The Four Lenses

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1.0 Introduction

There are four main concepts, or lenses, through which we can look at a physical event:

- momentum, which can be thought of as how hard it is to stop an object;
- energy, the ability to do work;
- dynamics, or forces change the momentum (or velocity) of an object.
- kinematics, the study of motion without considering its causes.

Traditional mechanics texts introduce and fully develop one concept at a time in depth before moving onto the next, usually starting with kinematics, then dynamics, energy, and momentum. Instead, we introduce all the concepts at the beginning, using simplified examples, developing depth and complexity as we practice through the length of the class. Our method is supported by studies indicating that people learn iteratively: by repeating back to increasingly familiar concepts. The way we will be learning physics is a little more like we all learned our first language – you just dive in and start doing it. Happily, we have already started many years ago, because you come to your first class with some familiarity of momentum, forces, energy, and motion. Over the next term, we will deepen your familiarity and practice problem solving.

Many of us have a “formulas and answers” approach to science and math:

- you give me a problem;
- I find a formula;
- I put in the numbers and get an answer;
- I find out if I’m right!

Instead, I encourage you to try a number of different strategies:

- **I don’t know the answer, but I am curious about what’s going on;**
- **I draw a picture;**
- **I look at the event through each of the four lenses and consider which is the most helpful;**
- I consider what would happen if things were different… if the problem was upside down, or if one of the masses were way way larger than the other.
- I simplify the problem to be really obvious.
- I imagine a scenario where I observed something like happening.
- **I get an answer and consider if it makes sense.**

Inside the third method, considering lenses, there may be a “formula and answer” process. However there may be other methods as well, such as using a drawing or a simplification. You may also have other strategies that you would like to try. However, in this course, the boldface strategies are important to utilize for every problem we will encounter.

Change often comes hard, and many of us will find ourselves defaulting into the “formulas and answers” way of looking at physics. We may also find ourselves using an approach that we all agree is a bad idea, like, “this mass *wants* to speed up when it is hit…” when none of us really think that a steel block has volition, or that volition would result in a change of velocity! One of the key differences in this course is that we will practice awareness of how we are looking at a problem as well as the reflective capacity to ask ourselves if this is a good way to look at a problem.

Are we in Pete’s class? As we build this text, some of the information is specifically for the classes facilitated by the author, Pete Schwartz. This material is identified by a (PS) before each paragraph.

(PS) Your responsibility in this class is to develop working relationships with other students. Our class is a social environment, and we will work together solving problems, arguing about concepts, studying for exams and doing projects. Many students enjoy office hours, because you can sit at a table together outside my office and call me over when you want to. Because I won’t always be there in front of you, you will need to work with your peers, and you will also need to take the initiative to say, “Pete, we have a question.” Lastly, you don’t need to wait until office hours to get together for study or group, and the working area outside my office is always there.

1.1 Momentum

Figure 1: Each rugby player has momentum, which will affect the outcome of their collisions with each other and the ground. (credit: ozzzie, Flickr)

If something has momentum it is hard to stop or change course. We use the term in regular day English, such as "Jenny's business has gained so much momentum this year that it is certain to succeed." However, we also use it in terms of a moving object, such as, "John hit a player from the other team, but John had enough momentum to carry the two of them over the line for a score!"

Momentum is about speed and mass. Thus we could make an ordering of increasing momentum: a flying insect, a child walking, an adult walking, a bicyclist at high speed, a speeding car, a speeding truck, a speeding train, a full cargo ship, another planet.

DEFINITION 1: Momentum

$$p = mv$$

p means momentum. m is mass, which is the measurement of matter in a physical object. v is velocity, how fast an object is moving in some direction. Based on the International System of Units, abbreviated SI, the standard is to express mass in terms of kilograms (kg), and velocity in terms of meters per second (m/s). Thus, the unit of momentum is (kg m/s).

Momentum is important because it is conserved. In other words, the total momentum of a system doesn't change. Only a few physical quantities are conserved in nature, including momentum, total energy, and angular momentum (which we will introduce later). Studying these conserved quantities yields fundamental insight into how nature works.

While total momentum of a system doesn't change, momentum can be transferred from one object to another through an interaction where a force transfers the momentum. Examples where momentum is transferred include a collision or some other force including springs, magnets, friction, etc.

Consider what happens when one car bumps into another, as shown in **Figure 2** (#car_example). Both cars are coasting in the same direction when the lead car (labeled m_2) is bumped by the (faster) trailing car (labeled m_1). Car 1 slows down as a result of the collision, losing some momentum, while car 2 speeds up and gains some momentum. Because momentum is conserved, each car experiences the same change in momentum...but in opposite directions! So the total change in momentum to the system is zero: yes, momentum is conserved.

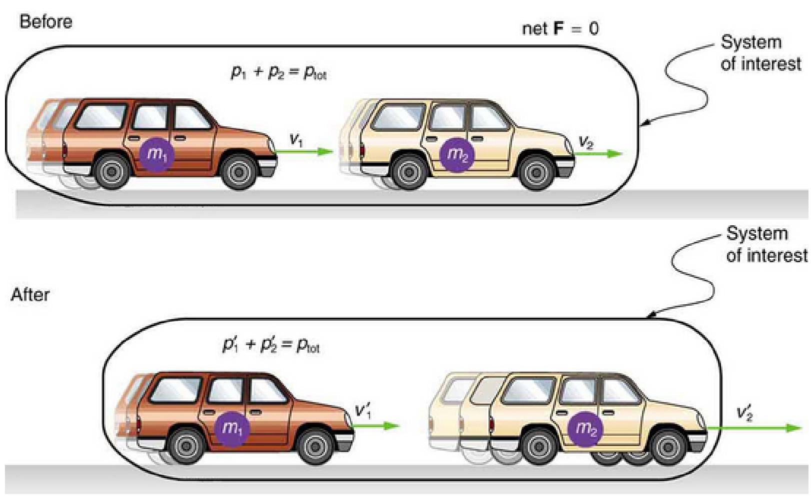

Figure 2: A car of mass m_1 moving with a velocity of v_1 bumps into another car of mass m_2 and velocity v_2 that it is following. As a result, the first car slows down to a velocity of v'_1 and the second speeds up to a velocity of v'_2. The

momentum of each car is changed, but the total momentum p_{tot} of the two cars is the same before and after the collision.

So, you might say, "momentum isn't conserved because the first car's momentum changed!" However, it was the total momentum of the system that remains unchanged. The repulsive force between the cars caused the momentum of the car in front to increase by exactly the same amount that the car in back lost. It would be the same for any other interacting body. For instance, have you ever seen a small child learn about momentum? They might reach out and try to stop an adult on a swing. The adult on the swing does lose momentum, but the child is surprised to find that they gain this same amount of momentum. So if you see something change momentum, you can be sure that it happened through a force interaction with another body, or bodies. And, you can be sure that the other body experienced an opposite change in momentum, ensuring that the total momentum of the system didn't change; it was conserved.

EXAMPLE 1

A fly smashes into your windshield as you are driving along. Between the car and the fly,

1. which one has the greater change in momentum, or are they the same?
2. Which one has the greater change in velocity, or are they the same?
3. Are both of your answers the same? If not, how can that be?

EXAMPLE 2

Say a car moving to the right hits a stationary truck and sticks to it. The truck is four times as massive as the car.

1. Does the car's momentum change? what is the direction of the change of momentum?
2. Does the truck's momentum change? What is the direction of the change of momentum?
3. What do you know about the magnitude (size) of the change of momenta of the car and truck?
4. Which has a greater change in speed, the car of the truck, or are they the same?
5. If the initial speed of the car is 20 mph, what is the final speed of the car and truck moving together immediately after the collision.

Conservation of Momentum Principle:

The total momentum of a system is constant. In other words, the initial total momentum before an interaction is equal to the final total momentum. **(1)**

1.2 Energy

Figure 3: How many forms of energy can you identify in this photograph of a wind farm in Iowa? Can you identify an energy transformation from one form of energy to another? (credit: Jürgen from Sandesneben, Germany, Wikimedia Commons)

You can likely name many forms of energy, including that provided by our foods and petroleum (chemical potential energy), to the energy our car gains as it speeds up (kinetic energy), to the sunlight (radiant energy) that warms us (thermal energy, same as microscopic kinetic energy). You can also cite examples of what people call energy that may not be scientific, such as someone having an energetic personality. Energy is another important quantity that is conserved: the total amount of energy in a system is constant. Energy can change forms, but it cannot appear from nothing or disappear without a trace. Your responsibility in reading this chapter is to become comfortable with the different kinds of energy and transitions. Part of this is to read and consider all three of the exercises.

Energy is one of the major building blocks of modern civilization. Energy resources are key limiting factors to economic growth. The world use of energy resources, especially oil, continues to grow, with ominous consequences economically, socially, politically, and environmentally.

We can loosely define **energy** as the ability to do work, admitting that we have yet to clearly define work. For now, we have to accept a circular definition in that work is done when energy flows from one body to another, sometimes changing form. For instance when a compressed spring beneath a toy rocket is released, the rocket is propelled into the air. The spring does *work* on the rocket as the *spring potential energy* is converted to *kinetic energy* of the rocket, which eventually turns to *gravitational potential energy* of the rocket as it gains height and slows down.

Kinetic and Potential Energy

There are two classes of energy worth distinguishing: kinetic energy and potential energy.

Kinetic energy is a form of energy associated with the speed of a body. Potential energy comes from stored energy and we can think of it as having the *potential* to do some work. For example, if you lift an object, your work provides gravitational potential energy to the object, related to the object's mass and its height off the ground. If you drop the mass or let the spring go, that *potential* can become kinetic energy.

Transformation of Energy

The transformation of energy from one form into others is happening all the time. The chemical energy in food is converted into kinetic energy and thermal energy through metabolism; light energy is converted into chemical energy of sugar through photosynthesis in plants. The chemical energy contained in coal is converted into thermal energy as it burns to turn water into steam in a boiler. This thermal energy in the steam in turn is converted to mechanical energy as it spins a turbine, which is connected to a generator to produce electrical energy.

Another example of energy conversion occurs in a solar cell. Sunlight impinging on a solar cell (see **Figure 4** (#import-auto-id1626980)) produces electricity, which in turn can be used to run an electric motor. Energy is converted from the primary source of solar energy into electrical energy and then into mechanical energy. Solar cells also get hot - some of the radiant energy is converted to heat. The solar cells also are only about 20% efficient at producing electricity, so the electrical energy they put out is only about 1/5 of the radiant energy absorbed by the sun. Because energy is *conserved*, all the radiant energy impinging on a solar cell is equal to the sum of the electrical energy and thermal energy produced.

Figure 4: Solar energy is converted into electrical energy by solar cells, which is used to run a motor in this solar-power aircraft. (credit: NASA)

Section Summary

- The law of conservation of energy states that the total energy remains constant through any process. Energy may change in form or be transferred from one system to another, but the total energy remains the same.
- Commonly encountered forms of energy include kinetic energy, thermal energy (or microscopic kinetic energy) and potential energy (including gravitational, spring, chemical, and nuclear).

Conceptual Questions

EXERCISE 1

Consider two identical solar panels next to each other in the sun. One is hooked to a motor that is doing work, while the wires o the other solar panel are not connected to anything. Which solar panel is warmer? Please explain your reasoning.

EXERCISE 2

Consider that you eat an "energy bar" and then ride your bike very fast and then slow down as you coast up a hill. Starting with the chemical potential energy in the energy bar, please identify the energy conversions in this process. Finishing with the energy bar, please identify the energy conversions that gave rise to that energy bar.

1.3 Dynamics

Dynamics is the study of the forces that can change momentum of an object or accelerate an object. To understand this, we need a working definition of force. Our intuitive definition of **force**—that is, a push or a pull—is a good place to start. For example, a cannon fires vertically upwards, exerting a strong force on a cannonball for an instant, launching the cannon ball upwards into the air. The earth exerts a smaller downward gravitational force on the cannonball. However, over a long period of time, this smaller downward force will slow the upward momentum of the cannon ball, bring the cannon ball to rest, and then increase the downward momentum of the cannon ball. The ball will continue to fall faster and faster, gaining more momentum from the force of gravity, and will stop in an instant again when it hits the ground. The ground changed the momentum of the ball very quickly by exerting a large upward force on the cannonball called a *normal force*.

Relationship #1: The amount of force put on an object is proportional to the resulting rate of change of the momentum.

$$F = \frac{\Delta p}{\Delta t}\ .$$

In this text the upper case Greek letter Δ (delta) always means "change in" whatever quantity follows it; thus, Δp means *change in mometum*. We know that momentum is always conserved, so if one body gets some momentum, another body must get the opposite momentum. Hence, a force is an *interaction between two bodies, whereby each gains equal momentum in opposite directions*. We see this all the time: if I push on you away from me, I get pushed away from you. When the cannon pushed the ball upward, the cannon was pushed downwards. We see this as the "kick back" of a gun or cannon.

It's important to note that force isn't *the same as* the rate of change of the momentum. The force is the push or pull on the body. However, the force acting on the body *produces* a rate of change of momentum as indicated above. This is an *empirical* law, meaning it is universally observed to be true.

It is also informative to say that forces make objects accelerate. Isaac Newton originally put it this way: What happens when you push something? It speeds up in the direction you pushed it. The longer you push it, the faster it gets. And, the more massive the object is, the more force you will need to produce the same effect. This leads us to our second definition of force.

Relationship #2: The force on a body produces acceleration such that the mass times the acceleration is equal to the applied force. Acceleration is how fast the velocity is changing.

$$F = ma$$

Relationship #3: A force also results in work being done on an object as it moves over a distance. So the amount of energy gained by an object per distance traveled is equal to the force exerted on it,

$$F = \frac{\Delta E}{\Delta x}\ .$$

Or force provides an *energy gradient* for a body.

The second relationship, $F = ma$ is the most common one quoted conventionally. However, we may find that the first relationship is more informative. When you put a force on something, its momentum changes, it accelerates, and it can gain (or lose) energy. The SI (standard) unit of force is the Newton (N) after Isaac Newton. And we can see from the rate of change of momentum that a Newton = $\text{kg}\ \frac{m}{s^2}$, or a kilogram meter per second squared.

Again, I stress that none of these relationships are definitions: Force is NOT the rate of change of momentum, mass times acceleration, nor the gradient of the energy. Force is how hard you are pushing or pulling on the object that results in these three things.

EXERCISE 1

Now we have a problem: a force changes momentum, but we just learned that momentum must be conserved. How can this be? It might be best to imagine yourself on a boat, and you push another boat away from you. Describe the forces and momentum changes to both you and the boat. How does the momentum of your body and the boat change? What do you know about the force on you and the force on the boat?

1.4 Kinematics

Kinematics: The study of motion without concern for the forces that cause the motion. Kinematics is the explicit study of position, velocity, acceleration as a function of time.

You're driving along the road. How fast are you going? Maybe you say 30 miles per hour. What does this mean? This is a rate... your position is changing at a rate of 30 miles every hour. So in two hours you would travel 60 miles and in 10 minutes your position would change by 5 miles. In this class, we'll use meters and seconds, so you'd express velocity in terms of meters per second. What is a meter per second? Can you walk at one meter per second? Please do that now. The fastest humans can run at a rate of 10 meters per second. At this rate, how long would it take someone to run the length of a soccer field, about 100 meters? Close your eyes and imagine seeing that happen. Does this seem reasonable?

EXERCISE 2

Please guess off the top of your head, how many miles per hour is 1 m/s. Then, please use your knowledge that a mile is about 1.6 km = 1,600 m, and there are 3600 s in an hour. Please use this to estimate the speed of 1 m/s in miles per hour. Please show work and cancel units.

EXERCISE 3

Sometimes I teach a rocket course to children at the San Luis Obispo MakerSpace. The kids make rockets out of paper. You use a bicycle pump to fill a small chamber at high pressure (~100 psi is the pressure in a bike tire). Then a lawn sprinkler valve is used to release the pressure through a small PVC tube, propelling the paper rockets really high. We take videos with our cell phones to calculate the rocket take-off velocity knowing that normal videos record at 30 frames per second. Please see below three consecutive frames from a rocket taking off. Please use these frames to estimate the speed of the rocket. I say, "estimate" because I don't give you a meter stick. However, I trust that you can find things in the picture that provide adequate scale for you to get a measurement within 10% uncertainty.

a. What is the take-off speed in m/s?

b. What is the take-off speed in mi/hr?

c. Does your calculated answer surprise you? Does it seem reasonable?

Figure 5: Three consecutive frames of a rocket launch at 30 frames per second. Red circle identifies rocket position

Getting used to terms

What we see is that $v = \frac{\Delta x}{\Delta t}$, or $v = \frac{dx}{dt}$, where

- v is **velocity**
- x is **position**
- t is time,

and the terms "Δ" and "d" represent "the difference in." Therefore, we see that velocity is the rate of change of position over time. Change in position, Δx, is also referred to as **displacement**, so velocity is also the "time rate of displacement."

Graphing

Because $v = \frac{dx}{dt}$, if you graph your position as a function of time, the rate of change of your position is the *slope* of the line.

EXERCISE 4

Please consider making a graph of yourself walking with constant velocity down an American football field next to the numbers indicating distance in yards. What would the graph of your position versus time look like as you walk at a constant speed? As you speed up? As you slow down to a stop and stay in the same place?

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