IS1

Physics of the Universe Instructional Segment 1: Forces and Motion

What does a mountain peak have in common with a car (figure 7.44)? If the vehicle is involved in a crash, its hood will crumple and bend under the force of the collision. Mountain ranges, like the Himalayas, are shortened and pushed upwards just like the hood of a crashed car. Even though the two processes occur at very different **scales [CCC-3]**, both are governed by Newton's laws.

PHYSICS OF THE UNIVERSE INSTRUCTIONAL SEGMENT 1: FORCES AND MOTION

Guiding Questions

- How can Newton's laws be used to explain how and why things move?
- How can mathematical models of Newton's laws be used to test and improve engineering designs?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration. [Clarification Statement: Examples of data could include tables or graphs of position or velocity as a function of time for objects subject to a net unbalanced force, such as a falling object, an object rolling down a ramp, or a moving object being pulled by a constant force.] *[Assessment Boundary: Assessment is limited to one-dimensional motion and to macroscopic objects moving at non-relativistic speeds.]*

HS-PS2-2. Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system. [Clarification Statement: Emphasis is on the quantitative conservation of momentum in interactions and the qualitative meaning of this principle.] *[Assessment Boundary: Assessment is limited to systems of two macroscopic bodies moving in one dimension.]*

HS-PS2-3. Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision. [Clarification Statement: Examples of evaluation and refinement could include determining the success of the device at protecting an object from damage and modifying the design to improve it. Examples of a device could include a football helmet or a parachute.] *[Assessment Boundary: Assessment is limited to qualitative evaluations and/or algebraic manipulations.]*

HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

HS-ETS1-2. Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

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HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a practice or disciplinary core idea.

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-1] Asking Questions and Defining Problems [SEP-4] Analyzing and Interpreting Data [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS2.A: Forces and Motion PS2.B: Types of Interactions ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-2] Cause and Effect [CCC-4] Systems and System Models

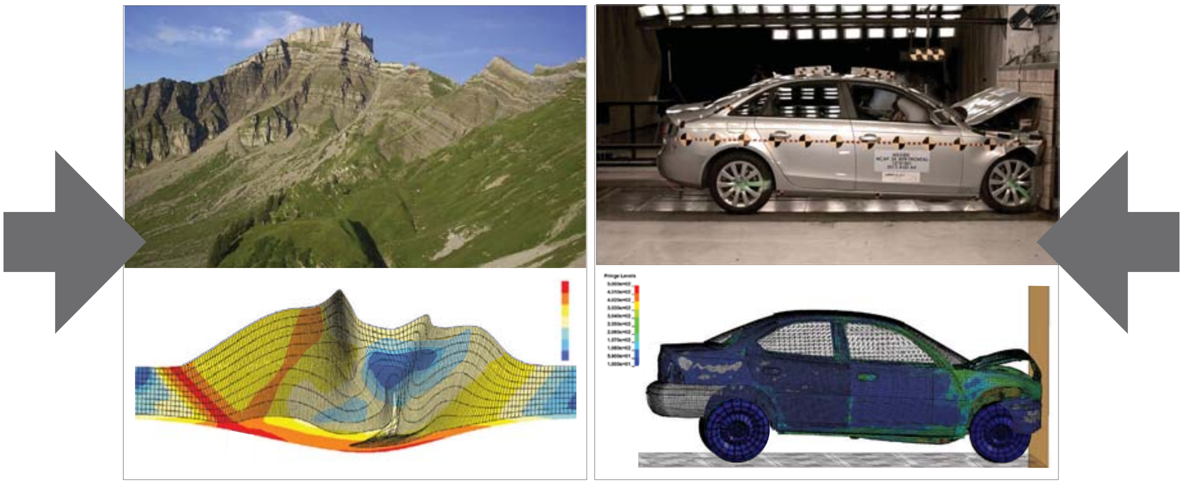
Highlighted California Environmental Principles and Concepts:
Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes.

CA CCSS Math Connections: N-Q.1-3; A-SSE.1a–b, 3a–c; A-CED.1, 2, 4; F-IF.7.a–e; S-ID.1; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.4, 5; RST.11–12.1, 7, 8; WHST.9–12.9

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

Figure 7.44. Collisions Occur in a Variety of Contexts



Mountains and car crashes involve collisions whose movement and forces can be modeled in computer simulations (bottom). *Sources*: Cinedoku Vorarlberg 2009; National Highway Traffic Safety Administration 2016; Willett 1999; Livermore Software Technology Corporation 2017

Newton's laws (table 7.7) provide a basis for understanding forces and motion and, therefore, serve as a foundation for a study of physics. Engineers and scientists apply Newton's laws **mathematically [SEP-5]** or with computational **models [SEP-2]** to predict the motion of objects. These calculations (such as depicted in the bottom panels of figure 7.44) enable applications as diverse as building safer automobiles and providing more reliable forecasts of earthquake hazard. Applying Newton's laws becomes quite complicated when considering the forces within deforming bodies like in figure 7.44, but these simple laws lie at the heart of even the most sophisticated computer simulations.

Table 7.7. Newton's Laws of Motion

First Law **Law of Inertia**	Every object in a state of uniform motion tends to remain in that state of motion unless it is subjected to an unbalanced external force
Second Law **Definition of Force**	$F = ma$. An object's acceleration, a, depends on its mass, m, and the applied force, F.
Third Law **Law of Reciprocity**	For every action, there is an equal and opposite reaction. When one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction on the first body.

Opportunities for ELA/ELD Connections

As a foundation for the study of physics, have students create mini-lessons on Newton's Laws of Motion to present to the class. Each team or group of students uses at least two different sources to research a law of motion for a visual presentation to the class. The presentation should include a general description/definition of the law plus an example demonstrating the application of the principle. Visual presentations make strategic use of digital media to enhance findings, reasoning, evidence, and add interest.

CA CCSS for ELA/Literacy Standards: RST.9–12.2, 7; WHST. 9–12.6, 7, 8; SL.9–12.5
CA ELD Standards: ELD.PI. 9–12.6, 9

In the middle grades, students investigated forces to establish a relationship between force, mass, and changes in motion (MS-PS2-2) and designed solutions to minimize the impact of a collision (MS-PS2-1). These experiences form the basis of a solid conceptual model of Newton's laws. Now, they are ready to **extend these models [SEP-2]** using **mathematical thinking [SEP-5]** so that they can use their models to predict precise outcomes. This process begins with mathematical descriptions of motion.

HS-PS2-1 requires students to "analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration." Before jumping into quantitative calculations, teachers should help students engage with their preconceptions about forces and motion through conceptual challenges. Teachers can administer the Force Concept Inventory (Hestenes 1998) to assess students' knowledge at the beginning of the course. Guided inquiry tutorials (see University of Maryland Physics Education Research Group, Tutorials in Physics Sense-Making at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link42) help students refine their conceptual models and are specifically designed for students to confront misconceptions. With these foundations, students **analyze and interpret [SEP-4]** tables or graphs of position or velocity as a function of time for objects subjected to a constant, net unbalanced force and compare their observations to predictions from the mathematical model (HS-PS2-1). Given the force and the mass, students learn to calculate the acceleration of an object. Given the mass and the acceleration, students should be able to calculate the net force on the object. Accordingly, students should be able to analyze simple free-body diagrams to calculate the net forces on known masses and, subsequently, determine their acceleration. In each of these cases, the clarification statement for HS-PS2-1 states that students should be examining situations where the force remains constant during the interaction. Gravity is the most consistent way to apply a constant force, so the most consistent results will come from analyzing objects moving down ramps or falling. Computer simulations and digital video analysis tools generate graphs of position versus time, speed versus time and acceleration versus time, providing an opportunity to visualize, analyze, and model motion.

The standard formulas of velocity, acceleration, and Newton's second law are all mathematical **models [SEP-2]**. In the CA NGSS, students should be able to use models to make predictions. Curriculum should therefore provide students with opportunities not only to perform calculations, but to test them using hands-on activities and computer simulations.

Engineering Connection: Testing Material Strength

Newton's second law can also be used to test the strength of different materials for a design challenge. A satellite must withstand vibrations from a rocket launch, a hospital must withstand earthquake shaking, and a child's toy must be able to withstand being sat on by a toddler. In many of these cases, it is not practical to do iterative testing on the actual objects (they cannot build various trials of a hospital and have each of them fall down—each one takes years and cost millions of dollars to complete). Instead, engineers do calculations to test their designs before investing the time and materials to actually build a prototype. In the classroom, students could determine the maximum force a toothpick can withstand before it snaps or a toilet paper tube before it buckles. They do this by placing heavy objects on top of the test material and measuring the amount of mass that **causes [CCC-2]** the material to break. Since the acceleration of gravity is constant, the force can be calculated using the mathematical model $W = mg$ (a special case of $F = ma$ where W is the force of the object's weight, m is mass, and g is the constant of gravitational acceleration). By comparing this force to calculations of the expected force on impact during a design challenge, they can make informed decisions about materials. Engineers perform similar calculations to provide evidence that their design will withstand the expected forces. They often use computer simulations like in figure 7.44 to perform these calculations.

Students extend their study of forces and motion to include collisions and the concept of momentum. The law of conservation of linear momentum states that for a collision occurring between object one and object two in an isolated **system [CCC-4]**, the total momentum of the two objects before the collision is equal to the total momentum of the two objects after the collision. Again, students will use **mathematical representations [SEP-5]** of these systems as **models [SEP-2]**. They should be able to apply these models to a range of scenarios.

The assessment boundaries for HS-PS2-1 and HS-PS2-2 are limited to one-dimensional

systems [CCC-4] with constant forces. Most everyday interactions, however, are more complicated and involve complex, three-dimensional systems in which forces and accelerations change. Thus, the motion of such things as a swinging trapeze artist, the crushing of a car door during a side impact, or the ground shaking during an earthquake can be broken down and analyzed qualitatively in terms of the three-dimensional forces acting on the objects at each moment during the motion. Computational **models [SEP-2]** employ this exact strategy, using Newton's laws to calculate changes in motion over a series of short, successive time increments. The following snapshot is one example of a complex problem in Earth science motivated by rich context and then addressed using tools appropriate for the high school level in the CA NGSS.

Physics of the Universe Snapshot 7.11: Applying Newton's Laws to the Earth

Mr. H ran an efficient technology-enhanced classroom where he was helping students become self-starters on engaging individual projects. After a few weeks investigating Newton's laws through laboratory **data analysis [SEP-4]** (HS-PS2-1), direct instruction, guided practice, and homework problem sets, Mr. H. wanted his students to be able to relate them to Earth processes.

Anchoring phenomenon: Many ocean trenches, oceanic ridges, mountain ranges, valleys, and plateaus on Earth are long and relatively straight.

As Mr. H.'s students entered the room, they opened the class Web site on their mobile devices and found the day's agenda. Each group of three students was assigned to investigate and characterize one of the following land and sea-floor features with a virtual globe, map, and geographical information program such as Google Earth: trenches (Mariana, Aleutian, Puerto Rico, Japan), oceanic ridges (Mid-Atlantic, East Pacific, Nazca, Mid-Indian), seamounts (Loihi, Davidson, Tamu Massif, Banua Wuhu), mountain ranges (Himalaya, Sierra Nevada, Rocky Mountains, Alps), valleys (California Central Valley, Ethiopian Rift Valley, Yosemite Valley, Rhone Valley), or plateaus (Kukenan Tepui, Monte Roraima, Table Mountain, Auyantepui). As the opening bell rang, students were already actively searching their geomorphic features. Mr. H. used a remote desktop to freeze their devices so he could clarify the instructions printed on the agenda Web page. Each team was to develop a tour-guide script that one of their members would read as they introduced their geomorphic feature to the class. Each group was to create a narrated animated tour in which they provided voiceovers, and descriptive pop-up balloons as they "flew" their audience around the globe in a video-like experience. Each animated fly-by or float-by tour had to include a description of the constructive forces (such as volcanism and

Physics of the Universe Snapshot 7.11: Applying Newton's Laws to the Earth

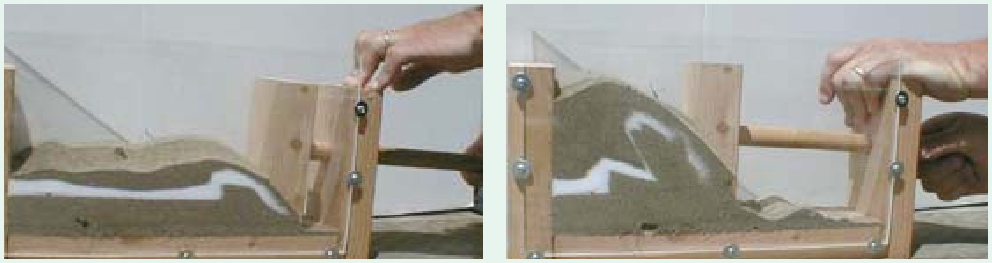
tectonic movements) and destructive mechanisms (such as weathering, landslides, and coastal erosion) that have shaped their feature (HS-ESS2-1). Students worked throughout the period, integrating their knowledge of plate motions and surface processes with the features they observed. Students were required to make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in their presentations to enhance understanding of findings, reasoning, and evidence and to add interest, thereby meeting CA CCSS for ELA/Literacy SL.11–12.4–5.

The following day, students proudly presented their fly-by videos, providing the class with an introduction to key oceanic and continental geomorphic features. Following the video presentations, Mr. H. asked students to describe how Newton's laws helped explain the formation of such features. Students typed their responses into an online form that allowed Mr. H to monitor their thinking in real-time. It soon became clear that although his students seem to have a good grasp of Newton's laws as measured by a traditional assessment, and although they seemed to have a good understanding of key geomorphic features, they appeared unable to apply Newton's laws to explain the formation of such features.

Investigative phenomenon: Layers of sand in a squeeze box deform as a plunger presses against one end.

Mr. H. proceeded with an interactive lecture on the concept of geological stress (pressure), the ratio of force per unit area. Although pressure is easy to conceptualize and measure using the simple, homogeneous, discrete objects commonly used in physics investigations, it is much more difficult to understand when discussing complex, heterogeneous, continuous objects such as the Earth's crust. To help students visualize the application of Newton's laws in geological systems, Mr. H. presented a squeeze box with a screw mechanism (figure 7.45).

Figure 7.45: Physical Model of Forces Deforming Layers in a Sandbox

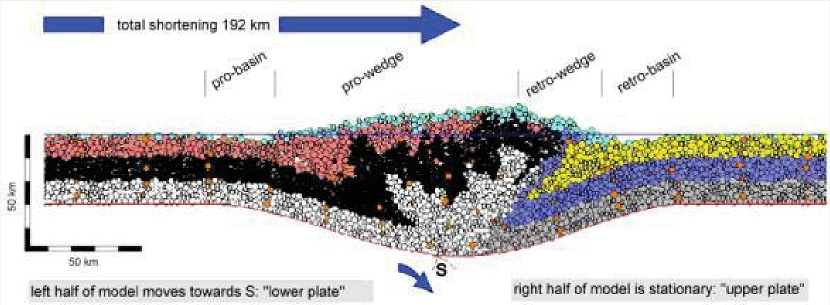


Source: Muller 2000. Used with permission, from the Squeeze Box Science Snack, http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link43 by Eric Muller, © Exploratorium, http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link44

Physics of the Universe Snapshot 7.11: Applying Newton's Laws to the Earth

Layers of dark and light sand were placed in alternating horizontal layers in the box and pressure applied with a screw mechanism. As the crank turned, layers deformed, simulating geological folding and mountain building. Unlike other physics problems the students had encountered using rigid objects, the sand was clearly not rigid. Scientists often break down complex problems like this into much smaller pieces, where the smaller pieces each behave like a rigid body. Mr. H showed an example in which scientists used this sort of **computational thinking [SEP-5]** by means of computer simulations called *discrete element analysis*. (figure 7.46)

Figure 7.46: Computer Model of Layers Deforming During Continental Collision



Source: Handy 2006

Mr. H asked students to work in pairs to label the forces acting on a small section of sand near the middle of the model. Students uploaded photos of their diagrams to the class Web page so that everyone could see their peers' work. Mr. H selected two student diagrams to show side-by-side and asked the class to identify the differences (figure 7.47). Most of the students had correctly identified the force related to the crank pushing on one side, but a substantial fraction of them forgot to include the force of the opposing wall. Mr. H asked students to consider the vector sum of the forces to make sure it pointed in the same direction as the change in motion.

Figure 7.47: Example Student Diagrams

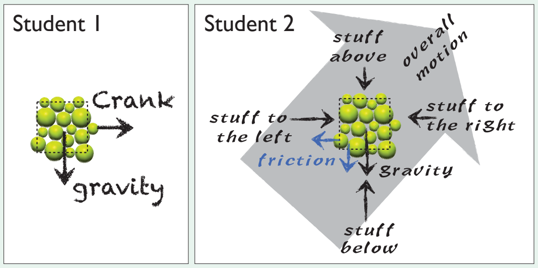


Diagram by M. d'Alessio

Physics of the Universe Snapshot 7.11: Applying Newton's Laws to the Earth

Mr. H next asked students how Newton's second law ($F=ma$) applied to this situation using the online student response form. This time, many students mentioned that force (applied through the screw) caused the mass of the individual particles (sand) to accelerate as evidenced by the movement of layers within the box. Mr. H told the students that there was some truth to that statement, but he disagreed that this explanation described most of the motion within the system. He challenged his students to **identify the evidence on which he based his argument [SEP-7]**. They were confused at first, but Mr. H walked around as teams of students discussed his statement. He asked them leading questions, such as "How would you describe the velocity of the wall?" Each team eventually realized that once it started moving, the wall continued to move at a constant velocity and was therefore not accelerating. A large fraction of the sand in the model moved constantly but did not deform, so it too did not accelerate. At any given time, only a small fraction of the model was accelerating. The same thing happened in the real world. Mr. H showed observations from precise GPS measurements that revealed that most plates move at constant rates in constant directions for decades (i.e., no acceleration). Clearly forces are being applied to the **system [CCC-4]**, so why doesn't it accelerate despite the constant force applied on the edges? Some students recognized friction as being important as the grains of sand slid past one another. They reasoned that friction or other forces within the system must balance the external forces. Earth scientists studying plate tectonics consider both the driving forces that push and pull the plates (related to gravity and convective processes in Earth's interior) as well as friction along the boundaries of plates (including drag along the bottom), momentum transfer from collisions with other plates, and the forces that arise from energy dissipation from friction within materials (often called *plastic deformation*). Even today, scientists are still trying to find ways to measure or estimate the strength of these forces to determine which ones are most important for causing the plates to move and deform. Beyond plate motions, plastic deformation is an important part of the energy balance of devices that minimize force during collisions such as vehicle crumple zones (related to HS-PS2-3).

Engineering Connection: Collision Challenge

Equipped with a basic understanding of classical mechanics, including Newton's three laws of motion and the momentum conservation principle, students should now be able to "apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision" (HS-PS2-3). A classic activity that meets this performance expectation is the egg-drop contest, in which students are challenged to develop devices that protect raw eggs from breaking when dropped from significant heights (figure 7.48). In the process, students demonstrate competence with HS-ETS1-1; they start by considering a complex problem such as automobile collisions or sports injuries, and then they **define the problem [SEP-1]** in terms of qualitative and quantitative criteria and constraints for solutions. With teacher guidance the students can then divide the entire problem into smaller, more manageable problems that can be solved through engineering (HS-ETS1-2). The students should be encouraged to **generate multiple solutions [SEP-6]**, and to evaluate their ideas based on prioritized criteria and trade-offs (see the section on decision matrices in chapter 11 of this framework), taking into account cost, safety, and reliability as well as social, cultural, and environmental impacts (HS-ETS1-3). Students then build and test a model of their most promising idea and modify it based on the results of the tests. Testing can include computer simulations that model how solutions function under different conditions (HS-ETS1-4).

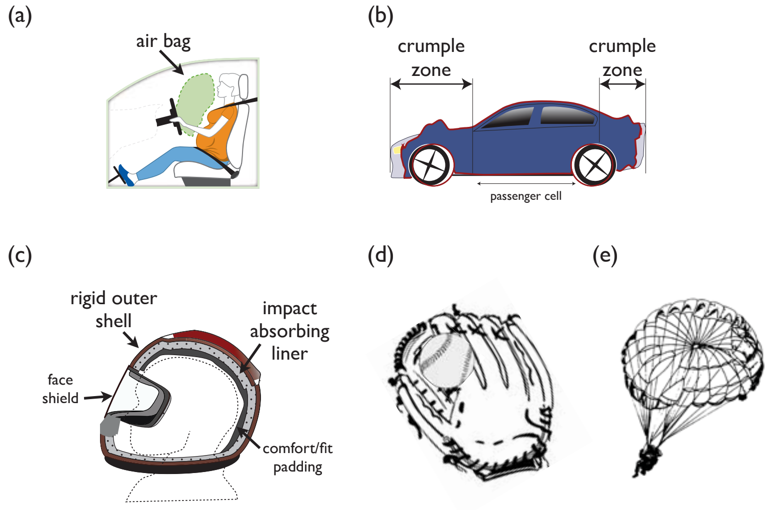
Figure 7.48. Engineering Solutions to an Egg Drop Challenge

Students learn physics principles such as impulse and momentum while simultaneously learning engineering design and testing principles while designing and developing devices for challenges such as the classic egg-drop contest. *Source*: Buggy and Buddy 2014

Throughout the process, students should **justify [SEP-7]** their design choices and revisions in terms of physics concepts, rather than using trial and error or guesswork. The engineering solutions students create are examples of **systems [CCC-4]** of interacting components. Students discover that the exact physical **structure [CCC-6]** (the arrangement of the components) can have a large impact on the function of their design. Students can draw pictorial **models [SEP-2]** showing the direction forces act and can label the role each piece plays in their solution.

Engagement in this activity also tests student understanding of the momentum-impulse connection: $F\Delta t = m\Delta v$, where F = *force*, t = *time*, m = *mass*, and v = *velocity*. The product of force and the time over which the force is applied is known as the impulse ($F\Delta t$) and is equal to the change in momentum of the object to which the force is applied ($m\Delta v$). One can decrease the force necessary to bring a moving object to rest by increasing the time over which the force is applied. For example, air bags, car crumple zones, helmets, parachutes, and padded catcher's mitts (figure 7.49) reduce the potential for injury by decreasing the force necessary to bring objects to a halt by increasing the time over which such forces are applied.

Figure 7.49. Real-World Engineering Applications of Momentum-Impulse Connections



The product of force and the time over which the force is applied is known as the impulse ($F\Delta t$), and is equal to the change in momentum of the object to which the force is applied ($m\Delta v$). One can decrease the force (F) necessary to bring a moving object to rest by increasing the time (Δt) over which the force is applied, such as is accomplished by (a) an automobile air bag, (b) a helmet, (c) a baseball catcher's mitt, or (d) a parachute. *Sources*: M. d'Alessio with images from National Highway Traffic Safety Administration 2015; adapted from KTEditor 2014; adapted from OpenClipart-Vectors 2013b; Clker-Free-Vector-Images 2012; OpenClipart-Vectors 2013a; Headquarters Department of the Army 2012