

A Novel Approach to Skeleton-Note Instruction in Large Engineering Courses: Unified and Concise Handouts that are Fun and Colorful

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A Novel Approach to Skeleton-Note Instruction in Large Engineering Courses: Unified and Concise Handouts that are Fun and Colorful

Skeleton notes (partially completed hand-outs that are completed during class by the instructor and the students) can be an effective pedagogy for delivering engineering material to large sections when factors such as a high student-instructor ratio and/or inadequate Teaching Assistant support prohibits a fully flipped model. This paper describes an innovative hybrid approach to instruction that features a novel approach to skeleton notes.

As examples, we will draw upon two case studies. The first is a sophomore-level Mechanics of Materials course at Colorado School of Mines, in which the instructor has developed a robust and sophisticated set of skeleton notes over the course of seven semesters. General benefits of skeleton notes are well-documented (enhancement of critical thinking during lecture, active participation rather than passive observation, and the instructor's ability to maintain eye contact with students without turning his/her back to the class). In the paper, we discuss the unique aspects of these handouts that contribute to their success:

- In contrast to other courses taught with multiple streams of information (traditional lecture, skeleton notes, supplementary handouts, slides, reading assignments, etc.), these handouts consolidate the technical material into a single unified message; they are truly complementary with and integrated into the oral lecture.
- The handouts are hand-written on a tablet computer, are highly graphic, colorful, and even “cartoonish” in nature, and are interspersed with humor to maximize their appeal to undergraduate students.
- The handouts are created with software that enables the author to easily employ principles of graphic design related to hierarchy of information: key points covered during lecture are large and bold; supporting details, case studies, anecdotes, and supporting derivations that are to be reviewed by students after class are very small and bubbled in the margins.

The second case study is a set of skeleton notes developed by an undergraduate student who completed this Mechanics of Materials course and emulated the instructor's skeleton note approach in a workshop he taught at Red Rocks Community College.

The resulting data from both case studies suggests that this teaching technique results in better-engaged students who have a better conceptual understanding of the technical material at the conclusion of the course. On student course evaluations, the handouts are overwhelmingly cited as an effective teaching method.

The purpose of the paper is to stimulate discussion in this effective hybrid teaching technique for large engineering courses. We will describe student feedback and metrics by which the effectiveness of this technique has been assessed, and give the reader explicit step-by-step instructions on how to use technology to implement such a system in other courses.

1.0 The Pedagogy, Features, and Strategies of Skeleton Notes

“Skeleton Notes” are partially completed handouts that are completed during class by the instructor and the students. Other common terms for Skeleton Notes include “Guided Notes,” “Outline Notes,” “Semi-Notes,” and “Skeletal Notes.” Skeleton Notes can be contrasted to other common methods of content delivery in computational engineering courses, such as the traditional lecture and the flipped classroom, and have aspects of a hybrid approach of these two techniques.

In a traditional engineering lecture, the instructor typically transfers written notes to a physical surface (whiteboard), or projects them on a screen using physical transparencies or a tablet computer. This method of content delivery is generally characterized by limited interaction between the lecturer and the students; the content tends to be presented in a linear and chronological manner. Students typically do not practice the art of note-taking, as they would for a history or literature course, which requires active listening and the ability to synthesize information and identify major topics and supporting details. Instead, note-taking for analytical courses based in computational engineering is typically characterized by line-by-line copying of the instructor’s marks. If the lecturer’s style includes oral commentary to accompany the technical content, some (but not all) of the students will summarize this commentary in their notes. In this environment, the students tend to only be passively engaged in the content, as they are primarily occupied with copying down the calculations.

In a flipped classroom for a computational engineering course, technical content is delivered to the students outside of the classroom through videos or reading assignments, and class time is spent working problems in small groups with guidance from the instructional team (generally the instructor and teaching assistants). Some students may choose to take notes while studying the videos and/or reading assignments; others may feel that note-taking is not necessary, since the instructional materials can be accessed and reviewed at any time.

Skeleton notes can be considered a hybrid approach to the traditional engineering lecture and the fully flipped classroom. General benefits of the use of skeleton notes are well-documented^{1,2,3,4,5,6} (enhancement of critical thinking during lecture, active participation rather than passive observation, and efficiency in delivering content by reducing time spent copying figures and diagrams). In a study by LoPiccolo³, a group of students using “guided notes” (skeleton notes), achieved an average test score of 25.71% higher than a control group.

Depending on the design of the content delivery system and the instructor’s intent, the skeleton note approach can emulate and improve upon either the traditional lecture approach or the flipped classroom approach. For example, an instructor that simply seeks to make his/her traditional lectures more efficient could take a straight-forward approach to the design of skeleton notes. The content and sequence of the traditional lecture would be copied into handout format in outline form. Problem statements and corresponding diagrams would be incorporated, thus saving a significant portion of class time, and the computational problems would still be worked out in class as they were in the traditional lecture approach. The efficiency of this method would allow the instructor to cover the same amount of material at a slightly slower pace, and even pausing more often to add supplementary information and details that increase

the depth and breadth of the content. However, the student experience is not substantially changed: there is minimal active engagement in the material and the bulk of lecture time is still spent copying calculations line by line.

Alternatively, consider an instructor that wishes to provide more structure to group problem-solving activities in a flipped classroom environment. Skeleton notes could summarize key points from the out-of-class videos and/or reading assignments, provide supporting plots and graphs, and use anecdotes or case studies to give the technical content appropriate context.

This paper is intended to stimulate discussion in an innovative approach to the development of skeleton notes that incorporate the following key characteristics:

1. The handouts consolidate the technical material into a single unified and concise message. Multiple streams of information (lecture, supplementary handouts, slides, reading assignments) are avoided; the handouts are complementary with and integrated into the oral lecture. Discussion of the underlying concepts accompanies the detailed technical content.
2. The handouts are hand-written (on a tablet computer), highly graphic, colorful, and even “cartoonish” in nature. They are also interspersed with occasional humor to maximize their appeal to undergraduate students. In a word, they are “fun” - at least as fun as can be expected for undergraduate engineering coursework.
3. The handouts are created with software that enables the author to easily employ principles of graphic design related to hierarchy of information: key points covered during lecture are large and bold; supporting details, case studies, anecdotes, and supporting derivations that are to be reviewed by students outside of class are small and bubbled in the margins.

Figures 1 and 2 illustrate a blank and completed 4-page sample handout designed with these characteristics for a 50 minute undergraduate engineering lecture course.

Specific details and examples that embody the key characteristics itemized above are presented in the following two case studies. The first case study discusses the iterative and gradual development of a robust set of skeleton notes for a sophomore-level Mechanics of Materials course at Colorado School of Mines (CSM) over the course of seven semesters. The second case study is the development of a set of skeleton notes developed by an undergraduate student at CSM who completed the aforementioned course and emulated the instructor’s approach in designing skeleton notes for a 3D-Printing Mini-Course. These two case studies illustrate similarities and differences in the design of skeleton notes for two different engineering education environments.

CEEN 311 - MECHANICS OF MATERIALS - REYNOLDS - COLORADO SCHOOL OF MINES

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Thermal Stresses and Deformations

As you know, solid materials expand when heated and contract when cooled.

Some expand and contract more than others under the same change in temperature.

For example, if you are having trouble opening a metal lid from a glass jar, you can put the metal under warm water so that it expands and makes the jar easier to twist open.

Let's start by considering a beam that supports an interstate:

The amount of thermal deformation is dependant on a few variables:

- 1.) WHAT TYPE OF _____ IS IT?
(some materials are more reactive to temperature than others)
- 2.) WHAT IS THE TOTAL CHANGE IN _____
(relative to the "initial condition" or "resting condition")

The "coefficient of thermal expansion and contraction" is a property of each material, and we call it:

SYMBOL: _____ UNITS: _____

Our governing equation for thermal expansion is:

$$\delta_{THERMAL} = \alpha \Delta T L$$

and $\epsilon_{THERMAL} = \frac{\delta_{THERMAL}}{L}$

By the way, thermal expansion is actually a volumetric expansion. The material expands in the x-direction, y-direction, and z-direction. For most of our problems in this class, though, we are primarily interested in thermal effects along the longitudinal axis -- in other words -- linear deformations.

Combine those expressions to get:

$$\delta_{THERMAL} = \alpha \Delta T L$$

Thermal Coefficients of Expansion and Contraction: (UNITS: E/P)

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When you are designing a system with dissimilar materials, if temperature change is expected, use compatible materials (similar coefficients of expansion and contraction), or design the system so that it accommodates thermal deformations.

EXAMPLE PROBLEM: THERMAL -> STATICALLY DETERMINATE

When the ambient temperature is 60 degrees Fahrenheit, a micrometer is used to measure an initial length of 24".

What is the new length at a temperature of 120 degrees Fahrenheit?

Step 1. Solve for the thermal (axial) strain.

$$\epsilon_{THERMAL} = \alpha \Delta T$$

Step 2. Solve for the thermal deformation.

$$\delta_{THERMAL} = \epsilon_{THERMAL} L$$

Step 3. Solve for the deformed length of the bar.

$$L' = L + \delta_{THERMAL}$$

Step 4. Solve for the reaction at A due to thermal deformation.

Step 5. Solve for stresses in the steel caused by the change in temperature.

EXAMPLE PROBLEM: THERMAL -> STATICALLY INDETERMINATE

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Let's work the exact same problem as on the previous page, but this time, let's say that plane D is also fixed.

GIVEN: $\Delta T = +60^\circ F$

From the previous page, we know that if one of the Z ends was free to translate in the x-direction, then a deformation of 9.504 E-3 inches would result.

Now, bar is pushing against both fixed supports at A and B.

This time, reactions WILL BE DEVELOPED. We will also be able to compute THERMAL STRESSES. And by definition of a plane of fixity, there will be no net deformation of the bar ($L = L' = 24"$).

SINCE THIS IS AN INDETERMINATE PROBLEM, WE MUST WRITE A:

Let's partition the structure into 2 substructures and then superimpose them together:

Substructure ① AND Substructure ②

Compatibility Equation:

TRICKY CONCEPT!

The reactions at A & B will be equal & opposite.

(continued)

Solve for the reactions that result from the thermal increase.

$$P = \alpha \cdot \Delta T \cdot AE$$

And finally, draw a stress element to show the state of stress.

$$\sigma = \frac{P}{A}$$

For a more complex problem, be very careful and rigorous with your sign conventions.

Consider this axial member that is loaded with a force P and also subjected to a temperature decrease.

GIVEN: $P = 200 \text{ kN}$
 $d_1 = d_2 = 50 \text{ mm}$
 $E_1 = E_2 = 200 \text{ GPa}$
 $\Delta T = -60^\circ C$
 $\alpha = 12 \times 10^{-6} (1/^\circ C)$

What reactions would result from the temperature change alone?

What reactions would result from the applied force P (neglecting the change in temperature)?

Based on the direction of the reactions, let's assume that the internal force in member 1 is tensile. (If you're ever unsure, it's OK to make an assumption and you'll get a negative at the end of the problem if you guessed wrong.)

Use FBDs to write equations for internal force in member 1 and 2 in terms of Ax:

Now write a deformation compatibility equation so that the total deformation (both thermal and from the force) is equal to zero.

$$(\alpha \cdot \Delta T \cdot L)_1 + (\alpha \cdot \Delta T \cdot L)_2 + \left(\frac{PL}{AE}\right)_1 + \left(\frac{PL}{AE}\right)_2 = 0$$

$$-(12 \times 10^{-6} \times 1/^\circ C \times 60^\circ C \times 500 \text{ mm}) - (12 \times 10^{-6} \times 1/^\circ C \times 60^\circ C \times 500 \text{ mm}) + \frac{A_x (500 \text{ mm})}{\frac{\pi}{4} (50 \text{ mm})^2 \times 200 \text{ GPa}} + \frac{(A_x - 200 \text{ kN}) (500 \text{ mm})}{\frac{\pi}{4} (50 \text{ mm})^2 \times 200 \text{ GPa}} = 0$$

$$\therefore A_x = +383 \text{ kN or } 383 \text{ kN } (\leftarrow); \text{ by force equal, } C_x = 183 \text{ kN } (\rightarrow)$$

Figure 1 - Sample 4-page handout as distributed to the students

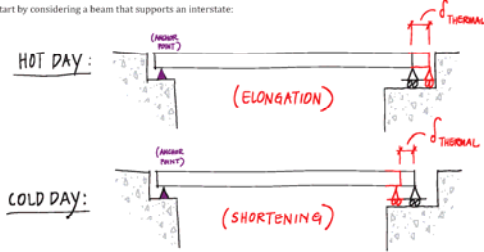
Thermal Stresses and Deformations

As you know, solid materials expand when heated and contract when cooled.

Some expand and contract more than others under the same change in temperature.

For example, if you are having trouble opening a metal lid from a glass jar, you can put the metal under warm water so that it expands and makes the jar easier to twist open.

Let's start by considering a beam that supports an interstate:



The amount of thermal deformation is dependant on a few variables:

1.) WHAT TYPE OF MATERIAL IS IT?

(some materials are more reactive to temperature than others)

2.) WHAT IS THE TOTAL CHANGE IN TEMPERATURE

(relative to the "initial condition" or "resting condition")

The "coefficient of thermal expansion and contraction" is a property of each material, and we call it:

SYMBOL: α UNITS: $\frac{(\text{strain})}{^\circ\text{F}}$ or $\frac{(\text{strain})}{^\circ\text{C}}$

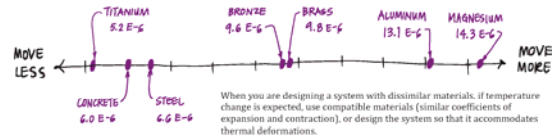
Our governing equation for thermal expansion is:

$$\delta_{\text{THERMAL}} = \epsilon_{\text{THERMAL}} \cdot L \quad \text{and} \quad \epsilon_{\text{THERMAL}} = \alpha (\Delta T)$$

Combine those expressions to get:

$$\delta_{\text{THERMAL}} = \alpha \cdot \Delta T \cdot L$$

By the way, thermal expansion is actually a volumetric expansion. The material expands in the x-direction, y-direction, and z-direction. For most of our problems in this class, though, we are primarily interested in thermal effects along the longitudinal axis -- in other words -- linear deformations.

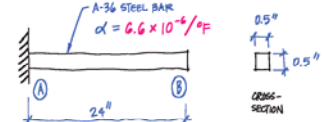
Thermal Coefficients of Expansion and Contraction: (UNITS: $1/^\circ\text{F}$)

When you are designing a system with dissimilar materials, if temperature change is expected, use compatible materials (similar coefficients of expansion and contraction), or design the system so that it accommodates thermal deformations.

EXAMPLE PROBLEM: THERMAL -> STATICALLY DETERMINATE

When the ambient temperature is 60 degrees Fahrenheit, a micrometer is used to measure an initial length of 24".

What is the new length at a temperature of 120 degrees Fahrenheit?



Step 1. Solve for the thermal (axial) strain.

$$\epsilon_{\text{thermal}} = \alpha \Delta T = 6.6 \times 10^{-6} \left(\frac{1}{^\circ\text{F}} \right) [120^\circ\text{F} - 60^\circ\text{F}] = +396 \times 10^{-6}$$

Step 2. Solve for the thermal deformation.

$$\delta_{\text{thermal}} = \epsilon_{\text{thermal}} L = 396 \times 10^{-6} (24") = 9.504 \times 10^{-3} \text{ in.}$$

Step 3. Solve for the deformed length of the bar.

$$L' = L + \delta = 24" + 9.504 \times 10^{-3} \text{ in} = 24.009504 \text{ in.}$$

Step 4. Solve for the reaction at A due to thermal deformation.

DO NOT BE TEMPTED TO USE PL/AE HERE!
PLANE B TRANSLATES TO THE RIGHT. $A_x = 0!$

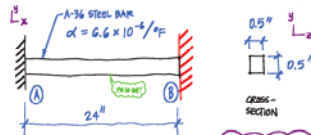
Step 5: Solve for stresses in the steel caused by the change in temperature.

DO NOT BE TEMPTED TO USE $E = \sigma/\epsilon$ TO SOLVE FOR STRESS. $\sigma = 0!$

EXAMPLE PROBLEM: THERMAL -> STATICALLY INDETERMINATE

Let's work the exact same problem as on the previous page, but this time, let's say that plane D is also fixed.

GIVEN: $\Delta T = +60^\circ\text{F}$



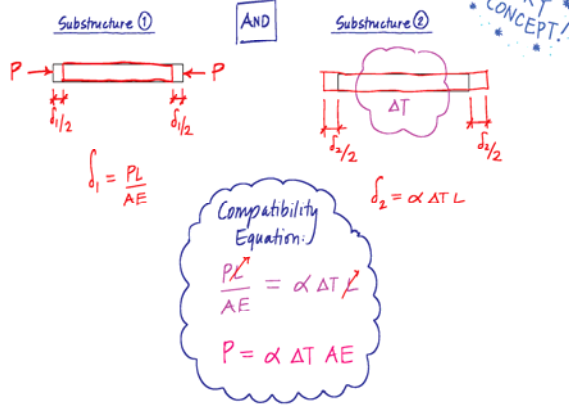
From the previous page, we know that if one of the Z ends was free to translate in the x-direction, then a deformation of 9.504 E-3 inches would result.

Now, bar is pushing against both fixed supports at A and B.

This time, reactions WILL BE DEVELOPED. We will also be able to compute THERMAL STRESSES. And by definition of a plane of fixity, there will be no net deformation of the bar ($L = L' = 24"$).

SINCE THIS IS AN INDETERMINATE PROBLEM, WE MUST WRITE A:

Let's partition the structure into 2 substructures and then superimpose them together:



(continued)

Solve for the reactions that result from the thermal increase.

$$P = \alpha \cdot \Delta T \cdot AE = 6.6 \times 10^{-6} \left(\frac{1}{^\circ\text{F}} \right) (60^\circ\text{F}) (0.5 \text{ in})^2 (29,000 \text{ ksi}) = 2.871 \text{ k}$$

And finally, draw a stress element to show the state of stress.

$$\sigma = \frac{P}{A} = \frac{2.871 \text{ k}}{(0.5 \text{ in})^2} = 11.48 \text{ ksi (c)} \quad \rightarrow \quad \square \quad \leftarrow 11.48 \text{ ksi}$$

For a more complex problem, be very careful and rigorous with your sign conventions.

Consider this axial member that is loaded with a force P and also subjected to a temperature decrease.

GIVEN: $P = 200 \text{ kN}$
 $d_1 = d_2 = 50 \text{ mm}$
 $E_1 = E_2 = 200 \text{ GPa}$
 $\Delta T = -60^\circ\text{C}$
 $\alpha = 12 \times 10^{-6} (1/^\circ\text{C})$



What reactions would result from the temperature change alone?

What reactions would result from the applied force P (neglecting the change in temperature)?



Based on the direction of the reactions, let's assume that the internal force in member 1 is tensile. (If you're ever unsure, it's OK to make an assumption and you'll get a negative at the end of the problem if you guessed wrong.)

Use FBDs to write equations for internal force in member 1 and 2 in terms of A_x :

$$A_x \rightarrow P_1 = A_x$$

$$A_x \rightarrow P_2 = A_x - 200 \text{ kN}$$

Now write a deformation compatibility equation so that the total deformation (both thermal and from the force) is equal to zero.

$$(\alpha \cdot \Delta T \cdot L)_1 + (\alpha \cdot \Delta T \cdot L)_2 + \left(\frac{PL}{AE} \right)_1 + \left(\frac{PL}{AE} \right)_2 = 0$$

$$-(12 \times 10^{-6}) (1/^\circ\text{C}) (60^\circ\text{C}) (500 \text{ mm}) - (12 \times 10^{-6}) (1/^\circ\text{C}) (60^\circ\text{C}) (500 \text{ mm}) + \frac{A_x (500 \text{ mm})}{\frac{\pi}{4} (50 \text{ mm})^2 (200 \text{ GPa})} + \frac{(A_x - 200 \text{ kN}) (500 \text{ mm})}{\frac{\pi}{4} (50 \text{ mm})^2 (200 \text{ GPa})} = 0$$

$$\therefore A_x = +383 \text{ kN or } 383 \text{ kN } (\leftarrow); \text{ by force equal, } C_x = 183 \text{ kN } (\rightarrow)$$

Figure 2 - Sample 4-page handout as completed by the instructor during class

2.0 Case Study #1 - Mechanics of Materials

At Colorado School of Mines, CEEN 311 Mechanics of Materials is a 3.0 credit hour required course for eight different engineering majors, and is taught to approximately 500 students each academic year. The course is administered centrally by a Course Coordinator, who is responsible for standardizing the content across different sections, instructors, and Graduate Teaching Assistants (GTAs). Section sizes for the course generally range from 60-80 students, with 1 GTA assigned to each 2 sections. The GTAs are fully utilized for delivering Recitation sections and grading homework, and could not be used in support of a flipped classroom approach without reducing their other responsibilities.

The first iteration of skeleton notes was developed as a better alternative to the traditional engineering lecture approach historically used in the course. In the traditional lecture approach, the pace of the lecture was perceived to be too fast to facilitate the attainment of the course's learning objectives. In these early iterations, the design of the skeleton notes emulated the traditional lecture approach, but figures were placed in the handouts in order to increase the pace of the delivery (Fig. 3 and 4).

Over time, as an instructor re-teaches the same course in subsequent semesters, he/she learns a little more about the students' common questions and misunderstandings. As these are identified, supplementary information can be layered into the skeleton notes. The careful layering and juxtaposition of supplemental information consolidates the content into a single stream of unified and concise instruction.

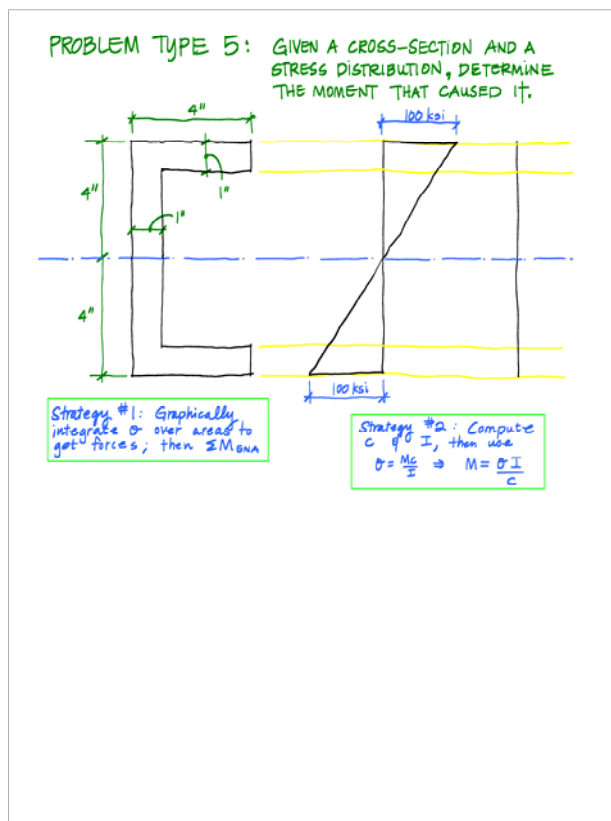


Figure 3 - Handout designed to facilitate solution of an example problem as photocopied and distributed to each student

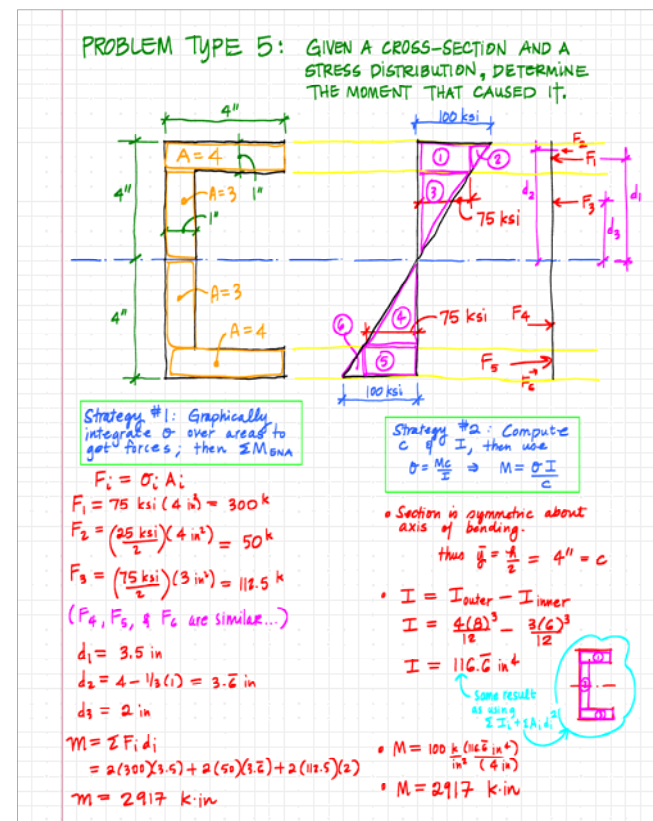


Figure 4 - Handout designed to facilitate solution of an example problem as completed by the instructor during class

For example, although Statics is a prerequisite for Mechanics of Materials, some students do not adequately retain the fundamental information that must be carried over from one semester to the next. Fig. 5 illustrates an approach that caters to both sets of students: those that recall how to compute the moment of inertia of a cross-section and those that do not.

MOMENT OF INERTIA

Here's the equation we'll use via the parallel axis theorem:

$$I = \sum I_i + \sum A_i d_i^2$$

By the way, in this class we only use the **area** moment of inertia, not the **mass** moment of inertia. Thus the units of the moment of inertia are length to the fourth.

tip: to avoid common errors on calculating distances for the moment of inertia calculation, draw your cross-section very large!

See GoStructuresGo: Pear for an in-depth tutorial on concepts covered on this page

LE01
page 2/2

component areas

perpendicular distance from each component centroid to _____

moment of inertia for each component area about _____

$$I_{\text{rect}} = \frac{bd^3}{12}$$

$$I_{\text{circle}} = \frac{1}{4} \pi r^4$$

These equations are on your exam formula sheet, but you're probably better off memorizing them because you'll use them quite a bit. I know these calculations seem really simple, but they are super-critical for this course, and students make a lot of mistakes, so test yourself with GoStructuresGo: Duku

Figure 5 - Skeleton note excerpt that illustrates hand the handout directs students to supplementary resources

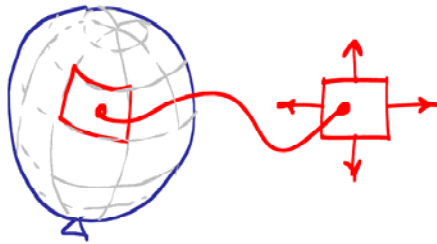
This approach permits the instructor to quickly review how the moment of inertia of a cross-section is calculated, emphasize the importance of this calculation, and also direct students to an additional resource. The small text at the top margin says “See GoStructuresGo: Pear for an in-depth tutorial on concepts covered on this page.” This is a reference to a YouTube video created by the instructor that provides more information on this concept. The video is designed for those students that need a refresher on this material. Their needs are met, and during class the instructor can quickly move ahead to new topics, therefore not boring and frustrating the students that do not need the review.

Fig. 6 provides an example of enhancing the lecture by prefacing technical engineering jargon with a conceptual introductory discussion that captures the students’ interest. In this handout, the topic of thin-walled pressure vessels is introduced using the analogy of a balloon, thereby making the notion of tensile stress in the membrane immediately accessible to the students. This content can be delivered very quickly, as most of the material is provided in the handout, and therefore enhances learning with minimal additional lecture time invested.

Fig. 6 also illustrates the occasional insertion of casual language used in the handouts. Certainly, the students benefit from a formal presentation that uses conventional engineering language, and most of the language in the handouts is of textbook quality. However, the occasional use of casual language breaks up the lecture, attracts students’ attention, and at its best, can make the course a little less intimidating.

Thin-Walled Pressure Vessels

This lecture will teach you about the stresses that develop in the walls of thin-walled pressure vessels. A pressure vessel is really a fancy term for a tank. We'll use the analogy of a balloon to frame the problem.



- As you inflate the balloon, you increase the pressure.
- As the internal pressure increases, the balloon gets larger.
- Therefore the balloon material is elongating.
- If we have elongation then we have tensile stress.

Figure 6 - Skeleton note excerpt that demonstrates an effective way to quickly relate a new engineering concept to an analogy

Skeleton notes can also facilitate a flipped-classroom environment by encouraging a dialogue with the class and problem-solving in small groups. Fig. 7 contains a chart that is used in class to teach one of the most challenging topics in the course: combined stresses. The chart illustrates a solid cylindrical member that is subjected to various forces, torques, and moments. The rows of the table contain the internal forces/torques/moments and the columns of the table distinguish between the state of stress at points A, B, and C. The instructor can work with the students in an interactive manner to determine which equation is appropriate in each cell in the table, and ask challenging follow-up questions, such as “is point B in flexural tension or compression?” The design of the handout facilitates a variety of pedagogical approaches, including “pair-share.” This format allows the instructor to teach fundamental concepts, such as selection of the appropriate equation for three different points (A, B, and C), instead of spending that time plugging numbers into the equations for the state of stress at a single point.

Another technique that is similar to the use of periodic casual language that captures students' attention over the course of a dense lecture is the occasional injection of humor in the handouts. The excerpt shown in Fig. 8 illustrates a ridiculous and humorous scenario used to introduce the Allowable Stress design philosophy. The instructor quickly describes a student putting together a film in which he plays Superman, and in which Superman flies over the surface of an alien planet characterized by boiling lakes of acid inhabited by acid-tolerant crocodiles. In order to maximize the film's authenticity, the student breaks into the Chemistry department and procures some acid to create the lakes. He then suspends himself over the acid from a cable, after carefully calculating that his weight subjects the cable to a stress of 100 psi, and that the cable is expected to fail at 101 psi. The instructor asks the students whether or not this is a reasonable and safe decision, and then goes on to explain Allowable Stress design using conventional engineering terminology. This silly anecdote does not take up much class time, is always well-received by the students, and facilitates an excellent conceptual understanding of Allowable Stress design.

The cartoonish nature of the handouts is a key characteristic that contributes to their readability. Anecdotally, students report that they are more accessible than other instructors' formal, computer-generated skeleton notes. Fig. 9 contains a graphic depiction of Hooke's Law, wherein the spring deformations are proportional to the applied force. This excerpt also contains another example of the layered information in the margins that is not necessarily referenced during class,

PRACTICE PROBLEM #1:
Consider points A, B, and C under the internal forces and moments diagrammed at left. What type of stress results?

	$\sigma_{ave} = \frac{P}{A}$ $\sigma = -\frac{My}{I}$ $\sigma = 0$ $\tau = \frac{T\rho}{J}$ $\tau = \frac{VQ}{It}$ $\tau = 0$		$\sigma_{ave} = \frac{P}{A}$ $\sigma = -\frac{My}{I}$ $\sigma = 0$ $\tau = \frac{T\rho}{J}$ $\tau = \frac{VQ}{It}$ $\tau = 0$		$\sigma_{ave} = \frac{P}{A}$ $\sigma = -\frac{My}{I}$ $\sigma = 0$ $\tau = \frac{T\rho}{J}$ $\tau = \frac{VQ}{It}$ $\tau = 0$
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Figure 7 - Skeleton note excerpt that illustrates use of the handout to teach concepts quickly and effectively

ALLOWABLE STRESS

Context:

You are playing Superman, you weigh 100#, and the cable has an area of 1 in² -> so the material is stressed to 100 psi. And say that the cable was tested in a lab and failed at 101 psi.

Figure 8 - Skeleton note excerpt that illustrates use of humor to engage students

but is available for the student to peruse as they study: in the left margin is a mnemonic device that can be used to remember Hooke's Law ("Hooke liked to hang little weights on hooks").

Hooke's Law

Sir Robert Hooke lived in England from 1635-1703. Among other things, he hung weights from springs and observed that the displacement of the end of the spring was proportional to the amount of weight.

The Experiment

Memory trick for remembering that "Hooke's Law" corresponds to this concept:

Hooke liked to hang little weights on hooks.

← undeformed deformed →

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Figure 9 - Skeleton note excerpt that illustrates insertion of mnemonic device into handout

Another key feature of this approach to skeleton notes is the incorporation of a graphic hierarchy that helps students distinguish between key facts and supporting details. In Fig. 10, the governing equation for beam deflection is in heavy black ink at the top of the page, signifying that this is an important and key equation in the course. We then see a table that illustrates the relationships between load, shear, moment, rotation, and deflection. Finally, the small print at the bottom of the page provides a step-by-step procedure applicable to homework problems. During lecture, the instructor can choose to spend more time on the meaning of the governing equation, and only make a passing comment on the step-by-step procedure, saving tremendous time, compared to traditional engineering lecture.

Similarly, Fig. 11 illustrates a spatial organization of stress calculations for a member subjected to bi-axial bending. The left column contains supporting calculations for strong-axis bending; the right column contains those calculations for weak-axis bending. The spatial organization helps the students compare and contrast the axes, enhancing their understanding of this challenging concept. In each of these excerpts, large and bold font is used for the most important concepts; supporting details, case studies, anecdotes, etc. are then fleshed out with small text. For example, the small text at the bottom of Fig. 11 reads as follows: *"The beam on the left is being loaded transverse to the strong-axis, so we call this "strong-axis bending." Conversely, the beam on the right is subjected to "weak-axis bending." How can you tell the difference? Well, you simply compare the moments of inertia for the 2 cross-sectional axes. If your applied forces are transverse to the big I value, that's strong-axis bending. It's more efficient to orient beams so that the largest I value is used to resist the largest bending moments. Be sure you know the difference for the exams!"* The instructor can therefore reduce the amount of explicit instruction giving during class time, and the students can review the details as they work on their homework assignments and prepare for exams.

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Deflection of Beams I: Method of Integration for Determinate Beams

We will spend the next 4 lectures on Beam Deflection. It's one of the trickiest topics of this course, but it's also FUN!!
We'll do the derivation for this later -- for now, all you need to know is the governing differential equation for beam deflections:

$$\text{CURVATURE} \left\{ \frac{d^2 v}{dx^2} = \frac{M}{EI} \right.$$

Note: curvature increases as the internal bending moment increases, but it's controlled by the flexural stiffness EI .

Let's break this down, starting with the LOAD function.

$w(x)$	LOAD FUNCTION	$= v'''' EI$
$V(x) = \int w(x) dx$	SHEAR FUNCTION	$= v''' EI$
$M(x) = \int V(x) dx$	MOMENT FUNCTION	$= v'' EI$
$\theta(x) = \frac{1}{EI} \int M(x) dx$	SLOPE OF THE DEFLECTED SHAPE	$= v'$
$v(x) = \int \theta(x) dx$	EQUATION OF THE ELASTIC CURVE OR DEFLECTED SHAPE	$= v$

This is what $v(x)$ and dv/dx are:

Sign convention: $v(x)$ is positive in the positive y direction (up); dv/dx is positive when the rotation from undeformed to deformed is counter-clockwise.

PROCEDURE FOR WRITING $v(x)$:

1. Sketch the moment diagram and deflected shape. Determine how many different moment functions are present over the length.
2. For each $M(x)$ function, create a coordinate system. This is usually "x" if you have a simple beam with only 1 $M(x)$. You can use x_1 and x_2 for a beam with 2 $M(x)$ functions. Be strategic when setting up your coordinate system. Sometimes, it's easier to write x_1 from left to right and x_2 from right to left, for example.
3. For each $M(x)$ function, cut a FBD. Consider the left side and the right side of the beam, and pick the side with the fewest number of terms. Make sure that you draw the internal moment in the positive direction. Use moment equilibrium about the cut to write the equation for internal bending moment. If you are given a problem with numbers in it, change them to symbols (w, P, L , etc.) to minimize errors during the integration process.
4. For each $M(x)$ function, integrate it with respect to x and divide by EI . This is your theta. Don't forget to include a constant of integration. Call it C_1 .
5. Integrate theta with respect to x . This is your $v(x)$ equation. Don't forget to include a constant of integration. Call it C_2 .
6. Use the motion of **Boundary Conditions** to plug in values for v and theta in order to solve for C_1 and C_2 .
7. Plug C_1 and C_2 into the equations for theta(x) and $v(x)$.

Figure 10 - Skeleton note excerpt that illustrates the use of a graphic hierarchy in the design of the handout

BI-AXIAL BENDING (Bending About Both Cross-Sectional Axes)

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What is the state of stress at point D?

Force P_1 causes bending about: z
The internal shear force is transverse to: z
Therefore the ENA is: z

Force P_2 causes bending about: y
The internal shear force is transverse to: y
Therefore the ENA is: y

PARTITION IT INTO 2 SUB-STRUCTURES, ANALYZE EACH INDIVIDUALLY, THEN SUPERIMPOSE THE RESULTS.

STRONG-AXIS BENDING.

Look at the near side of the beam in the xy plane:

$I_y = \frac{d_1 (d_1)^3}{12}$
(because d_2 is \perp to ENA)

WEAK-AXIS BENDING.

Look at the top side of the beam in the xz plane:

$I_z = \frac{d_2 (d_2)^3}{12}$
(because d_1 is \perp to ENA)

Flexural Stresses:

Transverse Shear Stresses:

The beam on the left is being loaded perpendicular to the strong-axis, so we call this "strong-axis bending." Conversely, the beam on the right is subjected to "weak-axis bending." How can you tell the difference? Well, you simply compare the moments of inertia for the 2 cross-sectional axes. If your applied forces are transverse to the big I value, that's strong-axis bending. It's more efficient to orient beams so that the largest I value is used to resist the largest bending moments. Be sure you know the difference for the exams!

Figure 11 - Skeleton note excerpt that illustrates the use of spatial organization techniques in the design of the handout

3.0 Case Study #2 - 3D-Printing Mini-Course

Red Rocks Community College (RRCC) is a 2-year community college located roughly 5 miles away from Colorado School of Mines. RRCC attracts many pre-engineering students due to its strong relationship with Colorado School of Mines and articulation agreement for transfer of credits, thus facilitating the transfer of students from RRCC to CSM and completion of their B.S. degree in an engineering field.

In early 2012, RRCC made a concerted effort to improve students' preparedness to transfer into CSM, including the launch of a pilot class called Introduction to Design and Engineering Applications (IDEA). This in turn launched the IDEA Lab: a makerspace where students could network with working professionals to build and test solutions to design challenges posed by groups such as the National Science Foundation. The IDEA Lab's vision necessitated the training of a staff of student workers capable of supervising patrons of the lab, thus ensuring a safe environment. Workshops to train IDEA Lab staff were developed by students with ties to RRCC and CSM.

One such workshop was designed to teach the fundamentals of 3D-Printing and the specifics of how to maintain and operate the Replicator 2 3D printer by Makerbot. This workshop was created by a former RRCC student, who had transferred to CSM and was exposed to skeleton notes through the Mechanics of Materials class in case study #1. The Replicator 2 is an

extrusion-type 3D printer which works by feeding a solid filament into a heater chamber, thereby liquefying it, and then depositing the liquid in layers onto a build plate where it quickly hardens. The workshop learning objectives included a brief history of 3D-Printing, the fundamental principles common to all extrusion type printers, the specific nuances of the Replicator 2, troubleshooting, and best-practices for running a 3D-Printing lab.

The skeleton notes for case study #2 (Figs. 12, 13, and 14) were created using the three key characteristics outlined above. They were organized to parallel the chronological layout of the 3-hour workshop. This organization allowed students to move linearly through the lecture portion of the workshop without being distracted by having to reference previously covered material. Care was taken to ensure that foundational concepts covered early in the workshop were reinforced in multiple places later in the skeleton notes. The workshop broke down into a two-hour in-class lecture delivered via skeleton notes, followed by a one hour hands-on lab. In the lab students were required to use the information presented in the lecture to identify problems and fix the printers, which had been deliberately miscalibrated before the lab.

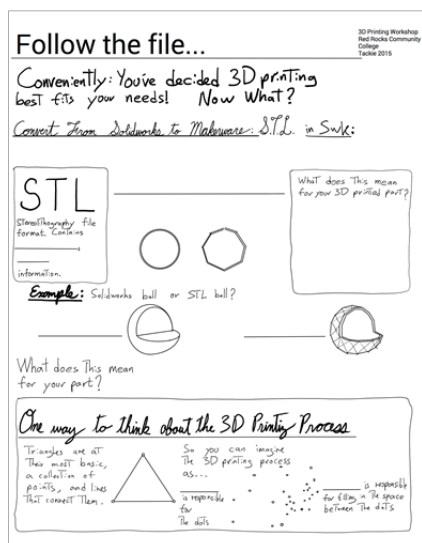


Figure 12 - Skeleton note excerpt that shows the blank version received by a student

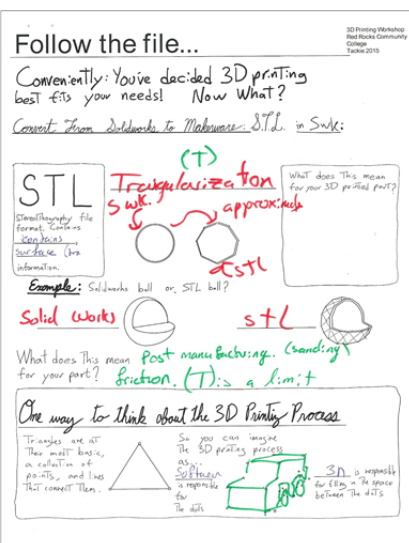


Figure 13 - Skeleton note excerpt that shows a completed student version

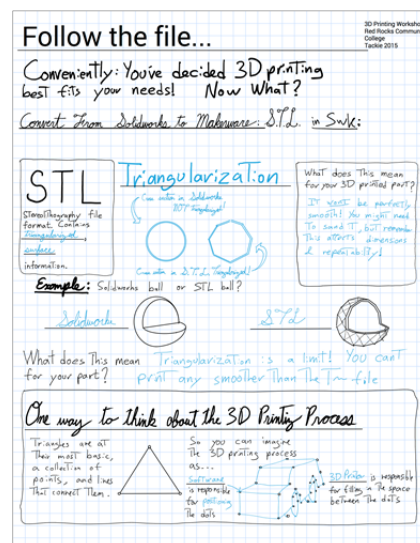


Figure 14 - Skeleton note excerpt that shows the instructor's master copy

The workshop was originally designed for a class of about 15 students, but the design of the skeleton notes is also suitable for smaller or larger class sizes. The first page of the note packet contained an agenda of the day's activities, which were divided into four sections: the pre-assessment, the lecture, the lab, and finally the post-assessment and feedback form.

The pre-assessment was designed with several goals in mind. First, it was intended to gauge students' level of knowledge on the subject material prior to receiving instruction. By comparing it to a post-assessment administered at the end of the workshop, instructors could determine whether the workshop introduced new material to the students, or whether it simply reinforced previously held knowledge. The post-assessment also allowed instructors to gauge retention of concepts by the workshop attendees.

The learning outcome of the workshop was to train students with no previous 3D-Printing experience to attain a level of proficiency that not only allowed them to successfully and safely do the printing themselves, but also to gain enough of a foundation to teach others. As such, the material had to begin with basic concepts that were accessible and easy to understand.

Thus the workshop began with a brief background and history of 3D-Printing. This section was heavily illustrated with depictions of progressively more modern 3D-Printing methods and products. It also leveraged a humorous cartoon depicting Benjamin Franklin on a \$100 bill resisting a large hand that attempts to pull him out of a wallet to punctuate the fact that early 3D-Printing methods were expensive (Fig. 15). The cartoon approach was chosen over a more formal engineering-style chart with exact costs, because the objective was simply to emphasize the high expense of early 3D-printing methods. In the design of the skeleton note, the choice to omit exact numbers in favor of the cartoon of Franklin, the material becomes memorable. In fact, a future updated version of the workshop will include a second cartoon of a relieved Benjamin Franklin leaning on a modern 3D printer.

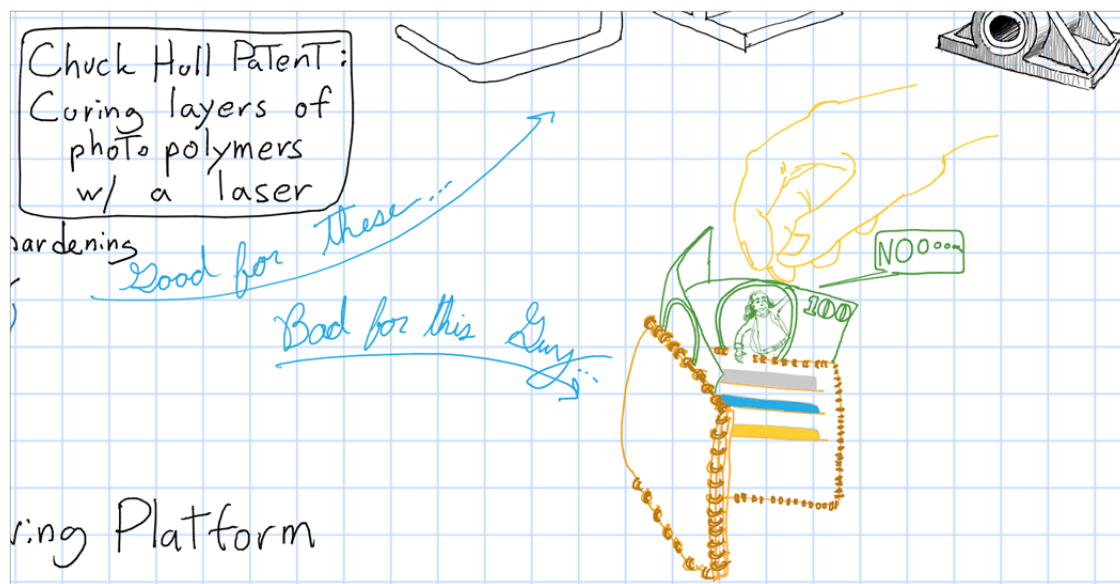


Figure 15 - Example of leveraging humor and "fun" to maintain student engagement

As the workshop continued, and the subject matter transitioned into modern 3D-Printing, the notes visually showed the improvements that were possible with modern methods, contextualizing the material by making visual references to common objects. The students were instructed to write and sketch situations that demonstrated understanding of the concepts. In this particular section, after the class first generally agreed that 3D-Printing a set of handles was an acceptable use of the technology, they were instructed to sketch a motorbike near one handle, and a parachute next to the other. This aided the students' understanding of the subject with regard to safety. Here, in a similar fashion to the Benjamin Franklin cartoon, the students are encouraged to remember the material through easily digestible cartoons, while similarly discouraged from copying down vast amounts of overly detailed information.

At this point, the topic departs from the physical world of 3D-Printing and enters the less tangible world of software. Although these concepts are much more abstract, the notes continue

to feature prominent sketches that illustrate the concepts. However, it is at this point that the sketches begin to transition away from being static supporting evidence for the topics; it is here that students are encouraged to interact with the sketches by sketching onto pre-existing artwork in a fashion guided by the instructor. This represents a graphical version of what students have already become accustomed to doing at this stage of exposure to skeleton notes: filling in missing information as it is presented in the lecture.

One example of this interactive sketching is illustrated in Fig. 16. While the instructor introduces different ways to think about the roles software and hardware play in the 3D-Printing process, the student is presented with what appears to be a random assortment of 30 dots on the page. The instructor explains that part of the software's job is to determine where the vertices of an object lie in 3-dimensional space, and at the same time begins to connect the dots, while commenting that it is the job of the hardware to connect those vertices. The students follow along on their own notes, and shortly thereafter realize that they are drawing another common object: a car. The objective of the interactive sketching technique is to facilitate the students' understanding that any 3D object that undergoes the 3D-Printing process will be treated in such a fashion.

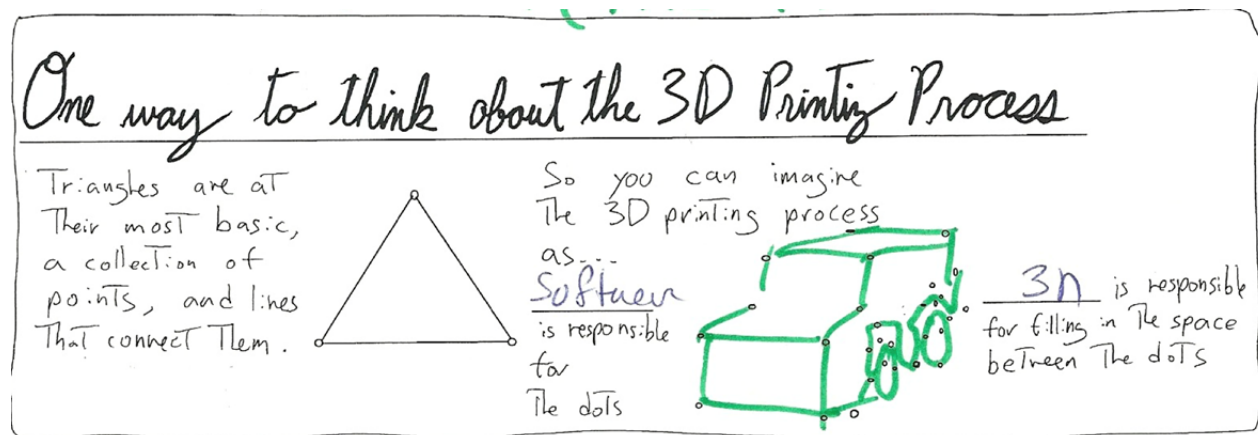


Figure 16 - Example of an interactive sketch, as completed by a student

As the workshop continues, and after students have understood the conceptual framework behind the hardware and software, the skeleton notes outline the process behind operating the 3D-printing software. This section of the notes is marked by sketched versions of screenshots to call out the location of important tools, options, and features. Here again an interactive approach is utilized in the sketches: students are asked to form hypotheses about the function of various buttons, before being guided to circle and annotate the most commonly used ones. During actual operation, the print window would show the user a 3-dimensional representation of their part, and would allow the user to manipulate its orientation with respect to the build plate. This is depicted on the skeleton notes with 3-dimensional sketches of a simple object in similarly varying positions and orientations. Students are guided to interact with these objects by drawing the resulting structures and situations they would observe, given particular settings in the software.

The final segment of the workshop begins with an interactive labeling exercise on a sketch of the Replicator 2, and segues into further detailing of specific components and specification of their

operation. The purpose of this section is two-fold. First, it educates students on how to perform startup, printing, and maintenance procedures on the Replicator 2. Second, and more importantly, once filled out, this section is designed to act as a quick reference guide to aid students in the lab portion of the workshop, as well as in future use after the workshop is concluded. Because these sketches are to serve as a permanent reference, they must be more complex and realistic in nature to help students identify the respective parts on their own machines. To ensure students continue to focus on the lesson, these sketches are less interactive and more static, giving the instructor ample time to detail and emphasize the key points, which are all written on the handout so the students simply have to listen to the instruction.

4.0 Assessment of Skeleton Notes

The primary assessment method for the CEEN 311 Mechanics of Materials skeleton notes is a statistical analysis of key questions posed to the students in the course evaluations. Colorado School of Mines began collecting digital course evaluations (rather than hard copies) in Spring 2015. Thus, data is limited to two semesters: Spring 2015 and Fall 2015.

The course evaluation contains a closed-format question: “Teaching methods used in this course are effective for promoting student learning.” The responses to this question are tabulated in Table 1. There were no substantial changes to the design of the skeleton notes between these two semesters, the instructor was unchanged, and the course structure was unchanged, and as shown in the table, there are no significant differences between the two semesters of data.

Table 1 - Responses for "Teaching methods used in the course are effective for promoting student learning" for Case Study #1

	Spring 2015	Fall 2015
Return Rate	105 / 139, or 75.54%	65 / 108, or 60.19%
Strongly Agree	79.05%	70.77%
Agree	15.25%	21.54%
Neutral	4.76%	4.62%
Disagree	0.00%	3.08%
Strongly Disagree	0.95%	0.00%
Not Applicable	0.00%	0.00%

In Spring 2015, 94.30% of the students marked either “strongly agree” or “agree” to the statement. In Fall 2015, 92.31% marked either “strongly agree” or “agree.” While this is an indirect measurement of the teaching methods in the course, and does not specifically ask the students about the skeleton notes, the data does show that the students are generally pleased with the teaching methods in the course.

One of the open-response questions on the course evaluation survey prompted a number of comments on the skeleton notes: “What aspects of instruction in this course do you find are effective for promoting your learning?”

The return rate on this question was 73/139 or 52.52% in Spring 2015 and 37/108 or 34.26% in Fall 2015. There are no significant differences in student responses between these two semesters, and when the data is lumped together, 93/110 or 84.55% of the comments specifically referenced

the skeleton notes. A collection of the most insightful comments are included (as submitted) in Table 2¹:

Table 2 - Selected comments from Spring 2015 and Fall 2015 Course Evaluations for Case Study #1

Comments related to fundamental advantages of skeleton notes	This is the first time I've had a lecture style where we are given partial notes before lecture. This was effective in keeping me better engaged in the material. // The method of providing notes is the most effective way I have seen yet of teaching. This is something all instructors at this school should try to implement into their curriculum. // The note format that you use is by far the most effective way I've had a professor present information to me at this school, it made mech of mat a very enjoyable experience. // The printed notes are super helpful, as they take off attention of tedious note-taking and actually allow me to pay closer attention to lecture. // The printouts are a good way to learn the material, as more time can be used for doing example problems. // I like the notes pages. There is the perfect balance between the amount that is already on the page and the amount that is added later. // The printed out lecture notes where we fill in are THE BEST EVER and really help us take effective and organized notes. // The guided lecture notes are one of the best resources there are. These are practically worth more than a textbook and more useful. // The handouts are very helpful because we don't waste time writing each little thing, but can follow along and quickly understand the material. // The handouts with notes for each class are extremely effective. In other classes, it can be difficult to balance taking notes and actually listening to what the instructor is teaching, but with the handouts, I can easily keep up with the lesson and have detailed notes to reference later when doing homework. // I love her lecture notes. They are definitely the best notes I have had at mines. They are way better than teaching of a powerpoint or off the white board. // I love the way she lectures, with the already printed-out notes and "follow-along" style of lecturing. She uses technology to her advantage and makes the classroom an engaging place that facilitates learning. // I like how class time is devoted to getting a strong basic understanding of the concepts rather than doing elaborate examples.
Comments related to graphics and drawings	The pre-set up note sheets were amazing. It helps to have everything laid out so I can tell what the important things are, and I don't have to waste time copying down all of the diagrams. I can spend my time focusing on what is being said instead of trying to write as fast as possible. // The notes are useful and help visualize everything // The lecture notes are AMAZING. the colors and crazy hype for every lesson and dedication to the students and this course were more than I could have expected for mech of mat. I really disliked Statics, but the way she taught mech of mat turned that completely around for me. // The Notes and illustrations are fantastic. Best teaching method I've had at this school. // The print outs are nice. I don't have to scribble down some crummy drawings while trying to keep up with what is being said. // The drawings and awesome handwriting that Susan Reynolds uses are very

¹ Instances of incorrect grammar, punctuation, and spelling in the students' comments are left uncorrected.

	<p>effective. // The notes help to keep together what Susan is teaching and make it so that I don't have to spend time drawing what is happening, which I found took away from what I was learning back in statics. // The lecture sheets also helped out. I remember that in statics they were not available and instead of paying attention to the lecture I was spending a lot of time making the fbd's for the lecture problems. // I really liked having the handouts for the lectures because it allowed me to pay attention to them rather than focus on taking notes. This class is taught very effectively. // The notes provided are very helpful and encourage all students to actually take notes. // I really like having the notes printed off for class. I spend less time writing and more time actually listening to the lecture. // I thought that the note worksheets were very helpful. In this class there is a lot of pictures and it is helpful not to have to draw them and focus on making them perfect and instead focus what were are learning. They are also a good way to organize notes.</p>
Comments comparing teaching methods in this course to those employed in other courses	<p>The organization of the course, from lectures to exam review to homework assignments, was incredible and extremely beneficial in learning the material. As an engineering physics major, I was completely blown away by this. Nothing that I've experienced in the Physics department thus far, especially including 300-level classes, even approaches anything as good as the teaching in this course. // The notes are incredibly helpful by having most of the material on the pages but engaging with some blanks to fill in. This helped me concentrate more on the concepts rather than rushing to write down everything like in other classes. // The lectures are very well laid out and is probably the best taught class I have had at Mines. // most efficient use of class time ive ever seen. most professional and concise 50min presentations I have ever had the pleasure to attend; I learned more material in this one class than all my other classes combined for the semester. i like the use of time to derive proof of formulas beyond whats covered on the exam for interested students to absorb more than the average student. // The notes given out in lecture are immeasurably helpful, and this is one of the best classes I've had here.</p>

5.0 Implementation Techniques and Strategies

This section contains step-by-step instructions on how to use technology so others may adopt this style of skeleton notes in their own courses. The process should be guided by the key characteristics listed in section 2.0, and supported by the proper technology that ensures that the notes can be created and edited efficiently.

There are two major requirements for the technology (software and hardware) required for the creation of skeleton notes. First, it must be suitable for the creation of the notes, which involves typing, freehand writing, and sketching. Second, it must be able to screencast the notes to a projector during the class while allowing for freehand writing and sketching in real-time.

The instructor may either choose to select a single set of hardware and software to meet both of these requirements, or they may choose one set of hardware and software to meet the first requirement, and a second set of hardware and software to meet the second requirement.

To create the lecture notes in Case Study #1 (Mechanics of Materials), the instructor used a Lenovo Thinkpad X230, which is a Windows based laptop with a reversible touch screen and stylus. The software chosen was Microsoft Journal, a popular software program designed specifically for taking notes with a tablet PC. The authors have experimented with the use of Microsoft Word and Microsoft Powerpoint for skeleton notes, and neither are recommended. It is possible to use a stylus and digital “inking” tools in these softwares, but Microsoft Journal is much better suited for this task.

The equipment used in Case Study #2 (the 3D-Printing workshop) included an android-based Samsung 10.1 tablet with a built in stylus, running the free note-taking application Squid. This set up allows for the creation of the notes, but the screencast can prove challenging as the HDMI-out port requires a separate power source. Because of this, the instructor chose a separate set-up to screencast the notes. This setup involved a projector-connected SMART Podium running SMART Ink software.

Alternative approaches certainly exist. Typically, a digital solution to skeleton note creation can be achieved through the use of any pressure-sensitive stylus used directly in combination with a tablet computer, or touch-screen computer, and software capable of recognizing the stylus. Additionally, an external pen-tablet connected directly to a computer running annotation or sketching software will also create a solution. For screen-casting, many modern tablet computers contain a video-out port which can be directly connected to most modern projectors, televisions, and smart boards. Analog solutions also exist via transparencies, a permanent marker, an overhead projector, and colored dry-erase markers for annotation. While this method would work, digital solutions are favored by the authors as they allow for efficient revision and sharing of the notes.

The first step in creating skeleton notes requires a thoughtful organization of the subject matter as this is crucial to the success of the notes and ultimately determines how the information will be delivered to the student. In other words, this planning allows the instructor to create the unified and concise message that is so critical to the success of this method. During this stage, the instructor should assemble a thorough list of all main topics and supporting details to be included in the lecture, thus ensuring that none of the relevant topics are omitted from the notes.

An inspection of this list of topics and subtopics will reveal that some topics are of great importance, while others may only need to be briefly mentioned in the lecture. To reflect this relative importance in the skeleton notes the instructor should rank each topic in the list; in effect creating a hierarchy of importance. The next step is to reorder the list of topics as they would appear chronologically in a lecture; the topics should build on one-another in a logical fashion to create a progression of thought that serves to inform the student and demonstrate how the concepts relate to one another. This reordering can take many forms, and should be written in a way that encourages the instructor to think about how the topics are related. Some instructors

may find that a bulleted list serves this purpose best, while others may create a concept map, such as in Fig. 17, and graphically group topics on a page with arrows to highlight related ideas.

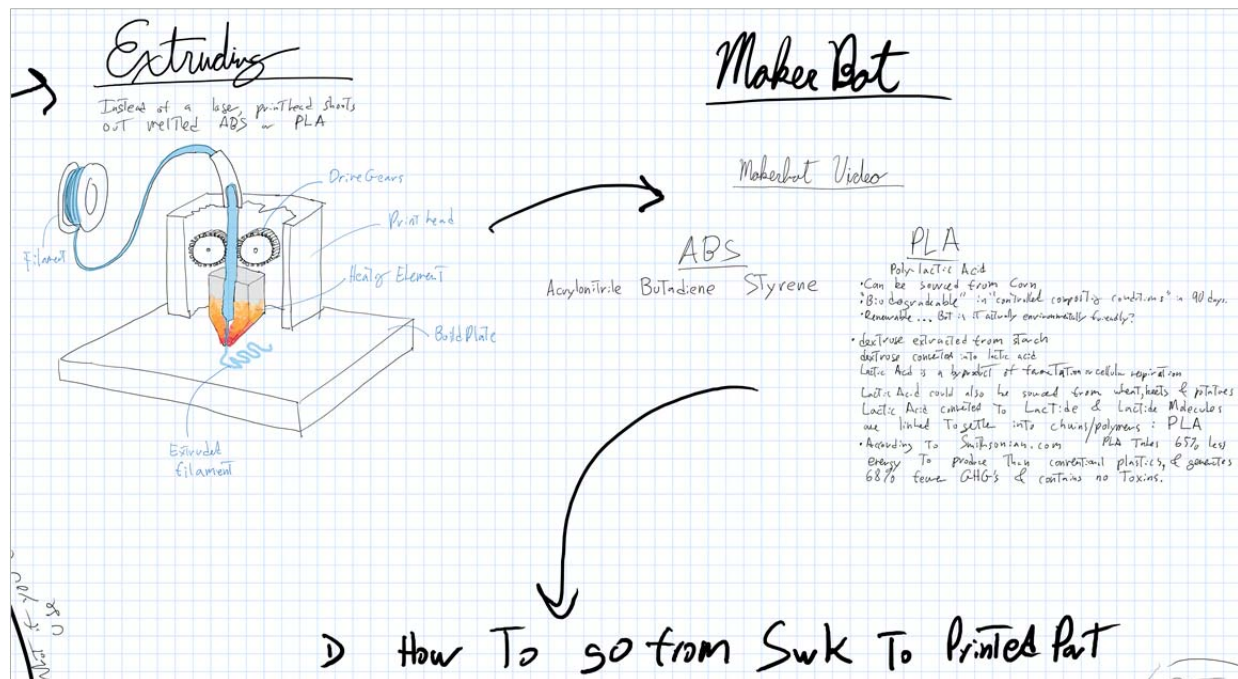


Figure 17 - An excerpt from the concept map used to develop the workshop in Case Study #2

The final step in the planning phase involves determining the physical layout of concepts on the page. This can be accomplished by blocking out specific areas on each page, effectively reserving them for particular topics, while referring to the chronological list of topics to ensure they are in the correct order. Because the chronological list also contains hierarchical importance information, the instructor should use it to determine the relative sizes of each topic box.

Different applications of skeleton notes require different allocations of space for topics. Case Study #1 consistently utilized 4 sheets of paper for each 50 minute lecture. This set length assisted the instructor in pacing the lecture, and ensured that the amount of material covered in the 50 minutes was neither too long nor too short. Case Study #2 used 20 pages for a 2 hour lecture, essentially halving the amount of time students spent on each page. In spite of this, student feedback indicated that students generally did not feel rushed during the workshop, due to the differences in the technical content of the two case studies. Specifically, Case Study #1 was computation-intensive and Case Study #2 was not.

After allocating appropriate space for each topic, fill each topic box with a bold header, as it ensures that each main point finds its way into the skeleton notes, and also helps the instructor begin to develop a feel for the form of the notes. At this point, care should be taken to graphically reflect the hierarchy of information developed in the planning stage. Supporting information and subtopics should follow, along with any supporting illustrations. Microsoft Journal offers robust tools for controlling ink weight and color that are ideal for developing the graphic hierarchy.

In this process, the creator of the notes should recall all 3 key characteristics as presented in Section 2.0. Specifically, notes need to capture the students' attention by incorporating handwriting, colorful graphics, and humor into a concise message, while also emphasizing important information. The illustrations can provide an excellent opportunity to introduce humor into the notes while still supporting the concepts.

Working through each page of the notes in this way will result in a completed set of notes that differ from skeleton notes in one important way: they are complete, while skeleton notes are incomplete. To derive skeleton notes from the completed notes, the instructor must discern between what should be filled out by the student, and what should be appear in the student's printed handout. Select items that are to be completed by the student, and color-code them in red. Thus the instructor's copy of the notes is complete, and the student handouts can be created by saving the file with a different file name, and deleting all of the items in red.

A successful implementation of skeleton notes requires a proper understanding of how to prepare and organize the notes, access to the right technology, and the ability to draw freehand diagrams. This section contains a brief discussion of a few obstacles to overcome in creating and implementing skeleton notes, and accompanying alternatives.

Instructor's Inability to Draw. This poses a major obstacle for some as skeleton notes rely heavily on illustration, even though they do not typically require highly detailed sketches. Indeed, the skeleton notes utilized in Case Study #1 primarily use 2D sketches. Instructors that seek an alternative to drawing can import photos or diagrams. In Microsoft Journal, it is possible to sketch directly on top of an image, and then delete the source, simply leaving the cartoon. Another viable option is to hire an artistically-inclined student to assist in producing the cartoons.

Instructor's Poor Handwriting. Poor handwriting negatively impacts skeleton notes in the same way it negatively impacts students' perception in a traditional lecture course. While we recommend using hand-writing as much as possible to make the handouts more accessible to the students, certainly word-processing is also a viable option.

Insufficient Printing Budget. Anecdotally, students greatly prefer that the handouts are printed by the instructor and distributed at the beginning of each class. However, in the event that an instructor does not have a suitable printing budget, students could be asked to print their own copies prior to each course. Alternatively, the entire set of notes could be purchased by the students from the university bookstore at the beginning of the semester.

6.0 Conclusions and Future Work

The purpose of this paper is to stimulate discussion in this approach to creating skeleton notes for large engineering courses. Other studies have confirmed that skeleton notes are an effective teaching pedagogy, and indirect assessment of course evaluations from Case Study #1 supports that assertion. Anecdotally, the authors have observed that this approach results in actively engaged students that possess an enhanced conceptual understanding of the technical material.

The approach to skeleton notes documented in this paper asserts that the success of skeleton notes can be enhanced by focusing on 3 characteristics in their design. In abbreviated form, these are:

1. Creating notes that truly complement the lecture -- forming a single unified message.
2. Incorporating highly graphic, colorful, and “cartoonish” hand-written content, interspersed with occasional humor, resulting in a “fun” note-taking experience.
3. Leveraging software to employ principles of graphic design related to hierarchy of information.

Future work in exploring this pedagogical technique will include indirect and direct assessment of the three key characteristics summarized above in a controlled experiment. The instructor for Mechanics of Materials will teach two sections of the course during the same semester. One will be taught using the “fun and colorful” set of notes, and the other will be taught with another set of skeleton notes that is identical in content, but with the removal of the colors, the humor, and the occasional casual language. In this way, the notes will emulate an approach to skeleton notes currently used by other engineering faculty. Direct assessment in the form of student performance on the final exam, and indirect assessment in the form of student course evaluations with new customized questions specifically related to the skeleton notes will be used to further explore this pedagogy.

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