internet or print for an innovative material of interest then try to replicate the fabrication of this material or similar material. Students plan all processing steps and prior to execution of any major studio effort, the proposed steps are discussed with the entire class. This group discussion period investigates the intent of the step and discusses any materials science issues such as processing reactions and properties changes that may be a result the fabrication process. This also presents the opportunity where the deeper materials science understanding of the processing and of the property relationship can be introduced. A complete record of these discussions and outcomes are kept in the students' journal.

After the studio work has replicated a material, students are then asked to consider processing or material changes that would be desirable in a design goal (such as changing to sustainable/recycled raw materials, material reduction, density reduction etc.). This activity stretches the student's creativity and challenges their practical skills requiring the student to

weigh the risks associated with the innovation and evaluate the possibility of failure (or success) and to explore the material challenges associated with recycling, resource, and/or processing changes. As a final task, students are asked to reflect on their learning and revisit the material selection process. As discussed earlier, this closure of comparing their initial design approach to the approach now developed incorporating basic materials engineering knowledge serves to underscore the learning objectives of the course.

Evaluation of Studio Work

A studio, being quite different from the traditional engineering lab raises many open questions regarding the evaluation of work. Whereas in the science or engineering lab, grading might involve an evaluation of procedure, demonstration of a principle or replication and understanding a specific outcome, the studio lab is a place for the student to explore combinations, unscripted approaches and outcomes. Expecting the traditional comprehension and replication of engineering concepts by design students would not reflect what had been cognitively internalized during the course.

To evaluate student learning in the studio, a more holistic approach has been taken. Recalling that the intention of the studio work was for the student to interact with the material, experientially gaining knowledge as they transition from an introduction to the material, to the goal of producing a material that is hopefully closer to their design needs. The evaluation of this effort includes; the incorporation of journal records of their ideas, class discussions, critiques and changes in work product; the adherence to the students' newly developed decision framework and; the extent to which the student combined materials concepts to enlarge the possibility of creating a new material product. The physical success of obtaining a final successful material during the studio work is diminished and the students design logbook is used as the submitted work. To evaluate the growth in learning, students completed a weekly summary that documented the studio goal for the work, the expectations of the outcome, and a step by step documentation of the work accomplished following a similar reporting style as used by Parisi et al [11]. This report is discussed during a weekly meeting which allows for explanation of the observations and careful guidance through materials related issues that the student can then take for further exploration or consideration.

As student progress through the weekly experiential learning, they exhibit a deeper understanding of materials science and experience the limits or difficulties in achieving their goals with their materials. In almost every case, the first attempt in material formulation results in a product that is unsatisfactory to the final goal, proving either more difficult in fabrication than expected or presenting different properties than what was first imagined. These difficulties require re-examination of the goal, the material, and the approach.

To illustrate the growth of the student in understanding and progression through the design decision framework, sequential examples of a student's studio work is shown in Figure 3. This student was examining the possibility of producing a textured polymer tracing sheet for use on a tablet as described in 3a.

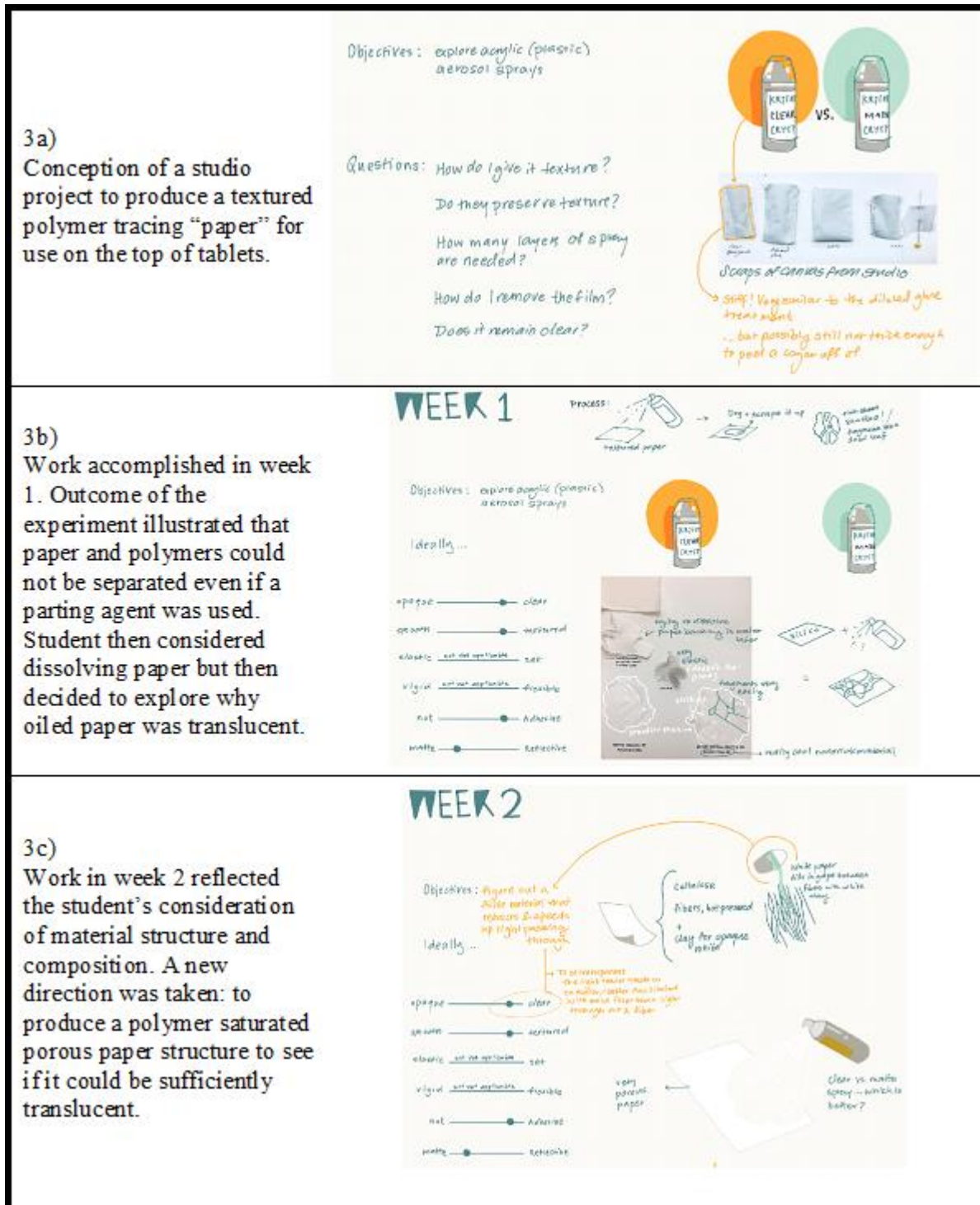


Figure 3 Progression through the studio work illustrating the experiential learning process.

The student had planned to spray a liquid polymer solution on paper with hope that removal of the paper would leave a polymer sheet. After initial tests in week 1 (3b), the student realizes that the porous nature of paper is a problem and has to research more deeply into the structure and composition of paper and into the reasons that light passes through papers that are wetted (for

example by oils). Week 2 eventually led to a conclusion that a more porous paper (without fillers) could be made translucent and that separation of the polymer may not be required (3c). The student continued this pursuit, discovering the differences in paper construction, and in a cursory manner, the physics of light transmission, deepening knowledge in two areas not usually explored by design students. This is an excellent example of the experiential learning goal of the studio work. The students progress until barriers of understanding are reached, then with discussion and some guidance can resolve these barriers with supplemental learning before the next iteration of studio work.

Summary

Two experiential learning approaches have been presented for the teaching of material science to non-engineering programs. In both programs, students that may have limited opportunities to study this subject matter, or may be hesitant to enroll in a materials science course because of intimidation by the potential technical analysis can expand their understanding through integration of basic knowledge and hands-on studio work. The self-driven direction of the experiential process helps build the connection and understanding of materials science and their discipline interests.

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