According to the NGSS storyline,

> The Performance Expectations associated with the topic Forces and Interactions supports students' understanding of ideas related to why some objects will keep moving, why objects fall to the ground, and why some materials are attracted to each other while others are not. Students should be able to answer the question, "How can one explain and predict interactions between objects and within systems of objects?" The disciplinary core idea expressed in the Framework for PS2 is broken down into the sub ideas of Forces and Motion and Types of Interactions. The performance expectations in PS2 focus on students building understanding of forces and interactions and Newton's Second Law. Students also develop understanding that the total momentum of a system of objects is conserved when there is no net force on the system. Students are able to use Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. Students are 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. The crosscutting concepts of patterns, cause and effect, and systems and system models are called out as organizing concepts for these disciplinary core ideas. In the PS2 performance expectations, students are expected to demonstrate proficiency in planning and conducting investigations, analyzing data and using math to support claims, and applying scientific ideas to solve design problems; and to use these practices to demonstrate understanding of the core ideas. (NGSS Lead States 2013)

Background for Teachers and Instructional Suggestions

What does a mountain peak have in common with a pickup truck? 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***, they are both governed by Newton's Laws.

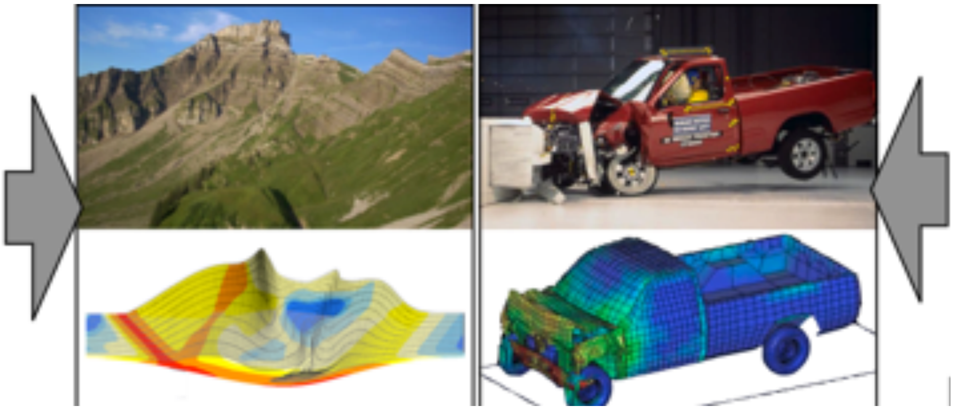

Figure 1. Mountains and car crashes involve collisions whose movement and forces can be modeled in computer simulations (bottom). (Insurance Institute for Highway Safety 2011; Cinedoku Vorarlberg 2009; Willett 1999; Structural Tech 2006)

Engineers and scientists can apply Newton's Laws mathematically or with computational models to predict the motion of objects. These calculations (including those depicted in the bottom panels of Figure 1) enable them to do things like build safer automobiles and provide more reliable forecasts of earthquake hazard. Predictions applying Newton's Laws have been shown to be accurate for all objects except those at certain extreme ***scales*** (such as objects traveling near the speed of light and extremely small particles such as atoms or subatomic particles that obey the principles of quantum mechanics). Newton's Laws provide a basis for understanding forces and motion, and therefore serve as a foundation for a study of physics. Newton's first law, the law of inertia, states that 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. Newton's second law, the definition of force, states the relationship between the applied force, F, an object's mass m, and its acceleration a, expressed as $F = ma$. Finally, Newton's third law, the law of reciprocity, states that 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, often described as "for every action, there is an equal and opposite reaction".

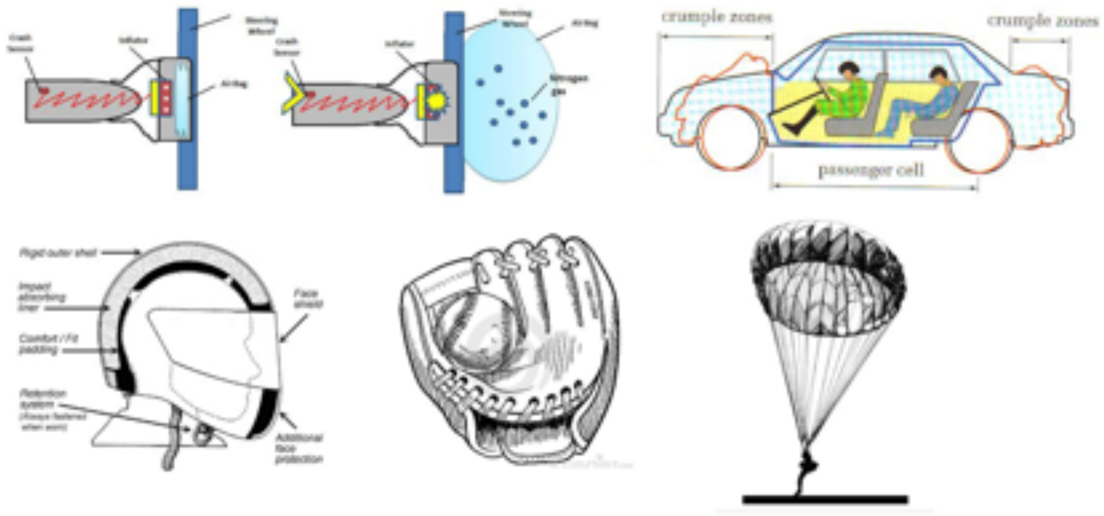

Figure 2. Students can analyze many devices that minimize the force on a macroscopic object during a collision. (Clemson University Vehicular Electronics Laboratory 2015; Grabianowski 2008; Chandigarh Traffic Police 2015; VectorStock 2015)

Like practicing engineers, this instructional segment is organized around a design challenge where students design a device that “minimizes the force on a macroscopic object during a collision” (*HS-PS2-3*). For example, air bags, car crumple zones, helmets, parachutes, and padded catcher’s mitts (Figure 2). 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. In the process, students are demonstrating competence with *HS-ETS1-1*, which involves starting by considering a complex problem, such as automobile collisions, or sports injuries, and specifying qualitative and quantitative criteria and constraints for solutions. With teacher guidance the students can then break down the problem into smaller, more manageable **problems** that can be solved through engineering (*HS-ETS1-2*). The students should be encouraged to generate multiple solutions, which they would then evaluate based on prioritized criteria and trade-offs, taking into account cost, safety, and reliability as well as social, cultural, and environmental impacts (*HS-ETS1-3*). Students can experience additional phases of the engineering design process by building and testing a model of their most promising idea and then modifying it based on the results of the tests. Testing can include computer simulations that model how such solutions would function under different conditions (*HS-ETS1-4*). Students performed a similar design challenge at the middle grade level in which they applied Newton's third law to design a solution to a problem involving the collision of two objects (*MS-PS2-1*). The high school ETS standards also have greater emphasis on quantifying trade-offs and prioritizing criteria (*HS-ETS1-3*), so this design challenge might include added constraints about material costs. Middle grade ETS standards heavily emphasize iterative testing and may lend themselves to an emphasis on trial and error. The high school challenge implies a more detailed understanding and calculation of forces. Throughout the process, the emphasis is on **explaining** design choices and revisions in terms of these physics concepts. The design challenge therefore serves as a culmination of the instructional segment, but students should be introduced to the challenge at the beginning of the instructional segment and the specific phenomenon investigated throughout the instructional segment should be chosen to build towards the specific design challenge.

In order to successfully complete the design challenge, students need to develop the mathematical tools to relate forces and motion. At the middle grade level, students **analyzed data** to identify a relationship between force, mass, and motion (*MS-PS2-2*). Now students employ **mathematical thinking** to apply the simple mathematical **model** formulated in Newton's second law (F=ma, Force = mass x acceleration). They **analyze and interpret** tables or graphs of position as a function of time, or velocity as a function of a 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 vs. time, speed vs. time and acceleration vs. time, providing an opportunity to visualize, analyze and model motion.

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 upon 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 of actually building 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*** 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 their design challenge, they can make informed decisions about materials. Engineers perform similar calculations to provide evidence that their design will withstand the expected forces. Often, computer simulations like Figure 1 are used for these calculations.

Newton's second law is written from the perspective of an isolated object with a net external force acting upon it. With a ***system*** of two or more objects interacting (such as during a collision), Newton's third law also becomes important for describing the forces between the objects. Students made qualitative **explanations** of the exchange of ***energy*** during collisions at the middle grade level (*MS-PS3-5*), but now students use a mathematical **model** to describe a different aspect of the collision. A consequence of Newton's laws is that a quantity called linear momentum stays constant within a system that has no net external forces acting upon it. Momentum is expressed as mass times velocity and conservation of momentum means that the momentum lost by one object in a two body system must equal the momentum gained by the other object. Conservation of momentum can be applied to collisions and students can predict how much the velocity of objects with known masses will change when they collide. Comparing predictions to measurements provides evidence to support the claim that momentum is conserved during a collision (*HS-PS2-2*).

The assessment boundaries for HS-PS2-1 and HS-PS2-2 are limited to one-dimensional ***systems*** 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** employ this exact strategy, using Newton's laws to calculate changes in motion over a series of short, successive time increments.

There are a number of observations based on everyday experience that seem to contradict Newton's laws and the law of conservation of momentum that can be derived from them. For example, a rolling basketball will come to a stop unless given an additional push, while the momentum of a basketball reverses simply by bouncing off a backboard in the absence of a visible force. Similarly, a runner races forward without the earth moving backwards. In each of these situations, there are forces or parameters that students often neglect in their intuition (such as friction or elastic forces). With experience, they can begin to recognize **evidence** of these processes so that they can slowly replace their preconceptions of how the world works with one that truly incorporates the physics of Newton's laws.

Snapshot of a Physics Lesson: Forces and Motion in Geology

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

As Mr. H.'s students enter the room, they open the class website on their mobile devices and find today's agenda. Each group of three students is 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, Yosemite Valley, Rhone), or plateaus (Kukenan Tepui, Monte Roraima, Table Mountain, Auyantepui). As the opening bell rings, students are already actively searching their geomorphic features. Mr. H. uses remote desktop to freeze their devices so he can clarify the instructions printed on the agenda webpage. Each team is to develop a tour-guide script that one of their members will read as they introduce their geomorphic feature to the class. Each group is to create a narrated animated tour in which they provide voiceovers, and descriptive pop-up balloons, as they "fly" their audience around the globe in a video-like experience. Each animated "fly-by" or "float-by" tour must include a description of the constructive forces (such as volcanism and tectonic movements) and destructive mechanisms (such as weathering, landslides, and coastal erosion) that have shaped their feature (*HS-ESS2-1*). Students work throughout the period, integrating their knowledge of plate motions and surface processes with the features they observe. Students are 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 *CCSS SL.11-12*.

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

Mr. H. proceeds 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, homogenous, discrete objects commonly used in physics investigations, it is much more difficult to understand when discussing

Connections to the CA CCSSM: MP. 2
Connections to CA CCSS for ELA/Literacy: SL.11-12.4, SL.11-12.5
Connection to CA ELD Standards : ELD.P1.11-12.C9-11
Connections to the CA EP & Cs: none

The design challenge described at the beginning of the instructional segment tests students' 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. *HS-PS2-3* gives students the opportunity to design and test devices that minimize the force necessary to bring moving objects to a standstill. A classic activity that meets this PE 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 3). This challenge employs a wide range of science and engineering practices and enhance their understanding of crosscutting concepts. For example, students **define the problem** by understanding the design objective and their material constraints. They can break the mechanical problem of minimizing force down into smaller, more manageable problems (*HS-ETS1-2*) such as finding ways to slow the descent or lengthen the time of contact during the collision. Like many mechanical engineering tasks, they are designing an object whose ***structure*** achieves a specific ***function***. The process of optimizing **solutions** forces students to isolate specific ***cause and effect*** relationships between components of their structure and the performance result. They realize that their device operates as a ***system*** with interacting components where changes in one part of their design often lead to consequences for other parts.

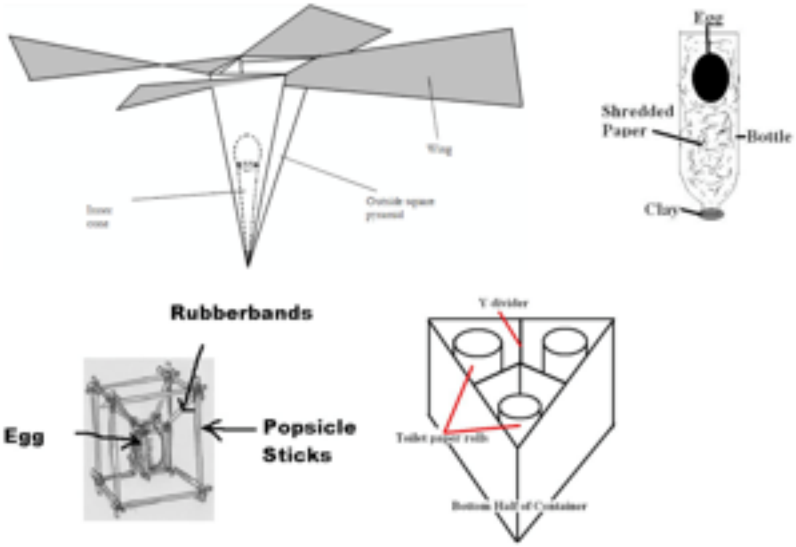

Figure 3. Students learn physics principles such as impulse and momentum while simultaneously learning engineering design and testing principles while designing and developing devices for challenges such as the classic egg-drop contest.