Designing & Performing Experiments

Unit: Laboratory & Measurement

NGSS Standards/MA Curriculum Frameworks (2016): SP1, SP3, SP8

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): SP3.A, SP3.B, SP3.C

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 manipulated variables.
- Procedure explains how to measure responding variables.

Language Objectives:

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

Tier 2 Vocabulary: inquiry, independent, dependent, control

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.

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.

Use this space for summary and/or additional notes:

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.

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.

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"Actions"

Most experiments involve ***actions*** that are required in order to cause data to be generated. For example, if you are determining the acceleration of a toy car going down a ramp, you need to place the car at the top of the ramp and let go of it. These *actions* are essential to the experiment, and need to be planned, executed, and documented.

Some actions are obvious when designing the experiment, but others may be discovered as you decide how to takeyour data. For example, if you are measuring the distance and time that an object travels before it coasts to a stop, you will need to mark a "starting line." The *actions* will include setting the object in motion before it crosses the starting line, the object itself crossing the starting line, and the object coming to rest.

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***, ***manipulated (independent) variables***, and ***responding (dependent) variables***.

control variables: conditions that are being kept constant. These are usually 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 (also known as independent variables): the conditions you are setting up. These are the parameters that you specify when you set up the experiment. They are called *independent variables* because you are choosing the values for these variables, which means 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 *manipulated (independent)* variable.

responding variables (also known as dependent variables): the things that happen during the experiment. These are the quantities that you won't know the values for until you measure them. They are called *dependent variables* 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 *responding (dependent)* variable.

Use this space for summary and/or additional notes:

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

- "What did you vary on purpose (manipulated variables)?"
- "What did you measure (responding 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 **manipulated variable**, and whether or not the thing happens is your **responding 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 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 of your manipulated variable. Then perform the experiment using a range of values for the manipulated 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 of your manipulated variables should span at least a factor of 10.

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Letting the Equations 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 determine, you need to find the values of the other quantities in the equation.

For example, suppose you need to determine 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.

Use this space for summary and/or additional notes:

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:

- **<u>final velocity</u> (*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.*)
- **<u>initial velocity</u> (v_o)**: not known; we need to either measure or calculate this.
- **<u>time</u> (*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:

- **<u>time</u> (*t*)**: as noted above, we can measure this directly with a stopwatch. (*Underlined because we can measure it directly.*)
- **<u>displacement</u> (*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 helpful to use a table. Place the quantity of interest at the beginning of the table (the ***Desired Quantity***). Write the equation, and place *each variable* in the equation (other than the desired quantity) into one of the three final colums: ***Known Quantities*** (physical constants or control variables that don't need to be measured), ***Measured Quantities*** (quantities that can be measured, including some control variables, manipulated variables, and responding variables), and ***Quantities to be Calculated*** (quantities that are needed for the equation, but that are not known and cannot be measured directly). Each ***Quantity to be Calculated*** becomes a new row in the table.

For the above experiment, such a table might look like the following:

Desired Quantity	**Equation**	**Description/ Explanation**	**Known Quantities**	**Measured Quantities**	**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	$\vec{a}$
$\vec{a}$	$\vec{v} - \vec{v}_o = \vec{a}t$	Kinematic equation #2	$\vec{v} = 0$	t	$\vec{v}_o$
$\vec{v}_o$	$\frac{\vec{d}}{t} = \frac{\vec{v}_o + \vec{v}}{2}$	Kinematic equation #1	$\vec{v} = 0$	$\vec{d}$, t	—

In this table, we started with the quantity we wanted to determine ($\vec{F}_f$). We found an equation that contains it ($\vec{F}_f = \vec{F}_{net}$). (This tells us that we need to set up our experiment so that the other forces cancel.) In that equation, $\vec{F}_{net}$ is neither a known quantity nor a quantity that we can measure, so it is a *quantity to be calculated*, and becomes the start of a new row in the table.

This process continues until every quantity that is needed is either a *Known Quantity* or a *Measured Quantity*, and there are no quantities that are still needed.

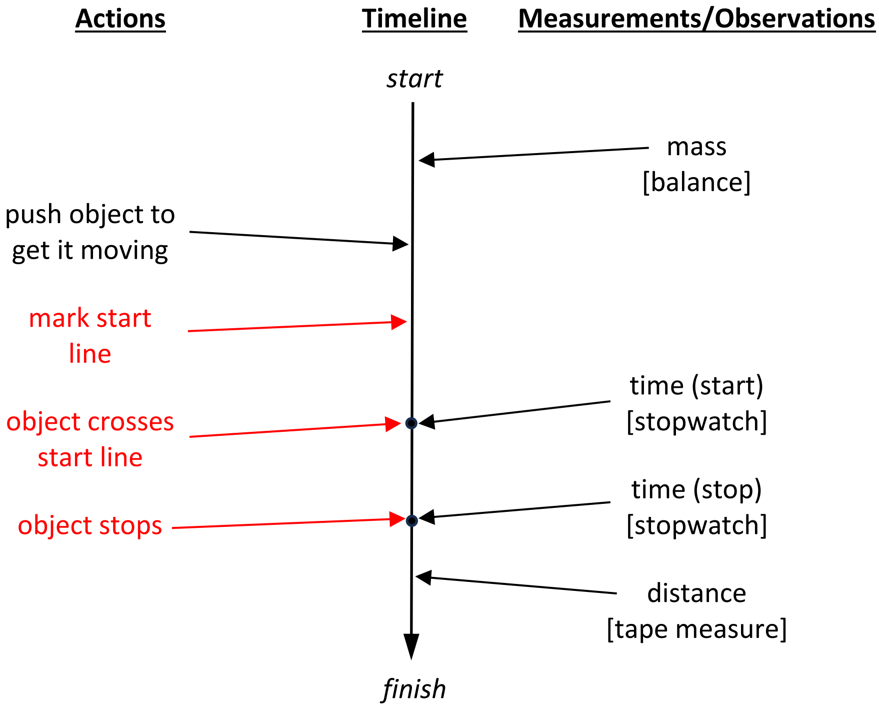
- Notice that every variable in each equation is either the desired variable, or it appears in one of the three columns on the right.
- In this example, notice that when we get to the third row, the equation contains a control variable that is designed into the experiment ($\vec{v} = 0$ because the object stops at the end), a quantity that can be measured (t, using a stopwatch), and a quantity that is still needed ($\vec{v}_o$).

Use this space for summary and/or additional notes:

- Notice that every quantity that you need to measure appears in the "Measured Quantities" column.
- Notice that your experimental conditions need to account for the control variables in the "Known Quantities" column.
- Notice that your calculations, in order, are the entire "Equation" column, starting at the bottom and working your way to the top.

Flow Chart

In the flow chart, note that actions are on one side and measurements (which appear in the "Measured Quantities" column of the table) are on the other. It is helpful to include equipment in the "measurements/obervations" column, but ***do not include anything else in the flow chart.***



When we realized that measuring time must involve both starting and stopping the stopwatch, we needed to add actions so we can determine when to start and stop the stopwatch.

Note that a dot on the timeline indicates that the action on the left and the measurement on the right need to happen at exactly the same time.

The purpose of this flow chart is to show the procedure in a visual, easy-to-follow manner. The procedure starts at the top ("*start*" on the timeline) and ends at the bottom ("*finish*" on the timeline). As you move down the timeline, perform each action and/or measurement in order from top to bottom.

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The flow chart makes it easy to perform the experiment and later on when writing the procedure into a lab report, because it shows everything that is happening in chronological order.

Procedure

The procedure follows directly from the flow chart. If we start at the top of the timeline ("start") on the flow chart and proceed downward, the first thing we encounter is "mass," on the "Measurements/Observations" side. This means the first thing we need to do is measure the mass.

Next, we encounter "push object to get it moving," on the "actions" side, so that is the second step.

After that, we encounter "object crosses start line" and "time (start)" that must happen at the same time (as indicated by the dot on the timeline arrow). The third step needs to therefore include both.

Continue down the flow chart in the same manner until we reach "finish" at the bottom. The resulting procedure looks like this:

1. Measure the mass of the object with a balance.
2. Mark a start line.
3. Get the object moving.
4. Start a stopwatch when the object crosses the start line.
5. Stop the stopwatch when the object stops.
6. Measure the distance the object traveled with a tape measure.
7. 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 51) of every quantity we need in order to calculate our result. In this experiment, we need measurements for **mass**, **displacement** and **time**.

Use this space for summary and/or additional notes:

Analysis

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

In this experiment that means start with: $\frac{d}{t} = \frac{v_o + \cancelto{0}{v}}{2}$

The reason we needed this equation was to find v_o, so we need to rearrange it to: $v_o = \frac{2d}{t}$

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

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

$$\cancelto{0}{v} = v_o + at$$

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

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 77.

Use this space for summary and/or additional notes:

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 the actions and measurements that are needed.
4. Create a flow chart that shows the order of events.
5. Turn the flow chart into a procedure. (You should take notes on the detailed procedure while performing the experiment. Don't write it out until afterwards, because you will almost certainly make decisions while performing the experiment that affect your procedure.)

Data & Observations

6. 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.
7. Record your measurements and other data.
8. Remember to record the uncertainty for *every* quantity that you measure. (See the "Uncertainty & Error Analysis" section, starting on page 51.)

Analysis

9. 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 can answer the experimental design question by doing a quick, abbreviated version of this process:

1. Make the experimental design table.
2. Draw the flow chart.
3. List and follow your equations in order (bottom-to-top) to calculate the quantities needed for the equation in the top row.
4. Linearize the equation in the top row, and rearrange it into $y = mx + b$ form.
5. Plot a graph of the linearized equation and state that the desired quantity is the slope of the graph.

Use this space for summary and/or additional notes: