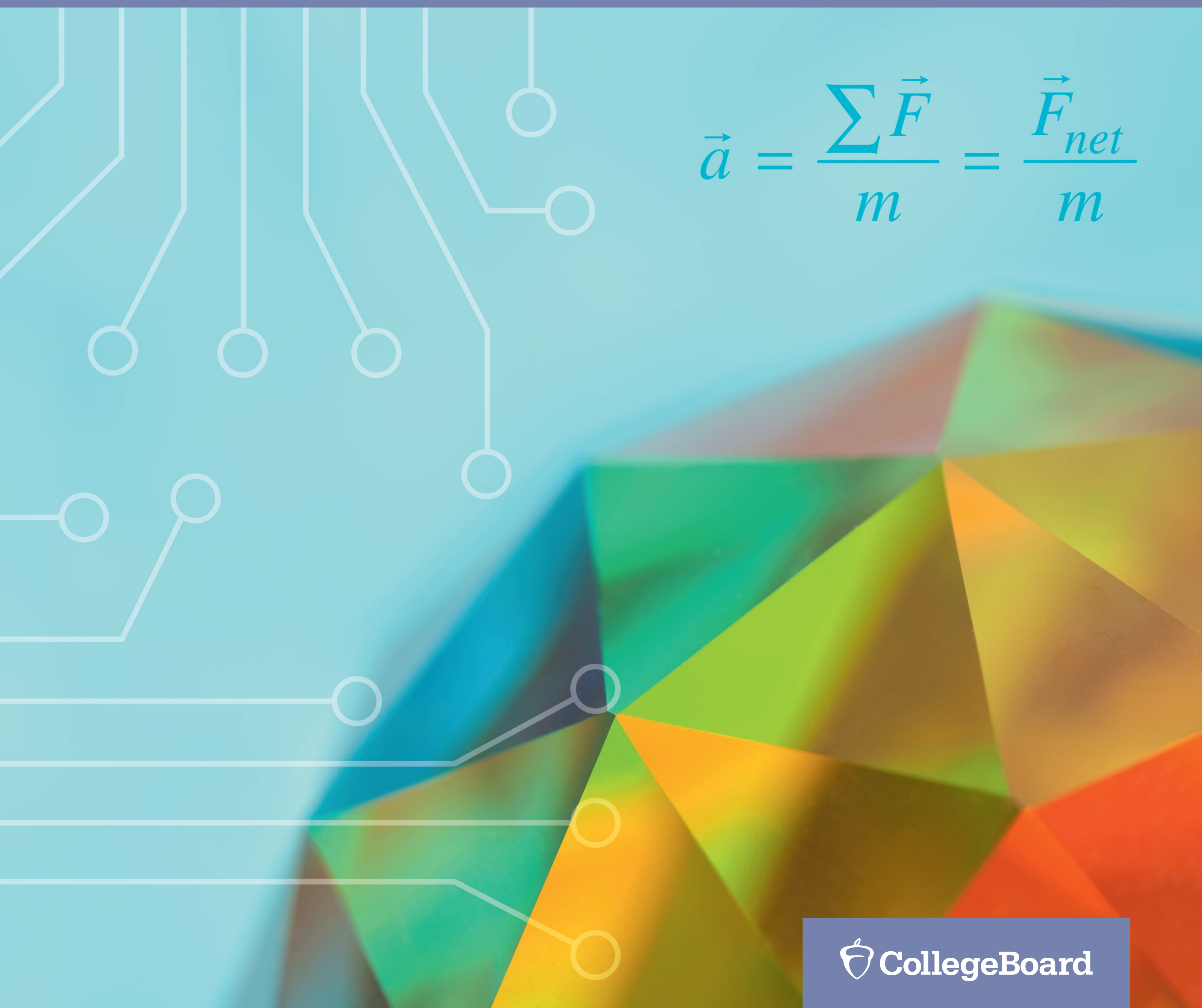
AP® Physics 1 and 2 Inquiry-Based Lab Investigations

Teacher's Manual

Effective Fall 2021



$$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$$

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Appendix A: Science Practices for AP Physics 1 and 2

Science Practice 1: The student can use representations and models to communicate scientific phenomena and solve scientific problems.

The real world is extremely complex. When physicists describe and explain phenomena, they try to simplify real objects, systems, and processes to make the analysis manageable. These simplifications or models are used to predict how new phenomena will occur. A simple model may treat a system as an object, neglecting the system's internal structure and behavior. More complex models are models of a system of objects, such as an ideal gas. A process can be simplified, too; free fall is an example of a simplified process, when we consider only the interaction of the object with the Earth. Models can be both conceptual and mathematical. Ohm's law is an example of a mathematical model, while the model of a current as a steady flow of charged particles is a conceptual model (the charged particles move randomly with some net motion [drift] of particles in a particular direction.) Basically, to make a good model, one needs to identify a set of the most important characteristics of a phenomenon or system that may simplify analysis. Inherent in the construction of models that physicists invent is the use of representations. Examples of representations used to model introductory physics are pictures, motion diagrams, force diagrams, graphs, energy bar charts, and ray diagrams. Mathematical representations such as equations are another example. Representations help in analyzing phenomena, making predictions, and communicating ideas. An example here is using a motion diagram and a force diagram to develop the mathematical expression of Newton's second law in component form to solve a dynamics problem.

1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.

1.2 The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.

1.3 The student can *refine representations and models* of natural or man-made phenomena and systems in the domain.

1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

1.5 The student can *re-express key elements of natural phenomena across multiple representations* in the domain.

Science Practice 2: The student can use mathematics appropriately.

Physicists commonly use mathematical representations to describe and explain phenomena as well as to solve problems. When students work with these representations, we want them to understand the connections between the mathematical description, physical phenomena, and the concepts represented in the mathematical description. When using equations or mathematical representations, students need to be able to justify why using a particular equation to analyze a particular situation is useful, as well as to be aware of the conditions under which the equations/mathematical representations can be used. Students tend to rely too much on mathematical representations. When solving a problem, they need to be able to describe the problem situation in multiple ways, including picture representations, force diagrams, and so on, and then choose an appropriate mathematical representation, instead of first choosing a formula whose variables match the givens in the problem. In addition, students should be able to work with the algebraic form of the equation before they substitute values. They also should be able to evaluate the equation(s) and the answer obtained in terms of units and limiting case analysis: Does the equation lead to results that can be predicted qualitatively if one of the quantities in the problem is zero or infinity? They should be able to translate between functional relations in equations (proportionalities, inverse proportionalities, etc.) and cause-and-effect relations in the physical world. They should also be able to evaluate the numerical result in terms of whether it makes sense. For example, obtaining 35 m/s^2 for the acceleration of a bus — about four times the acceleration of a freely falling object — should raise flags in students' minds. In many physics situations, simple mathematical routines may be needed to arrive at a result even though they are not the focus of a learning objective.

2.1 The student can *justify the selection of a mathematical routine* to solve problems.

2.2 The student can *apply mathematical routines* to quantities that describe natural phenomena.

2.3 The student can *estimate numerically quantities* that describe natural phenomena.

Science Practice 3: The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.

Research scientists pose and answer meaningful questions. Students may easily miss this point since, depending on how a science class is taught, it may seem that science is about compiling and passing down a large body of known facts (e.g., the acceleration of free-falling objects is 9.8 m/s^2; $\vec{a} = \frac{\Sigma \vec{F}}{m}$). At the opposite end of the spectrum, some students may believe that science can solve every important societal problem. Thus, helping students learn how to pose, refine, and evaluate scientific questions is an important instructional and cognitive goal, albeit a difficult skill to learn. Even within a simple physics topic, posing a scientific question can be difficult. When asked what they might want to find out about a simple pendulum, some students may ask, "How high does it swing?" Although this is a starting point from which a teacher may build, students need to be guided toward refining "fuzzy" questions and relating questions to relevant models and theories. As a first step to refining this question, students might first consider in what ways one can measure physical quantities relevant to the pendulum's motion, leading to a discussion of time, angle (amplitude), and mass. Follow-up discussions can lead to how one goes about evaluating questions such as, "Upon what does the period of a simple pendulum depend?" by designing and carrying out experiments, and then evaluating data and findings.

3.1 The student can *pose scientific questions.*

3.2 The student can *refine scientific questions.*

3.3 The student can *evaluate scientific questions.*

Science Practice 4: The student can plan and implement data-collection strategies in relation to a particular scientific question.

[**NOTE:** Data can be collected from many different sources, e.g., investigations, scientific observations, the findings of others, historic reconstruction, and/or archived data.]

Scientific questions can range in scope from broad to narrow, as well as in specificity, from determining influencing factors and/or causes to determining mechanism. The question posed will determine the type of data to be collected and will influence the plan for collecting data. An example of a broad question is, "What caused the extinction of the dinosaurs?" whereas a narrow one is, "Upon what does the period of a simple pendulum depend?" Both questions ask for influencing factors and/or causes; an answer to the former might be "An asteroid collision with Earth caused the extinction of the dinosaurs," whereas an answer to the latter might be "The period depends on the mass and length of the pendulum." To test the cause of the pendulum's period, an experimental plan might vary mass and length to ascertain if these factors indeed influence the period of a pendulum, taking care to control variables so as to determine whether one factor, the other, or both influence the period. A question could be posed to ask about mechanism, e.g., "How did the dinosaurs become extinct?" or "How does the period of a simple pendulum depend on the mass and length?" In the second question, the object is to determine a mathematical relationship between period, mass, and length of a pendulum. Designing and improving experimental designs and/or data collection strategies is a learned skill. A class discussion among students in a pendulum experiment might find some who measured the time for a single round-trip, while others timed 10 round-trips and divided by 10. Such discussions can reveal issues of measurement uncertainty and assumptions about the motion. Students need to understand that the result of collecting and using data to determine a numerical answer to a question is best thought of as an interval, not a single number. This interval, the experimental uncertainty, is due to a combination of uncertainty in the instruments used and the process of taking the measurement. Although detailed error analysis is not necessary to convey this pivotal idea, it is important that students make some reasoned estimate of the interval within which they know the value of a measured data point and express their results in a way that makes this clear.

4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

4.2 The student can *design a plan* for collecting data to answer a particular scientific question.

4.3 The student can *collect data* to answer a particular scientific question.

4.4 The student can *evaluate sources of data* to answer a particular scientific question.

Science Practice 5: The student can perform data analysis and evaluation of evidence.

Students often think that to make a graph they need to connect the data points or that the best-fit function is always linear. Thus, it is important that they can construct a best-fit curve even for data that do not fit a linear relationship (such as quadratic or exponential functions). Students should be able to represent data points as intervals whose size depends on the experimental uncertainty. After students find a pattern in the data, they need to ask why this pattern is present and try to explain it using the knowledge that they have. When dealing with a new phenomenon, they should be able to devise a testable explanation of the pattern if possible (see Science Practice 6.4). It is important that students understand that instruments do not produce exact measurements and learn what steps they can take to decrease the uncertainty. Students should be able to design a second experiment to determine the same quantity and then check for consistency across the two measurements, comparing two results by writing them both as intervals and not as single, absolute numbers. Finally, students should be able to revise their reasoning based on the new data, data that for some may appear anomalous.

5.1 The student can *analyze data* to identify patterns or relationships.

5.2 The student can *refine observations and measurements* based on data analysis.

5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Science Practice 6: The student can work with scientific explanations and theories.

Scientific explanations may specify a cause-and-effect relationship between variables or describe a mechanism through which a particular phenomenon occurs. Newton's second law, expressed as $\vec{a}=\frac{\Sigma\vec{F}}{m}$, gives the acceleration observed when a given combination of forces is exerted on an object with a certain mass. Liquids dry up because randomly moving molecules can leave liquids if their kinetic energy is higher than the negative potential energy of interaction between them and the liquid. A scientific explanation, accounting for an observed phenomenon, needs to be experimentally testable. One should be able to use it to make predictions about a new phenomenon. A theory uses a unified approach to account for a large set of phenomena and gives accounts that are consistent with multiple experimental outcomes within the range of applicability of the theory. Examples of theories in physics include kinetic molecular theory, quantum theory, atomic theory, etc. Students should understand the difference between explanations and theories. In the AP Physics 1 and 2 Curriculum Framework the word "claim" means any answer that a student provides except those that constitute direct and simple observational evidence. To say that all objects fall down is not a claim, but to say that all objects fall with the same acceleration is a claim, as one would need to back it up with evidence and a chain of reasoning. Students should be prepared to offer evidence, to construct reasoned arguments for their claim from the evidence, and to use the claim or explanation to make predictions. A prediction states the expected outcome of a particular experimental design based on an explanation or a claim under scrutiny. Consider the claim that current is directly proportional to potential difference across conductors based on data from an experiment varying voltage across a resistor and measuring current through it. The claim can be tested by connecting other resistors or lightbulbs in the circuit, measuring the voltage, using the linear relationship to predict the current, and comparing the predicted and measured current. This procedure tests the claim. Students should be able to design experiments to test alternative explanations of phenomena by comparing predicted outcomes. For example, students may think that liquids dry because air absorbs moisture. To test the claim they can design an experiment in which the same liquid dries in two conditions: in open air and in a vacuum jar. If the claim is correct, the liquid should dry faster in air. If the outcome does not match the prediction, the explanation is likely to be false. By contrast, if the outcome confirms the prediction, it only means that this experiment does not disprove the explanation; alternate explanations of the given outcome can always be formulated. Looking for experiments that can reject explanations and claims is at the heart of science.

6.1 The student can *justify claims with evidence.*

6.2 The student can *construct explanations of phenomena based on evidence* produced through scientific practices.

6.3 The student can *articulate the reasons that scientific explanations and theories are refined or replaced.*

6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.

6.5 The student can *evaluate alternative scientific explanations*.

Science Practice 7: The student is able to connect and relate knowledge across various scales, concepts, and representations in and across the domains.

Students should have the opportunity to transfer their learning across disciplinary boundaries so that they are able to link, synthesize, and apply the ideas they learn across the sciences and mathematics. Research on how people learn indicates that providing multiple contexts to which major ideas apply facilitates transfer; this allows students to bundle knowledge in memory together with the multiple contexts to which it applies. Students should also be able to recognize seemingly appropriate contexts to which major concepts and ideas do not apply. After learning various conservation laws in the context of mechanics, students should be able to describe what the concept of conservation means in physics and extend the idea to other contexts. For example, what might conservation of energy mean at high-energy scales with particle collisions, where Einstein's mass–energy equivalence plays a major role? What does conservation of energy mean when constructing or evaluating arguments about global warming? Another context in which students may apply ideas from physics across vast spatial and time scales is the origin of human life on Earth coupled with the notion of extraterrestrial intelligent life. If one views the age of the Earth in analogy to a year of time (see Ritger & Cummins, 1991) with the Earth formed on January 1, then life began on Earth around April 5; multicellular organisms appeared on November 6; mammals appeared on December 23. Perhaps most amazingly, humans appeared on December 31 just 28 minutes before midnight. What are the implications of this for seeking intelligent life outside our solar system? What is a reasonable estimate of the probability of finding intelligent life on an earthlike planet that scientists might discover through astronomical observations, and how does one go about making those estimates? Although students are not expected to answer these very complex questions after a single AP science course, they should be able to talk intelligently about them using the concepts they learned.

7.1 The student can *connect phenomena and models* across spatial and temporal scales.

7.2 The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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