CHAPTER 3

Momentum and Energy

Demonstration Equipment

- Air track and carts of equal and unequal mass (if you're so fortunate!)
- A simple pendulum (any ball tied to a length of string)
- The swinging balls apparatus (optional)

This chapter begins by continuing where Chapter 2 leaves off. Newton's 2nd and 3rd laws lead directly to momentum and its conservation. We emphasize the impulse-momentum relationship with applications to many examples that have been selected to grab the students' interest. In presenting your own, the exaggerated symbol technique as shown in Figures 3.4–3.6 is suggested. Draw a comparison between momentum conservation and Newton's 3rd law in explaining examples such as rocket propulsion. You might point out that either of these is fundamental—that is, momentum conservation may be regarded as a consequence of Newton's 3rd law, or equally, Newton's 3rd law may be regarded as a consequence of momentum conservation. Momentum continues to energy, the most central concept in physics, which is discussed in various forms throughout the remainder of the text.

A system is not only isolated in space, but in time also. When we say that momentum is conserved when one pool ball strikes the other, we mean that momentum is conserved during the brief duration of interaction when outside forces can be neglected. After the interaction, friction quite soon brings both balls to a halt. So when we isolate a system for purposes of analysis, we isolate both in space and in time. System identification is developed in the Practice Book page 20.

The concept of reduced force for collisions involving extended times is wonderfully employed by air bags in cars. Some airlines use the same idea with similar air bags inside seatbelts. Softer speedway barriers, which extend times of contact during collisions, are on some racing tracks, including the Indianapolis Motor Speedway. These barriers consist of vertically stacked rectangular steel tubes and up to 14 inches of polystyrene foam, which together absorb more than a third of the energy of impact. Air-bag vests are also available for motorcycle riders.

In the Practice Book:

- Momentum
- Systems
- Impulse-Momentum
- Conservation of Momentum
- Work and Energy
- Conservation of Energy
- Energy and Momentum

Next-Time Questions on the IRDVD:

- Momentum Conservation of Jocko the Clown
- Fired Gun
- Long Cannon
- Car-Truck Collision
- Ball Toss
- Ball Tracks
- Roller Coaster

In the Lab Manual:

- An Uphill Climb
- Dropping the Ball
- Fountain of Fizz

Screencasts:

- Momentum
- Conservation of Momentum
- Fish-Lunch Problem
- Freddy-Frog Momentum Problem
- Work and Potential Energy
- Potential and Kinetic Energy

- Work-Energy Theorem
- Conservation of Energy
- Energy of Acrobats
- Ballistic Pendulum
- Machines and Energy

SUGGESTED PRESENTATION

Momentum—Inertia in Motion

Begin by stating that there is something different between a massive cement truck and a roller skate—they each have a different inertia. And that there is still something different about a moving cement truck and a moving roller skate—they have different momenta. Define and discuss momentum as inertia in motion.

> CHECK YOUR NEIGHBOR: After stating that a cement truck will always have more inertia than an ordinary roller skate, ask if a cement truck will always have more momentum than a roller skate.

Cite the case of the supertankers that cut off their power when they are 25 or so kilometers from port. Because of their huge momentum (due mostly to their huge mass), about 25 kilometers of water resistance are needed to bring them to a halt.

Impulse Changes Momentum

Derive the impulse-momentum relationship. In Chapter 2 you defined acceleration as $a = \Delta v/t$ (really Δt, but you likely used t as the "time interval"). Then you defined acceleration in terms of the force needed, $a = F/m$. Now simply equate; $a = a$, or $F/m = \Delta v/t$, with simple rearrangement you have, $Ft = \Delta mv$ (as in the footnote on page 63).

Then choose your examples in careful sequence: First, those where the object is to increase momentum—pulling a slingshot or arrow in a bow all the way back, the effect of a long cannon for maximum range, driving a golf ball. Second, those examples where small forces are the object when decreasing momentum—pulling your hand backward when catching a ball, driving into a haystack versus a concrete wall, falling on a surface with give versus a rigid surface. Then lastly, those examples where the object is to obtain large forces when decreasing momentum—karate.

Point of confusion: In boxing, one "follows through" whereas in karate (or more properly called "tae kwon do") one "pulls back." But this is not so—an expert does not pull back upon striking his target. He or she strikes in such a way that the hand is made to bounce back, yielding up to twice the impulse to the target (just as a ball bouncing off a wall delivers nearly twice the impulse to the wall than if it stuck to the wall).

> CHECK YOUR NEIGHBOR: Why is falling on a wooden floor in a roller rink less dangerous than falling on the concrete pavement?
> [Superficial answer: Because the wooden floor has more "give." Emphasize that this is the beginning of a complete answer—one that is prompted if the question is reworded as follows:] Why is falling on a floor with more give less dangerous than falling on a floor with less give? [Answer: Because the floor with more give allows a greater time for the impulse that reduces the momentum of fall to zero. A greater time for Δ momentum means less force.]

The loose coupling between railroad cars is a fascinating example of impulse-momentum. The loose coupling brings a long train initially at rest up to speed in a longer time. If the cars were tightly fastened, too much of a load would have to be moved in the same time. The looseness breaks the times of momentum change into segments. This is important in braking the train as well. (I compare this to taking school load in proper sequence, rather than all at once where for sure one's wheels would simply spin.)

Bouncing

Discuss bouncing and how Lester Pelton made a fortune from applying some simple physics to the old paddle wheels.

Bouncing does not necessarily increase impact force. That depends on impact time. Point out that bouncing involves some reversing of momentum, which means greater momentum change, and hence greater impulse. If the greater impulse is over an extended time (bouncing from a circus net), impact force is small. If over a short time (plant pot bouncing from your head), impact force is large. Damage from an object colliding with a person may depend more on energy transfer than on momentum change, so in some cases damage can be greater in an inelastic collision without bouncing.

> DEMONSTRATION: Consider doing as Howie Brand does in Figure 3.8. The tip of a dart has half of a "happy ball" on its end. This end bounces well. The other end of the dart has half a "sad ball" that bounces poorly. You can arrange the displacement of the dart so that collision of the sad part doesn't topple the block. When you turn the dart around so the happy side makes contact with the block, toppling occurs. There is more impulse delivered by a bouncing dart than one that stops upon collision. Interesting.

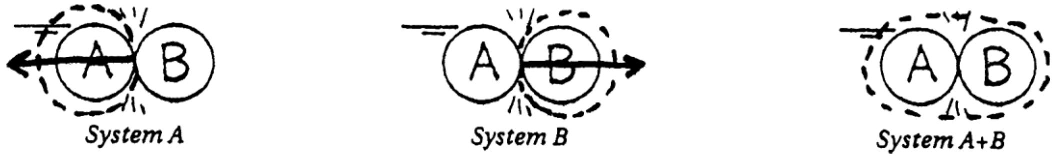
Conservation of Momentum

Distinguish between external and internal forces and lead into the conservation of momentum. Show from the impulse-momentum equation that no change in momentum can occur in the absence of an external net force. This is your introduction to the all-important concept of conservation in physics. Soon you'll treat conservation of energy, then conservation of charge, conservation of nucleons in nuclear reactions. In Appendix B you'll treat conservation of angular momentum. The conservation principles of physics are very important.

Defining Your System

Momentum is not conserved in a system that experiences an external net force. Consider the simple case of a pool ball striking one at rest. If the system is the ball at rest, then an external force acts on it and momentum is increased. Momentum for this ball is not conserved. Or if the system is the moving ball, then a reaction force acts on it when it strikes the ball at rest. This external force stops the ball in its tracks. Momentum for this ball is not conserved. Now consider the system of interest to be BOTH balls. For this system, no external force acts. The action and reaction forces occur within the system. For this system, Figure 3.11 in the text, net momentum doesn't change, and momentum IS conserved. (It is merely transferred from one part of the system to the other without net change.)

How deeply you want to treat the notion of systems is your call. It can be glossed over for general students, or delved into in depth with students who value further study in physics.



Collisions

The numerical example of the air-track carts in the CheckPoint question on page 70 might be discussed. This emphasizes the vector nature of momentum—particularly for the case of the carts approaching each other. The emphasis you give to this coverage will vary from class to class. It will be important if you are fortunate enough to have an air-track apparatus. Relate this to the Problems at the end of the chapter, particularly Think and Solves 55, 56, and 57.

DEMONSTRATION: Show momentum conservation with an air-track performance.

[This is a good breaking place.]

The Concept of Energy

Begin by standing on a chair against a wall with an extended heavy pendulum bob held at the tip of your nose. Say nothing. Release the bob and let it swing out, then back to your nose. Don't flinch. Then comment on your confidence in physical laws and lead into a distinction between potential and kinetic energy. That is, point out that where the bob is moving fastest, it is lowest, and where it is highest, it doesn't move at all. The bob transforms energy of motion to energy of position in cyclic fashion. Allow the pendulum to swing to-and-fro while you're talking. Its motion decays. Why? Then point out the transformation of energy from the moving bob to the molecules of air that are encountered, and to the molecules in the bending string or wire at the pivot point. The energy of the pendulum will end up as heat energy. I quip that on a very hot day, somebody, somewhere, is swinging a giant pendulum to-and-fro.

Work—Force × Distance

Define work and compare it to impulse. In both cases, the effect of exerting a force on something depends on how long the force acts. In the previous case, how long was meant as time, and we spoke of impulse. Now, however, how long is meant as distance, and we speak of work. Cite the examples of the drawn slingshot and the long barreled cannon, where the added length produces greater speed. We described this greater speed in terms of greater momentum: Now we describe this greater speed in terms of greater energy—that is, greater kinetic energy (KE).

Work is done on an object only when an applied force moves it. Emphasize work done ON an object. If work is done on an object, then its energy state is different than before work was done on it. Confusion about work often involves exactly what the work acts on. This is highlighted by this Check Question.

CHECK YOUR NEIGHBOR: Is work done when a weight lifter holds a barbell stationary above her head?
[Yes and no. With each contraction of the weight lifter's heart, a force is exerted through a distance on her blood and so does work on the blood. But this work is not done on the barbell.]

Power

Power has to do with how quickly work gets done. A watt of power is the work done in vertically lifting a quarter-pound hamburger with cheese (approx. 1 N) one meter in one second.

Mechanical Energy

Cite the various forms of energy, and state that we'll consider only mechanical energy for now, which takes the form of potential energy and kinetic energy.

Potential Energy

Return to your pendulum: With the pendulum at equilibrium show how the force necessary to pull it sideways (which varies with the angle made by the string) is very small compared to the force necessary to lift it vertically (its weight). Point out that for equal elevations, the arced path is correspondingly longer than the vertical path—with the result that the product of the applied force and distance traveled—the work done—is the same for both cases. (Without overdoing it, this is a good place to let your students know about integral calculus—how calculus is required to add up the work segments that continuously increase in a nonlinear way.) Then discuss the work needed to elevate the ball in Figure 3.19.

> CHECK YOUR NEIGHBOR: Does a car hoisted for lubrication in a service station have PE? How much work will raise the car twice as high? Three times as high? How much more PE will it have in these cases?

You can give the example of dropping a bowling ball on your toe—first from a distance of 1 mm above your toe, then to various distances up to 1 m above your toe. Each time, the bowling ball would do more work on your toe, because it would possess more gravitational potential energy when released.

Kinetic Energy

Relate force × distance = ΔKE to examples of pushing a car, and then to braking a car as treated in the text. To a close approximation, skidding force is independent of speed. Hence change in KE is approximately equal to change in skidding distance. When the car's brakes are applied, the car's kinetic energy is changed into internal energy in the brake pads, tire, and road as they become warmer.

You may or may not at this point preview future material by relating the idea of the KE of molecules and the idea of temperature. State that molecules in a substance having the same temperature have the same average KE. If the masses of the molecules are the same, then it follows that the speeds of the molecules are the same. But what if the masses are different, for example, in a sample of gas made up of light and heavy molecules at the same temperature? Which molecules would move faster? (If you shook a container of billiard balls mixed with Ping-Pong balls so that both kinds of balls had the same kinetic energy, which would move faster in the container?) (If an elephant and a mouse run with the same kinetic energy, which is to say both will do the same amount of work if they bump into the door of a barn, can you say which of the two is running faster?) You might consider the demonstration of inhaling helium and talking at this point—particularly if you are not including the chapters on sound in your course design. Relate the higher temperature due to the faster moving helium molecules to the higher temperature in a bugle when faster moving air is blown through it.

Work-Energy Theorem

When discussing whether or not work is done, be sure to specify done on what. If you push a stationary wall, which my friend Bob Minor is doing in Figure 3.15, you may be doing work on your muscles (that involve forces and distances in flexing), but you do no work on the wall. Key point: If work is done on something, then the energy of that something changes. Distinguish between the energy one expends in doing things, and the work that is actually done on something.

> CHECK YOUR NEIGHBOR: When a car slows down due to air resistance, does its KE decrease? [Most certainly!]

CHECK YOUR NEIGHBOR: Which is greater, 1 joule or 1 newton?
[Whoops! The comparison is silly, for they're units of completely different things—work and force.] An idea about the magnitude of 1 joule is that it is the work done in vertically lifting a quarter-pound hamburger with cheese (approx. 1 N) one meter.

Note the pair of photos showing the heat generated by friction on a skidding bicycle tire (Figure 3.25 on page 75). How interesting it would be to see infrared photos of the heat generated when a couple of carts collide. Recall that half the KE for a collision of identical cars goes into heat. Seeing that via an infrared photo would be interesting.

Conservation of Energy

Discuss Figures 3.19 and 3.20 and then return to your pendulum. Explain how the kinetic energy and hence, the speed of the bob at the bottom of its swing is equal to the speed it would have if dropped vertically through the same height. This is shown in Figure 3.22. Then discuss Figure 3.23.

CHECK YOUR NEIGHBOR: Consider a block of wood freely sliding down an incline. When released from rest, it will slide to the bottom with a certain speed. Suppose it slid down a steeper incline, but through the same vertical distance. Will the speed at the bottom be different?
[It is impressive that the speeds will be the same. The lesser acceleration down the sloped ramp is compensated by a longer time. But return to the situation and ask how the times to reach the bottom compare and be prepared for an incorrect response, "The same!" Quip and ask if the colors and temperatures will also be the same. Straightforward physics can be confusing enough!]

DEMONSTRATION: Preview electricity and magnetism and bring out the horseshoe magnet hand-cranked generator that lights up the lamp shown ahead in Figure 9.37 (page 236). Have student volunteers attest to the fact that more work is needed to turn the crank when the lamp is connected than when it is not. Then relate this to the extra effort a bicyclist exerts when a generator is affixed to a bicycle wheel to activate a lamp.

When gasoline combines with oxygen in a car's engine, the chemical potential energy stored in the fuel is converted mainly into molecular KE (thermal energy). Some of this energy in effect is transferred to the piston and some of this causes motion of the car. Now we have hybrid cars, and soon, all electric cars.

Go over the CheckPoint in the text about fuel economy on pages 79–80—very important. (I pose the same question on my exams, which to the student is the definition of what's important!) As a side point, gas economy is increased when tires are inflated to maximum pressures, where less flattening of the tire occurs as it turns. The very important point of this exercise is the upper limit possible.

Machines

Show how a lever is a simple machine, obeying the work in = work out principle. And show that a pulley is an extension of a simple lever. CCSF physics instructor Jill Johnsen's photo nicely opens this chapter.

Efficiency

It should be enough that your students become acquainted with the idea of efficiency, so I don't recommend setting the plow setting too deep for this topic. The key idea to impart is that of useful energy. To say that an incandescent lamp is 10% efficient is to say that only 10% of the energy input is converted to the useful form of light. All the rest turns to heat. But even the light energy converts to heat upon absorption. So all the energy input to an incandescent lamp is converted to heat. This means that it is a 100% efficient heater (but not a 100% device for emitting light)!

Sources of Energy

It is important that students don't see electricity, steam, and other transporters of energy as energy sources. Sources include solar, geothermal, and nuclear. Electricity, for example, involves some source such as a waterfall (potential energy) or fuel to produce steam. Call attention to Figure 3.36 on page 81, a sensible and future contender of power.

Another contender for electric power is the concept of undersea turbines which are activated by tidal flows. Test sites are being researched in Norway, the United Kingdom, and the United States. Watch for development in tidal generators of electricity.

It has been correctly said that hydrogen is the ultimate fuel. When burned in vehicles, as is presently being done with commercial vehicles in various parts of the world, only water vapor is ejected by the exhaust. This makes it seem like a dream fuel. The big problem is that there is no free hydrogen to burn. It must be removed from molecules where it is abundant. And the removal takes energy, which must come from some energy source. If gasoline is the source, then it is argued that it might as well be used in the vehicles to begin with, for even more pollutants would result at the conversion site. Saying cars should be powered with hydrogen is akin to saying they should be powered with electricity. But when hydrogen is produced from solar energy, it is a win-win scenario. The point to stress is that hydrogen is not a source of energy, but a carrier of energy—akin to electricity.

Fuel cells, as touted by my good friend David Vasquez in Figure 3.36, show much promise.

Some 8 million panels of photovoltaic solar cells at the edge of the Mohave Desert in California are now producing some 550 megawatts of energy, equaling that of a conventional power plant. And that's just a beginning. Interestingly, sooner or later, all the sunlight that falls on an ecosystem will be radiated back into space. Energy in an ecosystem is always in transit—you can rent it, but you can't own it.

A personal concern of mine is what seems as ignoring the enormous amount of thermal energy beneath our feet. Years ago on a train trip though Italy my children and I viewed the lava pouring from Mount Vesuvius. I remarked about the energy involved. Then the train progressed by a large assemblage of buildings obscuring our view of nature's energy. The buildings were those of a fossil-fuel power plant. Fossil fuels were being turned into heat and smoke while appreciably more energy flowed down the mountain sides in the background. How ironical! Hence my touting of dry-rock geothermal energy as shown in Figure 3.37, a figure I have repeated for decades in my books.

When biologists talk of energy in living systems, they're talking about the same energy discussed in this chapter. Our bodies obey the same principles that levers and other machines obey.

An important point to make, especially in this time where nuclear power is controversial, is that the source of ALL energy is nuclear. Energy radiated by the Sun is the result of nuclear fusion in its interior. Energy in Earth's interior is the result of nuclear disintegration (radioactivity) and of nuclear fission occurring in Earth's core. Again for emphasis, the source of all energy, including solar, is nuclear.

NEXT-TIME QUESTION: Show the Swinging Wonder after you've treated both momentum and energy conservation. If two balls are raised and released, why doesn't one ball emerge with twice the speed? Note that momentum would be conserved in this case—but not energy.

Sample Advanced Problem and Solution (that shows how an equation guides thinking! Note how each step dictates the next step).

Problem:
A bicyclist traveling along a level road at speed v slams on the brakes and skids to a stop. If the force of friction on the bicycle is half the combined weight of the bicycle and rider, how far does the bicycle slide? (Hint: Use the work-energy theorem and solve for d.)

Solution:
By the work-energy theorem,

$$W = \Delta KE$$

Work done on the bicycle is Fd, so

$$Fd = \Delta\left(\frac{1}{2}mv^2\right)$$

The only force F that does work to reduce the kinetic energy is the force of friction. This force acts through d, the distance of skidding. The mass of the rider and bicycle is m, and its initial speed is v. In this problem the final speed of the bicycle will be zero, so the change in kinetic energy is simply the initial kinetic energy at speed v. You're looking for distance, so write the equation in a "d =" form. It becomes

$$d = \frac{\Delta\left(\frac{1}{2}mv^2\right)}{F} = \frac{\frac{1}{2}mv^2}{f} = \frac{\frac{1}{2}mv^2}{mg/2} = \frac{v^2}{g}.$$

where F is half the weight of rider and bicycle, mg/2.

Note how the terms in the equation dictate subsequent steps and guide your thinking. The final expression tells you the stopping distance is proportional to speed squared, which is consistent with it being proportional to *KE*. It also tells you that if g were greater, the force of friction would be greater and skidding distance less—which is quite reasonable. Cancellation of mass tells you that the mass of the system doesn't matter. All vehicles skidding with the same initial speed, with friction equal to half their weights, will skid the same distance. And as for units, note that v^2/g has the unit $(m^2/s^2)/(m/s^2) = m$, a distance, as it should be. How nice that much can be learned by a thoughtful examination of a simple equation.