Instructor Guide: Force and momentum in collisions

This instructor guide gives detailed guidance for teaching the ACORN Physics momentum tutorial. For more general guidance on facilitating ACORN Physics Tutorials, see our facilitator guide.

Overview & learning goals

ACORN Physics Tutorials are designed to support students in constructing their own models for physics concepts. This worksheet guides students to construct a qualitative model for impulse and momentum conservation in 1-dimensional collisions, based on research on students' generative ideas about linear momentum. This Tutorial supports learning goals related to both scientific practices and disciplinary content.

Students will practice:

- Generating rules (about changes in momentum) based on experimental observations and applying those rules to predict/explain the behavior (relative speed and direction) of (colliding) objects.
- Selecting or designing an experiment to test a rule (about changes in momentum).

Students will be able to:

- Explain and predict relative speed and direction of colliding objects in terms of conservation of momentum.
- Explain changes in momentum in terms of forces and Newton's second and third laws: e.g., for specific collisions, "forces transfer momentum" or "the change in momentum is equal to the impulse."

This worksheet focuses on the process of constructing a model eliciting ideas and sense-making, rather than a particular canonical model. We encourage instructors to support students in testing and refining their ideas as a scientist would, rather than guiding students toward a specific set of ideas. Students will construct a variety of models that are appropriate. Example models for the relationship between forces and momentum that the worksheet has supported students in constructing include:

> *"Force and momentum are both connected to velocity and acceleration. The force of an object is equal to the mass of the object multiplied by the acceleration of the object. The momentum of a physical object is equal to the mass of the object multiplied by the velocity of the object.*
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> *The experiment with the clay being thrown at a drawer and the rubber bouncy ball being thrown at the other drawer shows that an object with a higher elasticity will exert a greater force meaning there is a greater rate of change in momentum. Since the clay ball is inelastic it will not bounce off but stick to the object it is hitting and move with it and have the same final velocity as the object it sticks to.*
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> *This can also be explained using Newton's third law, which states every force occurs as one member of an action/reaction pair of forces. To have an action/reaction pair of forces is made up of two objects that interact by exerting a force on each other that are equal in magnitude but opposite in direction."*

> *"Like an object's velocity changing while a force is applied, the momentum of an object will change as long as a force is applied. This is evident in the equation for force, $F_{net} = ma$. The acceleration of an object, a, is given as the change in velocity over time.*
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> *Therefore, the equation for force can be rewritten as $F_{net} = m\Delta v/\Delta t$. Because momentum is given as p = mv, force can be reduced to include momentum as $F_{net} = \Delta p/\Delta t$. By manipulating this equation to $F_{net}\,\Delta t = \Delta p$, it is even more evident that the longer a force is applied (or more specifically, the larger Δt*

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is) the larger the change in momentum will be. There is clearly a direct relation between the change in momentum and the amount of force, along with the time of exertion.

Furthermore, the momentum of a system is conserved and will remain the same unless there is an external force enacted on the system. While the elasticity of a collision will not affect whether the momentum is conserved, it does affect the force experienced between colliding objects. During an elastic collision, there is a more dramatic change in the momentum of each object. Looking at the previous equations, it is evident that a greater change in momentum in a constant amount of time would yield a greater force. Therefore, objects will experience a greater amount of force during an elastic collision, and a lower amount of force in an inelastic collision."

Supplements to this worksheet:

Section II of this worksheet guides students to examine several 1-dimensional collision experiments. The **Supplement** to this worksheet includes descriptions and accompanying data for a variety of collision experiments for students to refer to. Videos of collisions can be found on this YouTube playlist.

What is this ACORN Physics Tutorial designed to do?

This Tutorial has three major sections: the first examines two everyday collisions, the second examines empirical data from a set of collisions between two carts on a track, and the third scaffolds students' process of building a conceptual model by generalizing, connecting, and refining the ideas they articulate in the first two sections.

I. Everyday collisions

Section I of this tutorial includes a set of **explain-style** questions about two everyday collisions. The questions in this section ask students to explain observations in terms of both forces and momentum and prompt students to draw diagrams to illustrate their explanations. The purpose of this structure is to ensure that students articulate a preliminary relationship between forces and momentum.

First, students consider a scenario in which one person throws a ball to another person while both are sitting on longboards. For clarity, we chose to break the scenario into two parts: the throw (instants 1-3) and the catch (instants 3-5). Students **explain** each of these interactions using ideas about momentum and forces. Students should be encouraged to draw force and momentum diagrams that are consistent with representations from other parts of their class. We expect these will involve vectors that represent an object's momentum or the forces that an object experiences, but we've kept our instructions about the diagrams relatively general so that you can adapt them to suit your course. Appropriate instants for momentum diagrams are before and after the collision (e.g., instants 1 and 3), while force diagrams are drawn for instants during the collision (e.g., instant 2).

Next, students compare two collisions: one between a drawer and a bouncy ball and one between a drawer and a clay ball. The "bouncy ball/clay" scenario has been used extensively in our research and was selected to elicit students' ideas about elastic and inelastic collisions and to refine students' models of force and momentum to account for the observations presented in this scenario. This section also uses a series of **explain** questions that target either force or momentum ideas, and asks students to draw diagrams to represent their ideas. Students may use the same ideas that they used to explain the first scenario. We've also seen students use ideas about energy conservation or thermal energy to make sense of this scenario. This Periscope lesson showcases an example of how students may sensemake about the "bouncy ball/clay" scenario.

Fruitful ideas (e.g., conceptual resources) that students commonly use to make sense of either or both of these scenarios include (Hansen et al. 2021):

- ***Momentum is conserved and/or transferred.*** Conservation and/or transfer of momentum is a fundamental constraint that students use to explain and/or predict the motion of objects after a collision.
- ***Momentum is directional.*** Students treat momentum as the kind of quantity that has a direction and the direction is for momentum calculations.
- ***The kind of collision (e.g., elastic or inelastic) matters.*** Students reference that the type of collision that an object undergoes (e.g., elastic or inelastic) affects its final momentum; in using this resource, students formally or informally apply a constraint to their analysis of the system.
- ***Forces cause objects to speed up or slow down.*** The force on an object changes its motion. In the context of momentum questions, students may use this resource in addition to or as an alternative to the above resources as they explain changes in motion that occur during collisions.
- ***For every action there is an equal and opposite reaction.*** This resource is a nascent or colloquial form of Newton's third law, and in the context of collision questions it is often used to explain why objects change direction or begin moving as the result of a collision. This resource may be used as an alternative or addition to the momentum resources listed above.

Instructors are encouraged to listen for and highlight ideas like these in students' conversations, and to ask open-ended questions to understand students' thinking more clearly. Instructors should encourage students to write down their relevant ideas in the "model-building box" on the first page of the worksheet. It is not important that students' ideas are completely correct or fully fleshed out at this stage of the worksheet, because they will spend significant time testing and revising their thinking in the following section. However, it is essential that students recognize what force and momentum ideas they *are using* so that they can test and refine them.

II. Experiments

Section II is designed to provide scaffolding for students to test and refine the models of force and momentum in collisions that they begin to develop in the first section. The worksheet suggests a set of open-ended questions that support students use the data provided to apply and test their ideas.

Graphs of velocity vs. time and force vs. time from a variety of collisions between two carts are provided in the supplement. The masses of the carts, the 'bumpers' of each cart (i.e., a spring, a magnet and copper tube, or clay), or the initial speed is varied. Alternatively, instructors can direct students to conduct their own experiments if appropriate equipment is available. (We used PASCO carts with force and motion sensors.)

Instructors may need to offer more support in this section, drawing students' attention to various features of the data and helping them decide whether the evidence supports or contradicts their models. Choosing an experiment and interpreting the results to test and refine a scientific model is challenging for students, and instructors can facilitate this process by highlighting important or recurring ideas they have heard students discussing, or drawing out connections between students' ideas.

III. Conceptual rule

Here, students revisit, connect, and refine the set of ideas used throughout the worksheet. This is a challenging task, and instructors may want to highlight important ideas and connections, ask questions to probe particular ideas that are unclear, or suggest thought experiments to test the developing model. It is important that students develop models from their own ideas (rather than instructors' suggestions), but

instructors can encourage students to add to or refine their model if it does not accurately predict or explain the behavior of an experiment they examine. The example models at the top of this guide illustrate that students can develop models that are purely conceptual or that are more mathematical.

What are specific strategies to help students with this worksheet?

- Keep track of questions that students express and suggest ways they can test their questions using equipment or simulations.
- Suggest thought experiments to clarify what a student is thinking or to resolve inconsistencies in their ideas.

What research has been done to develop and/or test this worksheet?

We developed this tutorial based on our analysis of hundreds of students' ideas about electric circuits and tested it in university physics courses, where students used the tutorial in small groups during regular class sessions. Learn more about the research involved in this worksheet here: https://www.physport.org/curricula/ACORN/research#momentum