# Designing & Performing Experiments

**Unit:** Laboratory & Measurement

**MA Curriculum Frameworks (2016):** SP1, SP3, SP8

**AP® Physics 2 Learning Objectives:** SP 1, SP2, SP3, SP4, SP5, SP6, SP7

**MA Curriculum Frameworks (2006):** N/A

**Mastery Objective(s):** (Students will be able to…)

- Create a plan and procedure to answer a question through experimentation.

**Success Criteria:**

- Experimental Design utilizes backward design.
- Experimental Design uses logical steps to connect the desired answer or quantity to quantities that can be observed or measured.
- Procedure gives enough detail to set up experiment.
- Procedure establishes values of control and independent variables.
- Procedure explains how to measure dependent variables.

**Tier 2 Vocabulary:** inquiry, independent, dependent, control

**Language Objectives:**

- Understand and correctly use the terms "dependent variable" and "independent variable."
- Understand and be able to describe the strategies presented in this section.

**Tier 2 Vocabulary:** design, perform, control, independent (variable), dependent (variable)

## Notes:

If your experience in science classes is like that of most high school students, you have always done "experiments" that were devised, planned down to the finest detail, painstakingly written out, and debugged 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.

If someone asked you immediately after the "experiment" what you just did or what its significance was, you had no answers for them. When it was time to do the analysis, you followed the steps in the handout. When it was time to write the lab report, you had to frantically read and re-read the procedure in the hope of understanding enough of what the "experiment" was about to write something intelligible.

This is not how science is supposed to work.

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In an actual scientific experiment, you would start with an objective, purpose or goal. You would figure out what you needed to know, do, and/or measure in order to achieve that objective. Then you would set up your experiment, observing, doing and measuring the things that you decided upon. Once you had your results, you would figure out what those results told you about what you needed to know. At that point, you would draw some conclusions about how well the experiment worked, and what to do next.

That is precisely how experiments work in this course. You and your lab group will design every experiment that you perform. You will be given an objective or goal and a general idea of how to go about achieving it. You and your lab group (with help) will decide the specifics of what to do, what to measure (and how to measure it), and how to make sure you are getting good results. The education "buzzword" for this is ***inquiry-based experiments***.

## Types of Experiments

There are many ways to categorize experiments. For the purpose of this discussion, we will categorize them as either qualitative experiments or quantitative experiments.

### 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.
- How you will observe it.
- 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.

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**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.

## What to Control and What to Measure

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***, ***independent variables***, and ***dependent variables***.

control variables: conditions that are being kept constant. These are usually parameters that could be independent 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.

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. 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 experiment begins, so height is the *independent* variable.

dependent variable: the things that happen during the experiment. These are the quantities that you won't know the values for until you measure them, because they are *dependent* on what happens in the experiment. For example, if you are dropping a ball from different heights to find out how long it takes to hit the ground, the times depend on what happens after you let go of the ball. This means time is the *dependent* variable.

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If someone asks what your independent, dependent and control variables are, the question simply means:

- "What did you vary on purpose (independent variables)?"
- "What did you measure (dependent variables)?"
- "What did you keep the same for each trial (control variables)?"

## 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're really testing is whether or not it happens under different sets of conditions that you can test. In this case, you need to test three situations:

1. A situation in which you are sure the thing will happen, to make sure you can observe it. This is your **positive control**.
2. A situation in which you sure 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 **independent variable**, and whether or not the thing happens is your **dependent variable**.

## Variables in Quantitative Experiments

If the goal of your experiment is to quantify (find a numerical relationship for) the extent to which something happens (the dependent 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 independent variable) and still be able to measure the result. This gives you the highest and lowest values of your independent variable. Then perform the experiment using a range of values for the independent value that cover the range from the lowest to the highest (or *vice-versa*).

For quantitative experiments, a good rule of thumb is the **8 & 10 rule**: you should have at least 8 data points, and the range from the highest to the lowest values tested should span at least a factor of 10.

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# Letting the Physics Design the Experiment

Most high school physics experiments are relatively simple to understand, set up and execute—much more so than in chemistry or biology. This makes physics well-suited for teaching you how to design experiments.

Determining what to measure usually means determining what you need to know and then figuring out how to get there starting from *quantities that you can measure*.

For a quantitative experiment, if you have a mathematical formula that includes the quantity you want to measure, you need to find the values of the other quantities in the equation.

For example, suppose you need to calculate the force of friction that brings a sliding object to a stop. If we design the experiment so that there are no other horizontal forces, friction will be the net force. We can then calculate force from the equation for Newton's Second Law:

$$F_f = F_{net} = \underline{\boldsymbol{m}}a$$

In order to use this equation to calculate force, we need to know:

- **<u>mass</u>**: we can measure this directly, using a balance. (*Note that **<u>m</u>** is underlined because we can measure it directly, which means we don't need to pursue another equation to calculate it.*)
- **<u>acceleration</u>**: we could measure this with an accelerometer, but we do not have one in the lab. This means we will need to find the acceleration some other way.

Because we need to *calculate* acceleration rather than measuring it, that means we need to expand our experiment in order to get the necessary data to do so. Instead of just measuring force and acceleration, we now need to:

1. Measure the mass.
2. *Perform an experiment* in which we apply the force and collect enough information to *determine the acceleration*.
3. Calculate the force on the object, using the mass and the acceleration.

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In order to determine the acceleration, we need another equation. We can use:

$$\underline{\boldsymbol{v}} = v_o + a\underline{\boldsymbol{t}}$$

This means in order to calculate acceleration, we need to know:

- **final velocity (*v*)**: the force is being applied until the object is at rest (stopped), so the final velocity $v = 0$. (*Underlined because we have designed the experiment in a way that we know its value.*)
- **initial velocity ($v_o$)**: not known; we need to either measure or calculate this.
- **time (*t*)**: we can measure this directly with a stopwatch. (*Underlined because we can measure it directly.*)

Now we need to expand our experiment further, in order to calculate $v_o$. We can calculate the initial velocity from the equation:

$$\boldsymbol{v}_{ave.} = \frac{\underline{\boldsymbol{d}}}{\underline{\boldsymbol{t}}} = \frac{v_o + \cancelto{0}{\underline{\boldsymbol{v}}}}{2}$$

We have already figured out how to measure $\underline{\boldsymbol{t}}$, and we set up the experiment so that $\underline{\boldsymbol{v}} = 0$ at the end. This means that to calculate $v_o$, the only quantities we need to measure are:

- **time (*t*)**: as noted above, we can measure this directly with a stopwatch. (*Underlined because we can measure it directly.*)
- **displacement (*d*)**: the change in the object's position. We can measure this with a meter stick or tape measure. (*Underlined because we can measure it.*)

Notice that every quantity is now expressed in terms of quantities that we know or can measure, or quantities we can calculate, so we're all set. We simply need to set up an experiment to measure the underlined quantities.

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To facilitate this approach, it is often helpful to use a table. For the above experiment, such a table might look like the following:

| Desired Variable | Equation | Description/ Explanation | Fixed Control Variable(s) or Constants | Quantities to be Measured | Quantities to be Calculated (Still Needed) |
|---|---|---|---|---|---|
| $\vec{F}_f$ | $\vec{F}_f = \vec{F}_{net}$ | Set up experiment so other forces cancel | — | — | $\vec{F}_{net}$ |
| $\vec{F}_{net}$ | $\vec{F}_{net} = m\vec{a}$ | Newton's 2nd Law | — | $m$ | $\vec{a}$ |
| $\vec{a}$ | $\vec{v} - \vec{v}_o = \vec{a}t$ | Kinematics equation | $\vec{v} = 0$ | $t$ | $\vec{v}_o$ |
| $\vec{v}_o$ | $\frac{\vec{d}}{t} = \frac{\vec{v}_o + \vec{v}}{2}$ | Kinematics equation | $\vec{v} = 0$ | $\vec{d}$, $t$ | — |

In this table, we started with the quantity we want to determine ($\vec{F}_f$). We found an equation that contains it ($\vec{F}_f = \vec{F}_{net}$). In that equation, $\vec{F}_{net}$ is neither a fixed control variable nor a constant and we cannot measure it, so it is "still needed" and becomes the start of a new row in the table.

This process continues until every quantity that is needed is either a Fixed quantity (control variable or constant) or can be measured, and there are no quantities that are still needed.

- Notice that every variable in the equation is either the desired variable, or it appears in one of the three columns on the right.
- Notice that when we get to the third row, the equation contains a control variable that is designed into the experiment ($\vec{v} = 0$ because the object stops at the end), a quantity that can be measured ($t$, using a stopwatch), and a quantity that is still needed ($\vec{v}_o$).
- Notice that every quantity that you need to measure appears in the "Quantities to be Measured" column.
- Notice that your experimental conditions need to account for the control variables in the "Fixed Control Variable(s) or Constants" column.
- Notice that your calculations are simply the entire "Equation" column, starting at the bottom and working your way back to the top.

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## Procedure

Looking at the "Quantities to be Measured" column, we have determined that we need to measure mass (*m*), time (*t*) and distance (*d*). This makes sense because the objective is to determine the force of friction, which means we need to measure the distance that the object travels and the time that it spends moving while it is sliding.

Our procedure is therefore to (a) make sure the event that we are trying to measure happens, (b) measure everything in the "Measured Variable(s)" column, and (c) set up the experiment so that everything in the "Control Variable(s) & Constants" column has the appropriate values:

1. Measure the **mass** of the object.
2. Determine a way to measure the **displacement** of the object. (A simple way would be to mark a starting line and use a tape measure.)
3. Determine a way to measure the **time** that the object spends moving. (A simple way would be to start a stopwatch when the object crosses the starting line and stop the stopwatch when the object comes to rest.)
4. Get the object moving.
5. Allow the object to slide until it stops (**final velocity** = 0), measuring time and displacement as determined above.
6. Repeat the experiment, using different masses based on the **8 & 10 rule**—take at least **8 data points**, varying the mass over at least a **factor of 10**.

## Data

We need to make sure we have recorded the measurements (including uncertainties, which are addressed in the Uncertainty & Error Analysis topic, starting on page 53) of every quantity we need in order to calculate our result. In this experiment, we need measurements for **mass**, **displacement** and **time**.

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## Analysis

Most of your analysis is your calculations. Start from the bottom of your experimental design table and work upward.

$$\frac{d}{t} = \frac{v_o + \cancel{v}^{\,0}}{2}$$

In this experiment that means start with:

$$v_o = \frac{2d}{t}$$

The reason we needed this equation was to find $v_o$, so we need to rearrange it to:

(We are allowed to use *d* and *t* in the equation because we measured them.)

$$\cancel{v}^{\,0} = v_o + at$$

Now we go to the equation above it in our experimental design and substitute our expression for $v_o$ into it:

$$0 = \frac{2d}{t} + at$$

The purpose of this equation was to find acceleration, so we need to rearrange it to:

$$a = \frac{-2d}{t^2}$$

(We can drop the negative sign because we are only interested in the magnitude of the acceleration.)

Our last equation is $F_f = F_{net} = ma$. If we are interested only in finding one value of $F_f$, we can just substitute and solve:

$$F_{net} = ma = m\left(-\frac{2d}{t^2}\right) = \frac{-2md}{t^2}$$

However, we will get a much better answer if we plot a graph relating each of our values of mass (remember the 8 & 10 rule) to the resulting acceleration and calculate the force using the graph. This process is described in detail in the "Graphical Solutions (Linearization)" section, starting on page 73.

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## Generalized Approach

The generalized approach to experimental design is therefore:

### Experimental Design

1. Find an equation that contains the quantity you want to find.
2. Using a table to organize your information, work your way from that equation through related equations until every quantity in every equation is either something you can calculate or something you can measure.

### Procedure

3. Determine how to measure each of the quantities that you need (dependent variables). Decide what your starting conditions need to be (independent variables) and measure any that are needed, and figure out what you need to keep constant (control variables).

### Data & Observations

4. Set up your experiment and do a test run. *This means you need to perform the calculations for your test run before doing the rest of the experiment,* in case you need to modify your procedure. You will be extremely frustrated if you finish your experiment and go home, only to find out at 2:00 am the night before the write-up is due that it didn't work.
5. Take and record your measurements and other data.
6. Remember to record the uncertainty for every quantity that you measure. (See the "Uncertainty & Error Analysis" section, starting on page 53.)

### Analysis

7. Calculate the results. Whenever possible, apply the **8 & 10 rule** and calculate your answer graphically.

*AP®*

If you are taking one of the AP® Physics exams, you should answer the experimental design question by writing the Experimental Design, Procedure, and Analysis sections above.

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