MA 546 – Design and Analysis of Experiments

Fuller Labs 311

Tuesday & Thursday 4:00 PM – 5:20 PM

Professor Carly Thorp (she/her)

Email: cthorp@wpi.edu

Office: Stratton Hall 413

Office Hours: W/R 2:30pm-3:30pm in SH 413 or by appointment

Why is a course on designing experiments important?

For nearly a decade, prior to coming to WPI, I worked in the medical device industry, first as a design quality engineer and then as an R&D statistician. Many problems encountered by project teams could have been solved more easily if steps had been taken to design and implement an experiment, rather than using less efficient methods, such as one-factor-at-a-time (OFAT) methodology. Therefore, the purpose of this course is to introduce you to the design and analysis of a variety of statistical experiments and how to apply those methods to a range of real-world scenarios, such as what I encountered in medical device product development and manufacturing.

What will you be learning in this course?

This course is designed as an introduction to design of experiments, with an assumed familiarity of basic statistical tools, such as those covered in MA 511, and a working knowledge of linear algebra.

By the end of this course, you should be able to:

- ◊ Sketch and define out the key terminology used in experimental design
- ◊ Evaluate and interpret the results for experiments with a single factor and multiple factors
- ◊ Understand how to utilize blocks in experimental design
- ◊ Design factorial experiments with the addition of blocking and fractionating
- ◊ Understand how to design and analyze controlled experiments using *R* and *RStudio*
- ◊ Design, implement, analyze, and present the results of a controlled experiment that meets the requirements of pre-determined project criteria
- ◊ Develop a foundation in repeated measures designs (if time allows)

Textbook and Reference Materials

The course will cover material throughout ***Design and Analysis of Experiments*** **by Douglas E. Montgomery (8th Edition or higher)**. While the textbook is not required *per se*, if you can obtain a used, older edition, it is highly encouraged, since the course material will occasionally reference a section in the book.

As some additional references for this course:

- ◊ Books on learning and using *R* that will, hopefully, not become coffee table books:
  - *Design and Analysis of Experiments with R by John Lawson*
  - *The Book of R: A First Course in Programming and Statistics* by Tilman M. Davies
  - *R Cookbook: Proven Recipes for Data Analysis, Statistics, & Graphics* by J.D. Long & Paul Teetor
- ◊ Books on statistics for a bit of lighter, bedtime reading:
  - *Naked Statistics: Stripping the Dread from the Data* by Charles Wheelan
  - *The Lady Tasting Tea: How Statistics Revolutionized Science in the 20th Century* by David Salsburg

Grading Methodology

This course will be using an alternative grading methodology known as standards-based grading (SBG). Some of you may have encountered it before in other courses or in undergrad, while some of you may not have. Regardless of your experience with alternative grading, the intent of SBG is to create a learning environment that allows you to successfully learn the material.

The standards are separated into three categories: **Concept (C)**, **Application (A)**, and **Project (P)**. Each category has a set number of standards, found in further detail in the following "Course Standards" section, and some standards will ***need to be completed more than once*** to receive credit. Each standard will be completed through either an assignment or your final project.

Your final grade will be dependent on meeting these standards, which are relative to the material you will be learning throughout the course, rather than being based on meeting X% in your homework assignments and project, as is done with traditional grading methodology.

For further details on your final course grade, see the "Course Grade Breakdown" section.

Course Standards

Concept (C) Standards represent the core material and concepts you will be learning. These use wording associated with the lower tiers of Bloom's Taxonomy. As shown below, some of these standards will need to be completed **more than once** to receive credit.

Number	Standard Description	Completion Count
C.1	Effectively use the R Markdown tool in RStudio to generate and output a homework assignment and/or the project report into PDF or Word.	2
C.2	Correctly identify and interpret the usage of key terminology for controlled experiments relative to a provided problem scenario.	1
C.3	Identify the null and alternative hypotheses for evaluating the difference between two samples relative to a provided problem scenario.	2
C.4	Using *R* (or similar software), generate the appropriate graphs to look at the difference between two samples and include added details (i.e. colors and axis labels) on those graphs.	2
C.5	Identify the null and alternative hypotheses for evaluating the difference between two variances relative to a provided problem scenario.	1
C.6	Demonstrate the relationship between the χ^2 and F distributions.	1
C.7	Identify the layout of and calculate the components of a one-way ANOVA table.	2
C.8	Using R (or similar software), generate the appropriate graphs to look at the differences between multiple levels of a single factor and include added details (i.e. colors and axis labels) on those graphs.	2
C.9	Identify the difference between replicates and repeats.	1
C.10	Estimate the model parameters of a single factor fixed effects model.	2
C.11	Prove the maximum likelihood estimator of the variance is not equivalent to the expected value of the mean square treatment for a single factor fixed effects model, unless there are no significant treatment effects.	1
C.12	Identify how a block differs from a factor.	1
C.13	Estimate the model parameters of a single factor fixed effects model with the adding blocking parameter.	2
C.14	Identify how the one-way ANOVA table for a single factor experiment changes with added blocks with or without replicates.	2
C.15	Prove the maximum likelihood estimator of the variance is equivalent to the expected value of the mean square error for a single factor fixed effects model with blocks.	1
C.16	Prove the maximum likelihood estimator of the variance is not equivalent to the expected value of the mean squares for treatment and blocks, unless there are no significant effects from the treatments and/or blocks.	1
C.17	Construct the layout of a balanced incomplete block design (BIBD) relative to a provided problem scenario.	1
C.18	Estimate the treatment and interaction effects for a multi-factor design with or without replicates.	3
C.19	Identify the layout and calculate the components of an ANOVA table for a multi-factor design with or without replicates.	3
C.20	Using *R* (or similar software), generate the code and output for the layout of a multi-factor factorial design with replicates and at least three factors.	1
C.21	Identify how an ANOVA table changes when main effect and/or interaction terms are removed for a factorial design with at least three factors.	2

C.22	Construct and interpret a two-factor interaction plot, relative to a provided problem scenario, manually and check using *R* (or a similar software). Include appropriate details (i.e. colors and labels).	3
C.23	Construct and interpret a main effects plot, relative to a provided problem scenario, manually and check using *R* (or a similar software). Include appropriate details (i.e. colors and labels).	2
C.24	Estimate the model parameters of a multi-factor fixed effects model with or without blocks.	2
C.25	Generate and interpret a three-factor interaction plot, relative to a provided problem scenario, using *R* (or a similar software). Include appropriate details (i.e. colors and labels).	1
C.26	Eliminate insignificant terms in an ANOVA table while maintaining hierarchy for a multi-factor fixed effects model, with at least three factors.	3
C.27	Prove the maximum likelihood estimator of the two-factor interaction is not an unbiased estimator of the variance, unless there are no significant interaction effects, in a factorial design.	1
C.28	Identify what cannot be estimated when replicates are not included in a multi-factor fractionated factorial design.	2
C.29	Identify how the ANOVA table changes when blocks are added to a multi-factor factorial design with or without replicates.	2
C.30	Identify the confounded term, generate the defining contrast, and create the design layout for a 2^k factorial, where $k \geq 4$, with at least two blocks.	2
C.31	Generate the defining relation, alias structure, and design layout and identify the design resolution for a 2^{k-p} factorial, where $k \geq 4$ and $p \geq 1$.	2
C.32	Generate the defining contrast, alias structure, and design layout for a blocked 2^{k-p} factorial, where $k \geq 5$ and $p \geq 1$, with at least two blocks.	2
C.33	Identify the usage of the sparsity effects principle for fractionating factorials.	1
C.34	Identify the alias structure of a 2^{k-p} factorial, where $k \geq 4$ and $p \geq 1$, that meets the requirements of a minimum aberration design.	1
C.35	Using *R* (or similar software), generate the code and output for the layout of a blocked factorial 2^k or fractionated 2^{k-p} factorial design, with or without replicates, where $k \geq 4$ and $p \geq 1$ and there are at least two blocks.	1

Application (A) Standards represent your ability to take the base content learned and successfully apply it to realistic problem scenarios, as you will likely do in your future careers or research. These use wording associated with the middle tiers of Bloom's Taxonomy, and, like the Concept (C) Standards, some will need to be met more than once.

Number	Standard Description	Completion Count
A.1	Apply the steps and interpret the results when conducting a hypothesis test to evaluate the difference between two samples, with assumed unknown variances, relative to a provided problem scenario, using manual calculations and then checking results with *R* (or similar software).	2
A.2	Apply the steps and interpret the results when conducting a hypothesis test to evaluate the difference between two variances relative to a provided problem scenario, using manual calculations and then checking results with *R* (or similar software).	1
A.3	Apply the steps for analyzing a single factor experiment, with or without replicates, and interpret the results relative to a provided problem scenario. This should be done using manual calculations and then checking results with *R* (or	3

	similar software), including the interpretation of adequacy checks (generated with software) and usage of an appropriate pairwise comparison.	
A.4	Apply the steps for analyzing a RCBD experiment, with replicates, and interpret the results relative to a provided problem scenario. This should be done using manual calculations and then checking results with *R* (or similar software), including the interpretation of adequacy checks, which can be directly generated with applicable software.	2
A.5	Apply the steps for analyzing a BIBD experiment and interpret the results relative to a provided problem scenario.	1
A.6	Apply the steps for analyzing a multi-factor factorial designed experiment, with or without replicates, and interpret the results relative to a provided problem scenario. This should be done using manual calculations and then checking results with *R* (or similar software), including the interpretation of adequacy checks, which can be directly generated with applicable software.	3
A.7	Apply the steps for analyzing and interpret the results for a confounded 2^k factorial, where $k \geq 4$, with replicates and at least two blocks, relative to a provided problem scenario. This should be done using manual calculations and then checking results with *R* (or similar software), including the interpretation of adequacy checks, which can be directly generated with applicable software.	1
A.8	Apply the steps for analyzing and interpret the results for a 2^{k-p} fractionated factorial, where $k \geq 4$ and $p \geq 1$, with replicates relative to a provided problem scenario. This should be done using manual calculations and then checking results with *R* (or similar software), including the interpretation of adequacy checks, which can be directly generated with applicable software.	2

Project (P) Standards represent you and your group's ability to apply the material learned to a controlled experiment of your own design. These will encompass your ability to use the material learned and meet the project requirements in your final report and presentation. Unlike the Concept (C) and Application (A) Standards, each of these standards only need to be completed once to receive credit.

Number	Standard Description
P.1*	Design, implement, and analyze the results for a controlled experiment that meets the base requirements laid out in the project criteria.
P.2	Use the correct terminology (i.e., factors, factor levels, response(s), block(s), and treatments) for controlled experiments in the final report and presentation.
P.3	The report and presentation contain **at least two** scientific hypotheses which clearly relate back to the objectives of the experiment and are evaluated in the results.
P.4	The report and presentation contain all appropriate sections and components, based on the provided project criteria, and those sections and components are complete.
P.5	The statistical analysis in the report and presentation includes all appropriate inference methods with no significant errors in calculations.
P.6	Usage of software is fully relevant to the statistical analysis and properly cited in the report.
P.7	All content in the report and presentation flows logically and is organized into clear sections, and there is clear introductory information (including a roadmap or table of contents).
P.8	During the presentation, the group demonstrates appropriate "soft" skills and a clear understanding of individual roles while presenting.
P.9	Content in the report and presentation is completely free of any opinion or emotion and uses only facts to formulate conclusions and make recommendations.
P.10	The report and presentation include **at least three** appropriate graphical visualizations and/or tables that are fully legible, integrated well, and add value to the report and presentation.

P.11	Content in the report and presentation is clearly checked and free of most structural, grammatical, punctuation, and typographical errors.
P.12	Provides a detailed recommendation for future iterations of the experiment for developing a predictive model based on the lessons learned and are logically derived from the analysis.

*needs to be completed to meet the course requirements

Course Assignments and Final Group Project

Throughout the semester, there will be a variety of opportunities to meet the required course standards for your desired grade in the course.

The **first part** of your grade are at-home assignments which will be used to meet the Concept (C) and Application (A) Standards:

- **Concept Checks**: These will focus solely on the Concept (C) Standards and be available to take on Canvas, with a total of 8 over the course of the semester. Once available, you will have until the end of the semester to submit for credit. However, I ***strongly*** encourage you to complete each one within the first week of its availability to stay on track with the learning material and complete standards in a timely manner, rather than waiting until the end of the semester to meet most of the required concept standards for your intended grade!

  These will be graded as “Standards Met” or “Try Again.” You will be allowed 5 attempts for each concept check, but, once started, you will have an hour to submit, as you would a quiz, unless an approved accommodation applies.

- **Homework Assignments**: These will mostly focus on the Application (A) Standards but will have a few of the Concept (C) Standards included. There will be 5 of these to complete over the course of the term and, to be accepted for credit, must be submitted **within one week of the due date**. If you are unable to submit on time, you may use a token for an additional 24-hour extension (see the “Tokens” section for further details).

  These will be graded, according to a rubric, as “Standards Met” or “Revisable,” but will show up as “Complete” or “Incomplete” in Canvas. You will be provided feedback as to which standards were completed and which ones need additional work with suggestions on how to meet the incomplete standard(s). To revise the standards within a homework assignment, you will need to submit a token (see the “Tokens” section for further details).

The **other part** of your grade consists of a group project, with a group of your choosing, which will be used to meet the Project (P) Standards. For your project, as a group, you will need to demonstrate an understanding of how to design, implement, analyze, and interpret the results of a controlled experiment based on a real-world scenario of your choice.

Your group will be required to submit a final technical report and give a final presentation of your project to the rest of the class on the last day of the course. You will also have required "project checkpoints," graded as "Complete" or "Incomplete," throughout the semester to ensure your group is on track to complete the project on time. Further project details are posted on Canvas.

Refer to the course calendar on Canvas for due date reminders.

Course Grade Breakdown

To receive a particular grade in this course, each category requires a minimum number of standards that must be completed, as shown in the table below:

	Concept (C) Standards	Application (A) Standards	Project (P) Standards
	Out of 35	Out of 8	Out of 11*
A	32	7	10
B	30	6	9
C	25	5	7
D	22	4	6

*for the Project (P) Standards, every group project must meet P.1, which is not included in this count

Additionally, to meet the course requirements, every homework assignment must be completed and submitted <u>within one week of the due date</u>.

There's a bit more flexibility on the weekly concept checks. By the end of term, to receive an/a:

- A: must complete all 8 concept checks
- B: must complete at least 7 (out of 8) concept checks
- C: must complete at least 5 (out of 8) concept checks
- D: must complete at least 4 (out of 6) concept checks

Throughout the semester, I encourage you to keep track of the standards you have met using the Excel spreadsheet linked on the course Canvas page under the module "Course Need-To-Knows." This will not only help you with tracking your grade in the class, but it will also allow you to maintain awareness of what topics or material you may need additional guidance understanding.

I reserve the right to modify the above grading criteria, but not to lower the grade you would have received. If your grade does not meet the minimum criteria for a "D," then you will receive an "F" as your final grade.

Software Requirements

For your homework assignments and group project, the statistical software you will be recommended to use is *R* in conjunction with *RStudio*. However, if you have a stronger familiarity with another coding software and **you can make the argument** that it can be used to effectively conduct statistical analyses and generate experimental layouts you will not be discouraged from using it.

Why *R* and *RStudio*? Well, for a couple of reasons…

First, it's free and open source, which makes it easily accessible for anybody, no matter what field they are studying or where they are working. Secondly, because it is open source, it is the primary software used by researchers and statisticians, so many of you will find it useful in your future studies and careers. Plus, it never hurts to add a new skill your resume!

Other statistical software packages are used within a variety of industries, some of which you may encounter in your careers, such as Minitab, JMP, SAS, and StatEase Design Expert. Additionally, Microsoft Excel can be used to conduct basic statistical calculations and create graphical visualizations but is generally not recommended if other statistical programs are available.

Refer to the Canvas module "Course Need-To-Knows" for instructions on installing R and RStudio.

Tokens

To allow a bit of flexibility throughout the semester, you will be granted 5 tokens at the beginning of the semester, which can be put towards the following:

- ◊ Revisions of standards on any assignment, ***except*** for the final project report and presentation (see the following section "Assignment Revisions" for further details).
- ◊ 24-hour extensions on any of your assignments, except for the final project report and presentation. Requests for extensions must be submitted **before** the assignment is due.
- ◊ Any other bending of the course rules you might want – just discuss with me first!

Token requests must be submitted via the Google form linked here and on the Canvas course page under "Course Need-To-Knows." Requests submitted via email will **not** be accepted.

These tokens can be used at any time throughout the semester. However, the last day to submit a token for an approved revision or extension is **December 13th** and any revised or extended assignments / standards must be submitted by **midnight on December 15th**.

Assignment Revisions

After submitting a token for revising standards on a particular homework assignment, you will be provided access to a revision submission on Canvas. Your revision does not need to include your entire assignment (i.e., work for problems associated with standards which were met), but it must meet the following criteria to be accepted for assessment:

- ◊ List of standards which are being revised in your submission
- ◊ A detailed explanation as to why each standard needs to be revised relative to the problem context (e.g., if your calculations for the ANOVA for a multi-factor factorial design were done incorrectly, specify how they were done incorrectly)
- ◊ Your revised work on each standard, including explanations, calculations, coding input / output, etc…as applicable relative to the problem context

Course Communication

The best method of communication for directly contacting me or your TA is through email. However, any announcements, assignments, or any other information you need will be found on the course Canvas page. Lecture materials, under each of the respective modules, will be posted prior to class and any notes added to the lecture materials will be posted within 24 hours after class.

If I forget, at any point, to post the lecture slides or notes, please do not hesitate to send me an email (cthorp@wpi.edu) to remind me. I do occasionally forget ☺

Class Attendance and Echo360 Class Recordings

If you are unable to attend a class or would like to review a particular class for studying, there will be recordings available via Echo360 on the Canvas page.

Unless an approved accommodation applies, it is ***expected*** you will attend class and not attempt to utilize the Echo360 recordings as your primary source material. While attendance is not mandatory or required for course completion, I encourage all of you to attend class to participate in discussions and hands-on activities to facilitate your learning.

Tips for Success

To be successful in this course, I encourage you do to the following:

- ◊ **Attend class regularly**. In addition to the lectures, there will be regular in-class discussions and hands-on activities to help facilitate your learning.
- ◊ **Ask questions**. This can be done during class, office hours, or via email. If there is a topic or homework problem you need additional guidance understanding, please let me know.
- ◊ **Engage and participate (in the way in which you feel most comfortable)**. While it may not seem like it, I'm an introvert by nature but I have a passion for education and want to help you gain a solid foundation in statistics. I am not the type of professor who calls out their students, but I also do not want to be the one talking the whole class.
- ◊ **Be open-minded**. My approach to teaching and grading is entirely about ensuring you learn the material to the best of your abilities. If it's not the typical approach you have seen by other professors, I encourage you to give it a chance, but if there is ever a point in the course when it is not working for you, please let me know!

Statement of Respect

As your professor, I expect you to treat your peers with respect and engage in considerate communication. Everybody comes to the table with different strengths, and weaknesses, so I encourage you to focus not only on your own strengths but also those of your peers.

To ensure you feel respected and part of a safe and inclusive learning environment, please do not hesitate to reach out to me if any of the following are relevant to you:

- If you have a name and/or pronouns that differ from those in your official WPI records
- If something was said in class (by anybody) that made you feel uncomfortable and/or you feel like your performance is being negatively impacted by experiences outside of the course

Academic Honesty

You are expected to be familiar with WPI's Academic Honesty policies.

All acts of fabrication, plagiarism, cheating, and facilitation can be prosecuted according to the WPI's policies. If you are ever unsure as to whether your intended actions are considered academically honest, please contact me directly.

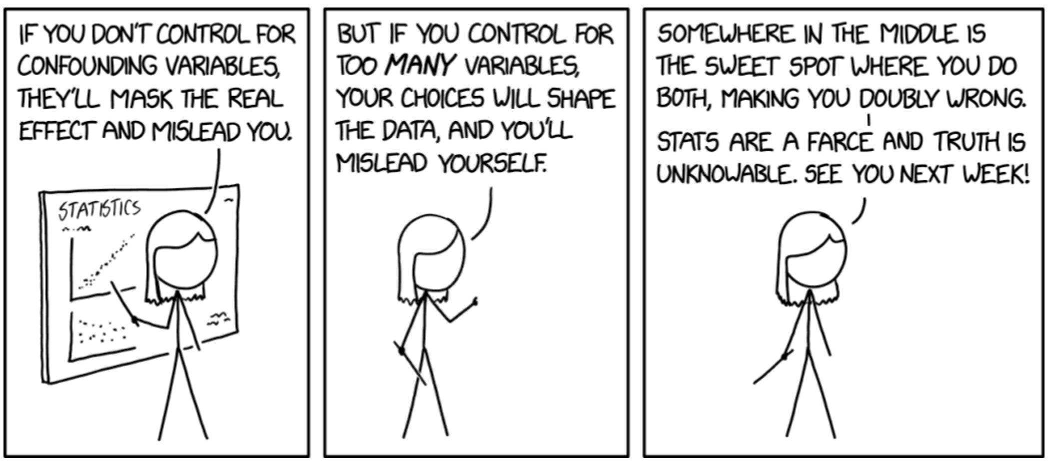
Student Resources

Mental Health & Physical Wellbeing

Your mental health and physical wellbeing are of utmost importance. If you are struggling with your health or wellbeing, please reach out to the Wellness Center or Student Development & Counseling Center (SDCC). Resources can be found on wpi.edu/student-experience/resources/be-well-together.

Accommodations

If you need accommodations or support throughout this course, you are encouraged to contact the Office of Accessibility Services (OAS) as soon as possible to ensure that such accommodations are implemented in a timely fashion. The OAS is in Unity Hall and can be reached via phone (508-831-4908) and/or email (accessibilityservices@wpi.edu).



https://xkcd.com/2560/