Instructor Toolkit for Engineering Capstone Design

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Overview

Capstone courses are by their very nature complex. Students are tasked with synthesis of material learned in earlier courses, and need to solve complex, open-ended problems, while demonstrating effective teamwork skills. The learning outcomes of capstone courses typically match all or most of the ABET learning outcomes, so these courses are also important for program accreditation. Designing or redesigning a capstone course is both challenging and rewarding. Effective course design directly affects the development of student career readiness and life skills, and departmental ABET accreditation. From an educational standpoint, capstones provide opportunities for authentic learning by requiring application of major-specific knowledge to solve open-ended problems.

This toolkit consists of modules for Capstone Design Course Instructors with concrete suggestions for

- scaffolding and creating an appropriate level of challenge,
- creating diverse teams and increasing the odds of effective teamwork,
- structuring the course for students to synthesize material from multiple prerequisite courses with new discipline-specific content and a big-picture perspective of a real-world application,
- making students more comfortable with ambiguity and open-ended problems, and
- designing assignments that develop workforce and life skills, with rubrics that reinforce the importance of these skills.

The material in the toolkit is arranged in a modular fashion so that instructors can focus on one aspect of course design at a time. The intention for this organization is two-fold: 1) to obviate the need to comb through the entire guide to extract information of interest, and 2) to make course redesign less intimidating by providing suggestions for discrete incremental changes, and also having all the principles clearly laid out for those who wish to do a full course design or redesign.

In each module, I list the guiding principles I use for capstone course design and refer to examples from one of my course offerings, Thermal Fluids System Design, that I redesigned over the summer of 2022. This is one of two capstone courses in the thermal fluids stem that students in our mechanical engineering department can choose from to fulfill their degree requirement. Of note is that each of my offerings for this course is different. I use new and modified content for a fresh project and adapt my instructional methods to address evolving student learning needs.

Classes are scheduled for 50 minutes on Mondays, Tuesdays, Thursdays, and Fridays and a WPI term lasts for 7 weeks. I booked the same classroom for the same time slot on Wednesdays for team collaboration and open office hours. For the first half of the term, the teaching assistants and the instructor were available to answer questions during these open office hours on Wednesdays and additional office hours outside of class time. For the second half of the term, teams worked exclusively on their projects with instructor support during class time 5 days a week. I also held office hours outside of class time. The teaching assistants were not involved in design projects during the second half of the term.

I have bookended the modules with the general course structure in the beginning and ABET considerations at the end. The scaffolded layers, which each contain a progression of increasing complexity, are addressed in the intermediate modules. Finally, I present a collection of excerpts of materials I have used, so that the reader can see some concrete examples of how I apply the design principles listed in the modules.

I wish to acknowledge my colleagues who have worked with me on this course. First and foremost is my colleague and role model, Brian Savilonis, who gave me an apprenticeship by co-teaching two different offerings of this course with me in 2019. He imparted comprehensive course design principles, which I continue to use, and demonstrated how to navigate the complexity of this course, from the planning stages through final report submissions. Next are Charlie Morse, Emily Perlow, Valerie Smedkin, Lisa Stoddard, and Anne Ogilvie who consulted with me in the summer of 2022 when I redesigned multiple course elements and scaffolded the course structure to address the changed learning landscape and create an explicit focus on workforce development skills, effective teamwork in a technical setting, and strengthening community. I would also like to thank WPI's Center for Project Based Learning for providing Summer Fellowship funding so I could write this toolkit, and specifically the support of Kris Wobbe, Kimberly LeChasseur and Sara Ringer of the institute, and my fellowship cohort Marja Bakermans, John-Michael Davis and Hermine Vedogbeton for their encouragement and feedback.

Module 1: General course structure – my guiding principles for capstone course design

A capstone course is complex, open-ended and involves ambiguity. This can be overwhelming for students, so scaffolding these elements into the course design and communicating the course design principles with the students helps to map out a clear pathway for instructor, teaching assistants and students. I aim to achieve a balance between holding student interest, achieving student learning outcomes, satisfying ABET criteria, career preparation, strengthening community and developing teamwork skills in a technical setting.

As I embark on the journey of planning a new offering of my capstone, I spend some time thinking about the current context of society, recent technological developments, changes in the educational landscape and then employ a backwards course design. This uses the end-goal and learning outcomes of the course as the starting point for course design. I consider many factors during this process, and I have attempted to distill the essence of this into a list of my guiding principles, below.

A. Base the final project on a relevant societal need that can be tackled with the technical know-how in the field of study covered by the capstone.

B. Pay attention to the scope and complexity of the project, so that teams members need to work together to complete it and are also able to complete it within the given time. Since most integrated technical design projects cannot be solved in a few weeks, limit the scope of the project by focusing on select aspects and/or making some clearly stated simplifications. Find appropriate models that can be worked into the course and guide students in finding other models if needed.

C. Build flexibility into the course structure. This will allow for adjustments based on the knowledge and skills of the students when they start the course.

- Create building blocks for the final design project before starting the course.
- Create the first two or three assignments before the start of the course, and adjust the complexity of second assignment onwards before posting if needed.
- Have other assignments and final design project mostly figured out, with contingencies for what can be added for more student interest/challenge, or cut/modified if students are not ready, and what parameters could be set by the class to make it more of their project.

D. State the end goal up front, so students know where they are headed and outline the path that students can expect to take to get there, both in the syllabus and on the first day of the course. Communicate clearly with students about course expectations.

E. Give a general overview of the project on the first day of class and in the syllabus, focusing on the need and context, and how this relates to the content area.

F. Use a layered approach – the overall complexity of project is the end-goal, and each layer outlined in Modules 2-4 starts at a junior (third year) level and increases in complexity as the course progresses, building to full complexity by the mid-point of the course.

G. During the first half of the course, guide students through individual aspects of the project that will be helpful for the design project.

H. Structure the course and office hours to be able to provide support to teams during the second half of the course as they tackle the final design project autonomously.

I. Create rubrics that are consistent with course expectations.

J. Provide detailed formative feedback on the foundational assignments during the first half of the course. Work with the teaching assistants before the course starts so they feel comfortable with their role in this. Be available to answer detailed questions about the project during the second half of the course.

K. Use the foundational assignments to gauge where students are at, which will help with deciding which, if any, adjustments to make to the course.

L. Scaffold the course by layering multiple increasingly complex learning outcomes in progressive assignments. Begin by setting clear expectations on the first day and throughout the term, and reinforce these with consistent messaging in class, on the syllabus, in announcements, and by assigning grades associated with teamwork and skill development.

M. Reinforce the learning outcomes and takeaways I would like to impart to students, both explicitly and implicitly.

N. Encourage students to embrace a holistic approach where all team members use and develop technical AND life and career readiness skills.

Many of these design principles are woven through the text of example course material presented in Module 6 - syllabus excerpts, two presentations given on the first day of class – the course and design project overview and the overarching course goals, assignment guidelines, team charter, rubrics and final report guidelines.

Module 2: Technical skills

Students at WPI learn how to work in a team during their junior year in the context of a one-term community-based project. Working as a team on a technical project requires additional skills. In this module, I describe strategies that I use for guiding students through the process of developing and practicing the skills I referred to in slide 5 of the overarching course learning outcomes that I presented on the first day of class:

- Use and adapt fundamental skills to a new problem
- Break down a large task into smaller parts
- Mesh different technical skills
- Piece together small parts and iterate to solve the large task
- Consider real-world applications
- Include ethics in your design considerations
- Use engineering standards
- Consider cost implications

A. Review the foundations from prerequisite courses in class, focusing on the essentials, with particular attention given to material applicable to the design project. In a seven-week course, I spend approximately one week on each of the three foundational courses: thermodynamics, fluid mechanics and heat transfer.

B. For each of the review sections, weave in additional content relevant to the design project. This can include additional or more advanced material in the prerequisite stem: modeling tools, cost analysis, ethical and geographical considerations, engineering standards and the like.

C. Create an applied assignment for each of the review weeks. Make it related to the final design project, but not exactly what they will use. That way students will develop the tools needed to synthesize multiple concepts later. The focus of each of these group homework assignments should be on the APPLICATION of principles covered that week, both from previous courses and new material introduced. Each assignment relates directly to one aspect of the design project, in the context of the big picture view, why the work is important and how it fits in.

D. Keep each of these assignments within the context of a real-world application. By the very nature of a more realistic context, each assignment will contain contextual complexities and won't lend itself to small closed-form questions. This also ties to open-endedness and ambiguity, which is covered in Module 3.

E. Be specific about what students should produce in each assignment, and back this up with point distribution in the rubric. I give points both for solutions as well the process of getting there, such as shoring up foundations, learning new skills, checking for errors, and clarity of reports.

F. Provide substantive formative feedback for each of the foundational assignments. I work through the assignments with the teaching assistants and develop thorough rubrics so that they can provide consistent and detailed pointers that will help students to understand the material better and correct conceptual errors. The rubrics focus on engineering thought process, making appropriate assumptions, using relevant equations, using correct units and conversion factors and presenting work in a clear, professional manner. Students are then able to apply these foundations to the integrated final design project and focus on synthesis and system level design, which is a senior level skill that many students are introduced to for the first time during this course.

G. Set up the first 2 or 3 assignments and create the building blocks for the other assignments and the final project ahead of time. I only publish the first assignment to the course site before the course starts and keep these others unpublished while I assess the level of understanding and background knowledge of the class as a whole. I expect each class to be different, in terms of both technical preparation and broader learning needs.

H. Have contingency plans at the start of the course for how to adjust the remaining assignments for more interest/challenge or cutting/modifying based on this assessment. Keep the syllabus general enough to be able to make these modifications. As an example, part of an assignment might be split off and combined with an earlier assignment, or with a later assignment, or the scope of an assignment could be modified.

I. Gauge where students are in terms of their learning during class, open office hours, and by receiving feedback from the TA's about questions they are receiving from students, and observations made during the grading of assignments. This helps with pitching teaching material to provide an appropriate level of challenge.

J. Work broad solutions for each assignment during the planning stages for a basic envelope of expected answers. Check that this range of answers fits into realistic ranges and that the modeling and thought processes used for these assignments will be helpful and transferrable to the final design project. As an example, I find relevant heat transfer correlations that students can use in their heat exchanger design assignment that fall within the expected operational and design range. I also show students how I find these correlations to afford them latitude in their final design and give them tools for potential future projects.

K. Keep the assignment length to within the standard time commitment for a course load. Items G, H and I above will help with this.

L. Show students how to divide the technical aspects of each assignment by suggesting which parts sub-teams can do. Also show the groups how to mesh these pieces together into a unified system. Encourage teams to use tools that work for the group as a whole. For example, some teams might prefer to work on a shared spreadsheet such as Excel or Sheets, while others prefer MATLAB or the like. Subdividing and meshing is imminently doable if these systems are set up clearly, with labels for each variable and equation, units explicitly stated, the general logic flow of which calculations are used for each subsystem and how these are used for the full system. For the first assignment (thermodynamics), I gave teams specific instructions on how to divide the work, with examples of tasks that each student could tackle independently, how to collaborate to check accuracy and reasonableness of assumptions of each other's work and then mesh their partial contributions into a unified assignment report.

M. Show students how to check for errors by going through their spreadsheet, code or handwritten calculations with them when they encounter unreasonable answers. Humanize the experience of making errors – there are countless examples of engineers who have NOT found their errors with disastrous results. Once students realize the importance of this and have a method for checking their own work and the work of the team members, their overall process becomes more streamlined and efficient.

N. Provide guidance on report writing and presenting consistent results with a unified voice. This needs special attention with the meshing of subsystems into the whole.

O. Have a presentation day on the last day of the course to showcase the variety of solutions to the open-ended prompt. My teams presented their work to the rest of the class and me on the last day of term with a 2-minute presentation followed by a 1-minute Q&A. This provided motivation to produce high quality work, and students enjoyed seeing the different approaches that were used.

P. Expect to have variation in skill sets within groups and between groups. During the course, most students learned new skills in at least one of the scaffolded layers of technical foundations, technical report writing, taking learning risks/asking for help, routinely cross-checking to find technical errors such as units or conversion factors or typos in formulas, etc.

Q. Have fun teaching! I found that the overall quality of the projects improved compared to previous years since students were able to focus more on the project itself and spent less time backtracking.

Module 3: Ambiguity and open-endedness

Capstone projects are typically complex, have multiple viable solutions, are open-ended, and contain ambiguity. In fact, it is often the first time that students get to work with the messy reality they are going to encounter in their engineering careers. Many assessments in lower-level courses require closed form solutions to bite-sized problems, and students have grown accustomed to needing to produce *the* correct answer. In my opinion, this has been exacerbated by the emphasis on standardized testing in K-12 education and was made even worse by online assessments during the pandemic. I wanted to teach all the students in the class to be comfortable with ambiguity and open-endedness. I hoped that many of them would embrace it. Below are a few design principles that I use to scaffold this important layer into my course, and then some examples of how I applied these in my redesigned offering.

A. Increase the complexity, open-endedness, and ambiguity throughout the foundational assignments until the final design project.

B. Give students more autonomy as the course progresses.

C. Work directly with each group to provide formative feedback as they are interpreting information, solving problems, checking for accuracy and troubleshooting questionable results.

D. Balance structure and responsiveness. Each year is different, with new circumstances, challenges, learning needs, even new technologies.

To illustrate these principles, I give some examples in the following paragraphs of this progression through the assignments in my redesigned offering.

- *Introductory assignment (solo)*

I asked students to tackle this individually within the first few days of the course. They needed to do some data gathering, use unfamiliar units and make local and global comparisons. I only required them to make one easy assumption.

- *Thermodynamics assignment (teams of two)*

I created this for groups of two to complete within the first full week of the term. The assignment covered new material as well as material encountered before. I did an example in class that was very similar to the new material portion of the homework assignment, just with different sequencing, so students had a roadmap for figuring out pieces of their assignment. I did another worked example related to the part of assignment covering review material in less detail. I left out one piece of essential information and groups needed to make an assumption about what they needed and where to find it in reference materials. When students questioned me about missing information, I reminded them that this was intentional as a first step to becoming comfortable with open-endedness and ambiguity as outlined at the beginning of the course.

- *Fluids assignment (teams of four)*

This was the first assignment for the final teams and the technical part of the assignment was shorter than the thermodynamics assignment so that teams had time to figure out teamwork logistics. I introduced new tools during the review sessions and gave guidelines for how to do the assignment but provided less detail in the worked class example than I did for the first assignment. I showed the class how to solve for some similar and closely related, but not identical, situations so that students needed to synthesize and apply knowledge and skills. I required teams to make more (2-3) assumptions, learn how to manipulate spreadsheets, and cross-check their work for errors. I helped teams subdivide work into two smaller pieces, discuss assumptions amongst themselves, source needed information, discuss their individual pieces for reasonableness, cross-check for errors and synthesize into a unified whole.

- *Heat transfer assignment (teams of four)*

I made this assignment significantly more open ended, with a design focus. Groups needed to make many assumptions as well as design choices. This assignment was primarily focused on heat exchanger design, which is new to most students and follows from the prerequisite material. I provided guidelines and an example of a differently sized system and governing equations. Groups submitted significantly different assignments due to the variety of design choices they made. Students found this level of open-endedness and complexity challenging, and they appreciated the formative feedback both during the solving process and in the assignment grading. This assignment was at the level of the final design project in terms of open-endedness, complexity, and ambiguity, with an introduction to design iteration to arrive at reasonable dimensions and operating parameters. The difference between this assignment and the final design project was that this assignment had a narrow focus of a single subsystem, whereas the final design required synthesis of many concepts and several subsystems with more iteration to account for optimization of multiple parameters.

- *Small segue assignment (teams of four)*

The last assignment was small (2-3 days) and could be incorporated directly into the final design project. Teams developed an optimization tool which gave them a running start with the project which I assigned at around the same time. This allowed stronger teams to move ahead quickly to the final project. It also allowed other teams a few days to digest formative feedback from the foundational assignments before needing to apply these principles to the final project. Teams chose which platform to use for this tool; some chose to use a spreadsheet; others chose to use engineering software.

Up to this point in the course, at least one TA (Teaching Assistant) attended the Wednesday classes to answer team questions about the assignments. Both TA's held weekly office hours, and the TA's graded the technical portion of the assignments with substantial formative feedback based on comprehensive rubrics.

- *Final design project (teams of four)*

The second half of the term was entirely dedicated to group work on the final design project. Due to the open-ended nature of the work, each team produced a unique design. I held open office hours during every scheduled class, and walked around the classroom meeting with teams as they had questions. I held additional office hours outside of class time. The TA's did not hold office hours or participate in the course during these weeks, apart from attending the presentations on the last day of term.

The prompt was open-ended with room for creativity and enquiry. However, I provided some limitations and assumptions to keep the project's scope reasonable. I pre-selected some subsystems, gave certain cost estimates and specified which other subsystems teams needed to design or cost out. I garnered class input for general directions they wanted to explore in the project before finalizing it. I aimed for an appropriate level of challenge and autonomy based on observations and feedback from the first half of the course.

The project required synthesis of the foundational material from the three prerequisite courses and the new concepts and skills learned during the first half of the course. There was a significant amount of iteration, cross-checking, synthesis, and integration of multiple subsystems into a whole, and teams made many design choices and assumptions.

Overall, teams enjoyed the autonomy of these choices. They also enjoyed getting a taste of engineering, with its messy realistic complexity, knowing of course that there was not enough time for a full system design, but that the part of the system they were designing needed to be considered from a realistic perspective. For many, this had been the most challenging yet the most rewarding course they had taken.

Module 4: Teamwork and accountability

In this module I share the guiding principles I used when redesigning my course to emphasize to students the personal and professional benefits of effective teamwork and provide them tools and opportunities to hone these skills. In this age of increasing loneliness among adolescents, I focused on forging connections within the class and teaching transferable skills for working with new people and in diverse teams. I challenged students to learn new skills, both technical and non-technical, by taking learning risks and to employ psychological safety within their teams to optimize their problem-solving. I also guided teams through the logistical challenges of figuring out schedules and developing strategies for working together outside of class time. I structured the course so that students were accountable to themselves for their own learning, to their teams for the project's success and to the class with an end-of-term presentation. I shared many of these course goals with the class on the first day term (slides 2-4 of Overarching course goals).

A. Use effective teamwork and communication as a framework for the other learning outcomes. Successful teamwork requires coordinating schedules, communication with a variety of people, planning for tasks and time management, which are essential workforce skills. The skills needed for effective teamwork spill over into other areas of life.

B. Emphasize psychological safety and accountability. Psychological safety allows for taking risks and leads to more effective teamwork and better results. I played parts of Amy Edmundson's TED Talk on the first day of class. She explains that having the freedom to take risks such as questioning assumptions increases the likelihood of finding errors. A research study conducted by Google showed that teams that can take learning risks and can be vulnerable and honest about questions they have about the work tend to have better outcomes, such as coming up with fresh perspectives and project angles, and improved creativity. (Amy Edmondson- Building a psychologically safe workplace)

C. Extend psychological safety beyond the bounds of the individual groups and create an environment where students can feel comfortable asking for help both from their team members and the instructor. Part of the capstone experience is to learn to apply knowledge from previous courses to a realistic application. This works best when team members either feel confident in what they are doing or feel comfortable asking for help. With the required use of multiple skills, both are needed. Take-aways I wanted students to get from this are: (1) it's OK to not have all the answers and to not have all the knowledge, and (2) teams are helpful because we have multiple perspectives and skill sets so we can have a bigger impact on solving the problem.

D. Challenge students to learn new skills by taking learning risks. I underscored this with a grading system that reflected learning as a priority. As part of each assignment, students submitted individual reflections on new skills developed, teamwork, professional development and life skills. I graded these while the TA's graded the teams' technical assignments (one assignment per team).

E. Schedule group project presentations to the rest of the class on the last day of term. This accountability provides an incentive for high quality work and enforces the deadline for project completion.

F. Structure class meeting times to make group work an integral part of the course. For the first half of the course, assignments were due on Fridays. Class time on Wednesdays was devoted to group work on the weekly assignment with instructor and TA support and formative feedback (ie, “open office hours” in the classroom). Students reported that scheduling time to work together was one of the biggest challenges, and they appreciated the opportunity to work together in their teams during scheduled class time. Most teams worked in the classroom so they could ask questions since these working sessions were effectively open office hours.

G. Provide a safe space to learn and practice new skills needed for career success. Learning new skills can be intimidating, and it is helpful for students to know that they are not alone in this endeavor and that they are learning these new skills together and with support from the instructor. I communicated the rationale for the course structure as intentionally centering learning skills related to open-endedness, ambiguity, making assumptions, taking learning risks, effective teamwork, incorporating diversity, equity, and inclusion, and learning how to subdivide tasks and combine parts into a whole. Some take-aways I wanted to impart to students were (1) effective team interactions improve project outcomes, (2) most problems in life are new with ambiguity and (3) applications are complex and have many parts that mesh, so team members need to do pieces individually, check each other’s work, stitch pieces together, adjust as needed and iterate to achieve a consistent and meaningful final product.

H. Encourage group collaboration. Interaction with others builds a sense of community, which is important on both a personal and professional level. Reinforce this with course structure. For example, I required students to ask questions as a group. This prevented the situation where a single group member handles the technical aspects while the other members do the writing and report layout.

I. Assign students into initial teams based solely on schedules. I tasked students with completing a small introductory assignment individually during the first few days of the class. I simultaneously polled students for the best times to collaborate on their first team assignment outside of class time (morning, afternoon, or evening) and then assigned students into teams of two for this assignment.

J. Wait until the class list has settled to create final teams. I waited until the end of the first week in a seven-week term. There were 42 students in the class after the first week. One student had intermittent attendance and this student ultimately did not participate in the class, but the other 41 completed the course.

K. Use a more sophisticated method to create final teams which will work together for the remainder of the term on all subsequent assignments and the final design project. I created teams of four using the CATME (Comprehensive Assessment of Team Member Effectiveness) Team-Maker tool, which is part of a collection of tools in the CATME Smarter Teamwork system (https://info.catme.org/), licensed through the School of Engineering Education at Purdue University. WPI (Worcester Polytechnic Institute) holds an institutional license for CATME and pays for access to this web-based tool based on the number of students who are signed into teams using the software.

L. Choose the criteria for successful teams based primarily on student schedules. I used CATME team maker and selected two criteria: (1) group diversity based on gender, race and GPA and (2) student schedules and commute for group work outside of class time. I listed schedules as the most important consideration. I wanted to have diverse teams so that (i) students would learn how to work with people other than their friends, which is a critical aspect of collaborating in the workforce and forming connections, and (ii) so teams would have a diverse set of skills, which I considered important for professional development. I selected student schedules as the most important criterion based on a recommendation from one of WPI's experts in team-based learning [personal communication with Lisa Stoddard, summer 2022]. In her experience, ensuring that students had common blocks of time to collaborate outside of class was the biggest factor determining the success of diverse teams. As a side note, I avoided self-selection of teams in my redesigned course since in the past this led to unbalanced teams, kept students siloed, and kept students in their comfort zones with little room for further development of team-based skills.

M. Consider potential roadblocks for successful teamwork before finalizing team groupings. I considered (1) the potential for dropping the class, indicated by minimal class attendance and unresponsiveness to emails, and (2) self-initiated confidential request(s) to avoid other student(s) based on personal circumstances. Once I had used the Team-Maker tool to generate initial potential team matches, I assessed these for suitability based on this third criterion. I used the Team-Maker tool with the 41 regular attendees until the algorithm suggested appropriate grouping for 10 groups of 4 and one group of 5. I manually added the student with spotty attendance to one of the groups of 4, and the student ultimately did not participate in the class.

N. Require final teams to draw up a team charter based on strengths, weaknesses, what they would like to learn, what they can teach their fellow group members, group work scheduling availability, working style etc. Student assets should include both technical and non-technical considerations. I assigned this as a sizeable portion of the assignment when teams of four worked together for the first time (fluids assignment). The team charter counted 20% of the grade for that week. I reduced the size of the technical portion of the assignment so that teams would have sufficient time to devote to this. I based the team charter portion of the assignment on Stoddard and Pfeiffer's recommendations and provided students with their example asset map with permission.

O. Keep students accountable for their learning by having them write multiple reflections throughout the term about technical and non-technical skills learned and developed as well as their contributions to teamwork and the assignments and project. Ten percent of each assignment grade was for individual reflections on teamwork, learning risks taken, and new skills developed. I created a separate submission portal for these and graded them myself. This kept students accountable for their learning and helped identify situations that benefitted from timely intervention, including team dynamics issues, personal challenges, and weak course foundations.

P. Pay careful attention to team dynamics and intervene proactively. In addition to "reading between the lines" in the individual reflections, I observed team interactions during class group-work times. Early intervention often circumvents inevitable friction later in the term.

Q. Size the teams appropriately for the total number of students in the class. I find 10-11 teams manageable and prefer team sizes of 3-4 from the perspective of synergy and load distribution. For a class size fluctuating between 40 and 45 at the start of the term, I chose a team size of 4 for the final design project. However, since the first week was the add/drop period, I created smaller groups of two for the first team assignment for two reasons (1) students were able to start using teamwork strategies with unfamiliar people early in the term and (2) I was able to wait until the class list had settled before creating the final teams.

R. Size the project appropriately for the team size. This is relevant to the design of assignments from a technical standpoint, and also bears cognizance if some teams are larger or smaller than others. For smaller teams, I reduce the size of the final project by judicious cutting of some of the deliverables, making sure that the learning outcomes are still met. For larger teams, I either add an extra piece that can be easily tied into the rest of project if team members are finding the team size unwieldy, or I ask for more comprehensive deliverables. This helps with work distribution and team dynamics since I intentionally size the final project for all the team members to work together synergistically.

S. Suggest specific teamwork strategies to increase efficiency, accuracy, and overall quality of the submitted work as teams tackle problems. For example, in a team of four, many tasks can be completed by a sub-team of two, and the other sub-team can check for accuracy of work, relevance of assumptions and errors. This keeps all the team members abreast of the project as a whole and allows for fresh perspectives. It also helps with stitching the pieces back together and using a unified voice to present the findings and describe the thought process that went into the work. I tie this overall process back to psychological safety; giving and accepting help and suggestions is an integral part of a successful project.

Module 5: ABET

In this module, I list strategies I use to meet ABET learning outcomes (LO's). Each of the seven LO's is given in full as it appeared in ABET.org in May 2023.

LO1: identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.

A. Select a design problem that contains realistic complexities and needs the application of principles from all the foundational courses in that stem of the curriculum. For a mechanical engineering capstone design course in thermal fluids, I ask students to design a system that will need them to apply principles from thermodynamics, fluid mechanics and heat transfer. Complex engineering problems are by their very nature open-ended with multiple possible solutions.

B. Limit the scope of the project so that students can complete the project with a sufficient level of detail and complex considerations within the timeframe of a single course. I asked students to design part of a system that would reduce the use of fossil fuels for HVAC needs. I limited the scope of the project by giving students some of the components they would need to incorporate as well as some modeling equations they could use for their optimizations. I also asked students to do a detailed design for one given set of conditions (temperature and humidity inside and outside on a hot summer's day) at steady state. Groups needed to make many assumptions and show how they optimized their design choices. They also needed to consider non-ideal scenarios, such as non-adiabatic components and pressure drops throughout multiple subsystems due to fluid friction. This iterative process required the use of equations and principles from all three prerequisite courses as well as the material learned in the course and resulted in a distinct design for each group.

C. Ask teams to also consider the bigger design without the same level of detail as (B). I asked students to do some basic calculations for assessing the system for use in other seasons and in other summer conditions.

LO2: apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

and

LO4: recognize ethical and professional responsibilities in engineering situations and make informed; judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.

D. Require students to specifically list their design criteria and constraints, discuss economic considerations with a cost analysis, and describe how their design affects any relevant topics such as health, safety, and environment. All of these should be discussed within the context of global, cultural, ethical, and societal considerations.

E. Assign part of the course grade for a section dedicated to this in the final report. This will stress the importance of thinking carefully about the broader context of engineering design.

F. Give students the tools they need to formulate this section effectively, such cost analysis and estimation tools, and structuring the assignments in a way that encourages a big picture approach to the problem. By encouraging students to think out of the box, these broader considerations often lead to creative approaches to the project.

LO3: communicate effectively with a range of audiences.

G. Give groups time to work together in class. This helps team members to establish effective communication channels with each other and with the instructor and TA's. I set aside one day a week for the first half of the term while we are covering new and review material, and every class day for the second half of the term.

H. Answer questions as a group, both during office hours and in the classroom, so that teams discuss their questions amongst themselves. This also provides all students with opportunities to practice effective communication with the instructor and TA's.

I. Spend time in the early part of the course giving students tools for effective communication within a team for coordinating work schedules, breaking the assignments and project into smaller parts and then meshing these parts into the bigger whole, brainstorming, checking each other's work, and collaborating on the technical and non-technical aspects of the project.

J. Provide specific guidelines in each assignment for presenting work in the written report. I have included examples in the second part of Module 6.

K. Have a presentation day at the end of the course where groups present their work. I gave each team 2 minutes for the presentation and 1 minute for answering questions. Their audience was me and the rest of the class.

LO5: function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.

Teamwork is addressed in detail in Module 4, but here are some guiding principles that I use for the capstone:

L. Acknowledge that teamwork in a technical setting is different to teamwork in a humanities-based class. Students need to communicate about technical aspects of the project and collaborate on design decisions. Students also need to co-ordinate their schedules in order to have time for collaboration, and they need to plan their overall goals, how they would like to get there, who is going to do each of the subtasks, and then work together to mesh the subtasks into an integrated whole in order to meet their design objectives.

M. Emphasize that it is more effective to have collaboration and division of labor for both technical and non-technical aspects of the project, rather than divide up the work with one (or some) member(s) doing all the technical work and (an)other member(s) doing all the report writing.

N. Ask students to write an individual graded reflection as part of each assignment describing both their technical and non-technical contributions to the work, learning risks taken and new skills developed.

O. Insist on all students being involved in all aspects of the work. This ensures that the work distribution is equitable. This does three things: (i) it allows all students to know that they are making valuable contributions to the final product, (ii) it helps students develop skills in areas that have not been their traditional area of strength, and (iii) it addresses inclusion needs by preventing work distribution along gender disparity lines of women organizing, scheduling and writing reports and men focusing on the technical aspects of the work, or along technical acuity lines of stronger students making the important decisions and weaker students being sidelined.

LO6: develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

Below, I list my guiding principles for a capstone course in which students produce a theoretical design of a thermal fluids system that does not involve any physical experimentation. In the latter regard, LO6 is only partially met in this course, and is met in other parts of our curriculum.

P. Structure the assessments so that there is no single correct answer for any of the assignments or final project, including the introductory assignment. Rather, I emphasize correct understanding of the principles and methods.

Q. Integrate modeling, optimization and data analysis into the assignments and final project.

R. Require teams to use engineering judgement when making design choices and recommendations. As teams are thinking through these during class team-work time, ask individual teams questions that guide their thought process. With increasing open-endedness and ambiguity, students practice making assumptions, drawing conclusions, and developing and using engineering judgment to evaluate their options. They learn to discuss this amongst themselves and to use me as a sounding board as they embark on this journey. As the course progresses, students become more comfortable with this process.

LO7: acquire and apply new knowledge as needed, using appropriate learning strategies.

S. Include new or more advanced material relevant to each prerequisite course for applied use in the associated assignment. Combine this with a review of previously studied material as well as material related to the broader context, such as costing, optimization, ethics, engineering standards and the like.

T. Task teams with finding certain information needed for the more open-ended assignments and interpreting it and using it appropriately. The scaffolded approach helps students develop confidence in their ability to tackle this.

Module 6: Excerpts of course material

Syllabus excerpts

Objectives

To expand your ability to analyze thermofluid systems and to model open-ended problems. Integration of fluid mechanics, thermodynamics, and heat transfer. Introduction to thermofluid design.

Your work should contain clearly formulated problem statements; specific design requirements and constraints, including social, economic, geographical, ethical considerations; assumptions made; relevant analyses, including formulas, properties; brief explanations for design choices, including when there is a trade-off between different criteria or constraints. **Course focus**: design of a thermofluid system.

Teamwork will be an essential aspect of this course, and we will work on honing transferable skills for your careers/professional development. I am also going to be intentional about structuring the course in a way that forges connections within the class and provides opportunities to practice working within a diverse team.

Grading: Assignments 40%. Project 60%. A portion of the grade for each group assignment will be for demonstrating teamwork and developing new skills. This will be assessed from your individual [reflections]...

Initial assignments: [Individual] Introductory assignment… Assignment 2 in assigned teams of two, Assignment 3 onwards in your assigned team of four. Teams will be assigned based on self-reported student schedules.

Group Design Project: Work in your assigned team of four. There will be progress check-ins throughout the term...the final report ...is due ...the last day of class.

Design: Air conditioning, space heating and hot water heating together account for 70% of household energy consumption in the USA. Much of that energy comes from non-renewable sources. The goal of this project is to design, optimize and cost out a system for a single household in Massachusetts that harnesses solar energy for a portion of the indoor climate control and water heating needs. The design focus will be thermal fluids.

Week 1 Review of thermodynamics [for use in introductory assignment and thermodynamics assignment]

Week 2 Review of [fluid mechanics topics for use in the fluids assignment and the rest of the course]

Week 3 Review of heat transfer [for use in the heat exchanger assignment and the final design]

Week 4 [Additional] considerations, move on to design project.

Weeks 5-7 Design project with regular check-ins.

First day presentation of general course and design project overview

Please note the link shown in slide 11 is not live for this toolkit.

ME 4429 A-term 2022

Design project – where we going and how we are going to get there

FCL ME 4429 2022

1

General course structure, Canvas, meet the team

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2

Overarching course goals

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3

Design project – context and broad overview

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4

U.S. household energy use:

space heating and air conditioning (51% in 2015)

seasonal
geographic variation
home size and structure
equipment and fuels used

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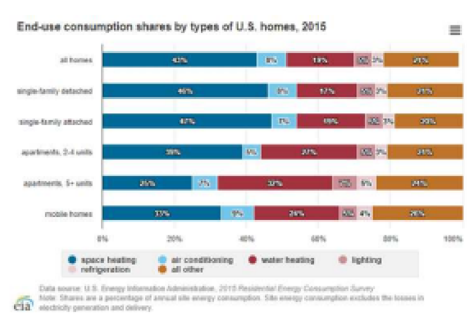
5



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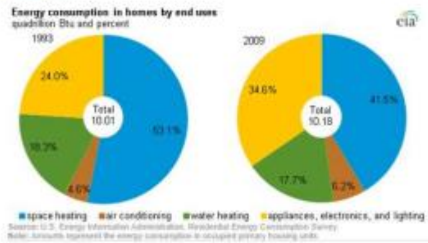
6

Heating and cooling no longer majority of U.S. home energy use



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7

About 70% indoor climate control and water heating

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8

Currently, what energy sources are used for this?

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9

What can we do to make a difference?

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10

Some examples

Drake landing solar community

https://www.dlsc.ca/animation.htm

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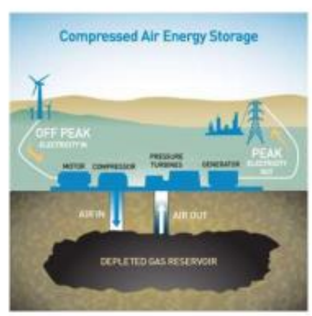
11



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12

Gravity: Pumped hydro, Mechanical

Chemical: batteries

Thermal: PCM's, thermal reservoirs

etc…

What about individual household scale?

Tomorrow:
- some thermo review
- intro to psychrometrics
- poll for teamwork times

First day presentation of overarching course goals

Please note the hyperlink shown in slide 3 is not live on this page. A live link is given in Module 4.

Overarching learning outcomes

ME 4429 Capstone thermofluids design course

FCL ME 4429

1

Professional development

- Teamwork – individual contributions and combining these to get a unified end result
  - whole is bigger than the sum of the parts
- Work in a diverse team
- Work with people you don't know
- Become comfortable with open-ended tasks and ambiguity
- Present clear, unified reports
- Personal and team growth

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2

Team effectiveness

- Psychological safety – allows for taking risks

Building a psychologically safe workplace | Amy Edmondson | TEDxHGSE - YouTube

- Personal and team growth
- More effective communication
- Better results – find mistakes, fresh perspectives and project angles, improved creativity

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3

Forge connections

- Human level
  reduce isolation
  sense of community
  happier
  more productive
  …
- Professional level
  "it's not what you know, it's who you know"

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4

Technical

- Use and adapt fundamental skills to a new problem
- Break down a large task into smaller parts
- Mesh different technical skills
- Piece together small parts and iterate to solve the large task
- Consider real-world applications
- Include ethics in your design considerations
- Use engineering standards
- Consider cost implications

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5

And most importantly…

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6

General Guidelines for Assignments

•Work in your assigned group. As a first step, go through the assignment together during assigned class time and decide on what work needs to be done. Talk about things you feel prepared to do and things you want to learn. Then divide tasks amongst yourselves and do these initial tasks independently outside of class time. Exchange work and check each other's work for valid assumptions, units, unit conversions, understandability, correct calculations, reading charts and tables correctly, using correct numbers. Give each other constructive feedback. Then combine your work, iterate your solution using the systems you have just set up, and write up the assignment using a cohesive writing style. Make sure the assignment meshes as a single entity.

•Submit your assignment as a team – one assignment with all (both) names.

•Submit individual reflections to canvas (under quizzes > surveys) with an outline of your what parts of the assignment you did individually, what feedback you gave to your team member(s), learning risks you took individually and as a team, and skills you learned or started to develop (technical and non-technical).

Team Charter

A. Each member should create an asset map of all their skills (technical and non-technical, or what is referred to as hard skills and soft skills). Also write down how you like to approach deadlines, (e.g. finish the work three days before the deadline or finish the work 1 minute before it is due). Lastly, look at your schedule and write down the times of the week where you are able to work on the course (i) individually and (ii) with your team. [I provided the asset map example (shared by permission of Prof. Stoddard), which can be found in the stand-alone asset mapping assignment on page 10 of the original publication by Stoddard and Pfeiffer.]

B. Meet with your other team members to discuss your strengths as well as areas where you would like to improve. Decide as a team how you can use your combined strengths to function effectively as a team. Also discuss opportunities for growth and professional development, by learning or practicing new skills with support from your team members and offering your support and expertise to others. Share your schedules, as well as how you like to handle deadlines.

C. Write down how you plan to function as a team based on your discussion in B. Remember that you can modify this later if you find it needs to be tweaked.

Rubrics for Assessing Student Learning

85% technical content (initial assignments graded by TA, prof graded final project)

5% clearly presented work (graded by TA for the initial assignments, graded by prof for the final project)

5% feedback and teamwork (graded by prof)

5% evidence of new skills being developed (graded by prof)

The exception was the rubric for the fluids assignment (which was the first time the team of four worked together) which was:

65% technical content (graded by TA)

20% team charter (graded by prof)

5% clearly presented work (graded by TA)

5% feedback and teamwork (graded by prof)

5% evidence of new skills being developed (graded by prof)

Guidelines for final project report

…

The focus of the report should be on the thermal fluid design aspects of the project. The report must include:

- A clearly formulated problem statement.
- Specific design requirements.
- Design constraints, both from an engineering perspective as well as contextual factors, including social, economic, geographical, ethical considerations.
- Assumptions made.
- Relevant analyses, including relevant equations and methods, properties, and sample calculations with numbers, correlations, constants used etc.
- Explanations for design choices, including when there is a trade-off between different criteria or constraints.
- Include a short section on the broader impacts of your design. [I provided a link to the guidelines that the department provides for all capstone projects.] Note that not all aspects outlined in the guidelines will be relevant to your project – discuss the aspects that do pertain to your project.

You should check your work for reasonableness and validity and make sure that your work is clearly written and presented logically. You may [provide your] spreadsheet [or code], but [I should not need to use this to understand your work].

I will be doing all the grading using the following point distribution:

85% technical content (assessed from team project report)

5% clearly presented work (assessed from team project report)

5% feedback and teamwork (assessed from observation and individual reflection submission)

5% evidence of new skills being developed (assessed from individual reflection submission)