Teaching Experimental Design

in Middle and High School Science Classes

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About the Author

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1. Science and Experimentation

There is an unwritten rule that a book about science and how to approach it should start with a chapter on the nature of science. This, of course, is that chapter.

When we think of scientists, we think of people doing experiments in a laboratory, but science covers everything in the universe and how it works, from atoms and sub-atomic particles to living things to forces and energy to planets and galaxies.

Science has always existed, and human understanding of science has developed as the human species developed. Science includes many processes, including observation (noticing things that happen) and experimentation (deliberately causing something to happen and observing the results), deductive reasoning (answering questions like “How?” and “Why?”) and inductive reasoning (making predictions based on what we already know or have observed).

These processes are, of course, interconnected. At the core is the idea that things happen because of laws of nature and the way those things interact with those laws. Scientists are inherently curious people; in order to understand how a thing fits in with the laws of nature, we poke and prod the thing to see what happens. That deliberate poking and prodding that humans start doing when we are toddlers and continue to do throughout our lives is experimentation.

When a toddler knocks things off of a table, they are performing a random experiment, observing how everything falls rapidly toward the floor. When they find something that behaves differently, such as a piece of tissue paper that floats down slowly, this new knowledge is interesting, and requires more investigation. Adult scientists do the same things.

However, scientists have shown that we learn more and can draw better conclusions if we create robust experiments in which we know what is being tested, control what is not being tested, and in which we attempt to remove conscious and unconscious biases that might lead us to erroneous conclusions.

This process of creating robust experiments needs to be learned, and the subject is complex enough that if it is to be learned, it needs to be taught. This book, therefore, is an attempt to describe the process of teaching experimental design, specifically to middle and high school students.

2. Why Teach Experimental Design?

There are a lot of versions of the scientific method taught in schools, but the common thread is that the centerpiece of science is performing experiments. However, when we teach science to our students, many of us teach the content and give our students scripted "experiments" that provide an example of that content. Here are two stories that illustrate some of the problems with this approach:

"I don't remember what we did."

When I start teaching my high school students about experimental design at the beginning of each school year, I ask "What was your favorite experiment from science class last year?" Most of them struggle to remember enough details about the experiments that they did to be able to answer the question.

For students who took chemistry, they usually remember "the one with the colored fire" (flame tests). However, most of them have no idea *why* they did the experiment or *what caused* the flame to change colors, despite having previously answered those questions in a lab report. And when I follow up by asking what their *second*-favorite experiment was, almost none of them can recall one.

"No offense, but I hate science."

Early in my teaching career, a student came into my classroom and said, "No offense Mr. Bigler, but I hate science."

I asked, "When did you first start hating science?"

The student replied, "In fifth grade."

I asked, "What changed that year?"

The student replied, "That's when we stopped *doing things* and started learning out of a *book*."

Students understand that science is about *doing things*. They want to understand what they are doing and why, and they get frustrated and shut down when they are left out of that part of the process.

How We Got Where We Are

Of course, science teachers understand that science is about *doing things*. However, several factors always seem to get in the way:

- *"There's too much preparation. I have to get out the equipment and set it up, and then I have to write super-detailed instructions that the kids can't mess up."*
- *"I have too much content to cover. I only do a handful of labs so my students can see a few 'real-world' examples of the content."*
- *"My students don't follow the directions."*
- *"Some of my students don't know what to do, so they sit and do nothing. Sometimes it takes halfway through the class period before I can get to them, and then they don't have enough time to do the experiment."*
- *"My students get off-task and play with the equipment or create other behavior problems."*
- *"A few of my students monopolize my time by asking for clarification about every step."*
- *"After we do the experiment, my students don't remember the details."*
- *"My students forget to write down their data."*
- *"My students' lab reports are terrible. They copy the procedure I gave them, but they don't make corrections for the things we did differently."*
- *"My students can't do the calculations without extensive scaffolding."*

These statements are all symptoms of the same problem: the experiment was designed by someone else. Students were not privy to the thought process that went into designing the experiment, so they never had a chance to become invested in it.

Because the students did not actually understand the experiment before starting it, they had no choice but to follow the directions blindly, being as careful as possible even though they did not understand what they were doing or why. This left them with no remaining cognitive capacity to think about the experiment at a higher level, where they could consider the reasons for the procedural steps.

The problem also affects students' ability to perform analysis afterwards. Because the directions tell students in excruciating detail how to take their measurements (and often "helpfully" provide a blank to write the number into), they don't have cognitive capacity to keep track of which quantities they measured or why they needed those quantities. When it comes time to perform the calculations, they need to read through the procedure to try to figure out which quantities they measured. Then they need to figure out which equation to substitute their measurements into, and which quantity they need to substitute for which variable. With sufficient scaffolding they can get the "right" answer, but the answer is worthless if the scaffolding that was required prevented them from understanding how they got it.

A Solution that Works

To solve these problems:

1. Involve students in the experimental design process.
2. Stop giving them written directions.

Step 2 is scary for teachers who are not used to doing inquiry-based experiments. Most teachers respond, "But if I don't give them written directions, they won't know what to do!"

Those teachers are right. Of course students won't know what to do because the solution to the problem is not as simple as merely withholding the directions—if that were the case, teachers would have figured it out long ago and a book such as this would be unnecessary. The task of the teacher is to *teach* the experimental design process, such that students can:

- Figure out which quantities they need to measure.
- Figure out a procedure for causing the "action" of the experiment to happen and a procedure for obtaining the necessary measurements.
- Figure out how to use their data to calculate the desired quantity.

An example of how well this can work happened in one of my classes in 2022:

> *My physics students were doing a calorimetry experiment, in which they had to determine the specific heat capacity of an unknown metal. Because my students had taken chemistry remotely due to the COVID-19 pandemic, they had not done any chemistry lab experiments and had never used a Bunsen burner. This meant the pre-lab discussion needed to include teaching them how to safely light, adjust and use the burners.*
>
> *Just as the groups had finished lighting and adjusting their burners, obtained and set up their equipment, and started heating their metals in a hot water bath, one student arrived tardy to class and in tears. I stood in the doorway, splitting my attention between talking with the student (who stood just outside the classroom) and watching the students in the classroom as they did the experiment. By the time I had finished consoling the student and gone back into the classroom to check in with each lab group, all but one of the groups had already finished the experiment, collected all of their data, and were starting the clean-up process.*

The students understood the experiment and knew exactly what they needed to do and which measurements they needed. None of the students needed to ask any clarifying questions during or after the experiment, and except for a couple of algebra mistakes, all of the students calculated their metal's specific heat capacity correctly.

Of course, students did not arrive in my class at the beginning of the year with this level of autonomy. This experiment was performed near the end of the school year, and in addition to learning physics content, my students had spent the year learning how to design experiments, and how to carry them out.

3. Inquiry-Based Experiments *vs.* Experimental Design

If your experience in science classes was like that of most people, you probably always did "experiments" that were devised, planned down to the finest detail, with directions that were painstakingly written out and debugged long before you ever saw them. You learned to faithfully follow the directions, and as long as everything that happened matched the instructions, you knew that the "experiment" must have come out right.

As a science teacher in the 21st century, you are likely familiar with *inquiry-based experiments*, which attempt to address this problem. In a typical inquiry-based experiment, students are given an experimental objective and a set of materials. Students work out the procedure and then carry out the experiment. There has been a significant and successful shift toward these types of experiments starting in the late 2000s.

"Inquiry-based experiments" is a broad topic, and can be implemented in many different ways. (Friessen & Scott, 2013)* The degree of success depends on giving students just the right amount of scaffolding. Open or "unguided" inquiry, where the inquiry is so broad and open-ended that students have no idea how to begin, is often unsuccessful at the K-12 level. (Kirschner, Sweller, & Clark, 2006)†

Teachers who are familiar with Lev Vygotsky's theory of the Zone of Proximal Development (ZPD) (The Decision Lab, n.d.)‡ understand that open inquiry is impossible for most students, even with assistance, and following a scripted procedure is already possible without assistance (which means the student does not learn any new skills from the task). *Guided inquiry*, however, provides scaffolding that enables students to work within their ZPD to determine an experimental procedure for themselves.

Guided inquiry will be used in this text to refer to the way that guided inquiry is often taught in high schools: an experiment in which students are given an objective and an approach to achieving it. That approach usually includes the action(s) necessary and the quantities that need to be determined. Students are tasked with determining the procedure and iteratively modifying it based on their data and analysis.

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* Friesen, S., & Scott, D. (2013). Inquiry-based learning: A review of the research literature. *Alberta Ministry of Education*, *32*.

† Kirschner, P., Sweller, J., & Clark, R. E. (2006). "Why unguided learning does not work: An analysis of the failure of discovery learning, problem-based learning, experiential learning and inquiry-based learning." *Educational Psychologist*, *41*(2), 75-86.

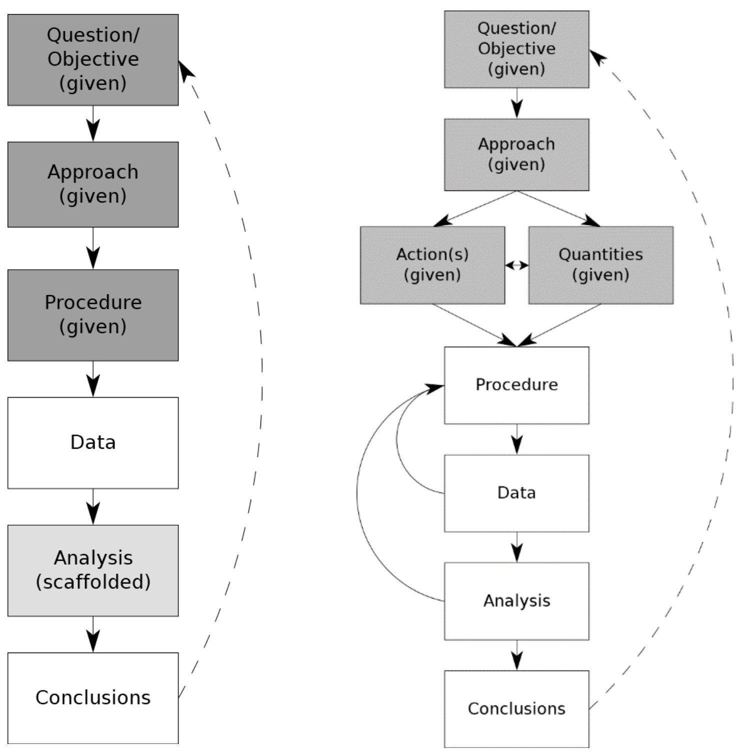
‡ https://thedecisionlab.com/reference-guide/neuroscience/zone-of-proximal-development accessed 7 August 2022.

In a traditional scripted procedure experiment, students are given the experimental objective. The approach is explained in an introduction, which students usually skip over or skim. They attempt to follow the scripted procedure, which tells them which data to take. They perform a heavily scaffolded analysis, attempting to get the "correct" answers, and then struggle to write a meaningful conclusion.

Guided Inquiry (GI) experiments are a tremendous improvement over traditional ("scripted procedure") experiments. Students are still given the objective and basic approach (which often includes the experimental actions), but students are tasked with developing their own procedures, and revising those procedures based on their data and analysis. Analysis in a GI experiment is usually much less scripted, and students are responsible for figuring out the analysis based on what they did for their procedure.

Scripted Procedure High School Experiment

Guided Inquiry (GI) High School Experiment



In GI experiments students are usually given a limited choice of equipment (often only equipment that is specific to the experiment, though sometimes whatever equipment is available in the classroom). Given the objective and the equipment, students can usually envision the entire experiment and the task that remains is for them to devise a procedure to "connect the dots".

GI experiments are relatively straightforward for the teacher because the experiments are well-defined, and the skills that students need in order to be able to fill in the steps can be taught over the course of a few lab experiments. Once teachers get used to having their students do GI experiments, the teachers benefit from not having to write an ironclad procedure, and from the students having a much better understanding of what they are doing and why. Although inquiry is initially outside most teachers' comfort zones, once they get past the initial hurdles, most teachers find it easier and more rewarding to have their students do experiments this way, rather than the scripted procedure experiments that they had done previously.

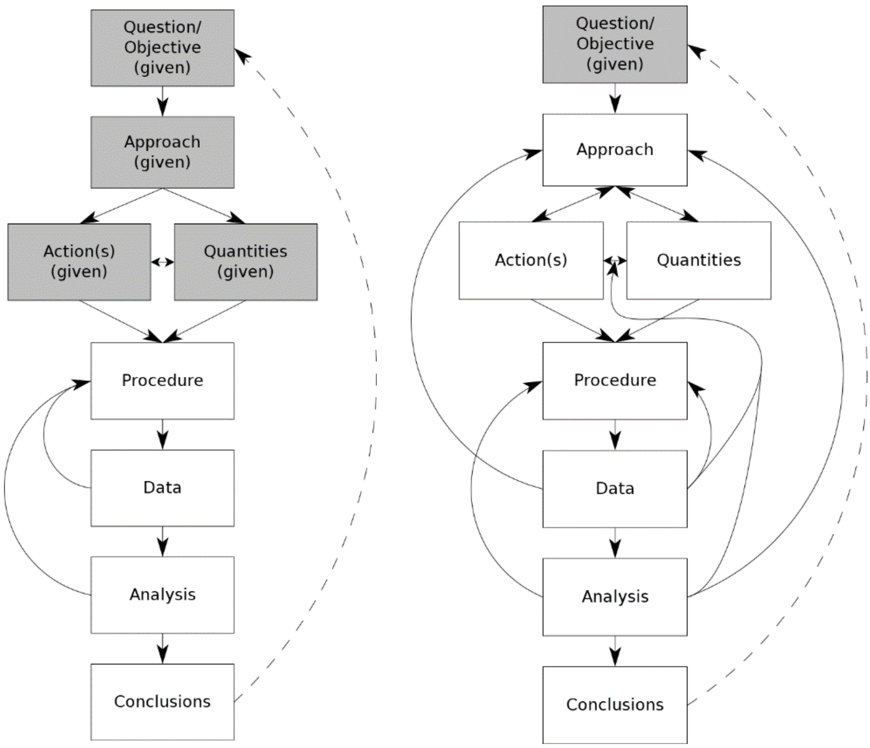
These GI experiments are essential to students' understanding of how science works, and are one of the major stepping stones that teachers use to lead students down the path of experimental design. However, while guided inquiry experiments do a good job of teaching students to be able to figure out how to perform *specific* experiments, they are only part of the larger picture.

Students frequently have trouble making the leap to the higher-level task of being able to figure out what those experiments should be in the first place. When guided inquiry turns into *open inquiry* ("figure out what you want to do and then do it"), students are often stymied by the process and as often as not, teachers end up needing to provide enough one-on-one help to turn the process back into guided inquiry.

The reason that most students struggle with open inquiry is the same reason students struggle with anything else: it requires skills that they do not yet have. The reason that many teachers struggle to teach open inquiry is because there is not much information available about identifying what those skills are and how to teach them.

In this text, the distinction between GI experiments and the "experimental design process" is that in the experimental design process, students are given an objective and are tasked with developing an approach that meets that objective. This process involves determining the action(s) of the experiment and the measurements that will be needed for themselves, and then using those to develop a procedure as they did with guided inquiry experiments. In this sense, those guided inquiry experiments are a subset of the experimental design process.

Typical High School Guided Inquiry Experiment **Experimental Design Process for a High School Class**



Of course, the term "guided inquiry" does not have a fixed definition and can be implemented in many ways other than what is described here. The intent of this book is not to disparage GI in any form. Indeed, GI is an essential part of the broader concept of experimental design. Moreover, it is arguably the most essential piece of that process, and it needs to be explicitly taught and practiced.

Experimental design is a broad topic. Learning to design experiments is in some ways analogous to learning to read; it is a process that students need to learn incrementally over several years. Children start design experiments when they are toddlers, knocking or throwing things off their high chairs to see what will happen. However, this text is focused on those aspects of experimental design that can be taught effectively starting in middle school.

4. The Experimental Design Process

In one sentence, experimentation is about doing something in order to see what happens or figure something out. Experimental design is therefore the process of figuring out what experiment to do and how to do it.

Many educational reforms are implemented as immediate changes, with expectations of immediate results. Learning to design experiments is more like learning to read. Becoming a great reader is a lifelong process that involves learning and combining a wide array of skills over many years. Similarly, becoming skilled at experimental design involves learning and combining a wide array of skills over many years. Each step on the path brings the student closer to the goal, and it is important that students master each step along the way before moving on to the next.

In this book, the process of learning experimental design is described as a journey of several years, spread out from middle school through at least eleventh grade. While this timeline may be ideal, most of us do not teach under ideal conditions. Although it is often disastrous to try to teach students skills before they are ready (see chapter 5. Cognitive Development & Experimental Design starting on page 21), it is usually possible to compress the timeline on the other end. Although students will incorporate the principles of experimental design much more naturally and automatically if they are taught over several years, students who never learned principles of experimental design prior to 10th or 11th grade can still learn and apply many of the skills described in this book in just one or two years.

The Anatomy of an Experiment

The "doing something" part of an experiment involves one or more "actions". The objective of the experiment is usually to see what happens as a result of the action (which usually involves changing one or more parameters), and in most cases, use the results to answer a question, calculate a quantity, *etc.*

As an analogy, we can think of an experiment the way we think of a story:

Story	**Experiment**
setting, background, point of view	*apparatus, setup*
characters' thoughts, observations & reactions	*measurements*
plot	*actions*
resolution	*outcome(s)*
denouement	*conclusion(s)*

To extend the analogy, designing an experiment is like writing a novel. There are many essays on "how to write a novel." While no two are the same, most of them have some version of the same instructions. Each step of those instructions has an analogous step in experimental design:

Writing a Story	**Designing an Experiment**
1. *Decide on the genre, the characters and the world.*	1. *Decide what you want to investigate or find out.*
2. *Choose a point of view.*	2. *Determine what is possible with the resources that you have.*
3. *Establish the conflict and decide on its resolution.*	3. *Establish the objective and how you will determine if it has been met.*
4. *Create an outline.*	4. *Create a flow chart.*
5. *Write the plot.*	5. *Create a procedure and perform the experiment.*
6. *Edit and revise.*	6. *Analyze your results and plan follow-up experiments.*

The process of setting up an experiment and taking measurements is often active, but for the purpose of this text, there are important distinctions among setup, measurements, and actions.

The word ***action*** will be used throughout this document. The "action" of an *experiment* refers to some event or change that must occur in order for the experiment to produce the outcome. An action can be something that the researcher initiates, such as releasing a ball that proceeds down a ramp, or an action can be something that happens spontaneously, such as the chemical reaction between sodium bicarbonate (baking soda) and acetic acid (vinegar), which occurs as soon as the molecules come into contact. Experiments can have zero or more actions; for example, some experiments such as looking at cells under a microscope will not have an action.

Actions sometimes occur as soon as the experimental conditions are set up, and sometimes need to be initiated by hand. Either way, the experimenter needs to ensure that the way that the action is initiated does not affect the outcome.

Control, Manipulated and Responding variables

In every experiment, there are some quantities that you need to keep constant, some that you need to change, and some that you need to observe. These are called ***control variables***, ***manipulated variables***, and ***responding variables***.

control variables: conditions that are being kept constant.* These are often parameters that could be manipulated variables in a different experiment, but are being kept constant so they do not affect the relationship between the variables that you are testing in this experiment. For example, if you are dropping a ball from different heights to find out how long it takes to hit the ground, you want to make sure the wind is the same speed and direction for each trial, so wind does not affect the outcome of the experiment. This means wind speed and direction are *control* variables.†

manipulated variables (*independent variables*): the conditions you are setting up. These are the parameters that you specify when you set up the experiment. You are choosing the values for these variables, so they are *independent* of what happens in the experiment. In general, ***manipulated variables can be measured or predetermined before the "action" takes place***. In most experiments at the K-12 level, there will be only one manipulated variable.‡

For example, if you are dropping a ball from different heights to find out how long it takes to hit the ground, you are choosing the heights before the "action," which makes height a *manipulated variable*.

responding variables (*dependent variables*): the things that happen during the experiment. These are the quantities or outcomes that you won't know the values for or results of until you measure them or they happen, because they *depend* on what happens in the experiment. In general, ***responding variables cannot be measured until the "action" takes place***.

* Note that this text makes a distinction between *control variables*, which are being kept constant but whose values may need to be determined as part of the experiment, and *constants*, whose values can be looked up.

† Of course, variables can be controlled by design, which is what this text describes, or they may be controlled through application of statistics. The latter is beyond the scope of most high school courses, but is something students should expect to encounter if they study STEM subjects in college.

‡ Experiments can have multiple manipulated variables, but the statistical analysis required to determine the effects of multiple independent (or codependent) variables is beyond the scope of a K-12 course.

For example, if you are dropping a ball from different heights to find out how long it takes to hit the ground, the time that the ball takes to reach the ground *depends* on what happens after you let go of the ball. This means time is a *responding variable*.

Qualitative *vs.* Quantitative

There are many ways to categorize experiments. For the purpose of this discussion, we will categorize them based on whether the responding variables are qualitative (collected through observations) or quantitative (numerical data collected through measurements). In this text, those experiments will be described as "qualitative experiments" and "quantitative experiments" respectively.*

Qualitative Experiments

If you are trying to cause something to happen, observe whether or not something happens, or determine the conditions under which something happens, you are performing a qualitative experiment. Your experimental design section needs to address:

- What it is that you are trying to observe or measure.
- If something needs to happen, what you will do to try to make it happen.
- What you can observe that will tell you whether or not the thing you were looking for actually happened.
- How you will determine whether or not the thing you were looking for actually happened.

Often, determining whether or not the thing happened is the most challenging part. For example, in atomic & particle physics (as was also the case in chemistry), what "happens" involves atoms and sub-atomic particles that are too small to see. For example, you might detect radioactive decay by using a Geiger counter to detect charged particles that are emitted.

Examples of Qualitative Experiments

- Observing or detecting an event or phenomenon.
- Determining whether or not an event or phenomenon occurs.
- Determining the conditions under which an event or phenomenon occurs, *e.g.,* determining the effects of different amounts of light on plant growth.

* An experiment can have multiple outcomes, which could even include a mixture of qualitative and quantitative variables. However, for most middle and high school experiments, it is easier to assume that experiments will have only one kind of responding variable or the other.

- Ranking outcomes, *e.g.,* reacting different metals with salts to determine some subset of the activity series.

Essential Questions for Designing a Qualitative Experiment

- Can I observe the phenomenon directly? (If so, the experiment is to simply do that.)
- Do I need to cause the phenomenon to happen?
    - How do I cause it to happen?
    - Can I create a situation in which it *always* happens?
    - Can I create a situation in which it *never* happens?
- If I cannot observe the phenomenon directly:
    - What can I observe that will give me information about the phenomenon?
    - How do I connect what I can observe with the phenomenon I am trying to detect?

Variables in Qualitative Experiments

If the goal of your experiment is to find out ***whether or not*** something happens at all, you need to set up a situation in which the phenomenon you want to observe can either happen or not, and then observe whether or not it does. The only hard part is making sure the conditions of your experiment don't bias whether the phenomenon happens or not.

If you want to find out *under what conditions* something happens, what you are really testing is whether or not it happens under different sets of conditions that you can test. In this case, you need to test at least three situations:

1. A situation in which you are certain that the thing will happen, to make sure you can observe it. This is your *positive control*.
2. A situation in which you certain that the thing cannot happen, to make sure your experiment can produce a situation in which it doesn't happen and you can observe its absence. This is your *negative control*.
3. A condition or situation that you want to test to see whether or not the thing happens. The condition is your *manipulated variable*, and whether or not the thing happens is your *responding variable*.

Quantitative Experiments

If you are trying to determine the extent to which something happens, your experiment almost certainly involves measurements and calculations. Your experimental design section needs to address:

- What it is that you are trying to measure.
- If something needs to happen, what you will do to try to make it happen.
- What you can actually measure, and how to connect it to the quantities of interest.
- How to set up your experimental conditions so the quantities that you will measure are within measurable limits.
- How to calculate and interpret the quantities of interest based on your results.

Examples of Quantitative Experiments

- Quantifying the extent to which an event or phenomenon occurs, *e.g.,* determining the elasticity of a "super ball" as it bounces off of a lab table.
- Quantifying relationships among variables that may affect one another, *e.g.,* determining the effect of acid concentration on the production of colloidal sulfur from sodium thiosulfate, or determining the effects of using materials with different coefficients of kinetic friction on the acceleration of a block down a ramp.

Essential Questions for Designing a Quantitative Experiment

- Do I need to cause something to happen in order to measure the outcome?
- Can I measure the relevant quantities directly? (If so, the procedure is to simply do that.)
- If I can't measure the relevant quantities directly, can I calculate them? If so:
    - Is there an equation that contains the quantities that I need?
    - Can I measure, look up, or control the values of each of the variables in the equation?
    - If there are variables that I cannot measure, look up, or control, is there another equation that I can use to calculate them?

Variables in Quantitative Experiments

In a quantitative experiment, the variables are generally the manipulated and responding variable(s).

If the goal of your experiment is to quantify (find a numerical relationship for) the extent to which something happens (the responding variable), you need to figure out a set of conditions that enable you to measure the thing that happens. Once you know that, you need to figure out how much you can change the parameter you want to test (the manipulated variable) and still be able to measure the result. This gives you the highest and lowest values for your manipulated variable that result in a measurable outcome. Then perform the experiment using a range of values for the manipulated variable(s) that cover the range from the lowest to the highest (or *vice-versa*).

For K-12 level quantitative experiments, a good rule of thumb is the "**8 & 10 rule**": have **at least 8 data points**, and the range from the lowest to the highest values tested should span **at least a factor of 10** (assuming that range gives measurable results).

Group Work

One challenge for science teachers is managing group work. While it is common for students have to do one or two group projects each year in several of their classes, science classes are usually the only place where group work is an ongoing part of the class throughout the year.

Designing experiments lends itself to group work, but the groups need to be appropriately chosen for students to derive the maximum benefit. There are many different opinions about how to set up groups, each of which has valid reasons behind it. Groups need to be large enough to encourage the sharing of ideas, but small enough to discourage hiding behind the rest of the group. Also, smaller groups are more likely to take the time to ensure that each member understands everything, whereas when the group gets larger, students who are lost can feel self-conscious about holding the rest of the group back.

I personally have found that the sweet spot seems to be groups of 4, and that 3 is generally better than 5 when the numbers do not come out even. It is important for the teacher to circulate as the groups are working out their experimental designs, asking Socratic questions as needed to help each group make its plan.

5. Cognitive Development & Experimental Design

There has been a disturbing trend in American education over the past thirty years of teaching concepts to children earlier and earlier.* The rationalization is that exposing children to concepts sooner, even if it is before they are developmentally ready to learn those concepts, means that those concepts will be familiar when the children are finally developmentally ready for them. Unfortunately, this does not work in practice.

For example, numerous articles on cognitive development conclude that children are developmentally ready to begin working with fractions—writing, comparing, and placing them on a number line—in fourth or fifth grade.† However, many state standards require teachers to teach these skills in third grade. For example, the Massachusetts standards for third grade state:

> Students develop an understanding of fractions, beginning with unit fractions. Students view fractions in general as being built out of unit fractions, and they use fractions along with visual fraction models to represent parts of a whole. Students understand that the size of a fractional part is relative to the size of the whole. For example, ½ of the paint in a small bucket could be less paint than ⅓ of the paint in a larger bucket, but ⅓ of a ribbon is longer than ⅕ of the same ribbon because when the ribbon is divided into 3 equal parts, the parts are longer than when the ribbon is divided into 5 equal parts. Students are able to use fractions to represent numbers equal to, less than, and greater than one. They solve problems that involve comparing fractions by using visual fraction models and strategies based on noticing equal numerators or denominators.‡

Because third graders need to demonstrate fluency with fractions on high-stakes tests, teachers have no choice but to teach these children rote procedures that generate correct answers. Unfortunately, people imprint on the first way they learn to do a task, and this applies to children as well as adults. As nearly all musicians and athletes have discovered, learning to do something differently is much more difficult than learning to do the thing another way in the first place, because it requires extensive retraining of behaviors that have become automatic.

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* Bassok, D., Latham, S., & Rorem, A. (2016). "Is Kindergarten the New First Grade?" *AERA Open.* https://doi.org/10.1177/2332858415616358

† https://www.understood.org/en/articles/math-skills-what-to-expect-at-different-ages, accessed 2022-09-04.

‡ *Massachusetts Curriculum Framework—Mathematics* (2017). Massachusetts Department of Elementary and Secondary Education

In the case of working with fractions, children continue to use those procedures that they learned in third grade (often incorrectly) through middle and high school, even after they are cognitively ready to understand how fractions actually work. A significant fraction[*] of these children struggle with fractions throughout their lives.

Other aspects of academic education work the same way. When children are taught how to get the "right" answers or are taught to memorize the "right" procedure for doing something, they imprint on the procedure, not the thought process that led to it. When children are taught experimental design, they need to be taught a mindset and a thought process, not a scripted procedure. For this reason, the teaching of experimental design needs to follow children's cognitive development—expanding at precisely the rate needed to remain within their ZPD. This will enable children to continually process and understand new ideas, and absorb them into what they already know about experimentation and the world around them. *Trying to teach too much too soon will backfire in a way that will not only cause students to fail to grasp the concepts being taught, but that will sabotage future concepts that attempt to build on them.*

Many teachers are familiar with Swiss psychologist Jean Piaget's theory of cognitive development, which defines the following developmental phases and their approximate corresponding ages:

- *Sensorimotor*: birth to age two
- *Preoperational*: ages 2 – 7
- *Concrete operational*: ages 7 – 11
- *Formal operational*: ages 11 – 16 and onwards

In the *concrete operational* phase, children can think logically, but are limited to what they can see and physically manipulate. During the *formal operational* phase, which begins to develop in middle school, children begin to develop the ability to think abstractly, use metacognition, and solve multi-step problems.[†]

[*] Yes, I used that word on purpose.

[†] Babakr, Zana & Mohamedamin, Pakstan & Kakamad, Karwan. (2019). "Piaget's Cognitive Developmental Theory: Critical Review." 10.31014/aior.1993.02.03.84.

Middle School Students' Cognitive Abilities

In middle school, children's high-level thinking and problem-solving and thinking skills are just beginning to develop. In middle school, children start to use more flexible thinking, looking at their work metacognitively and checking it for mistakes, and trying different approaches in order to achieve a goal.* This is a point when they begin to understand cause and effect not just as something that happens, but as something they can manipulate.

To the exasperation of many middle school teachers, one of the ways middle schoolers experiment with cause and effect is to deliberately hurt other people's feelings and observe the results. While these "experiments" are not exactly ethical, the children performing them are engaging in the principles of experimental design: intentionally manipulating experimental conditions and observing the results.

Given that middle schoolers are already designing their own (social) experiments, middle school is an ideal time to start explicitly teaching them to do so in a scientific context.

High School Students' Cognitive Abilities

It is important to remember that the development of *formal operational* thinking is an ongoing process in middle and high school. Each year, children's ability to think abstractly, use metacognition, and solve multi-step problems increases. Problems and concepts that might be beyond a student's ability to understand in 8th grade might routine by 10th or 11th grade.

It is also important to remember that children develop at their own pace and no two children are exactly alike. For example, some children are able to understand algebra as 8th graders, while other children are not ready to grasp it until 9th or 10th grade. As math teachers have discovered, requiring children to demonstrate skills that they are not developmentally ready to acquire ends up backfiring—it causes them to fall back on the concrete skills that they developed when they were younger. (Remember that all of the skills children acquire during the *concrete operational* and earlier phases are still present, and are still a substantial part of the child's cognitive toolbox.)

As any teacher (or parent) who has ever had to explain to a child why a rule doesn't apply in a specific situation can attest, once a response to a situation is codified in a child's brain it is much harder to get them to revisit and reevaluate it. For this reason, teaching experimental design in early high school (9th and 10th grade) is particularly challenging, and requires multiple cognitive entry points.

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* https://www.understood.org/en/articles/developmental-milestones-for-typical-middle-schoolers, accessed 2022-05-28.

6. Experimental Design in Middle School

As mentioned in the previous section, middle schoolers are already thinking about cause and effect as something they can manipulate and are looking for ways to try it out. However, what is usually not on middle schoolers' radar screens is the idea that they should consider possible outcomes first. ("Fire!…aim…ready.")

Middle schoolers are not developmentally ready to fully take on the experimental design process, but it is an ideal time to lay the groundwork. There are several games and class activities that can be used to teach students the thought processes that they will need when they design experiments in their high school classes.

Games

Types of thinking that are necessary for experimental design can be introduced through different types of games:

- **Games and tasks that challenge assumptions**, such as "*minute mysteries*," encourage students to "think outside the box".
- **Games with concealed rules**, such as *scissors*[*] or *desert island*[†] encourage students to consider additional variables.
- **Games in which players bluff each other**, such as the card game *I Doubt It*[‡] encourage students to scrutinize the actions of fellow players closely, and to question results and demand evidence.

[*] *Scissors*" is a game in which imaginary scissors are passed, and the person passing them states whether they believe they are passing the scissors open (blades apart) or closed (blades together). The leader/judge states whether the person passing the scissors described the state correctly, and the players have to figure out how the leader made the determination. The secret is that the leader is looking at something unrelated to the imaginary scissors, such as whether the person passing them had their legs crossed or uncrossed at the time. The object is for students to guess the rule.

[†] Desert island is a game in which the teacher says "I'm going to a desert island and I'm going to bring _____." If students say that they're bringing something that follows the secret rule (such as "words that start with the letter C"), they are told that they can come. If they say that they're bringing something that doesn't follow the rule, they can't come. The object is for students to guess the rule.

[‡] The game is also known as *B.S.*, *Cheat*, or *Bluff*. (If students use the term B.S., I like to claim that it stands for "*bovine scatology*".)

- **Games in which the rules can be changed during play**, such as *Democrazy*,[*] encourage students to metacognitively think about how rules (which are analogous to experimental conditions) lead to outcomes, and how changing the rules affects the range of outcomes that are possible.

Classroom Activities

While there are undoubtedly some middle schoolers who are ready to design entire experiments, it is important not to rush the process. Students who are asked to perform tasks that they are not ready for are more likely to find the tasks stressful and unpleasant, which would have a negative effect on the process and future science classes in general.

Activities that build the kinds of thinking needed for experimental design include:

- Demonstrations (live or video) followed by discussions of "How can you tell that something happened," "How can you tell *what* happened," and "If you think *nothing* happened, how can you be sure? Or can you?"
- Tasks with a step-by-step process in which some steps are out of order.
- Having students create an "instant invention" to perform a specific task, using a specific set of materials.

Writing

Communicating the results of an experiment is as important as performing the experiment itself. Especially for middle schoolers, much of the learning and understanding of the experimental design process happens after the fact. A common way to organize the task is to use the Claim/Evidence/Reasoning (CER) process.

Claim: a statement by the experimenter that something is believed to be true. This might be the answer to a question posed by the teacher, or it might be a statement that the objective of an experiment was met. The claim is brief, often only one sentence, but it should fully describe what is believed to be true.

Evidence: the data that directly support the claim. Evidence can be quantitative (measurements and/or calculations) or qualitative (observations).

[*] *Democrazy* is a commercial board game for groups of 4–10 players that takes about 30–60 minutes to play. Each player, on their turn, proposes a change to the rules and submits the change to a vote by all players. If the rule passes, it is adopted. If it is rejected, it fails. Of course, each player will try to pass rules that benefit themselves, and obstruct rules that don't.

Reasoning: an explanation (usually 1–3 sentences at the middle school level) of how and why the evidence supports the claim. The reasoning should discuss the relevant scientific principles and explain how the evidence resulted from those principles.

Avoid "Gotcha" Assignments

It is important to avoid "gotcha" assignments, which can do a lot more harm than good.

A popular "gotcha" assignment is a "test" with instructions that say "*Read all of the questions fully before writing anything.*" The final question says "*Now that you have finished reading, put your name on the paper and turn it in without answering any of the questions.*" Students who don't follow the directions and write answers to all of the questions receive a failing grade.

These kinds of assignments are intended to reinforce the importance of reading directions and having a plan before diving in. However, middle schoolers' egos are fragile, and an experience like this can sour them on a teacher, a class, or science in general. A better version of this assignment would be to have the same directions, but have the last question say, "*Putting your name on this paper is the only thing that is worth any points. If you have read all of the questions before writing anything (as the directions instructed you to), you have just saved yourself a lot of effort!*" Reframing the assignment this way still gives bragging rights to students who followed the directions. However, all of the students end up learning the lesson (which is, after all, the goal), and therefore all of the students get a perfect score.

7. Observational Experiments in Ninth Grade Science

As mentioned above, cognitive differences among high school freshmen make them challenging to teach. Some ninth graders have developed a sufficient level of *formal operational* thinking to be able to design a fairly simple experiment from scratch, given only the objective. However, other ninth graders are still mostly *concrete operational* thinkers, who need to make decisions in order to continue to develop their *formal operational* thinking, but need substantially more structure.

Classroom Activities

Some types of activities that work well for ninth graders include:

- Put steps in order (as with middle schoolers) and/or fill in missing steps. One popular version of this is to have students attempt to write detailed instructions for doing something such as making a peanut butter* & jelly sandwich, and have someone else follow the instructions to the letter, deliberately trying to "mess up" the instructions and fail to achieve the desired outcome.

  The peanut butter & jelly sandwich activity is often done with younger students as a way to simply show the problems with underspecifying details. For ninth graders learning experimental design, the goal is not just to show problems, but to get them thinking about solutions. (Of course, one of the biggest challenges is to get them to take the activity seriously enough.) Getting the students to collaborate as they write the instructions and allowing the groups to iterate a couple of times as they discover omissions would likely be helpful.
- Change the steps of a procedure in order to change the outcome. This could happen several different ways, such as "Which of these steps/parameters would you like to change and see what happens?" or "What do you think might happen if we changed this particular step/parameter?"
- Simple (requiring relatively few steps) backward-designed hands-on activities, in which students are asked to come up with steps that would produce a particular result.
- Have students create something complex (such as an origami shape or building a structure out of LEGO building bricks). Have them write up a detailed set of instructions and have them take a picture of their resulting object. Then redistribute the instructions (but not the pictures) and have the new group take a picture of the object that they made by following the directions as closely as possible.

* You may need to substitute another spreadable ingredient if peanut allergies are an issue.

Observational Experiments: Biology and Earth Science

In most high schools, ninth graders take biology, physical science or Earth science. While plenty of complex experiments are performed in these sciences, high schoolers generally do not have the background knowledge or skills to perform them. Most often, ninth grade biology or Earth science experiments are about making observations, with a focus on what is needed to observe the phenomena.

Making observations in biology and Earth science present challenges for the student, because most biological, geological, atmospheric and planetary processes happen on a physical scale and/or time scale that is impossible to observe in real time. Thus the skills that students develop in these classes focus on how to observe things that cannot be readily seen with the naked eye on a time scale of seconds or minutes.

In many instances, simulations can be useful in speeding up the time scale and/or representing the physical scale. However, the simulations themselves follow a script (regardless of whether the script is visible to the students) and parameters that students can manipulate generally fall within a narrow range. While these simulations are useful for teaching concepts, they are generally much less useful for teaching experimental design.

In these classes, hands-on activities that represent the processes or computer simulations can provide opportunities for students to hone their experimental design skills:

- In biology, students are required to learn the steps in protein synthesis starting from the DNA sequence. Once students have gone through the process in the forward direction, they can develop experimental design skills by starting from the amino acid sequence and working backwards to find the DNA sequence.
- In biology students are often asked to put the steps of mitosis in chronological order. This could be further enhanced by giving them an incomplete set of steps, so they need to add the “missing” ones as well as ordering the ones that were given.

Sometimes students can be given pictures and asked to work out the sequence of events.

- In Earth science, students might be asked to determine the sequence of events that produced layers of rock.

This can be done using pictures of actual rock layers (as shown below),

© 2001 Michael C. Rygel via Wikimedia Commons. Used with permission.

or as an activity in which the teacher modifies candy bars (such as Snickers®) by bending them, cutting them and shifting the pieces, *etc.* A variation of this activity might involve one group of students creating a "geologic" sequence with layered candy bars and giving it to another group to determine the sequence of events.

These activities encourage students to think about the actions that produced the evidence they are studying as fluid processes rather than static snapshots. When students think about factors that could change those processes, they are engaging in experimental design, even if they are not performing experiments in which they cause something to happen.

Examples of Student-Designed Experiments

Equilibrium

The concept of equilibrium *vs.* nonequilibrium appears in one form or another in most scientific disciplines. An easy way to demonstrate equilibrium is with a bucket that has a hole in the bottom. You can make one from a plastic 10-quart mixing bucket, which has volume markings and costs about $6 at a hardware store.

If you cut a hole in the bottom of the bucket (on the side of the bucket near the bottom is best, for reasons that will be explained later), you can ask the students to determine the maximum flow rate of water (in liters per minute) into the bucket without it overflowing.

At first, this sounds like an easy experiment. Students will probably start by filling up the bucket with the hole covered and timing how long it takes for the water to drain out of it. It is useful to allow them to do this and let them come up with an initial answer.

Then, point out to students that the water flows faster when the bucket is full, and the flow rate slows down as the bucket empties. (If the hole is placed in the side of the bucket instead of the bottom, students can see this because the water sprays farther when the bucket is full, and the stream slows down and the water lands closer and closer to the bucket as it empties.)

Container adapted from a design by Matt Cook.
Used with permission under a Creative Commons license.
Faucet adapted from a design by Brgfx / Freepik. Used with permission.

This discussion will probably require some guidance. Students need to realize that:

1. At equilibrium, the flow rate into the container from the faucet must equal the flow rate out of it.
2. The flow rate out of the container depends on the liquid level.
3. Therefore, the flow rate from the faucet will need to be different for different liquid levels.

The students will puzzle over how to get a better number. It is best to let them try different things. Some will measure the flow rate at different water levels and extrapolate. Others will adjust the flow rate from the tap until the level remains approximately constant and then measure the flow rate by collecting water that comes out of the hole.

Some students or groups will undoubtedly get stuck and be unable to come up with ideas. For those students, this is the "teachable moment" and needs to be managed by the teacher—by providing enough help to get them unstuck, but no more.

This experiment provides a good example of the iterative nature of problem-solving: students need to come up with their first answer before they have enough information to realize that their first procedure was inadequate, but gave the information needed to create the second procedure that gave a better answer.

As the students perform the experiment, the teacher can point out how it demonstrates equilibrium (the water stays at the same level), nonequilibrium (the water level changes until the bucket overflows), and hysteresis (the rate of water coming in affects where the equilibrium level ends up).

Density

In physical science and often also in Earth Science classes, one of the concepts that is introduced is density. For many students, this is the first time that they encounter a quantity that that they need to calculate, instead of being able to measure it directly.*

Of course, there are several different ways that students could perform an experiment to determine the densities of different objects. If the activity is scripted, students are given objects and given a data sheet in which they fill in the masses and the quantities needed in order to calculate the volumes. Often, the worksheet also heavily scaffolds the calculations. This type of overly-scaffolded activity prevents students from needing to engage with the concept and its equation at a high level.

Instead, this is a perfect opportunity to introduce students to the concept of using the equation to help them design the experiment. If this is their first attempt at designing a full experiment (which it most likely will be), it is probably best to go through the process as a class (or large group) discussion:

1. Point out that students need to find *density*, which is represented by the Greek letter ρ in equations.†
2. Have students find an equation that has density in it: $\rho = \frac{m}{V}$
3. Ask students which quantities in the equation they would need to know in order to calculate density: mass (m) & volume (V).
4. Ask them how they could measure the mass and volume of an object.
5. Once they have answered these questions, give them several objects and have them calculate the densities.

It is advantageous to let the students start with a blank piece of paper instead of giving them a data sheet. This causes them to think about how they want to present the data. (Or, in many cases, they don't think about presenting the data, and realize after the fact that some organization would have been helpful.)

* Of course, students can measure specific gravity of a liquid directly, but this is not how the concept is typically taught, and would be counterproductive to using it to teach experimental design.

† In ninth and tenth grade science texts, the variable for density is often given as D instead of ρ. Because the Greek letter ρ is used for density in physics, it is useful for students to get used to using it from the start.

It is also helpful to give them some irregularly-shaped objects. Let them puzzle over finding the volume for at least a few minutes before teaching them about water displacement.* This forces them to create connections in their brains between the problem (finding volume) and multiple potential solutions. When the technique that you teach them is used to solve a problem that they are already wondering about, they will remember it much better.

For students who grasp the concepts quickly and are in need of an additional challenge, you can give them something irregularly-shaped that floats in water, such as a piece of cork.

As with any new skill, students will need a lot of help and guidance doing experiments this way (starting with the desired endpoint and working backwards) at first. The first couple of experiments may end up being planned in a Socratic whole-class discussion. However, as students become more comfortable with the process, the teacher can gradually release the responsibility of coming up with procedures to the students. Note, however, that given the impulsivity of ninth graders (Fire!...Ready…Aim), it may be a good idea for the teacher to have each group briefly explain their approach before performing the experiment.

Writing

As with middle schoolers, ninth graders still do much of their learning as post-processing. This means writing about experiments using techniques like CER (see page 26) is valuable, both in helping students understand the experiments and their connection to scientific principles, and in developing their ability to communicate information about their experiments. By ninth grade, the experiments will be slightly more complex, and it is reasonable to expect a full paragraph for the reasoning section.

* Note, however, that if you use metal nuts & bolts and you give your students glass graduated cylinders, at least one student will drop a bolt into the graduated cylinder and break the glass.

8. Projects: Engineering Design

Some courses, such as engineering and physical science, lend themselves to projects that involve designing and building something for a specific purpose. These are popular for ninth grade classes because they develop the thinking needed for experimental design without requiring extensive math.

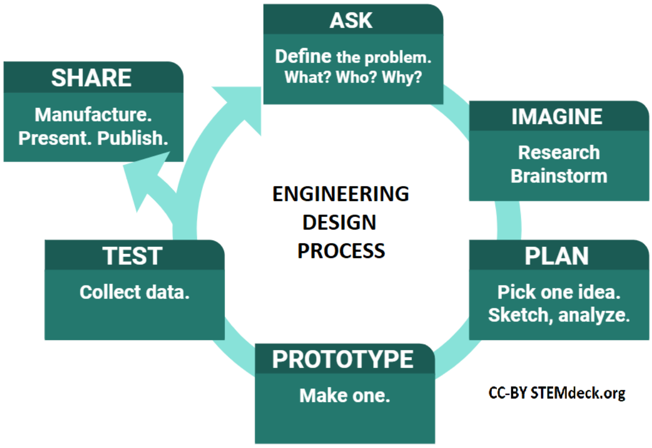
Most ninth graders are used to being able to conceive of an entire task in their heads. Once they understand the task, they start at the beginning and perform it once. The task is complete when they reach the endpoint, and they are loath to think about it beyond that point. However, as soon as the task becomes larger than they can keep track of in their heads, the task becomes overwhelming and seems impossible. (Ask any English teacher who has taught ninth graders to plan, write and revise a major paper.)

As a starting point, it is useful to give students fairly simple tasks that reinforce this process. These can be quick lab activities that illustrate or make use of specific concepts throughout the year. The teacher need not even pre-plan how to use these. One of my colleagues would routinely give her physical science students objects, such as marbles and wood blocks, and would tell her students, *"Use these (and any other objects you want) to make something that demonstrates __________.* * *Once you have built your 'something,' show it to me and explain how it represents __________."*

As projects become larger and more complex, students need some sort of framework to keep track of both the project itself (all of the parts and how they interrelate), and the steps they need to follow in order to complete it.

* In one example I recall, the concept the teacher instructed her students to demonstrate was transfer of momentum in a collision.

Almost all of the materials that discuss how to teach engineering in K-12 contain circular diagrams similar to this one:



While this is a good representation of the entire process, the process is highly simplified. The boxes labeled "PLAN: Pick one idea. Sketch, analyze." and "PROTOTYPE: Make one." are too vague to be useful to ninth graders.

When students attempt to plan the entire process in their heads, they come up with their one idea, work out one possible sequence of events that could achieve the goal, and start building the prototype immediately. As projects become more complex, this often leads to frustration when the students have put several hours of work into a project only to discover that some crucial piece did not work as they envisioned, rendering much of their work useless.

Teachers frequently respond to this frustration by shrugging and saying, "Yes, engineering is a lot of trial and error. If at first you don't succeed, try, try again." (I have certainly done this.) However, what many students take away from the experience is that engineering is frustrating and not something they want to consider as a career.

Another problem that is frequently not addressed in high school engineering classes is that the trial-and-error process is not finished when they succeed in building a prototype that works. Students need to learn to think of and test for *all* of the possible failures they can envision, in order to prevent failures from happening after the design and build processes are complete.

This is easier said than done, however. History is full of examples of structures that passed all of the tests for failure modes that the engineers could envision, only to have those structures fail because of a failure mode that was not tested.

One example is railroad rails, which are made of steel. It is therefore important to account for thermal expansion.

U.S. Department of Transportation.
Public domain.

Rail junction at the Beskyd station of the Lviv railway in Ukraine.
Photo by Helgi. Shared under a Creative Commons license.

The picture on the left shows what happens when the rails expand due to higher than foreseen temperatures. This problem is avoided by adding expansion joints between sections of rail, as shown on the right.

There have been many spectacular failures due to other unforeseen problems, such as the collapse of the Nanfang'ao Bridge in Taiwan in 2019.

Nanfang'ao Bridge (Taiwan) collapse in 2019.
Photo from the Taiwan Coastal Guard Administration.

Finding Failure Modes

Before giving students complex projects, they need to understand the engineering mindset. The goal of the engineer is not to build a device that *can* perform a task, but to build a device that *cannot fail* to perform its task, at least under the conditions in which the device is expected to operate.

Scientists make claims and invite other scientists to refute the claims. Any claim that is unable to be refuted, despite attempts by a large body of people to do so, is considered to be provisionally true. Similarly, engineers invite others to find the potential failure modes or weaknesses in their designs. A device that does not fail despite attempts by a large body of people to exploit its weaknesses is considered to be provisionally successful.

High school students need to be taught the mindset of finding and exploiting failure modes. As with many concepts in education, gamifying the task can result in high levels of engagement and students learning without realizing that they are doing so. Some games and activities that teach or reinforce this skill include:

Card Houses

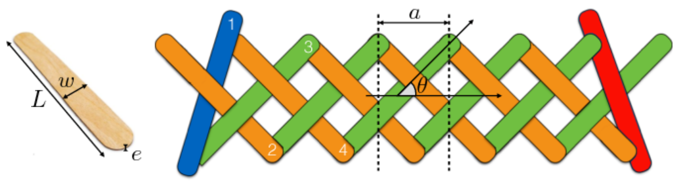
An activity that shows both the design process and the testing process is to have groups of students build card houses with different designs, then have other groups of students use various means to knock them over (rolling a marble, blowing on them from some pre-determined distance, *etc.*).

Jenga®

Jenga® is a block-stacking game in which players remove blocks from a stack one at a time until the stack collapses. The strategy is to remove blocks in a way that creates failure modes that make it more difficult for the other players to remove blocks without causing the tower to fall.

Cobra Wave

A cobra wave is made by arranging craft (Popsicle®) sticks in a weave that places all of the sticks under tension.



(a) (b)

In the above diagram[*], L, w and e are the respective length, width and thickness of the stick. Sticks are woven in numerical order, starting with #1 (blue) and ending with the final stick (shown in red). To initiate the wave, slide either the first or last stick out from under the stick that rests on top of it (while holding down that stick). When you release the stick, the tension in the bending of the sticks will be released causing the sticks to “explode” in a wave that progresses from one end to the other.

[*] Boucher, J.P., Clanet, C., Quéré, D., & Chevy, F. (2017). “Popsicle-Stick Cobra Wave.” *Physical review letters*, 119 8, 084301.

Bridge Building

A longer-term and more complex project is a bridge-building contest. There are many variations, but the project usually involves building a bridge out of either balsa wood or craft sticks that needs to span a given distance, and loading weight in a specific location (often by hanging a bucket from that location and adding weight to the bucket) until the bridge collapses.

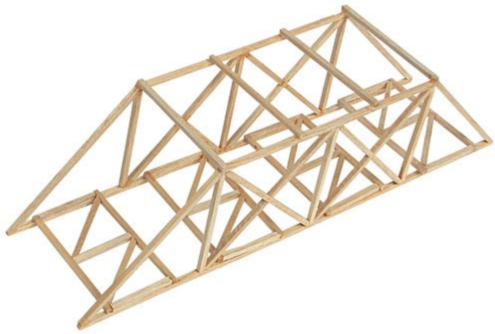


Image from Pitsco Education website: https://www.pitsco.com/Competitions-Clubs-and-Programs/4-H/Bridges-Refill-Pack

Typically, use of materials other than wood (glue, tape, *etc.*) is explicitly limited. Bridges are typically rated according to the formula:

$$\text{efficiency} = \frac{\text{maximum load}}{\text{weight of bridge}}$$

Teaching Project Design as a Process

Once students grasp the ideas of building and testing a device that needs to perform only one task, they are ready to apply it to more complex machines and devices that perform multiple actions. This is the point when the design process needs to be *planned*, rather than allowing it to evolve organically. Students do not already know how to do this, which means it needs to be taught, using appropriate scaffolding.

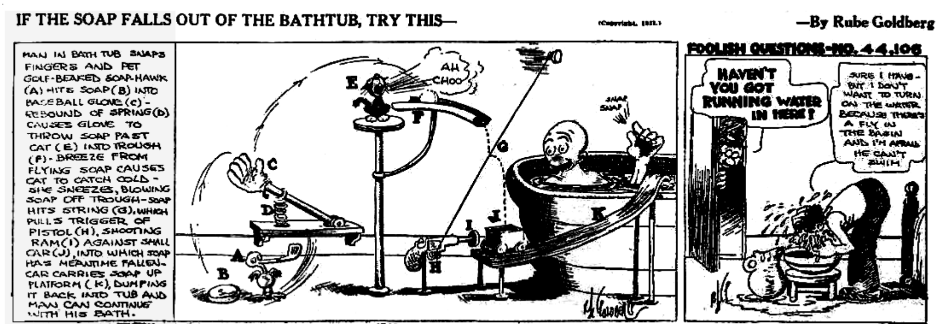
There are, of course, many ways to go about designing a solution to a complex problem. In my experience as a high school teacher, more of my students have been linear thinkers than global thinkers. Linear thinkers tend to get lost in the details. Scaffolding a top-down approach will help them keep the overall problem in mind and understand how the specific piece they are working on fits into the larger picture. I recommend a process similar to the one described on the following pages.

Note that this is an extremely formalized description of the process. Even in a very small project which students can conceive of entirely in their heads, students are doing (or should be doing) each of these tasks though they may not realize it. For a small project that is just barely too complex for students to hold in their heads (which is exactly the kind of project they should be tackling at first), many of these steps will still happen organically, and/or end up combined.

The basic steps of the design process are:

1. Define the problem and what it will mean to have solved it.
2. Create a high-level design for the overall project. Define the individual components (what they need to do, how they will be combined into the final device).
3. Design, build & test the individual components.
4. Combine the individual components and test the entire device.
5. Evaluate the final project. (How well did it solve the problem?)

A popular activity that can be used to teach this process is to have students build a Rube Goldberg device. Rube Goldberg was a cartoonist who was famous for his depictions of overly complicated machines that performed simple tasks.



This cartoon by Rube Goldberg is in the public domain. (Published 18 November 1921.)

While the humor of the devices in Rube Goldberg's cartoons comes from their complexity (leaving the reader to imagine the possible failure modes), the teacher can adjust the rules and the required level of complexity based on where students are in the learning process.

As a means of both describing this process in detail and illustrating it, we will consider the problem of building a Rube Goldberg device that uses a marble to knock down a tower of blocks. (Descriptions of the steps are presented in upright text; *examples illustrating the concept are presented in Italics*.)

The detailed process would look like the following:

1. **Define the Problem**
    a. **Scope**: What is the problem? What does the solved problem look like?

       A marble, released from rest, needs to knock down a tower of blocks. The problem is solved when the original tower has fallen and no stack more than two blocks high remains.

b. **Research**: Has this problem or a similar problem been solved in the past? How well have previous solutions worked? Was anything lacking or insufficient in those previous solutions.

There are several examples, such as a small block or domino knocking down a larger one, which knocks down an even larger one, and so on.

From a YouTube video by Domino effect simulation Dude*

c. **Design Requirements/Constraints**: Besides solving the problem, are there other constraints on the solution, such as size, energy consumption, noise produced, *etc.*?

The entire device needs to fit on a lab table, so a practical limit is a footprint of 100 cm × 75 cm.

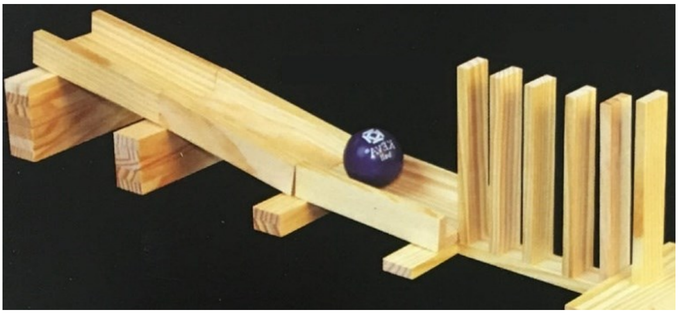
2. **High-Level Design**

a. **Break the Problem into Specific Tasks**: Determine which tasks need to be accomplished in order to solve the problem. (Think of them as milestones along the way to the solution.) It is often best to work backwards from the solution to the starting point.

* https://www.youtube.com/watch?v=5uHUVyy3rNw

i. *The marble needs to gain enough speed to hit something with force.*

ii. *The "something" needs to have enough stored (potential) energy to knock over the tower of blocks once the marble hits it.*



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b. **Define a Component to Perform Each Task**: Treat each of the tasks from part a above as a separate problem. Brainstorm and work out the details for components that will solve each of those separate problems.

i. Ramp: marble is released and rolls down.

ii. Lever: swings and hits bottom block in tower.

c. **Determine How the Components will Interoperate**: Before beginning to build anything, determine how each component will "hand off" whatever is being transferred (kinetic energy, electricity, information) to the next component. This needs to happen both for the start of the component's task—what it will receive from the previous component and the end of the task—what it will "hand off" to the next component. Note that both handoffs involve negotiations and compromises. What a component needs from the previous component must be possible for the previous component to hand off. Otherwise, an additional interim component may be necessary.

i. <u>Marble</u>: rolls down ramp when released and hits lever.

ii. <u>Lever</u>: swings and hits blocks

This highlights the problem of how the lever is able to swing once the marble hits it. The solution is for the lever to have potential energy but to be held by some sort of release mechanism that is triggered when the marble hits it.

Students briefly return to step b above and add a release mechanism between steps i and ii,, which could be another lever.

3. **Low-Level Design, Building & Testing**
    a. design requirements for each component
        - *Marble rolls to bottom of ramp.*
        - *Marble must have enough energy to move lever.*
        - *Bottom of ramp must be aligned with lever.*
    b. potential failure modes for each component (including handoffs)
        - *Marble does not start down ramp.*
        - *Marble gets stuck.*
        - *Marble fails to hit lever.*
        - *Marble does not hit lever hard enough to engage it.*
    c. build, test & refine each component

4. **Combining the Components**
    a. Combine components one pair at a time
        - *Connect bottom of ramp to lever.*
    b. Test each component's ability to initiate from a handoff and to handoff successfully to the next component
        - *Test handoff with various marble speeds and angles.*
        - *Test ability of lever to knock down block towers of different arrangements.*
    c. start-to-finish operation

5. **Evaluation**
    a. ability of device to perform task
    b. consistency
    c. reliability (resistance to failure)

For a device that performs a sequence of actions (such as a Rube Goldberg device), students need to think about:

- What are each of the separate actions that the device needs to perform?
- Do the actions need to happen in a specific order? If so, what is the order?
- How does the device make the transition from one action to the next?

As with machines and devices that do not move or perform multiple steps, students need to consider possible failure modes. However, there are several additional opportunities for failure:

- Structural failure of any part of the machine.
- Failure to perform the required action consistently.
- Failure to consistently respond to the initiating action.
- Failure to initiate the next action consistently.

If students are working in groups, group members can divide tasks in several different ways. They can have each group member make a separate component, they can have one member build the components while others test the components and make adjustments. One of the learning goals of group work is for students to assess their own strengths and each other's and divide the work accordingly.

Organizing the Design & Testing Process

One way to help students plan the design and testing process is to have them describe each component on a separate index card:

Action/Task: **Number in Sequence:**

Initiated by:

Handoff:

Anticipated failure modes, tests & adjustments: (*continue on back*)

For example, consider our Rube Goldberg device consisting of:

1. A marble goes down a ramp.
2. The marble hits a lever.
3. The lever knocks out the support from a tower of blocks.

Index cards for the first two steps might look like the following:

Action/Task: **Number in Sequence:** *1*

Marble goes down ramp

Initiated by:

Student

Handoff:

Marble hits lever

Anticipated failure modes, tests & adjustments: (*continue on back*)

Marble gets stuck → repeated trials & adjustments

Marble misses lever → repeated trials & adjustments

Marble does not hit lever hard enough → steeper ramp, heavier marble

Action/Task: **Number in Sequence:** *2*

Lever swings & knocks over tower of blocks

Initiated by:

Marble going down ramp

Handoff:

Tower of blocks falls

Anticipated failure modes, tests & adjustments: (*continue on back*)

Lever doesn't move → repeated trials & adjustments

Lever doesn't hit blocks → repeated trials & adjustments

Lever fails to knock over tower → adjust lever (make it swing easier, longer lever arm, less friction)

Some advantages of having separate index cards for each component include:

- Index cards remain with the component if different group members work on different components.
- It is easy to add, delete, or change the order of the components.

Projects and Group Work

A common frustration for teachers is the need to teach students how to work effectively in groups. There are a lot of materials that advise teachers how to assign groups, help groups establish norms and ensure that everyone participates. Unfortunately, when the group needs to accomplish something more than "have a discussion," groups are left to flounder on their own. Students do not understand project management without being taught, so teachers need to explicitly teach the necessary skills.

The process of managing a successful project is much like the process of designing a successful experiment.

Experiment	**Project**
Objectives clear & understood	Goals clear & understood
Experimental actions determined	Required tasks determined
Necessary measurements identified	Tasks assigned to people
Timeline (dependencies and order of operations)	Timeline (dependencies and order of operations)
Perform experiment	Complete tasks
Analyze & report data	Analyze & report results

Students, especially in middle school and ninth grade, need to be explicitly taught how to do each phase of project planning/management. For example, groups need to identify the tasks and split them in a way that the amount of work is similar for each one. They need to inventory the skills of group members so that tasks are assigned to the group members who are best able to complete them.

High school students are often unable to envision a task in the abstract, so they will need scaffolds to help them work through the order of operations and the complexities of how tasks depend on one another. There also need to be checks and balances, so that the rest of the group can intervene if a group member needs help or becomes sick and is unavailable to complete their tasks. Teachers need to help students learn how to accomplish these project management tasks in a way that is socially appropriate and not hurtful.

Experimental Design in Chemistry

Chemistry, which is usually taught in 10^{th} or 11^{th} grade, presents two unique challenges:

1. Most of chemistry is concerned with the behaviors of atoms, molecules and ions. Because these particles are too small to observe directly, chemistry experiments need to address both what is happening at the atomic/molecular level and how it can be observed at the macroscopic level.
2. High school chemistry experiments involve more set-up and planning than for other science subjects:
   - reagents need to be prepared at appropriate concentrations
   - techniques need to be taught and practiced
   - safety needs to be addressed in advance as well as throughout the experiment

However, chemistry is also an ideal course to begin the process in earnest of teaching experimental design. Initially, it makes sense to focus on guided inquiry (GI) experiments, which are the gateway to the experimental design process. Chemistry is well-suited to GI experiments for the following reasons:

- Most chemistry experiments at the high school level have clear, easy-to-understand objectives.
- In most high school chemistry experiments, it is clear what the ***action*** is and when it has occurred.
- In most high school chemistry experiments, students can envision a workable procedure once they understand the objective and how to use the available equipment.

There are many resources available that discuss and give examples of GI chemistry experiments. Rather than attempt to present a list of experiments here, this text will focus on how an experiment might be taught as a GI experiment, and how that same experiment might be taught in a way that requires a higher level of experimental design.

Stoichiometry of an Acid-Base Reaction

Stoichiometry is one of the most confusing concepts in high school chemistry classes. Applying the concept involves several steps (measurable quantity of reactant → moles of reactant → moles of product → measurable quantity of product), which means students who are still developing their formal operational thinking skills can easily become lost. This problem is compounded if there are multiple steps involved in measuring the quantity of reactants and/or products.

In order to make the measurements conceptually easy, so students can focus their understanding on the concept, a popular stoichiometry experiment is one that evolves a gas. This removes the need for a separation step after the reaction is complete.

A "green chemistry" version of this experiment uses the reaction of sodium hydrogen carbonate (baking soda) and citric acid in an Alka-Seltzer® tablet:

$$3\ NaHCO_3\ (s) + C_6H_8O_7\ (s) \rightarrow 3\ CO_2\ (g) + 3\ H_2O\ (\ell) + 3\ Na^+\ (aq) + C_6H_5O_7^{3-}\ (aq)$$

An Alka-Seltzer® tablet already contains the citric acid (1.000 g) and sodium hydrogen carbonate (1.916 g)*, plus acetylsalicylic acid (aspirin, 0.325 g, which can be considered inert for the purpose of this experiment).

This is a good inquiry-based experiment because students can easily envision what they need to do:

1. Place the Alka-Seltzer® tablet in water.
2. Collect and measure the volume of gas produced.
3. Measure the final temperature of the water (for use in the ideal gas law).
4. Measure the barometric pressure.†

The challenges to the students are:

1. Get the Alka-Seltzer® tablet into the water without starting the reaction. This requires some way to keep water away from the Alka-Seltzer® tablet until the tablet is in the appropriate position so the gas can be collected.
2. Collect the gas in a way that the volume can be measured. This seems straightforward at first—eudiometers‡ are designed for the purpose. However, one Alka-Seltzer® tablet produces 380 mL of gas, and eudiometers typically have capacities of 50 mL or 100 mL.

Guided Inquiry Version

In a guided inquiry version of this experiment, the teacher would most likely do some version of the following:

1. Present the chemical reaction and give the objective of determining the amount of CO_2 gas produced.

---

* This equals 0.0228 mol $NaHCO_3$ and 0.0052 mol $C_6H_8O_7$, which means $NaHCO_3$ is the limiting reactant. One Alka-Seltzer® tablet, if reacted completely, would produce 0.0156 mol CO_2, which has a volume of approximately 380 mL of gas at 21 °C.

† If you do not have a barometer, you can look up the barometric pressure using a weather app or website.

‡ A eudiometer or eudiometer tube is sometimes called a "gas measuring tube".

2. Give students a list of the masses of the relevant chemicals in the Alka-Seltzer® tablet.
3. Present equipment available to be used, including some way of keeping the Alka-Seltzer® from getting wet during set-up* and some way of measuring the volume of gas collected (eudiometer).
4. Recommend that students use approximately ⅕ or ⅒ of a tablet, depending on the size of the eudiometer tube that you have (reminding them to accurately measure the actual mass that they use).
5. Instruct students to devise a procedure and carry out the experiment.
6. Instruct students to calculate the masses of reactants used, moles of reactants, moles of CO_2 produced, and volume of CO_2 produced (perhaps suggesting that they will need to use the ideal gas law).

Early in the school year, when students are first learning experimental design, this level of guidance is needed. Students should perform several guided inquiry experiments of this type before being asked to design the experiment at a higher level.

Experimental Design Version

Once students are ready to design the experiment, they will need to come up with the above steps #3–6 themselves. At first, this will require significant guidance from the teacher—possibly so much that it may seem like a guided inquiry experiment that is being taught Socratically.

The experimental design process starts at a high level with the objective and required action(s), and narrows down to finer and finer details, finishing with the guided inquiry version of the experiment. Students who are naturally global ("big picture") thinkers will have a relatively easy time doing this, whereas students who are linear thinkers may need more help.

* One suggestion is to grind up the Alka-Seltzer® tablet and put a measured quantity of the powder into an empty gelatin capsule, which can be purchased from a health food store or the internet.

Highest (Broadest) Level

- **Objective**: Determine the volume of CO_2 gas produced in the chemical reaction between sodium hydrogen carbonate and citric acid in an Alka-Seltzer® tablet, and compare with the prediction given by stoichiometry.
- **Action**: Sodium hydrogen carbonate reacts with citric acid in water to produce CO_2 gas.

↓

- Variables of interest are volume of gas (responding) and quantities of reactants (manipulated).

↓

- Measure the volume of CO_2 gas evolved using a eudiometer.
- Measure the mass of the Alka-Seltzer® using a balance. Use proportions to find the masses of sodium hydrogen carbonate and citric acid that reacted.
- Pressure and temperature (control variables) are assumed to be constant, but will need to be measured so they can be used in the ideal gas equation.

↓

- Create a flow chart and link measurements to steps in the flow chart.

↓

- **Guided Inquiry Piece**: Turn the flow chart into a procedure, at which point the student has successfully reduced the problem to the guided inquiry version of the experiment described above.

Finest Details

A template similar to the one on the following pages can be used to help guide students through the experimental design process. (A blank template with download link is shown on pages 94–95.)

Experimental Design Template: Qualitative

Objective:

Predict and measure the amount of CO_2 produced when an Alka-Seltzer tablet dissolves in water

What is the ***action*** of this experiment?

(What needs to happen in order to meet the objective?)

Citric acid reacts with sodium hydrogen carbonate to produce CO_2 gas:

$3\ NaHCO_3 + C_6H_8O_7 \rightarrow 3\ CO_2 + 3\ H_2O + 3\ Na^+ + C_6H_5O_7^{3-}$

What will cause the ***action*** to happen?

(Are there specific conditions necessary for the action to occur? If so, how will they be met?)

The reaction happens spontaneously when the reactants are dissolved in water

How will you determine the result?

predict volume using the ideal gas law: $PV = nRT$

measure volume (eudiometer) and compare

What do you need in order to determine the result?

For measured quantities, indicate how you are going to measure them.

- **Constants** (quantities to be looked up)

  gas constant $R = 0.0821\ \frac{L \cdot atm}{mol \cdot K}$

- **Control Variables** (quantities you are keeping the same)

  pressure (barometer) (convert to atm)

  temperature (thermometer) (convert to K)

- **Manipulated (independent) variables** (quantities you can determine before the ***action*** occurs)
  Describe how each one will be determined/measured.

  mass of Alka-Seltzer (balance)

  mass of $NaHCO_3$ and $C_6H_8O_7$ (mass of Alka-Seltzer above & proportion from ingredient list)

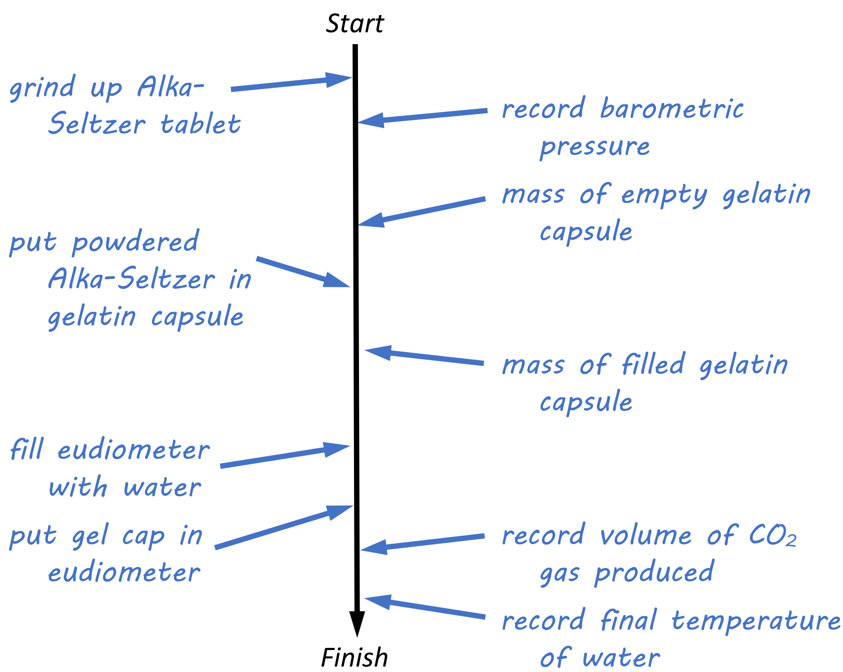
- **Responding (dependent) variables** (quantities that cannot be determined until the ***action*** occurs)
  Describe how each one will be determined/measured.

  volume of CO_2 (eudiometer) (convert to L)

Flow Chart

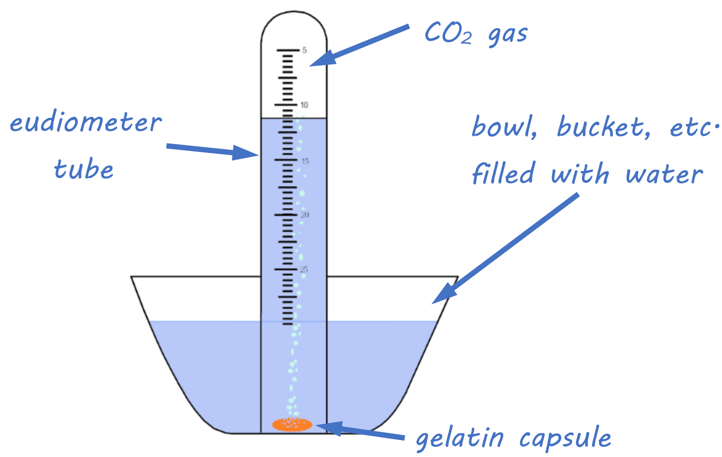
Show the timeline in the center. List actions on one side and measurements on the other, in chronological order. Use arrows to connect each to its place in the timeline.

Actions **Timeline** **Observations/Measurements**



Labeled Sketch or Photograph of Experimental Set-Up:

Include a sketch or photograph of your experimental set-up, with ***each*** *piece of equipment* ***labeled***. *(Include dimensions if relevant.)*



Notice that most measurements take place *between* actions, not *during* them. This is useful to point out to students—in most cases, measurements are taken immediately before or after an action takes place, and the difference is attributed to the action. An example in this flow chart is measuring the mass of the gel cap before and after putting the Alka-Seltzer® into it. The volume of CO_2 gas is taken after the reaction has stopped. Because the eudiometer started with no gas in it, the initial volume is zero.

Teachers should be aware of some of the factors that affect the yield of CO_2. These are not factors that one would expect a student in a first-year chemistry class to be aware of, but are useful in a discussion of results and of sources of uncertainty:

- CO_2 is soluble in water, which means the volume of the gas collected will not account for dissolved CO_2.
- CO_2 reacts with water to form carbonic acid, which means the volume of the gas collected will not account for the CO_2 that is lost to production of the acid.
- Reactions that produce gases tend to be endothermic, because some of the free energy of the reaction is provided by the increase in entropy. This means the temperature will decrease as the reaction proceeds, and the final temperature of the water may be lower than the final temperature of the gas.

For a first-year chemistry class, it is probably best either to mention these factors before the experiment to set expectations, or wait until after the experiment and bring them up as part of a discussion of sources of uncertainty.

Gradual Shift toward Experimental Design

As stated above, students who enter a chemistry class with little or no experience in experimental design or any form of guided inquiry (which is most likely the case) need to learn this process gradually. The first experiments should be simple, and should focus on teaching the skills that students need in order to perform guided inquiry experiments. As students master these (which will probably take several months), the teacher can introduce the other aspects of the experimental design process.

Remember that learning experimental design is a journey. Depending on the skills with which your students arrive in your class, your students may or may not be able to fully design a chemistry experiment by the end of the year. However, your students will enjoy the benefits of these skills no matter where they are when they finish the year.

9. Experimental Design in Quantitative Physics

Most high school students take quantitative (algebra-based) physics in their junior or senior year. By this point, students should have reasonably strong algebra skills, at least with linear equations.* Ideally, they will also have some experience with experimental design. If they don't, the skills can be taught as presented here, but some additional scaffolding will be necessary.

Quantitative high-school physics courses focus on relationships between quantities that are based on equations. This means that relationships among these equations can be used as a basis for experimental design. This is a logical next step following guided inquiry, because the relationships among the equations provide useful scaffolding to teach students to identify relationships and dependencies in experiments in general.

Letting the Equations Define the Experiment

This process is an extension of the density experiment on page 34. In that experiment, the equation $\rho = \frac{m}{V}$ was used to show students that if they wanted to know the value of ρ, they could calculate it by measuring m and determining V, and then substituting those values into the equation.

This process is fairly straightforward when only one equation is involved.

Sample Experiment: Acceleration of a Cart on a Ramp

If a student wanted to determine the acceleration of a cart as it travels from the top of a ramp to the bottom, they could use the following reasoning:

1. Acceleration appears in three of the kinematics equations:

	Equation	Variables
i.	$v - v_o = at$	a, v_o, v, t
ii.	$d = v_o t + \frac{1}{2}at^2$	a, v_o, d, t
iii.	$v^2 - v_o^2 = 2ad$	a, v_o, v, d

* This is, of course, not always the case. Because the experimental design strategies in this text rely heavily on the use of algebra, it may be necessary to scaffold these skills early in the school year.

2. The equation that the student chooses will determine which quantities need to be obtained:

    i. If the student chooses equation (i), it is necessary to obtain the initial velocity (v_o), final velocity (v) and time (t).

    ii. If the student chooses equation (ii), it is necessary to obtain the initial velocity (v_o), distance (d) and time (t).

    iii. If the student chooses equation (iii), it is necessary to obtain the initial velocity (v_o), final velocity (v) and distance (d).

3. As the student considers how each quantity could be obtained:

Quantity	How Determined
a	desired value; calculated
v_o	cart starts from rest → $v_o = 0$
v	**cannot be measured directly**
d	tape measure / meter stick
t	stopwatch

   The student should quickly realize that it is not practical to measure the final velocity of the cart. This means:

    a. The only equation that does not contain final velocity (v) is $d = v_o t + \frac{1}{2} a t^2$.

    b. The student needs to use this equation, and therefore needs to determine the initial velocity (v_o), distance (d) and time (t).

4. Once the student determines what needs to be measured, the experiment has become a straightforward guided inquiry experiment.

The "keep everything in your head and figure it out" approach works for a simple experiment such as this one. However, as experiments become more complicated, some additional scaffolds are necessary in order to organize the process.

Sample Experiment: Friction on a Block Sliding Down a Ramp

When an experiment requires multiple relationships and therefore multiple equations, it is more difficult for students to conceptualize. For example, consider an experiment in which the student needs to determine the force of friction acting on a block as it slides down a ramp.

This experiment is significantly more complex than the previous one. It requires students to use multiple equations and some trigonometry. If this experiment were assigned as a typical guided inquiry experiment, most students would be unable to figure out what to do without significant scaffolding.

Note also that this experiment requires students to understand basic trigonometry. Consequently, depending on students' math abilities, the experiment may be appropriate only for honors and AP® classes.

One of the reasons students struggle to understand an experiment like this one is because they do not understand the connections among the quantities and equations, which prevents them from purposefully starting from the desired quantity and working through equations until they have the ones they need.

The Quantitative Experimental Design Template on the following pages (similar to the qualitative one from the previous chapter) is designed to provide scaffolding for this task. At the beginning of the template is a chart that uses equations to guide students through the process, starting from the equation that contains the desired quantity and identifying quantities that need subsequent equations. The process is complete when every quantity that is needed for all of the equations is either known or measured.

To create the Experimental Design table:

1. Start with the desired variable (the force of friction, in this example) that is the objective of the experiment.
2. Fill in the equation, description, and put ***each variable*** from the equation into one of the columns.
   a. The desired variable is already in the left column ("Desired Quantity").
   b. Any quantity that is known—constants or control variables that do not need to be measured—goes in the "Known Quantities" column.
   c. Quantities that can (need to) be measured directly go in the "Measured Quantities" column.
   d. Quantities that are needed but do not fall into any of the above categories go in the last column ("Quantities to be Calculated").
3. Each quantity in the "Quantities to be Calculated" column becomes the "Desired Quantity" in a new row of the table.
4. Continue adding rows until there are no unsolved variables in the "Quantities to be Calculated" column.

Notice in particular that ***every line after the first*** *in the Quantities table* ***is determined by the Quantities to be Calculated*** from previous lines.

Once the table of quantities has been completed, designing the rest of the experiment is similar to the experiment described in the Qualitative Experimental Design Template on pages 53–54.

The design of this experiment is shown in the Quantitative Experimental Design table on the following pages. (A blank template with a download link is shown on pages 96–97.)

Experimental Design Template: Quantitative

Quantities

Desired Quantity	Equation	Description (where equation comes from)	Known Quantities	Measured Quantities	Quantities to be Calculated
F_f	$F_{net} = F_f + F_{ramp}$	$F_{net} = \sum F$	—	—	F_{net}, F_{ramp}
F_{ramp}	$F_{ramp} = ma_{ramp}$	Newton's 2^{nd}	—	m	a_{ramp}
a_{ramp}	$a_{ramp} = g \sin\theta$	ramp equation	g	—	$\sin\theta$
$\sin\theta$	$\sin\theta = \frac{H}{L}$	trig formula	—	H, L	—
F_{net}	$F_{net} = ma$	Newton's 2^{nd}	—	m	a_{net}
a	$d = v_o t + \frac{1}{2}at^2$	kinematic eqn	v_o	d, t	—

these are the quantities that need to be measured

Action(s) Needed to Produce Outcome

block slides down ramp

Known Quantities (*Known without having to be measured.*)

- **Constants** (*to be looked up*):

  $g = 9.81 \frac{N}{kg} \equiv 9.81 \frac{m}{s^2}$

- **Unmeasured Control Variables** (*determined by experimental set-up*):

  $v_o = 0$ (block starts from rest)

Measured Quantities (***Indicate how each will be measured.***)

- **Measured Control Variables** (*kept constant, but need to be measured*):

  mass (m), balance

  height (H) & length (L) of ramp, meter stick

- **Manipulated (independent) variables** (*can be measured before the action occurs*):

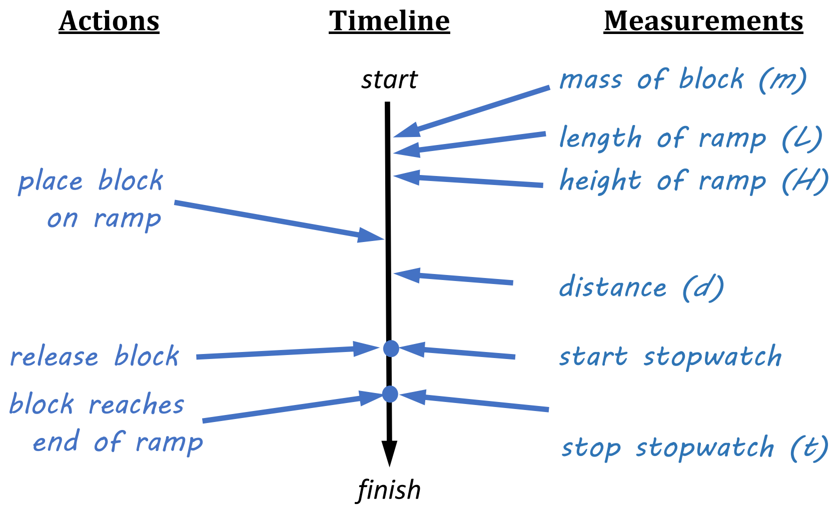
  distance (d), meter stick

- **Responding (dependent) variables** (*cannot be measured until the action occurs*):

  time (t), stopwatch

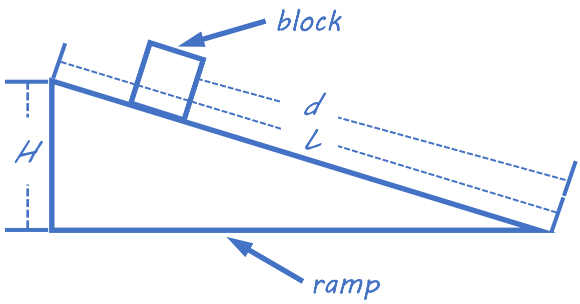
Flow Chart

Show the timeline in the center. List actions on one side and measurements on the other, in chronological order. Use arrows to connect each to its place in the timeline. Use a dot on the timeline when an action and a measurement need to take place at the same time.



Sketch or Labeled Photograph of Experimental Set-Up

Include a sketch or photograph of your experimental set-up, with ***<u>each</u>*** *piece of equipment and important dimensions* ***<u>labeled</u>****.*



There are several features of this form that are helpful in planning the experiment:

- Each quantity that needs to be measured in the experiment appears in the "Quantities to be Measured" column of the table.

  Each quantity to be measured will also appear on the "Measurements" side of the flow chart.
- Each quantity in the "Known Quantities" column needs to be looked up or designed into the experiment.
- On the flow chart, the timeline is in the center.
- On the flow chart, every action and measurement is connected to the timeline according to when it takes place.
- Note the use of a dot on the timeline arrow in the flow chart to indicate when an action and a measurement need to take place at the same time.
- The procedure will be determined from the flow chart, as was the case when using the Qualitative Experimental Design Template on pages 53–54.
- After the experiment is finished, the table of equations will guide the students through the calculations. Because the experiment was "backward-designed," the equations will be in reverse order. *I.e.,* when performing calculations, students will start with the equation at the bottom of the table and work their way to the top.

Teaching Students to Use the Template

Just as teaching experimental design from upper elementary or middle school through high school is a process, teaching every piece of that process is its own sub-process. Just as guided inquiry experiments need to be taught, scaffolded, and the scaffolding gradually removed as students internalize the process, the same is true for higher-level experimental design.

Regardless of whether or not your students have several years of learning experimental design for you to build on, using a template such as this one is one of the procedures that needs to be taught—usually in stages—at the beginning of the year.

Sample First Experiment: Thickness of Aluminum Foil

A simple experiment that can be used to teach students to use the template is to have them find the thickness of a sheet of aluminum foil. The students need to come to two realizations in order to do this experiment/activity, and the teacher can provide whatever amount of guidance/scaffolding the students need.

1. A sheet of aluminum foil is a three-dimensional object, which has length, width, and height.
2. Length, width, and height are used in the equation for the volume of a rectangular solid.

This means that if students have a way of finding the volume, they have all of the variables in the equation except for height (thickness). There are several ways students might find the volume. Two of the most obvious are:

- Water displacement, using a graduated cylinder
- Giving students/letting them look up the density of aluminum and using the equation for density.

Both of these approaches have merits. If students choose water displacement, they have opportunities to learn a couple of key lessons about sources of uncertainty, namely that (a) a sheet of aluminum foil takes up a small volume, which means the uncertainty is a significant fraction of the measurement, and (b) if they crumple the aluminum foil instead of cutting it up, the trapped air affects their volume measurement.

However, for the purpose of teaching students to use this template (or one like it), it is helpful if they choose to use the density of aluminum. Simply giving them the value will most likely be taken as a suggestion to do so—students are used to the notion that every problem will give them exactly what they need to solve it, and that they will need to use everything that is given![*]

The teaching benefit of having students use the density equation is that it forces them to use two separate equations in order to find the desired quantity, which allows the teacher to guide them through the use of the table. Because this experiment is simple enough that students can visualize it in its entirety, their understanding of how to achieve the outcome leaves them with plenty of cognitive load available to learn how the table and the rest of the template guide them through the experimental design process.

[*] This is a habit that it will be useful to force them to break as they school year goes on. As a general rule, I recommend giving students more information than they will use—perhaps by giving them a set of reference tables at the beginning of the year where they can look up anything that they need.

An example of how the experimental design template can be applied to this experiment appears on the following page. (Because there is no action and no apparatus, the second page is not needed.)

Experimental Design Template: Quantitative

Quantities

Desired Variable	Equation	Description (where equation comes from)	Known Quantities	Measured Quantities	Quantities to be Calculated
H	$V = L \cdot W \cdot H$	volume of rect. solid.	—	L, W	V
ρ	$\rho = \frac{m}{V}$	density equation	ρ	m	—

Action(s) Needed to Produce Outcome

none

Known Quantities (*Known without having to be measured.*)

- **Constants** (*to be looked up*):

  $\rho = 2.70 \frac{g}{cm^3}$

- **UnmeasuredControl Variables** (*determined by the experimental set-up*):

  none

Measured Quantities (***Indicate how each will be measured.***)

- **Measured Control Variables** (*kept constant, but need to be measured*):

  none

- **Manipulated (independent) variables** (*can be measured before the action occurs*):

  length (L), width (W), ruler
  mass (m), balance

- **Responding (dependent) variables** (*cannot be measured until the action occurs*):

none

Subsequent Experiments

One of the advantages of the typical sequence of topics in most high-school physics courses (kinematics → forces → energy/momentum) is that the equations used for forces, energy, and momentum rely on the kinematic equations to calculate quantities such as velocity and acceleration. This means that after a first experiment such as the thickness of aluminum foil to teacher students how the process works, followed by a second experiment such as determining the acceleration of a cart down a ramp (as described on page 57, but using the template), most students have enough experience with the process to be comfortable and reasonably self-sufficient with it.

Once students are used to the process, it is straightforward for them to progress to an experiment that uses the equations in more complex ways, such as one involving motion in two dimensions or the friction of a block on a ramp experiment (described starting on page 59). By the end of the school year, students should be mostly self-sufficient at designing experiments to find a quantity that can be derived from a series of related equations.

10. Uncertainty

Every measurement has uncertainty. The concept that every measurement has limitations is as fundamental to science as experimentation itself.

Introducing the Concept of Uncertainty in Elementary School

Children should be introduced to the idea of uncertainty and precision as young as possible. Most children understand when they are three or four years old that a parent's promise that "we're going to leave in five minutes" includes a little (or sometimes a lot of) plus or minus.

Ideally in fourth or fifth grade (by the time they have an understanding of fractions), but no later than middle school, children should make analog measurements (*e.g.,* with rulers) in which the instruments are marked to different levels of precision. They should understand (ideally by discovery) the concept that a measurement can have a value that is *in between* the markings.

Teaching Uncertainty in Middle School

In middle school science classes, students should be introduced to the idea of *random error* (variation that is randomly distributed around the actual value) *vs. systematic error* (variation that is skewed in one direction or the other).*

When middle schoolers carry out experiments that they have designed, it is useful to include discussions about uncertainty. However, middle schoolers are just learning experimental design; they will be better served by focusing on experimental design, and looking at uncertainty after the fact.

* A good example of systematic error is measuring the distance that an object travels by using a tape measure to measure from the start to the finish. Because an object can never travel in a perfect straight line, the distance measured with the tape measure will always be less than the distance that the object actually traveled.

A good way to introduce the concept is to start by having students make their best educated guess about how much uncertainty ("plus or minus") each of their measurements had. You can encourage this mindset through questioning: *"You measured the width of your desk and found it to be 49.7 cm. Do you think maybe it could have actually been 49.6 cm? 49.5 cm? 49.4 cm?"* Keep going (in either direction) until the student says, *"No, I don't think so."* The difference between the student's measurement and the farthest value that sounds reasonable to the student is their uncertainty.*

For analog measurements (*e.g.,* length), students should at first consider their own measurements. ("Which numbers was it between?") After a few experiments, students should be encouraged to look at what happens when multiple students measure the same quantity (*e.g.,* the length of an object).

Later on, perhaps in eighth grade, students should be encouraged to estimate the ± when they take the measurements instead of estimating it after the fact.

While middle school students can learn the steps required for quantitative error propagation, it is best left until high school. If middle schoolers are taught a method of error propagation (*e.g.,* relative error or significant figures), they will most likely either memorize the steps of the calculation without understanding what those steps accomplish, or they will simply be confused, creating a mental block against learning how to do error propagation when they get to high school.

Teaching Uncertainty in Ninth Grade

Ideally by ninth grade, students have been learning experimental design and have been exposed to the idea of uncertainty. If that is not the case, they need to start with the elementary and middle school concepts described in the previous section.

Also, ninth graders have ideally already had some experience with estimating the uncertainty (±) for each measurement they take. (If they haven't, this is a good time to start!) As the course progresses, students should be asked (at least a few times) to look at an experiment in which multiple measurements are combined to produce a result. The students should be asked to make a best educated guess as to which quantity contributed most to the uncertainty of the result.

* Of course, uncertainty goes far beyond what "sounds reasonable to the student." However, at this point the goal is to get students thinking about the *concept* in terms that they already understand intuitively.

Teaching Uncertainty in Chemistry and Physics

In chemistry (both at the high school and college levels), uncertainty is often estimated using significant figures. Significant figures have their problems, one of which is that students often do not understand how or why they work. (Does this sound familiar?) However, because many college chemistry professors and researchers use significant figures extensively, it is important that students learn to work with them in their high school chemistry classes.

In my experience, most high school students find significant figures to be non-intuitive, and many of them memorize the rules (often incorrectly or incompletely) but do not understand the reason for them, or how they give an approximation of the uncertainty.

For the purpose of actually teaching students about uncertainty, it is better to teach them the concepts of absolute and relative error* and have them use relative error for experiments. In my experience, students understand significant figures much better as an approximation of relative error.

Because almost all of the equations used in chemistry and physics are based on multiplication and division, when teaching error propagation, it is advantageous to spend most of the class time and effort on relative error. By only spending a brief amount of time teaching about how and when to combine absolute errors, students will be more likely to think of combining relative error as the rule and combining absolute errors as an exception. This mindset will be helpful throughout the rest of the year.

If students have already learned to estimate the uncertainty of their individual measurements in earlier grades, they should already be in the habit of doing so (or should need little reminder/reinforcement). However, if students start the class without this skill (or without being in the habit of it every time they take a measurement), it would be helpful for them to practice this skill in isolation on their first experiment or two, and then learn to calculate and propagate relative error in subsequent experiments. Remember that error propagation is a goal by the *end* of the school year, so your students will have all year to get used to it.

Recall that the relative error† of a single measurement is defined as:

$$\text{relative error} = \frac{\text{uncertainty } (\pm)}{\text{measurement}}$$

* Because the word "error" has a very different meaning in the vernacular, I often replace it with "uncertainty", as in "relative uncertainty" and "sources of uncertainty".

† If you are used to percent error, relative error is the same quantity but expressed as a (usually decimal) fraction out of 1 instead of as a percentage out of 100%.

To propagate uncertainty using relative error, add the relative errors*, then convert total relative error to the absolute error of the calculated result by multiplying the total relative error by the final result.

Once students understand how relative error works, it is a simple matter to show how significant figures are derived from relative error, with the assumption that the uncertainty of the measurement is ± 0.5 in the last unrounded digit.

There are, of course, plenty of other ways to do error propagation, which students who study STEM subjects in college will learn about. However, most college professors will be thrilled to have students enter college with even the most basic understanding of uncertainty and error propagation.

* If the equation uses exponents, first multiply the relative error for any variable that has an exponent by its exponent. This includes multiplying by fractions if the equation involves roots, *e.g.,* multiplying by ½ for a square root.

11. Graphs & Linearization

Whenever there is a mathematical relationship between two variables, the relationship can be shown as a graph, with the slope (or its inverse) representing the numerical value of the quantity that relates them. Representing a relationship in this manner almost always gives more (or better) information than simply taking an average of the values, because it shows that relationship over a range of values.

However, linearization requires a solid understanding of algebra and facility with graphing. As with every other aspect of teaching experimental design, attempting to teach a skill to a student who is not conceptually ready to understand it will result in the student not only failing to learn the skill, but will undermine the student's understanding of other related skills. For this reason, at the high school level, linearization is usually only taught in honors and AP® classes.

A Sample Experiment With Linearization

In its simplest terms, linearization involves rearranging an equation into $y = mx + b$ form, where *x* is the manipulated variable of interest, *y* is the responding variable of interest, and *m* (the slope) is the value of the quantity of interest that relates the two variables.

Imagine that students are performing a Hooke's Law* experiment in which students are to determine the spring constant of a spring. Imagine that students have recorded the following data:

Applied Force (N)	0.0	1.0	2.0	3.0	5.0
Displacement (m)	−0.01†	0.05	0.16	0.20	0.34
Uncertainty (m)	± 0.06	± 0.06	± 0.06	± 0.06	± 0.06

* In physics, Hooke's Law is the relationship between the force applied to a spring and the distance that it stretches or compresses: $F_s = kx$

† This data point is intentional, in that it illustrates that if students forgot to do something such as zeroing the scale, they still need to use whatever data they actually have.

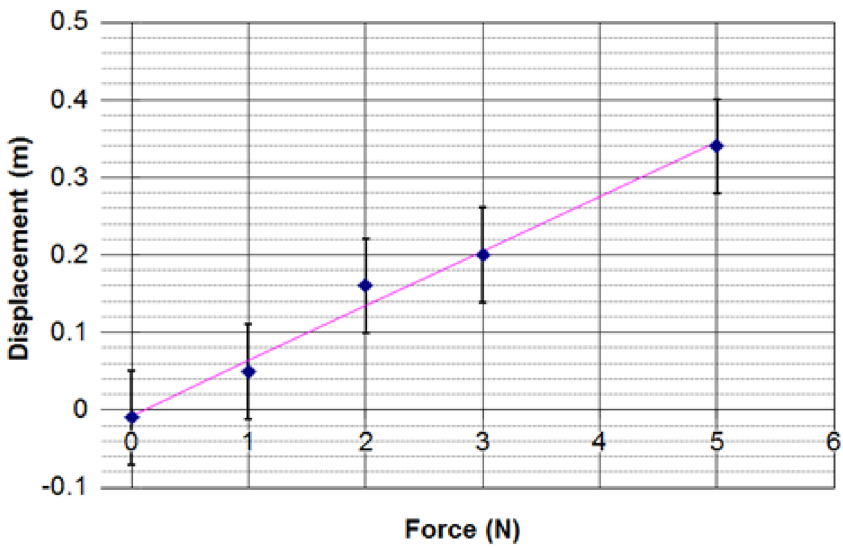
The equation is $F_s = kx$, which is already in $y = mx + b$ form. However, the experiment varied the force and measured the displacement, which means force is the manipulated variable (x-axis), and displacement is the responding variable (y-axis). Therefore, the equation should be rearranged* to:

$$\begin{array}{ccccc} y & = & m & x & +b \\ \downarrow & & \downarrow & \downarrow & \downarrow \\ x & = & \left(\frac{1}{k}\right) & F_s & +0 \end{array}$$

Therefore, if students plot a graph of F_s *vs.* x, the graph will have a slope of $\frac{1}{k}$.

Students therefore need to:

1. Plot the data points. If they measured uncertainty, they should express the uncertainties as error bars.
2. Draw a best-fit line† (which should pass through each error bar, if applicable). The graph looks like the following:



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* Graphs of Hooke's Law are usually plotted with displacement on the abscissa (x-axis) and force on the ordinate (y-axis). The graph works mathematically either way. It is presented this way partly because most graphs are plotted with the manipulated variable on the abscissa and the responding variable on the ordinate, and partly to show that the slope of the graph is sometimes the reciprocal of the quantity of interest.

† Recall that the definition of a best-fit line is one that minimizes the total accumulated distance away from each data point.

Students then compute the slope using the rise (Δy) and run (Δx) from the graph. The best-fit line goes through the points (0, 0) and (3.0, 0.21). Based on these points, the slope is:

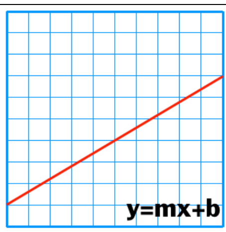
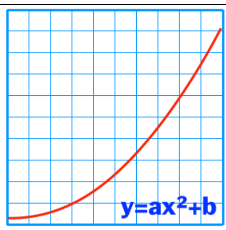
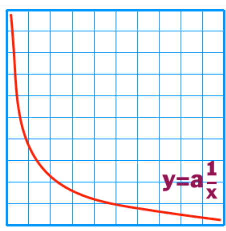
$$m = \frac{\Delta y}{\Delta x} = \frac{0.21-0}{3.0-0} = 0.07$$

Because the slope is $\frac{1}{k}$, the spring constant is the reciprocal of the slope of the above graph: $\frac{1}{0.07} = 14\,\frac{\text{N}}{\text{m}}$.

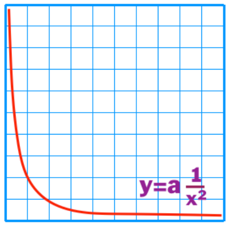
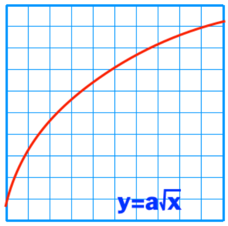
Teaching Linearization

Most of the process of teaching linearization involves teaching students to algebraically rearrange equations into $y = mx + b$ form, especially when those equations involve fractions or exponents.

If students will be taking data and then inferring an equation from the data, it is also important to teach them to recognize the shapes of plots of different functions.*

Plot of *y vs. x*	Equation	Linear Plot
	**Linear** $y = mx + b$ b = y-intercept	y vs. x slope = m
	**Power** $y = ax^2$ or $y = ax^2 + b$ b = minimum y-value	y vs. x^2 slope = a
	**Inverse** $y = \frac{a}{x}$ or $y = a \cdot \frac{1}{x}$ undefined (∞) at $x = 0$	y vs. $\frac{1}{x}$ slope = a

* Graphs by Tony Wayne. Used with permission.

Plot of *y vs. x*	**Equation**	**Linear Plot**
	**Inverse Square** $y = \frac{a}{x^2}$ or $y = a \cdot \frac{1}{x^2}$ undefined (∞) at $x = 0$	y vs. $\frac{1}{x^2}$ slope = a
	**Square Root** $y = a\sqrt{x}$	y vs. $\sqrt{x}$ slope = a

Because linearization is an analytical process applied to an equation, it is best to introduce it after students are already well-versed in using equations to drive experimental design. Assuming you are using an approach similar to the Experimental Design Template in this document, students should be fairly self-sufficient in designing experiments and calculating results using the template before introducing linearization. This enables students to build the concept into a solid understanding of how experimental design relates to the equations relating the quantities and avoids the confusion that results from trying to learn both concepts at the same time.

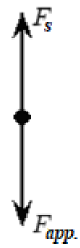
When students perform their first experiment that requires linearization, the first equation (at the top of the Quantities chart in the Quantitative Experimental Design Template) is almost always the one that they will need to rearrange into $y = mx + b$ form to use for the graph.

When deciding on the number of data points to take for a typical high school experiment, the "**8 and 10 rule**" is a good guideline: have a minimum of **8 data points**, and the values of the manipulated variable should span a range of at least a **factor of 10** from the smallest to the largest.

It is also useful to teach students that a graph is valid and useful regardless of which quantity is plotted on which axis. For example, the graph shown on page 74 is plotted with the manipulated variable (force) on the abscissa (x-axis), and the responding variable (displacement) on the ordinate (y-axis). However, almost every other graph of Hooke's Law is plotted with the axes switched—with displacement on the abscissa and force on the ordinate—regardless of which was the manipulated *vs.* responding variable in the experiment.

Either representation is equally valid. Hooke's Law, $F_s = kx$ (in *y* = *mx* + *b* form), shows that the force applied by the spring is a function of its displacement. Thus, a graph of the force applied *by the spring vs.* displacement would normally be plotted with displacement on the abscissa and the spring force on the ordinate. However, displacement of the spring is caused by the applied force, which Newton's Third Law tells us must be equal to the force applied by the spring. Thus:

- The externally applied force is the manipulated variable.
- Displacement of the spring is a responding variable (which depends on the external force and the spring constant).
- The force applied by the spring in response is a responding variable (which also depends on the external force and the spring constant).



Of course, curve-fitting of data is much broader than just linearization. It is useful for students to be able to recognize graphs of other functions, such as exponential, logarithmic, *etc.* However, as with other concepts in this work, adding too much complexity can make it harder for students to understand the underlying concept. As is the case with uncertainty, college professors will be thrilled if their students can linearize data and represent relationships graphically using a best-fit line, and students can learn curve-fitting to other functions as their college studies require it.

12. Laboratory Reports

Laboratory reports are the bane of many students' and teachers' existence. Every teacher and every student begrudgingly understand the necessity of communicating the details of an experiment. However, lab reports are usually difficult for students to write, and tedious for teachers to grade, resulting in much procrastination and resentment on both sides.

It is tempting to allow students to turn in group lab reports, both to reduce the grading load and to reduce the level of complaining from the students. However, because students plan and carry out their lab experiments in groups, it is valuable for each student to write a separate lab report. This requires each student to engage separately with the experiment and its design as they write it up. Students who were less involved in designing the experiments end up having to put more effort into understanding the design of the experiment when they write it up, with the result that most students end up participating actively enough in the process to learn from it.

Two common reasons students have difficulty with lab reports are:

1. They do not understand the experiment.
2. They do not understand how the lab report relates to the experiment.

The first of these is perhaps the most significant benefit of having students design their own experiments. When students are active participants is the design of an experiment, every step of the procedure is connected to the rest of the design of the experiment, and every step of the procedure has a reason for being done that students understand because they are the ones who decided to do it. The second can be addressed by structuring the lab report around the experimental design process.

Often, teachers give little thought to the reasons behind the structure of lab reports. Frequently, they choose a lab report format because:

- *"That's the way I had to write lab reports when I was in high school."*
- A colleague, mentor, or someone in a science teachers' networking group said, *"You should have your students use this lab report format because it's the one I use and it works for me."*

Reports for Experiments

Frequently, lab report formats are a variation of the following:

1. Objective
2. Introduction
3. Procedure
4. Results & Discussion
5. Conclusions

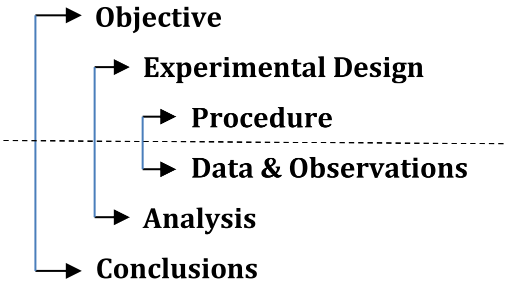
The Introduction is particularly tricky for students who do scripted experiments, because it requires them to explain an experiment that someone else designed. Also, if the lab was scripted students are likely to copy the Procedure exactly as it was given, without making corrections for any steps that were changed; if the lab was inquiry-based, they usually write what they did in the order that it happened. Their Results & Discussion section usually consists of their measurements followed by their calculations, ending with the result that they believe that they were supposed to get, and their Conclusions are usually something hand-wavey that relates the experiment to something else.

A more useful way to organize a lab report at the high school level is in parallel to the way the experiment was designed and carried out. I use the following sections:

1. Objective
2. Experimental Design
3. Procedure
4. Data & Observations
5. Analysis (using CER; see page 26)
6. Conclusions

Notice that the Introduction section has been replaced by an Experimental Design section. Students use information from the experimental design process (which would be recorded on the Experimental Design Template, if you use it) to write that section. This section explains how and why the experiment was set up the way it was. The Procedure section, as before, is where the *action* and each of the measurements are described in detail.

The following graphic shows the hierarchy and correspondence of the sections of the report:



Notice that each of the sections that describe setting up and performing the experiment (above the dashed line) have a corresponding section that describes the outcome (below the dashed line). The Conclusions section addresses the Objective—whether and how well the objective of the experiment was met. The Analysis section addresses the Experimental Design. Each equation in the Experimental Design section has corresponding calculations in the Analysis. Each measurement in the Procedure section has a corresponding value in the Data & Observations section.

Notice also that the sections start broad (with the Objective) and become more focused until the experiment is performed (the dashed line). The sections then broaden out from the experiment to the Conclusions. The Objective produces the Experimental Design, which produces the Procedure. The Data & Observations section follows directly from the Procedure, which enables the Analysis, which then enables the Conclusions.

A laboratory report for the Sample Experiment: Friction on a Block Sliding Down a Ramp (which is described starting on page 59) might look like the following. You will undoubtedly notice that the Experimental Design section of the report is identical to the template. This is intentional; while there are good reasons to formalize the writing in this section, keeping it identical to the template lowers students' perceived barriers to completing the write-up. If nearly half of the write-up is already done by the time they start writing, students are more invested in completing it.

Force of Friction on a Block Accelerating Down a Ramp

Name: Anita Nay

Lab Group: Anita Nay, Stu Dent, Sarah Bellum

Objective

Determine the force of friction on a block as it accelerates down a ramp.

Experimental Design

Quantities

Desired Quantity	Equation	Description (*where equation comes from*)	Known Quantities	Measured Quantities	Quantities to be Calculated
F_f	$F_{net} = F_f + F_{ramp}$	free-body diagram	—	—	F_{net}, F_{ramp}
F_{ramp}	$F_{ramp} = ma_{ramp}$	Newton's 2nd Law	—	m	a_{ramp}
a_{ramp}	$a_{ramp} = g \sin\theta$	ramp equation	g	—	$\sin\theta$
$\sin\theta$	$\sin\theta = \frac{H}{L}$	trig. formula	—	H, L	—
F_{net}	$F_{net} = ma_{net}$	Newton's 2nd Law	—	m	a_{net}
a_{net}	$d = v_o t + \frac{1}{2}at^2$	kinematic eqn. #2	v_o	d, t	—

Action(s) Needed to Produce Outcome

(What needs to happen in order to meet the objective?)

block slides down ramp

What will cause the action(s) to happen?

(Are there specific conditions necessary for the action to occur? If so, how will they be met?)

gravitational force

Known Quantities

- **Constants**

  $g = 9.81 \frac{\text{N}}{\text{kg}}$

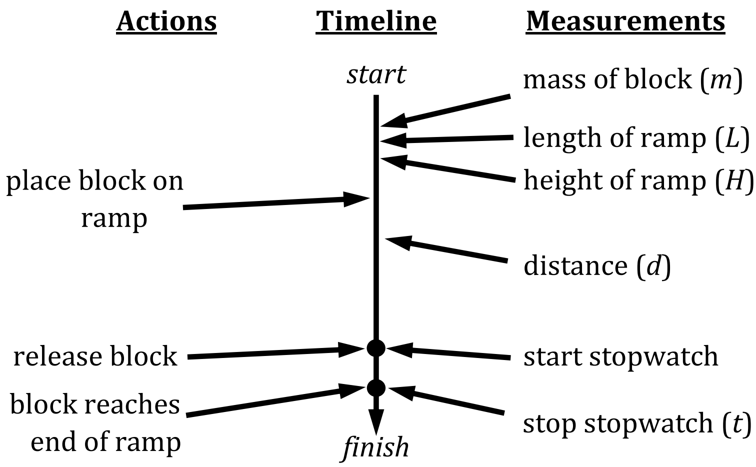
- **Unmeasured Control Variables**

  $v_o = 0$ (block starts from rest)

Measured Quantities

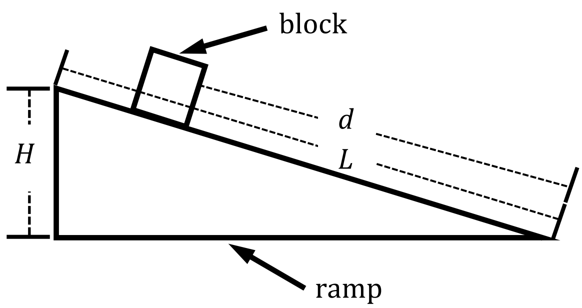
- **Measured Control Variables**
  mass (m) — balance
  height (H) & length (L) of ramp — meter stick
- **Manipulated (independent) variables**
  distance (d) — meter stick
- **Responding (dependent) variables**
  time (t) — stopwatch

Flow Chart



Procedure

1. A ramp was set up as shown:



2. The mass of the block was measured using a balance.
3. The length and height of the ramp were measured, using a meter stick.

4. The block was placed on the ramp and a starting line was marked at the front edge of the block.
5. The distance from the starting line to the end of the ramp was measured, using a meter stick.
6. The block was placed on the ramp with the front edge at the starting line.
7. The block was released and a stopwatch was started at the same time.
8. The stopwatch was stopped when the block reached the bottom, and the time was recorded.
9. Steps 4–8 were repeated four more times, starting from different points on the ramp.

Data & Observations

Height of ramp: 0.536 m
Length of ramp: 2.55 m

Trial #	*m* (g)	*d* (m)	*t* (s)
1	123.72 ± 0.02	0.502 ± 0.02	3.71 ± 0.2
2	123.72 ± 0.02	1.001 ± 0.02	5.28 ± 0.2
3	123.72 ± 0.02	1.498 ± 0.02	6.51 ± 0.2
4	123.72 ± 0.02	2.001 ± 0.02	7.37 ± 0.2
5	123.72 ± 0.02	2.473 ± 0.02	8.21 ± 0.2

Trial #	v_o (m/s)	v (m/s)	a_g (m/s^2)	a (m/s^2)	a_f (m/s^2)	F_f (N)
1	0	0.271	2.062	0.0729	-1.989	
2	0	0.379	2.062	0.0718	-1.990	
3	0	0.460	2.062	0.0707	-1.991	-0.25 ± 0.03
4	0	0.543	2.062	0.0737	-1.988	
5	0	0.602	2.062	0.0734	-1.989	

Analysis

Summary of Experiment

A cart was rolled down a ramp from different starting points. Distances and times were measured. The block accelerated at a constant rate of approximately $0.074\,\frac{\text{m}}{\text{s}^2}$.

The force of friction acting on the block as it slid down the ramp was determined to be 0.25 N ± 0.03 N.

Discussion*

Claim: The slope of the ramp caused the block to accelerate at a constant rate of $0.074\,\frac{\text{m}}{\text{s}^2}$. This resulted from the combination of the forces of gravity pulling the block down the ramp and friction.

Evidence: The velocity of the block increased as it went down the ramp.

Reasoning: The increase in the velocity of the block was constant with respect to time, as shown by the fact that the points lie on or near the best-fit line. This shows that acceleration was constant. The slope of the best-fit line was $0.074\,\frac{\text{m}}{\text{s}^2}$, which is the acceleration of the block.

Acceleration of the block was caused by a combination of gravity and friction. Acceleration down the ramp due to gravity (a_g) without friction was assumed to be $g\sin\theta = 2.062\,\frac{\text{m}}{\text{s}^2}$.

Acceleration was calculated by applying Newton's second law, $F_{net} = \sum F = ma$.

$F_{net} = F_g + F_f = m(a_g + a_f)$. Acceleration is a vector quantity, which means the acceleration due to friction must be $a_f = a_{observed} - a_g$. The force of friction was calculated using $F_f = ma_f$.

The nonzero *y*-intercept of the graph may be a result of the conversion from static to kinetic friction that occurred when the block was released.

* Note that the discussion appears at the beginning of the Analysis section, immediately after the Summary of Experiment. However, the Discussion cannot be written until after the calculations have been performed and the graph plotted.

Sample calculations

Calculations were performed by a spreadsheet, using the equations from the Quantities table in the Experimental Design section. The following sample calculations from trial #3 show how the equations were used:

$$d = v_o t + \tfrac{1}{2}at^2 \quad a = \frac{2d}{t^2} \quad a = \frac{(2)(1.498)}{6.51^2} = 0.0707\,\tfrac{\text{m}}{\text{s}^2}\ ^*$$

$$F_{net} = ma_{net} \quad F_{net} = (123.72)(0.0741) = 0.00917\,\text{N}$$

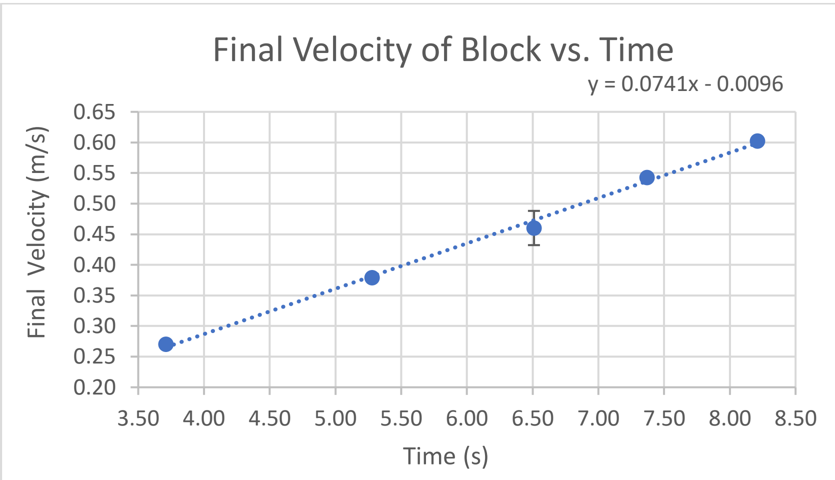
$$a_{ramp} = g\sin\theta \quad a_{ramp} = (9.81)\left(\frac{0.536}{2.55}\right) = 2.062\,\tfrac{\text{m}}{\text{s}^2}$$

$$F_{ramp} = ma_{ramp} \quad F_{ramp} = (0.12372)(2.062) = 0.255\,\text{N}$$

$$F_{net} = F_f + F_{ramp} \quad F_f = F_{ramp} - F_{net} = 0.255 - 0.00917 = 0.246\,\text{N}$$

Graph

A graph of final velocity of the block *vs.* time gives acceleration.



A best-fit line was plotted and the slope (acceleration) of the best-fit line was found to be $0.0741\,\frac{\text{m}}{\text{s}^2}$. This value for the overall acceleration of the block was used for calculations.

* The value of *a* used for the rest of the calculations is the one determined graphically using a best-fit line.

Sources of Uncertainty

- mass: The published uncertainty of the balance that was used is ±0.02 g.
- distance: Distance was measured using a meter stick. The uncertainty of each measurement was estimated when the measurement was taken.
  It was assumed that the block slid in a straight line. However, there could have been additional uncertainty due to the actual path of the block down the ramp.
- time: Time was measured using a stopwatch. Uncertainty was assumed to be the typical human reaction time of ±0.2 s.

Quantitative Analysis of Uncertainty

Uncertainty of the force of friction was calculated using relative error. Relative errors were calculated for the measured quantities mass, distance and time. Total relative error was the sum of the maximum relative errors for each quantity. This number was multiplied by the calculated force of friction to produce the uncertainty.

Conclusions

A block was allowed to slide down a ramp, starting from different positions and the mass of the block, distance and time were measured. Acceleration of the block was calculated using a best-fit line, and the force of friction acting on the block was found to be 0.25 N ± 0.03 N.

This experiment could be improved by using an electronic photogate to measure the time it took to slide down the ramp, by taking additional data points, and by taking data using a greater range of distances.

In the above laboratory report, you may have noticed that in the graph of final velocity *vs.* time, time is a responding variable and velocity is a calculated quantity. As mentioned on page 76, it is useful to teach students that while it is traditional to plot manipulated variables on the abscissa (x-axis) and responding variables on the ordinate (y-axis), it is valid to place any quantity on any axis, and the choice of which quantity is plotted where may depend on other factors besides the manipulated *vs.* responding variable.

Of course, there are as many lab report formats as there are teachers, and each one has its benefits and its drawbacks. One potentially controversial decision I made in this format was to include calculated quantities in the Data and Observations section. My rationale is that I want students to believe in the idea that every item in the lab report is important and is worth their time and effort. Keeping those quantities together in the same table means they are still able to convey the necessary information, but with less effort.

Reports for Design Projects

The report for a design project is necessarily different from the report for an experiment. In a design project, there are usually no overarching measured and responding variables, and the objective is not to determine or calculate something, but rather to make something happen reliably. Consequently, a design project requires a different style of report.

Teaching Students to Use Spreadsheets

The data table and graph in this sample report were produced using a spreadsheet program. Spending class time teaching students to use spreadsheets, such as Google Sheets or Microsoft Excel for these kinds of calculations and graphs is an investment that will pay off tremendously for them in college. Many high school students either are never taught to use a spreadsheet, or they take a computer literacy class in which they complete one assignment in a spreadsheet using sample data, after which they forget everything they learned because it is never reinforced. As is the case with lab experiments that use scripted procedures, students are so focused on getting the steps right that they never internalize how spreadsheets actually work.

Grading Laboratory Reports

For many (most?) teachers, grading is one of the least enjoyable parts of the job. After grading ten or fifteen lab reports, it is apparent what students understand and what they don't, and these first ten or fifteen reports generate several ideas for what to do differently the next time. However, now that the learning (on the teacher's part) has happened, teachers are impatient to move on and try their new ideas, but they still have 100 or more lab reports to grade.

Rubrics are useful for several reasons—they convey the specifications to students and they make grading more objective and more consistent. However, the traditional 4–3–2–1 rubric leaves a lot open to interpretation, both on the part of the students and the teacher, and grading with this type of rubric is still tedious.

A checklist rubric* alleviates many of these problems. It shows students in detail exactly what is required in each section, and it is quick to grade because each item is worth one point (though fractional points may, of course, be awarded when appropriate). Thus each decision amounts to a quick "yes, it's there" or "no, it's not there".

Notice that the rubric is divided into sections corresponding with the sections in the lab report. There are 41 checkboxes on the rubric plus 10 points for timeliness, for a total of 51 points. Note that each item has two checkboxes. Students are instructed to check one of the checkboxes for each item when they verify that they have included it, before handing in the report. The other checkbox is used for the teacher to verify that the item is, in fact, included and sufficient to receive the point.

* This rubric was developed starting with 4 criteria for each of the items that was worth 4 points on a traditional 4–3–2–1 rubric. Each of those criteria became its own checkbox on the new rubric. The new rubric proved to be much faster and easier to use, and the grades came out essentially the same (± 2 points) using either rubric. (Of course, the rubric continues to evolve, because teaching is a reflective and iterative process.)

The points on the rubric are:

Title, Objective, *etc.* (4 points)

☐ ☐ title included in report
☐ ☐ lab partner(s) listed
☐ ☐ objective stated in report
☐ ☐ title & objective both adequately describe purpose of experiment

Experimental Design (5 points)

☐ ☐ section included in report
☐ ☐ table showing relationships between relevant quantities
☐ ☐ describes actions & how they are caused
☐ ☐ describes control, manipulated, and responding variables
☐ ☐ flow chart of experiment from start to finish showing how to produce outcome and when to take measurements

Procedure (7 points)

☐ ☐ section included in report
☐ ☐ includes photo or sketch of set-up, *with **objects** and **dimensions** explicitly **labeled***
☐ ☐ all significant materials & equipment are explicitly mentioned (*can be listed separately and/or mentioned within steps*)
☐ ☐ describes ***action(s)*** (how the outcome was produced) in sufficient detail
☐ ☐ describes how each measurement was acquired in sufficient detail, including the equipment used
☐ ☐ complete (*someone following the procedure closely would achieve the same results*)
☐ ☐ easy to follow & understand

Data & Observations (7 points)

☐ ☐ section included in report
☐ ☐ all measurements are included
☐ ☐ measurements have appropriate precision
☐ ☐ units included for ***all*** measurements
☐ ☐ relevant qualitative observations included
☐ ☐ uncertainty given for ***each*** measured quantity
☐ ☐ data are presented effectively

Analysis (10 points)

- ☐ ☐ section included in report
- ☐ ☐ summary of experiment included & accurate
- ☐ ☐ Discussion: *claim* is reasonable and relates to objective
- ☐ ☐ Discussion: *evidence* comes directly from measurements and calculations
- ☐ ☐ Discussion: *reasoning* is correct and supports the claim based on the evidence
- ☐ ☐ calculations are shown, readable and in logical order
- ☐ ☐ calculations are correct
- ☐ ☐ graph is included
- ☐ ☐ graph is complete, plotted accurately & correct
- ☐ ☐ sources of uncertainty are listed & explained (minimum one source for *each* measured or observed quantity; *explain the ± assuming that the experiment went perfectly with no mistakes*.)

Conclusions (4 points)

- ☐ ☐ section included in report
- ☐ ☐ includes 1–2 sentence summary of objective, action & measurements
- ☐ ☐ includes 1–2 sentence summary of results & discussion (including quantitative result with uncertainty)
- ☐ ☐ suggests improvements to design/procedure (*ways to reduce the uncertainty of each of the measurements*).

Format, *etc.* (4 points)

- ☐ ☐ sections have headings & are in correct order
- ☐ ☐ each section contains the appropriate information
- ☐ ☐ no significant conceptual mistakes
- ☐ ☐ relatively free from minor mistakes in spelling, grammar, superscript & subscript errors, *etc.*

Timeliness (10 points)

_____ 10 points if lab report is turned in on time. One of these points is deducted for each school day after the due date.

Note that the maximum deduction for lateness is 20%. I cap the deduction at 20% or less because I believe that the penalty for turning in an assignment late should never be so much that it dissuades students from deriving the benefit from doing the assignment at all.

13. The Experimental Design Question on AP® Exams

If you are teaching an AP® course, one of the obvious applications of this process is the Experimental Design question. Students often struggle with this question for the same reasons that inspired this work.

Once students are comfortable with the experimental design process, they need to understand that they have to go through that process in some fashion in order to be able to answer the question. However, they have only about 15–20 minutes to do so.

Assuming your students are using a process similar to the one in this work, their familiarity with the process will help them answer the question efficiently:

1. Create a table of quantities like the one in the Quantitative Experimental Design Template, leaving out the explanation because of time constraints.
2. Once they have the table of equations, they have a list of the equations, and a column that contains the quantities that they need to measure.
3. Skip to the flow chart. Write the timeline, action(s) and the measurements, with arrows showing exactly when the measurements need to be taken.
4. Write the procedure from the flow chart.

The experimental design question almost always asks students to show how to calculate the desired quantity. Because students will have their calculations spelled out in the table of quantities, they just need to go through the equations from the bottom up. When they get to the equation at the top, they should *always assume that the final calculation needs to be done graphically, using linearization.*

The experimental design question also typically includes a question about improving the experiment. One of the suggested improvements should always be to take additional data points. This is a good time to reference the "8 and 10 rule," though students should *describe* the rule because the readers who score the exams may be unfamiliar with the term. Assuming students have been quantitatively estimating the uncertainties of their measurements throughout the year, each those sources of uncertainty represents an opportunity to reduce the uncertainty of the result.

Appendix: Templates

This appendix contains blank copies of the templates and lab report rubric that were used in this text, and includes links for downloading copies in docx (Microsoft Word) format.

List of Templates

- Experimental Design Template: Qualitative:
  https://www.mrbigler.com/downloads/ED-Qualitative.docx
- Experimental Design Template: Quantitative:
  https://www.mrbigler.com/downloads/ED-Quantitative.docx
- Lab Report Fill-In Template:
  https://www.mrbigler.com/downloads/Report-Template.docx
  (Note that this template is not shown in this document.)
- Lab Report Rubric: Qualitative:
  https://www.mrbigler.com/downloads/Report-Rubric-Qualitative.docx
- Lab Report Rubric: Quantitative:
  https://www.mrbigler.com/downloads/Report-Rubric-Quantitative.docx

Experimental Design Template: Qualitative

Objective:

What is the *action* of this experiment?

What needs to happen in order to meet the objective?

What will cause the *action* to happen?

Are there specific conditions necessary for the action to occur? If so, how will they be met?

How will you determine the result?

Note that this can be an observation or a calculation.

What do you need in order to determine the result?

For measured quantities, indicate how you are going to measure them.

- **Constants** (quantities to be looked up)

- **Control Variables** (quantities you are keeping the same)

- **Manipulated (independent) variables** (quantities you can determine before the ***action*** occurs)
  Indicate how each one will be determined/measured.

- **Responding (dependent) variables** (quantities that cannot be determined until the ***action*** occurs)
  Indicate how each one will be determined/measured.

Flow Chart

The timeline is shown in the center. List actions on one side and measurements on the other, in chronological order. Use arrows to connect each to its place in the timeline.

Actions	**Timeline**	**Measurements**
	start	
	↓	
	finish	

Labeled Sketch or Photograph of Experimental Set-Up:

Include a sketch or photograph of your experimental set-up, with ***each*** *piece of equipment* ***labeled****. (Include dimensions if relevant.)*

Experimental Design Template: Quantitative

Quantities

Desired Variable	**Equation**	**Description** *(where equation comes from)*	**Known Quantities**	**Measured Quantities**	**Quantities to be Calculated** *(Still Needed)*

Action(s) Needed to Produce Outcome

(What needs to happen in order to meet the objective?)

What will cause the action(s) to happen?

(Are there specific conditions necessary for the action to occur? If so, how will)they be met?

Known Quantities

- **Constants** (*to be looked up*):

- **Unmeasured Control Variables** (*determined by the experimental set-up*):

Measured Quantities

Indicate how each will be measured.

- **Measured Control Variables** (*kept constant, but need to be measured*):

- **Manipulated (independent) variables** (*can be measured before the action occurs*):

- **Responding (dependent) variables** (*cannot be measured until the action occurs*):

Flow Chart

The timeline is shown in the center. List actions on one side and measurements on the other, in chronological order. Use arrows to connect each to its place in the timeline. Use a dot on the timeline when an action and measurement need to happen at the same time.

Actions	**Timeline**	**Measurements**
	start	
	↓	
	finish	

Labeled Photograph or Sketch of Experimental Set-Up

*Include a sketch or photograph of your experimental set-up, with **each** piece of equipment and important dimensions **labeled**.*

Rubric: Laboratory Write-Up (Qualitative)

Author of write-up: ______________________________ Period: ________

One checkbox is for students to use before turning in the lab report to verify that they have included each item. The other is for the teacher to use for grading.

Title, Objective, *etc.* (4 points)

- ☐ ☐ title included in report
- ☐ ☐ lab partner(s) listed
- ☐ ☐ objective stated in report
- ☐ ☐ title & objective both adequately describe purpose of experiment

Experimental Design (4 points)

- ☐ ☐ section included in report
- ☐ ☐ describes actions & how they are caused
- ☐ ☐ describes control, manipulated, and responding variables
- ☐ ☐ flow chart of experiment from start to finish showing action(s) & measurements

Procedure (7 points)

- ☐ ☐ section included in report
- ☐ ☐ includes photo or sketch of set-up, *with* ***objects*** *explicitly* ***labeled***
- ☐ ☐ all significant materials & equipment are explicitly mentioned (*can be listed separately and/or mentioned within steps*)
- ☐ ☐ describes ***actions*** in sufficient detail
- ☐ ☐ describes measurements in sufficient detail, including equipment used
- ☐ ☐ complete (*someone following the procedure closely would achieve the same results*)
- ☐ ☐ easy to follow & understand

Data & Observations (7 points)

- ☐ ☐ section included in report
- ☐ ☐ all measurements are included
- ☐ ☐ measurements have appropriate precision
- ☐ ☐ units included for ***all*** measurements
- ☐ ☐ relevant qualitative observations included
- ☐ ☐ uncertainty given for ***each*** measured quantity
- ☐ ☐ data are presented effectively

<u>Analysis</u> (6 points)

- ☐ ☐ section included in report
- ☐ ☐ summary of experiment (actions & measurements) included & accurate
- ☐ ☐ <u>Discussion</u>: *claims* are reasonable and related to objective
- ☐ ☐ <u>Discussion</u>: *evidence* comes directly from measurements and calculations
- ☐ ☐ <u>Discussion</u>: *reasoning* is correct and supports the claim based on the evidence
- ☐ ☐ sources of uncertainty are listed & explained (*explain the uncertainty assuming that the experiment went perfectly with no mistakes*.)

<u>Conclusions</u> (4 points)

- ☐ ☐ section included in report
- ☐ ☐ includes 1–2 sentence summary of objective, actions & measurements/observations
- ☐ ☐ includes 1–2 sentence summary of results & discussion
- ☐ ☐ suggests improvements to design/procedure (*ways to reduce uncertainty*)

Format, *etc.* (4 points)

- ☐ ☐ sections have headings & are in correct order
- ☐ ☐ appropriate information in each section
- ☐ ☐ no significant conceptual mistakes
- ☐ ☐ relatively free from minor mistakes in spelling, grammar, superscript & subscript errors, *etc.*

Timeliness (10 points)

_____ 10 points if lab report is turned in on time. One of these points is deducted for each school day after the due date.

Rubric: Laboratory Write-Up (Quantitative)

Author of write-up: ______________________ Period: ________

One checkbox is for students to use before turning in the lab report to verify that they have included each item. The other is for the teacher to use for grading.

Title, Objective, *etc.* (4 points)

- ☐ ☐ title included in report
- ☐ ☐ lab partner(s) listed
- ☐ ☐ objective stated in report
- ☐ ☐ title & objective both adequately describe purpose of experiment

Experimental Design (5 points)

- ☐ ☐ section included in report
- ☐ ☐ table showing relationships between relevant quantities
- ☐ ☐ describes action & how they are caused
- ☐ ☐ describes control, manipulated, and responding variables
- ☐ ☐ flow chart of experiment from start to finish showing action(s) & measurements

Procedure (7 points)

- ☐ ☐ section included in report
- ☐ ☐ includes photo or sketch of set-up, *with* ***objects*** *and* ***dimensions*** *explicitly* ***labeled***
- ☐ ☐ all significant materials & equipment are explicitly mentioned (*can be listed separately and/or mentioned within steps*)
- ☐ ☐ describes ***actions*** in sufficient detail
- ☐ ☐ describes measurements in sufficient detail, including equipment used
- ☐ ☐ complete (*someone following the procedure closely would achieve the same results*)
- ☐ ☐ easy to follow & understand

Data & Observations (7 points)

- ☐ ☐ section included in report
- ☐ ☐ all measurements are included
- ☐ ☐ measurements have appropriate precision
- ☐ ☐ units included for ***all*** measurements
- ☐ ☐ relevant qualitative observations included
- ☐ ☐ uncertainty given for ***each*** measured quantity
- ☐ ☐ data are presented effectively

<u>Analysis</u> (10 points)

- ☐ ☐ section included in report
- ☐ ☐ summary of experiment (actions & measurements) included & accurate
- ☐ ☐ <u>Discussion</u>: *claims* are reasonable and related to objective
- ☐ ☐ <u>Discussion</u>: *evidence* comes directly from measurements and calculations
- ☐ ☐ <u>Discussion</u>: *reasoning* is correct and supports the claims based on the evidence
- ☐ ☐ calculations are shown, readable and in logical order
- ☐ ☐ calculations are correct
- ☐ ☐ graph is included
- ☐ ☐ graph is complete, plotted accurately & correct
- ☐ ☐ sources of uncertainty are listed & explained (minimum one source for *<u>each</u>* measured or observed quantity; *explain the ± assuming that the experiment went perfectly with no mistakes*.)

<u>Conclusions</u> (4 points)

- ☐ ☐ section included in report
- ☐ ☐ includes 1–2 sentence summary of objective, actions & measurements/observations
- ☐ ☐ includes 1–2 sentence summary of results & discussion (including quantitative results with uncertainties)
- ☐ ☐ suggests improvements to design/procedure (*ways to reduce the uncertainty of each of the measurements*).

Format, *etc.* (4 points)

- ☐ ☐ sections have headings & are in correct order
- ☐ ☐ appropriate information in each section
- ☐ ☐ no significant conceptual mistakes
- ☐ ☐ relatively free from minor mistakes in spelling, grammar, superscript & subscript errors, *etc.*

Timeliness (10 points)

_____ 10 points if lab report is turned in on time. One point deducted for each school day after the due date.

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