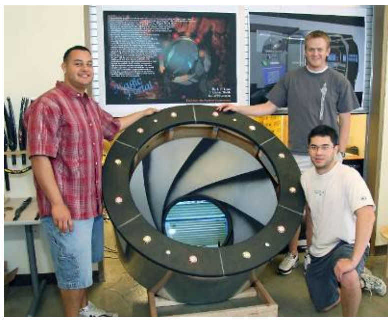
Senior Project Student Success Guide



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1 Introduction - Welcome to your Senior Project!

What is a Senior Project?

According to the University's website:

> *The senior project is a capstone experience required for all Cal Poly students receiving a baccalaureate degree. It integrates theory and application from across the student's undergraduate educational experiences.*

In this three-quarter sequence of courses (ME 428-429-430), you will integrate knowledge and skills you have gained throughout your undergraduate education to *design*, *build*, and *test* hardware that solves an externally supplied problem for a customer. Design is what most engineers do most of the time and is practically synonymous with the verb "to engineer". It is a process you will learn best by doing! You will be proud of the things you create, but what is of more importance is the understanding you will take away of the process. You will find this design process useful throughout your life.

Senior project will be quite different from most other courses you have taken. First, the courses cover three quarters, and you will be working with the same team on the same project for the entire time. Your team output (documentation, presentations, hardware, etc.) will be the result of a team effort. Your grade for the courses will be primarily based on these team products; therefore, it is our experience that any project "failures" will be the result of a team failure.

Every quarter, your team will have two weekly lab periods scheduled with your faculty coach/advisor. The basic structure of the ME Senior Project experience is:

Quarter 1 – ME 428
During the first week of labs, all potential sponsors will present their design challenges to the class. After viewing the presentations and getting your questions answered, you'll complete a project survey to indicate your level of interest in the different design challenges. The teaching team will use this information to form teams and assign labs. If your project ends up in a different lab section than the one you registered for, you will need to change your registration. Once on a project team, you'll spend a couple of weeks getting to know your team and researching the customers, their needs, and the desired outcomes. You'll use this to determine your project scope and write a Scope of Work (SOW) report for your sponsor. Next, you'll spend a couple of weeks developing, evaluating, and selecting concept solutions (ideas). You'll construct a Concept Prototype to demonstrate your selected design and then present your design to your sponsor as a Preliminary Design Review (PDR). You will spend the rest of the quarter making the major design decisions and sorting out the details of your design.

Quarter 2 – ME 429
The second quarter starts with an informal Interim Design Review (IDR) in lab, in which you present your design status and receive input from peers about potential issues. Then, you'll finish defining your design, build a Feasibility/Structural Prototype and present your detailed design to your sponsor in a Critical Design Review (CDR). After getting approval from your sponsor, you'll spend the rest of the quarter obtaining materials and building your Verification Prototype. At the end of the quarter, you'll

present your build status and testing plans in a Manufacturing & Test Review in lab. During this quarter, you'll also participate in engineering ethics activities.

Quarter 3 – ME 430

In the third quarter, you will finish building and assembling your Verification Prototype, have it safety-checked at a Verification Prototype Sign-Off in lab, and then test it to see if it meets your project goals. Confirm your test results in a Testing Sign-Off. Also, during this quarter, you will also complete the Senior Exam and Senior Survey. The quarter finishes with a Final Design Review (FDR), which includes your Senior Project Report, Verification Prototype and a Project Expo where you'll share your work with the public.

Throughout the three quarters, your faculty coach/advisor will guide you through the process of designing, building, and testing a solution to a design problem. This success guide will help you by providing answers to some of your questions. The best way to use it will be to read it! Please let us know if you find errors so we can promptly get them corrected. Good luck as you embark on a journey of learning, discovery, hard work, and hopefully great personal satisfaction for your completed project!

1.1 Course Logistics

This section covers the key course organization for the three-quarter senior design project courses.

1.1.1 Course Objectives

1. Apply a formal engineering design process to solve an open-ended, externally supplied engineering design problem.
2. Work effectively on an engineering team.
3. Develop, analyze and maintain an engineering project schedule using a Gantt chart and appropriate software.
4. Use Quality Function Deployment (QFD) to evaluate customer requirements.
5. Formally define an engineering problem.
6. Generate an engineering specification document.
7. Apply creative techniques to generate conceptual design solutions.
8. Apply structured decision schemes to select appropriate engineering concepts in a team environment.
9. Design systems within constraints (strength, size, materials, performance, cyclic loads, etc.).
10. Evaluate potential design solutions using engineering and physical science analysis techniques and tools.
11. Apply current industrial design practice and techniques such as DFX, FMEA and/or TQM to engineering design problems.
12. Construct and test prototype designs.
13. Develop and implement a Design Verification Plan and Report (DVP&R).
14. Communicate and present engineering design project results orally, graphically, and in writing.
15. Discuss and take a stand on open-ended topics involving engineering ethics and product liability.
16. Discuss engineering professionalism and its responsibility to society.
17. Understand the codes of ethics and their implications in engineering practice.

1.1.2 Student, Faculty, and Sponsor Roles

The student design team is responsible for completing all tasks required to produce a final product and report in a professional manner. This is **YOUR** project. The project sponsor, faculty coach/advisor, and course organizer are available to provide technical and management assistance and to help you keep your project on schedule. Here is a list of responsibilities:

Student Design Team:

- Attend all labs and participate in activities
- Manage project (define team roles, schedule and track tasks, establish and maintain budget, etc.)
- Define project scope in a written *Scope of Work (SOW)*
- Use engineering skills to design a product
- Document design progress in a *Design Logbook* (recommended daily)
- Build a Concept Prototype
- Prepare and present a *Preliminary Design Review (PDR)* report and presentation to the sponsor.
- Build a Feasibility/Structural Prototype
- Prepare and present a *Critical Design Review (CDR)* report and presentation to the sponsor.
- Procure materials, fabricate, build, and/or supervise construction of Verification Prototype
- Establish a test plan, procure diagnostic equipment, and perform testing
- Complete Senior Exam
- Complete Senior Survey
- Present verification prototype and poster at *Project Expo*
- Document entire process in a *Senior Project Report*
- Meet additional intermediate course requirements outlined on syllabus
- Complete all required forms for purchasing and traveling
- Interact with faculty coach/advisor (required twice each week)
- Interface regularly with sponsor (recommended weekly)

Faculty Coach/Advisor (Lab Instructor):

- Work with team to define an appropriate project scope
- Coordinate lab activities and presentations
- Mentor team about:
  - Team development (roles, responsibilities, and handling conflicts)
  - Design process & project management (planning, scheduling, tracking)
  - Resources for technical issues
  - Resources for fabrication and testing
- Assist with sponsor-team interactions
- Evaluate all team assignments and assign course grades

Sponsor:

- Provide initial design challenge and present to students and faculty
- Be accessible to provide technical assistance and data
- Identify proprietary information to ensure company protection (if applicable)
- Critically review *Scope of Work* to ensure appropriate scope
- Mentor team on customer issues
- Mentor team on resources for fabrication and testing

- Provide funds for building verification prototype
- Evaluate team progress at *Preliminary* and *Critical Design Reviews*
- Evaluate team product at *Project Expo* and in *Final Design Review Report*
- Take possession of Verification Prototype at the Project Expo

Course Organizer:

- Collect projects from sponsors and review initial project scope
- Facilitate and coordinate senior design experience
- Arrange *Project Expo* and poster printing
- Work with ABET coordinator to administrate Senior Exam and Senior Survey

1.1.3 Grading and Assessment

All students, regardless of lab section, will be evaluated based on a common set of deliverables (things you turn in). See chapter 2, Deliverables, for details. These deliverables will be graded by your lab instructor. Reports, presentations, and hardware are the responsibility of the team and will be assigned a single grade shared by all team members. Your faculty coach/advisor can modify this if he or she feels any members are performing less work than others! Other sources of assessment are provided by faculty members who may attend presentations, peer review by fellow students, and input from the project sponsors. In addition, there will be some individual activities (e.g., logbook, ethics memo, senior exam) throughout the courses. Consult the course syllabus and your faculty coach/advisor for details.

Late projects are unacceptable. If there are unforeseen circumstances in which students cannot complete the project on time, a binding contract will be drawn up for the delayed team indicating specific completion milestones and dates. Failure to fulfill this contract will result in a failing grade and the requirement that students enroll in the next section of ME 428 with a new project and a new team. This may delay graduation by up to a full year.

1.1.4 Intellectual Property and Non-Disclosure Agreements

Two types of legal documents are common during the start of a project initiated between different organizations:

1) An Intellectual Property (IP) agreement is used to declare up-front the ownership of any intellectual property (typically patentable ideas) that may be developed during the project.
2) A Non-Disclosure Agreement (NDA) is used to protect any confidential information shared by the parties or developed during the project.

Important! Do not sign ANY agreement before consulting your faculty coach/advisor.

To protect your rights, Cal Poly Grants Development department will need to review any document the sponsor asks you to sign. The sponsors have been made aware of this, but they may forget and ask you to sign an agreement at some point in the project. Give these agreements to your faculty coach/advisor for review.

Many sponsors have agreed to use a standard Cal Poly Class Project Sponsorship Agreement. For these projects, you will be asked to sign Cal Poly Project Confidentiality and Intellectual Property Agreement. Your faculty coach/advisor will provide you with a copy to sign. Many of our sponsors (e.g., Cal Poly, Non-Profit, and most Individual sponsors) do not require IP or NDA agreements.

If you sign an agreement, you should comply fully with its terms. It would be highly unprofessional and unethical to violate the terms of an agreement. Our sponsors have been generous enough to open their doors to us, to bring us projects, to support the projects and teams financially and with their time. The last thing we want to do is to have a student or a group of students use information learned in the course to complete a project to the disadvantage of the sponsor in violation of a legal agreement.

1.2 Budget & Travel Information

This section provides an overview of the senior project travel, purchasing & reimbursement, and budgeting process. Please refer to the Senior Project Purchasing section on the ME Department's Administrative Tools for Students website for the most up-to-date information and forms.

1.2.1 Travel Policies and Required Forms

By its nature, Senior Design Project may involve travel to visit your sponsor or interact with end users. It is essential for you to understand your customer's requirements. Seeing their needs first-hand is the most efficient way to do this. When possible, you should arrange a meeting at your sponsor's site during the second or third week of the first quarter. Where appropriate, some teams will be given a travel budget. This budget is for all three quarters and the team is responsible for managing that budget appropriately. Preliminary and Critical Design Review presentations in the first and second quarter can be conducted in person or by teleconference, as agreed with your sponsor.

NOTE: If International Travel is part of your Senior Project, a supplementary set of forms is necessary and must be completed over a month before intended travel. See the Administrative Tools website, above, for instructions.

1.2.2 Purchasing and Reimbursements

During ME 429 you or your sponsor will need to procure parts and materials for your verification prototype. **All purchases should be discussed and approved by your faculty coach/advisor BEFORE any purchases are made**. The preferred method of procurement is to have your sponsor purchase materials for your team and have them drop-shipped (sent directly from the source) to Cal Poly. For some projects, the purchasing process will be handled at Cal Poly. Most Cal Poly purchases should be made using the on-campus ProCard through the Mechanical Engineering Department office. In a few special cases, you may need to purchase local materials yourself and be reimbursed. How you are reimbursed will depend upon the project. There are three basic methods you will use for materials procurement (see the Senior Project Purchasing section on the ME Department's Administrative Tools for Students website for more info):

1. **SPONSOR PURCHASES YOUR MATERIALS** (**1st choice**) – If your project has an off-campus sponsor, in most cases your project sponsor should procure the materials for your team and ship them to Cal Poly at the address below.
2. **CAL POLY PURCHASES YOUR MATERIALS (2nd choice)** – If you have an on-campus budget managed by the ME department, you will submit requests for material purchasing using the Purchase Request Form.
3. **YOU PURCHASE YOUR MATERIALS (3rd choice)** – In special cases (with faculty coach approval), you may need to purchase local items yourself and submit receipts for reimbursement.

For delivery of all equipment and components, use this address: your full name, cell phone number, & e-mail address c/o Cal Poly Mustang '60 Machine Shop 1 Grand Avenue San Luis Obispo, CA 93407 [Use the correct zip code!]

Important: Materials should be shipped to Cal Poly – not to your home.

Purchasing Restrictions
(We don't anticipate any senior project needing these!):

- Any purchase from a single vendor over $5,000 (tax and shipping included) must be processed as a purchase order. A formal quote will be required from the vendor in order to initiate this.
- Any purchase from a single vendor that exceeds $5,000 (tax and shipping included) will require three formal bids or a *Sole Source Justification* to process a purchase order.

1.2.3 Project Materials & Travel Budget

Whether or not you directly purchase materials for your verification prototype, your team must create and maintain a Materials & Travel Budget for your project. You can download a template from the Senior Project Purchasing section on the ME Department's Administrative Tools for Students website. Your budget is your means of ensuring (a) you have adequately planned for all project expenses and (b) as you purchase, you are not exceeding your planned amounts.

You should prepare your budget file early in the first quarter, while you are developing your Scope of Work. At this point, it would consist of line items for any anticipated travel and an overall budget limit (provided by your sponsor) for prototypes and testing. All budget details (prices and sources for all purchased components) should be added to the budget spreadsheet as you finalize the design details during the second quarter. When you travel or make a purchase, track the actual expenses for all items in a separate column from the planned expenses, so you can easily see how well you are keeping to your budget.

1.3 Senior Project Safety

The ASME Code of Ethics' first Fundamental Canon is:

> "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties. "

In this class you are learning what it means to be a professional engineer, by acting as a professional engineer on your project. It is imperative that you place safety first in all your senior design project work. This means that you will:

- Design a safe product that does not impose any undue hazard to a user.
- Construct your prototypes in a safe manner
- Test your prototypes in a safe manner.

Preventing injuries or property loss during your time in this class and by the products you design is your first priority. Effective injury prevention involves a process of identifying hazards and quantifying risks. Hazards and risks can be defined as:

- A **hazard** is any unsafe condition where there is the potential for human, property, or environmental damage.
- **Risk** is the likelihood, probability, or frequency of a hazard materializing during use.

Liabilities stemming from the design and product development process are usually based on one or more of the following premises:

- A concealed danger has been created
- Available safety devices have not been incorporated
- Materials are of inadequate strength
- Failure to comply with accepted standards
- Failure to consider foreseeable possible misuses of the product
- Warnings and instructions are inadequate

1.3.1 Design for Safety

During the process of designing and developing products, you must determine whether hazard potential is being properly assessed. You must ensure that appropriate product safety features are implemented. The primary concern of product designer(s) should be to develop "reasonably safe" products that are reliable and maintainable. A product is considered "reasonably safe" if the potential risks are judged to be acceptable by society. In general, U.S. society deems products as being not reasonably safe through litigation.

Designers should make every effort to minimize and control such hazards using techniques like:

- Established design safety criteria
- Applicable mandatory and voluntary (proprietary, industrial, and consensus) standards
- State of the art technologies
- Design safety reviews
- Documentation for the decision-making process

In practice, there are three approaches that a designer can take to improve the safety of their designs:

1) BEST: Design to remove hazards.
   Whenever possible, designers should remove hazards from their design. To do this may require a new way of achieving the design's functions (a great ideation opportunity), but it often is as simple as just thinking carefully about what the design really needs to do. When designing for safety, spend your time trying to follow this approach; it will give you the best results.
2) BETTER: Design to reduce risk by protecting users from hazards.
   If a hazard can't be removed from the design, a designer should do everything they can to protect users from harm while using the design. This can include a variety of automatic or integrated safety features in the design. There are standards governing this approach, so use these to create the most effective & efficient protection you can.
3) GOOD: Design to warn users about hazards.
   The final (and less effective) approach in designing for safety is to be sure that users are aware of the hazards in your design. Like above, there are standards for proper warnings/labels, and you should follow these to create the most effective & efficient warnings.

Since product safety is not easily quantified, you should employ guidelines as you work on your design. A typical set of guidelines (from Dieter and Schmidt) is shown in Figure 1.

At a minimum you should use the following guidelines as you evaluate your design:

1. Recognize and identify the actual or potential hazards, and then design the product so they will not affect its functioning.
2. Thoroughly test prototypes of the product to reveal any hazards overlooked in the initial design.
3. Design the product so it is easier to use safely than unsafely.
4. If field experience turns up a safety problem, determine the root cause and redesign to eliminate the hazard.
5. Realize that humans do foolish things and allow for it in your design. More product safety problems arise from improper product use than from product defects.
6. There is a close correspondence between good ergonomic design and safe design.
   - Arrange controls such that the operator does not have to move to manipulate them.
   - Make sure fingers cannot be pinched by levers.
   - Avoid sharp edges and corners.
   - Products that require heavy or prolonged use should be designed to avoid cumulative trauma disorders like carpal tunnel.
7. Minimize the use of flammable materials, including packaging
8. Paint and other surface finishing materials should be chosen to comply with EPA and OSHA regulations. For toxicity to the user and when they are burned, recycled, and discarded.
9. Think about the need for repair, service, or maintenance. Provide adequate access without pinch or puncture hazards to the repairer.
10. Electrical products should be properly grounded. Provide electrical interlocks so that high-voltage circuits will not be energized unless a guard is in place

Figure 1: Design for Safety Guidelines (Dieter & Schmidt)

1.3.2 Cal Poly's Safety Procedures

Like all organizations, Cal Poly has established Safety procedures and guidelines. Since you will be working in different places on campus, it is important that you review the University's safety guidelines. They are maintained by Cal Poly's Environmental Health and Safety department. The document is called the Injury and Illness Prevention Plan.

Your first order of business in lab for senior project will be to review and sign the Mechanical Engineering Department's Senior Project Safe Practice Procedures (Figure 2). The purpose is to raise awareness of the importance of following safe procedures in all activities you engage in at Cal Poly.

Senior Project Safe Practices & Procedures

1. Read the course Senior Project Safety Section of the Success Guide.
2. Do not do any Senior Project hardware development (i.e., manufacturing or testing) outside a Cal Poly facility without the authorization of your faculty coach.
3. All hardware testing must follow written testing procedures reviewed by your faculty coach or the department safety coordinator.
4. When working on your senior project in a Cal Poly facility, you must follow all those facilities Safety Procedures.
5. Use proper Personal Protective Equipment (safety glasses or goggles, ear plugs, gloves etc.) when operating laboratory equipment or experiments.
6. Wear appropriate attire when operating equipment. Secure long hair around rotating equipment or open heat source, proper shoes where drop hazards exist, etc.
7. No equipment shall be operated without the instructor's permission.
8. No unsupervised use of laboratories without prior written authorization by the instructor.
9. No working alone in the laboratories.
10. Any accident or illness must be immediately reported to the instructor and/or the Mechanical Engineering Department office.
11. Any unsafe or hazardous condition in lab (liquid spills, electrical hazards etc.) must be immediately reported to the instructor.
12. In case of an emergency dial **911** and tell the dispatcher:
    - The nature of the emergency
    - Your name
    - The location of the emergency
13. To evacuate the building in an emergency, follow routes posted near the exits of the building.

Figure 2: Senior Project Safe Practices & Procedures

1.3.3 Safety Processes in Senior Project

With these guidelines in mind, you will be developing concepts and finalizing the detailed design of your solution. At the end of ME 428 you will assess potential Hazards of your design and submit a Design Hazard Checklist (Figure 3) and Design Hazard Plan (Figure 4). This will focus your attention on the most common potential hazards, to evaluate if they are present in your concept. Any boxes checked will require special attention during your detailed design work.

To ensure your final design will result in a safe and robust product, after PDR you will perform a Failure Modes & Effects Analysis (FMEA). This analysis will result in a set of focused analysis steps you can undertake to address any safety hazards in your design.

After completing your detailed design (including changes to address the safety hazards you identified), you'll update your Design Hazard Checklist (Figure 3) and Design Hazard Plan (Figure 4) in preparation for your Critical Design Review (CDR). The CDR is typically held around the middle of ME 429.

After CDR, you'll complete a Risk Assessment / Safety Review of your design, which will help you identify the risks involved with testing and operating your design. The Risk Assessment will also guide you in writing safe Test Procedures and User Manuals.

A timeline of the key safety milestones for senior project is laid out below.

ME 428 (1st quarter)

- Week 2 – Review and sign the Senior Project Safe Practices & Procedures (Figure 2)
- Week 10 –Submit a Design Hazard Checklist (Figure 3) and Design Hazard Plan (Figure 4).
- Week 10 – Create a FMEA for your concept design.

Important: Do NOT wire any electrical circuits with voltage >40 volts. Instead, purchase enclosed components/systems or outsource the electrical design/build. (If a conductor carries >40 volts and someone can touch it, then it cannot be in your design!)

ME 429 (2nd quarter)

- Weeks 1-5 – Assess and mitigate identified risks while working on the details of your design. Document your work with an updated Design Hazard Checklist (Figure 3) and Design Hazard Plan (Figure 4) in the appendix of your CDR report.
- Week 6 – Prepare a Risk Assessment for your design and review it with mechanical and/or electrical technicians to discuss safety risks and plans. Document any recommendations and plans.
- Week #7 – Develop Test Procedures and a draft User Manual to address all safety hazards identified in your Risk Assessment.
- Weeks #6-10 – Follow machine shop safe practices and procedure while manufacturing parts of your design.

Important: Do NOT work on your senior project hardware at home!

ME 430 (3rd quarter)

- Weeks #1-10 Follow machine shop safe practices and procedures while manufacturing, assembling, and testing your design. Please note:
  - For any project with identified hazards, your hardware MUST be inspected by a qualified electrician or mechanical technician prior to operation. This can occur at the Verification Prototype Sign-Off, or earlier by appointment if you build is complete and you are ready to begin testing.
  - Update your draft User Manual and ensure it fully captures all safety hazards and procedures to keep the users safe/
  - Prior to the Design Expo, final hardware with any known hazards must be reviewed by a safety professional who will determine whether it can run at the Expo.
  - Install safety placards/labels at all safety hazards on your verification prototype.

Remember that safety is everyone's responsibility. As an engineer it is your primary ethical duty. Injuries and property damage often occur when you are in a hurry. There is NO reason you should be in such a hurry to design, manufacture, assemble or test your senior project that you increase the risk of injury. Your and others' safety is more important than the deadlines! Keep in mind that you are not an expert in product safety, and neither are the teaching staff. If you have any question about hazards and risks, bring them to your faculty coach/advisor's attention so s/he can help find the right resources to assess the hazard.

DESIGN HAZARD CHECKLIST

Team: ____ Faculty Coach: ______________________

Y	N	
☐	☐	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☐	2. Can any part of the design undergo high accelerations/decelerations?
☐	☐	3. Will the system have any large moving masses or large forces?
☐	☐	4. Will the system produce a projectile?
☐	☐	5. Would it be possible for the system to fall under gravity creating injury?
☐	☐	6. Will a user be exposed to overhanging weights as part of the design?
☐	☐	7. Will the system have any sharp edges?
☐	☐	8. Will you have any non-grounded electrical systems?
☐	☐	9. Will there be any large batteries or electrical voltage (above 40 V) in the system?
☐	☐	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☐	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☐	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☐	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☐	14. Could the system generate high levels of noise?
☐	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?
☐	☐	16. Is it possible for the system to be used in an unsafe manner?
☐	☐	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, complete a row in your Design Hazard Plan including (a) a description of the hazard, (b) a list of corrective actions to be taken, and (c) the date you plan to complete the actions.

Figure 3: Design Hazard Checklist

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date

Figure 4: Design Hazard Plan

2 Deliverables

There is a minimum set of deliverables required of all student teams in Senior Project. These have been designed to help you practice a structured design process while completing your project in a timely and professional manner. Your lab instructor may have **further** requirements and deliverables as she or he guides you through the process. Note that any additional work is designed to assist you in completing the fixed set of deliverables in the most timely and professional manner and should not be considered “extra” work. This section describes the common deliverables in detail; check with your faculty coach/advisor for additional requirements. The team deliverables include:

ME 428 (First Quarter)

- Letter of Introduction to Sponsor
- Team Contract
- Quality Function Deployment (QFD) House of Quality
- ***Scope of Work***
- Concept Models and Concept Prototype
- ***Preliminary Design Review (PDR)*** Report & Presentation
- Failure Modes and Effects Analysis (FMEA)

ME 429 (Second Quarter)

- Interim Design Review (IDR)
- Feasibility/Structural Prototype
- ***Critical Design Review (CDR)*** - Report & Presentation
- Risk Assessment
- Ethics Activities
- Manufacturing and Test Review

ME 430 (Third Quarter)

- Project Update Memo
- Verification Prototype Sign-Off
- Testing Sign-Off
- ***Final Design Review (FDR)***
  - Verification Prototype
  - Expo Poster Presentation
  - Senior Project Report
- Senior Project Completion Checklist

In addition to these, there are four individual deliverables throughout Senior Design Project:

- Design Logbook (throughout the project)
- Ethics Memo (2nd quarter)
- Senior Exam (3rd quarter)
- Senior Survey (3rd quarter)

See below for detailed information about each of these deliverables.

2.1 Design Logbook

There are three distinct types of documentation required with any engineering project:

1) In-Process documentation (Logbook). Each idea, design decision, feature change, analysis, justification, test, etc., should be documented in a project logbook. This documentation is invaluable for:
    a. Recording your early ideas, thoughts, and justifications for later permanent recording (in more formal reports).
    b. Proving that you have done due diligence in creating your design (evidence of thoroughness).
    c. Showing you are a key contributor to project outcomes.
    d. Enabling you to return quickly to early tasks and revise them as needed.

    Logbooks are NOT about showing the results. Results go in the reports. Logbooks are about showing you did all the work that led up to the result. They allow you to review all those steps in detail, and correct them, if necessary, later.

2) Design Tools. There are a number of useful design tools/techniques used in engineering practice (and taught in senior project). For example, you'll apply QFD, Pugh Matrices, Weighted Decision Matrices, FMEA, DVP&R, and Risk Assessments. Using these processes and documenting the results in their summary tables are a good form of documentation that you have followed a rigorous process. However, because each of these have specific formats, they often leave out the background information that is critical to helping you reconstruct your thought processes. This is why you also need a logbook!

3) Formal Reports. Reports like SOW, PDR, CDR, and your final Senior Project Report provide archival documentation of your project status and results and should also provide firm justification of why you made your design decisions. To create these reports/presentations, you will need to go back through your In-Process documentation (Logbook) and design tools to recall your decisions, then arrange that information in a clear format, ready for review.

Unfortunately, many people only focus on the final type of documentation. They tend to have mediocre quality reports as a result.

The purpose of the design notebook is to document your design process. You can't begin to realize how important this information is until it is missing; and then it is too late! For any design project, the final drawings, models or prototypes are only a part of the value of the design. There is also value in the *process* used to generate the design. For example, if you contracted with somebody to design a new piece of inexpensive outdoor furniture and the final design calls for aluminum instead of plastic, you would want to know why. The answer might be that the price of plastic was too high or maybe the stiffness was too low. This is useful information and adds to the value of the design, because you will now be able to switch to plastic if an oil glut results in a decrease in the bulk price of plastics (not likely to happen soon!).

Parts of the design process that need to be documented include:

- Ideas, questions, and notes from group meetings.
- Notes on sponsor meetings and customer interviews.
- Customer needs/requirements.
- Preliminary sketches, doodles, outlines, half-baked ideas and plans for different aspects of the design. Make sure to annotate these to explain them.

- The analysis you performed. Do calculations directly in your logbook.
- A record of the setup and results from any tests that you conducted.
- Evaluation of data. If you used software, explanations of what it does.
- References and notes on relevant literature and research findings– particularly your conclusions concerning articles that you read or discussions with experts in the field.
- The choices you made at each step: what you chose, what you rejected, and why.
- Conversations with associates and vendors, pasted-in catalog or handbook pages, websites, etc.
- Personal thoughts and reflections concerning the project or process.

[Note that this last one is not normally included in an industrial setting, but it is important from an educational standpoint. One of the objectives of this class is for you to grow personally so that you understand your particular strengths and weaknesses in approaching a team-based design project. Keep in mind that your lab instructor will be reviewing your logbooks so only put notes and observations that you are willing to share.]

2.1.1 Logbook Details

Most engineers use a paper logbook so they can sketch freehand and not worry about bringing it into dirty/damp locations. Consult your lab instructor as s/he may modify the suggested guidelines or details that follow (e.g., in some cases a lab instructor may allow you to create/use an online logbook instead of a paper one).

Use an **unlined**, **bound** sketchbook of high quality large (at least 7.5” x 9.5” inch) paper with at least 80 pages. Examples of completed logbooks can be reviewed at the office of the course organizer. Here are some additional logbook specifications:

- Contact Info: Put your name, phone number, email, project name, group contact information, and other pertinent information on the inside cover or the first page. This is especially important should you misplace your logbook!
- Table of Contents: Leave three pages BLANK at the beginning, so you can fill them in as a table of contents later as you make entries.
- Time Log: Create a time log for your project work starting at the LAST page and moving forward. Each time you do any work on the project (and you should do this at least 5 times each week), you will record the date and amount of time you worked in your time log.
- Page Numbers / Dates: Number each page sequentially and date all entries.
- Chronological: Do not remove pages and do not skip pages. Do not backfill. If you realize you forgot to put something in, simply note that as you continue forward in the book by chronological entry. This process is critical, as it allows your logbook to potentially serve as legal documentation of your complete design process!
- Timing: You should be making entries in your logbook **at least 5 times each week!**
- Entries: Plan to use your logbook to include the following types of information:
    - Planning, communication and team activities (10-20% of entries)
    - Research, sketching and engineering analysis (65-75% of entries)
    - Personal notes and review of team and/or product performance (10-15% of entries)

Make sure all your entries are clear with context provided. In other words, don’t just cover a page with sketches – put a date and title on that page so later you know what you were trying to capture.

2.1.2 Logbook Assessment

Your logbook is NOT expected to be a polished, edited document (that is what the formal reports are for). But another engineer should be able to look at your logbook and tell what you did and why. Your logbook is like your project journal or diary. It is an integral part of your project and its use as such should be reflected in its pages. It should be MUCH more than a few scribbled notes and a repository for taped-in meeting agendas (in fact, leave out the meeting agendas). To know what to aim for in your logbook, pose these questions to yourself:

- If my logbook was the only thing used to grade my contributions to the project, how would I fare?
- Is everything I did either written down or referenced in the logbook?

Logbooks will be graded based on tracking of project management information, product development, organization, and personal reflection. Be sure to follow the logbook format specifications given above. In the past we have found a correlation between good notebooks, good designs, good end of the quarter projects and grades, and functioning hardware that meets the design specifications.

Two common problems we've noticed with students' logbooks:

- Many students think of the logbook as just notes written for the writer. It is not! The logbook is a dialogue about the project, written in a fashion that is understandable by a third party. Two key things to remember are:
  - Annotate, annotate, annotate.
  - Explain, explain, and explain.
- Often the context of a calculation or a sketch is missing. Why was the calculation or sketch done? What was concluded from it? Ask these questions upon making every entry:
  - *Is what I have written understandable by a third party not involved in the project?*
  - *Is the context clear (what the entry concerns, why it is even in the logbook)?*
  - *Is the reason I am making a calculation or sketch made clear in an annotation?*
  - *Is what I have concluded from the sketch or calculation stated clearly?*

2.2 Sponsor Introductory e-mail

As soon as your team is assigned a project, you need to write a letter of introduction to your sponsor. Before doing this, get together with your team and decide:

- Who will be the main point of contact with the sponsor? All future correspondence will go through this team member. You may wish to generate a team email address as well.
- How will you exchange information with the sponsor and store all your project files? Will you use Dropbox, OneDrive, GoogleDocs, or another method?

Then, compose an e-mail to your sponsor (with a copy to your faculty coach/advisor), identifying the team and clearly stating who will be the main point of contact. Your letter should include ALL of these:

- Team introductions (names, phone numbers, and e-mail addresses), including a bit of each member's background and why you each chose this project. You might want to include pictures.
- A single point of contact (the email should be sent from this person's email address)
- Restate in your own words the problem you believe the sponsor proposed
- Explain your planned initial steps (through SOW)
- Request a meeting or teleconference within a week
- Propose some alternatives for regular weekly meetings. Do not plan any sponsor meetings during your Tuesday labs. Check with your faculty coach to see if they are OK with you meeting during Thursday labs.

In the letter, include a restatement (in your own words) of the problem you believe the sponsor proposed. Also indicate that your initial goals are to study the project requirements and scope as well as perform necessary background research. State that you need to meet or have a teleconference <u>within a week</u> to discuss the detailed scope of the project and specific requirements. For local sponsors you should travel to the sponsor's site during this week to assess first-hand your sponsor's needs. You may also want to suggest a weekly meeting time (teleconference, Skype, Google hangout, etc.) with your sponsor.

Remember to correspond in a formal and professional manner when contacting your industry sponsor. Document all correspondence and always remember to copy your faculty coach/advisor. Do not send an email with only an attachment. If you do attach a formal letter, make sure you introduce and sign your email message. Think in terms of "friendly" letters. Dear Ms. Sponsor…. Thank you for the opportunity…. Sincerely, J. Student.

2.3 Team Contract

To help ensure your team agrees on the best way to operate, prepare a team contract (or set of bylaws) that defines your team's organizational structure and commits all members to agreed-upon operating procedures. This "contract" should emerge from substantive team discussions and from full member agreement. The team contract must be prepared as a formal agreement signed by all members and referenced regularly during team business.

Your team contract should address each of the following issues:

- Roles and Responsibilities - Define roles that will be assigned within the team and the responsibilities of the person in each role. State who is assigned the role and any plans for review or reassignment of roles to achieve team and member goals. Specifically address roles for managing (a) team progress and (b) budget, (c) conducting meetings, (d) documenting team information, and (e) communicating with project stakeholders. Also address issues of back-up for members needing help or encountering unexpected challenges.
- Team Relationships - Define relationships that are expected among team members and the methods employed to establish and maintain these supportive relationships. Specifically address your establishment of an inclusive and supportive climate, gaining strong member commitments to success of all members, and ways in which conflicts will be managed constructively.
- Joint Achievements - Define what is expected and methods the team will use to achieve high quality work done together (i.e., when members are working together on the same outcome). Specifically address establishing shared goals, planning and monitoring progress toward team goals, and conducting effective team meetings.
- Member Contributions - Define what is expected from team members when conducting work individually. Define how individual work assignments will be made, by whom, and with what definition of expectations. Explain how work quality and timeliness will be monitored and enforced (be specific). As appropriate, describe a process by which the team will allocate credit and/or project assets based on member contributions. Also describe how members will be supported in their efforts to develop skills and abilities needed for the project.
- Information Management - Define what is expected from team members regarding the recording and sharing of team information (e.g., ideas, drawings, meeting minutes, work status, problems, and coach/advisor/sponsor communication). Specifically address the ways and frequency of keeping members and outside stakeholders informed. Also define how project information will be recorded and made available to members, but also guarded to protect confidentiality and support patentability.

If you search online for “Team Contract,” you’ll find lots of good examples of how to write yours. When your contract is complete and signed by all members, scan it to a pdf document and save it.

2.4 Quality Function Deployment House of Quality

Quality Function Deployment (QFD) is a process for determining the appropriate specifications for a new design, based on market and customer needs. Done properly, it can be a lengthy process involving customer interviews, benchmarking tests, and supporting analysis. In this course, you will follow an abbreviated form of the QFD process to develop a House of Quality chart that explains how you arrived at your target design specifications. See the Quality Function Deployment section for more details.

2.5 Senior Project Reports – Overview

During senior project, your team will prepare and submit four major reports:

1. Scope of Work (SOW)
2. Preliminary Design Review (PDR) Report
3. Critical Design Review (CDR) Report
4. Final Design Review (FDR) Report

Each of your reports will reference the contents of the previous report(s), so you don't have to keep repeating the same information. When preparing each report, read its Success Guide description carefully and be sure to include all the required contents. DO NOT REMOVE any content from a previous report, unless instructed to do so.

As you prepare your reports, focus on these three principles:

- Completeness – Include everything required with sufficient detail
- Clarity – Make sure it is easy for the reader to understand everything you include
- Brevity – Keep the document as short as possible. Use tables, figures, and lists whenever you can.

In addition, follow these guidelines:

- Write professionally: Use professional language, include high quality figures, and proofread!
- Think about your audience (sponsor, coach/advisor, others who know nothing about the project).
- Use numbered sections and subsections (4.3, 5.9.3 …) like in this Success Guide.
- Include short introductory paragraphs at the start of each section.
- Have other students critically review your report before you send it to your sponsor.

The following two subsections list common grammar, spelling, and formatting errors found in students' technical reports.

Important! Check your report against these lists before submitting to ensure high quality!

2.5.1 Common Grammar/Spelling Errors

1. Run-on sentences and improper use of the word "however:"
    - ***Incorrect***: The testing process was detailed, however we recommend further analysis.
    - ***Correct***: The testing process was detailed; however, we recommend further analysis.

    A semicolon is necessary when "however" is used in this way.
2. Improper or inadequate use of commas:
    - ***Incorrect***: We placed the sample in the water and we measured the displacement.
    - ***Correct***: We placed the sample in the water, and we measured the displacement.

    Because there are two complete clauses, each containing a subject and verb, the clauses must be separated by a comma. These could also be separate sentences.
    - ***Incorrect***: In the wild, a panda eats, shoots, and leaves.
    - ***Correct***: In the wild, a panda eats shoots and leaves.

    In this case, too many commas are used. The meaning of the sentence is changed by them.
3. Improper capitalization. Here are two examples:
    - ***Incorrect***: The Higher Heating Value is determined using Equation 5.4.
    - ***Correct***: The higher heating value is determined using Equation 5.4.

The term “higher heating value” is not a proper noun and should not be capitalized.

- ***Incorrect***: As shown in figure 1, the function shows a linear dependence with time.
- ***Correct***: As shown in Figure 1, the function shows a linear dependence with time.

“Figure 1” is the name of a figure and should be treated as a proper noun.

4. Incorrect use of “there,” “their,” or “they’re:”
    - ***Incorrect***: Each of the students in the group submitted there data.
    - ***Correct***: Each of the students in the group submitted their data.

   The word “their” only applies to the possessive form (needed in this case). Also remember that “they’re” is a contraction of “they are.”

5. Incorrect use of “its” and “it’s:”
    - ***Incorrect***: We put the item on the scale and measured it’s mass.
    - ***Correct***: We put the item on the scale and measured its mass.

   The word “its” is a possessive article. The word “it’s” is a contraction of “it is.”

6. Incorrect use of “which” and “that:”
    - ***Incorrect***: I do not like grammar which is incorrect.
    - ***Correct***: I do not like grammar that is incorrect.

   “That” is used to provide <u>essential</u> clarification to a sentence. If we left out “that is incorrect,” the sentence would have a different meaning.
    - ***Incorrect***: He does not like grammar that is incorrect that is fine by me.
    - ***Correct***: He does not like grammar that is incorrect, which is fine by me.

   “Which” is used to add a related, but <u>not essential</u>, phrase to a sentence. “Which” is always separated by a comma from the rest of the sentence.

7. Mixed or incorrect verb tenses:
    - ***Incorrect***: First, we measured the temperature, then we record the time.
    - ***Correct 1***: First, we measured the temperature, then we recorded the time.
    - ***Correct 2***: First, we measure the temperature, then we record the time.

   Be careful with your use of verb tenses. In general, don’t mix past and present tense in a single report section. If the section refers to things you did in the past, then write it in past tense. If it refers to current activities, then present tense is appropriate.

8. Incorrect spelling:
    - ***Incorrect***: Chosing the best work for a sentence is hard wok.
    - ***Correct***: Choosing the best word for a sentence is hard work.

   Misspelled words really make a report look unprofessional! Don’t just rely on a spell-checker. Software just checks to see if a word exists in a common language dictionary; it does not know whether that word is the one you intended to use.

2.5.2 Common Formatting Errors

1. Missing citations:
    - Whenever you include a figure, data, or text that your team did not create, you need to credit the source. This is important because it shows respect for your sources and highlights your diligent research.
    - Citations need to show up near the cited information. For figures, citations should always be in the figure caption.

2. Improper or incomplete formatting of References:
    - Use the IEEE style at the Purdue Online Writing Lab (OWL) for all your citations.
    - For IEEE, references should be numbered in the order you cite them in the text.
    - Do not include URLs in references unless they are online-only, and then use the shortest URL possible (remove extra info at end of URL).
    - For conference or journal articles, include the conference or journal title and date.
    - Generally, each reference should include Author, Title, Publication Source, and Date Published (or, Date Accessed, for online-only)
    - The reader should easily find the reference based on the information given (not just URL).
3. Improper placement of figure and table captions:
    - Table captions are placed above the table.
    - Figure captions are placed below the figure.
    - Captions should appear on the same page as the object it describes.
4. Figures, tables, references, or appendices not mentioned in the text before shown. For example:
    - ***Incorrect***: The results are shown in the table below.
    - ***Correct***: The results are shown in Table 5.

    Every figure, table, reference, or appendix should be specifically referenced in the text that it supports, before you show it (so, you should not start a section with a figure).
5. Figures, tables, or appendices out of order:
    - Figures, tables, and appendices should all appear in the order they are mentioned in the text.
    - Example: Appendix A is the first appendix that you mention in the text.
6. Incorrect tables formatting:
    - Tables should be set up so that all rows fit on the same page. If there are too many rows to do this, then the table should be split into separate tables.
    - Table column widths should be set to minimize the table length.
7. Hanging titles:
    - Section titles should be immediately followed by regular text.
    - Do not put a title at the bottom of a page.
    - Do not put a subsection heading directly below a section heading. Instead, include at least a sentence overview of the full section before entering a subsection.
8. Unnecessary blank space in the text:

    Most document editors will prevent figures from wrapping over a page break. However, this may result in excessive blank space at the bottom of a page. After you are done with your text edits, move your text and figures around to make sure that there are no large blank spaces. Exception: If you start each new section on a new page, you can leave space on the prior page.
9. Incorrect page numbering:
    - Don't put a page number on your cover page.
    - Pages numbers for Abstract, Table of Contents, List of Figures, and List of Tables should be lower case Roman numerals (i, ii, iii...).
    - Page 1 should be on the first page of the Introduction.

      (Use section breaks in Microsoft Word to create separate regions for page numbering.)

2.6 Scope of Work (SOW) (1st quarter)

The Scope of Work (SOW) is one of the most important documents that an engineer prepares – whether you work in government, industry or academia; and whether you are a designer, researcher, or production engineer. The SOW will also be the start of your formal documentation for your project. The information in your SOW supports your later deliverables: ***Preliminary Design Review (PDR)***, ***Critical Design Review (CDR)***, and ***Final Design Review (FDR***).

The purpose of your senior project SOW is to confirm this information with your sponsor:

- Problem definition, including engineering specifications.
- Scope and deliverables for the project
- Project timeline and next steps
- Summary and synthesis of background research conducted.

The goal of your senior project reports is to efficiently convey the key information and supporting data in a concise and relevant way. For the SOW, please follow the outline below to ensure you include all key information:

- Title Page including Name of Project, team members, submission date and logo.
- Four Panel Chart – *Chart summarizing the current project status.*
- Overview – *Text introducing the customer, problem, and team; explaining the purpose of this report; and describing what's included in each of the sections.*
- Customer Needs – *Table linking Customer Needs & Engineering Specifications.*
- Engineering Specifications – *Table explaining Engineering Specifications.*
- Researched Topics – *Table categorizing & summarizing existing solutions and existing technology.*
- Annotated Bibliography – *Reference list and summary of relevant background research sources.*
- Appendices:
  - A: QFD House of Quality
  - B: Functional Decomposition
Boundary Diagram
  - C: Gantt Chart
  - D: Preliminary analyses and/or benchmarking test results (*optional*)

Here is more information on each part of the SOW:

- The Four Panel Chart provides a quick summary of key aspects of your project status in an easy-to-read format for your sponsor. Follow the template and example to capture what's important without over-filling the panels. See Figure 2.

Project Name

Project Overview	**Key Specifications**
• *Problem statement, sponsor, and other key stakeholders such as end users, operators, manufacturing personnel, etc…..* • *Add a relevant figure illustrating the problem/need.*	*Table of the most important (top 5-10) engineering specifications.*
Scope and Deliverables	**What's Next**
Clearly state what you will deliver to the sponsor at the end of the project: • *Full design details, final prototype, test results, analysis, report* • *Will you test for all specs?*	*List/explain key next steps to the next deliverable (PDR) and nature of that deliverable.*

Figure 5: Four-Panel Chart for Scope of Work

- The Overview is the main text-based part of the SOW. Include the problem statement again, along with paragraphs on:
  - the stakeholders and the team
  - the goal(s) of this report and what you need back from the sponsor
  - a description of what's included in each of the following sections, including the appendices.
- The Customer Needs table demonstrates the traceability of your engineering specifications (determined in your QFD) by listing your customer needs and identifying which engineering specifications support each need. The justification column of the table contains short statements and in-text citations of relevant references. This shows that your engineering specifications are meaningful, and the target values (in the following table) are realistic relative to the current state of the technology; thus, it establishes the feasibility of your engineering specs. Include a paragraph that introduces the table including a reference to the QFD in the Appendix and how the tool was used to develop the engineering specifications from the stakeholders' needs/wants.

Table 1: Customer Needs

Customer Need/Want (Stakeholder)	Engineering Spec: Number and Description	Justification
e.g. Inexpensive (Sponsor)	*Spec1: Max Cost*	*Sponsor has a budget of $1000*
e.g. Powerful (user)	*Spec 2: Min HP* *Spec 3: Min Torque at 30 mph*	*Research comparable systems [1][2][3]*

- The Engineering Specifications table will have a numbered row for each engineering specification you identified in your QFD. This table ensures your engineering specs are unambiguous and identifies your planned verification methods. It also captures the perceived difficulty in meeting the specified target value and tolerance. Introduce the table with a short paragraph that explains how you arrived at the specifications and how they quantify the project scope with reference to Appendix B: Functional Decomposition.

Table 2: Engineering Specifications

Spec. #	Specification Title	Specification Description	Target (units)	Tolerance	Risk*	Compliance**
1	*Total System Weight*	*Describe the specification and how you will assess it.*	*5000 lb*	*Max.*	*H*	*A, I*
2	*Total System Length*		*10 in*	*±0.005*	*L*	*A, I*
3	*Production Cost*		*$450*	*Max*	*M*	*A*
4	*Max Power Capability*		*10 hp*	*Min*	*L*	*T*

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
** Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

- The Researched Topics table provides a synthesis of what you learned from existing products, patents, and methods you researched. It is NOT a list of solutions. Rather, you will identify 3-5 solution types based on your research, and describe how those solution types work, what they do well, and in what ways they can be improved. Introduce the table with a short paragraph about what categories were researched and why.

Table 3: Existing Solutions

Research Category	Summary	Evidence
e.g. Rotary Motors	*Research into multiple examples of rotary motors used in ……*	*Product Examples [7][8]*
e.g. Carbon Fiber Sheet Manufacturing	*State of art tools.*	*American Composites Manufacturing Association*

- The Annotated Bibliography is a numbered list of the published sources of information you reviewed as part of your research. Each source should be given using IEEE reference format, followed by 2-3 sentences about what you learned from the source. Each senior project report needs to include at least 20 different published sources, including at least 5 engineering journal articles and at least 5 patents. Here is an example format:

  [1] Authors, "Article Title," in *Journal Title*, volume. Publisher name, location, year (use IEEE reference style).
  Brief (3 sentence) description of the document, why it's relevant, and what you learned from it.

- For each appendix, include a cover page that explains the contents of that appendix.

2.7 Ideation Models & Concept Prototypes

Ideation Models (a.k.a. Concept Models) are simple and quick (<20 min each) physical models of key aspects of your design alternatives. The goals of Ideation Models are to help you:

- Visualize and share ideas
- Perform (very) preliminary tests/evaluations on your ideas
- Develop new ideas.

Ideation Models allow you to spend little time checking out alternatives to see if they are viable. While exploring your design alternatives, take some time to build simple models of some of your concepts. These can be as simple as foam-core builds or Lego assemblies but should allow you to perform simple tests to determine whether or not your concept could meet your design goals. You will share your Ideation Models and explain what you learned from them in an informal presentation in lab. Figure 6 shows examples of Ideation Models.

Figure 6: Ideation Model Examples

A Concept Prototype is a more realistic representation of some important aspect of your chosen design. It should be at least partially functional so you can discover more about that function. Your Concept Prototype should:

a) Illustrate the full system concept you have chosen (to better explain it to your sponsor), OR
b) Allow you to perform simple tests/evaluations of the highest-risk function(s) of your chosen concept (to verify it will work), OR
c) Illustrate alternative concepts (to share with stakeholders to help you make a final decision).

The Concept Prototype should be higher quality than an Ideation Model, but it should still not take more than a day or two to build. Try to use easily modified materials - wood, plastic pipe, bolts, hinges, bike parts, etc. The Concept Prototype is also an effective way to get more shop hours so you can earn your Yellow Tag! You'll present your Concept Prototype as part of your PDR presentation. shows some examples of Concept Prototypes. Figure 7 shows examples of Concept Prototypes.

Figure 7: Concept Prototype Examples

2.8 Senior Project Presentations – Overview

During senior project, you will prepare and deliver two formal presentations, in lab and to your sponsor:

1. Preliminary Design Review (PDR) Presentation (section 0)
2. Critical Design Review (CDR) Presentation (section 2.18.2)

In addition, you will present one informal presentation (Interim Design Review) and one poster presentation (Project Expo). As you prepare for these presentations, remember what you learned in your Communications courses. As a refresher, check out http://www.garrreynolds.com/preso-tips/design/. Here are general guidelines:

- Preparing your Presentation: Visual Aids (slides)
    - Plan on 2-3 minutes per content slide (not including title slides or closing)
    - Every visual should have a purpose. What should your audience take away from each slide?
    - Keep it visual. Base it on your key figures, but:
        - Figures should be informative, not just decorative.
        - Figures should have legible captions and labels to improve understanding
        - Figures should be in high resolution, so they are clear when projected onto a screen.
    - Include tables when needed to provide more information, but:
        - Summarize tables to minimize the text. You don't need every bit of data!
        - All table text should be large enough to easily read.
        - Highlight table columns or rows when you discuss them.
    - Keep text on slides simple and clear:
        - No more than 5 bullets per slide.
        - No more than 5-7 words per bullet.
        - Text is large enough to read from the back of the room (nothing smaller than 18 pt.).
    - Pay attention to the visual details. For example,
        - Lines are aligned
        - Colors are consistent
        - Text is centered
    - Be careful with your choice of background:
        - Ensure that there is sufficient contrast between foreground and background.
        - Use care with dark backgrounds. Test with regular room lighting.
        - Avoid distracting background images. Simple backgrounds are best.
    - Limit dynamic transitions or animations.
    - Test presentation in the room with its projector to verify that all information is legible.
- Practicing your Presentation
    - Practice stage management. Who will be presenting what, and when?
    - Plan good transitions. Introduce the next speaker and what they will be covering.
    - Decide what you will say. Write it down (at least an outline) so you don't forget anything. Then practice saying it.
    - The more practice you do, the better your presentation will be.
- During your Presentation
    - Clothing should be appropriate for a business setting (A good description of business casual is at https://www.thebalance.com/business-casual-dress-code-1919379).
    - Don't wear flip-flops, hats, or sunglasses.
    - Explain the purpose of the presentation and who will be presenting each topic.
    - Don't look at your slides. Use them only to provide a visual aid for your audience.
    - Don't read from your slides.

    - Avoid interrupting or contradicting each other.
- Ending your Presentation
    - Conclude your presentation with a request for questions and comments.
    - Do not put a big question mark on the last slide. They know they can ask a question! Instead,
        - Use a picture of your chosen design
        - List concerns or questions for your sponsor
        - Include a timeline of the next steps.
    - Plan who will answer each type of question. For example:
        - One person handles technical questions
        - One person handles manufacturing questions
        - One person handles part sourcing/budget questions
    - End strong – restate the presentation's goals and ask for agreement/approval.

2.9 Preliminary Design Review (PDR)

The purpose of the Preliminary Design Review is to outline your solution concept for your sponsor. It should clearly describe what you are planning for your solution and justify why the sponsor should support your concept (i.e. with funding). To do this, your PDR must document your process, explain your selected design direction, and justify your choice. The PDR consists of three components: A written report, an oral presentation (with visual aids), and a Concept Prototype (see section 2.7).

2.9.1 PDR Report

Remember that the goal of your senior project reports is to efficiently convey the key information and supporting data in a concise and relevant way. For the Preliminary Design Review (PDR) report, please follow the outline below to ensure you include all key information:

- Four Panel Chart – *Chart summarizing the current project status.*
- Overview – *Text introducing the concept; explaining the purpose of this report; and describing what's included in each of the sections.*
- Concept description and justification – *Description of your chosen concept with justification*
- Alternative Solutions Table – *Table summarizing the key concepts you considered*
- Appendices: Include the following appendices at a minimum. Include other appendices as needed for your specific project. Feel free to reference any information in the appendices in your concept description and justification section.
  - A: Preliminary analysis – *Description of any preliminary testing and/or analysis you have done for your chosen solution*
  - B: Idea list (Include all ideas generated. Ideas can be displayed as short descriptions, sketches, images, etc.)
  - C: Weighted design matrix
  - D: Up to date Gantt chart
  - E: References

Here is more information on each part of the PDR:
- The Four Panel Chart provides a quick summary of key aspects of your project status in an easy-to-read format for your sponsor. Follow the template and example to capture what's important without over-filling the panels. See Figure 8. This table will take up about a page

Project Name

Project Overview	**Concept description**
Problem statement, sponsor, and other key stakeholders. This will likely be similar to SOW	*Concise description and appropriate image(s) to describe concept*
Concept justification	**What's Next**
Concise justification of concept. Can reference ideation methods, engineering specifications, etc. as appropriate to justify your process and concept.	*List/explain key next steps and upcoming deliverables.*

Figure 8. Four-Panel Chart for Preliminary Design Review

- In the Overview, include paragraphs on:
  - Describe the status of where you on in the design process
  - the goal(s) of this report and what you need back from the sponsor
  - a description of what's included in each of the following sections, including the appendices.

- The Concept description and justification is the main text-based part of the PDR. It should clearly describe and justify the concept you have decided on. It should use written descriptions, sketches, pictures of concept models or prototypes, references to literature and engineering specifications, etc. as needed. Limit this section to no more than 1200 words (not including captions and tables). Justification should show evidence of a structured design process and technical feasibility of chosen concept.

- The Alternative Solutions table (example below) should clearly summarize the top concepts you considered.

  Example Table : Alternative Solutions considered

Solution Name	Description (Can include written description, sketches, pictures of concept models, etc.)	Justification (Can include, for example, pros and cons of concept)

- For each appendix, include a cover page that explains the contents of that appendix.

2.9.2 PDR Presentation

Since the PDR report provides all the details of your project work and selected design direction, the PDR presentation only needs to hit the highlights. As with any professional presentation, you should prepare a concise, clear story about your design, with hidden back-up slides to answer questions if they arise. Plan (and practice!) your presentation to ensure you can present it in 15 minutes or less.

Your presentation should cover the following points:

- Introduction: Brief review of your project's scope & goals (for a general audience).
- Alternatives: Brief descriptions of the other (~5) top alternative design concepts you considered.
- Design Direction: A more in-depth description, explanation, and justification of your chosen design direction. Share your Concept Prototype. (This topic is the focus of this presentation!)
- Potential Issues: Brief discussion of the issues you anticipate with this design direction.
- Next Steps: Brief timeline of your planned activities to prove-out your design by CDR.

Before delivering your presentation to your sponsor, you will first deliver it to your lab group. This will be graded and will also serve as a final "dress rehearsal" for your sponsor presentation. After your (15 minute!) presentation, you will get feedback from your coach/advisor and peers so you can improve your delivery with your sponsor. Be prepared to take copious notes about their feedback in your logbooks!

As you prepare your PDR Presentation, review section 2.8 (Senior Project Presentations – Overview).

2.10 Failure Modes & Effects Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a process for reviewing your design and finding how to improve it. You focus initially on ways in which the design might fail to perform its functions (failure modes). Then, you consider how these failures might affect the customer (including safety risks). Then, what might cause those failures to occur? The process allows you to focus on the most critical potential issues, so that your development efforts can be as efficient as possible. The FMEA can also allow you to focus your analysis efforts while developing your detailed design. Your faculty coach/advisor will provide more information on developing an FMEA.

2.11 Interim Design Review (IDR)

The goal of the Interim Design Review (IDR) is to get feedback from your peers in lab about your design and its implementation plans, to help you identify and overcome any issues. Unlike the PDR & CDR, the IDR is an informal status presentation in lab. You do not need to present your IDR to your sponsor (though you may want to include parts of it in your next sponsor meeting). There is no written report associated with the IDR.

In the IDR, you will present the current status of your design, along with supporting information. You are expected to have made all the major decisions about your design that were left open from the PDR, but most likely you won't have had time to select every component. IDR is a checkpoint to ensure your key design decisions are nearly complete, and to get feedback from your peers about potential issues before you invest a lot of efforts in documenting the details.

For most teams, the IDR will be best presented just by showing your current CAD model(s) and pointing out the design details you have decided upon. With these as your visual aids, discuss:

- Function and operation of your design (briefly!)
- Status of your major subsystems (discuss each subsystem separately):
    - Form, material, function
    - Changes since PDR
    - Anticipated manufacturing process
    - Analyses/tests completed
    - Remaining analyses/tests to do by CDR
- Plans for Feasibility/Structural Prototype
- Current concerns – what might not work out or might take too long?
- Seek feedback – what suggestions do you peers have?

Take careful notes about potential issues identified during the review.

As you prepare your IDR Presentation, review Senior Project Presentations – Overview (section 2.8).

NOTE: Because the focus of the IDR is on your design status, there may be confidentiality concerns if your sponsor is very restrictive. Please check with your coach/advisor and sponsor ahead of time to determine whether or not it is appropriate for you to present your IDR to the full class or just your coach.

2.12 Feasibility/Structural Prototype

Like the Concept Prototype, the Feasibility/Structural Prototype is an early prototype phase. In the auto industry, structural prototypes include the underlying structure of a new vehicle, coupled with rough prototypes of trim components. They are used to evaluate crash safety and vehicle dynamics, early enough in the design process that changes can be made to these critical systems without delaying production.

Your Feasibility/Structural Prototype should help you gain confidence about whatever is currently the most challenging part of your project. This prototype should help you decide if you can overcome that challenge or if you should redesign. For some teams, this means building the final version of the most complicated part, to make sure it can be built. For others, it is building a rough model of a full system to make sure it can (roughly) function as intended. Still other teams will focus on a prototype to get early customer feedback to continue evolving the design aesthetics and functions. YOU need to decide what is the right thing to build for this deliverable.

In senior project, the Feasibility/Structural Prototype could be either:

a) A rough version of your overall system, so you can see that everything fits together and will function as intended.
b) A semi-functional version of all or part of your design that you can get into users' hands to get early feedback before committing to your design details.
c) A final version of one or more key components, so you can start performing critical tests early and/or confirm your manufacturing plan for those parts.

As with all prototypes, a key step is PLANNING what you want to learn from it. Don't just build to build … have a plan so that what you build will deliver what you need to know.

It's up to your team, in consultation with your coach/advisor and sponsor, to decide what is most important for you to include in this prototype. Your Feasibility/Structural Prototype, and associated test results, should be shared in your Critical Design Review (CDR) report and presentation.

2.13 Indented Bill of Materials (iBOM)

Ever since your first CAD class, you have heard the term Bill of Materials (BOM). So, why do we have a specific deliverable for one? Well, it turns out that the BOM provided by most CAD packages is not nearly as useful as the software makers would like you to believe!

A good BOM is far more than just a list of parts in your final assembly. It should:

- Show a logical arrangement of all component parts into sub-assemblies and assemblies, giving an overview of how your part will be assembled.
- Assign assembly and part numbers using a logical system
- Identify the source for all purchased parts.
- Identify which parts are custom manufactured or modified.

In senior project, you will create an indented Bill of Materials (iBOM, see Figure 9). The key steps are:

1) List all the component parts in your design.
2) For Purchased (unmodified) components, record the source, item number, and price.
3) For Modified or Built (custom) components, list the manufacturing process to be used.
4) Develop a logical plan for how you will assemble your design, including subassemblies.
5) Create a part numbering system that reflects your assembly process.

Assembly Level	Part Number	Description					Qty	Cost	Ttl Cost	Source	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*					
0	100000	Final Assy								------	
1	110000		Top Assembly							------	
2	111000			Cartridge Top			1			custom	mold in ABS
2	111100			Latch Hook			1	0.59	0.59	McMaster	item 45792A
2	111200			Reel Lock			2	3.00	6.00	McMaster	item 98711
2	111300			Write Protect Slide			1	10.00	10.00	3M	item 23-4509
2	111400			Door Assy						------	
3	111410				Door		1			custom	vac-formed PET
3	111420				Door Lock		1	2.15	2.15	McMaster	item 98725
3	111430				Door Lock Spring		1	0.30	0.30	McMaster	item 48005
2	111500			Door Spring			1	0.35	0.35	McMaster	item 48123
2	111600			Hub Spring Assembly						------	
3	111610				Hub Spring		1	0.35	0.35	McMaster	item 48250
3	111620				Ball Retainer Assembly					------	
4	111621					Ball Retainer	1			custom	mold in ABS
4	111622					Ball	1	0.50	0.50	Bearing Inc.	item 27-100
2	111700			Hub Assembly						------	
3	111710				Hub		1			custom	machined aluminum
3	111720				Wear Pad		1	2.50	2.50	Bendix	item US259874
1	120000		Cartridge Bottom				1			custom	mold in ABS
1	130000		Screws				4	0.18	0.72	Home Depot	#3-1/2-in
	Total Parts						19				

Figure 8: Sample Indented Bill of Materials (iBOM)

Please remember that the iBOM should ONLY list those final COMPONENTS and SUBASSEMBLIES that will be in your final design. Your iBOM should NOT include:

- Testing Materials: Any components or materials that will be consumed during testing but do not appear in the final assembly. These are important project costs, and should be included in your Project Budget, but since they are not in the final design, they should not be in the iBOM.
- Raw Materials. The raw materials used to manufacture your components are important, but they are not components in your final design, so should not be listed as line items in your iBOM. Feel free to list the material in the More Info column for each components, but put the full purchasing details for that raw material in your Project Budget.
- Manufacturing Costs. Since your labor cost required to work or rework components is unknown, do NOT list a cost for components that require you to modify raw materials. In industry, you would work with a Cost Estimator to develop an accurate estimate of the total cost (material + labor + tooling). However, without that estimate any cost you list would just be wrong/incomplete. Leave the costs blank here for any parts you will manufacture or modify (but put the raw material cost into your Project Budget!).

2.14 Drawing & Specifications Package

Your Drawing & Specifications Package is arguably the most important part of your Critical Design Review. This is because it is here that you fully document *WHAT* your design is. Most mechanical engineers do not manufacture or assemble the systems they design, so they use part drawings, assembly drawings, iBOMs, and purchased parts specifications to document their design details. Your Drawing & Specifications Package needs to include **all** the information required for someone to manufacture custom parts, obtain purchased components, and assemble your design.

Specifically, your Drawing and Specifications Package will include:

- Indented Bill of Materials (iBOM, as described in Section 2.13): Your iBOM effectively serves as the 'table of contents' for your assembly and part drawings. Your main assembly, each subassembly, and all manufactured parts should each have a drawing included. Purchased parts do not need a drawing, but should all be listed in a Purchased Parts Table.
- Purchased Parts Table: A table listing all purchased parts in your design, with enough details to select a replacement part if your selection is no longer available. See example in Table 2.
- Assembly Drawings: Label all parts and sub-assemblies
  - Assembly Exploded View (add "E" to drawing #): Label all parts and sub-assemblies.
- Part Drawings: Include a fully-dimensioned part layout drawing for EVERY custom part in your assembly, including parts you will manufacture and parts you will modify. For *modified* parts, you only need to clearly dimension the modifications (explain in a note).
- If applicable to your design:
  - Welding Drawings (add "W" to drawing #)
    - Be sure to include part drawings (or cut list, if appropriate) for each manufactured component in the weldment.
  - Cut List: If you are cutting a stock material into pieces of different lengths, you can describe all parts on a single Cut List drawing instead of separate part drawings.
  - Wiring Diagrams (or electrical schematics): Include if you have wiring or circuits in your design.

When assembled, the pages in your Drawing and Specification Package will look like this:

- iBOM
- Purchased Parts Table
- 1000 – Main Assembly drawing
- 1000E – Main Assembly exploded view
  - 1100 – first sub-assembly drawing
  - 1100E – first sub-assembly exploded view
    - 1101 – first part in first sub-assembly layout drawing
    - 1102 – second part in first sub-assembly layout drawing
  - 1200 – second sub-assembly drawing
  - 1200E – second sub-assembly exploded view
    - 1201 – first part in second sub-assembly layout drawing
    - 1202 – second part in second sub-assembly layout drawing

etc…

Table 4: Example Purchased Parts Table

Your Part #	Part Name	Vendor	Vendor's Part #	Price	Manuf.	Manuf. Part #	Key Features / Specs	Webpage
1302	Gear 16T	Amazon	B07ZX22F2G	16.99	MakerDolt	n/a	16 teeth, 32 pitch, face width ¼ in, bore 1/8 in, set screw, hardened steel	https://www.amazon.com/Hardened-Pinion-Compatible-Metric-Pitch/dp/B07ZX22F2G

Here are a few things to remember as you assembly your Drawing and Specifications Package:

- Drawings should appear in the same order as listed in your iBOM.
- The correct part number(s) should be clearly shown on EVERY drawing.
- Custom part drawings need a complete title block, including the material, the drawing author, and the drawing reviewer (list team member names!).

NOTE: If your parts will be produced directly from the CAD model (e.g., by additive manufacturing, CNC, laser-cut, or waterjet), then it is acceptable to use simplified dimensioning on the part drawings, along with a note explaining the full dimensions are in the CAD. Ask your faculty coach if you have parts like this so you can document them correctly.

2.15 Design Verification Plan (& Report) – DVP&R

A thorough design process requires that you verify your design meets the goals (specifications) you set for yourself. The DVP(&R) is a formal approach to planning and tracking the status of your design in meeting the specifications. There are two stages to the DVP&R process:

1. PLAN: The DVP table is used to document all the tests (not inspections!) that need to be completed with your prototypes to verify that your design meets its goals.
2. REPORT: As tests are completed, the rest of the DVP&R table documents the key results of each test. The DVP&R constitutes a formal statement that your design does (or does not) meet its goals. Wherever a design doesn't meet the goals, the DVP&R should include recommendations for design changes to improve performance.

Why should you prepare a DVP&R?

- Ensure you have a plan to test each of your specifications.
- Start thinking about tests early so you can arrange needed facilities, prototypes, and equipment.
- Documents test results so you do not repeat mistakes.
- Recommends changes based on test results.

What should be included in a DVP&R?

- Every specification (from your Spec Table) that you intend to verify by TEST.
- Additional tests you identified from your FMEA

For planning, how do you complete the DVP form?

1. Your instructor will provide you with a template.
2. Fill in <u>Spec #</u> and a brief <u>Test Description</u> for each specification that need to be tested.
3. Add any additional tests that came from your FMEA (technically, you should update your Specifications Table to add these also…)
4. Note any <u>Special Equipment</u> that will be required to complete each test.
5. Fill in the <u>Acceptance Criteria</u> (# of cycles, minimum load, etc...). This too comes from your Specifications Table.
6. Pick one team member as the <u>Responsible</u> person to organize each test
7. Identify the type of prototype needed in the <u>Test Stage</u>: Concept Prototype (CP), Feasibility/Structural Prototype (SP), or Final Prototype (FP). (Note: you may need to test multiple stages for the same Specification.)
8. List the <u>Quantity</u> of prototypes that need to be tested (for statistical purposes). In senior project, we're usually limited to one, but that's generally not the best approach for testing!
9. Specify the <u>Type</u> of prototype needed to perform the test: one component (C), one subsystem (Sub), or the full system (Sys).
10. Estimate a realistic <u>Start Date</u> for each test.

How do you complete the DVP&R when you complete a test?

1. Verify the test information on the DVP is correct, and update where necessary.
2. Add a <u>Finish Date</u> to indicate when the test was completed.
3. In the Test Result, state what was measured, along with the numerical values and qualitative assessments.
4. Indicate whether your test met the Acceptance Criteria in the <u>Pass/Fail</u> column.

5. Document any design change recommendations based on the test results in the Notes column (i.e., over performed then reduce stock size or failed so change material)

What is not included in the DVP&R?

- The DVP&R doesn't include the detailed procedures for setting up and performing each of these tests. You will write (and follow) these procedures later.
- The DVP&R doesn't include the data collection and notes taken during testing. You will need to keep these for each of your tests as a separate document.

2.16 Manufacturing Plan

No matter how great a design is, if it can't be produced in an efficient way, it won't amount to anything. So, a key part of your design work is to define <u>how</u> your design will be produced. A Manufacturing Plan should include three pieces:

1) A table summarizing the manufacturing needs for your full design, including:
   a) A list of all components in your design, broken down by subassembly (Note: this is similar in format to an iBOM). Your subassemblies should represent how you actually plan to assemble your design.
   b) For each component, state whether it will be *purchased*, *modified* (from purchased), or *built* from raw materials. (Note: Choose to purchase components whenever possible. Not only is this less work for your team, it will also lead to the highest quality final build!)
   c) For each component, identify where & how you plan to procure the materials.
   d) For each *modified* or *built* component, list key equipment & operations you anticipate using to manufacture the component (e.g., Manual Lathe to turn down diameter, drill press for each hole).
2) To supplement the summary table, for EACH of your *modified* or *built* components, create a numbered list describing the steps required to manufacture it (e.g. (1) Cut steel bar to approximate length per drawing, (2) Face off each end in lathe until exact length is achieved, (3) Use drill press to drill three 1/16" holes, …). If you wish, you could also put this list into a second, more detailed, table.
3) Following your description of manufacturing operations, prepare a description of the steps required to assemble your design: For your main assembly and <u>each</u> subassembly, create a numbered list describing the assembly steps.

The goal of your Manufacturing Plan, in conjunction with your assembly and part drawings, is to provide enough information so someone else could procure, manufacture, and assemble your design without you being present. Since most mechanical engineers do not directly manufacture and assemble the components they design, creating clear drawings and manufacturing plans is a crucial part of your design work!

Note: In industry, a Manufacturing Plan will focus on the industrial (often high-volume) production of your design. However, in senior project each team should prepare a Manufacturing Plan to describe the production of their final Verification Prototype (VP).

2.17 Project Budget

A key part of project management is managing your budget. Your team should have a budget spreadsheet to track all completed and planned purchases. You can download a sample budget sheet from the Template Resource folder on ME429 Canvas or make your own.

Include at least these columns in your Project Budget table:

- Item Description *(purchased part, raw material, or travel expense)*
- Vendor
- Vendor's part number
- Your part number(s) *(which of your components this material is used in)*
- Item Cost
- Shipping & Tax *(combine or separate columns; estimate initially, then update when known)*
- Total Cost *(including shipping & tax)*
- How Purchased *(sponsor, team reimbursement, or ME Pro-Card*).
- Account Used *(if you have different campus accounts to draw from)*
- Date Purchased *(fill in after purchase is made)*
- Location *(fill in after you receive the item)*

List each item on its own line and include donated/borrowed items as well. At the end of the item list, include three totals to help you easily keep track of your budget:

1) Your overall project budget (total amount allocated to your project)
2) Total amount spent to-date
3) Total amount planned to be spent

Please note that while a Project Budget and an iBOM are similar, they track different information:

- <u>An iBOM lists all components included in your final design</u>. It is most useful for tracking the number of components and how they fit together. However, it does NOT include any additional purchases and cannot be used to track purchased materials used for manufacturing components.
- <u>A Project Budget lists all planned and completed purchases for your project</u>, whether or not they result in parts that are in your final assembly. Your Project Budget allows you to keep track of ALL your project expenses, and includes these items that are excluded from an iBOM:
    - Materials that are used in earlier prototype stages.
    - Materials that are used for testing.
    - Travel expenses.
    - Raw material stock that is used to manufacture components in your final design.

2.18 Critical Design Review (CDR)

The CDR consists of three components: A written report, an oral presentation (with visual aids), and a Feasibility/Structural Prototype (section 2.12).

2.18.1 CDR Report

The purpose of the Critical Design Review is to give details of your solution for your sponsor. It should clearly describe what you are planning for your solution and justify why the sponsor should support your concept (i.e. with funding). The goal of your senior project reports is to efficiently convey the key information and supporting data in a concise and relevant way.

For the CDR, please follow the outline below to ensure you include all key information:

- Four Panel Chart summarizing the current project status.
- Overview
- Concept description
- Justification table
- Manufacturing Plan Table
- Design verification Table
- Budget
- Appendices: Include the following appendices at a minimum. Include other appendices as needed for your specific project. Feel free to reference any information in the appendices in your concept description and justification section.
    - References
    - Design Analysis
    - Up to date Gantt chart
    - FMEA
    - Design Hazard Checklist
    - Anything else you need to reference in the body of the report that is too long to include in the body of the report.
    - If appropriate, you should also include these in appendices:
        - Flowcharts and/or pseudocode (if your design includes programming).
        - Wiring diagrams (if your design includes wiring).

In addition to this report, you will be asked to submit your Drawing Package and give a presentation on your solution. The drawing package should include your iBOM at the start. Please see Canvas for more details about the drawing package requirements.

Here is more information on each part of the CDR:

- The Four Panel Chart provides a quick summary of key aspects of your project status in an easy-to-read format for your sponsor. Follow the template and example to capture what's important without over-filling the panels. See Figure 10. This table should take up about one page.

Project Name

Project Overview *Problem statement, team members, sponsor, and other key stakeholders. This will likely be similar to SOW and PDR*	**Design Description** *Concise description and appropriate image(s) to describe concept.* *Will likely be similar to, but with more detail, than PDR* *Include rough breakdown of costs*
Design Specifications *List key specifications and briefly explain how you determined that your design will meet each.*	**Manufacturing and Testing Plan** *Overview of your plans for manufacturing and testing*

Figure 10. Four-Panel Chart for Critical Design Review

- In the Overview, include a description of the status of where you on in the design process, the goal(s) of this report and what you need back from the sponsor, and a description of what's included in each of the following sections, including the appendices.

- The Concept description is the main text-based part of the CDR. It should clearly describe the solution you have decided on. Include a detailed description of your chosen concept with justification (explanation of why you believe it will work). This should include much more detail than the PDR. It should reference your CAD drawing package, specs tables, design analysis, preliminary testing data, etc. as needed. It should use written descriptions, sketches, pictures of concept models or prototypes, references to literature and engineering specifications, etc. as needed. Limit this section to no more than 2000 words (not including captions and tables). Include:
  - Complete description of your overall final design, including clearly labeled figures (3D isometric works well).
  - Explanation of the functionality of your design – what it does and how it does it.
  - Detailed descriptions of all major subsystems and components, with appropriate figures.

- Justification table should include a table that lists each specification and what justifies your assertion that the design will meet that specification.

- Manufacturing Plan Table should include details of your manufacturing plan. Please use the template available on Canvas.

- Design verification plan. Use Table 1 to outline how you will verify the function of your solution. Include at least one test in which you will collect numerical data and perform data analysis and uncertainty propagation calculations.

Table 1: Design Verification Plan

Planned Test	What it will test (user need or specific spec, whichever is most applicable for your project and sponsor)	Required resources

- Budget. Include your project budget.
- For each appendix, include a heading that explains the contents of that appendix.

2.18.2 CDR Presentation

The CDR report provides FULL details of your final design, so the CDR presentation only needs to hit the highlights! As with any professional presentation, you should plan a concise, clear story about your design, with hidden back-up slides to answer questions if they arise. Plan (and practice!) your presentation to ensure you can present it in 15 minutes or less.

Your presentation should cover the following points:

- Introduction: Briefly review your project's scope & goals (for a general audience).
- Design Description/Explanation: What does it look like? What does it do? How does it work? Show lots of pictures/animations, and your Feasibility/Structural Prototype.
- Design Justification: Summarize your analysis and testing to convince us that your design will meet each of your specifications. Focus on what you analyzed/tested and what you found.
- Manufacturing/Cost: Briefly summarize how you will procure or make each component of your design. Show a simplified iBOM and list cost by subsystem or major component.
- Testing: Briefly summarize your test plans (time, equipment, locations, etc.).
- Potential Issues: Briefly discuss any issues you anticipate with making/testing your design.
- Next Steps: Summarize major tasks and your dates through the end of the project.

Before delivering your presentation to your sponsor, you will first deliver it to your lab group. This will be graded but will also serve as a final "dress rehearsal" for your sponsor presentation. After your (15-minute!) presentation, you will get feedback from your coach/advisor and peers so you can improve your delivery with your sponsor. Be prepared to take copious notes about their feedback in your logbooks! If your sponsor requests that you make this presentation in person, please review the travel policies before making your plans.

As you prepare your CDR Presentation, review Senior Project Presentations – Overview (section 2.8).

2.19 Risk Assessment / Safety Review

Before testing your design or handing it off to a user, you should prepare a Risk Assessment. In this assessment, you will consider the operations that a user (or you, as the tester) will need to perform with your final design. For each operation, you'll identify all the risks present and then develop a plan for managing those risks. We'll provide you with software tools to guide you through this process.

After your coach/advisor reviews your risk assessment, you may be asked to meet with one of the campus technicians to discuss your risk management plan. If so, please bring the following to that meeting:

- Your risk assessment
- Your drawing package (especially, your assembly and exploded view drawings)
- Your wiring diagram (if you have any electrical risks)

During the discussion, take detailed notes of any suggestions from the technicians on how to improve the safety of your design, and come up with specific tasks after the meeting. Report the results of the meeting in a memo to your coach/advisor and the technicians.

2.20 Test Procedures

Before conducting any tests with your prototypes, especially if those tests are destructive (can't be repeated) or if there are any safety hazards, it's important to prepare a detailed Test Procedure.

You need a Test Procedure for each planned test. Each procedure should include:

- Goal(s) of the test
- Safety protocol, including identification of all hazards and needed Personal Protective Equipment (PPE)
- Location, facilities, and equipment needed to conduct the test.
- Step-by-step listing of how to set up, conduct, and end the test.
- Planned data collection & documentation.

See Appendix A. for a sample test procedure.

2.21 Status Reports

While moving from the second to the third quarters, you will prepare a status report consisting of an oral Manufacturing and Test Review presentation in lab and a Project Update Memo to your sponsor.

2.21.1 Manufacturing and Test Review

At the end of the second quarter your team will make a short presentation in lab to report the status of your manufacturing and the details of your test plans. The presentation should answer these questions:

- Have you ordered & received all materials to build your Verification Prototype? If not, do you have a good plan to finish ordering?
- What manufacturing have you completed (show samples)? What processes will you use to manufacture all remaining components?
- What is your plan (including timeline) for finishing manufacturing? Have you considered potential delays?
- Have you identified key facilities and equipment needs for all of your tests?
- Have you completed any testing? What is your plan (including timeline) for performing all remaining tests? Have you considered potential delays?

This presentation will be scheduled through your faculty coach/advisor, and all students in a lab section are expected to participate and provide feedback.

2.21.2 Project Update Memo

In addition to the in-class presentation, teams are expected to keep their sponsors up to date with their status. While much of this is done during your periodic meetings, at the beginning of your 3rd quarter, each team should prepare a brief (3-5 page) status memo that updates your sponsor on your project. Since this memo is written well into the build phase of your project, it will report primarily on your progress through the build phase and planned testing. You should have taken a number of photos of your progress in constructing the product or system that you have designed, so the report can be written as a narrative accompanying these pictures.

To write this report, review your CDR Report and then ask yourself: What has changed? What's been accomplished since then? The Project Update Memo should be a description of these changes and accomplishments, with accompanying photos. Also use this as an opportunity to update your Gantt chart and to highlight activities completed since CDR. Give your assessment of whether the project will be completed on time. If your budget has changed because of unforeseen components that you need to buy, you need to report this too.

2.22 ABET Activities

Senior Design Project fulfills many requirements necessary for the ME program's accreditation by ABET (Accreditation Board for Engineering and Technology). For the department to receive accreditation we must assess student learning and outcomes; therefore, we administer a ***Senior Exam*** during the third quarter. This exam is required for all ME students and your exam results contribute to your ME 430 course grade. Preparation for this exam is like preparation for the FE (Fundamentals of Engineering) licensing exam.

Also, to support accreditation, all senior project students must fill out a ***Senior Survey*** during ME 430. This is not graded, but completion of the survey is necessary to receive a grade for the course.

2.23 Verification Prototype (VP) Checkpoint

The Verification Prototype Checkpoint is when you will show your completed Verification Prototype and get approval to move forward with your testing plan. You will show your completed VP to your faculty coach/advisor and safety technicians to demonstrate that you implemented all reasonable precautions to protect yourselves and future users. In addition to your final assembled hardware, bring copies of these safety-related documents to the demonstration:

1. FMEA
2. Design Hazard Checklist
3. Risk Assessment
4. Design Verification Plan (DVP)

Be prepared to point to features in your prototype that show how you implemented changes in your design to address every recommended action you identified in your FMEA, Hazard Checklist, and Risk Assessment.

2.24 Design Verification Plan & Report (DVPR) Checkpoint

The DVPR Checkpoint is when you will show that you have completed testing your Verification prototype and documenting all of the results in your DVPR. At this time, you should also have a draft of the Design Verification chapter of your Final Design Review (FDR). The format of this review is up to your faculty coach/advisor, but it usually can be done as part of a regular weekly project meeting. They key point is that you should have completed all the planned testing of your Verification Prototype and collected/analyzed the results in a timely fashion.

2.25 User Manual

Your design is not complete until you have fully documented the correct method of operation and identified any known safety concerns. This will result in a user manual that is similar in format to those provided for many consumer products. Your user manual should be included as an appendix in your FDR report. It is also nice to print a copy and attach it to your Verification Prototype before you hand it over to your sponsor.

Your user manual should include at least:

- Discussion safety hazards and any required PPE (personal protective equipment) needed while using your design.
- Specific operational steps, especially when these are required to maintain user safety (refer back to your Risk Assessment to see what you said you'd include here).
- Many fully labeled pictures (either from your CAD or of your VP) to illustrate operations and highlight all safety hazards.
- Assembly and/or repair procedures, if users will be doing either of these.

2.26 Final Design Review (FDR)

The FDR milestone consists of three deliverables: A Verification Prototype, a written FDR Report, and a Project Expo Poster.

2.26.1 Verification Prototype

Part of the culminating experience for senior design project is the process of bringing your design to physical form so that you can evaluate how well your design achieves your project's goals. The verification prototype you produce is therefore an important part of your deliverable in your Final Design Review. This prototype will be reviewed for:

- How well it matches your design intent
- Quality of workmanship
- Whether it allowed you to test to your specifications.

2.26.2 FDR Report

The Final Design Report will be your last report given on your project. It will represent three quarters of your team's work and should communicate your final solution and how you have verified your prototype. It will be submitted to your sponsor, project coach, and will be posted to the Cal Poly library. The goal of your senior project reports is to efficiently convey the key information and supporting data in a concise and relevant way.

For the FDR, please follow the outline below to ensure you include all key information:

- Title Page
- Statement of Disclaimer
- Four Panel Chart which serves as an Executive Summary of the project.
- Overview *(Introduce the full project; explain this document's contents)*
- Concept description *(Concisely summarize your solution)*
- Implementation *(Describe all completed procurement, build, and assembly activities)*
- Design Verification *(Describe how you conducted your tests and the results your obtained (reference test procedures in appendix).*
- Conclusion and next steps
- Appendices: Include the following appendices at a minimum. Include other appendices as needed for your specific project. Feel free to reference any information in the appendices in your concept description and justification section.
    - References
    - Final budget
    - User manual
    - Risk assessment
    - Test results
    - Design analysis, code for any software used, etc. as necessary

We recommend you review past Senior Project reports on Digital Commons through the library website at http://digitalcommons.calpoly.edu/mesp/, though be aware that the format has changed.

Include the following statement of disclaimer at the beginning of your report:

Statement of Disclaimer Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Here is more information on each part of the FDR:

- The Four Panel Chart provides a quick summary of key aspects of your project. See Figure 11. This table should take up about one page.

Project Name

Project Overview	**Design Description**
Problem statement, team members, sponsor, and other key stakeholders.	*Concise description. List key specifications*
Design Image	**Design Verification**
Include a key image or two to represent your final prototype.	*Include key results/analysis for your design verification.*

Figure 11. Four-Panel Chart

- In the Overview, include a concise overview of your project, the goal(s) of this report, and a description of what's included in each of the following sections, including the appendices.

- In the Concept description, concisely describe the solution you have implemented. This section should use written descriptions, pictures of models or prototypes, references to literature and engineering specifications, etc. as needed. Focus your writing on the solution itself.

- The Implementation section should include information about the activities you completed for your verification prototype. This section should focus on your tasks and how you implemented them. Your description may include the full work of the project (including previous quarters), but should focus on your work from the final quarter. Include images of manufacturing as needed.

- The Design Verification section should explain how you met (or did not meet) your design specifications with evidence to support your claims. Your evidence should include test results, analysis, etc. Reference test procedures in the appendix as needed. Include a table to show whether your design met each of your specifications.

- The conclusion and next steps section should include 2-3 sentence summary of your project and then focus on future work for the project.

<Project Title>
Senior Project Report
Prepared for: <Sponsor name, Company/Organization>

By

<Student Name>
<Student Name>
<Student Name>
<Student Name>

Mechanical Engineering
California Polytechnic State University
San Luis Obispo

<Date>

Figure 9: Sample Title Page (you can modify this).

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Contents of this Report

This report fulfills the Senor Project requirement for the Mechanical Engineering Department. This document contains:

1. Scope of Work (SOW)
2. Preliminary Design Review (PDR) Report
3. Critical Design Review (CDR) Report
4. Final Design Review (FDR) Report
5. Project Expo Poster

Figure 10: Statement of Disclaimer and Contents (include exactly as written)

2.26.3 Project Expo Poster Presentation

The Project Expo is the culminating event of your Senior Design Project. Your team will present your senior design project in a poster session with accompanying hardware (Figure 14). If there is a compelling reason that hardware cannot be at the event, then photos and/or video should be displayed. Advisors, sponsors, other faculty, and guests will attend the Expo. We encourage you to invite your friends and family as well. (In our experience, parents of graduating students love to come see their child's *magnum opus*.) Your faculty coach/advisor will let you know the specific timing/details of the day, but you should expect these key activities:

1) Setup: All posters and hardware should be set up during a specific time window.
2) Safety Review: Teams who want to 'run' their systems during the Expo should be prepared to review their safety plan with the senior project coordinator and safety technician (see below).
3) Grading: We request all students to leave the Expo area during the grading time when a panel of ME faculty will grade the posters.
4) Public Expo: At least one team member should be present to explain your design throughout the Public Expo time (besides, it's fun!).
5) Cleanup: Everyone should return Expo poster stands and tables and pick up around the area. In addition, we recommend all teams hand off their hardware to their sponsors at the end of the Expo.

Figure 11: Scene from a successful Design Expo

Poster Design

All teams should create a 30x40-inch or 36x48-inch poster (check with your advisor to verify the size!). PowerPoint is an effective tool to create your poster. You can also use Adobe Illustrator or other graphic design tools. Review your poster with your Sponsor and Coach/Advisor prior to printing it, to be sure they approve of the content and layout.

At a minimum, your poster should include this information:

- Overview of your design challenge
- Description/illustration of your final design
- Your engineering analysis
- Your key test results
- Conclusions/Recommendations

Many teams also like to illustrate their design process or the evolution of their design.

Posters will be graded by a faculty panel using two main criteria:

1) **Organization / Visual Appeal**: The posters should be neat and professionally arranged so that they are easy to understand. There should be a logical progression through problem definition, conceptual design, and final design; with analysis, testing, and conclusions shown. Figures should be clearly labeled, and all text should be clearly legible from 5-8 feet away.

2) **Technical Content:** This is an engineering project, so your poster needs to highlight the engineering content. This includes analysis, decision techniques, prototype testing, and so on. Your poster should use the technical content to explain why your final design is the best solution. Final test results are essential.

A third category for your Expo grade will come from your Verification Prototype(s). Specifically, graders will assess the quality and completeness of the prototype.

<u>Poster Do's:</u>

- DO use large font sizes. It should be clearly readable from 5-8 feet away.
- DO include <u>lots</u> of pictures and minimal text (someone can ask you if they want more information)
- DO include titles for different sections of the poster to guide the reader
- DO organize your content so that it is easy to follow.

<u>Poster Don'ts:</u>

- DON'T use a dark background color. Some color is fine, but dark text on light backgrounds are much more readable, use less ink, and enable faster poster printing/drying.
- DON'T use any font sizes smaller than 24 points.
- DON'T use a lot of text (no full paragraphs!). Keep it brief; you can add verbal explanations during the expo.

Poster Printing/Mounting

Posters will be printed in the plotters in the ME labs. For best appearance, the ME department will load glossy photo paper into specific plotters on specific days leading up to Expo. Each team will sign up for a timeslot to print your poster. There are instructions near each plotter to help you print your poster. Please make sure you arrive early with your file ready to print!

After printing, your poster will need some time to dry, and then needs to be glued to a flat (NOT trifold) support board using spray adhesive. Your coach/advisor may provide you with the board, spray adhesive, and instructions during the last lab before the Expo. Your poster will need to be printed prior to this lab!

Note that foamboard is NOT recyclable. If your sponsor does not want your poster after the Expo, please give it to your coach/advisor.

Attire
The Project Expo is a formal Exposition, and project sponsors and other industry representatives will be traveling to see the event. Please dress appropriately and professionally (e.g. business casual).

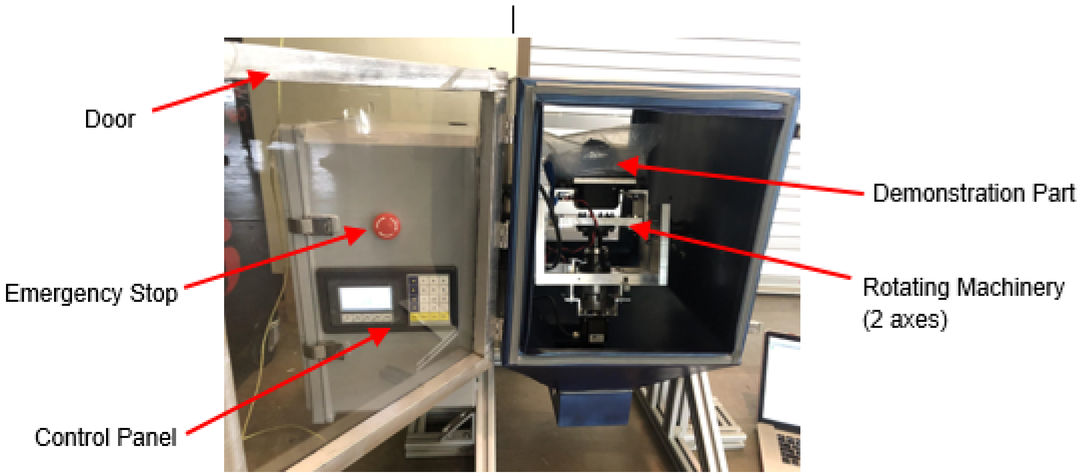
Expo Safety Review
If you would like to operate (run) anything on your Verification Prototype during the Expo, you will need to prepare these items and have printouts at your display for the Expo Safety Review:

- Expo Operation Safety Plan (see sample in Figure 15)
- Verification Prototype with proper safety labels & placards attached
- Risk Assessment

During the Expo Safety Review, the senior project coordinator and safety technician will review your display. If they approve of your safety plan and hardware, an “OK TO RUN” sticker will be added to your poster. If you do not receive one of these stickers, you MAY NOT run (operate/actuate/demo) your prototype during the Expo.

At the End of the Expo
In addition to being present to show off your work to Expo attendees, most teams should plan to hand off their Verification Prototype and Operator’s Manual to their sponsor at the conclusion of the Expo. If complete, we also encourage you to give them a flash drive with all of your CAD and software files and the full Senior Project Report at the same time (so you can be finished!).

Expo Safety Checklist PROJECT NAME HERE



Operation:

- Close Door
- Plug in device
- Run an automated vibration cycle from the Control Panel
- Jog axes from Control Panel

Prototype Response:

- The system will rotate and vibrate a clean printed part inside an enclosure

Safety Plan

Hazard	Protection	Failure	Action
Electrical shock	Ensure electronics enclosure remains closed and latched at all times	Electronics enclosure is opened or wires are exposed	Unplug system immediately
Rotating machinery, pinch points	Ensure enclosure door is closed while in operation	Operator or spectator is caught in rotating machinery	Stop cycle from Control Panel or Emergency Stop
Suspended weight	Ensure enclosure door is closed while in operation	System loses power or primary motor slips, causing weight to freely swing down	Step back, stop cycle from Control Panel or Emergency Stop and unplug.

Figure 12: Sample Expo Operation Safety Plan

2.27 Senior Project Completion

After the Senior Design Expo, you still need to submit your final report to the library, return any borrowed equipment, clean up your project work areas and complete a few other necessary tasks. A checklist of the required project wrap-up activities is shown in Table 3. As a team, complete the checklist and turn it in to your faculty coach/advisor as soon as possible after Expo to verify you have fully completed your senior project. You will not be issued an ME 430 grade until the checklist is completed.

2.27.1 Submitting your Senior Project Report

Non-confidential ME senior project teams should upload their project documentation to the Library's Digital Commons site for permanent repository. In particular, please upload a **single** PDF using the combine files feature in Adobe. This file should contain the final version of the following documents in the order listed:

1. Scope of Work (SOW)
2. Preliminary Design Review (PDR) Report
3. Critical Design Review (CDR) Report
4. Final Design Review (FDR) Report
5. Project Expo Poster

Follow these instructions:

https://guides.lib.calpoly.edu/digitalcommons/SeniorProjects

If you signed an NDAIP-1 form for your project, ask your sponsor if you can upload your full report to Digital Commons, and if so, whether you should embargo it (restrict access) for 1- or 5-years. If your sponsor does NOT want you to upload the full report at all, then ask them if they are willing to have you submit just Part I (your Scope of Work) and your Expo Poster, potentially with some parts removed.

NOTE: If your sponsor is very resistant to uploading any form of report, talk with your advisor about alternatives. You may need to forego any library upload (though, then your senior project will not be listed in Digital Commons).

Table 5: Senior Project Completion Checklist

Complete all the items on this checklist and bring it to your faculty coach/advisor for review.

Project/Team: ____

✓	Task
	Verification Prototype tested to verification plan and all results documented in DVP&R. (coach/advisor will verify this in your Senior Project Report)
	User Manual (including safe usage instructions) completed. (coach/advisor will verify this is in your Senior Project Report)
	Verification Prototype (and any extra components) delivered to Sponsor. (have sponsor email coach/advisor confirming receipt)
	Expo Poster delivered to Sponsor. (deliver to coach/advisor if sponsor does not want)
	Senior Project Report delivered to Sponsor. (copy coach/advisor on the email)
	Upload these final documents to Canvas (ME 430 week 10): - Senior Project Report PDF - Expo Poster PDF - Final Project Budget spreadsheet - Project CAD and software files (coach/advisor will verify these)
	Upload Senior Project Report to Digital Commons. [see * below for confidential projects] (coach/advisor will review & approve online).
	Fabrication area cleaned up & tools returned to shop. Workspace: ______________________________(room #, workbench #, cage #, etc.) Shop Tech Signature: ____________________ Print Name: ____________________
	Test equipment returned: Equipment: ______________________________ (list what you borrowed) Technician Signature: ________________ Print Name: ________________

* If you signed an NDAIP-1 and your sponsor confirms that they do not want the full report posted, upload the following:

1. Abstract (remove any confidential information)
2. SOW (remove any confidential information).
3. Expo Poster (this already should not have anything confidential!)

3 Senior Project Resources

This chapter provides information about resources available to all ME senior project students.

3.1 Labs & Support Facilities

This section provides brief descriptions of the campus facilities you may use during your senior project.

3.1.1 Bonderson Student Project Center

The resources of the Bonderson Student Project Center (Building 197) are available to you to complete your senior design project. The center offers senior project teams locked storage in three sizes:

- Storage lockers (1x1x2 ft)
- Outdoor cages (3x4x3 ft)
- Workbenches/cabinets in dedicated project rooms (only for projects with large builds)

Storage will be assigned based on availability and the specific needs of your project. Contact Mustang 60 to reserve space, see https://machineshops.calpoly.edu/reservations-services/.

3.1.2 24-hour Computer Labs

All ME students have access to the following labs 24/7 with their Cal Poly ID:

- 13-107
- 192-120
- 192-131
- 192-132
- 192-134

Students from other majors who are enrolled in the ME senior project courses can also get access to these labs – ask your Faculty Coach to request access for you.

3.1.3 Sponsor Communications

Large Files - Sometimes your sponsor wants to send you a large file or you want to send one to them. Many email systems limit the file size that can be received. To transfer large files to- or from- your sponsor, you can use a shared OneDrive or SharePoint directory. See https://tech.calpoly.edu/services/cloud-storage-and-sharing-onedrive-and-sharepoint.

Audio/Video Conferencing –To arrange screensharing, audio-, and video-conferences, use the Zoom Conferencing tools (see https://tech.calpoly.edu/services/web-conferencing-zoom for info).

3.1.4 Meeting Rooms

192-133

Room 192-133 is a small meeting room available for senior project teams to reserve. Visit the ME Department (room 13-254, 805-756-1334, email me-dept@calpoly.edu) to reserve the room and get ID card access. The facilities in this room include:

- Speaker Phone (on table) with cell phone connector.
- 8-person Conference table with built in AC and Ethernet for your notebook

Important: Do not use dry erase markers on the smart board in 192-133!

<u>13-124B</u>
Room 13-124B is another meeting room available for senior project team video- and audio-conferences. Visit the ME Department (room 13-254, 805-756-1334, email me-dept@calpoly.edu) to reserve the room. You'll need to pick up the key from 13-254 before your meeting and return it after.

In both rooms, the telephone rules are:

- If you need to use the phone, then:
  - Have the sponsor call you
  - Call only toll-free numbers
  - Make collect calls
- Don't talk more than necessary (i.e., plan the call, don't waste time)
- Log all outgoing calls, including faxes sent

<u>ME Department Rooms</u>
Other rooms controlled by the ME department can be reserved for ME senior project work. Mostly, these consist of our department labs and one lecture room (13-109). To reserve any of these rooms, visit the ME Department office (room 13-254, 805-756-1334, email me-dept@calpoly.edu).

<u>Other Campus Rooms</u>
Most campus classrooms are reservable when they are not being used for classes. Visit the Registrar's Scheduling website at https://eventscalendar.calpoly.edu/location-availability for information about making room reservation requests. Senior project teams fall into the "Formal Study Group" category on this page. Note that to reserve a room, you'll need to enter a "Chartfield String (Department/Sponsor Acct. #)". Contact the ME Department office (room 13-254, 805-756-1334, me-dept@calpoly.edu) for this number.

3.1.5 Audio Visual Equipment

If you require any audio/visual equipment including digital cameras, video recorders, etc., these are available through Information Technology Services (ITS). See https://tech.calpoly.edu/services/tech-rentals.

3.2 Manufacturing Resources

This section provides an overview (with links) to the campus facilities that can be used to build the final prototype of your senior design project.

Important: Do NOT work on your senior project hardware at home!

3.2.1 Student Project Shop Facilities (Aero Hangar and Mustang 60)

The Hangar shop and Mustang 60 shop are the main fabrication facilities available to you for manufacturing your senior project prototype. The shop is open to all, regardless of abilities, but for safety reasons, shop access requires completion of the License to Drill (Red Tag) Tour & Test. Your senior project will likely require access to more machines, so all ME senior project students are required to obtain one of the Intermediate Skills Trainings (mill, weld, or lathe) before the end of ME 429. This will give you access to these machines for the rest of your time at Cal Poly. For information about the shops, check out their website at https://machineshops.calpoly.edu/.

All ME Senior Project Students must earn their Yellow Tag by the end of ME 429

The Student Technicians ("Shop Techs") can provide help and guidance in the manufacture of your project. You will build it yourself and possibly learn new skills and techniques through Cal Poly's "Learn by Doing" philosophy.

If there is a more complicated part that either requires high precision or is safety-critical and you do not feel you are qualified to build it, you have three options:

1) Discuss the manufacturing with a Shop Tech. They may be able to find a more efficient, effective way of manufacturing it that you can perform yourself.
2) If a Shop Tech can't help you do the manufacturing yourself, your project can "hire" a Tech to build it for you. This will require a paid "Fee for Service" (FFS) agreement with a student technician, so requires approval by your sponsor and your faculty coach/advisor. See Contract Fabrication, below.
3) In some cases, your sponsor will have access to more advanced manufacturing facilities and will build some of the components for you. This is encouraged but be sure to discuss it with your faculty coach/advisor.

If you have any questions about the shops, call the Mustang 60 office at (805) 756-5634.

Shop Procedures and Safety Tests

To take a tour and test to use the Shop you must:

- Wear appropriate clothing for the Tour. If you wear shorts, open-toed shoes or excessively loose clothing or loose jewelry, you WILL NOT be allowed to take the Tour and Test for safety reasons.
- Arrive on time. The Tech giving the tour won't let you join late. The Shop Safety Tour and Test takes approximately three hours and is limited to the first FIFTEEN (15) people who arrive promptly.
- See https://machineshops.calpoly.edu/tours-tests/.

The ***License to Drill (Red Tag)*** Tour and Test is the REQUIRED standard introduction to the Hangar Shop and has no prerequisites. You MUST read the Red Tag Tour and Test Manual (see above link) prior to your tour and safety test. This Tour and Test introduces you to different tools that allow you to fabricate a wide variety of materials. It DOES NOT include machining or welding tools.

Intermediate Skills Trainings allow you to expand your fabrication skills into machining (mill or lathe) or welding. You MUST work in the shop for at least two hours after completing your RED tag and spend an hour cleaning the shop prior to taking an intermediate skills training course. All senior project students need to complete at least one intermediate skills training course before the end of ME 429!

Safety Reminders

Whenever you are working in the shops, please follow these safety rules:

- Wear appropriate clothing. If you wear shorts, open-toed shoes or excessively loose clothing or loose jewelry, you WILL NOT be allowed to use the shop.
- Have your set-ups checked by a Tech before beginning any operation.
- Ask questions if in doubt about safety or operations or when you are unfamiliar with a tool.
- Always wear safety glasses when in the shop.

Manufacturing Tips So You Can Finish Your Project

- Begin your project well in advance, as tool and machine time can be limited.
- Discuss your plans with the Shop Techs early. They may know a "trick" or tool that could save you time.
- Design your project for tools that you know how to use. It's OK to learn to use one or two new tools in your project, but don't design the majority of the project to be built by processes or machines that you don't know how to use. The shop Techs are there to teach you, NOT to do your manufacturing for you!
- Techs want you to succeed. They will help you, but they won't "bail you out". As they say, "Poor planning on your part does not necessarily constitute an emergency on my part."
- As a rule of thumb, if you've never done a process before, it will take FOUR TIMES as long as you think! If you have done it before it will take only THREE TIMES as long as you think! This is not an attempt at humor, this is a reality! We see it every quarter.
- Start building your prototype as early as you can. It gets harder to check out the tools that you need as the shop gets busier near the end of the quarter.

Important: Triple how long you think any machine shop project will take.

3.2.2 Additional Campus Resources

Other Cal Poly departments have manufacturing resources that can support senior project students.

Digital Fabrication Lab (dFab)

The dFab Lab is located on the 2nd floor of the Simpson Strong Tie building, with four laser cutters, one CNC router, three 3D printers, and one digitizer for student use. See https://dfab.calpoly.edu/.

Industrial & Manufacturing Engineering (IME)

The IME department has plastic and metal 3-D printers, a foundry, welders, and CNC milling machines. Some of these can be used for specific senior project activities. Start by talking to your faculty coach/advisor or professors from your IME classes.

Industrial Technology & Packaging (ITP)

The ITP department has injection molding, vacuum molding, and other plastic manufacturing tools. Talk to your faculty coach/advisor or check out their website at https://www.cob.calpoly.edu/itp/.

Innovation Sandbox

Innovation Sandbox, on the second floor of the Bonderson building, is a great resource for all campus design teams. They offer free 3D printing in addition to other resources. Their website is https://www.theinnovationsandbox.com/.

3.2.3 Using the 3D Printers or Laser Cutter in Mustang 60

Instructions for using the rapid prototyping tools can be found in the Mustang 60 shop. These machines must be reserved ahead of time, up to a week in advance. Plan ahead and be proactive to use these popular tools. To speed up your time on the laser, the appropriate Illustrator Template is available on the ME Dept. Read-Only Drive: (R:\Mustang 60 Laser Template\Mustang60LaserTemplate.ait). Using this file to start your Illustrator files will save time and keep everything running smoothly. Applicable costs:

- Vinyl Cutters: $2/linear foot of Self-Adhesive Vinyl Sheeting (15" wide)
- 3D Printers: First print is free up to 100g. For more prints or larger parts, Project Teams must purchase a spool of PLA for every 1000g of material printed or portion thereof to replenish shop supplies. 1.75mm diameter PLA ONLY. Recommended brands are Amazon Basics and 3D Solutech. Both are available on Amazon for ~$20.

3.2.4 Waterjet Cutting in Mustang 60

The Mustang '60 waterjet can cut almost any flat material up to several inches thick. You will need to provide your own material plus upload a .DXF file of the 2D part as well as a fully dimensioned .PDF of the part drawing. Follow these steps to request parts to be cut:

- Create layout drawing(s) for your final part(s) and save them as PDF files.
- Procure the stock (raw material) to be cut.
- Create DXF file(s) for the 2D cuts desired.
- Label (permanent marker) your stock and place it in the rack near the Waterjet.
- Complete the Waterjet Request Form at https://machineshops.calpoly.edu/reservations-services/.

Contact Mustang 60 shop techs if you have any questions about these steps.

3.2.5 Contract Fabrication ('Fee for Service')

The Student Projects Shop offers contract fabrication services for senior projects. This service is provided for parts that are beyond the capability of your team to fabricate including CNC, complex welding, and precision machining. **This service is not supposed to replace the "learn by doing" nature of these projects**. These services must be paid for by the project sponsor. To utilize this service:

- Consult with a Shop Tech early in the process to determine if you do in fact require this service, or if there is a simpler way to manufacture your part that you might be able to accomplish on your own.
- Get a quote from the Tech on the cost of producing your part and an estimate for the turnaround time. You will need to provide the materials and arrange for payment from your sponsor (or an on-campus account).
- Produce *complete* drawings, CAD, and/or datasets as requested by the Tech.
- Complete the Fee for Service Agreement available in the Mustang 60 Office.
- Schedule the job with the Tech.

See https://machineshops.calpoly.edu/contact/fee-for-service-work for more information.

Remember: The Student Techs will give you what you asked for as described in the documentation you provide them. They will not give you what you "need." That is to say that accurate and thorough CAD/drawings will go a long way in receiving your parts in a usable, timely manner.

CNC Machines

- CNC machinery is restricted to skilled machinists. You should be able to operate *both* CAD and Manual Machines without assistance before considering applying for an apprenticeship to be trained for our machines.
- Start on your project as early in the quarter as you can!
- Submit your project design as a CAD file for consideration at least a week in advance of your need for a decision, NOT your due date. MINIMUM Turnaround time for CNC work is 2 weeks IN ADDITION to this review period.
- Turnaround time varies wildly depending on your experience in our shop, the complexity of the process, Tech availability, time considerations for other CNC projects and other factors. Techs are students, and often the ones working on CNC projects have Senior Projects of their own.
- All decisions are FINAL, there is no appeals process.
- Have a contingency plan in place to manufacture your project using available manual machines and tools. Start on your project as early in the quarter as you can.
- Your CNC project must be approved by the CNC Supervisor Technician or Eric Pulse.

3.3 Material Resources

- Scrap Bins
  There are scrap bins near each shop (ask a Tech for the location) that have metal and other scrap materials that are free for the taking **for use on your Senior Design project**.

- Surplus Materials
  There is a collection of surplus material (leftover from other projects) that is sold by weight (at competitive prices!) by the shops. But properties are unknown. Ask a Tech.

- Heilmann Salvage & Metals
  - 6450 Rocky Canyon Rd., Atascadero
  - (805) 466-4893
- PRW Steel Supply (https://prwsteel.com/)
  - 2925 Union Rd., Paso Robles
  - (805) 239-1688
- The Craft Fiberglass Supply (http://thecraftglassworks.blogspot.com/)
  - 141 Suburban Rd., E-1, San Luis Obispo
  - (805) 782-9802

- Web Resources
  A few websites that have been used by the ME department and student clubs are listed below. This is by no means a comprehensive list, but it is a good starting point.

  a) Fiberglass Hawaii (http://www.fiberglasshawaii.com/)
     Fiberglass, carbon, Kevlar, resins, molding materials…

b) McMaster Carr (http://www.mcmaster.com/)
   Almost anything you could imagine. Freakishly fast delivery times. But, expensive.
c) Misumi USA (https://us.misumi-ec.com/)
   All types of machine components, including semi-custom parts.
d) Online Metals (http://www.onlinemetals.com/)
   Good for small orders of aluminum and steel structural shapes and tubes.
a) Protolabs (https://www.protolabs.com/)
   Custom prototyping, especially 3D printing.

3.4 *Testing Resources*

Designs are verified by some combination of analysis, similarity to existing hardware, inspection, and testing. It is a requirement of the ME senior project class that every project includes at least one test with numerical data collection, data analysis, and uncertainty propagation.

This section briefly describes mechanical inspection and testing resources available to senior project teams in the mechanical engineering department at Cal Poly.

3.4.1 Testing Consultants

The mechanical engineering department hires student technicians to help you with questions on manufacturing and testing your project. Testing is a critical phase of these projects, and you must start preparing your test plan parallel to your design activity. The student technicians can help you plan and perform your design verification. Ask your faculty coach/advisor for contact information.

The Cal Poly Statistics Department provides free consulting services to the campus community. Read more about this at https://statistics.calpoly.edu/content/consulting, and when you're ready, contact statconsulting@calpoly.edu to set up an appointment or find out their office hours.

3.4.2 Dimensional Inspection or Measurement

Engineering parts and systems are built to print or drawing with dimensions and tolerances. Parts and systems are inspected to verify they meet drawing requirements and thus will function as the designer intended. The mechanical engineering department has measurement or inspection equipment available for student teams. This equipment is in the Hangar or Mustang 60 shop facilities and is described briefly below.

Scales and Tape Measures

Both student shops have a variety of scales, squares and measuring tapes. These can be used to things like basic lengths, spacing, clearances, bores, and hole patterns. Dimensional inspection to interface requirements is usually the first thing after completion of hardware prior to assembly any other mechanical testing.

Calipers and Micrometers

More accurate dimensional measurements of parts are made with calipers and micrometers which are also available in both student shops. Mustang '60 has Mitutoyo Micrometers ranging from 0-6 inches and calipers from 0-12 inches.

Granite Surface Plate

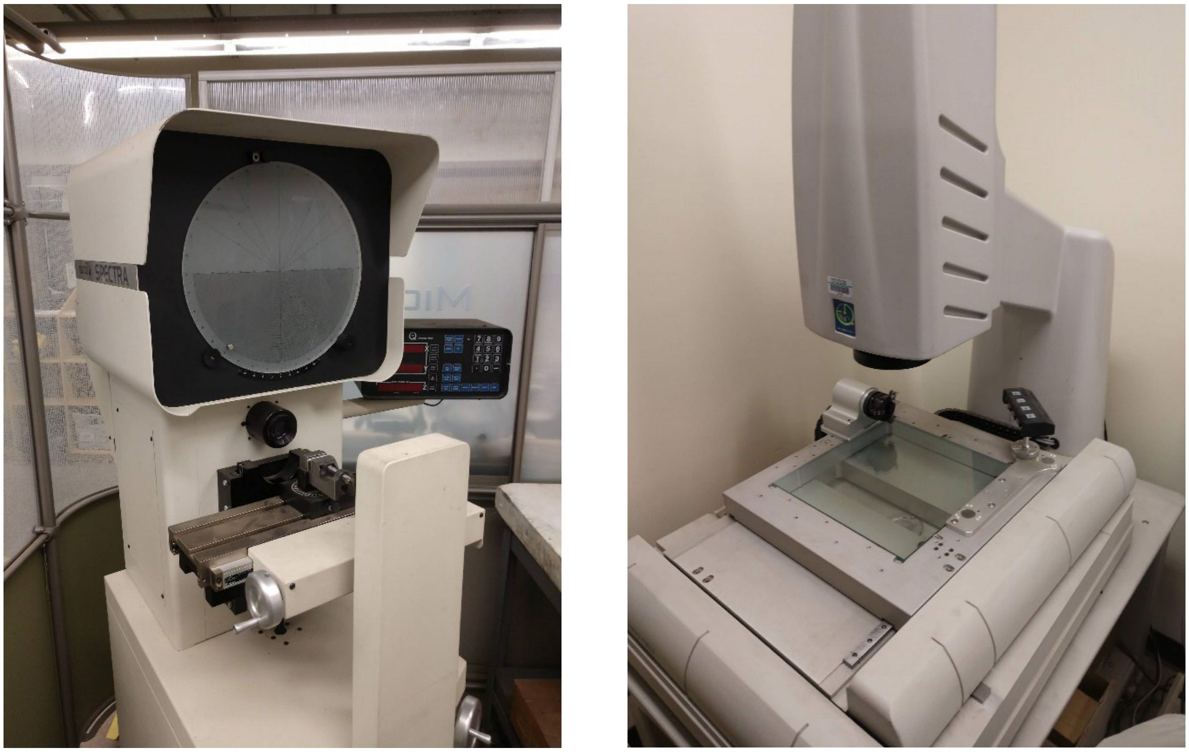
The hangar also has a small granite surface plate which serves as a flat reference or zero datum for measuring parts. This dimensionally stable flat part is used in conjunction with measuring instruments.

Height gage and Dial Indicators

A height gage is like a caliper but has a flat base and thus is most often used in conjunction with a surface plate or "ways" of machines tools. Dial indicators are used similarly and have a variety of bases (including magnetic) to attach to your hardware directly to make measurements of heights and run out. These come in a variety of travel and accuracies. These could be used to measure the deflection of a loaded structure at critical locations. These tools are available at both student shops.

Precision Measurement Tools

Mustang ’60 shop has a metrology area with two precision Micro Vu measurement tools, an optical comparator and a CMM with light, laser, and touch probe measurements systems (Figure 16).



(a) (b)

Figure 13: Micro Vu (a) Spectra Optical Comparator and (b)Vertex 312HC CMM

Weight and Mass

Part weight and mass are critical design information for many mechanical engineering components and systems. There are a variety of scales in the ME department. Check in Mustang ’60, the Hangar Shop, and the Vibrations Lab.

3.4.3 Mechanical Testing

There are a variety of resources in the ME department for materials characterization and structural testing. Most of the structural testing equipment and associated instrumentation are in the Composites and Structures lab, 192-135. To access the lab, visit during Lab TA office hours (posted next to the door of 192-135), or contact Dr. Elghandour or the current lab coordinator for details.

Hardness

Recall that hardness and tensile strength are related for materials like steel. Also remember wear and contact stresses are functions of hardness as well. There is a Starrett hardness tester in the Mustang ’60 metrology area, just inside the shop entrance (Figure 17).

Figure 14: Starrett Rockwell C Hardness Tester

Load Frames

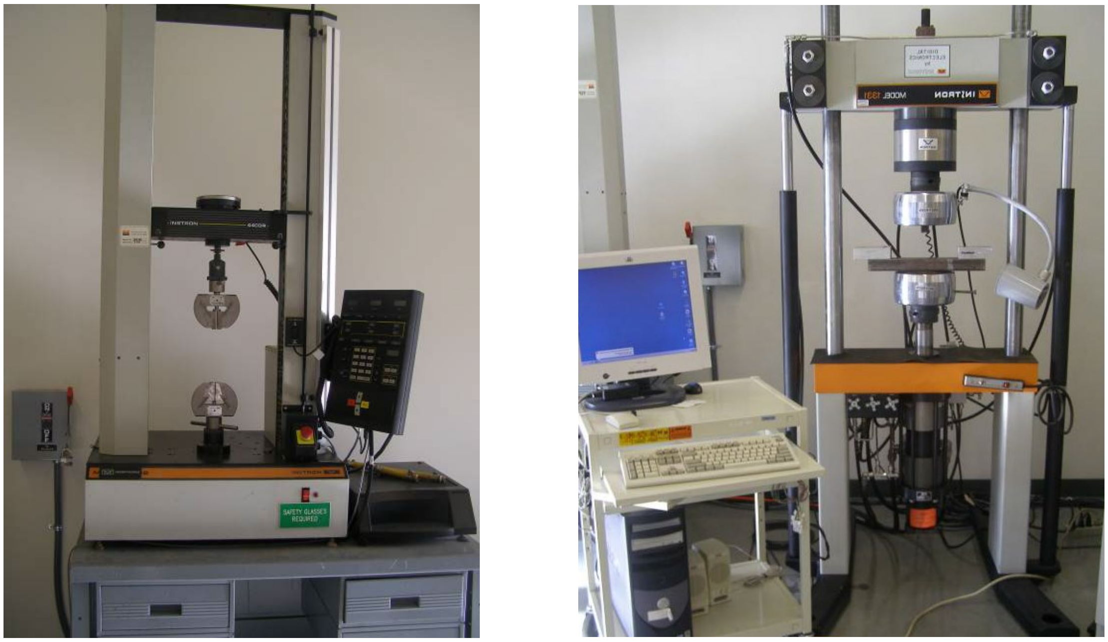
The composites and structures lab in 192-135 has two tensile test machines that can be used to test either material coupons or structural components (Figure 18). Use of these machines require appointments an appointment made two weeks prior to your planned test date. To set an appointment, you first need to submit a test plan that includes a detailed sketch of your setup that includes tooling and instrumentation needs.

Small Instron Tensile Test Machine

A 2000 lb mechanical load frame is available for tensile testing. This machine is pictured below. It has wedge action grips which can used to pull on small specimens or structural components in tension only. Note the grips can be removed and purpose-built tooling installed for testing of small structural components   Load can be recorded along with crosshead displacement. This machine is best suited for quasi-static tests. This machine has upgraded controls and a front panel which is user-friendly. Note the new "on switch" is at the back of the black box on resting on the tabletop. This machine is lead-screw based and can produce forces that can cause injury. Do not use this machine without permission and a safety briefing from an instructor.

Servo-Hydraulic Load Frame

A servo-hydraulic load frame is available for higher loads up to 22,000 lb. This machine has sophisticated controls and can be used for fatigue and other static and dynamic tests. This machine has hydraulic grips that grasp coupons or tooling stubs that are am maximum of 0.25 in thick by 1.0 in wide with a grip length of 1.0-1.5 in. Dedicated flex test tooling is also available for performing small 3-point bending tests such as ASTM 790 for characterizing polymer materials.



(a) (b)

Figure 15: Instron Tensile Test Machines, (a) Small and (b) Servo-Hydraulic

This machine is instrumented to measure load, cross head displacement and strain via clip on extensometers. Strain can also be measured using strain gages. A dedicated PC equipped with a NI/LabView hardware and software has virtual instruments (Vis) which can be used to record values from strain and load instrumentation. Operating procedures are documented and available, but use must be coordinated with faculty, technicians or trained student technicians as this machine can generate tremendous loads and strain energy.

MTS 100-kip Tensile Tester

For large loads, the Civil Engineering department has a 100-kip load frame. If you need to use this machine, please contact Dr. Dan Jensen in Civil Engineering.

Strong Floor

The composites and structures lab has an 8-foot square load floor for bolting structures down for testing (Figure 19). The interface is ½ inch T-nuts which go in metal slots in the floor. Load application can be performed using hanging weights and electric actuators or things like hydraulic "bottle" jacks. The floor has insert fastener maximum loads of about 2000 lbs in any direction. All test set-ups again must meet faculty approval for safety considerations. The photo below shows a purpose-built pendulum tester bolted to the strong floor.

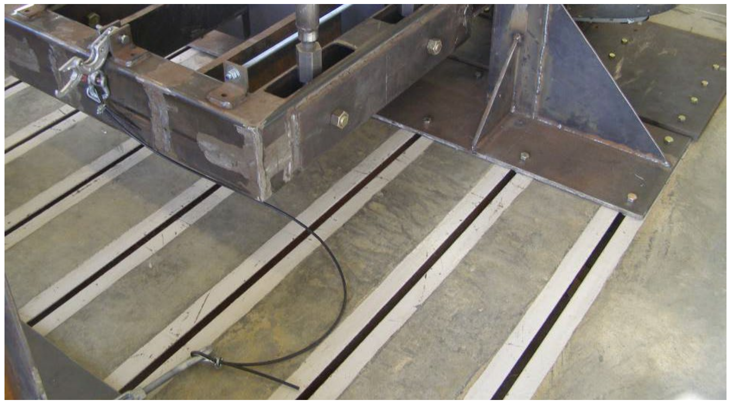


Figure 16: Composites Lab Strong Floor

Electric Actuators

Two electric actuators are available for testing (Figure 20). These have a 2000 N capability and a 300 mm stroke. These are picture below. They are lead screw based and the user pushes the buttons to raise and lower the actuator. These could be bolted between a structure and the load floor for proof testing.

Figure 17: Electric Actuators

Dynamic testing (Solar Turbines and Bently Nevada Vibrations and Rotordynamics lab)

The Vibrations Lab (13-101) can be used by permission from the lab coordinating instructors, Dr. Hemanth Porumamilla (HP) at hporumam@calpoly.edu. or Dr. Xi Wu xwu@calpoly.edu. The below mentioned equipment in the vibrations lab is also available for student project use, but cannot be loaned out for use outside the lab. In addition, students will also need to notify the lab coordinators on the exact equipment that they plan to utilize for testing so that they can receive appropriate training ahead of time. A minimum of two students will need to be present in the lab at all times during the testing and proper safety protocol as instructed by the coordinators must be strictly followed.

Safety/First-Aid

The vibrations lab is equipped with a first-aid kit with the necessary medical supplies including eyewash in case of an emergency (figure 21). However, the use of this first-aid kit is primarily meant for use in case of minor injuries. In the event of a significant injury, students must dial 911 immediately both for notifying as well as for receiving guidelines from trained personnel on the first-aid procedures. The students are encouraged to use the wall-mounted telephone located behind the large electrodynamic shake table and next to the door adjoining the Controls lab (Figure 22) to call 911, because it has the added advantage of connecting directly to the Police Department at Cal Poly, thereby, expediting help. In the event of a fire, a fire extinguisher situated at the entrance to the lab can be utilized (Figure 21).

Figure 18: First Aid kit w/ Eyewash and Fire Extinguisher and location of Telephone

Shake Tables

The vibrations lab has several shake tables that are used both for teaching and research/ student project purposes. One of the shake tables is hydraulically actuated while the several others are electrically (electrodynamic) actuated.

Hydraulic Shake Table

The hydraulic shake table (Figure 22) is primarily used for research/student project purposes. It is a high-capacity shake table most suited for applications comprising of large mass (>100lb) and a frequency range between (.5Hz and 500 Hz). The hydraulic power source for the shake table is located in the storeroom of the lab and will need special access in addition to that for the lab. The shake table is controlled by a power amplifier (Figure 23) which accepts a 0-10v pilot signal from any signal generator/DAQ system. The shake table is however not equipped with a DAQ and hence would require one for data acquisition, which the students will need to arrange for themselves. The use of the shake table would require training from the lab coordinators ahead of time.

Figure 19: Hydraulic Shake Table and Power Amplifier

Electrodynamic Shake Tables

The lab has a total of six electrodynamic shake tables. Two of the shake tables which are of larger capacity (Figures 23 and 24) are mainly used for research and other student projects and the four shake tables of smaller capacity (Figure 26) are mainly used for teaching, but are available for use for research or student projects. As compared to the hydraulic shake table, the load bearing capacity is smaller (<100lb), but, they have a much larger actuating frequency range (0.5 Hz to 1500 Hz). These shake tables are used most often by all the student groups. Just like the case of the hydraulic shake table, operating these shake tables requires training from the lab coordinators ahead of time. The details of these shake tables are as mentioned below.

Large capacity Electrodynamic Shake Tables

Figures 23 and 24 show the two large capacity electrodynamic shake tables in the lab. The shake table in figure 23 is oriented to produce vibration in the vertical direction while the one in figure 24 is similar to the other one but tilted 90° to produce vibration in the horizontal direction. The shake table is also coupled with a slip table also seen in figure 24 to facilitate attaching the equipment to be tested. Both these shake tables are actuated through the same power amplifier (Figure 26) by swapping the appropriate electrical cables. This cable swap will have to be authorized by the lab coordinators and performed by a department authorized technician. In addition, operating the shake tables requires a startup/shutdown procedure with guidelines posted on the Power Amplifier tower. These guidelines must be followed meticulously every time the shake table is operated. The lab coordinators will provide training on this procedure as well.

Figure 23: Electrodynamic Shake Table (Vertical Direction)

Figure 20: Electrodynamic Shake Table w/ Slip Table (Horizontal Direction)

Small capacity Electrodynamic Shake Tables

Smaller capacity electrodynamic shake tables (Figure 25), which are primarily used for lab instruction are also available for student project use. As compared to their larger capacity counterparts, the load bearing capacity is much smaller (<5lb) while having the same actuating frequency range (0.5 Hz to 1500 Hz). Hence, these shake tables should only be utilized for small and light components so as to not damage them. These shake tables are connected to power amplifiers situated under the desk (Figure 25) and are actuated with the help of signal generators/ DAQ systems supplying a DC voltage between 0v and 10v.

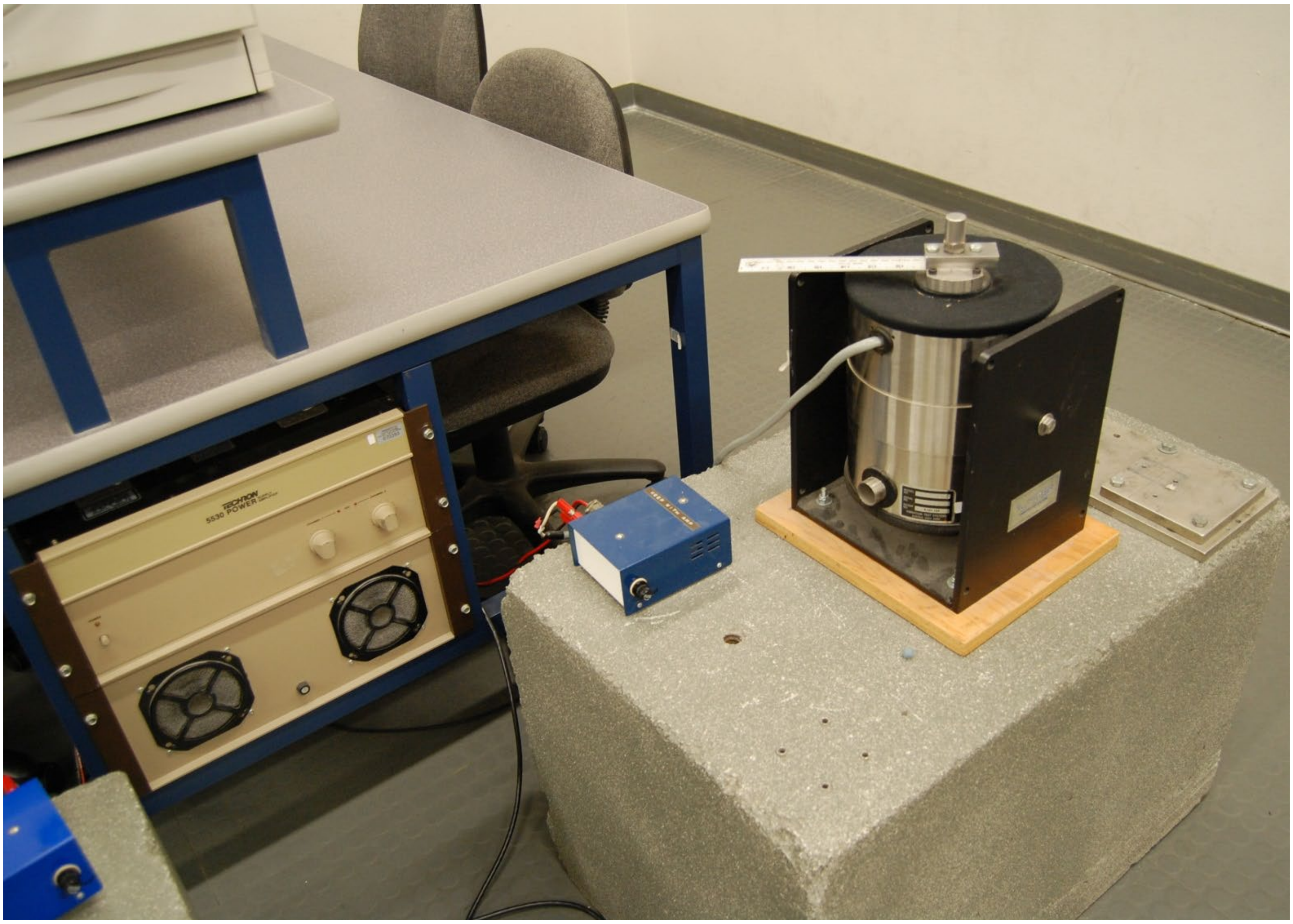


Figure 5: Small Electrodynamic Shake Table w/ Power Amplifier

DAQ and Measurement system

The two large capacity electrodynamic shake tables (Figures 23 and 24) are controlled through a data acquisition system from Crystal instruments (figures 26 and 27). The system can be utilized to not only conduct specific vibration tests such as sine sweep, random noise and shock spectrum, but to also post process the data in time domain and frequency domains which can then be saved and transferred. The lab coordinators can provide documentation to help with setting up and running the different vibration tests using the Crystal instruments DAQ system. Additional help can also be obtained by directly contacting Crystal instruments.

Figure 26: DAQ System for the Large Electrodynamic Shake Tables

Figure 27: Crystal Instruments DAQ System Module

Spectrum Analyzers and Oscilloscopes

The vibrations lab is equipped with other data acquisition systems in the form of HP P35665A Spectrum Analyzers and Keysight DSOX1204G InfiniiVision 1000 X-Series Digital Oscilloscopes located on the mobile cart as shown in figures 28 and 29. Among the several capabilities, the Spectrum Analyzers can perform system identification through inputs such as sine sweep and random noise. The Spectrum Analyzers can also be used in conjunction with Modal Hammers (Figure 30) to also perform system identification through Modal Analysis. The digital oscilloscopes also have a wide functionality in addition to capturing waveforms due to their inbuilt wave generator component which when used in conjunction with the acquisition capability of the oscilloscope, functions very similar to the Spectrum Analyzers for the purposes of system identification.

Figure 28: Additional DAQ Systems

Figure 29: Keysight Digital Oscilloscope and HP Spectrum Analyzer

The data acquisition capability of the lab is further augmented by Computer Workstations capable of interfacing with DAQ boards either through USB ports or Ethernet (Figure 28).

Instrumentation

The vibrations lab is equipped with sensors in the form of Load Cells and Accelerometers for measurement (Figure 30). In addition, the lab also has Modal Hammers for performing vibration measurement in conjunction with the Spectrum Analyzers. The above-mentioned devices require the use Signal

Conditioner boxes which are also shown in figure 30. The electrical connections are done with the help of microdot and BNC cables.

Figure 30: Sensors, Actuators, Signal Conditioners and Cables

Simpson Strong Tie (SST) Strong Frame

The Construction Management Department has a Strong Frame that can be used to attach equipment which needs to be suspended under loads. Contact Professor Jason Hailer at jhailer@calpoly.edu for details.

3.4.4 Test Equipment Available for Checkout

To support your other test equipment needs, the department has a collection of mechanical test instruments available for checkout. Table 4 provides a list of the instrumentation that may be borrowed for use on your senior project. Contact Graham Roberts (grober19@calpoly.edu) for information and to get an *Equipment Loan Agreement*, which requires your faculty coach/advisor's approval to start the checkout process.

Table 6: Senior Project Test Equipment Available for Checkout

Group	Instrument	Notes or Description	Source	Part Number
DAQ	DAQ	Data Acquisition System	Omega	OM-DAQ-USB_2401
Force	Force Gauge	100 lb	Omega	DFG35-100
Load	Load Cell	50 lb	Omega	LC101-50
Load	Load Cell	100 lb	Omega	LC101-100
Load	Load Cell	1000 lb	Omega	LC101-1K
Load	Load Cell	2000 lb	Omega	LC101-2K
Load	Load Cell Indicator	No Outputs	Omega	DP25B-S
Load	Load Cell Indicator	AO	Omega	DP25B-S-A
Load	Load Button	2000 lb	Omega	LBC-012
Load	Load Button	200 lb	Omega	LBC-014
Load	Rod End	200 lb	Omega	REC-014M
Load	Rod End	2000 lb	Omega	REC-012M
Position	LVDT	0.5 in	Omega	LD620-15
Position	LVDT	1 in	Omega	LD620-25
Position	LVDT	2 in	Omega	LD620-50
Position	LVDT Tip		Omega	LD-TIP
Position	LVDT U Joint		Omega	LD-UJOINT-KIT
Position	LVDT Indicator	No Outputs	Omega	DP25B-E
Position	LVDT Indicator	Analog Output	Omega	DP25B-E-A
Speed	Tachometer Pouch		Omega	HHT13-CC10
Speed	Tachometer Tape	5 ft roll	Omega	HHT-RT-5
Temp	Tachometer		Omega	HHT13
Strain	Vishay P3 Box	Digital Strain Indicator	Vishay	P3
Pressure	Digital Media Gauge	For Gases	SSI	MGA-30-A-9V-R
Temp	Thermocouple Reader	Data Logging	Omega	RDXL4SD
Temp	T/C Reader Hard Case		Omega	HC-SD
Electrical	Function Generator		Tektronix	CFG253
Electrical	DC Power Supply	0-15V (7A) 0-30V (4A)	Agilent	E3632A
Weight	Scale	11 lb	Ohaus	CS500P
Weight	Scale	44 lb	Ohaus	C11P210
Load	Hydraulic Actuator		Harbor Freight	36396
Visual	Thermal Camera	Infrared	FLIR	SC300

4 Supplemental Reading

This chapter contains sections focused on various topics of interest during senior project. Each of these will be used as assigned reading at some point during the three quarters of senior project.

4.1 Design Process and Methodology

The engineering design process is a type of problem solving which can be summed up by five basic steps:

1) Establish a need
2) Explicitly state the problem
3) Generate possible solutions
4) Evaluate the solutions and pick the best one
5) Document the work

The process of designing a mechanical, electrical, electro-mechanical, software or any other type of engineering system is more complicated and certainly not linear. In this class you will gain experience with the engineering design process by experiencing it as you solve an externally supplied engineering design problem. The problems are real and do not have a single "right" answer. Instead, we will apply a formal (although nonlinear) process to find the "best" answer over a 30-week period. The flowchart shown in Figure 31 (adapted from "The Mechanical Design Process" by David Ullman) gives a more complete picture of the steps of our engineering design process. Note the many arrows on the flowchart that point back towards the beginning of a project. This is an important and sometimes frustrating aspect of the design process which you will all experience in this class. Hopefully with guidance from your faculty coach/advisor, you can appreciate the effectiveness of this process and not be bogged down in frustration.

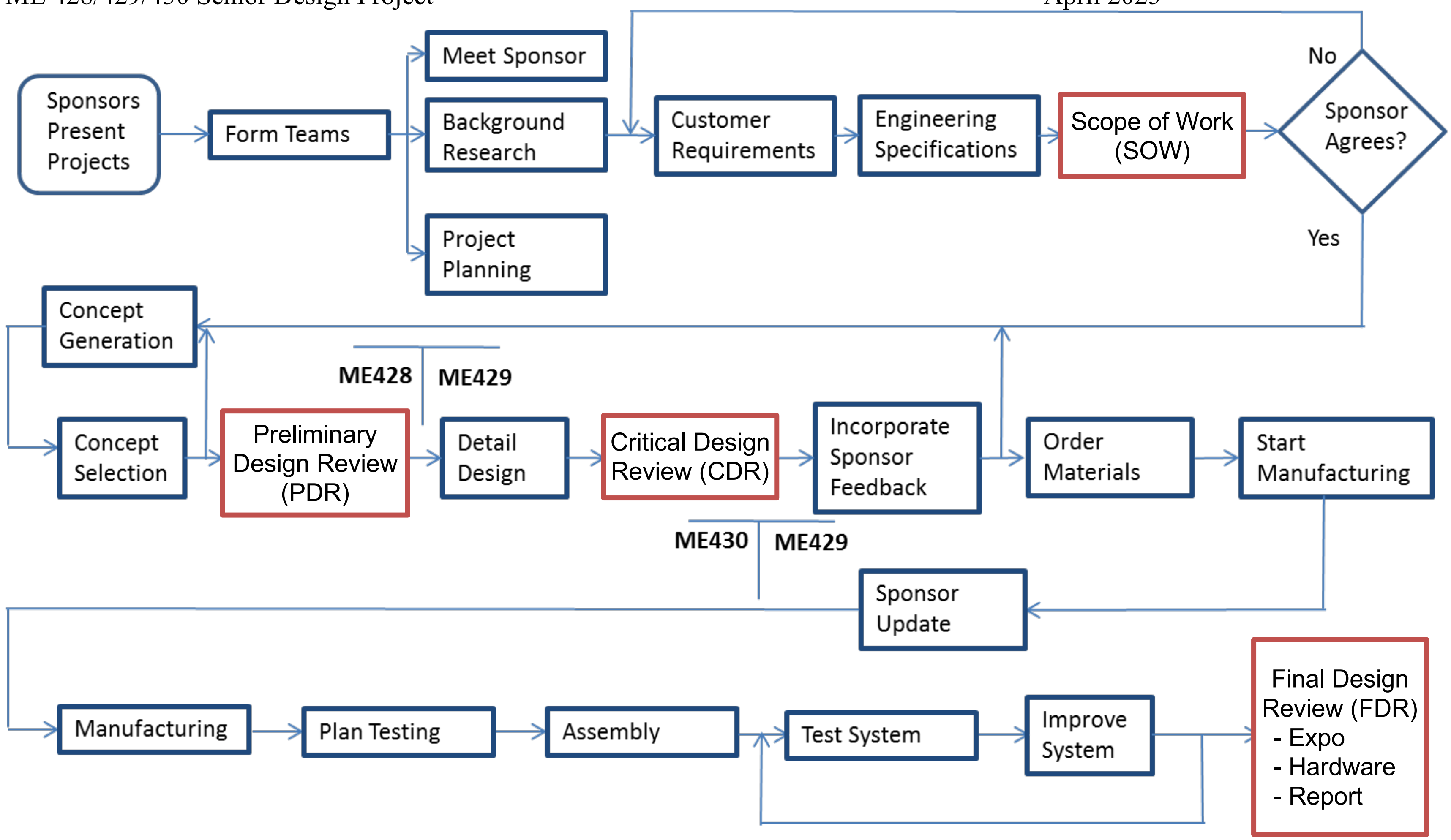


Figure 21: ME Senior Design Process

4.2 Working on a Team

Although you have certainly worked with other students on team-based projects prior to Senior Design Project, it is just as unlikely you have done so for 30 weeks. The success of the project is in large part determined by the success of the team. It is therefore important that all students in the Senior Design Project course understand teaming skills, knowledge and attitudes. Katzenbach defines a team as "… a small number of people with complementary skills who are committed to a common purpose, performance goals, and an approach for which they hold themselves mutually accountable." Teaming, especially in engineering, is necessary to complete any reasonably complicated task whether it is designing a new product, setting up a new production process or implementing a new management organization. In this class we are focusing on the design process and therefore we will focus on the design "team." Most of the deliverables for this class are "team" not individual items. Your ability to perform as part of a high-performance team has a direct bearing on the success of your project. Most of the project failures and poor results in the past can be directly attributed to inferior performance of the teams and most of the successes come from high-performing teams. It is essential for you to understand teams and team processes and to develop your skills as a team member and practice them on your design team during this class. Once you develop these skills, you will be able to apply them for the remainder of your career. An excellent reference for engineering students is provided by Levi, *et al.*, and much of what appears here comes from their manual on Student Teamwork.

4.2.1 Team Development Stages

In the 1960's, Bruce Tuckman a Professor of Education at Rutgers (and later at Ohio State University) published a paper about the development sequence of small groups which is now the most quoted and accepted model of the process of team development. He described four basic stages of team development as **Forming**, **Storming**, **Norming**, and **Performing**. 32 shows these stages as a pyramid with the top representing those teams which have obtained a high-level of performance. The idea is that all teams must go through these four stages to achieve peak performance.

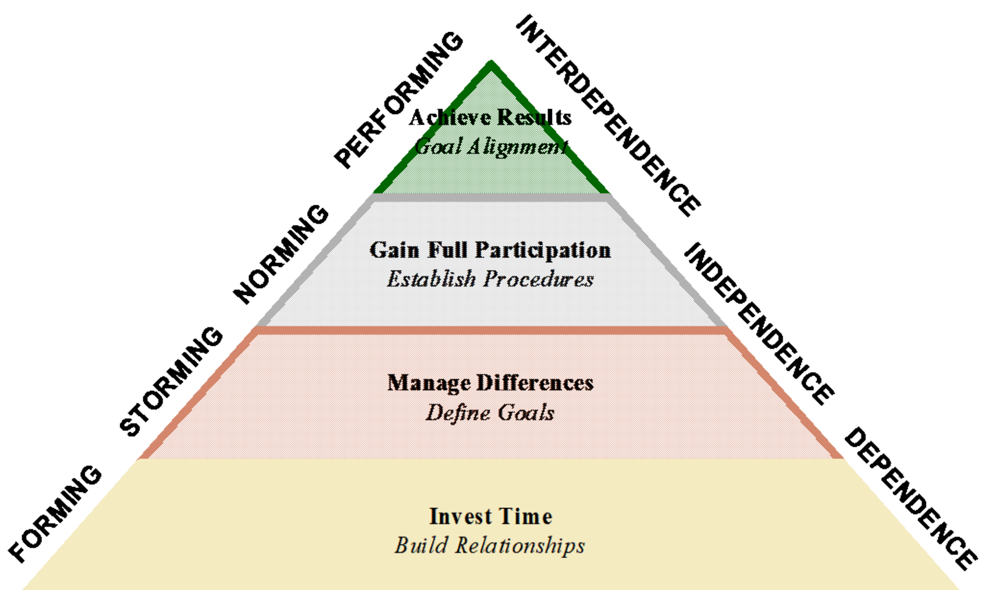


Figure 32: Stages of Team Development (after Anne Virkus and Mark Steiner)

Forming:

The forming stage begins when the team is first gets together. For you this was when you first met to discuss writing your Sponsor Introduction Letter. The length of time of this stage depends on many factors including the number of team members and the amount of time spent together. This is considered by some as the most critical phase. This is when you can build foundations of trust among your team members by learning about each other. This time also sets expectations among team members for success and behavior. The forming stage is usually an upbeat, happy time where team members are polite and responsive. Team members will usually have feelings of optimism for the outcome of the project. Also, there is usually no real progress made towards completing the task. The real work is forming the team. This is the ideal time in a design project for working on the problem definition, the scope and developing the detailed engineering specification.

Storming:

This second phase of team development is the most difficult. It is characterized by conflicts among team members and confusion about team roles. Team members recognize that progress towards solving the problem at hand must be made, but there is not yet an established structure within the team to move forward, reach consensus and make decisions. There can be power struggles at this time if multiple people vie to be team leaders and are not willing to share responsibility. Often, individuals will blame the "concept" of having a team for their problems. Some feelings associated with this stage include defensiveness, competitiveness, tension and jealousy. Team members' attitudes about the potential success of the project might swing wildly. Some typical behaviors at this stage include not completing tasks, excessive arguing about small points, choosing sides, establishing unrealistic goals and questioning the wisdom of having a team at all. Like the forming stage, little progress towards the completion of the design task is expected or possible at this stage. Real progress won't kick in until the Norming stage. Also, real understanding of the diversity of your team members will begin.

Norming:

During the *Norming* stage, the team members begin to agree on the structure of the team. You decide who will take what roles and how you will conduct "business." The team will start making progress on their task but will often bounce back and forth between "Storming" and *Norming*. This process does not happen all at once. Communication among team members will improve during this phase. Some feelings associated with this phase include an increasing optimism about the team's chance of success, a growing sense of team unity, acceptance of the team's individual diversity and a growing sense of harmony.

Performing:

This is the highest stage of team development and is characterized by a well-functioning team capable of completing the assigned task. At this point the team is primarily self-directed, needing little input from an outside manager. Roles are clearly defined, and tasks are regularly completed on time as promised. This team will be able to tackle almost any similar problem assuming they have the correct technical background. Feelings associated with this phase include pride both in the task progress as well as the team process. Team members respond positively to constructive criticism from their teammates and personal growth can be achieved. This is when the bulk of high-quality work will get done.

4.2.2 Establishing Team Norms/Effective Team Meetings

At the initial stages in team development, a team must establish the ground rules for meetings. These include what kind of behavior is acceptable and how the interaction will occur. Although many individuals prefer “loose” arrangements, some formal rules for meetings should be put in place if you want to become a high performing team. Some other hints that you need ground rules (suggested by Levi) include:

- Topics are avoided repeatedly.
- Irrelevant conversations keep reoccurring.
- Team members do not acknowledge or follow the norms.
- There is conflict over the meaning of norms.
- A meeting leader cannot get members to comply.

Scholtes suggests the following list of options for ground rules for team meetings:

- **Meetings** - When do they occur? How often? How long?
- **Attendance** - When is missing a meeting okay. How are missing members informed about decisions or task assignments? How will you manage excessive absence by team members?
- **Promptness** - What do you mean by on time? How is it enforced?
- **Participation** - How to ensure that everyone gets their say?
- **Conversational Courtesies** - Raise hand to talk? Don’t interrupt? Listen? Respect?
- **Assignments** - How do you make sure tasks are completed on time? How do you know who does what and when?
- **Roles** - Who will fill various roles? How should they be selected? How can they change?
- **Agendas and Minutes** - Who is responsible? What is the format?
- **Decisions -** What represents consensus? How is it attained? Do you vote? Is there veto power?

4.2.3 Team Roles

The primary reason for engineers to be included on design teams is their technical expertise and experience. Beyond that, there are secondary roles that team members must take on for successful teams. The role(s) that each team member takes depends on their individual problem-solving style. Based on work by R. M. Belbin, Ullman suggest eight secondary team roles that need to be filled on successful engineering design teams. Usually, team members fill more than one role and often multiple team members can fill the same role; however, the roles are consistent with the team member problem solving style preference. The roles are:

- **Coordinator** – This team member is typically mature, confident and trusting. They are good at clarifying goals and promoting effective decision making. This can be a good chairperson for a team
- **Creator** – This person is imaginative and can solve difficult problems. They can also be impractical, have no regard for established team norms and don’t necessarily like to work with facts.
- **Resource-Investigator** – This team member is usually an extrovert known for their resourcefulness. They excel at finding new opportunities and developing contacts. They can sometimes lose interest when the detail stage is reached.
- **Shaper** – This person may be dynamic, outgoing and assertive. They make things happen by finding a way around obstacles. They can also be impatient with vagueness but like to make logical and objective decisions.
- **Monitor/Evaluator** – The team member is good at seeing the “big” picture and accurately judging possible outcomes. They may not be inspirational leaders, but they are intelligent and shrewd.
- **Team Worker** – This is a consensus building who is concerned about making the team function in harmony and avoiding conflict. They are typically subjective decision makers.

- **Implementer** – This team member turns ideas into action. They are usually disciplined, reliable and efficient. They can be sometimes construed as resistant to change.
- **Completer/Finisher** – This team member is conscientious and detail-oriented and usually delivers results on time. This people are often reluctant to delegate authority and they worry about progress.

4.2.4 Team Decision Making

The decisions your team makes during the problem-solving process will mostly decide the quality of your solution. The process that you use to make these decisions will have an impact on how you feel about your team and the solution. According to Levi, there are generally four approaches to Team Decision Making. They are:

Consent: This is the approach to use when the decisions are straightforward or have been effectively already made by the team member best suited to make the decision. The typical approach is to create a Consent List on a meeting agenda. During the meeting, the facilitator asks if anyone has a problem with these items. If there are no objections, then the decision has been made. This is an excellent way to avoid wasting time discussing low importance decisions or items that have already been agreed upon by the relevant team members.

Consultative: In this method, one team member is given the authority to make the decision (usually due to a particular expertise). This person should elicit advice from team members, but they will make the final decision. It is usually obvious when a team member's qualifications give them the authority, but it should be stated and made clear to all team members that they will be making the decision.

Democratic: This seems like a good method (given the history of the U.S.), but it turns out to be the worst team decision making method. The popular vote always makes winners and losers (sometimes almost ½ of the team!). The losers may be quite unwilling to support and implement the decision after it is made. Although this is a quick and decisive method, it should be avoided.

Consensus: This is the best approach for any major team decision, and it sometimes requires the most work. The key is to continue discussion until all agree on accepting a decision. This does not mean that it is every team member's favorite decision, but by accepting, all team members are stating that they are willing to support and implement the decision.

How to achieve Consensus:
Hackett and Martin having the following suggestion on how to reach consensus:

Team facilitators can help to achieve consensus by:

- Giving adequate time to discuss and work through issues.
- View conflict as inevitable and ultimately beneficial.
- Encourage negotiation and collaboration among team members.
- Recognize that giving in on a point is not losing and that gaining a point is not winning.
- Encourage team members not to give in just to avoid conflict.
- Don't allow coin flipping or voting when differences emerge.

Ways to get unstuck when trying to reach consensus include:

- Agree to not agree and then move on to the issue.

- Change topics, call a recess or decide to decide later.
- Work towards a compromise, knowing it might not be the best decision.
- Ask for outside help and input.
- Use voting only as a last resort, understanding that this could undermine team cohesion.

If team members can say yes to the following statements, then consensus has been achieved:

1) Will you agree this is what the team should do next?
2) Can you go along with this position?
3) Can you support this alternative?

4.2.5 Managing Team Processes

Communication Skills

The ability to communicate is often agreed as the most important skill for effective teamwork. According to Levi, four important skills include how to ask questions, how to listen, how to give constructive feedback and how to manage feelings.

How to ask questions:

In general, open-ended questions are useful for promoting team discussions while yes/no questions are not. It is often useful to follow up on answers with questions that ask for further explanation. Questions asked to the meeting facilitator should be echoed back to the team for discussion.

Hackett and Martin have proposed a set of rules for asking non-threatening questions:

1) Initially ask each question of the entire team.
2) Pause and allow the team members time to consider the questions.
3) If a team member responds, acknowledge the remark and explore the response further if possible or necessary.
4) If no one responds, either ask a particular person or consider reworking the questions.
5) Avoid biased questions
6) Avoid asking too many yes/no questions
7) Avoid questions that put team members on the defensive

Active Listening:

The goal of active listening is to increase communication by giving the speaker feedback to clarify and promote further discourse. An active listener should communicate that you want to understand the speaker and their underlying feelings. In active listening, the receiver should paraphrase back to the speaker what they heard as a means of clarifying the message. They should also describe their perception of the speaker’s feelings. In this way the speaker and listener can go back and forth and reach consensus on the meaning. This is a method of avoiding the evaluation of a speaker’s communications which may make them defensive and thus decrease further discussion. Active Listening is also a highly effective method for conflict resolution.

Providing Constructive Feedback

A hallmark of a high performing team is the ability of the team members to provide and receive constructive feedback. Receiving feedback can sometimes be difficult and providing it can be ineffective. Table 5 provides some guidelines by Scholtes that can be helpful when providing this type of feedback.

Table 7: Constructive Feedback Guidelines (Scholtes)

START WITH	EXPLANATION
"WHEN YOU…"	Describes the behavior
"I FEEL…"	Tells how you are affected
"BECAUSE I…"	Why you are affected that way
PAUSE FOR DISCUSSION	
"I WOULD LIKE…"	Describe the change you want
"BECAUSE…"	Why you think it will fix the problem
"WHAT DO YOU THINK?"	Listen and discuss

How to Manage Feelings

Emotions can run high during a long-term project especially when important decisions are made. This can be especially true during the "Storming" stage of Team development. These emotions can be a source of great strength to the team's efforts, and it is critical that these emotions do not become destructive. All team members should learn how to manage emotional interactions between members. Kayser suggests the following:

1) Stay Neutral: Everyone has a right to their own feelings. The team should acknowledge the expression of those feelings
2) Understand rather than evaluate feelings: Be sensitive to verbal and non-verbal messages. When dealing with emotional issues, be sure to ask questions and seek information to better understand the feelings.
3) Avoid asking team members why they feel a certain way.
4) Process feelings in the group: When the team's operation is disrupted by emotions, stop and cool down. Then discuss the issues in the whole group.

Conflict Resolution

Conflicts occur for a variety of reasons that are desirable on a design team, especially as they work to solve difficult open-ended problems. Differences in opinions, ways of thinking and different methods of solving problems are some of the main reasons teams are more effective than individuals. Maddux points out that conflict become unhealthy when it is avoided or viewed as a competition. He points out five basic methods that are used to resolve conflict.

1) **Avoidance:** This is the "bury your head in the sand" approach; hoping that the problem will go away. It never does.
2) **Accommodation:** Certain team members give up their position just to be agreeable, but this costs the team their input.
3) **Confrontation:** By acting aggressively, some members may "win" a confrontation. This can become more important than making a good decision and leads to isolation and non-participation of the "loser"
4) **Compromise:** This way balances the goals of each team member by having each give a little. Unfortunately, the optimal decision is most likely not made.
5) **Collaboration:** The team agrees to solutions to the conflict that satisfy all team members. This requires cooperation and respect and takes the most time, usually with the most satisfying outcome.

Of the above approaches, collaboration usually leads to the best and most creative decisions and should be the preferred method of conflict resolution.

4.2.6 References

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4.3 Social Styles

One of the most important skills that a team can develop is the ability to manage the diversity inherent among its members. This diversity is one of the strengths of using teams to solve complex problems like your design project. Managed properly, the team's diversity can be leveraged to provide high performance for many of the tasks that need to be completed during the project. Managed improperly, misunderstanding of team diversity can lead to prolonged conflict, team member isolation and poor team performance. The types of diversity that design team members' exhibit include basic knowledge, skills, attitudes, ability, culture, behaviors, and problem solving and working styles. This document provides a framework for addressing team member's behaviors and how they are affected by Social Styles.

4.3.1 Social Styles

The social style model was originally developed by Dr. James Taylor who was a staff Psychologist at Martin (later Martin-Marietta) Corporation. It was based on earlier work by Dr. David Merrill and Roger Reed who were trying to understand how to predict individual success in business careers based on personality. The Social Style Model™ is now trademarked and owned by the TRACOM group which is a business consulting firm that helps companies get the most from their organizations. For our purposes, we are going to use the model to provide a framework for understanding team members behaviors based on their perceived social style.

The social style model is based on three main measures of human behavior: **Assertiveness**, **Responsiveness and Versatility**.

Assertiveness is the degree to which one tends to *Ask* or the opposite, *Tell* during interactions with teammates. For example, would you ask, "Should we sit down and do the analysis of this system?" or would you pronounce, "Let's draw the Free Body Diagram now!" Obviously, this is a gray area, and you probably might fall in between the two opposite. You may even switch between on or the other depending on the situation. Assertiveness can also be thought of as the degree to which others see you as trying to influence their ideas.

Responsiveness is the tendency that you emote or control your feelings. In social situations it is a measure of how you openly display or hide feelings or emotions. An *Expressive* behavior is marked by open displays or feelings while *Controlled* behavior is marked by mild or no open displays of emotion. These two measures, Assertiveness and Responsiveness can be plotted on orthogonal axes which divide a plane into four quadrants. Each quadrant as depicted in Figure 33 represents a Social Style. They are:

- **Driving** (Telling and Controlled): A team member with this social style is perceived as independent, practical, decisive, and one who values actions and results.
- **Analytical** (Asking and Controlled): A team member with this social style is perceived as serious, orderly, and logical and one who values facts and accuracy.
- **Amiable** (Asking and Expressive): A team member with this social style is perceived as dependable, open and supportive and one who values security and relationships.
- **Expressive** (Telling and Expressive): A team member with this social style is perceived as ambitious, enthusiastic and stimulating and one who values approval and spontaneity.

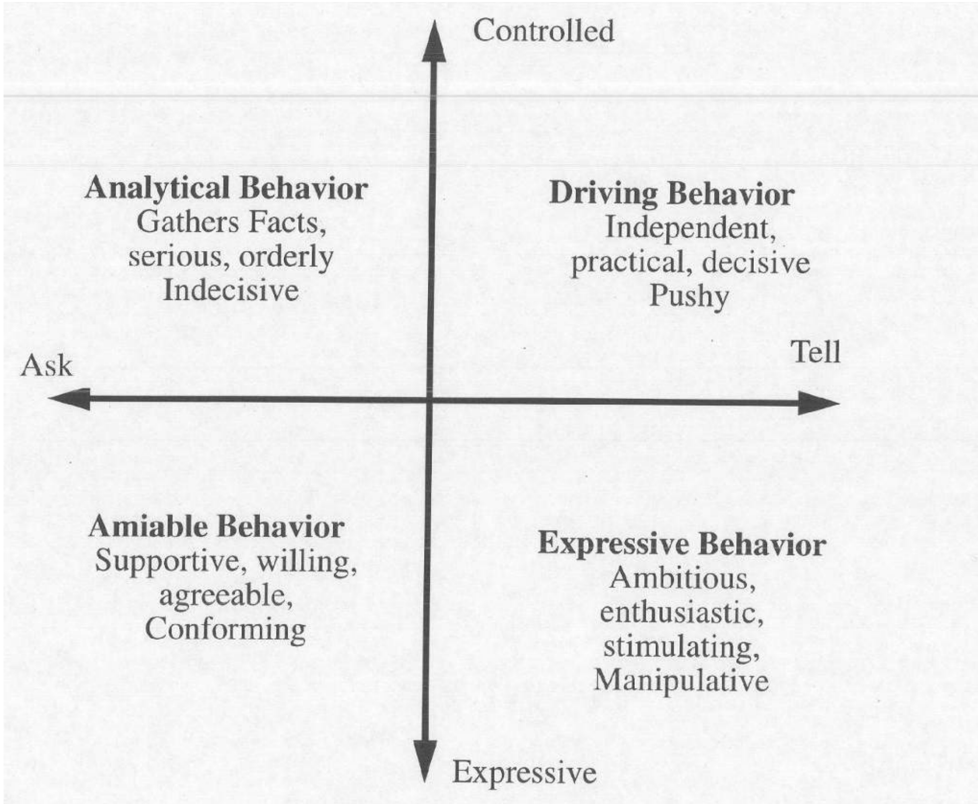

Figure 22: Social Styles with both positive and negative attributes

Versatility, the third measure, is the ability to adjust individual behavior in each situation to maximize team productivity. For example, your dominant social style might be Driving Behavior. If you have high Versatility, you may behave in an Amiable manner if it most benefits your team performance. Being versatile is not “changing” who you are; rather it is adjusting your behavior to meet the team’s needs to maximize performance. It is important to note that there is nothing inherently good or bad about your social style. Also note that it is how you are perceived, not how you are or think you are. It turns out that individuals who measure themselves are usually wrong 50% of the time, yet when assessed by others their social style is consistently identified. Keep in mind that these are not absolute measures.

4.3.2 Managing your Team’s Diverse Social Style

The most important aspect of managing your team’s social style diversity is basic understanding of your teammate’s behaviors and how your own behaviors are perceived. Then you can use your own versatility to adjust your behavior in certain situations to maximize team performance. Your adjustments based on understanding the social styles of your teammates can improve communication, trust, reduce conflict and ultimately increase your team’s performance.

4.3.3 References

- www.Tracom.com, accessed September 2007
- Sullivan, J., Personal Correspondence, ASEE Annual Conference, Honolulu, HI, June 2007

4.4 QFD: Quality Function Deployment

One of the first and most critical tasks in developing a product is understanding the problem. Individuals and companies large and small have been known to spend incredible amounts of time and money, solving the wrong problem and developing products or devices that do not satisfy the original need. This usually results in product development delays once functioning prototypes are built and it becomes obvious that they do not solve the intended problem. These types of delays are very costly to companies and often result in a huge competitive disadvantage. The best way to avoid solving the "wrong" problem is to work hard at defining the "right" problem. For an engineer, the problem is best defined in terms of a specification where actual measures can be used to determine whether a design has met an intended need. This is no easy task and probably you are starting to appreciate the difficultly in defining in engineering terms such ambiguous ideas of "looks good," "is safe" or "the best." One method to translate these ambiguous customer requirements into effective, measurable engineering specifications is Quality Function Deployment (QFD).

QFD was developed in the 1970s in Japan as part of a nationwide effort to improve the countries industrial competitiveness. It was so successful that companies in the U.S. started adopting the method in the 1980s. The American Supplier Institute in Michigan has been a strong proponent of its use in the U.S. auto industry. It has now been established as a proven design technique to assist in specification development and is taught formally to about 2/3 of graduating undergraduate engineers. By adopting this method Toyota Motor Company was able to lower the costs of bringing a new car to market by 60% and to decrease the time required by 1/3. Surveys of mid to large U.S. companies show that about 70-80% use the method and 83% of those feel that the method increases customer satisfaction with their products.

The QFD method is time intensive. It is reported that Ford Motor Company will spend 3-12 months developing its QFD of a new feature. The basic output of the QFD method is a "House of Quality". This is a diagram which contains all the information relating customer requirements to engineering specifications along with analysis of how competitors satisfy the customers. The best way to understand the value is to go through the process. You should develop a House of Quality (or QFD Table) for your design project and revisit it several times before you make a final conceptual decision for your design project.

4.4.1 Steps for the Method

Figure 34 shows a blank House of Quality worksheet (note this excel file is available on PolyLearn for your use). There are seven basic steps to filling this table and capturing what is referred to as the "Voice of the Customer" in appropriate engineering requirements (a.k.a. specifications)

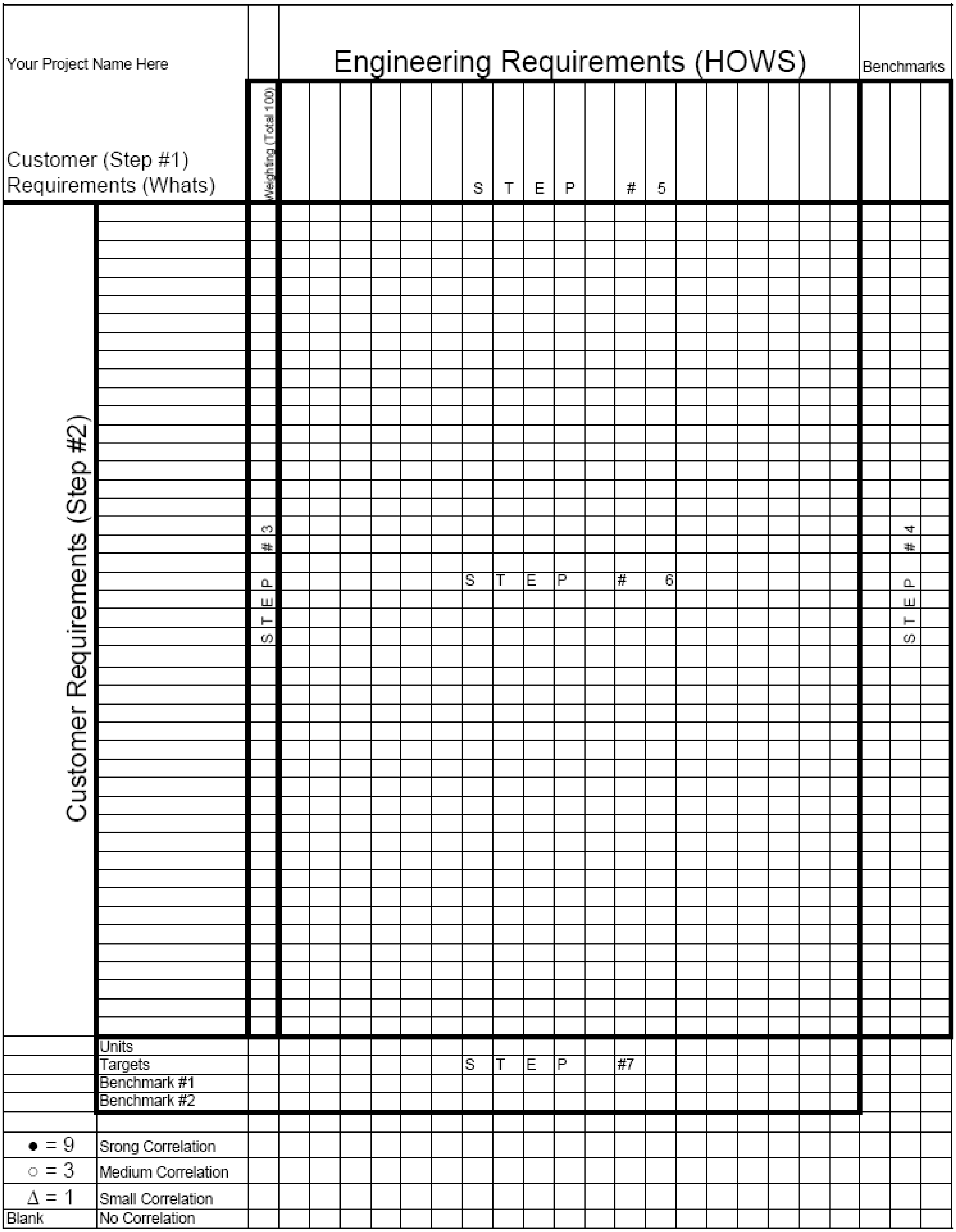

Figure 23: QFD House of Quality (blank)

Step 1 – Identify the Customers (Who)

In consumer product development, it is easy to see that the end-user of a product is a customer; however, they are not the only customer that a designer must consider while developing a product. Manufacturing, Marketing and Sales, and Service may also be important "customers" of a design. If the artifact that is going to be created is a device to increase manufacturing productivity, then the workers who will interface with the device directly might be considered the customers. For your project you must consider all the customers who need to be satisfied by your project, but you can focus on your sponsor. Often QFD tables will have multiple columns input in Step #3 indicating the relative importance of a requirement for the different customers.

Step 2 – Determine the Customer Wants/Needs (Whats)

Different customers want different things in a design. A customer need or want is a statement of "what" the customer wants, usually in their own words. For example, a consumer might want a product that works well, looks good, lasts a long time and is inexpensive. A manufacturing customer might want something easy to make out of easy to obtain materials and standard parts. A marketing and salesperson might want something attractive, reasonably priced and easy to display. There are many techniques to get these needs/wants, but the basic idea is to listen to your customers. It is best to get them in the same room. Surveys are also a great tool. For your projects you will be asking questions of your sponsors and you may add some customer needs/wants of your own as you will in some respects function as the manufacturing customer of your project. Figure 35 lists common customer needs & wants. You can use this to make sure you haven't overlooked any key areas.

Once the customer requirements are determined they can be filled into the House of Quality and grouped by Category

Step 3 – Weighting the Customer Requirements (Who vs. What)

Not all customer requirements are created equal. Some are more important to customers than others. Some are essential. In this step of the QFD process we will mark any must-have customer requirement with an *. One could use surveys and historical data to weight the customer requirements. Another method that we will use is to do pair wise comparison of each customer requirements asking which is more important, adding up how many times each requirement is more important than the others. Once these sums are made, they are scaled so that the total equals 100. Often QFD users make separate weighting columns for each customer so that it becomes clear which requirements are most important to which customer.

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension.
Kinematics	Type of motion, direction of motion, velocity, acceleration.
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, intertia forces, resonance.
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc).
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct protection systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clearness of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Costs	Maximum permissible manufacturing costs, cost of tools, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date.

Figure 24: Potential Types of Needs/Wants (Engineering Design by Paul & Beitz, Springer-Verlag 1988)

Step 4 – Benchmarking the Competition

In the columns of step 4, include the nearest competitors to your project. In many cases there is no competitor, but it is still important to compare against alternatives. The current situation (no new product) might be considered as an alternative. Next mark in the column how well each competitor device satisfies the customer requirements using the following scale:

1 = Design does not meet the requirement at all
2 = Design slightly meets the requirement
3 = Design somewhat meets the requirement
4 = Design mostly meets the requirement
5 = Design Fully meets the requirement

This step will indicate possibilities for competitive advantage and product improvement. It also will show what requirements the competition meets well. You should investigate how your competitor is doing that.

Remember that most "design" is redesign of existing concepts. The best way to get this data is to use "focus groups of users" who can rate the competition. We don't have this luxury although in some cases we can consult with our sponsor or other users of the benchmarked products.

Step 5 – Filling in the Engineering Specifications (Hows)

Hopefully, you have already generated a list of specifications. It probably is not yet complete. Remember from last week that these specifications must be measurable and verifiable. A way to get further specifications is to look down your customer needs/wants and determine how you can measure some aspect of each requirement. It is common to have multiple specifications for each customer need or want.

Step 6 – Relating Customer Needs/Wants to Engineering Specifications (Hows vs. Whats)

This step involves determining the relationship between each customer need/want and each specification. The intersecting cell in the house of quality is filled in depending on the strength of that relationship. You can either use symbols or numbers, although the symbols make for a better visual correlation of the strength of relationship. The symbols (or values) to use are:

● = 9 Strong Relation
○ = 3 Medium Relation
Δ = 1 Weak Relation
Blank – no Relation

This process should be done as a team and will likely lead to many detailed discussions since there is an element of uncertainty here. For a complicated system, filling out this portion of the House can take months!

Step 7 – Setting Engineering Targets (How Much)

This gets at answering the question of how good is good enough. These are the numbers and units of the Engineering Specifications. They must be derived using input from the customer, basic engineering knowledge and by comparing to any competition. There is also space in the section of the table to include any known specifications of your benchmarked competition.

4.4.2 Analyzing the Results

There is huge value in setting up a QFD table due to the discussion by your team about the problem. Note that there is nothing in the table about solving the problem, only defining it. You should always make sure that customer requirements are strongly addressed by one or more engineering specifications. If not (a blank row or a row with only triangles), then you are missing specifications and have not yet fully defined the problem. If you have specifications with no related customer requirements (blank columns or columns with only triangles) then you may be over specifying your problem, or you don't know what your customer wants. You should always be concerned whether your target values are different from your competition, especially if customers are satisfied with you competition. It might mean you are solving the wrong problem! Lastly this is considered a working document and will need to be updated as you learn more about your customer and the problem you are trying to solve. There should be discussion in the specification development portion of your SOW about what you learned from employing the QFD process.

4.4.3 References

- Ullman, D., *The Mechanical Design Process*, McGraw-Hill, 1997
- The American Supplier Institute, http://www.amsup.com/, Accessed September 2007

4.5 Design Thinking and Creative Techniques

Engineers are often called upon to develop innovative solutions to unique technical problems. Engineering is an applied science and combines elements of both Art and Science. One of the skill sets of successful engineers is their ability to solve problems not only with applied technology but with their creativity. With the current "Global" economy, U.S. businesses have been pushing innovation in attempt to have a competitive advantage over lower production cost competition. The idea is that new technology and innovation are the hallmarks of future successful enterprises in the U.S. This document is a summary of the most well-known and generally useful creative techniques for the design process that have been proven effective for engineers in both industry and in applied research. This document closely follows notes developed by Dr. Bernard Roth of Stanford University. He describes creativity as "… a mental process that can aid in the recognition of a problem and can motivate the person to formulate imaginative solutions, which are both valuable and innovative."

4.5.1 Creativity in the Design Process

Phase 2 of Ullman's general design process is titled "Conceptual Design." At this stage, the goal is to generate concepts that will solve the fully defined design problem. Note it is generally not useful to begin an earnest effort of generating concepts until the problem is fully defined. This may lead to wasted effort or worse yet, development of solutions that do not meet customer needs. The conceptual design phase is the prime time to apply formal creative techniques to generate as many concepts as possible to solve a design problem. That stated, the techniques described here are applicable to all stages of the design process and anytime problems that need solutions arise.

4.5.2 The Creative Person

Often "creativity" is associated with "genius." For example, it seems to be universally agreed that Albert Einstein was a creative genius. Many associate creativity with an elevated level of intellectual or artistic functioning. In practice, however, this seems not to be the case. According to Dr. Roth, "All persons of normal intelligence possess some ability to think creatively and to engage themselves in imaginative and innovative efforts." Not only that, but it is possible to improve one's ability to think creatively. Furthermore, creativity is not necessarily associated with elevated levels of intellectual ability. Studies have shown that over 70% of the most creative students do not rank in the upper 20% of their class in traditional IQ measures. Given that all college engineering students are of normal intelligence and know how to learn, it is proper to assume that they can all become more creative through study and practice. This is indeed the case if they are motivated. Motivation to use creativity can take many forms including the most basic to human existence. These might include the need for food and preservation, faith, love, aspirations for fame, fortune or freedom, competition, pride and loyalty. Personal feelings derived for the creative process include pleasure, frustration, exhilaration, fear and satisfaction and pride when a creative task is complete.

The following is a list of attributes that are associated with a creative person. Your further development of all these characteristics will improve your ability for better and more creative problem solving.

- Intellectual Curiosity
- Sensitivity to existing problems
- Acute powers of observation
- Directed imagination
- Initiative

- Ability to think in analogies and images
- Originality
- Intuition
- Memory
- Good verbal articulation
- Ability to analyze
- Ability to synthesize
- Patience
- Determination
- Persistence
- Intellectual integrity
- Good understanding of the creative process

The above list describes human attributes that stimulate creativity. There are many conditions that do the opposite and depress creativity. These will be described next.

4.5.3 Creative Blocks

Adams in his seminal work, "Conceptual Blockbusting" identified major blocks or obstacles to creative thinking and provides methods for overcoming them. The blocks are mental processes that function as a wall to prevent us from correctly understanding a problem or conceiving a solution. Others have identified further blocks so our list is not exhaustive. You can note as you read the list that the "peak" of creative energy for most humans occurs during their childhood where imagination can rule our experience. As we get older, our creative ability is usually eroded due to social pressures and lack of use. It is easy to see how these blocks may have been put in place to allow us to function in our everyday lives. It is equally important to know how to overcome these obstacles when solving design problems. The following gives a general overview of the most common conceptual blocks.

Perceptual Blocks: These are blocks that occur when first encountering a problem that prevents the engineer from correctly perceiving the problem. They include:

- Difficulty in isolating the problem
- Tendency to look at the problem to closely or narrowly
- The inability to view the problem from various viewpoints
- Stereotyped Seeing, "seeing what you expect to see" and premature labeling
- Saturation: The inability to process all problem information.
- Failure to use all sensory inputs.

Emotional Blocks: These blocks tend to color, shade, or limit how we see a problem and we think about it. They include

- A lack of challenge or the problem fails to interest
- Excessive zeal or over motivation to succeed quickly which usually results in going in one direction from the outset
- Fear of making a mistake, of failing, or of taking a risk
- The inability to tolerate ambiguity, or an overriding desire for security
- Preference to judge ideas rather than generate them
- The inability to relax and incubate, i.e., no patience for the creative process to work.

Cultural Blocks: These blocks are acquired by your exposure to a given set of cultural patterns in which you were raised and live. They include:

- The idea that fantasy and reflection are a waste of time and form of laziness. They may even be thought of as a sign of mental instability!
- The idea that playfulness is only for children
- Reason, logic, numbers, utility and practicality are good, and that intuition, qualitative judgments, and pleasure are bad.
- Traditional is preferable to change
- Any problem can be solved by science and money
- Taboos: Things that are considered forbidden or profane.

***Environmental Blocks*:** These blocks are imposed your immediate social and physical surroundings. They might include:

- Lack of cooperation and trust on your team
- Presence of an autocratic boss
- Job insecurity, unwilling to risk
- Distractions, i.e., mobile phones, roommates, etc.
- Lack of support to bring ideas into action

Imagination Blocks: These are blocks that interfere with the freedom with which we explore and manipulate ideas. Other than the first in the list below, most college students do not experience these blocks. They include:

- Fear of the unconscious
- Lack of access to imagination
- Lack of control of imagination
- The inability to distinguish reality from fantasy.

Intellectual Blocks: These blocks usually occur when information is collected or interpreted incorrectly. Much of your undergraduate engineering education has been focused on preventing these blocks from occurring. Some examples are:

- Incorrect information
- Missing information
- Inflexible or inadequate use of the intellectual problem-solving strategies
- Formulation of problems in the incorrect format or "language" (i.e., verbal, math or visual)

Expressive Blocks: These restrict conceptualization at the final stage of idea-expression and communication.

- Inadequate or imprecise language skills to express an idea (language includes verbal, visual, mathematical, musical, etc..).
- Slowness in expression that results in the inability to record ideas quickly enough
- In mechanical engineering, often time the inability to draw out ideas on paper can limit your expression.

4.5.4 The Creative Problem-Solving Process

Like the overall design process, there is a generally agreed upon process that most individuals use (some consciously, but most unconsciously). This process involves five major steps:

- **Preparatio**n: This is the problem formulation phase and involves gathering information and skills needed to work on a creative solution. Note the strong parallel to what is required in your Statement of Work.
- **Concentrated Effort** ("Perspiration"): As Tomas Edison says, Creative "Genius is 1% inspiration and 99% perspiration." This is a period of intense work and can be characterized by lots of frustration. There are many techniques that can be learned to increase the productivity of this phase which are outline in the next section
- **Withdrawal** ("Incubation"): This is a period where the conscious mind stops working on a problem and the subconscious takes over.
- **Insight** ("Illumination"): This is that magic "ah ha" moment when the light bulb goes on as the solution appears to the conscious mind. Make sure you are ready to document it!
- **Follow-Through**: The creative process is complete and accomplishes nothing if the there is no follow through on the idea including implementation.

Although in the best of all worlds, this would be a linear process with a fixed amount of time dedicated to each step with guaranteed results; none is true. Like the design process, it is not linear, and iteration is again an important characteristic. Also, the withdrawal ("incubation") phase may take some time. There are many documented magic moments of insight during times of idle thought. These famous situations were always preceded by preparation and concentrated effort!

4.5.5 Techniques to Improve Creativity

The following described techniques are well-documented and recommended to improve the Concentrated Effort phase of the creative problem-solving process. They are named separately but combining them is often desirable. They include:

- Set-Breaking
- Brainstorming
- Inversion
- Analogy
- Empathy
- Fantasy
- Check Lists
- Attribute Listings
- Morphological Analysis

***Set-Breaking*:** A "Set" is a word used by psychologists to mean a predisposition to or a particular method or way of thought in solving a problem. It is also sometimes referred to as a "schemata." A person who is "in a rut" connotes set. Being aware of a set is not easy and being aware that a set might be limiting your problem-solving creativity is even harder. To become aware of a set, one can use a "set-breaking" experience. This means forcing yourself to let go of your conventional ways of thinking. One technique is to imagine that you are trying to solve the same problem in a unique environment. For example, your user is in the Arctic, not California or maybe they live on another planet where gravity is reversed, and the inhabitants are handless and have no vision. In this imaginary world, your set will not work, forcing you outside it to look for solutions. When you return from this imaginary environment you may have lost some of your set.

***Brainstorming*:** This is clearly the most used and trusted idea generating technique. It can help remove obstacles of creativity that are caused by fear of criticism or fear of appearing foolish. The basic idea is to generate as many ideas as possible by avoiding all judgment during the process. There are basic rules that should be followed:

- Someone must keep a record of all ideas for all to see
- No Criticism or Judgment (good or bad) is allowed.
- Go for quantity and always say the first thing that comes to your head.
- Think as wild as possible and use humor.

A brainstorming session is over when you will have an extensive list of ideas that have spawned new ideas. If done correctly, you will be exhausted at the end of the session and should wait until a later date for evaluation and further elaboration.

***Inversion*:** This is set-breaking technique which calls for looking at problems from new vantage points. Osborn suggests a checklist to consciously set break by asking the following questions to ask of your problem.

- Could a solution be put to other uses? Are there other ways to use it or new ways if it was changed?
- Can you adapt another idea? Do similar things exits. What ideas do similar things suggest? Are there parallels?
- Can something be modified? Is there a new twist, color, motion, sound, odor, form, shape or any other change?
- Can ideas be magnified? What can you add, more time, more frequency, stronger, higher, longer, more value?
- Can an idea be minified? What can be subtracted, made smaller, condensed, miniaturize, lower, shorter or lighter?
- What can be substituted? Who else instead? What else instead? Other ingredients, other materials, other part, other power, other place, other approach, other process?
- What can be rearranged? Can components be interchanged? Other patterns, other layouts, other order, switch cause and effect, difference speed, different schedule?
- What can be reversed? Can positive and negative be switched? Can it be turned around,
- What can be combined? Can there be a blend? Alloys? Assortments, Combine purposes? Combine ideas? Combine appeal?

***Analogy*:** This method uses similar situations in other problems to stimulate new ideas. Analogies may come from other engineering solutions, or from nature, or even from literature non-technical areas. This can be done by individuals and is also useful for groups.

Examples: Could you design airplanes that fly like birds?
Can you make tunnel digging machines that dig like worms?
Can you make landing gear for an airplane that stows like birds' feet?
The original cars were built like horse-drawn carriages.

Empathy: This method involves identifying personally with the thing, part of process being devised. The object is to become the part that is the solution to a problem and see the problem from that position. A famous example is provided by an engineer who was tasked to remove walnut meat (whole) from a shell. By imagining himself as the meat, trying to get out of the shell by pushing, the engineer realized that internal pressure could remove the shell. He then devised a system of drilling a hole in the shell and pressurizing the shell to remove it, thus leaving the meat intact. This is an extremely useful method which requires the willingness to play act. This may require overcoming inhibitions.

Fantasy: Closely related to empathy, this technique requires directed daydreaming. Forget about the rules of nature and let your mind go in any direction your imagination takes you. Easy to do as individual but can also be done in groups.

Check Lists: General listings are useful during early idea development to avoid the omission of key features or customer requirements. They can also suggest possible improvements. The type of list is dependent on the product being developed. New ideas should be added as they occur for later use. When making lists you should keep an open mind for new ideas inspired by associations. Check lists should contain the following information:

- Physical Conditions including size, weight, shapes, taste, color, finish, pressure, temperature, vibration, shock acceleration, noise, radiation, etc.
- Functional Aspects including materials, production processes applications, packaging, etc.
- Attributes and unusual characteristics of shape, finish details, package, energy sources, appearance, feel, fashions, maintenance features, assembly methods, etc.
- Social Aspects including timing, human compatibility, degree of complexity, serviceability, cost, production potential, effect on living conditions, etc.
- Look for Possible rearrangements, recombination, modifications and elimination excessive details, features or waste.

Attribute Listings: this technique involves the list of attributes of various objects, or the specifications or limitations of certain need areas. After completing the list attributes or specifications can be modified allowing originally unrelated objects to be brought together to form new combinations that might better satisfy needs. For example, an old fashioned wooden-handled screwdriver has attributes such as:

- Round, steel shank
- Wooden handle attached by a rivet
- Wedge-shaped end for engaging a slot in a screw
- Manually operated
- Torque provided by twisting action

All these attributes have been changed to improve the screwdriver:

- Round shank – hex shank (can add a wrench for increased torque)
- Wooden handles – molded plastic handle (less expensive, more durable)
- Wedge shape – various interchangeable shapes for different screw heads
- Manual Power – Electric battery or pneumatic available
- Twisting action – “Yankee” type with pushing action

Morphological Analysis: This is a programmable method of using the attribute listing to make new combinations. The method involves breaking the problem into two or more dimensions, attributes or subsystems based on the functional requirements. Each attribute is brainstormed to generate an extensive list of possible ways of meeting the requirement. This list is then placed in an orthogonal matrix and then a new idea is generated by forming every possible combination and evaluation the feasibility of the combination. An example from Adams book is shown in Figure 36 for a new personal transportation device where the three dimensions are power, seating and operational media. Each cube represents a possible combination of the three dimensions for consideration.

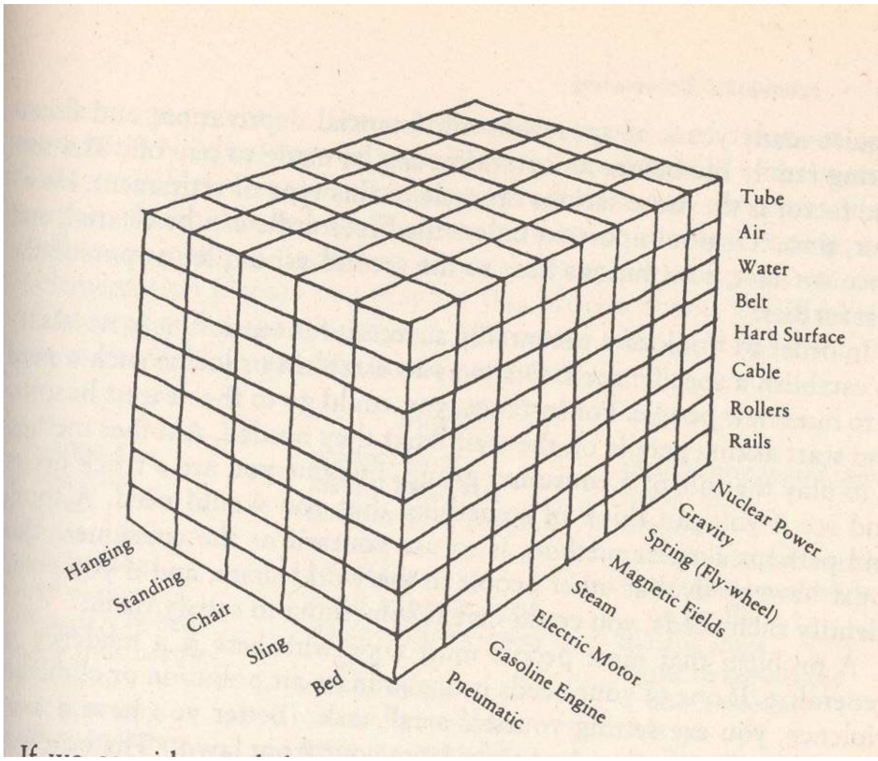

Figure 25: Example Morphological Cube

4.5.6 Last Thoughts on Creativity:

When working at being creative there are two major points to keep in mind:

1) Everyone can be creative
2) Everyone has mental blocks that limit their creativity

By working at the skills and being aware of the cause of your own blocks you can begin to fully tap your creative potential and improve it for the rest of your life!

4.5.7 References

- Adams, J., *Conceptual Blockbusting*, 3rd Edition, Addison Wesley, 1986
- McKim, Robert, *Experiences in Visual Thinking*, PWS Publishers, 1980
- Roth, B., *Notes on Creativity*, ME112 Stanford University, 1994
- Ullman, D., The Mechanical Design Process, McGraw Hill, 1992

Appendix A. Sample Test Procedure

Test Title:
Drill Penetration Rate and Chip Clearance

Test Goals: Verify drill function, determine maximum drill diameter, determine ideal weight on bit, test chip clearance methods, and find starting and continuous current.

Test Safety:

Safety Concern	Mitigation
Heavy Lift Items	• 1 man lift <40lbs • 2-man lift <70 lbs
Concrete Dust and assorted debris	• Closed toed shoes, long pants, safety glasses, and dust masks required for all attendees • Test to be conducted outside. Vacuum for dust extraction to be applied as needed • Air blast operator requires additional face shield

Test Equipment Required:

- Safety Glasses - for ALL attendees
- Dust Masks - for ALL attendees
- Face Shield
- Hammer Drill, drill bits, and test stand
- Buckets of regolith for testing
- Assorted dumbbells
- Air Hose with standard 'Dust off' style nozzle
- Clamp meter
- Extension cord

Test Procedure:

1. Verify all test participants are wearing proper safety equipment. These include Closed toed shoes, long pants, safety glasses, and dust masks. See Test Safety section for additional details.
2. Place Concrete and/or simulated regolith under test stand.
3. Mount Drill to test stand via multiple hose clamps. Verify function via trigger.
4. Mount Weights to drill test stand via hose clamps, fixed column, or multiple extra-strength zip ties.
5. Mark starting height of drill on frame's scale. Mark ending height (1" above bucket bottom).
6. Have stopwatch ready. Set clamp meter to measure max amperage mode to record starting current.
7. Test penetration rate with ½", ⅝", ⅞" and 1" Carbide masonry bits using various weights. Mark drill height every 1 min until drill reaches bottom height.
8. Calculate the average rate and fill in appropriate cell in Table 1.

9. Repeat steps 1-7 as necessary for various materials.

Table 1. Drill Penetration Rate [cm/min]

Drill Size	0 lbs	5 lbs	10 lbs	15 lbs
½”				
⅝”				
⅞”				
1”				

10. Use fastest penetration rate configuration from step 3 to drill holes with varying air blast frequency. Document penetration rate via marks on frame scale and average for Table 2. Test various means of dust containment. Repeat as necessary for various materials.
    - **a.** Air blast operator must wear **face shield**
    - b. Only the air blast operator should be near the test setup during chip clearance testing. All others must maintain 5ft clearance.
    - c. Air nozzle should be standard ‘dust off’ style
    - d. Record line air pressure via wall mounted gauge in machine shop.
    - e. Position nozzle 2” above top of regolith simulant
    - f. Keep bursts as short as possible

Table 2. Drill Penetration Rate [cm/min]

Drill Config	6 bursts/min	2 bursts/min	0.5 bursts/min	No air blast

11. Photograph setup before and after air blast. Also photograph any experimental dust containment methods. Import Photographs to Table 3.

Table 3. Photographs of Chip Clearance Experiments

Before Air Blast	After Air Blast
Dust containment experiment #1	Dust containment experiment #2

Advisor Comments:

Advisor Approval: