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

Summary of Concepts:

Every experiment had to be designed (figured out) the first time someone did it. The process involves:

1. Planning the experiment by starting from what you want to find out, and systematically working backwards through relationships and equations until you have reached a reasonable starting point.

2. Performing the experiment by working forward from the starting point, following the plan that you created.

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.

Use this space for summary and/or additional notes:

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. Starting from the objective, 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 will work in this course. You and your lab group will design the experiments that you will 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*.

Quantitative *vs.* Qualitative 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 needs to address:

- What it is that you are trying to observe or measure.

- If something needs to happen, what you will do 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 needs to address:

- What it is that you are ultimately trying to measure or calculate.

- If something needs to happen (the "action(s)"), what you will do to make it happen.

- If you cannot measure the quantity directly:

  o An equation that will enable you to calculate it.
  o The quantities from the equation that you need in order to calculate it.
  o What needs to happen (additional "actions") in order to obtain these quantities.
  o Repeat these steps with additional equations until you have a way to obtain every quantity that you need.

- How to set up your experimental conditions so the quantities that you need are within measurable limits.

- How to calculate and interpret the quantities of interest, based on your results.

"Actions"

In this text, an "***action***" is something that needs to happen in order to generate data.

For example, if you are determining the acceleration of a toy car going down a ramp, the car needs to accelerate. To make this happen, 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 take your 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.

Use this space for summary and/or additional notes:

Types of Quantities (Variables)

In every experiment, there are some quantities that you need to keep constant, some that you need to choose the values of, and some that you need to observe/measure as the result of one or more actions.. These quantities are called ***control variables***, ***manipulated (independent) variables***, and ***responding (dependent) variables***.

control variables: conditions that are being kept constant (controlled).

These are often parameters that might be manipulated variables in a different experiment, but are being kept constant in this experiment so they do not affect the relationship between the variables that you are testing.

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.

In a qualitative experiment, there are often two types of control variables:

positive control: A sample that contains something that your experiment ***must*** detect if it is present.   If your experiment fails to detect the positive control, it means something was wrong with the experiment.

negative control: A sample that ***does not contain*** something that your experiment must detect if it is present. If your experiment detects the thing you are testing for in your negative control, it means something was wrong with the experiment.

manipulated variables (also known as independent variables): the conditions you are choosing the values for.

These are the parameters that you specify when you set up the experiment. They are called *independent variables* because they are *independent* of the actions.

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 a *manipulated (independent)* variable.

responding variables (also known as dependent variables): things that happen in response to the actions in your experiment.

These are quantities that you can't know the values for until something—one of the actions in your experiment—happens. They are called *dependent variables* because they *depend* on the actions.

Use this space for summary and/or additional notes:

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.

Amount of Data Needed

You need enough data for your conclusions to be *statistically significant*. This means that the results that you claim must be unlikely to have occurred by random chance. Typically, scientists claim that a result is valid if it is less than 5% likely that the outcome could have happened due to random chance. The calculations are beyond the scope of this course, though they would be taught in a typical high school probability & statistics class.

For quantitative experiments in a high school class, 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.

The Experimental Design Process

In this course, we will use the following process for designing experiments:

The basic steps of experimental design are:

1. Decide what you are trying to determine (measure/calculate/observe/*etc.*).

2. How can you determine the quantity that you need?

   a. Do you know it without having to do anything, or can you look it up? (This is the easiest. If yes, do that.)

   b. If you don't know it, can you measure it directly? (If yes, do that.)

      • If you can measure it directly, do we need any actions to happen in order to measure it?

   c. If you don't know the quantity and you can't measure it, you need to calculate it. (This means you need to find an equation that has the quantity.)

3. If you need to calculate the quantity, find an equation that contains it.

4. Within the equation, decide which quantities you know or could look up, which ones you can measure, and which ones you need to calculate from a second equation. Use a chart like the following:

Desired Quantity	Equation	Description/ Explanation	Known Quantities	Measured Quantities	Quantities to be Calculated *(still needed)*

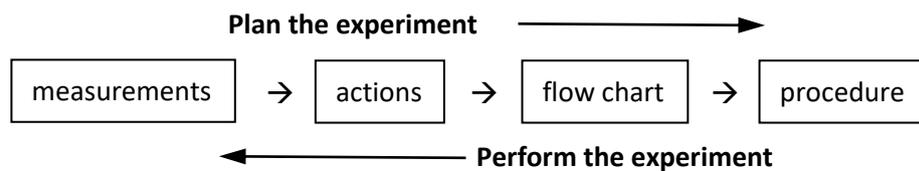Use this space for summary and/or additional notes:

5. If there are quantities to be calculated in the equation, repeat steps 3 & 4 above. Each quantity to be calculated becomes a new row in the table.

6. Identify which variables are kept constant (control variables), which ones can be measured without performing any actions (manipulated variables), and which ones require actions to happen in order to measure them (responding variables).

7. Make a flow chart that includes all of the actions **and** all of the measurements.

8. Think about things that could go wrong or things you need to keep in mind as you consider each of the actions and measurements. (You will need to write these into your procedure.)

9. Create your procedure from the flow chart.

Notice that:

- The measurements you need are determined by the quantities in each equation.
- The actions are determined by the measurements.
- The flow chart is determined by the order in which the actions and measurements need to happen.
- The procedure is determined by the flow chart.

Notice also that your plan starts from the measurements that you need, which determine the actions, which determine your procedure.

Your experiment starts with the procedure, which tells you which actions to take and when, and tells you which measurements to take and when.

Plan the experiment ⟶

| measurements | → | actions | → | flow chart | → | procedure |

⟵ **Perform the experiment**

Use this space for summary and/or additional notes:

Illustrative Example

Suppose you have a toy cart with a fan attached to it. If you turn on the fan, the cart will accelerate. You want to determine the amount of net force applied to the cart.[*]

air flow

cart accelerates
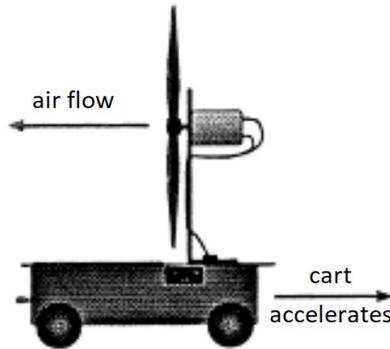
1. *Decide what you are trying to determine (measure/calculate/observe/etc.).*

    We need to determine the net force applied by the fan to the cart, F_{net} .

2. *How can you determine the quantity that you need?*

    a. *Do you know it without having to do anything, or can you look it up? (This is the easiest. If yes, do that.)*

        No, we don't already know F_{net} and we can't look it up.

    b. *If you don't know it, can you measure it directly? (If yes, do that.)*

        No, we can't measure F_{net} directly.

        *   *If we can measure it directly, do we need any actions to happen in order to measure it?*

            N/A

    c. *If you don't know the quantity and you can't measure it, you need to calculate it. (This means you need to find an equation that has the quantity.)*

        We will need to calculate F_{net} .

3. *If you need to calculate the quantity, find an equation that contains it.*

    We can use Newton's Second Law, $F_{net} = ma$.

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[*] This example uses concepts and equations that you have not learned yet. Don't worry about where the equations come from for now; the purpose of this example is to show how the experimental design process works. You will learn about these concepts and equations in the *Kinematics (Motion) in One Dimension* and *Forces in One Dimension* units.

Use this space for summary and/or additional notes:

4. *Within the equation, decide which quantities you know or could look up, which ones you can measure, and which ones you need to calculate from a second equation. Use a chart like the following:*

Desired Quantity	Equation	Description/ Explanation	Known Quantities	Measured Quantities	Quantities to be Calculated *(still needed)*
F_{net}	$F_{net} = ma$	Newton's 2nd Law	—	m	a

Notice that every variable in the equation appears in one other place in the table: the **desired quantity**, one of the **known quantities**, one of the **measured quantities**, or one of the **quantities to be calculated**.

5. *If there are quantities to be calculated in the equation, repeat steps 3 & 4 above. Each quantity to be calculated becomes a new row in the table.*

Desired Quantity	Equation	Description/ Explanation	Known Quantities	Measured Quantities	Quantities to be Calculated *(still needed)*
F_{net}	$F_{net} = ma$	Newton's 2nd Law	—	m	a
a	$d = v_o t + \frac{1}{2} a t^2$	2nd Kinematic equation	v_o	d, t	—

Once you have an equation for each calculated quantity and there are no new quantities to be calculated, the table is complete.

Notice that the quantities that you will need to measure are already in the measured quantities column:

Desired Quantity	Equation	Description/ Explanation	Known Quantities	Measured Quantities	Quantities to be Calculated *(still needed)*
F_{net}	$F_{net} = ma$	Newton's 2nd Law	—	m	a
a	$d = v_o t + \frac{1}{2} a t^2$	2nd Kinematic equation	v_o	d, t	—

quantities we need

Use this space for summary and/or additional notes:

6. *Identify which variables are kept constant (control variables), which ones can be measured without performing any actions (manipulated variables), and which ones require actions to happen in order to measure them (responding variables). Use lists like the following:*

Constants: none

Unmeasured Control Variables: $v_o = 0$

Measured Control Variables:

variable	how measured	actions needed
d	tape measure	mark starting point of cart mark finish line

Manipulated Variables:

variable	how measured	actions needed
m	balance	N/A

Responding Variables:

variable	how measured	actions needed
t	stopwatch	turn on fan release cart (start stopwatch) cart crosses finish line (stop stopwatch)

Use this space for summary and/or additional notes:

7. *Make a flow chart that includes all of the actions **and** all of the measurements.*

The flow chart proceeds from top (start) to bottom (finish), with actions on one side and measurements on the other.

Actions	**Timeline**	**Measurements/Observations**
	start	
mark start & finish lines ──		
		measure mass of cart (m)
		measure distance from starting line to finish line (d)
put cart at starting line ──		
turn on fan ──		
release cart ── ●		start stopwatch
cart reaches finish line ── ●		stop stopwatch (t)
	finish	
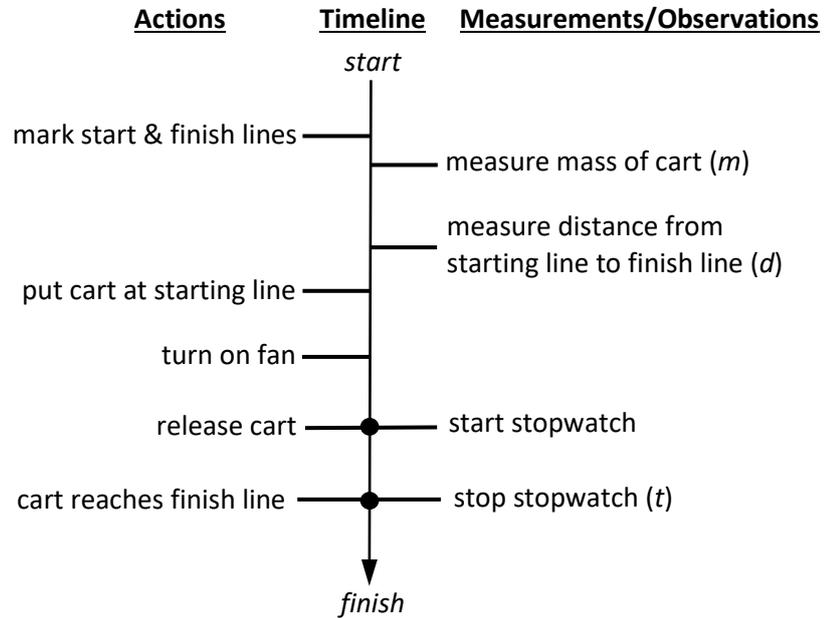
Notice:

- All of the actions needed from step are included.

- All measurements are included.

- Note that constants and manipulated variables can be measured any time (except while the cart is moving). We chose to measure the mass at the beginning and the distance at the end, but we could have done either one at either time.

- A dot on the timeline arrow means the action and measurement need to happen at the same time.

8. *Think about things that could go wrong or things you need to keep in mind as you consider each of the actions and measurements. (You will need to write these into your procedure.)*

- The fan cart should be on a track so it moves in a predictable, straight line.
- Mark and time the start and finish using the same point on the cart, *e.g.,* the front.
- You should take multiple data points, with different values of the manipulated variable (in this example, the amount of mass). Remember the "8 & 10 rule"!

Use this space for summary and/or additional notes:

- When you calculate your results, you should represent the equation that gives the desired quantity as a straight-line graph, such that the slope of the best-fit line contains the quantity of interest. (This will be discussed in detail in the section on *Graphical Solutions & Linearization*, starting on page 83.)

9. *Create your procedure from the flow chart. Follow the vertical arrow, starting from "Start". Every time a line hits that arrow (from either side), that will be the next item in your procedure.*

   If you have an action and a measurement that happen at the same time, write them into the same step.

   Procedures can be numbered lists or written in paragraph form. Our experiment as a numbered list might look like the following:

   1. Set up a track that a fan cart can ride on.

   2. Mark a starting line and finish line on the track.

   3. Measure the distance from the starting line to the finish line, using a tape measure or meter stick.

   4. Measure the mass of the fan cart, using a balance.

   5. Put the cart on the track so the front of it is at the starting line.

   6. While holding the cart so it does not move, turn on the fan.

   7. When you release the cart, start the stopwatch (at the same time).

   8. When the front of the cart reaches the finish line, stop the stopwatch.

   9. Add masses from a weight set to the cart and repeat steps 4 – 8 above at least 8 times, using a different amount of mass for each trial.

   Notice that you do not include steps like "Gather the materials." or "Use your data to calculate the acceleration." These are not part of the procedure (acquiring data), and they are assumed.

Performing the Experiment

When you perform the experiment, follow your procedure. If you end up doing something different from your procedure, be sure to make a note of it and edit the procedure accordingly. Record the data, including the estimated uncertainty (±) for each data point. ***Every measurement you record needs to include its uncertainty.***

If there was an obvious problem while you were taking a data point, take that data point over again. (However, once your experiment is complete, you must keep and use *all* of your data.)

Use this space for summary and/or additional notes:

Analysis

For your calculations, the equations are conveniently already in your experimental design table, in reverse order. Start with the equation in the bottom row, and work your way to the top.

Desired Quantity	Equation	Description/ Explanation	Known Quantities	Measured Quantities	Quantities to be Calculated *(still needed)*
F_{net}	$F_{net} = ma$	Newton's 2nd Law	—	m	a
a	$d = v_o t + \frac{1}{2}at^2$	2nd Kinematic equation	v_o	d, t	—

calculate

honors & AP®

When you get to the final equation (the one in the top row, which contains the quantity you are trying to find), it is best to calculate it using the slope of a best-fit line. (This process will be covered more extensively in the section on *Graphical Solutions & Linearization*, starting on page 83.)

1. Rearrange the equation so a graph of it would produce a straight line, with the quantity that you want to find as the slope.

   In our example, we would rearrange $F_{net} = ma$ to give $a = \dfrac{F_{net}}{m}$. In $y = mx + b$ form, this looks like $a = F_{net}\left(\dfrac{1}{m}\right) + 0$, which means we would plot a graph of a (on the *y*-axis, because it is a (calculated) responding variable) *vs.* $\dfrac{1}{m}$ (on the *x*-axis, because *m* was our manipulated variable).

2. Use linear regression (using a calculator, a spreadsheet or a statistics program) to plot a best-fit line of your data. The slope of the best-fit line (or its reciprocal) will be the result that you will report.

   In our example, the slope would be F_{net}, which was the objective of the experiment.

3. Use the measurement that had the largest relative error for each quantity to calculate your total relative error. Then use your total relative error to calculate the uncertainty of your result. This process is covered in detail in the *Uncertainty & Error Analysis* section, starting on page 56.

Use this space for summary and/or additional notes:

Big Ideas | Details | Unit: Laboratory & Measurement

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 on scratch paper. (Leave out the "description/explanation" column to save time.)

2. Draw the flow chart on scratch paper. (Do the parts about deciding which variables are control *vs.* manipulated *vs.* responding in your head to save time.)

3. Use your flow chart to answer the question that asks for a procedure (in your test booklet).

4. Use your equations in order (bottom-to-top) to answer the question that asks how to perform the calculations (in your test booklet).

5. Linearize the equation in the top row and rearrange it into $y = mx + b$ form (on scratch paper).

6. In your test booklet, state that you should plot a graph of the linearized equation (give the linearized form of the equation), and state what the desired quantity is in relation to the slope of the graph (usually the slope itself or its reciprocal).

Use this space for summary and/or additional notes: