Using Video to Tie Engineering Themes to Foundational Concepts

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Introduction

Multidisciplinary themes in a typical undergraduate engineering curriculum were identified through a curriculum concept mapping process. The identification of these themes guided the creation of a set of 24 educational videos with another 24 currently in production. Each 15-minute video highlighted one of these themes by connecting it to a pivotal concept or critical skill from the first three semesters of a traditional engineering curriculum. The content of the videos was carefully designed to highlight a concept that would reappear throughout the curriculum, but was rooted in concrete visual examples accessible to first- or second-year engineering students. The videos utilized animations, visualizations, demonstrations, and/or examples from a variety of engineering and science disciplines to further the intended learning outcomes. Times to pause the video were incorporated to allow for student interaction—providing opportunities for students to predict the result of demonstrations, engage in discussion of concepts, and perform classroom activities tied to the video's intended learning outcomes.

In order to classify concepts into multidisciplinary themes, we used a "backward design"[1] process beginning with what instructors from the foundational courses in engineering (i.e., chemistry, physics, mathematics) identified as their intended learning outcomes. From our own background in STEM teaching and learning, we then isolated the pivotal concepts and critical skills that supported these learning outcomes. We refined our list of those concepts and skills through a literature search on student misconceptions and integrated curricula. In the end, a concept or skill was identified as pivotal when it satisfied one of two criteria:

(1) it was multidisciplinary; or
(2) it was prerequisite for multiple concepts that would be taught in upper-level courses.

By sorting the pivotal concepts and critical skills and looking for commonalities at a higher level of abstraction, we were able to classify concepts and skills into the following multidisciplinary themes: Conservation, Derivatives and Integrals, Differential Equations, Equilibrium, Governing Rules, Information Flow, Linearity, Representations, Structure-Function-Properties, Modeling, Communication, Problem Solving, and Teamwork. These themes are apparent to engineering faculty and discipline experts, but are generally not made explicit to novice learners.

For each video, the themes contextualized the pivotal concept or critical skill presented, focusing the content. At the same time, the themes provided a broader lens to view cross-cutting ideas in science and engineering. By using the themes as the backbone for the video development process, we hoped to help students transfer their knowledge across domains and connect concepts that may otherwise appear to be from disparate disciplines.

The videos are designed for both in-class and outside-of-class use. Instructor's Guides containing relevant background information and suggested pre- and post-video activities accompany each video. The videos are currently in use at an undergraduate engineering university and will soon be made available online to the general public, free of charge. Preliminary feedback from the undergraduate engineering university has been positive and has led to continued funding for the additional 24 videos. The process used to design these multidisciplinary videos is explained below.

Context and Goals

Beginning in 2011, the MIT Teaching and Learning Lab began to develop a set of educational videos for use at the Singapore University of Technology and Design (SUTD). The videos targeted content from the first three semesters of the undergraduate curriculum at SUTD, which look very similar to the first three semesters of foundational coursework that students would encounter in the U.S. These courses include single-variable and multi-variable calculus, mechanics, electricity and magnetism, chemistry, biology, introduction to design, differential equations, linear algebra, numerical methods, and thermodynamics.

The videos were created at the request of SUTD's senior administration to help supplement the educational resources of a young university. The design parameters were largely left to the MIT Teaching and Learning Lab to define. In order to best support learning, the goals of the videos were three-fold: 1) to reinforce pivotal concepts and multidisciplinary themes, 2) to provide opportunities for students to actively engage with content, and 3) to provide real-world examples from everyday life, or from research, of the utility of these concepts. The videos were designed for a variety of usage scenarios: in class, in recitation sections, for students to review when studying, and during faculty training workshops (to provide faculty with ideas for ways they might approach teaching a concept).

Research-Based Framework for Video Design

This section details the literature that guided our video design process. The work of Robert Gagne[2] and Richard Mayer[3] are described in great detail. Their work served as a framework for the design process that directed the development of our videos and will be referred to throughout this paper.

Instructional designers have long worked to identify research-based processes and procedures for delivering high-quality instructional materials. While there are many instructional design models, Gagne's Nine Events of Instruction, based on a cognitive information processing theory of learning, is one of the most widely implemented. Gagne's Nine Events include gaining the learner's attention, informing the learner of objectives, stimulating recall of prior knowledge, presenting "stimulus" material, providing learner guidance, eliciting performance, providing feedback, assessing performance, and enhancing retention and transfer.[2]

In the First of Gagne's Nine Events, the goal is to gain the learners' attention. This can be done in a variety of ways, including the use of a surprising demonstration or unexpected result or by posing a question to the students. The key is to motivate students to want to learn more about the topic at hand.

The Second of the Nine Events, informing the learner of objectives, helps students to understand what is expected of them and what skills and knowledge they can expect to gain by the end of the instructional experience.

It is well known in the education community that learners retain new knowledge better if they can connect it to something they already know.[4, 5] The Third of the Nine Events, stimulating recall of prior knowledge, draws on this idea.

In addition to tying new information to prior knowledge, the use of real-world examples also enhances the retention of information.[6] In the Fourth of the Nine Events, presenting stimulus material, the content to be learned is presented to students, ideally in meaningful chunks and organized around examples that the learner can relate to. Bransford, Brown, and Cocking recognized the potential of technology, including videos, to bring real-world problems and examples into the classroom.[7]

Providing learning guidance, the Fifth of the Nine Events, also assists students in encoding information into their long-term memory. In a face-to-face learning environment, coaching from the instructor can help a student stay on track. Additional means of support can include advance organizers,[8] rubrics,[9] and worked examples.[10]

The Sixth of the Nine Events, eliciting performance, points to the importance of providing learners with opportunities to engage with the material they are learning. Others have also shown that students who are provided opportunities to actively engage with material as they are learning it attain deeper understanding.[11-13] Strategies for active learning include posing questions to students and stimulating discussions that require consideration of the material presented. It is important that these activities support the intended learning outcomes.

Through the use of active learning strategies, the instructor can assess a learner's understanding and provide feedback and clarification as needed. Providing feedback is the Seventh of Gagne's Nine Events. Feedback is the mechanism for providing information to learners so they can modify their behavior or thinking appropriately.[14] The frequency and level of detail of the feedback can have positive or negative effects on learning.[15] Immediate and frequent feedback helps learners stay on course early in the learning process. Later, delayed feedback, with less detail, allows students to develop skills for assessing and correcting their own work, allowing for deeper learning.

The Eighth of the Nine Events, assessing student performance, involves the use of assignments, projects, quizzes, and exams throughout an instructional unit. Assessments, aligned with the intended learning outcomes, help both the instructor and student determine if the intended learning has occurred.[1, 16]

The last of Gagne's Nine Events, enhancing retention and transfer, aims to prevent students from "storing" their knowledge in a context- or discipline-specific silo after learning has occurred. Providing students with a variety of situations in which to use their new knowledge will aid retention and transfer.[4]

While Gagne outlined elements of instruction based on information processing theory, Richard Mayer used information processing theory to develop research-based guidelines for how to present information to learners.[3] According to Mayer, any instructional material that utilizes a combination of words and pictures constitutes multimedia learning. Thus, a textbook with images is considered multimedia, as is a narrated video or animation. Mayer's theory of multimedia learning is based on three assumptions of cognitive processing: 1) dual channel—knowledge is represented and understood separately through the audio channel and the visual channel, 2) limited capacity—each channel has limited capacity for holding and storing information, and 3) active processing—deep learning occurs when learners are actively engaged in processing material. After many experiments testing these assumptions, Mayer developed several design principles for how to deliver content in multimedia contexts:

- Multimedia Principle—Use a combination of words and pictures.
- Contiguity Principle—Simultaneous presentation of narration and animations leads to deeper learning than successive presentation of narration and animation.
- Coherence Principle—Extraneous words, pictures, animations, music or other sounds distract learners and thus detract from deep learning.
- Modality Principle—Animation in combination with narration promotes deep learning, while animation in combination with written text results in cognitive overload.
- Redundancy Principle—Do not add written text that duplicates narration, short simple narrations in combination with animation is the ideal.
- Personalization Principle—A conversational style of narration personalizes content for students.
- Interactivity Principle—Give students the opportunity to interact with material.
- Signaling Principle—Highlight key ideas by using narration to signal important steps, processes, and ideas.

Choosing Concepts for the Videos

At the outset of the video development process, we recognized the need to focus the videos on pivotal concepts and critical skills that would then be organized into multidisciplinary themes in order to best enhance the educational experience. The first step in this process was to identify which concepts and skills from the first three semesters were truly "pivotal."

The process of identifying pivotal concepts was an intellectually challenging one. A number of engineering educators (as well as educationalists from other disciplines) advocate that the difficult task of constructing a curriculum should begin by thinking about what students should know and be able to do by the time they finish a specific unit of instruction, whether that unit is a single class, a semester-long course, or, as in the case of this project, the first three semesters of a four-year curriculum. John Biggs and Catherine Tang in the U.K. describe this approach as "constructive alignment." They believe when developing a curriculum, instructors first need to define the students' intended learning outcomes. Flowing from these intended learning outcomes are what they call "teaching learning activities" and "assessment tasks"; they are the means by which students achieve the intended learning outcomes and the measurements of the extent to which the intended learning outcomes have been mastered, respectively.[16]

We were fortunate that faculty and instructional staff had begun the process of defining SUTD's curriculum. Most of the courses in the first three semesters already had a number of intended learning outcomes associated with them. We took these learning outcomes, and used the "backwards design" principle created by Grant Wiggins and Jay McTighe to prioritize content along a spectrum from "big ideas and core tasks" to "important to know and do" to "worth being familiar with." [1]

We consulted two other streams in educational research to aid us in specifying the pivotal concepts and critical skills. First, the literature on integrated curricula helped us identify the concepts taught in the first three semesters that were truly multidisciplinary or had the potential to serve as a scaffold for more advanced concepts or skills.[17-19] Cognitive theory suggests that one factor that promotes long-term retention of knowledge is practice at retrieval—including spaced practice and practice within different contexts.[4] Allowing students to apply the same concept within different contexts helps them construct and re-construct their mental models and can promote deeper understanding of the concept.[5] If a course concept was found to have applicability in multiple courses, this added to the determination that it was pivotal.

We also went to the literature on student misconceptions and misunderstandings; this literature is quite rich in physics, chemistry, biology, and mathematics.[20-24] Finally, we examined concept inventories that test for those misconceptions and identify common student stumbling blocks.[25-28] If a course concept was found to have associated misconceptions, this reinforced our assumption that the concept was pivotal.

In the end, a concept or skill was identified as pivotal when it satisfied one of two criteria: (1) it was multidisciplinary; or (2) it was prerequisite for multiple concepts that would be taught in upper-level courses.

Identifying Multidisciplinary Themes

Once we had identified the pivotal concepts, we created a concept map that highlighted the connections and relationships among these concepts.[29, 30] By sorting and rearranging the pivotal concepts and looking for commonalities at a higher level of abstraction, we were able to identify the following multidisciplinary themes: Conservation, Derivatives and Integrals, Differential Equations, Equilibrium, Governing Rules, Information Flow, Linearity, Representations, Structure-Function-Properties, Modeling, Communication, Problem Solving, and Teamwork. These themes may be apparent to engineering faculty and discipline experts, but are generally not made explicit for novice learners.

The multidisciplinary themes provided a framework for the video design process. The themes contextualized the pivotal concept presented, focused the content, and provided a broader lens through which to view ideas in science and engineering that are critical for beginning engineering students to internalize.

Designing the Videos

This section describes the design process that guided the development of the videos. That process involved iterative stages of brainstorming, outlining, and drafting, and culminated in a final technical review and recording.

Brainstorm. For each video, the design process began with a brainstorming session. During this brainstorming, the designated primary author for the video reviewed the concept map, identified a potential concept to be addressed by the video, and evaluated it against the following criteria:

1. Did the concept align with the curriculum?
2. Did it align with a multidisciplinary theme?
3. Was an understanding of the concept essential to success in subsequent courses?
4. Did students commonly have difficulty understanding this concept or were there misconceptions associated with it?

For concepts that seemed promising, the primary author reviewed existing educational videos. This was done to ensure that our video was not duplicating effort, but was instead contributing to the collection of open educational resources.

After this background work by the primary author, the entire design team met to continue to debate the merits of the proposed topic. To take full advantage of video as an instructional medium, the team also brainstormed concrete visual examples that could help illuminate the concept for students. When possible, faculty, instructors, and practicing engineers were included in the discussion of appropriate examples. These examples would serve as the "stimulus" material for students (Gagne's Fourth Event). After honing in on a concept, a multidisciplinary theme, and visual examples, the primary author conducted necessary background research on the concept in order to present it accurately and effectively to students.

Outline. The primary author then created an outline for the video. The outline addressed several key elements: 1) the intended learning outcomes, 2) the prerequisite knowledge, 3) how the multidisciplinary theme would be addressed, 4) the context through which the pivotal concept would be presented, and 5) the general organization of the video content. Each element is described in more detail below.

The outline, as well as the resultant video, explicitly stated what students should know or be able to do by the end of the video. Gagne's Second Event, informing the learner of objectives, and Mayer's Signaling Principle, highlighting key ideas for students, support this practice. From a design perspective, clearly stating the intended learning outcomes of each video early in the design process helped us check for alignment between the proposed content and the intended learning outcomes.

The prerequisite knowledge needed to understand the subject of the video was also articulated. We refer to this prior knowledge throughout the video, cueing students with phrases such as "recall that," "as you have learned," or "pause and remind yourself." This design element supports Gagne's Third Event, stimulating recall of prior knowledge, and adheres to Mayer's Signaling Principle.

The outline then detailed how the multidisciplinary theme would be used to present the pivotal concept. As one can imagine, all of the important aspects of a pivotal concept cannot be presented in a 15-minute video. The multidisciplinary theme provided a framework for which specific facets of the pivotal concept would be presented. The theme also helped in the selection of relevant examples for the video.

Finally, the organization of the video content was detailed in the outline. Before the script for the video narration was drafted or any visuals were planned, the outline served as a check to ensure that a cohesive story was being presented. At this point, sections were added, deleted, or rearranged so that the content was properly scaffolded for the learner (Gagne's Fifth Event – providing learner guidance).

Draft. Once the outline was finished, the script for the video narration was drafted. Creating a script for a video is inherently different from creating written instructional materials, such as textbooks and course notes. There is considerable interplay between the creation of the narration and the conceptualization of the visuals.[31] As the script was drafted, ideas for supporting visuals were generated. By considering audio and visual channels simultaneously, we were able to create videos that adhered to Mayer's principles for multimedia design, particularly the Multimedia, Contiguity, Coherence, and Modality Principles.

As the content of the video was developed in the drafts of the script, the primary author inserted opportunities for student interaction. Video by its nature is a passive medium. In order to adhere to Mayer's Interactivity Principle and support Gagne's Sixth Event, eliciting performance, students are prompted at various times to pause the video and grapple with the material being presented. These pauses prompt students to engage in an activity, discussion, or computation before returning to the video. After the pause, the video provides students with feedback (Gagne's Seventh Event) by working through the activity or explaining possible responses. Each script underwent multiple rounds of revision, in response to team members' comments on organization, technical content, pedagogy, length, visual elements, language, and grammar.

Technical Review. Faculty with expertise in the area reviewed final drafts to ensure the accuracy of the technical content. The technical reviewer would often serve as the narrator for the video.

Record. The narration was recorded after a final script revision based on feedback from the technical review. Accompanying visuals were produced and recorded, and the audio and visuals were edited together. Before being finalized, the video was reviewed by the team for errors in the narration, visuals, or the syncing of the two elements.

Examples of Videos and Their Connections to Multidisciplinary Themes

The two examples below illustrate the culmination of the video design process, and how we used multidisciplinary themes to highlight a pivotal concept.

Video Title: Vectors
Pivotal Concept: Vectors represent objects that have magnitude, direction, and satisfy linearity conditions.
Multidisciplinary Theme(s): Representations - Representations enhance our understanding of a system's structure, properties, and function.

Linearity - Many complex systems are modeled or approximated linearly because of the mathematical advantages.
Prerequisite Knowledge: Students should be familiar with vector algebra in two and three dimensions.
Intended Learning Outcomes: After watching this video, students will be able to: • Understand the properties of vectors using displacement as an example, and • Determine whether or not a physical quantity can be represented using a vector.

The *Vectors* video addresses the common difficulty students have with identifying and applying the linearity properties of a vector. In other words, students forget how vectors interact with scalars and other vectors. It is precisely these interactions that determine whether or not a physical quantity can be represented by vectors.

The video is designed for use in both physics and math courses. It could be used to highlight the linearity of vectors—a mathematical property—in a physics class. The video could also be used to explain the representation of physical quantities by vectors in a math class. By combining mathematical and physical components, we hope to demonstrate the utility of real world examples in math courses, and the importance of conceptual mathematical understanding in physics courses.

The video opens by introducing a scenario where a gift is left for the viewer 7 meters from the center of a room. Because only the magnitude, and not the direction, is given, the location of the gift is not immediately obvious. Thus we introduce the vector: an object with both magnitude and direction. Students are asked to pause the video and brainstorm a list of physical quantities that have both magnitude and direction.

The displacement vector is introduced as the canonical example of vector behavior. We introduce the notion that the mathematics of vectors is tied to the expected behavior of displacements. We illustrate that the *linear* properties of vectors can be derived by thinking through what happens when you scale or add displacements.

We introduce the idea that a vector can *represent* a physical quantity if and only if the physical quantity has magnitude, direction, and satisfies the linearity conditions of vector addition and scalar multiplication. Students return to the list of physical quantities they brainstormed at the beginning of the video to see if they satisfy linearity conditions. As an example, the video shows a force balance demonstration, which suggests that forces are aptly represented by vectors. Students are then prompted to work through an example that proves rotations cannot be represented by vectors (since rotations do not combine commutatively).

Video Title: Latent Heat
Pivotal Concept: In an isolated system, energy is conserved.
Multidisciplinary Theme(s): Conservation - Conservation concepts can be used to predict system behavior.
Prerequisite Knowledge: Students should be familiar with the law of conservation of energy and the effects of intermolecular forces on phase transitions.
Intended Learning Outcomes: After watching this video, students will be able to:

- Describe the energy transformations that occur during a phase change, and
- Apply the law of conservation of energy to phase changes.

The *Latent Heat* video ties the pivotal concept of conservation of energy to phase change materials used in buildings. The concept of latent heat is an illustrative, but non-standard example of a phenomenon that can be explained using the law of conservation of energy. The law of conservation of energy is relevant in many courses, but most novice students are accustomed to applying it in physics courses. The goal is to help students transfer their understanding of conservation of energy to other disciplines.

The video begins with an attention-getting demonstration. A small container of water immersed in an ice-salt water bath is being supercooled. The students can see that the water is being supercooled because a thermocouple is immersed in it. The students are told that if a nucleation event, such as dropping a small piece of ice into the supercooled water, occurs, the supercooled water will freeze. The students are asked to make a prediction—upon freezing, do they expect the temperature on the thermocouple to increase, decrease, or stay the same? After pausing the video to discuss and justify their predictions, students see what happens to the temperature when the water freezes.

The video then goes on to ask students to think about what happens to intermolecular forces during a phase change; additionally, the concept of latent heat is discussed. Here, students see that the law of conservation of energy can be used to explain what they observed in the demonstration. Students are presented with an example of how melting ice is used to cool the Bank of America building in New York City. They then hear about phase change materials, and how they are used to harness latent heat and reduce the heating or cooling costs in buildings.

Supporting Use of the Videos

To support the intended implementation of the videos, an Instructor's Guide was developed to accompany each video. The Instructor's Guide outlines where in the curriculum the video might be used, the prerequisite knowledge students should have before watching the video, and the intended learning outcomes. The guide also explains why the particular video was developed—why the concept and theme were selected, why particular examples were chosen, and what related student misconceptions the video tries to address.

The Instructor's Guide includes pre-video activities aimed at checking that students have the prerequisite knowledge needed to comprehend the video. Post-video activities, aligned with the intended learning outcomes, encourage students to engage more deeply with the material presented in the video. Both pre- and post-video activities include concept questions, discussion questions, experiments, kinesthetic activities, or textbook-like problems. The activities in the Instructor's Guide support Gagne's Events Six through Eight: eliciting performance, providing feedback, and assessing student performance.

A section called "Going Further" explains how the subject of the video is relevant elsewhere in the curriculum. It also points out more advanced material that relies on the concept addressed in the video. The Instructor's Guide concludes with a References section that identifies materials that were used in the development of the video, which can aid instructors in their teaching and which may be made available to students. These materials include textbooks, research articles, and web links to other videos.

In addition to the Instructor's Guide, SUTD faculty participate in workshops that discuss how to use the videos. A multidisciplinary group of faculty attend these workshops where they are introduced to the goals of the videos and how the concepts and themes were chosen. At each workshop, faculty are shown two or three videos. The common features of the videos are highlighted, including the use of pauses to signal student activities. The faculty are asked to discuss different ways they might incorporate the videos into their courses. Common responses include having students watch the videos before, during, or after class or recitation. Some faculty envision showing a part of the video in class, having students do a related activity, and then having students finish watching the video as homework. Other faculty suggest they might simply use the demonstration or activity ideas from the videos and replicate them live in the classroom. Faculty are also asked to discuss other ways they might highlight the theme presented in the video in their class. This results in particularly interesting discussions. Faculty get to hear the ideas of their colleagues in other disciplines, raising their awareness of how different fields may incorporate similar or complimentary ideas.

Continuing Video Development

As noted above, based on a positive reception to the first 24 videos, we received additional funding to create a second set of 24 videos. While the first set of videos focused on the first three semesters of SUTD's undergraduate curriculum, the second set of videos will focus on semesters four and beyond. A full-scale evaluation of the first 24 videos has not been completed; however, pilot testing with students at MIT, anecdotal feedback from SUTD faculty, input from experts in video production, and the experience of our own video development team have led us to augment our video development process.

Student pilot testers and others who reviewed the first 24 videos commented that the videos were slow to start. Our original video design process did not focus on gaining learner attention—Gagne's First Event. In response, our new videos will begin with what we call a "TV style" introduction. The TV style introduction presents a thought-provoking example or problem at the beginning of the video, designed to grab student attention and pique interest. By the end of the video, the example is fully explained or the problem is resolved.

Many of the visuals in the first 24 videos were presented using PowerPoint® slides. Some viewers commented they were too reminiscent of a classroom experience. In response, the second set of videos will contain more live action video clips, animations, and "pen tableting," which allows us to sketch images and graphics digitally, as if using a pencil and paper. In the second set of videos, all mathematical computations and simple drawings will be done using a pen tablet. Students commented they really appreciate the pen tablet videos, especially when dealing with mathematical content.

In the first 24 videos, we tried to adhere to Mayer's Redundancy Principle—written text should not duplicate narration, however, we did not always succeed. For example, the intended learning outcomes and prerequisite knowledge tended to be words on the screen that were read by the narrator. We have learned over time how to translate these ideas into visuals that convey the same information with minimal text on the screen.

We have also tried to make the style of the narration more conversational—Mayer's Personalization Principle. However, we are very careful to make sure that the language stays precise, especially when working with engineering and math content. We err on the side of using accurate vocabulary, so that students do not misinterpret the narration because it is being said in a conversational tone.

Future Work

SUTD has had access to the first 24 videos since its opening in May 2012. While we have received some anecdotal feedback from faculty and students, an in-depth evaluation of the videos has not yet been possible.

In the spring of 2013, the videos and Instructor's Guides will be available to the public via the web as open educational resources. We intend to post a brief survey alongside each video to collect data from users about their experience with the videos. These data will help us determine what aspects of the videos viewers found most useful and will guide future revision and development appropriately.

If funding can be secured, an action research study with control and experimental test groups will be conducted to study the impact of the videos on student learning.

Acknowledgements

We would like to acknowledge the Singapore University of Technology and Design for the funding of this project; Aikaterini Bagiati, Leann Dobranski, Colin Fredericks, Sanjay Sarma, George Zaidan, and MIT Academic Media Production Services for helpful conversations and contributions; and two dozen MIT faculty and graduate students for reviewing concept vignette scripts and narrating them.

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