

to injury prevention. This complicates the quantitative analysis of our force-reducing strategies, however we recognize that lowering the peak force in turn lowers the average force so we will analyze force-reducing strategies in terms of the average force. We start with our definition for average acceleration:

$$a_{\text{ave}} = \frac{\Delta v}{\Delta t}$$

Then we can use Newton's Second Law to relate the average acceleration and average force:

$$\frac{F_{\text{ave}}}{m} = \frac{\Delta v}{\Delta t}$$



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Finally we can rearrange the result as needed to solve our problem. For example, if we want to know the time over which to extend an impact to keep the average force below a certain value, we could rearrange to get:

$$\Delta t = m \frac{\Delta v}{F_{\text{ave}}}$$

Of course we can always expand Δv if it helps us solve a problem:

$$\Delta t = m \frac{v_f - v_i}{F_{\text{ave}}}$$

Everyday Example: Key Drop

An everyday example in the previous unit helped us to determine that when a friend drops a set of keys to us from 35 ft up in their third story apartment, the keys will arrive at 47 ft/s, or 14 m/s, or 32 mph. We also mentioned that the keys smacking our hands at that speed would hurt, but that we would soon learn about strategies to prevent injury. We have arrived at that point. Now we know what to do: extend the time over which we bring the keys to rest and we will reduce the average (and peak) force applied to the keys. By Newton's Third Law, we know that the force on the keys is equal and opposite to the force on our hands, so analyzing the force on the keys tells us about the force on our hand. Let's get quantitative and approximate the impact time necessary to prevent damage to our hand. We will use the last equation from the text above, which we solved for Δt :

$$\Delta t = m \frac{v_f - v_i}{F_{\text{ave}}}$$

To use the above equation we first we need to estimate the force required for the key to break skin. If we placed a key on-edge on top

of our hand and someone stood on it, that would likely cause injury. If we instead placed a 5 **lb** textbook on the key it probably would not break the skin, so let's aim to keep the average force on the keys (and thus our hand) below 5 **lbs**, or 22 **N**. However, we know the peak force could be several times bigger than the average force (see the graph in the previous example), so let's include a safety factor of 10 and keep the force below 2.2 **N**. Now that we have a force value to work with, we just need a mass for the keys, which would be about 0.050 **kg** as you can see in this video of someone putting a car key on a scale. Now we can enter these values into our equation, being careful about our choice of directions. Let's say downward is the negative direction so our initial velocity is -14 **m/s** and the upward force on the keys from our hand is positive. Of course the final velocity of the key is zero after we catch them.

$$\Delta t = 0.05 \text{ kg} \frac{0 - (-14 \text{ m/s})}{2.2 \text{ N}} = 0.32 \text{ s}$$

We need to move our hands along with the keys as we catch them to ensure that our "soft catch" lasts for 0.32 **s** (about 1/3 of a second).

CHAPTER 73.

COLLISIONS

COLLISIONS

So far we have analyzed forces applied to the body by the earth during impact after a fall and during locomotion such as walking, jumping, and landing. These events are examples of collisions. In fact, any event that involves objects applying force on one another can be considered a collision. In each of these collisions we assumed the earth did not change velocity when it applied force to the body, even though we know from Newton's Third Law that earth felt a force back from the body. This was a reasonable assumption because the earth is so much larger than a human body, but ignoring the motion of the larger object in a collision is not always reasonable. For example, the following GIF shows a basic form of locomotion in which two objects push against one another and separate.

Animated GIF

Sitting in a wheeled chairs, Science Lab Technician Becky Kipperman (left) and Associate Chemistry Professor Sean Breslin (right) push against one another. This collision causes a leftward change in motion for Becky and a smaller rightward change in motion for Sean.

Notice that both objects experienced a noticeable change in velocity, but the velocity changes were not equal in size. In this example, the wheels minimize friction so that the net horizontal force on each person is just the force from the other person. Newton's Third Law tells us that these forces are equal in size, so why does one object experience a greater change in velocity, even though they have the same net force? Newton's Second Law provides the answer: given the same net force, a more massive object will experience a smaller acceleration.

$$(1) \quad \mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}$$

This effect becomes more apparent when the difference in mass between the objects is greater:



Sitting in a wheeled chairs, Science Lab Technician Becky Kipperman (left) and Associate Chemistry Professor Sean Breslin (right) push against one another while the author is attached to Sean in another chair, but not touching the floor. This collision causes a leftward change in motion for Becky and a much smaller rightward change in motion for Sean and the author. The objects experience equal and opposite changes in momentum though.

The combined mass of Sean and the author is more than 3x the mass of Becky, therefore they experience only $1/3$ the change in velocity. This mode of locomotion is really no different from you pushing against the ground when walking. When you push off the ground to walk forward you cause the Earth to move back in return. When you do a push-up, you actually push the Earth down just a little bit. Go you!

MOMENTUM

So far we have been ignoring the change in motion of the earth because the mass of the earth is so large that its change in motion is negligible. For example, when analyzing impact forces we assumed that the final

velocity of the body was zero after a collision with the earth and we used that final velocity to calculate acceleration and then net force. However, when objects of similar mass collide we have to keep track of all objects in the collision, which we call *the system*, because the final velocity of the objects in the system after the collision might not be zero. For example, in this video of a car accident we see that both cars are moving after the collision (they eventually come to rest due to friction, but we can analyze that separately from the collision forces).

To analyze how mass affects changes in velocity during a



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collision we use the combination of mass times velocity ($m\mathbf{v}$), which is known as the momentum ($\mathbf{p}$). Written in symbol form, the momentum is:

$$(2) \quad \mathbf{p} = m\mathbf{v}$$

CONSERVATION OF MOMENTUM

The Law of Conservation of Momentum states that the combined total momentum of all objects in a system must be the same immediately before and immediately after a collision:

$$(3) \quad \mathbf{p}_f = \mathbf{p}_i$$

If we have only two objects and their masses do not change during the collision we can write the Law of Conservation of Momentum as:

$$(4) \quad m_{1,i}\mathbf{v}_{1,i} + m_{2,i}\mathbf{v}_{2,i} = m_{1,f}\mathbf{v}_{1,f} + m_{2,f}\mathbf{v}_{2,f}$$

Everyday Example: Locomotion

When analyzing locomotion we have ignored the motion of the earth. Let's verify that to be a reasonable assumption. A person of about **65 kg** mass starts from rest and takes a step so they have a velocity of **1.2 m/s** at the end of the step. What is the resulting velocity of the earth? We only have two objects of constant mass (body and earth) so we will use the previous equation:

$$m_{1,i}\mathbf{v}_{1,i} + m_{2,i}\mathbf{v}_{2,i} = m_{1,f}\mathbf{v}_{1,f} + m_{2,f}\mathbf{v}_{2,f}$$

The initial velocity of both objects is zero, (so their initial momenta are also zero):

$$0 + 0 = m_{1,f}\mathbf{v}_{1,f} + m_{2,f}\mathbf{v}_{2,f}$$

Now we subtract the initial momentum of the person (object #2) to the left side:

$$-m_{1,f}\mathbf{v}_{1,f} = m_{2,f}\mathbf{v}_{2,f}$$

Finally we divide by the mass of the earth to isolate the final velocity of the earth:

$$\frac{-m_{1,f}\mathbf{v}_{1,f}}{m_{2,f}} = \mathbf{v}_{2,f}$$

And switching sides to have the final earth velocity on the left we are ready to enter numbers. We just need to look up the mass of the earth:

$$\mathbf{v}_{2,f} = \frac{-m_{1,f}\mathbf{v}_{1,f}}{m_{2,f}}$$

The mass of the earth is $5.6 \times 10^{24} \text{ kg}$ so we have:

$$\mathbf{v}_{2,f} = \frac{(-65 \text{ kg})(1.2 \text{ m/s})}{5.6 \times 10^{24} \text{ kg}} = 1.4 \times 10^{-23}$$

That's a final earth velocity of 14 with 22 zeros in front of it, or about the width of an atom per million years. I think we were justified in neglecting the earth velocity in our analysis so far.

Reinforcement Exercises: Locomotion

An astronaut becomes detached from the space station during a "space walk." In order to get back, she tosses a 12 kg bag of tools away from the station at 5 m/s/s. At what speed will she move toward the station if her total mass including suit and equipment is 120 kg?

Everyday Examples: Collisions

Let's analyze the car accident in the previous video. The initial momentum of the stopped car (car #1) was zero: $\mathbf{p}_{1,i} = 0$. The momentum of the jeep (car #2) was: $\mathbf{p}_{2,i} = m_2 \mathbf{v}_{2,i}$. Therefore the total initial momentum was

$$\mathbf{p}_i = 0 + m_2 \mathbf{v}_{2,i}$$

The cars lock together immediately after the collision and only separate later so they have the same final velocity immediately after the collision, we'll call it v_f . Sticky collisions like this are known as perfectly inelastic collisions, and for such collisions we can treat the objects moving together as a single object that has their combined total mass. The final momentum is then:

$$\mathbf{p}_f = (m_2 + m_1) \mathbf{v}_f$$

Conserving momentum during the collision tells us to set the initial and final momenta equal:

$$m_2 \mathbf{v}_{2,i} = (m_2 + m_1) \mathbf{v}_f$$

If we want to solve this perfectly inelastic collision equation for the final velocity we divide by the combined mass:

$$\mathbf{v}_f = \frac{m_2 \mathbf{v}_{2,i}}{m_2 + m_1}$$

We can look up some data on the cars and find that the length of the Jeep is 3.8 m, the mass of the jeep is about 1500 kg and a small sports car mass is about 1000 kg.¹² Now let's estimate some numbers from the video (a quick method is to use the slo-mo feature on a smartphone to film the video as it plays with a running stopwatch also visible in the frame). We see that before the collision the Jeep

1. "2016 Mazda MX-5 Curb Weight Released: Guess How Many Previous Miatas Are Heavier" by ALEXANDER STOKLOSA, Car and Driver

2. "Jeep Wrangler (TJ)" by Wikipedia

covers at least two of its own lengths in about 0.4 s so calling its direction the positive, its initial velocity will be:

$$v_{2,i} = \frac{2 \times 3.8 \text{ m}}{0.4 \text{ s} = 19 \text{ m/s}} = 42 \text{ MPH}$$

We are ready to calculate the final velocity of the jeep-car combination:

$$v_f = \frac{1500 \text{ kg} \times 19 \text{ m/s}}{1500 \text{ kg} + 1000 \text{ kg}} = 12 \text{ m/s} = 27 \text{ MPH}$$

This is an interesting result, but what's really cool is that if we estimate the collision interval we can calculate the average force applied to each car. From the video the collision time appears to be about 0.5 s. Let's do the Jeep first.

We start from Newton's Second Law:

$$(5) \quad F_{\text{ave}} = ma =$$

Then write out the acceleration as change in velocity over change in time:

$$(6) \quad F_{\text{ave}} = \frac{m(v_f - v_i)}{\Delta t}$$

We have the final velocity of 12 m/s from our previous work using momentum conservation, so we can enter all our values:

(7)

$$F_{\text{ave}} = \frac{m(v_f - v_i)}{\Delta t} = \frac{1500 \text{ kg}(12 \text{ m/s} - 19 \text{ m/s})}{0.5 \text{ s}} = -23,000 \text{ N}$$

The force on the jeep should be in the negative, just as we found, because we originally chose backward as the negative direction. We know from Newton's Third Law that the -23,000 N force on the Jeep from the car is paired with a 23,000 N force felt by the car from

the Jeep. That's over 5,000 **lbs** of average force on each vehicle, the peak force would be much greater.

Reinforcement Exercise

A 48 **kg** soccer player running 5 **m/s** and watching the ball in the air collides with another player of mass 68 **kg** running at 2 **m/s** in the opposite direction and they tangle together before falling. What is the velocity of the pair immediately after the collision, before hitting the ground?

If this collision lasts 0.3 s, what is the force on each player?

CHAPTER 74.

EXPLOSIONS, JETS, AND ROCKETS

EXPLOSIONS

We have found that locomotion can be achieved by collisions consisting of objects in contact being forced apart, similar to the way that pieces of an object separate during an explosion. Explosions must also obey the Law of Momentum conservation. If an object starts at rest, then when we add up the momentum of every piece of the object after the explosion we must end up with zero, just as in the previous examples of collisions with only two “pieces”. Watching an explosion in reverse helps to illustrate this point:

After the explosion of the watermelon the total momentum must be zero because it was zero before the explosion. The momentum of pieces moving in any one direction must cancel out the momentum of pieces moving in the opposite direction. Therefore, we see no particular direction that has noticeably more pieces, larger pieces, or faster moving pieces. The explosion is symmetric. (The table does redirect some pieces upward, so the explosion might not appear completely symmetric in the vertical direction.)

If we really pay attention to the watermelon explosion we can see that no pieces move downward because the table redirects them. If we were to actually add up all the momenta of all the pieces we would find that the watermelon system had a net upward momentum. There was an *external* force acting on the system of watermelon pieces and therefore the momentum of the watermelon system was not conserved in this explosion. If we include the table and the earth it's attached to in our system, then the forces between the watermelon pieces and the table are *internal* to our system and we would find that the momentum of that system was conserved. This idea is summarized by the Principle of Momentum Conservation, which states that *whenever the net external force on a system is zero, the momentum of the system will not change*. The Law of Conservation of Momentum is very similar and sort of tells us how to test the principle: *If you include all of the objects involved in a collision, so that there are no external forces from objects outside the system, and you add up the momenta of all those objects before and then again after a collision you will get the same value*.

IMPULSE

When the net external force on a system is not zero, such as for the watermelon, then the momentum will change and the Impulse-Momentum Theorem tells us how:

$$(1) \quad \mathbf{p}_f - \mathbf{p}_i = \Delta t \mathbf{F}_{\text{ave}}$$

We can see that the change in momentum is calculated as initial subtracted from final, similar to changes in velocity, position, time, or any other quantity. The right side of the equation, average force multiplied by the collision time, is known as the impulse (I). The force and resulting impulse on the watermelon system from the

table were upward, therefore the momentum of the watermelon system changed from zero to upward.

JET PROPULSION

The flyboard in the previous video operates with an externally located pump that shoots water up the hose to the board which re-directs it downward. The momentum of the water was not conserved when it collided with the board, therefore it must have felt an impulse, a.k.a a net force for some amount of time. Newton's Third Law tells us that the board must have felt an equal and opposite



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force back during that time, and that force balances the weight of the board and rider.

Everyday Examples

Let's estimate the mass flow rate (mass of water expelled per time) required just to hold up the board and a person. This video is helpful.

The board mass of the board and rider is **93 kg**, so multiplying by **g** (**9.8 m/s/s**) we get a weight of **911 N**. The board must apply **911 N** of downward force on the water in order to receive that same size upward force. The impulse on the water resulting from the



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downward force will change its momentum according to the impulse-momentum theorem:

$$\mathbf{p}_f - \mathbf{p}_i = \Delta t \mathbf{F}_{\text{ave}}$$

Assuming the water moves up the hose, bounces off the board, and exits at the same speed it entered, then the initial water momentum is just the opposite (negative) of the final momentum:

$$\mathbf{p}_f - (-\mathbf{p}_f) = \Delta t \mathbf{F}_{\text{ave}}$$

The double negative on the left becomes an addition:

$$2\mathbf{p}_f = \Delta t \mathbf{F}_{\text{ave}}$$

We don't have a specific mass of water having a specific collision because the process appears continuous, but we could think image many tiny chunks of water colliding, (even to the point of individual water molecules). We can write the final momentum of each water chunk in terms of its mass and final velocity:

$$2m\mathbf{v}_f = \Delta t \mathbf{F}_{\text{ave}}$$

Now if we divide each side by two and by the final velocity we can isolate the mass:

$$m = \frac{\Delta t \mathbf{F}_{\text{ave}}}{2\mathbf{v}_f}$$

We don't know the Δt for each collision, but we don't need to. Dividing by the time interval will give us the water mass that collides per time interval, which is exactly what we want:

$$\frac{m}{\Delta t} = \frac{\mathbf{F}_{\text{ave}}}{2\mathbf{v}_f}$$

Running the video in slow motion I made a very rough estimate of the water exit velocity and found 16 m/s downward. We already know the force on the water needs to be 911 N downward, so we can enter those values:

$$\frac{m}{\Delta t} = \frac{(911 \text{ N})}{2(16 \text{ m/s})} = 30 \text{ kg/s}$$

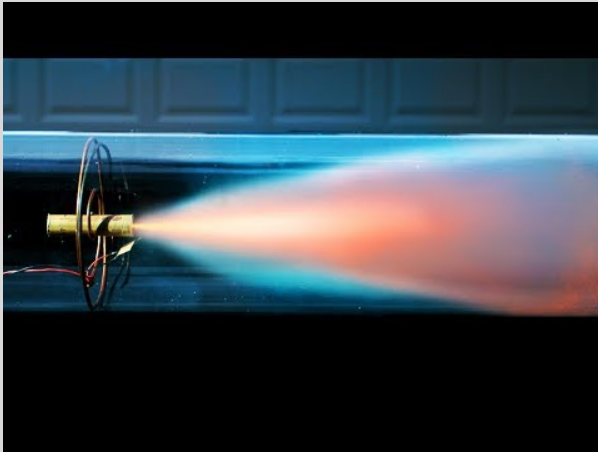
The board must redirect 30 **kg** of water each second in order to hold the rider. Water has a density of 1 Liter per **kg**, so 30 liters of water pass through the system each second. You may have noticed that “bouncing the water off the board, instead of just shooting it out like a rocket, reduced the flow rate by half. This is because this “bounce” doubled the impulse on the water (and back on the board). We will talk more about bouncy collisions in the next chapter.

ROCKET LOCOMOTION

Some machines actually use real chemical explosions for locomotion. For example, rocket fuel burns to produce hot, rapidly expanding gas which shoots out of the rocket backward, providing an impulse on the rocket. The force associated with that impulse is known as *thrust*. The analysis we used for the fly board doesn’t really work for the rocket because the mass of the rocket changes as it burns fuel, but that analysis is very interesting and you should ask your instructor about it.



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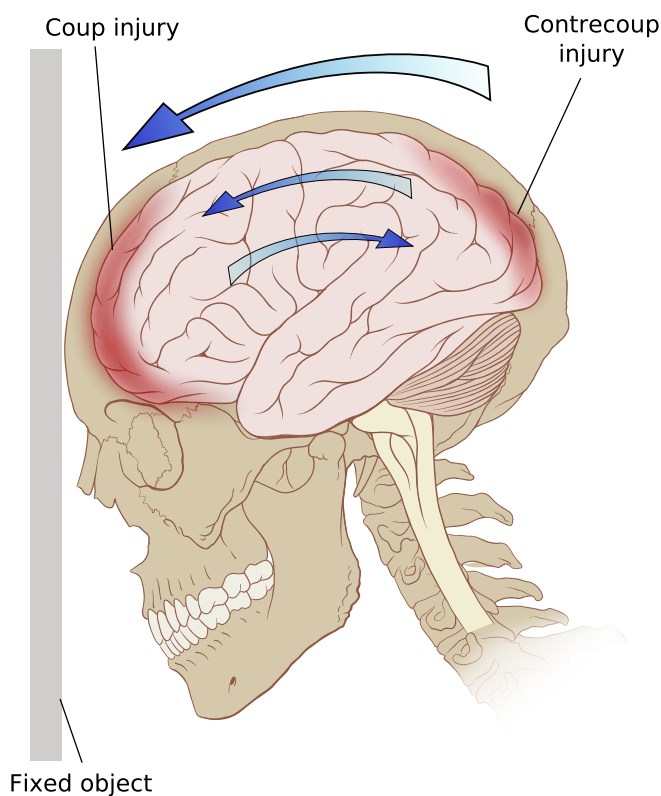
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CHAPTER 75.

SAFETY TECHNOLOGY

BOUNCE IS BAD

If the skull impacts a hard surface, but neither the skull or surface are significantly deformed, then the skull will bounce back. This type of collision is not perfectly inelastic because the skull did not stick to the surface. In this case the relative impact speed between the still-forward moving brain and the backward moving skull is nearly twice what it would have been if the skull had simply stopped.



The alternating accelerations of the skull and the inertia of the brain combine to cause impacts on opposing sides of the brain during a coup contrecoup injury.

Image credit: Contrecoup by Patrick J. Lynch, medical illustrator via Wikimedia Commons

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After the bounce, as the neck causes the skull to slow

1. Contrecoup by Patrick J. Lynch, medical illustrator [CC BY 2.5 (<https://creativecommons.org/licenses/by/2.5>), GFDL (<http://www.gnu.org/copyleft/fdl.html>) or CC-BY-SA-3.0 (<http://creativecommons.org/licenses/by-sa/3.0/>)], via Wikimedia Commons

down on the way backward, the inertia of the brain may lead to a second impact on the back of the brain, as illustrated in the previous image. Aside from an additional brain tissue injury, the combined swelling of the two opposed injuries will put amplify the pressure on the brain and increase the likelihood of permanent injury. This type of injury is known as a *Coup Countrecoup* , or translated from French by Google Translate, *blow, counter blow*.

AIR BAGS

Everyday Example: Airbags

Check out this video of crash-testing with and without airbags.

<https://youtu.be/NACA1W2A5Wk>

During the crash the driver's head starts out with the same velocity as the car. The airbag increases the time it takes for the head to come to rest, which will decrease the force on the head. In order make sure the head does actually come to rest instead of bouncing the airbag has vents that allow air to be pushed out during impact so it deflates instead of staying completely full and keeping its shape.

The impulse-momentum theorem introduced in the previous chapter will help us to analyze technology designed to minimize the forces on your the body:

$$(1) \quad \mathbf{p}_f - \mathbf{p}_i = \Delta t \mathbf{F}_{\text{ave}}$$

If we divide over the time, we see that there are two options for reducing the force on the body during a collision; you can maximize collision time, or minimize the change in momentum, or both:

$$(2) \quad \frac{p_f - p_i}{\Delta t} = F_{\text{ave}}$$

Our analysis of locomotion, falling, and landing has already taught us that increasing the collision time will reduce the force during a collision. How do we minimize the change in momentum you experience during a collision? Prevent the bounce! Let's examine why the bounce is bad using an the airbag example. First we write the momentum of the head in terms of its mass and velocity.

$$(3) \quad \frac{m\mathbf{v}_f - m\mathbf{v}_i}{\Delta t} = \mathbf{F}_{\text{ave}}$$

If the collision is perfectly inelastic so the head does not bounce at all, then final velocity is zero:

$$(4) \quad -m\mathbf{v}_i \Delta t = \mathbf{F}_{\text{ave}}$$

We see that the force on the head depends on the head mass, the initial velocity, and the collision time.

If instead the head bounces back at the same speed it went in (image the airbag was a rubber ball), then the final velocity is just equal and opposite (negative) the initial velocity:

$$(5) \quad \frac{m(-\mathbf{v}_i) - m\mathbf{v}_i}{\Delta t} = \mathbf{F}_{\text{ave}}$$

The left side can be combined:

$$(6) \quad \frac{-2m\mathbf{v}_i}{\Delta t} = \mathbf{F}_{\text{ave}}$$

That is twice the force compared to when the head just came to rest! If the head were to bounce back, but not at full speed, then the force would still be greater than the perfectly inelastic case, but not twice as great.

Reinforcement Exercises

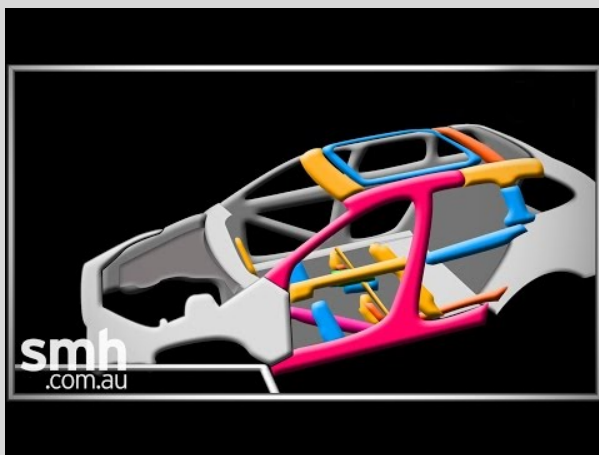
If we were to surround our cars with rubber we could avoid having to make repairs after a minor collision, they would just bounce back into shape. Explain why we don't do that.

CHAPTER 76.

CRUMPLE ZONES

KINETIC ENERGY

Crumple zones built into modern cars also serve the purpose of reducing force by increasing the collision time and minimizing bounce. Crumple zones cause cars to be totaled more often, but cars can be replaced and people can't be. Notice that the presenter in the previous video isn't talking about impulse or momentum, but he does keep mentioning absorbing energy. This energy that he is claiming will be absorbed by the crumple zone is the energy stored in the motion of the car. Any moving object has this type of energy, known as kinetic energy (KE). The



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amount of kinetic energy an object has depends on its mass and its speed:

$$(1) \quad KE = \frac{1}{2}mv^2$$

Notice that the kinetic energy depends on speed, but not velocity because KE doesn't have a direction (an object can't have negative KE). Even if we input a negative velocity into the KE equation, it gets squared so KE would come out positive anyway. The SI unit of kinetic energy is a **Nm**, which has its own name, the Joule (J).

Reinforcement Activity

What is the kinetic energy of a person with 65 kg mass running with a speed of 10 m/s?

What is the kinetic energy of a meteorite with 100x less mass than the person above, but entering the atmosphere at 100x greater speed (0.65 kg and 1000 m/s)?

Which is larger, the KE of the runner or the meteorite?

What matters more in determining kinetic energy, mass or speed?

ELASTIC POTENTIAL ENERGY

During the collision the car materials were compressed by the wall. If the stress remained below the yield points of the materials, so they were remained in the elastic region, then the kinetic energy from the car would have been transferred into elastic potential energy stored in the compression of the materials. This stored energy has the potential to become kinetic energy, which is exactly what would happen when the materials then

spring back causing the car to “bounce” back from the wall.

Reinforcement Exercise

Grab a paperclip. Bend it just enough so that it springs back when released. You applied a force over a distance to bend the clip, therefore you did work and transferred potential energy into the paperclip.

When you release the paperclip, what happens to that potential energy?

If the car had bounced back at the same speed that it had entering the collision, then the final kinetic energy would be the same as the initial, and we would say that kinetic energy had been conserved. Collisions that conserve kinetic energy are known as elastic collision. Collisions that don't are known as inelastic. In the previous chapter we learned that bounce was bad when it comes to minimizing the force on the body during a collision. The purpose of crumple zones is to ensure that very little of the kinetic energy remains after the collision by making them very inelastic. The key to accomplishing that is to ensure that kinetic energy is transferred into thermal energy instead of elastic potential energy by designing the materials to break instead of bounce.

Reinforcement Exercises

Try the springy paperclip experiment again. Did the paperclip

continue to oscillate between being in motion and being bent so that it was transferring energy back and forth from kinetic to potential forever?

Is the bending paperclip a totally elastic process?

THERMAL ENERGY

If you watch the video carefully, you see that the car was moving forward, then for a moment it was stopped and thus had zero kinetic energy, and then it was moving backward (though not as fast), so once again it had kinetic energy. Some of the original kinetic energy was stored as elastic potential energy and then released as kinetic energy again, but most of it was not. If you are wondering where that energy went, then you are very perceptive, because in fact the Principle of Conservation of Energy tells us that *energy cannot be created or destroyed, only transferred from one form to another and/or one object to another, via work.*

The force applied to the materials during the collision caused a stress on the materials. Some materials were stressed above their ultimate strength so they fractured. Some other materials didn't fracture, but were stressed beyond their elastic limit and into their plastic region so that they were permanently deformed. In either case, the work done to deform the materials transferred kinetic energy into thermal energy, effectively slowing the car down, but warming it up. Crumple zones are designed to deform permanently in order to convert kinetic energy into thermal energy.

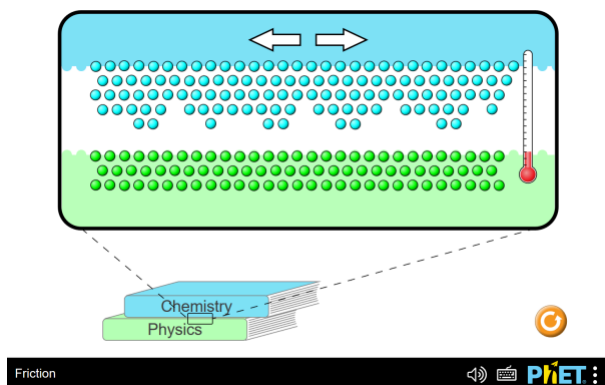
Reinforcement Exercises

Grab a paperclip and bend it rapidly back and forth, being sure to bend it past its elastic limit each time (far enough that it won't spring back to its original position on its own). Now touch the crease. You might notice that the paperclip feels warm. This is because you have done work on the paperclip to cause the plastic deformation, which requires reconfiguration of molecules, and that reconfiguration gave them more microscopic kinetic energy, or thermal energy.

Doing work implies a transfer of energy, where do you think the thermal energy received by the paper clip was transferred from?

MICROSCOPIC KINETIC ENERGY

Now that we have introduced thermal energy as a new type of energy, we will reverse course and say that thermal energy is not actually a new type of energy, but rather just kinetic energy on a microscopic scale. Thermal energy is the energy stored in the motion of atoms and molecules that make up a material. Transferring thermal energy to a system really just means that you caused its atoms and molecules to move faster. The work done in compressing objects past their elastic limit and the work done by kinetic friction will always transfer some energy into thermal energy. You can visualize this microscopic process for kinetic friction using the simulation below.



COEFFICIENT OF RESTITUTION

The relative elasticity of collisions is defined by the coefficient of restitution (COR) which relates the final kinetic energy and the initial kinetic energy. For a moving object striking a stationary object that doesn't move, as in the crumple zone video, the COR is calculated as final speed divided by initial speed.

$$(2) \quad COR = \sqrt{\frac{KE_f}{KE_i}} = \sqrt{\frac{1/2mv_f^2}{1/2mv_i^2}} = \frac{\text{final speed}}{\text{initial speed}}$$

A perfectly elastic collision would have a COR of one. If any materials are permanently deformed during a collision then you can be sure the collision was not perfectly elastic. In fact, perfectly elastic collisions don't really occur, but many situations come very close and we can approximate them as perfectly elastic.

Check out this simulation that allows you to visualize different types of collisions.

An interactive or media element has been excluded from this version of the text. You can view it online here:
<https://openoregon.pressbooks.pub/bodyphysics/?p=1060>

CHAPTER 77.

UNIT 8 REVIEW

Key Terms and Concepts

Inertia

Locomotion

Newton's Second Law

Newton's Third Law

Perfectly Inelastic Collision

Law of Conservation of Momentum

Impulse-Momentum Theorem

Kinetic Energy

Elastic Potential Energy

Thermal Energy

Learning Objectives

1. Describe how locomotion occurs in terms of Newton's Laws of Motion.[2]
2. Apply Newton's Second and Third Laws of motion to analyze the motion of objects.[3]
3. Apply the Law of Conservation of Momentum to analyze the motion of objects.[3]
4. Evaluate and explain strategies for reducing the forces experienced by objects undergoing collisions.[2]

CHAPTER 78.

UNIT 8 PRACTICE AND ASSESSMENT

Outcome 1

1) An asteroid speeds through space, distant enough from anything else to be essentially unaffected by gravity. Will the asteroid slow down because it has no power system to provide a force on it? Explain?

2) Does your car slow down when you take your foot off the gas? Compare and contrast this situation to the previous one involving the asteroid and *explain* the similarities or differences in the outcome.

Outcome 4

2) Imagine you are being chased by a horde of zombies across the frozen wasteland of a post-apocalyptic Northwest United States. You attempt to lose the zombies by running across a frozen pond, but slip and fall. Provide some strategies for landing that will minimize the likelihood that you break through the ice. Be specific about how you will move your body and explain your strategy using the in terms of Newton's Laws of Motion or the impulse-momentum theorem, elastic and inelastic

collisions, the relation between force and stress, and the definition of ultimate strength.

Outcome 2

3) You avoid breaking through the ice and get back to your feet, but the lead zombie is now only 1.5 **m** away and moving at 3 **m/s**....

a) How long do you have until the zombie reaches you?

b) You are trying to start running again, and you lift one foot while you push off horizontally with the other foot. What is the normal force the ice must supply to your foot in order to hold you up?

c) Calculate the maximum possible force your foot can apply to the ice horizontally without slipping. Cite your source for the necessary friction coefficient between ice and shoes.

d) If you take 3 steps, with each step putting your foot in contact with the ice for 0.30 **s** and apply the force you found above, what is the total impulse you apply to the ice?

e) What is the total impulse you received from the ice? How do you know?

f) How fast will you be moving after these three steps? [Hint: Use your previous answer and the definition of momentum].

Outcome 3

4) As you near the edge of the pond moving at 4.0 **m/s** on the ice and a zombie is behind you moving at 3.0 **m/s** when a helpful survivor like yourself throws you something to defend yourself with. It has a 11 **kg** mass

and a pretty much horizontal velocity of 5.0 m/s in the direction opposite to your motion when it reaches you.

a) If you were to catch the weapon, what would your new speed be after catching it? Use your own mass in answering the question. Don't forget to include the initial momentum of both objects in your analysis and be careful about directions.

b) Should you catch the weapon? (Would you still be moving faster than the 3.0 m/s zombie after catching it?)

PART IX.

UNIT 9: POWERING THE BODY

Learner Outcomes

1. Define, recognize, and differentiate work, kinetic energy, and potential energy, including elastic, gravitational, and chemical.[2]
2. Apply the Law of Conservation of Energy and The First Law of Thermodynamics to the analysis of physical processes.[3]
3. Determine the efficiency of physical processes and machines.[3]
4. Evaluate the power output of machines.[3]

CHAPTER 79.

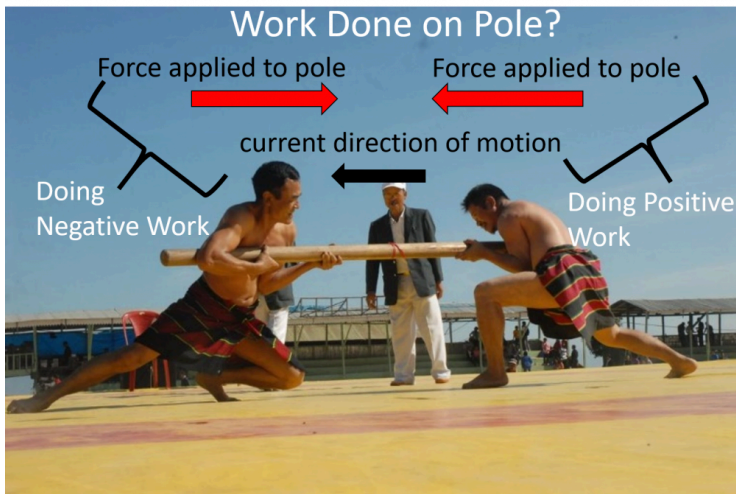
DOING WORK

We started the previous unit with a discussion of Jolene's motion during a shift on the medical floor of a hospital, including all the starts and stops that she makes. When Jolene is standing still she has zero kinetic energy. As she takes a step to begin walking she now has kinetic energy. Jolene had to supply that energy from within herself. When Jolene comes to a stop her kinetic energy is transferred to thermal energy by friction. When she begins walking again she will need to supply the new kinetic energy all over again. Even if Jolene walks continuously, every step she takes involves two inelastic collisions (the push-off and the landing) so kinetic energy is constantly being transferred to thermal energy. To stay in motion Jolene has to re-supply that kinetic energy. Walking around all shift uses up Jolene's stored energy and that is why she gets tired.

WORK

The amount of energy transferred from one form to another and/or one object to another is called the work. *Doing work* is the act of transferring that energy. Doing

work requires applying a force over some distance. The sign of the work done *on* an object determines if energy is transferred *in* or *out* of the object. For example, the athlete on the right is doing positive work on the pole because he is applying a force in the same direction as the pole's motion. That will tend to speed up the pole and increase the kinetic energy of the pole. The athlete on the left is doing negative work on the pole because the force he applies tends to decrease the energy of the pole.



Insuknawr, or Rod Pushing Sport is an indigenous game of Mizoram, one of the North Eastern States of India. A force applied in the same direction as an objects motion does positive work. A force applied in the opposite direction to motion does negative work. Image adapted from Insuknawr (Rod Pushing Sport by H. Thangchungnunga via Wikimedia Commons

The positive or negative sign of the work refers to energy transferring in or out of an object rather than to opposite directions in space so work is not a vector and we will not make it bold in equations.

CALCULATING WORK

The actual amount of work done is calculated from a combination of the average force and the distance over which it is applied, and the angle between the two:

$$(1) \quad W = Fd\cos\theta$$

Everyday Example: Lifting a Patient

Jolene works with two other nurses to lift a patient that weighs 867 N (190 lbs) a distance of 0.5 m straight up. How much work did she do? Assuming Jolene lifted 1/3 of the patient weight, she had to supply an upward force of 289 N. The patient also moved upward, so the angle between force and motion was 0°. Entering these values in the work equation:

$$W = Fd\cos\theta = 289 \text{ N})(0.5 \text{ m})\cos(0^\circ) = 144 \text{ Nm}$$

We see that work has units of Nm, which are called a Joules (J). Work and all other forms of energy have the same units because work is an amount of energy, but work is not a type of energy. When calculating work the *cos θ* accounts for the force direction so we only use the size of the force (*F*) in the equation, which is why we have not made force bold in the work equation.

The *cos θ* in the work equation automatically tells us

1. Adapted from Insuknawr (Rod Pushing Sport by H. Thangchungnunga [CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0>) or GFDL (<http://www.gnu.org/copyleft/fdl.html>)], from Wikimedia Commons

whether the work is transferring energy into or out of a particular object:

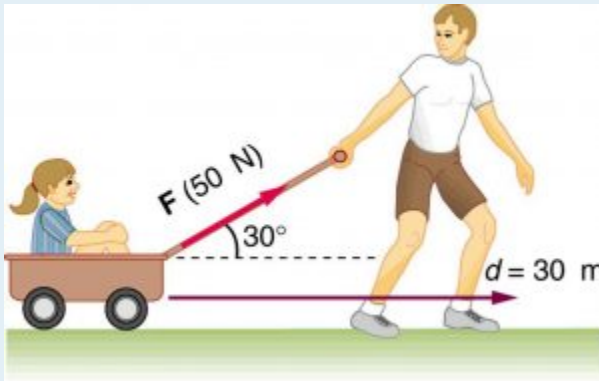
1. A force applied to an object in the opposite direction to its motion will tend to slow it down, and thus would transfer kinetic energy out of the object. With energy leaving the object, the work done on the object should be negative. The angle between the object's motion and the force in such a case is 180° and $\cos(180^\circ) = -1$, so that checks out.
2. A force applied to an object in the same direction to its motion will tend to cause it to speed up, and thus would transfer kinetic energy in to the object. With energy entering the object, the work done on the object should be positive. The angle between the object's motion and the force in such a case is 0° and $\cos(0^\circ) = 1$ so that also checks out.
3. Finally, if a force acts perpendicular to an objects motion it can only change its direction of motion, but won't cause it to speed up or slow down, so the kinetic energy doesn't change. That type of force should do zero work. The angle between the object's motion and the force in such a case is 90° and $\cos(90^\circ) = 0$ so once again, the $\cos\theta$ in the work equation gives the required result. For more on this particular type of situation read the chapter on weightlessness at the end of this unit.

The work equation gives the correct work done by a force, no matter the angle between the direction of force and the direction of motion, even if the force points off at some angle other than 0° , 90° , or 180° . In such a case, some part of the force will be doing work and some part won't,

but the $\cos\theta$ tells us just how much of the force vector is contributing to work.

Reinforcement Exercises

How much work is done by the larger child pulling the smaller one for a distance of 30.0 m in a wagon as shown?



A child pulls another in a wagon, exerting a force at an angle relative to the direction of motion. "This work" by BC Open Textbooks

CHAPTER 80.

JUMPING

WORK-ENERGY PRINCIPLE

How do we calculate the total work when more than one force acts on an object as it moves, so that each force is doing work? What if the forces point in opposite directions so one does positive work and the other does negative work? In this case we calculate the net work done by each force and add them up (keeping negative works as negative) to get the net work. Alternatively, add up the forces, including directions, to find the size and direction of the net force and then multiply by the distance over which the net force is applied to get the net work. Either way will give you the same answer, which will be the net work. The net work tells us how much energy is transferred into or out of the kinetic energy, causing a change in kinetic energy (ΔKE). Everything we have discussed so far can be summed up by the work-energy principle: *The change in kinetic energy of a system is equal to the net work on the system*, or written as an equation:

$$(1) \quad W_{net} = \Delta KE$$

Alternatively,

$$(2) \quad W_{net} = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

or even more explicitly:

$$(3) \quad F_{net,ave}d\cos\theta = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

Everyday Examples: Jumping

During a jump a person's legs might apply a force of 1200 N upward on their center of mass while the center of mass moves 0.3 m upward. Let's figure out what their launch velocity and hang-time will be if the person has a weight of 825 N.

First we calculate the work done by their legs.

$$W_L = (1200 \text{ N})(0.3 \text{ m})\cos(0^\circ) = 360 \text{ J}$$

Gravity was acting on them during the launch phase as well, so we need to calculate the work done by gravity, which acts in the opposite direction to motion ($\theta = 180^\circ$):

$$W_g = (825 \text{ N})(0.3 \text{ m})\cos(180^\circ) = -247.5 \text{ J}$$

Adding up the works to get the net work:

$$W_{net} = -247.5 \text{ J} + 360 \text{ J} = 112.5 \text{ J}$$

The work-energy principle tells us to set the change in kinetic energy equal to the net work. We will keep in mind that they started at rest, so the initial kinetic energy was zero.

$$112.5 \text{ J} = \frac{1}{2}mv_f^2 - 0$$

We isolate the final velocity at the end of the launch phase (as the person leaves the ground)

$$\frac{2(112.5 \text{ J})}{m} = v_f^2$$

We can see that we need the person's mass. We just need to divide their weight by $g = 9.8 \text{ m/s}^2$ to find it:

$$m = \frac{825 \text{ N}}{9.8 \text{ m/s}^2} = 84.2 \text{ kg}$$

We insert the mass:

$$\frac{2(112.5 \text{ J})}{84.2 \text{ kg}} = v_f^2$$

Finally we take the square root of the result to find the final velocity:

$$v_f = \sqrt{\frac{2(112.5 \text{ J})}{84.2 \text{ kg}}} = 1.6 \text{ m/s}$$

Reinforcement Exercises

When the person in the previous example reaches peak height their instantaneous velocity will be instantaneously zero just as they change direction, so their kinetic energy is also zero at this point.

What was the change in kinetic energy of the person from launch to peak of their jump?

While in the air, the only force acting on them was gravity. The work done by gravity must have caused the change in kinetic energy you found above. That work was done by gravity applied over the distance that they rose through the air. Apply the work-energy principle to the in-air section of the jump to determine the peak height of their jump. [Hint: You already know the size of the force of gravity, it's their weight of 825 N]

CHAPTER 81.

SURVIVING A FALL

MECHANICAL ENERGY

When you do work to lift an object and then release it, the energy converts back to kinetic energy as the object falls. This process appears similar to the storage and release of elastic potential energy that we learned about in the previous unit and suggests that we define a gravitational potential energy (PE_g). It's not obvious where gravitational potential energy is stored, but for our purposes can treat it as being stored within the system comprised of the Earth and an object that has been raised. The elastic potential energy, gravitational potential energy and kinetic energy are forms of mechanical energy. Forces and corresponding work that convert energy between forms of mechanical energy within a system are known as conservative forces and conservative work. We introduce these new terms because there are many cases when only conservative forces are acting and so energy just transfers between the forms of mechanical energy within the system. For such cases, any increase in potential energy is offset by a decrease in kinetic energy and *vice versa*, so we know

$\Delta PE + \Delta KE = 0$. Non-conservative forces do work that converts between mechanical energy, thermal energy, or chemical potential energy (we will learn more about chemical potential energy soon). Friction, drag force, air resistance, forces caused by muscular contractions, and forces resulting in permanent deformation are examples of non-conservative forces.

Reinforcement Exercises

Calculate the work you must do to raise 10 kg metal ball by a height of 10 m.

Work is a transfer of energy, in this case chemical potential energy in your body was transferred to what type of energy?

Was this a conservative work?

If you then dropped the ball, what kinetic energy would the object have just as it reached the ground (ignoring any work done by air resistance so that only gravity acts on the ball)? [Hint: Are there any non-conservative forces acting during the fall?]

What would be the speed of the ball immediately before impact with the ground?

Check out this simulation, which shows how energy is transferred among different types.

must be the same the amount that we have changed the gravitational potential energy.

$$(2) \Delta PE_g = W_{on} = Fd = mg\Delta h$$

Note that the previous equation automatically gives a decrease in gravitational potential energy when an object gets lower because the change in height will be negative. The work done to lift an object is an example of useful work, or work done on the outside environment.¹

Reinforcement Exercises

Calculate the change in gravitational potential energy when you climb 10 m high set of stairs.

How much useful work did you do while climbing the stairs?

Your body is not 100% efficient, so you actually did a bunch of additional work that didn't increase your gravitational potential energy, but increased thermal energy instead. We will learn more about your body's efficiency in the next unit.

Everyday Example: Rock Climbing Fall

A rock climber is 3.5 m above their last anchor point and fall. They will fall back 3.5 m back to the anchor point and then another 3.5 m below it before the rope comes tight for a total fall distance of 7.0 m (there was 3.5 m of rope out when they fell, so they will have to end

1. OpenStax, College Physics. OpenStax CNX. May 13, 2019 <http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@16.4>

up hanging by 3.5 m of rope). Neglecting air resistance, how fast will they be moving when the rope begins to come tight?

We will apply the Law of Conservation of Energy during the fall.

$$(3) W_{on} = \Delta KE + \Delta PE + \Delta TE$$

Neglecting air resistance there are no forces other than gravity on the person during the fall, so only conservative forces are acting and mechanical energy is conserved:

$$(4) 0 = \Delta KE + \Delta PE + 0$$

Next we write out the changes in each type of energy:

$$(5) 0 = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 + mg\Delta h$$



A YouTube element has been excluded from this version of the text. You can view it online here:
<https://openoregon.pressbooks.pub/bodyphysics/?p=2323>

We recognize the initial speed was zero at the start of the fall and that we can divide every term in our equation by mass mass to cancel it out:

$$(6) \quad 0 = \frac{1}{2}v_f^2 - 0 + g\Delta h$$

Then we isolate the speed:

$$(7) \quad v_f^2 = 2g\Delta h$$

Finally we take the square root:

$$(8) \quad v_f = \sqrt{2g\Delta h}$$

The climber fell 7.0 m, so the change in height was actually -7.0 m. We are ready to calculate the final speed:

$$(9) \quad v_f = \sqrt{2(9.8, \text{ m/s})7, \text{ m}} = 11.7, \text{ m/s}$$

Reinforcement Exercises

The climber in the example problem above will be caught by the rope. Do you think the rope should be designed to stretch so the catch occurs over a long distance or a short one? Explain.

What is the kinetic energy of the climber just as the rope begins to come tight?

How much work must be done by the rope in order to bring the climber to a stop?

If the rope stretches by 0.50 m while catching the climber, what is the average force applied to the climber? This type of stretchy *dynamic rope* is used in rock climbing. The rope only slightly elastic, (the climber doesn't bounce back up to nearly their original height). The rope is designed so that system has a small coefficient of restitution

and most of the energy in the fall is transferred into thermal energy during the process of stretching the rope.

If a *static* rope was used, so the stretch was only 0.05 m while catching the climber, what is the average force applied to the climber? This type of non-stretchy *static* rope should not be used for rock climbing.

CHAPTER 82.

POWERING THE BODY

CHEMICAL POTENTIAL ENERGY

We have learned that when you jump, bend a paper clip, or lift an object you transfer kinetic energy, potential energy, or thermal energy to the objects, but where did that energy come from and what form was it in before? The energy was stored as chemical potential energy in specific bonds within molecules in your muscle cells, specifically *ATP* molecules. We should note that chemical potential energy is stored in the separation electrically charged particles that make up atoms, analogous to the way gravitational potential energy is stored in the separation of masses. Therefore chemical potential energy is actually just a form of electrical potential energy, but we will not cover the details of electrical potential energy in this textbook, so we will talk about chemical potential energy as its own distinct type of energy.

THE BIOLOGICAL ENERGY CASCADE

The chemical potential energy stored in bonds within

ATP is released to do work on muscle fibers (Actin and Myosin) and then work must be done to reform those bonds. That work is done during the ATP cycle shown in the following animation:

The energy to power the ATP cycle is transferred out of chemical potential energy in glucose molecules during cellular respiration. Those glucose molecules entered your body through the food you ate, and ultimately, the chemical potential energy they stored was transferred from electromagnetic energy in sunlight by plants via photosynthesis. ¹. To learn more about these processes



A YouTube element has been excluded from this version of the text. You can view it online here: <https://openoregon.pressbooks.pub/bodyphysics/?p=2187>

consider taking courses in human anatomy and physiology, general biology, cell biology, molecular biology, and biochemistry.

Everyday Example: No work and all heat

Hold an object up in the air. Keep holding. Do you eventually get tired? Why? You are certainly applying a force, but the object hasn't moved any distance, so it would appear that you really done any work. Why should you get tired when you aren't doing any work? The animation in the previous video provides the answer, you haven't done any useful work, but you have work on a microscopic scale to transfer chemical potential energy to thermal energy. The ATP cycle occurs repeatedly just maintain muscle tension, even if the muscle does not actually move a noticeable distance. The ATP cycle continues to use up chemical potential energy even if you aren't doing any useful work. Where does that energy go? Into thermal energy. If you hold the object long enough, you might even begin to sweat! If using stored energy without doing useful work seems pretty inefficient, you're right. In fact the efficiency of the body in such a situation is zero! The next chapter will discuss the efficiency in greater detail.

ELASTIC POTENTIAL ENERGY IN THE BODY

There are biochemical limits on how quickly your body can break down ATP to release chemical potential energy, which limits the rate at which your body is able to do work, also known as power (P). For example, making a change in speed changes your kinetic energy, which

1. OpenStax College, Biology. OpenStax CNX. Feb 25, 2016 <http://cnx.org/contents/185cbf87-c72e-48f5-b51e-f14f21b5eabd@9.92>.

requires work. Quick changes in speed require the work to be done in short time interval, which equates to a high power output. You can apply some strategies to overcome biochemical power limitations in the short term by storing elastic potential energy in tissue tension and timing the release of that energy. For example you can store elastic potential energy in your Achilles tendon when you squat down before jumping, then release that energy during the launch phase of a jump. Your body isn't able to store this elastic energy potential energy for long, however, so it only provide short-term enhancements to power output.

Dr. Shelia Patek, Chair of the Biomechanics Division at the Society for Integrative and Comparative Biology, discovered that the mantis shrimp has doubled down on the elastic potential energy strategy by using a “structure in the arm that looks like a saddle or a Pringle chip. When the arm is cocked, this structure is compressed and acts like a spring, storing up even more energy. When the latch is released, the spring expands and provides extra push for the club, helping to accelerate it at up to 10,000 times the acceleration [caused by the] force of gravity on Earth [alone].”²

QUANTIFYING ELASTIC POTENTIAL ENERGY

We often model particular tissues or other material as a springs, so elastic potential energy is sometimes used interchangeably with *spring potential energy*. The amount of elastic potential energy you can store in a spring can be

2. "The Mantis Shrimp Has the World's Fastest Punch" by Ed Yong, Science and Innovation, National Geographic

calculated from the spring constant (k) and displacement Δx according to Hooke's Law:

$$(1) \quad PE_E = \frac{1}{2}k(\Delta x)^2$$

Everyday Example:

How much elastic potential energy is stored in the Achilles tendon during the crouch phase of a jump?

In the *Modeling Tissues as Springs* chapter of Unit 7 we estimated the



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typical spring constant of the Achilles tendon to be $8.1 \times 10^6 \frac{\text{N}}{\text{m}}$. During a jump the tendon may experience strain of more than 0.06, or 6 %.³ We can use our equation for elastic potential energy above, but first we need to find the stretch distance corresponding to that strain value for a typical Achilles tendon length of 0.15 m. Starting with the strain equation:

$$\text{Strain} = \frac{\Delta x}{L_0}$$

Rearranging for the stretch distance (displacement):

$$\Delta x = L_0 \times \text{strain} = (0.15 \text{ m})(0.06) = 9 \times 10^{-3} \text{ m}$$

We can now calculate the elastic potential energy stored in the tendon during a jump:

$$PE_E = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \left(8.1 \times 10^6 \frac{\text{N}}{\text{m}} \right) (9 \times 10^{-3} \text{ m})^2 = 324 \text{ J}$$

Using the equation for a change in gravitational potential energy we find out that the stored elastic potential energy is enough energy to launch a 65 kg person an additional 0.5 m into the air.

$$PE_g = mg(\Delta h) = (65 \text{ kg})(9.8 \text{ m/s})(0.5 \text{ m}) = 319 \text{ J}$$

Storing elastic potential energy in tissues for timed release in parallel with muscle contraction can significantly increase the power output during a jump.

3. "Achilles tendon material properties are greater in the jump leg of jumping athletes" by Bayliss, A. J., Weatherholt, A. M., Crandall, T. T., Farmer, D. L., McConnell, J. C., Crossley, K. M., & Warden, S. J., National Library of Medicine, U.S. National Institutes of Health

Reinforcement Exercises

A child's toy uses a spring to launch small plastic balls into the air. If it takes 8 N of force to compress the spring 0.025 m, what is the spring constant? [Hint: Use Hooke's Law]

Now that you know the spring constant, what is the elastic potential energy stored in the spring when fully compressed to 0.5 m?

If the spring were used to launch a 0.006 kg plastic ball, how fast would the ball be moving (ignoring friction and air resistance)?

POWER

We have seen that storage and time release of elastic potential energy can improve short term power output, or work done per unit time. The power for any energy conversion process can be calculated as:

$$P = \frac{work}{\Delta t}$$

Power has units of J/s, also known as Watts (**W**). Another common unit for power is horsepower (**hp**). There are 746 W per **hp**.

Reinforcement Exercises

A 65 kg person starts at rest and then speeds up to 4 m/s. What is the change in kinetic energy of the person?

If this change in kinetic energy occurred over 3 s, what is the mechanical power output of the person?

Convert this power from units of Watts to horsepower.

The true rate at which the person uses chemical potential energy is actually much greater than this because the body is not 100 % efficient at converting chemical potential energy into kinetic energy. We will learn more about the efficiency of the body in the next few chapters.

Everyday Examples: Power Plants

Power plants convert energy from one form to another. The most common type convert chemical potential energy into thermal energy via combustion, and then convert thermal energy stored in steam, and then into kinetic energy via turbines. A large power plant might have an output of 500 million Watts, or 500 **MW**.

When you receive a power bill in the U.S. the typical unit you are billed for is kiloWatt-hours (**kW-hr**). These units can be confusing because we see Watt and think power, but this is actually a unit of energy. This makes sense because you should be billed based on the energy you used, but let's break down the confusing units.

Power is energy divided by time, so a power multiplied by a time is an energy:

$$Power \times \Delta t = \frac{\text{energy converted}}{\Delta t} \times \Delta t$$

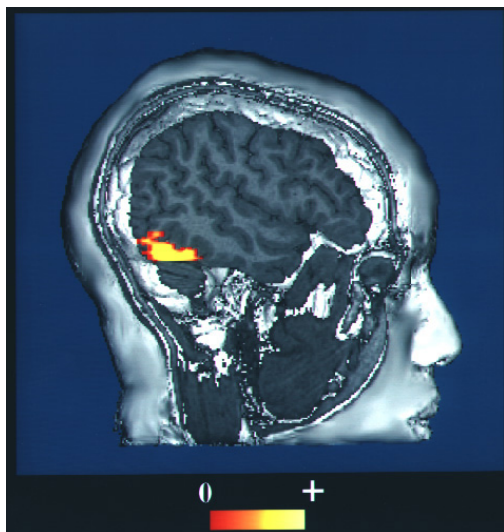
The issue here is we are mixing time units, specifically hours and the seconds that are inside Watts. The reason might be that customers can better relate to **kW-hr** than joules when thinking about their energy usage. For example, leaving ten 100 **W** light bulbs on for one hour would be one **kW-hr** of energy:

$$(10 \text{ bulbs}) \frac{100 \text{ W}}{\text{bulb}} (1 \text{ hr}) = 1000 \text{ W} \cdot \text{hr} = 1 \text{ kW} \cdot \text{hr}$$

CHAPTER 83.

EFFICIENCY OF THE HUMAN BODY

THE ENERGETIC FUNCTIONS OF THE BODY¹



*This fMRI scan shows an increased level of energy consumption in the vision center of the brain. Here, the patient was being asked to recognize faces.
Image credit: NIH via Wikimedia Commons*

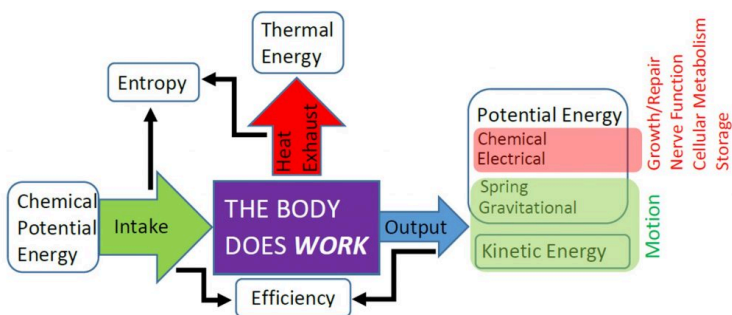
All bodily functions, from thinking to lifting weights, require energy. The many small muscle actions accompanying all quiet activity, from sleeping to head scratching, ultimately become thermal energy, as do less visible muscle actions by the heart, lungs, and digestive tract. The *rate* at which the body uses food energy to sustain life and to do different activities is called the metabolic rate. The total energy conversion rate of a person *at rest* is called the basal metabolic rate (BMR) and

1. Significant content in this chapter was adapted from: OpenStax, College Physics. OpenStax CNX. Aug 30, 2019 <http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@17.22>

is divided among various systems in the body, as shown the following table:

Basal Metabolic Rates (BMR)			
organ	power consumed at rest (w)	oxygen consumption (ml/min)	percent of bmr
Liver & spleen	23	67	27
Brain	16	47	19
Skeletal muscle	15	45	18
Kidney	9	26	10
Heart	6	17	7
Other	16	48	19
Totals	85 W	250 mL/min	100%

The largest fraction of energy goes to the liver and spleen, with the brain coming next. About 75% of the calories burned in a day go into these basic functions. A full 25% of all basal metabolic energy consumed by the body is used to maintain electrical potentials in all living cells. (Nerve cells use this electrical potential in nerve impulses.) This bioelectrical energy ultimately becomes mostly thermal energy, but some is utilized to power chemical processes such as in the kidneys and liver, and in fat production. The BMR is a function of age, gender, total body weight, and amount of muscle mass (which burns more calories than body fat). Athletes have a greater BMR due to this last factor. Of course, during vigorous exercise, the energy consumption of the skeletal muscles and heart increase markedly. The following diagram summarizes the basic energetic functioning in the human body.



The most basic functions of the human body mapped to the main concepts covered in this textbook. (Chemical potential energy is actually a form of electric potential energy, but we will not specifically discuss electric potential energy in this textbook so we have separated the two.)

THE FIRST LAW OF THERMODYNAMICS

HEAT

The body is capable of storing chemical potential energy and thermal energy internally. Remembering that thermal energy is just the kinetic energy of atoms and molecules, we recognize that these two types of energy are stored microscopically and internal to the body. Therefore, we often lump these two types of microscopic energy into the internal energy (U). When an object is warmer than its surroundings then thermal energy will be transferred from object to surroundings, but if the object is cooler than its surroundings then thermal energy will be transferred into the object from its surroundings. The amount of thermal energy exchanged due to temperature differences is often called heat (Q). When heat is transferred out of the body to the

environment, we say call this exhaust heat, as indicated in the previous figure. We will learn more about how temperature and heat transfer are related in the next unit.

ENERGY CONSERVATION

The Principle of Conservation of Energy states that energy cannot be created or destroyed. Therefore, if the body does useful work to transfer mechanical energy to its surroundings (W_{by}), or transfer thermal energy to the environment as heat, then that energy must have come out of the body's internal energy. We observe this throughout nature as the First Law of Thermodynamics:

$$(1) \quad \Delta U = Q - W_{by}$$

HEAT ENGINES

Your body uses chemical potential energy stored internally to do work, and that process also generates thermal energy, which you release as exhaust heat. The internal combustion engines that power most cars operate in similar fashion by converting chemical potential energy in fuel to thermal energy via combustion, then converting some of the thermal energy into useful work and dumping some into exhaust heat. Your body is capable of releasing the chemical potential energy in your food without combustion, which is good, because you are not capable of using thermal energy from your internal energy to do work. Machines that can use thermal energy to do work, such as a combustion engine, are known as heat engines. Heat engines are still governed by the First Law of Thermodynamics, so any exhaust heat must have been thermal energy that was not used to do work. The thermal energy input that can

be used to do work rather than wasted as exhaust heat determines the efficiency of the heat engine.

Reinforcement Exercises

You apply a 50 N force in order to slide an object 3 m. How much useful work did you do?

If you exhausted 500 J worth of thermal energy while doing the useful work above, how much did your internal energy change?

BODY EFFICIENCY

The efficiency of the human body in converting chemical potential energy into useful work is known as the mechanical efficiency of the body. We often calculate the body's mechanical efficiency, as a percentage:

$$(2) \quad e_{body} = \frac{W_{by}}{\text{Chemical Potential Energy Used}} \times 100 \%$$

The mechanical efficiency of the body is limited because energy used for metabolic processes cannot be used to do useful work. Additional thermal energy generated during the chemical reactions that power muscle contractions along with friction in joints and other tissues reduces the efficiency of humans even further.²

“Alas, our bodies are not 100 % efficient at converting food energy into mechanical output. But at about 25 % efficiency, we’re surprisingly good considering that most cars are around 20 %, and that an Iowa cornfield is only

2. "The maximum work and mechanical efficiency of human muscles, and their most economical speed" by A. V. Hill, National Library of Medicine, U.S. National Institutes of Health

about 1.5 % efficient at converting incoming sunlight into chemical [potential energy] storage.” ³For an excellent discussion of human mechanical efficiency and comparisons with other machines and fuel sources, see MPG of a Human by Tom Murphy, the source of the previous quote.

Everyday Example: Energy to Climb Stairs

Assuming a 20% mechanical efficiency in climbing stairs, how much does your internal energy decrease when a 65 kg person climbs a 15 m high flight of stairs? How much thermal energy does the person transfer to the environment as exhaust heat?

First, let's calculate the change in gravitational potential energy:

$$\Delta PE_g = mg\Delta h = (65 \text{ kg})(9.8 \text{ m/s/s})(15 \text{ m}) = 9,555 \text{ J}$$

The person did work in converting chemical potential energy in their body to mechanical energy, specifically gravitational potential energy. However, they are only 20% efficient, which means that only 1/5 of the chemical potential energy they use goes into doing useful work. Therefore the change in chemical potential energy must have been 5x greater than the mechanical work output

$$\text{Chemical Potential Energy Used} = (5 \times 9,555 \text{ J}) = 47,775 \text{ J}$$

The chemical potential energy used came out of the person's internal energy so:

$$\Delta U = -47,775 \text{ J}$$

We can use the First Law of Thermodynamics to find the thermal energy exhausted by the person:

3. "MPG of a Human" by Tom Murphy, Do The Math, UCSD Physics Department

$$(3) \Delta U = Q - W_{by}$$

Rearranging for Q :

$$Q = \Delta U + W_{by} = -47,775 \text{ J} + 9,555 \text{ J} = -38,220 \text{ J}$$

We find that the heat is negative, which makes sense because the person exhausts thermal energy out of the body and into to the environment while climbing the stairs.

Alternatively, we could have known right off that the exhaust heat must be 4/5 of the total loss of internal energy, because only 1/5 went into doing useful work. So the exhaust heat should be:

$$Q = \Delta U \times (4/5) = -47,775 \text{ J} \times 4/5 = -38,220 \text{ J}$$

FOOD CALORIES

For historical reasons we often measure thermal energy and heat in units of calories (**cal**) instead of Joules. There are 4.184 Joules per calorie. We measure chemical potential energy stored in food with units of 1000 calories, or kilocalories (**kcal**) and we sometimes write kilocalories as Calories (**Cal**) with with capital C instead of a lowercase c. For example, a bagel with 350 **Cal** has 350 **kcal**, or 350,000 **cal**. Converting to Joules, that would be $350,000 \text{ cal} \times (4.184 \text{ J/cal}) = 1,464,400 \text{ J}$ in the bagel.

Everyday Examples

What fraction of a bagel would you need to eat in order to make up for the 47,775 J loss of internal energy (as chemical potential energy) that we calculated in the previous everyday example about climbing stairs?

There are 1,464,400 J/bagel

Therefore we need to eat:

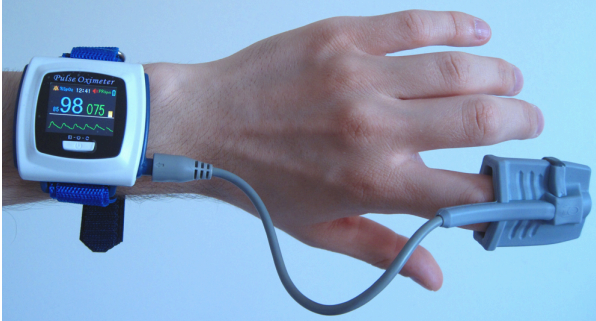
$$\frac{47,775 \text{ J}}{1,464,400 \text{ J/bagel}} = 0.03 \text{ Bagels or } 3\% \text{ of a bagel}$$

Reinforcement Exercises

How many Joules of energy are stored in a 260 Calorie candy bar?

How many candy bars would you need to eat to make up for the loss of internal energy we found in the previous stair climbing example?

CONSERVATION OF MASS AND OF ENERGY



A pulse oxymeter is an apparatus that measures the amount of oxygen in blood. Oxymeters can be used to determine a person's metabolic rate, which is the rate at which food energy is converted to another form. Such measurements can indicate the level of athletic conditioning as well as certain medical problems. (credit: UusiAjaja, Wikimedia Commons)

The digestive process is basically one of oxidizing food, so energy consumption is directly proportional to oxygen consumption. Therefore, we can determine the the actual energy consumed during different activities by measuring oxygen use. The following table shows the oxygen and corresponding energy consumption rates for various activities.

Energy and Oxygen Consumption Rates for an average 76 kg male

activity	energy consumption in watts	oxygen consumption in liters o₂/min
Sleeping	83	0.24
Sitting at rest	120	0.34
Standing relaxed	125	0.36
Sitting in class	210	0.60
Walking (5 km/h)	280	0.80
Cycling (13–18 km/h)	400	1.14
Shivering	425	1.21
Playing tennis	440	1.26
Swimming breaststroke	475	1.36
Ice skating (14.5 km/h)	545	1.56
Climbing stairs (116/min)	685	1.96
Cycling (21 km/h)	700	2.00
Running cross-country	740	2.12
Playing basketball	800	2.28
Cycling, professional racer	1855	5.30
Sprinting	2415	6.90

Everyday Examples: Climbing Stairs Again

In the previous examples we assumed stated that our mechanical efficiency when climbing stairs was 20%. Let's use the data in the above table to verify that assumption. The data in the table is for a **76 kg** person climbing **116 stairs** per minute. Let's calculate the rate at which that person did mechanical work while climbing stairs and compare that rate at which they used up internal energy (originally from food).

The minimum standard step height in the US is 6.0 inches⁴ (**0.15 m**) then the gravitational potential energy of a **76 kg** person will increase by **130 J** with each step, as calculated below:

$$\Delta PE = mg\Delta h = (76 \text{ kg})(9.8 \text{ m/s/s})(0.15 \text{ m}) = 112 \text{ J}$$

When climbing **116 stairs** per minute the rate of energy use, or power, will then be:

$$P = (112 \text{ J}) \left(116 \frac{\text{stairs}}{\text{min}} \right) \left(\frac{1 \text{ min}}{60 \text{ sec}} \right) = 216 \text{ W}$$

According to our data table the body uses **685 W** to climb stairs at this rate. Let's calculate the efficiency:

$$e = \frac{216 \text{ W}}{685 \text{ W}} = 0.32$$

As a percentage, this person is **32%** mechanically efficient when climbing stairs. We may have underestimated in the previous examples when we assumed a **20%** efficiency for stair climbing.

4. "1917.120 - Fixed stairways." by Occupational Safety and Health Administration, United States Department of Labor

Reinforcement Exercises

Every kilogram of fat that metabolized will release roughly 7,800 Calories, or 7,800,000 calories. Convert that energy to Joules.

Apply unit analysis and the data in the previous table to estimate how long you need climb stairs in order to break down 1 kg of fat.

We often talk about “burning” calories in order to lose weight, but what does that really mean scientifically?. First, we really we mean lose mass because that is the measure of how much stuff is in our bodies and weight depends on where you are (it’s different on the moon). Second, our bodies can’t just interchange mass and energy — they aren’t the same physical quantity and don’t even have the same units. So how do we actually lose mass by exercising? We don’t actually shed the atoms and molecules that make up body tissues like fat by “burning” them. Instead, we break down the fat molecules into smaller molecules and then break bonds within those molecules to release chemical potential energy, which we eventually convert to work and exhaust heat. The atoms and smaller molecules that resulting from breaking the bonds combine to form carbon dioxide and water vapor (CO_2 and H_2O) and we breath them out. We also excrete a bit as H_2O in sweat and urine. The process is similar to burning wood in campfire — in the end you have much less mass of ash than you did original wood. Where did the rest of the mass go? Into the air as CO_2 and H_2O . The same is true for the fuel burned by your car. For more on this concept see the first video below. The really amazing

fact is that your body completes this chemical process without the excessive temperatures associated with burning wood or fuel, which would damage your tissues. The body's trick is to use enzymes, which are highly specialized molecules that act as catalysts to improve the speed and efficiency of chemical reactions, as described and animated in the beginning of the second video below.

GENERAL EFFICIENCY

Similar to the body efficiency, the efficiency of any

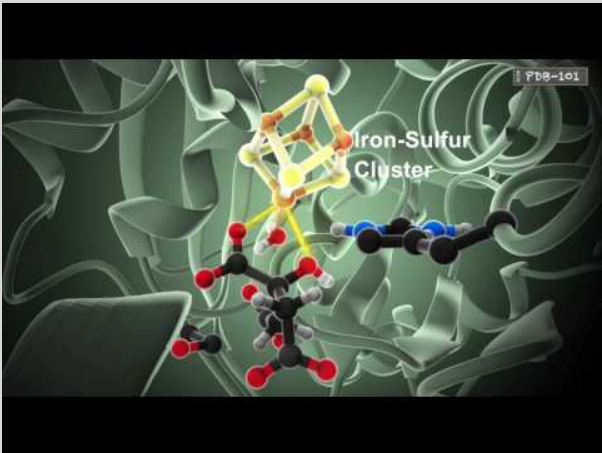


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energetic process can be described as the amount of energy converted from the input form to the desired form divided by the original input amount. The following chart outlines the efficiencies of various systems at converting energy various forms. The chart does not account for the cost, hazard risk, or environmental impact associated with the required fuel, construction, maintenance, and by-products of each system.

The Efficiency of the Human Body Compared to Other Systems

System	Input Energy Form	Desired Output Form	Max Efficiency
Human Body	Chemical Potential	Mechanical	25 %



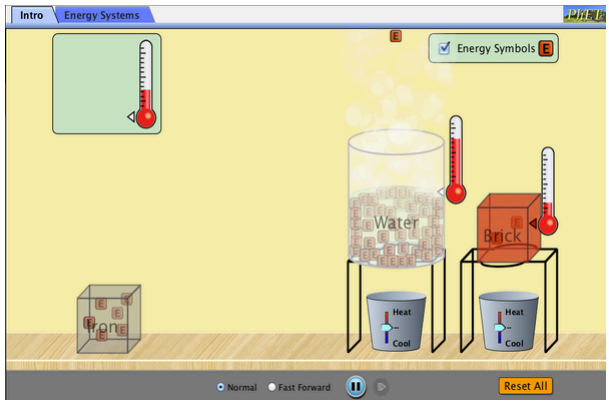
A YouTube element has been excluded from this version of the text. You can view it online here: <https://openoregon.pressbooks.pub/bodyphysics/?p=1067>

Automobile Engine	Chemical Potential	Mechanical	25 %
Coal/Oil/Gas Fired Stream Turbine Power Plants	Chemical Potential	Electrical	47%
Combined Cycle Gas Power Plants	Chemical Potential	Electrical	58 %
Biomass/Biogas	Kinetic	Electrical	40%
Nuclear	Kinetic	Electrical	36%
Solar-Photovoltaic Power Plant	Sunlight (Electromagnetic)	Electrical	15%
Solar-Thermal Power Plant	Sunlight (Electromagnetic)	Electrical	23%
Hydroelectric and Tidal Power Plants	Gravitational Potential	Electrical	90%+

567

Check out the energy systems tab in this simulation to visualize different energy conversion systems

5. "Managing Water in the West: Hydroelectric Power" by Bureau of Reclamation, U.S. Department of the Interior
6. "Efficiency in Electricity Generation" by EURELECTRIC "Preservation of Resources" Working Group's "Upstream" Sub-Group in collaboration with VGB, Union of the Electricity Industry
7. "Efficiency of Energy Conversion Devices" by John E. Dutton e-Education Institute, Penn State College of Earth and Mineral Sciences

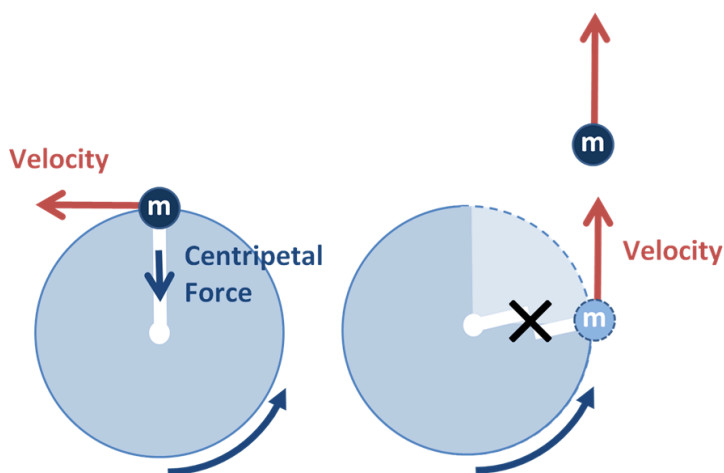


CHAPTER 84.

WEIGHTLESSNESS*

UNIFORM CIRCULAR MOTION

We have seen that if the net force is found to be perpendicular to an object's motion then it can't do any work on the object. Therefore, the net force will only change the object's direction of motion, change its kinetic energy) and the object must maintain a constant speed. The object will undergo uniform circular motion, in which case we sometimes refer to the net force that points toward the center of the circular motion as the centripetal force, but this is just a naming convention. *The centripetal force is not a new kind of force, rather the centripetal force is provided by one of the forces we already know about, or a combination of them.* For example, the centripetal force that keeps a satellite in orbit is just gravity and for a ball swinging on a string tension in the string provides the centripetal force.



Left: A ball on a string undergoing circular motion with uniform (constant) speed. Right: The ball's trajectory after the string breaks . Image Credit: Breaking String by Brews ohare via Wikimedia Common

1

For both the ball and the satellite the net force points at 90° to the object's motion so it can do no work, thus it cannot change the kinetic energy of the object, which means it cannot change the speed of the object. How do we mesh this with Newton's Second Law, which says that objects with a net force must experience acceleration? We just have to remember that acceleration is change velocity per time and velocity includes speed and direction. Therefore, the constantly changing direction of uniform circular motion constitutes a constantly changing velocity, and thus a constant acceleration, so all is good.

1. Breaking String by Brews ohare [CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>) or GFDL (<http://www.gnu.org/copyleft/fdl.html>)], via Wikimedia Commons

Due to Newton's Second Law, we know that the acceleration points toward the center of the circular motion because that is where the net force points. As a result, that acceleration is called the centripetal acceleration. If the net force drops to zero (string breaks) the acceleration must become zero and the ball will continue off at the same speed in whatever direction it was going when the net force became zero (diagram on right above).

CENTRIPETAL FORCE AND ACCELERATION

The size of the acceleration experienced by an object undergoing uniform circular motion with radius r at speed v is:

$$(1) \quad a_c = \frac{v^2}{r}$$

Combined with Newton's Second Law we can find the size of the centripetal force, which again is just the net force during uniform circular motion:

$$(2) \quad F_{net} = ma = m \frac{v^2}{r}$$

Everyday Example: Rounding a Curve

What is the maximum speed that a car can have while rounding a curve with radius of 75 m without skidding? Assume the friction coefficient between tire rubber and the asphalt road is 0.7

First, we recognize that as the car rounds the curve at constant speed the net force must point toward the center of the curve and have the value:

$$F_{net} = m \frac{v^2}{r}$$

Next we recognize that the only force available to act on the car in the horizontal direction (toward the center of the curve) is friction, so the net force in the horizontal direction must be just the frictional force:

$$F_f = m \frac{v^2}{r}$$

We want to know the maximum speed to take the curve without slipping, so we need to use the maximum static frictional force that can be applied before slipping:

$$\mu_s F_N = m \frac{v^2}{r}$$

Notice that we have used static friction even though the car is moving because we are solving the case when the tires are still rolling and not yet sliding. Kinetic friction would be used if the tires were sliding.

For a typical car on flat ground the normal force will be equal to the weight of the car:

$$\mu_s mg = m \frac{v^2}{r}$$

Then we cancel the mass from both sides of the equation and solve for speed:

$$v = \mu_s gr$$

Inserting our values for friction coefficient, g , and radius:

$$v = \sqrt{0.7(9.8 \text{ m/s}^2)(75 \text{ m})} = 22 \text{ m/s} = 49 \text{ MPH}$$

The inverted airfoils (wings) on a shape of a formula one race car create a downward aerodynamic force, increasing normal force from the road and thus friction as well. Image Credit: Italian V12 by Rob Oo via Wikimedia Commons

2

WEIGHTLESSNESS

When you stand on a scale and you are not in equilibrium, then the normal force may not be equal to your weight and the weight measurement provided by the scale will be incorrect. For example, if you stand on a scale in an elevator as it begins to move upward, the scale will read a weight that is too large. As the elevator starts up, your motion changes from still to moving upward, so you must have an upward acceleration and you must not be in equilibrium. The normal force from the scale must be larger than your weight, so the scale will read a value larger than your weight.

In similar fashion, if you stand on a scale in an elevator as it begins to move downward the scale will read a weight that is too small. As the elevator starts down, your motion changes from still to moving downward, so you must not be in equilibrium, rather you have a downward acceleration. The normal force from the scale must be less than your weight.

2. Rob Oo from NL [CC BY 2.0 (<https://creativecommons.org/licenses/by/2.0>)], via Wikimedia Commons

Taking the elevator example to the extreme, if you try to stand on a scale while you are in free fall, the scale will be falling with the same acceleration as you. The scale will not be providing a normal force to hold you up, so it will read your weight as zero. We might say you are *weightless*. However, your weight is certainly not zero because weight is just another name for the force of gravity, which is definitely acting on you while you free fall. Maybe *normal-force-less* would be a more accurate, but also less convenient term than weightless.

We often refer to astronauts in orbit as weightless, however we know the force of gravity must be acting on them in order to cause the centripetal acceleration required for them to move in a circular orbit. Therefore, they are not actually weightless. The astronauts feel weightless because they are in free fall along with everything else around them. A scale in the shuttle would not read their weight because it would not need to supply a normal force to cancel their weight because both the scale and the astronaut are in free fall toward Earth. The only reason they don't actually fall to the ground is that they are also moving so fast perpendicular to their downward acceleration that by the time they would have hit the ground, they have moved sufficiently far to the side that they end up falling *around* the Earth instead of *into* it.

Everyday Example: Orbital Velocity

How fast does an object need to be moving in order to free fall around the Earth (remain in orbit)? We can answer that question by

setting the centripetal force equal to the gravitational force, given by Newton's Universal Law of Gravitation ($F_g = mg$ is only valid for object near Earth's surface, remember):

$$F_g = \frac{Gm_1m_2}{r^2}$$

Recognizing that gravity is the centripetal force in this case, and that m_1 is the Earth's mass and m_2 is the orbiting object's mass:

$$\frac{Gm_1m_2}{r^2} = m_2 \frac{v^2}{r}$$

$$\frac{Gm_1m_2}{r^2} = m_2 \frac{v^2}{r}$$

Cancelling m_2 and one factor of r from both sides and solving for speed:

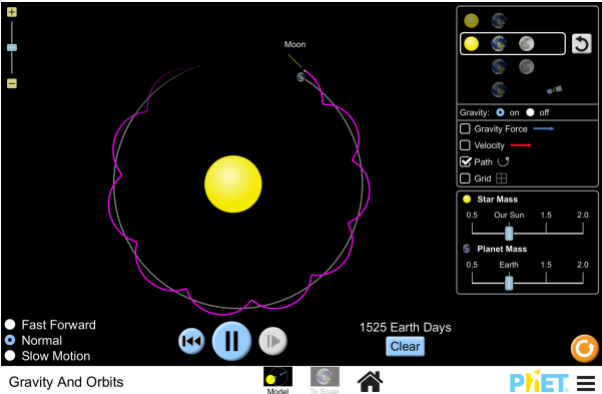
$$v = \sqrt{\frac{Gm_1}{r}}$$

We see that the necessary orbit speed depends on the radius of the orbit. Let's say we want a low-Earth orbit at an altitude of 2000 km, or $2000 \times 10^3 \text{ m}$. The radius of the orbit is that altitude plus the Earth's radius of 6378 km to get $r = 8378 \text{ km}$ or $r = 8378 \times 10^3 \text{ m}$. Inserting that total radius and the gravitational constant, $G = 6.67408 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$, and the Earth's mass: $m_1 = 5.972 \times 10^{24} \text{ kg}$:

$$v = \sqrt{\frac{(6.67408 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2})(5.972 \times 10^{24} \text{ kg})}{(8378 \times 10^3 \text{ m})}} \approx 7000 \text{ m/s} \approx 15,000 \text{ MPH}$$

That's fast.

Use this simulation to play with the velocities of these planets in order to create stable orbits around the sun.



CHAPTER 85.

COMPARING WORK-ENERGY AND ENERGY CONSERVATION*

In the previous chapters we analyzed a person's jump using the work-energy principle rather than the Law of Conservation of Energy. Examining that correspondence between these concepts will allow us to learn a few important concepts. Let's refresh ourselves with that example:

Everyday Examples: Jumping

During a jump a person's legs might apply a force of 1200 N upward on their center of mass while the center of mass moves 0.3 m upward. Let's figure out what their launch speed and hang time will be if the person has a weight of 825 N .

First we calculate the work done by their legs.

$$W_L = F_L d \cos\theta = (1200\text{ N})(0.3\text{ m})\cos(0^\circ) = 360\text{ J}$$

Gravity was acting on them during the launch phase as well, so we need to calculate the work done by gravity:

$$W_g = F_g d \cos\theta = (825\text{ N})(0.3\text{ m})\cos(180^\circ) = -247.5\text{ J}$$

The net work is then:

$$W_{net} = -247.5 \text{ J} + 360 \text{ J} = 112.5 \text{ J}$$

The work-energy principle tells us to set the change in kinetic energy equal to the net work. We will keep in mind that they started at rest, so the initial kinetic energy was zero.

$$112.5 \text{ J} = \frac{1}{2}mv_f^2 - 0$$

We can see that we need the person's mass. We just divide their weight by $g = 9.8 \text{ m/s}^2$ to find it:

$$m = \frac{825 \text{ N}}{9.8 \text{ m/s}^2} = 84.2 \text{ kg}$$

We isolate the final speed at the end of the launch phase (as the person leaves the ground) and insert the mass.

$$\frac{2(112.5 \text{ J})}{84.2 \text{ kg}} = v_f^2$$

Then we take the square root the result to find the speed:

$$v_f = \sqrt{\frac{2(112.5 \text{ J})}{84.2 \text{ kg}}} = 1.6 \text{ m/s}$$

In the first part of the jumping example we calculated the net work on the object and used the work-energy principle to find the change in kinetic energy. In equation form it looks like this:

$$W_L + W_g = \Delta KE$$

Moving the work done by gravity to the other side:

$$W_L = \Delta KE - W_g$$

The Law of Conservation of Energy looks like this:

$$W_{on} = \Delta KE + \Delta PE + \Delta TE$$

Remembering that we ignored friction and air

resistance, and that nothing was permanently deformed, $\Delta TE = 0$.

$$W_{on} = \Delta KE + \Delta PE + 0$$

Gravity did negative work because it points down and motion was upward, but the effect of that work was to increase potential energy by transferring some of the person's kinetic energy into their own gravitational potential energy. Therefore change in gravitational potential energy should be the negative of the work done by gravity. This work was internal to the Earth-person system, so the only work being done on the person's center of gravity from the outside was work done by the legs. Making these replacements we have:

$$W_L = \Delta KE - W_g$$

Which is exactly the work-energy principle we started with. We can either use the work-energy principle on a given object and include work done by resistance to compression and gravity in the net work, and say all of that work contributes to changing kinetic energy, or instead use the Law of Conservation of Energy and instead say that work done by elastic forces and gravity contributes to elastic potential energy and gravitational potential energy instead of kinetic energy. Either way is equivalent, as we have just seen.

CHAPTER 86.

UNIT 9 REVIEW

Key Terms and Concepts

Work

Work-Energy Principle

Gravitational Potential Energy

Law of Conservation of Energy

Chemical Potential Energy

Power

Internal Energy

First Law of Thermodynamics

Efficiency

Calories

Learner Outcomes

1. Define, recognize, and differentiate work, kinetic energy, and potential energy, including elastic, gravitational, and chemical.[2]
2. Apply the Law of Conservation of Energy and The First Law of Thermodynamics to the analysis of physical processes.[3]
3. Determine the efficiency of physical processes and machines.[3]
4. Evaluate the power output of machines.[3]

CHAPTER 87.

UNIT 9 PRACTICE AND ASSESSMENT

Outcome 1

1) A rubber ball is lifted to a height of 3.0 **m** at constant speed and then dropped. The ball bounces off the floor below and returns to a height of 2.2 **m**.

a) Does the ball have the same mechanical energy after the bounce as before? If not, where did that mechanical energy go?

2) Fill in the blanks in the following statements about the ball in question 1) using the terms listed. Don't forget that the body is not 100% efficient.

- chemical potential
- gravitational potential
- elastic potential
- kinetic
- thermal
- positive
- negative

- zero

a) While lifting the ball up, _____energy is being exchanged for _____ energy. The exchange occurs as you do _____work and gravity does _____ work. The ball moves at constant speed because the net work is _____.

b) While falling, gravity is the only force doing work and that work is _____, therefore the net work is _____ and _____energy is increasing. Overall, _____energy is being exchanged for _____ energy.

c) While in contact with the floor and compressing, the normal force from the floor is doing _____ work, gravity is doing_____ work. The ball is slowing down so net work must be _____. Therefore the normal force must be larger than the weight of the ball. Overall, _____energy and a bit of gravitational potential energy are being exchanged for _____ energy and _____energy. (Remembering that the ball does not reach the same height after bouncing).

d) While in contact with the floor and decompressing, the normal force from the floor is doing _____ work, gravity is doing_____ work. The ball is speeding up so net work must be _____. Therefore the normal force must be larger than the weight of the ball. Overall, _____energy is being exchanged for _____ energy

_____energy and a bit of gravitational potential energy.

e) While rising, gravity is the only force doing work and that work is _____, therefore the net work is _____ and _____energy is decreasing. Overall, _____energy is being exchanged for _____ energy.

f) Where did the energy come from to do the original work of lifting the ball to increase gravitational potential energy?

Outcome 2

3) In the absence of gravity or friction, a spaceship engine supplies 55,000 N of thrust force to a 1500 **kg** ship.

a) Use the work-energy principle to determine what distance the rocket will cover before it reaches a speed of 1200 **m/s** , starting from rest.

b) Use the impulse-momentum theorem (discussed in the previous unit) to determine how long it will take the rocket to get up to 1200 **m/s** speed. (This is also how long it took to cover that distance you found above).

4) A car is moving at 55 **mph** (26 **m/s**) on flat ground when a hazard is spotted 85 **m** (278 **ft**) ahead. (Such as deer, tree-limb, or broke-down car in the road).

a) What distance does the car travel before the brakes are even applied if the driver takes typical 1.5 **s** braking reaction time? ¹

b) Draw a free body diagram of this car, while brakes are applied.

c) What is the normal force on the car?

d) If the car slams on the brakes what is the frictional force? Assume that the car has anti-lock brakes that prevent sliding and the static friction coefficient between tire rubber and dry asphalt is 0.7.

e) Use the work-energy principle to determine the stopping distance.

f) What is the total stopping distance including distance covered during the reaction time and braking? Does an accident occur?

Outcome 3

5) A person uses a pulley system with mechanical advantage of three to lift a 65 **kg** load a distance of 0.5 **m**.

a) What force should the person need to apply?

b) What distance do they need to pull the rope? [Hint: Assuming friction in the pulleys is small enough to ignore, the work input to the pulley system and work output need to be the same].

b) How much potential energy is gained by the load?

c) If the person actually had to pull with 701 **N** due to friction in the system, how much work did they actually do?

d) What is the mechanical efficiency of this system?

e) Remembering that the body is only 20% mechanically efficient, how much chemical potential energy did the person expend?

6) Recently Colin Haley set a speed record for

1. "Why your reaction time matters at speed" by National Highway Traffic Safety Administration, U.S. Department of Transportation

ascending the classically difficult Cassin Ridge on Denali, the highest mountain in North America, located in Central Alaska. Haley started from the glacier at the foot of the mountain and climbed 8000 **ft** to reach the 20,310 **ft** summit in 487 minutes. ²

a) If Colin plus his clothes, gear, and light pack had a combined weight of 72 **kg**, how much gravitational potential energy did Colin gain (in units of Joules)?

b) If Colin is 15% mechanically efficient climbing ice and slogging through snow, how many Joules of chemical potential energy did he actually expend?

c) How many Joules of chemical potential energy were converted to exhaust heat?

Outcome 4

d) What was Colin's average mechanical power output in Watts?

e) What was Colin's average thermal power output in Watts?

f) What was Colin's total average power output in Watts?

g) How many 260 Calorie candy bars would Colin need to eat during his climb in order maintain a constant internal energy? [Hint: Remember, Calories are not the same as calories]

7) A typical microwave oven requires 1,100 **W** of electric power. The microwave needs 2.0 minutes to bring 0.25 **kg** of room-temperature water to a boil.

2. "Colin Haley Sets New Speed Record on Denali's Cassin Ridge" by Michael Levy, Rock and Ice Magazine

a) How much electrical potential energy does the microwave use in that time?

b) The thermal energy required to raise the temperature of 0.25 **kg** water from room temp to boiling is 84,000 **J** (more on this in the next unit). What is the efficiency of the microwave in converting electrical potential energy to thermal energy in water?

PART X.

UNIT 10: BODY HEAT AND THE FIGHT FOR LIFE

Learner Objectives

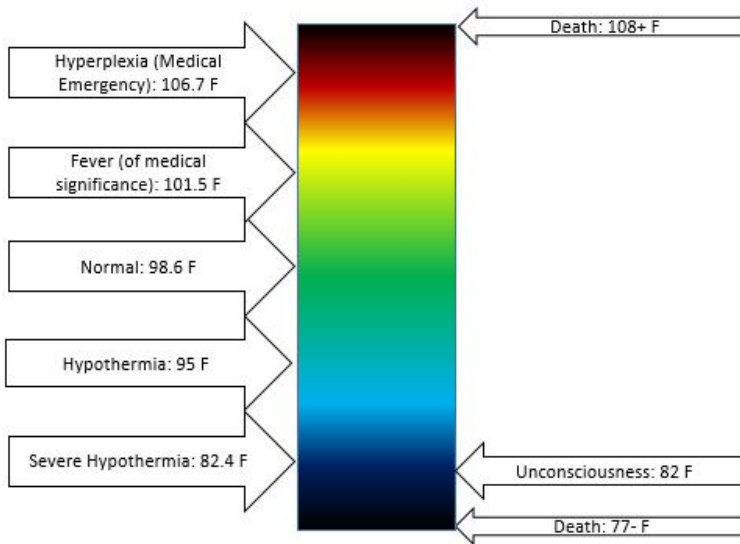
1. Compare, contrast, and convert between absolute and relative temperature scales.[1]
2. Evaluate the effectiveness of various types of insulation against different mechanisms of heat transfer.[3]
3. Apply the concepts of temperature, thermal expansion, specific heat, heat capacity, and latent heat, to analyze how physical objects respond to heat transfer.[3]
4. Apply the Second Law of Thermodynamics to predict the outcome of physical scenarios.[2]

CHAPTER 88.

HOMEOSTASIS, HYPOTHERMIA, AND HEATSTROKE

HOMEOSTATIS

In the previous unit we learned that the body is at best only 25 % efficient at converting chemical potential energy to useful work. The other 75% of the chemical potential energy becomes thermal energy, which the body exploits to manage body temperature as a part of homeostasis, or the body's act of maintaining a relatively constant internal environment. Thermal injuries occur when body temperature becomes too high or too low, but our body has strategies for preventing that from occurring.



*False-color scale indicating medically-relevant body temperature thresholds.
Image Credit: Human Body Temperature Scale by Foxtrot620 via Wikimedia Commons*

1

In order to analyze our body's response to different environmental temperatures we need to first define temperature and clear up the definitions for some other thermodynamic quantities:

1. Thermal energy(TE): Kinetic energy stored in the microscopic motion of atoms and molecules. The SI unit for thermal energy is Joules (**J**), though it is sometimes measured in calories or British Thermal Units (**BTU**)
2. Temperature (T): A measure of the *average* thermal

1. Human Body Temperature Scale by Foxtrot620 [CC BY-SA 4.0 (<https://creativecommons.org/licenses/by-sa/4.0/>)], from Wikimedia Commons

energy per atom or molecule. The SI unit for Temperature is Kelvin (**K**), though it is often measured in Celsius ($^{\circ}\text{C}$) or degrees Fahrenheit ($^{\circ}\text{F}$).

3. Heat(Q):The amount of thermal energy transferred between an object and its environment due to a difference in the object and environment temperatures. The units for heat are the same as for thermal energy.
4. Thermal Equilibrium: A state where the rate of heat transfer is zero because object and environmental temperatures are the same.

Reinforcement Exercise

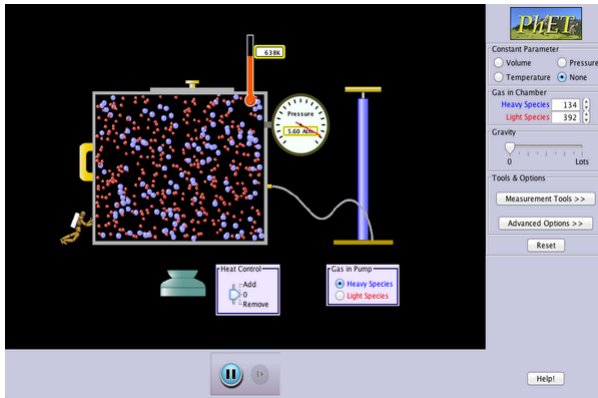
Read the following paragraph about forces and translational equilibrium. Then fill in the blanks in the following paragraphs about rotational equilibrium and thermal equilibrium.

An object in translational equilibrium experiences no net force. That doesn't mean no force is applied, it just means that all the forces cancel out, which occurs when there are equal amounts of force in each direction.

An object in rotational equilibrium experiences no net _____. That doesn't mean no _____ is applied, it just means that all the _____ cancel out, which occurs when there are equal amounts of _____ in each direction.

An object in thermal equilibrium with its environment experiences no net _____. That doesn't mean no _____ is transferred, it just means that equal amounts of _____ are transferred in and out of the object, which occurs when the object and environment have equal _____.

The following simulation allows you to visualize how temperature and atomic motion are related.



THERMAL INJURIES

Now that we have solid definitions for thermal energy, heat, temperature, and thermal equilibrium, we can follow the progression of thermal injuries:

1. As a measure of the average motion of atoms and molecules, temperature influences the rate of chemical reactions and the ability of molecules, such as proteins, to remain in a particular shape.
2. Due to the above, the body must maintain a relatively narrow range of temperature in order to function properly.
3. The body is inefficient and thus converts chemical potential energy to primarily thermal energy as part of basic metabolism and when doing useful work.
4. If heat transfer is limited, then thermal energy will build up in the body and temperature will increase, possibly resulting in hyperthermia and heat-related injuries such as heat stroke. We will learn to prevent hyperthermia by understanding how and when heat

transfer to the environment is limited in the following chapters.

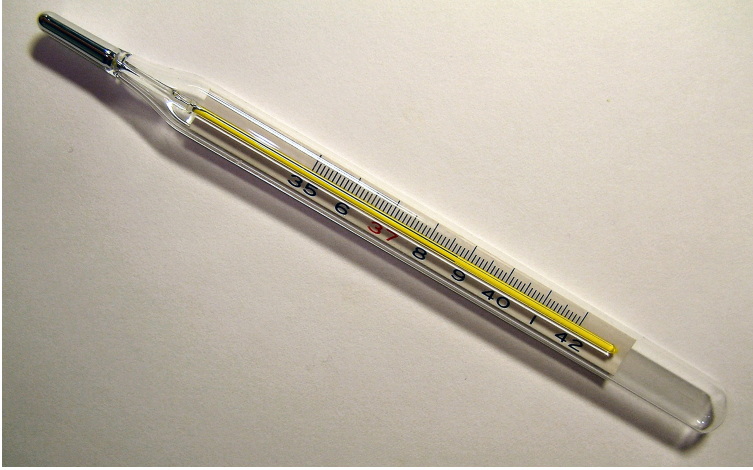
5. If instead, heat is transferred to the environment faster than thermal energy can be converted from chemical potential energy, then body temperature falls, possibly leading to hypothermia and cold-related injuries such as frost-bite. We will learn to prevent hypothermia by understanding how and when heat transfer to the environment can become too fast in the following chapters.

CHAPTER 89.

MEASURING BODY TEMPERATURE

LIQUID THERMOMETERS

We now know that an increase in temperature corresponds to an increase in the average kinetic energy of atoms and molecules. A result of that increased motion is that the average distance between atoms and molecules increases as the temperature increases. This phenomenon, known as thermal expansion is the basis for temperature measurement by liquid thermometer.



A clinical thermometer based on the thermal expansion of a confined liquid.

Image Credit: Clinical Thermometer by Menchi via Wikimedia Commons

1

Common liquid thermometers use the thermal expansion of alcohol confined within a glass or plastic tube to measure temperature. Due to thermal expansion, the alcohol volume changes with temperature. The thermometer must be calibrated by marking the various fluid levels when the thermometer is placed in an environment with a known temperature, such as water boiling at sea level.

Reinforcement Exercise

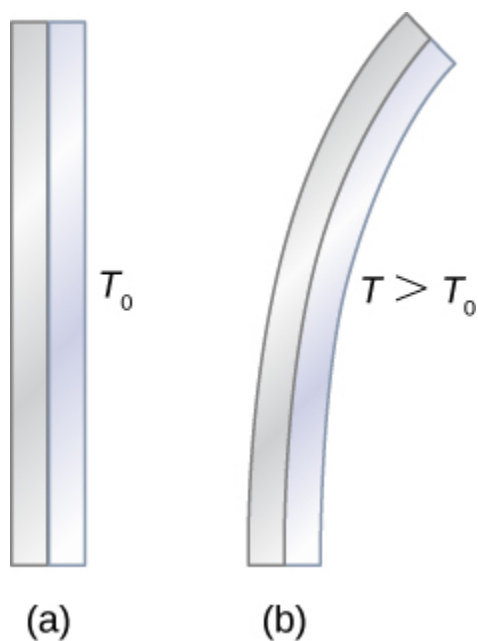
You may have noticed that when you place a liquid thermometer

1. Clinical Thermometer by Menchi [GFDL (<http://www.gnu.org/copyleft/fdl.html>) or CC-BY-SA-3.0 (<http://creativecommons.org/licenses/by-sa/3.0/>)] via Wikimedia Commons

into hot water, the liquid level actually drops momentarily, before beginning to climb as expected. Knowing what you do about thermal expansion, can you explain why this occurs?

BIMETALLIC STRIPS

Different materials will thermally expand (or contract) by different amounts when heated (or cooled). Bimetallic strips rely on this phenomenon to measure temperature. When two different materials are stuck together, the resulting structure will bend as the temperature changes due to the different thermal expansion experienced by each material.



The curvature of a bimetallic strip depends on temperature. (a) The strip is straight at the starting temperature, where its two components have the same length. (b) At a higher temperature, this strip bends to the right, because the metal on the left has expanded more than the metal on the right. At a lower temperature, the strip would bend to the left.
Image Credit: Openstax University Physics

2

LINEAR THERMAL EXPANSION

For most common materials the change in length (ΔL)

2. OpenStax University Physics, University Physics. OpenStax CNX. May 10, 2018
<http://cnx.org/contents/74fd2873-157d-4392-bf01-2fccab830f2c@5.301>.

) caused by a change in temperature (ΔT) is proportional to the original length (L_0) and can be modeled using the linear thermal expansion coefficient (α) and the following equation:

$$(1) \Delta L = \alpha L_0 \Delta T$$

The following table provides the linear thermal expansion coefficients for different solid materials. More expansive (ha!) tables can be found online.

Thermal Expansion Coefficients	
material	coefficient of linear expansion (1/°C)
<i>Solids</i>	
Aluminum	25×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Gold	14×10^{-6}
Iron or steel	12×10^{-6}
Invar (nickel-iron alloy)	0.9×10^{-6}
Lead	29×10^{-6}
Silver	18×10^{-6}
Glass (ordinary)	9×10^{-6}
Glass (Pyrex®)	3×10^{-6}
Quartz	0.4×10^{-6}
Concrete, brick	$\sim 12 \times 10^{-6}$
Marble (average)	2.5×10^{-6}

Everyday Example

The main span of San Francisco's Golden Gate Bridge is 1275 m long at its coldest. The bridge is exposed to temperatures ranging from -15°C to 40°C . What is its change in length between these temperatures? Assume that the bridge is made entirely of steel.

We can use the equation for linear thermal expansion:

$$\Delta L = \alpha L_0 \Delta T$$

Substitute all of the known values into the equation, including the linear thermal expansion coefficient for steel and the initial and final temperatures:

$$\Delta L = 12 \times 10^{-6} \frac{1}{^{\circ}\text{C}} (1275 \text{ m}) (40^{\circ}\text{C} - (-15^{\circ}\text{C})) = 0.84 \text{ m}$$

Although not large compared to the length of the bridge, the change in length of nearly one meter is observable and important. Thermal expansion could cause bridges to buckle if not for the incorporation of gaps, known as expansion joints, into the design.



Expansion joint on the Golden Gate Bridge. Image Credit: Expansion Joint Golden Gate Bridge by Michiel1972 via Wikimedia Commons

3

Reinforcement Exercises

A deep-space satellite made primarily of aluminum is 12 m long when launched at 22 °C (72 °F).

If the satellite comes eventually come to thermal equilibrium with the cosmic microwave background temperature at -270.45 °C (-455 °F).⁴

3. Michiel1972 [CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>)], via Wikimedia Commons

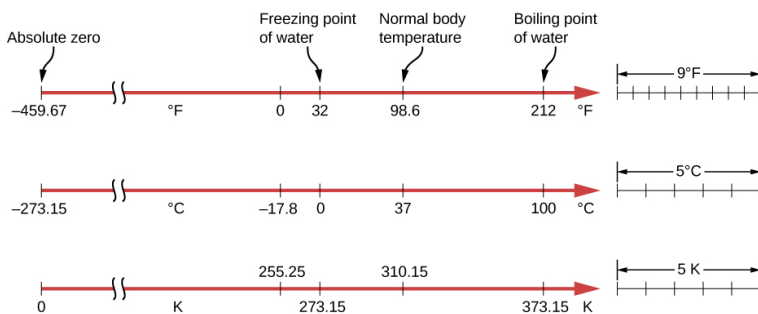
4. "Web-based hypothermia information: a critical assessment of Internet resources and a comparison to peer-reviewed literature" by Dr. Eric Christian, Cosmicopia, NASA is in the Public Domain

How much will the satellite change length?

What will the new length be?

TEMPERATURE UNITS

Thermometers measure temperature according to well-defined scales of measurement. The three most common temperature scales are Fahrenheit, Celsius, and Kelvin. On the Celsius scale, the freezing point of water is 0°C and the boiling point is 100°C . The unit of temperature on this scale is the degree Celsius ($^{\circ}\text{C}$). The Fahrenheit scale ($^{\circ}\text{F}$) has the freezing point of water at 32°F and the boiling point 212°F . You can see that 100 Celsius degrees span the same range as 180 Fahrenheit degrees. Thus, a temperature difference of one degree on the Celsius scale is 1.8 times as large as a difference of one degree on the Fahrenheit scale, as illustrated by the top two scales in the following diagram.



Relationships between the Fahrenheit, Celsius, and Kelvin temperature scales are shown. The relative sizes of the scales are also shown. Image Credit: Temperature Scales diagram from OpenStax University Physics[footnote]

THE KELVIN SCALE

The definition of temperature in terms of molecular motion suggests that there should be a lowest possible temperature, where the average microscopic kinetic energy of molecules is zero (or the minimum allowed by the quantum nature of the particles). Experiments confirm the existence of such a temperature, called absolute zero. An absolute temperature scale is one whose zero point corresponds to absolute zero. Such scales are convenient in science because several physical quantities, such as the pressure in a gas, are directly related to absolute temperature. Additionally, absolute scales allow us to use ratios of temperature, which relative scales do not. For example, 200 **K** is twice the temperature of 100 **K**, but 200 °C is not twice the temperature of 100 °C.

The Kelvin scale is the absolute temperature scale that is commonly used in science. The SI temperature unit is the Kelvin, which is abbreviated **K** (but not accompanied by a degree sign). Thus 0 **K** is absolute zero, which corresponds to -273.15 °C. The size of Celsius and Kelvin units are set to be the same so that differences in temperature (ΔT) have the same value in both Kelvins and degrees Celsius. As a result, the freezing and boiling points of water in the Kelvin scale are 273.15 **K** and 373.15 **K**, respectively, as illustrated in the previous diagram.

You can convert between the various temperature scales using equations or various conversation programs, including some accessible online.

Reinforcement Exercise

Convert 50 °F to °C and then to K.

TEMPERATURE MEASUREMENT

In addition to thermal expansion, other temperature dependent physical properties can be used to measure temperature. Such properties include electrical resistance and optical properties such as reflection, emission and absorption of various colors. Light-based temperature measurement will come up again in the next chapter.

5

5. Significant content in this chapter was adapted from OpenStax University Physics which you can download for free at <http://cnx.org/contents/a591fa18-c3f4-4b3c-ad3e-840c0a6e95f4@1.322>.

CHAPTER 90.

PREVENTING HYPOTHERMIA

HYPOTHERMIA

The Stages of Hypothermia

Stage	Core Body Temperature °C	Symptoms
Mild Hypothermia	35°-33°	shivering, poor judgment, amnesia and apathy, increased heart and respiratory rate, cold and/or pale skin
Moderate Hypothermia	32.9°-27°	progressively decreasing levels of consciousness, stupor, shivering stops, decreased heart and respiratory rate, decreased reflex and voluntary motion, paradoxical undressing.
Severe Hypothermia	< 26.9°	low blood pressure and bradycardia, no reflex, loss of consciousness, coma, death

1

1. Adapted from "Web-based hypothermia information: a critical assessment of Internet resources and a comparison to peer-reviewed literature" by M Spencer, Jeremy & Sheridan, Scott, Perspectives in public health, 135(2) · February 2014

THERMAL POWER

The rate at which chemical potential energy is converted to thermal energy by the body (and other systems) is the thermal power. When the thermal power is less than the heat loss rate then the body will lose thermal energy over time and body temperature will drop. The only options for preventing hypothermia are slowing down the heat loss rate and/or increasing the thermal power. You can fight off hypothermia by doing additional work, such as jumping around, because the body is inefficient so most of the chemical potential energy used to do the work actually becomes thermal energy that can replace what was lost as heat. Shivering is your body's way of forcing you to take this approach and signifies a mild stage of hypothermia. However, this strategy will only be successful until you have used up your readily accessible supply of chemical potential energy. Basically, as you get tired this method will fail. The overall chemical to thermal energy conversion rate can be supplemented by technology such as chemical hand/foot warmers and battery powered heated clothing, but in most situations your body does the bulk of the conversion. Eventually these supplemental energy sources will also run out and body temperature will continue to drop. Moderate hypothermia is indicated by the end of shivering and increased mental confusion, possibly including hallucinations. Severe hypothermia leads to loss of consciousness and if not treated, eventually death.²

2. "Hypothermia and Cold Related Injuries" by J. Justad, MD, DDP, Health and Safety Guidelines, Montana Department of Health and Human Services

Everyday Example: Human Thermal Power

The typical daily intake of chemical potential energy required by the human body is 2000 Calories. A hard 8 hours of manual labor only accounts for 1/3 of a day and during the other 2/3 almost no useful work is done by the body so nearly all chemical energy being used is converted to thermal energy. Even when useful work is being done, the body is only about 25% efficient so most of the chemical energy used is still converted to thermal energy. Therefore we can reasonably approximate the thermal power (P_H) of the human body to be roughly 2000 Calories/day by assuming all chemical energy used eventually becomes thermal energy. Remembering that food Calories with a capital C are actually **kcal**s and that 4.186 Joules are in one calorie, we can use unit conversion to find the thermal power in SI units of Watts.

$$P_H = \left(\frac{2000 \text{ Calories}}{1 \text{ day}} \right) \left(\frac{1000 \text{ cal}}{1 \text{ Cal}} \right) \left(\frac{4.186 \text{ J}}{1 \text{ cal}} \right) \left(\frac{1 \text{ day}}{24 \text{ hrs}} \right) \left(\frac{1 \text{ hr}}{60 \text{ min}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right) \approx 100 \text{ W}$$

PREVENTING HYPOTHERMIA

Your body loses heat to the environment due to a natural tendency of systems to move toward thermal equilibrium. In fact the Second Law of Thermodynamics tells us that *objects left to themselves will always spontaneously trend toward thermal equilibrium with their environment*. For two objects to reach thermal equilibrium, heat must transfer

away from the hot object and into the cold one so that their temperatures move closer together. Therefore, a consequence of the Second Law of Thermodynamics is that *heat will always spontaneously transfer from warmer temperature to colder temperature*. Homeostasis is a constant battle against the consequences of the Second Law of Thermodynamics. We aren't able to violate the second law of thermodynamics and stop or reverse the spontaneous thermal energy transfer away from the body in cold environments, we can only try to slow it down.

Reinforcement Exercises

If you add equal parts of 10 °C water and 80 °C water, will you get 90 °C water?

Explain your answer in terms of the Second Law of Thermodynamics.

Also explain your answer in terms of the definition of temperature as a measure of the average kinetic energy per molecule.

HEAT TRANSFER

Materials designed to slow the heat transfer rate, or thermal insulation, can be used to help prevent hypothermia. There are three ways that heat is transferred out of the body, but all three methods follow the Second Law of Thermodynamics and transfer heat from warmer temperature to colder. The heat transfer mechanisms are:

1. ***Conduction***
2. ***Convection***
3. ***Radiation***

The following chapters will discuss these mechanisms and the types of insulation used to prevent each.

Everyday Examples: Insulation

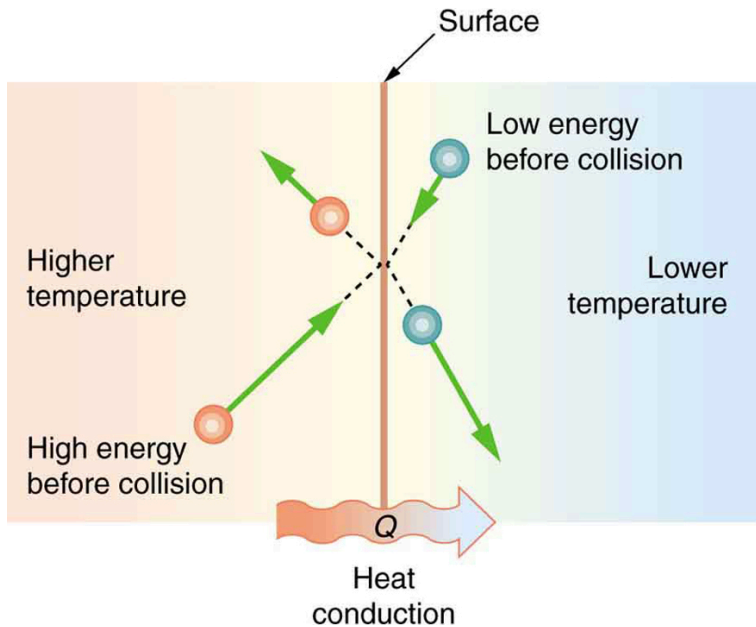
My father was a bush pilot in Alaska. When I was about 13 years old we were landing on a lake in our hometown and found two teenagers clinging to their overturned canoe. The first boy had a stocky build and second was tall and thin. The first boy climbed onto the float and into the plane with some assistance, the thin boy was unable to move and was dragged out of the water just before losing consciousness as we rode back to shore. We later learned that the thin boy had reached the third stage of hypothermia and was likely only minutes from death. The thin boy had less body mass, thinner layers of tissue to provide insulation, and less chemical potential energy stored up for conversion to thermal energy. Both boys were wearing cotton clothing, which did not provide much insulating value in the water. In the following chapters we will learn how each of these factors contributed to the dramatically different in responses of the two boys to their unplanned cold water immersion.

CHAPTER 91.

COTTON KILLS

CONDUCTION

Cotton is a great thermal insulator – as long as it's dry. Once wet, cotton becomes a poor insulator and does a poor job of preventing hypothermia-hence the old adage, “cotton kills”. To understand why cotton is sometimes good insulator and sometimes a poor one, we need to understand conduction, which is the transfer of thermal energy between objects by direct contact. The average kinetic energy of the molecules in a hot body is higher than in a colder body. If two molecules collide, an energy transfer from the molecule with greater kinetic energy to the molecule with less kinetic energy occurs. The cumulative effect from many collisions occurring at a surface of contact between the two objects results in transfer of heat from the hot object to the colder object, (or colder environment) in agreement with the Second Law of Thermodynamics.



The molecules in two objects at different temperatures have different average kinetic energies. Collisions occurring at the contact surface tend to transfer energy from high-temperature regions to low-temperature regions, in agreement with the second Law of Thermodynamics. In this illustration, a molecule in the lower temperature region (right side) has low energy before collision, but its energy increases after colliding with the contact surface. In contrast, a molecule in the higher temperature region (left side) has high energy before collision, but its energy decreases after colliding with the contact surface.

CONTACT AREA

The number of molecular collisions increases with increasing contact area (A_c), so the rate of heat conduction depends on the contact area. More collisions, and thus more time, will be needed to transfer the same amount of heat across a thicker material, so heat

transfer rate also depends on thickness, or length across which the heat is transferred (*d*). This model explains why thick clothing is warmer than thin clothing in winters, and why thin people are typically more susceptible to hypothermia.

TEMPERATURE DIFFERENCE

If the object temperatures are the same, the net heat transfer rate falls to zero, and thermal equilibrium is achieved. As the difference in temperature increases, the average kinetic energy transferred from fast to slow molecules during each collision also increases. Therefore the temperature difference also affects the rate of heat transfer by conduction.

THERMAL CONDUCTIVITY

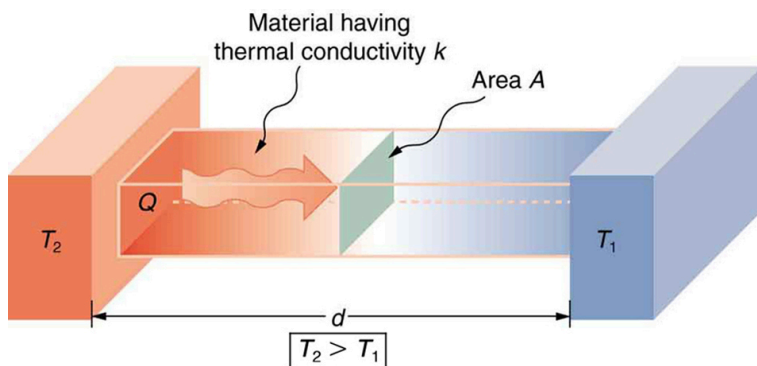
Lastly, some materials conduct thermal energy faster than others. In general, good conductors of electricity (metals like copper, aluminum, gold, and silver) are also good heat conductors, whereas insulators of electricity (wood, plastic, and rubber) are poor heat conductors. The effect of a material’s properties on conductive heat transfer rate is described by the coefficient of thermal conductivity (*k*), which is sometimes shortened to just *thermal conductivity*. The following table shows values of *k* for some common materials in units of Watts, per meter, per Kelvin ($W/(m \cdot K)$).

Thermal Conductivities of Common Substances	
substance	thermal conductivity ($W/(m \cdot K)$)
Silver	420
Copper	390

substance	thermal conductivity ($\frac{W}{m \cdot K}$)
Gold	318
Aluminum	220
Steel iron	80
Steel (stainless)	14
Ice	2.2
Glass (average)	0.84
Concrete brick	0.84
Water	0.6
Fatty tissue (without blood)	0.2
Asbestos	0.16
Plasterboard	0.16
Wood	0.08–0.16
Snow (dry)	0.10
Cork	0.042
Glass wool	0.042
Wool	0.04
Down feathers	0.025
Air	0.023
Styrofoam	0.010

CONDUCTION EQUATION

We can summarize all of the factors effecting the conductive heat transfer rate, which is an amount of energy transferred per time, in a single diagram:



Heat conduction occurs through any material, represented here by a rectangular bar, whether window glass or walrus blubber. The temperature of the material is T_2 on the left and T_1 on the right, where T_2 is greater than T_1 . The rate of heat transfer by conduction is directly proportional to the surface area A , the temperature difference, and the substance's conductivity k . The rate of heat transfer is inversely proportional to the thickness d .

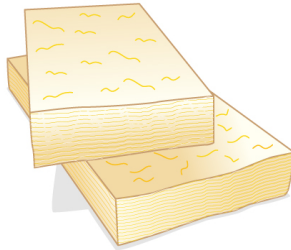
The rate of heat transfer across a material with temperature T_1 on one side and temperature T_2 on the other can be modeled by the conduction equation:

$$(1) \quad \frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

The rate of heat transfer (Q/t) refers to an amount of energy transferred per unit time so it has the same units as power (P). The term power is usually applied to a rate of transformation of energy from one form to another, but heat is a transfer of thermal energy from one place another, not a change in type of energy, thus we stick with $\frac{Q}{t}$ instead of P as the notation for this rate. This notation also reminds us that if we want to know how much energy was transferred during a certain time, we need to multiply the heat rate by the time.

INSULATION TECHNOLOGY

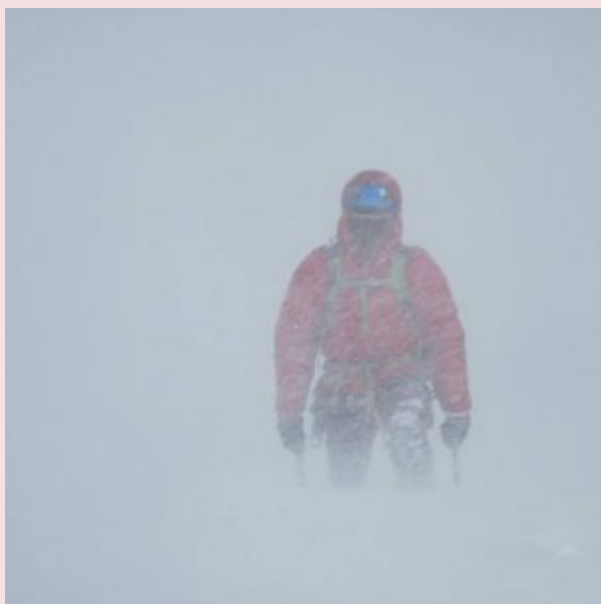
We can see from the conduction equation that combining thickness (loft) with low conductivity provides the greatest insulating effect. Goose down is the gold-standard insulation clothing for extreme-cold environments because it recovers loft after being compressed and it has low conductivity. As with most insulating materials, the effectiveness of down at reducing conduction is not due to the low conductivity of the feathers themselves, but rather their ability to trap air which has a very low conductivity. Double-pane windows, Styrofoam, animal hair, and the fiberglass insulation used in buildings all rely on this same strategy of trapping air to provide insulation.



The fiberglass batt is used for insulation of walls and ceilings to prevent heat transfer between the inside of the building and the outside environment.

Everyday Example: Down Insulation

Let's compare the insulating properties of a cotton sweatshirt and a down jacket, such as the one worn in the photograph below.



The author approaches the summit of Mt. Washington in the Central Oregon Cascades, in snowstorm, but wearing a down jacket. February 2017.

We will start with the conduction equation:

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

The outside temperature was about -10°C and skin temperature is roughly 37°C , so the temperature difference was about 47°C . When dry, the down jacket pictured is roughly 4 cm thick, which

0.04 m. The thermal conductivity of dry down is roughly $0.025 \frac{\text{W}}{\text{m} \cdot \text{K}}$. Using the methods in Chapter 17 we estimate the surface area of the upper body to be 0.5 m². Entering these values into the equation we find:

$$\frac{Q}{t} = \frac{(0.025 \text{ W}/(\text{m} \cdot \text{K}))(0.5 \text{ m}^2)(47 \text{ C}^\circ)}{0.04 \text{ m}} \approx 15 \text{ W}$$

So heat loss rate through the upper body in this situation is 15 W. That means 15 J of thermal energy is released to the environment as heat through the upper body each second. The typical human thermal power is 100 W so it appears that there is plenty of thermal energy available to maintain temperature. However, the 15 W value we found does not account for heat loss from the lower body, which we can see from the picture were not covered with down. In fact the single thin layer worn on the legs easily allowed for the other 85 W to escape so that body temperature was not elevated. In fact, doing the extra work of climbing the mountain likely raised the thermal power closer to 300 W so actually something closer to 285 W was being exhausted through the lower body. As a result, body temperature dropped quickly when climbing stopped and the thermal power fell back to about 100 W.

If the down were to get wet, things would change drastically. The down would lose its loft and end up with roughly 0.5 cm thickness. Even worse, the water would fill in the air spaces between the down fibers so the thermal conductivity would essentially be the same as for water, which is $0.6 \frac{\text{W}}{\text{m} \cdot \text{K}}$. Entering these values into the conduction equation we find:

$$\frac{Q}{t} = \frac{(0.6 \text{ W}/(\text{m} \cdot \text{K}))(1 \text{ m}^2)(47 \text{ C}^\circ)}{0.01 \text{ m}} \approx 5600 \text{ W}$$

Now that's a problem. The wet heat loss rate is nearly 190x faster than for the dry down in this situation, so to keep up we would need

to eat 188 candy bars every six hours, or 31 candy bars per hour! Our bodies would not be able to digest and convert chemical potential energy to thermal energy fast enough to keep warm in that situation and eventually hypothermia would occur. Later in this unit we will be able to estimate how long it would take for the body temperature to drop to dangerous levels in this situation. Down is clearly a poor insulator when wet, but even after drying the fibers do not naturally recover their original loft. Down is a poor choice of insulation in wet environments, though it does well in snow storms as long as the air temperature is cool enough that the snow doesn't melt when it lands on the jacket.

Everyday Examples: Cotton Kills

Just as with down, water can permeate the spaces between other fabrics like wool, synthetics, and cotton. The majority of water can be wrung out of wool and synthetics, partially restoring their insulating properties and helping them to dry out quickly and recover full insulation value. In the other hand, water fills space between cotton fibers and also saturates the fibers themselves. As a result cotton does not wring out well and dries slowly, so its thermal conductivity remains much closer to that of water than wool or synthetic. Cotton is a poor choice of insulation in wet environments.

Reinforcement Exercise: Single Pane Windows

Calculate the rate of heat loss through a window with dimensions $2\text{ m} \times 3\text{ m}$ with thickness of 5 mm when the inside temperature is

22 °C and the outdoor temperature is 12 °C. Use the thermal conductivity of glass listed in the table found in this chapter.

Find the heat lost through the window in one day, in units of **kW·hr**, by first converting your answer to kilowatts (**kW**) and then multiply by 24 hours .

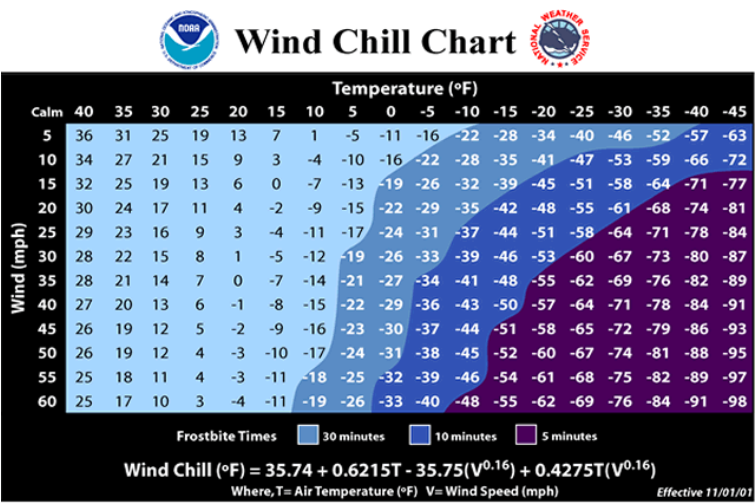
If electricity is \$0.12 per **kW·hr**, how much money is spent each day to replace the heat loss from the window using an electric heater?

Significant content in this chapter, including the table of conductivities, was adapted from College Physics, by BC Open Textbooks ¹

1. "Conduction" by College Physics, BC Open Textbooks is licensed under CC BY 4.0

CHAPTER 92.

WIND-CHILL FACTOR



The wind chill chart displays the theoretical calm air temperature which would produce the same cooling rate as the actual air temperature + wind combination. Image Credit: "Wind Chill Chart" by National Weather Service, NOAA

1. "Wind Chill Chart" by National Weather Service, NOAA is in the Public Domain

As stiff breeze can feel refreshing on a hot day and make a cool day feel quite cold. This phenomenon is known as the wind chill effect or just *wind chill*. Wind chill is a significant factor in thermal injuries such as hypothermia and frost bite, which is tissue damage caused by the formation of ice crystals within the tissue. The wind chill chart above shows what calm air temperature would be necessary to produce the same heat loss rate as the actual air temperature plus wind combination. The chart makes this calculation specifically for the skin on a human face. The chart also shows the exposure time which is likely to result in frostbite. For example, a day with 10 °F air temperature and 10 **mph** wind would feel as cold as a -7 °F day without wind.

Everyday Example

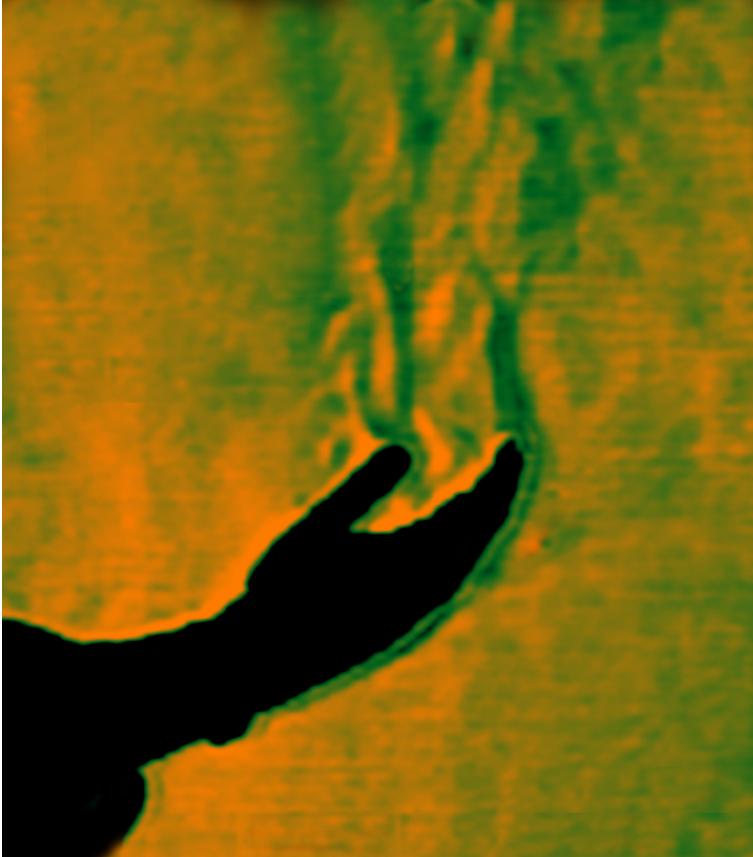
The author grew up in a small remote town on the tundra in Western Alaska. School was cancelled on days when the wind chill was less than -75 °F. According to the windchill chart, school could be cancelled on a -30 °F day with 55 **mph** wind or on a -45 °F day with 15 **mph** wind. Both of these combinations were entirely possible in Bethel, Alaska and growing up we usually had one or two wind chill cancellation days per year.

Reinforcement Exercises

What is the frostbite exposure time at -75 °F wind chill?

FORCED CONVECTION

In the absence of wind, a layer of warm air will form next to your skin, which effectively provides an additional layer of insulation known as a boundary layer. The thermal image below color-codes warm and cool air so that we can visualize the formation of the warm boundary layer. (In the next chapter we will learn how thermal images like this one are created.)



Thermal image showing air (green) warmed by conduction from the skin then rising within the surrounding cooler and more dense air due to natural convection, which is discussed in the following section. Forced convection is the reduction of this boundary layer by fluid due to factors other than the warming of the fluid itself, such as wind. Image Credit: "Thermal Plume from human hand" by Gary Settles via Wikimedia Commons

We can see that the skin-warmed layer is thin, but air has a very low thermal conductivity, so this layer can make an important contribution to slowing conduction. Wind tends to partially strip this insulating layer away and replace it with cooler air. The thickness of the warm boundary layer that is able to form depends on the wind speed, with higher speeds leading to thinner layers and causing greater wind chill effect. Wind chill is an example of forced convection, in which warm and cold fluid exchange places due to fluid motion caused by external factors such as blowing wind or flowing water.

Everyday Example: Hot Springs and Saunas

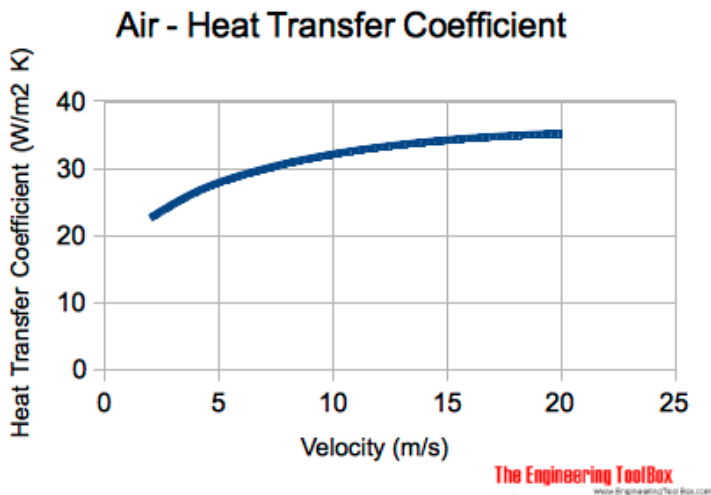
When submerged in fluid with a temperature higher than body temperature, such as in a hot spring or sauna, you may notice that the fluid suddenly feels hotter when you move around. Whether a fluid moves around you, or you move through the fluid, forced convection will occur in either case. When the fluid is warmer than your body then heat transfers out of the fluid into your body, leaving a slightly cooler boundary layer of fluid next to your skin. When you move this boundary layer gets left behind and replaced with new hot fluid that has not yet been cooled down by your body.

The rate of heat transfer by forced convection can be calculated using an empirical equation that looks very similar to the conduction equation:

$$(1) \quad Q/t = hA(T_2 - T_1)$$

Once again the heat transfer rate is proportional to a difference between the object and environment temperatures. Contact surface area (A), again plays a role, in this case between the object and the fluid. Finally the

convective heat transfer coefficient (h) incorporates fluid properties and accounts for the dependence of boundary layer thickness on fluid speed. The convective heat transfer coefficient is often determined experimentally. For example, the following graphs shows experimental data on the heat transfer coefficient for air at a range of wind speeds:



Graph of convective heat transfer coefficient data for air.

Reinforcement Exercises

Based on the data above, what is the convective heat transfer coefficient for air moving at 4.5 m/s?

Everyday Example: Cold Weather Survival

Cutting down on wind chill (forced convection) is an important part of the overall cold weather survival strategy. Let's evaluate the effects of forced convection during a wilderness survival situation at 25 °F (-3.9 °C) with a 10 mph (4.5 m/s) wind. Let's assume you are wearing thin fabrics that are fairly permeable to wind. Now we can approximate the effect of convection by assuming the fabric surface is the same as body temperature and applying the convection equation:

$$Q/t = hA(T_2 - T_1)$$

The difference between body temperature and the air temperature is 37 °C - (-3.9 °C) = 40.9 °C. The heat transfer coefficient is about 27, *boldfrac*Wm²·K according to the previous graph. Using the methods in Chapter 17 we estimate the surface of the upper body to be 1, *boldm*. Entering these values into the convection equation:

$$Q/t = (27 \frac{\text{W}}{\text{m}^2 \cdot \text{K}})(1 \text{ m}^2)(40.9 \text{ C}^\circ) \approx 1100 \text{ W}$$

The convective heat loss rate in this situation would completely overwhelm the 100 W resting thermal power of a typical person and body temperature would drop quickly. To see how quickly, check out the *Heat Capacity* chapter. Shivering can boost the thermal power

by up to 2.5 times, to roughly 250 W^4 , but even that would fall well short of balancing the convective heat loss rate. Finding shelter from the wind is an important part of the survival strategy. Carrying wind-stopping clothing is an important part of being prepared in the wilderness. Even a large plastic trash bag that could be worn over most of the body would significantly cut down on heat loss by convection.

Reinforcement Exercises

Use the conduction equation to estimate what air temperature would produce a *conductive* (no wind) heat loss rate equal to the 1100 W *convective* (windy) heat loss rate we calculated in the previous example.

Your answer is an approximation of the wind chill temperature for that situation of 25°F (-3.9°C) temperature with a 10 mph (4.5 m/s) wind. What is the difference between your answer the wind chill according to the chart? (Remember, the chart is developed specifically for exposed face skin).

NATURAL CONVECTION

Wind will not penetrate a well-sealed window, so it seems like forced convection should not be a significant factor in the heat loss through a window. However, a single pane of glass does a poor job of preventing conduction, so significant thermal energy still crosses the barrier. That thermal energy will warm up a boundary layer on the

4. "Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations" by Andrew J. Young, Michael N. Sawka and Kent B. Pandolf, National Center for Biotechnology Information, National Institutes of Health

outside of the window, which could then be stripped away by wind, so in fact wind chill may affect the rate of heat loss through the window. Double pane windows reduce conduction by using a layer of trapped air between two panes of glass.

A diagram showing two glass panes separated by a gap filled with a gas. Arrows indicate that conduction occurs across the glass panes from right to left. Arrows indicate that a convection cell has formed in the gap, with gas rising on the right and falling on the left.

The gap within a double pane window is too small for efficient convection cells to form. Filling the gap with a less conductive, more viscous (or slow-moving) and low pressure gas further reduces both conduction and convection through the gas. A mixture of krypton and argon gases is often used as a compromise between thermal performance and cost. Image Credit: "Gas Filled Windows" by John A Dutton e-science Institute, Penn State College of Earth and Mineral Sciences

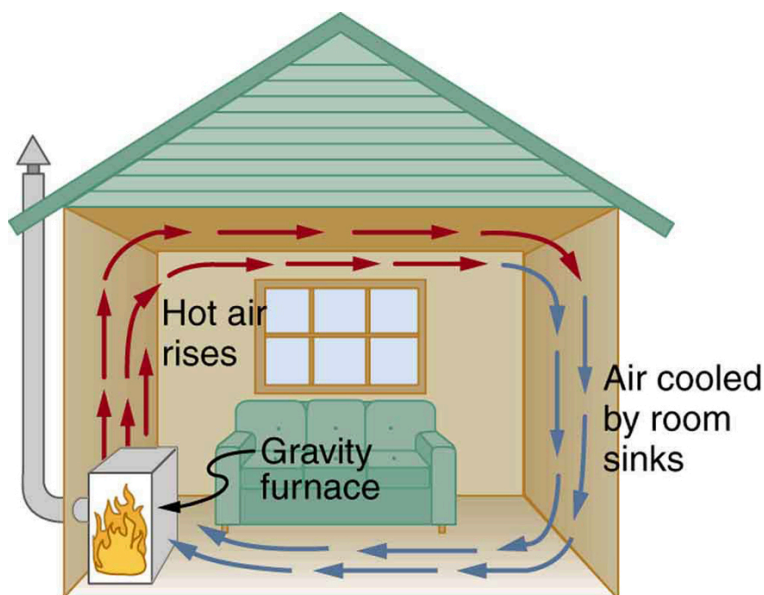
5

We know that conduction is reduced across a double pane window because the thermal conductivity of air is exceptionally low, but the air gap in a double pane windows is typically only about 2 **cm**. Considering that the rate of heat transfer by conduction decreases as the thickness of the air layer increases, why don't double pane

5. "Gas Filled Windows" by John A Dutton e-science Institute, Penn State College of Earth and Mineral Sciences is licensed under CC BY-NC-SA 4.0

windows have a much larger gap? Why not minimize conduction by making the gap almost the full thickness of the wall? Natural convection is the answer to that question. Natural convection is transfer of heat due to fluid movement caused by thermal expansion of the fluid itself, rather than by external factors such as wind. For example, you warm the air next to your skin and that air expands. After expanding, that same mass of air now has a larger volume, thus by definition it has a lower density. Being less dense than the surrounding cooler air, the warm air will float upward, as you can see in the previous thermal image of a person's hand. (To remind yourself why the warmer and less dense air will rise, see the earlier chapter on buoyant forces).

As the warmed air rises away from the skin it is replaced by cool air moving in from each side of the warm surface, which is then warmed before rising, creating a cyclic flow pattern known as a convection cell. Overall the convection cells transport thermal energy away from the skin (or any warm object).



*A convection cell powered by thermal energy input from a furnace transfers thermal energy throughout a room. Unfortunately most of the warm air is the top half of the room, not near the bottom half where people usually hang out.
Image Credit:OpenStax, College Physics*

6

Using double pane windows with a large air gap would allow for large convection cells to form and those cells would efficiently transfer thermal energy across the gap. Keeping the gaps size small prevents large convection cells from forming.

Everyday Examples: Down, double-pane windows, fiberglass and fur

Most insulation strategies create a fiber matrix that traps small pockets of air exploit the low thermal conductivity while preventing large convection cells from forming. Down, fiberglass batting, and fur are examples of this strategy. The fibers of these materials have conductivity greater than air, so trapping more air with fewer fibers provides the lowest overall average conductivity. In fact, some animals, such as polar bears, have hollow fur to increase the ratio of air to matrix material.⁷ The best insulation strategies combine an air trapping matrix to minimize conduction and natural convection with a wind-stopping outer coating to prevent forced convection. In wet climates the wind-stopping layer should also be water proof to prevent water from filling the air pockets created by the underlying fiber matrix.

WIND POWER

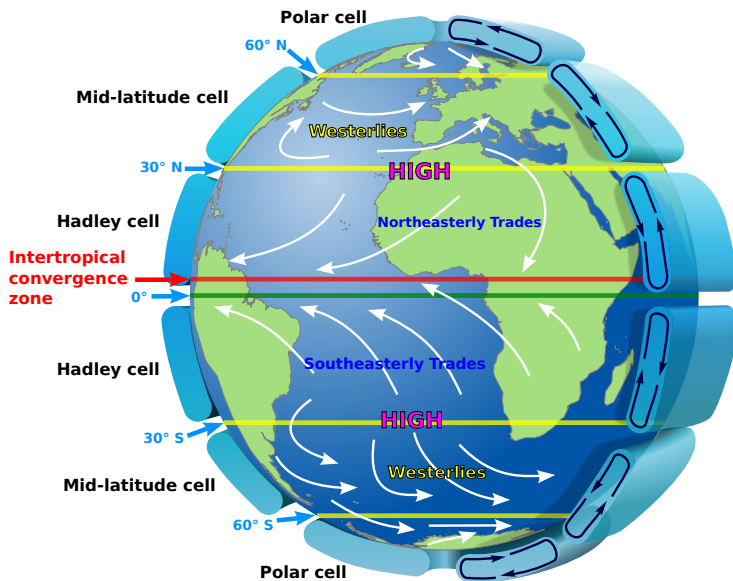
Convection cells drive heat transfer in a wide variety of systems on many scales. In fact the wind that serves to drive forced convection from your body is actually caused by natural convection cells. Such cells can form due to differential heating and cooling of the local geography. For example, the air above the ocean may remain cooler while the air above the coast warms rapidly during the day, resulting in an on-shore breeze (sea breeze) during the day. The convection cell reverses at night, creating an offshore breeze.

7. "Is Polar Bear Fur Transparent?" by Everyday Mysteries, The Library of Congress is in the Public Domain

Reinforcement Exercises

Draw the convection cells near a coastline both during the day and at night in order to show how on-shore and off-shore breezes are created by differential heating of ocean and coastline. Indicate the relative temperature of the water and land and air directly above for each case of day and night.

Wind is also produced by global scale convection cells. The following graphic shows the global-scale convection cells that drive the winds at various latitudes. Notice that the spinning of the Earth combined with the inertia of the air mass creates a Coriolis Effect, which causes the wind direction to curve away from the direction indicated at the bottom of the convection cell. You may notice that the latitudes of the great deserts and forests of the world match up with the boundaries between the cells. We will learn why in the next chapter.



Global convection cells and associated winds. Image Credit:

8

The predictability and stability of large scale convection cells allows for the growing implementation of wind turbine power plants. As our predictive skills continue to improve, along with turbine efficiency and energy storage technology, wind power is becoming a viable option for some communities.

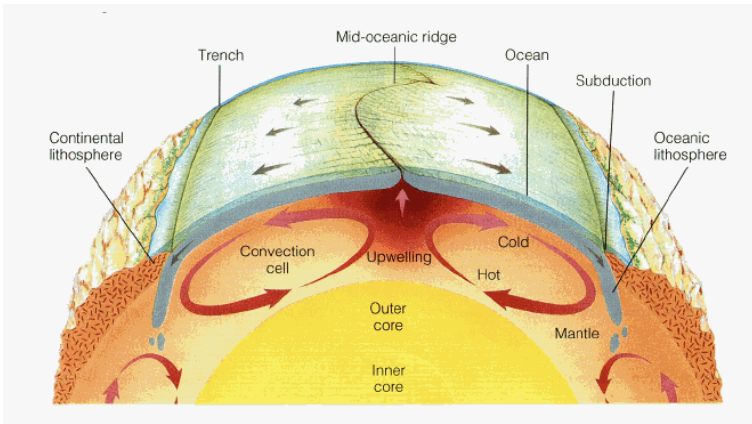


Burbo Bank Offshore Wind farm with North Wales in the background. Image credit: Burbo Bank offshore WindFarm by Ian Mantel via Wikimedia Commons

9

Convection cells are even responsible for moving the continents:

9. Burbo Bank Offshore WindFarm by Ian Mantel [CC BY-SA 4.0
(<https://creativecommons.org/licenses/by-sa/4.0>)], via Wikimedia Commons



Annotated illustration showing mantle convection and its relation to plate tectonics. Image Credit: Mantle Convection by Byrd Polar Research Center at Ohio State University, via the Science and Education Resource Center at Carlton College.

CHAPTER 93.

SPACE BLANKETS



U.S. Army Pfc. Robbin M. Chambers, a driver for 2nd Platoon, Alpha Company, 2nd Battalion, 162nd Infantry, 41st Infantry Brigade Combat Team, Oregon Army National Guard, opens a space blanket during a training exercise Oct. 24, 2014 in Kabul, Afghanistan.

1

1. "Oregon Soldiers complete medical training" by Capt. Leslie Reed, U.S. Army National Guard is in the Public Domain

THERMAL RADIATION

Space blankets, (a.k.a survival blankets) such as the one seen in the previous image, are very thin and have a thermal conductivity roughly 5x greater than air², therefore they are a poor at preventing heat loss by conduction. However, they do significantly reduce heat transfer by thermal radiation, which is the spontaneous emission of electromagnetic radiation by objects with temperature above absolute zero (so everything). Electromagnetic radiation sounds like a big deal, but it's really just the descriptive scientific way to say *light waves*. Depending on the temperature of the object, the emitted light may not be visible to us, but it's there nonetheless. For example, your body emits thermal radiation that we cannot see, but thermal imaging cameras can detect such light and allow us to "see" objects that are at a different temperature from their environment even when no external light source is present.

2. "Mylar Product Information" by DuPont Teijin Films



Thermograph of a persons face produced by a thermal imaging camera. The camera represents the intensity and color of detected thermal radiation that humans can't see with variations in visible color to create a false-color image. The actual light emitted by the person and detected by the thermal imaging camera has a color that we cannot see. Image Credit: "Self Portrait with Thermal Imager" by Nadya Peek via Wikimedia Commons

3

Space blankets reflect the electromagnetic radiation emitted by your body back to you, rather than letting it escape, thereby reducing the rate at which your body loses thermal energy to the environment. Thermal radiation transfer is the reason why clear nights feel colder than cloudy ones and why you frost forms on top of your car, but not on the ground beneath it. In order

3. "Self Portrait with Thermal Imager" by Nadya Peek [CC BY 2.0 (<https://creativecommons.org/licenses/by/2.0>)], via Wikimedia Commons

to explain these observed phenomenon and quantify heat loss from your body, we need to take a deeper look at thermal radiation.

STEPHAN-BOLTZMANN LAW

Some materials are more efficient at converting thermal energy to light than others and this material property, known as the emissivity (*epsilon*), affects the thermal radiation power (P_{out}). The radiated power also depends on the object's surface area (A) and temperature in Kelvin (T_o). The Stephan-Boltzmann Law relates the radiated power to all of these variables and the Stephan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{mK}^4)$):

$$(1) \quad P_{out} = \sigma \epsilon A T_o^4$$

Materials which are good at converting thermal energy into light will also be good at the reverse process of absorbing light and converting it to thermal energy in the material. As a result, the rate of heat transfer into an object by radiation ($P_{in} < em >$ " title="Rendered by QuickLaTeX.com" height="13" width="75" style="vertical-align: -2px;">) can also be modeled using the Stephan-Boltzmann Law with the same emissivity value, only the incoming radiation power is determined by the temperature of the environment (T_{env}) rather than the object.

$$(2) \quad P_{in} = \sigma \epsilon A T_{env}^4$$

NET THERMAL RADIATION RATE

Subtracting the emitted radiation power from the absorbed radiation power we can determine the net radiation power to the object:

$$(3) \quad P_{net} = \sigma \epsilon A (T_{env}^4 - T_o^4)$$

Notice that when the object is warmer than its environment, P_{net} will be negative because more radiation will be leaving the object than is absorbed.

Everyday Example: Space Blankets

Let's evaluate the effectiveness of adding a space blanket during the wilderness survival example from the previous chapter. The situation was a 25 °F (-3.9 °C) day with a 10 mph wind and you are in thin clothes that don't stop the wind very well. Layering the space blanket on top should cut the wind, so right off the bat you save most of the 1100 **W** of heat loss rate due to forced convection (wind chill effect) that we calculated in the last chapter. The blanket will reduce conduction somewhat by trapping a layer of air, but natural convection within that layer will move heat to the blanket where it will be conducted across, so you still experience much of the 160 **W** conductive heat loss we calculated previously.

A space blanket would effectively eliminate the thermal radiation heat loss by reflecting your emitted radiation back to you. Even though you will still transfer thermal energy to the inside of the blanket by conduction and natural convection from the inside, the blanket will do a poor job of radiating that energy away to outside because it has a relatively low emissivity.

Let's figure out your heat loss rate without the space blanket in order to see what heat loss it actually saves you. To make the calculation easier, let's assume there is a layer of low clouds or heavy forest vegetation so that very little of the cold upper atmosphere is visible. In that case, the overall environmental temperature is just the -3.9 °C air temperature. We know body temperature 37 °C, but before we can calculate the net heat loss due to thermal radiation we must convert our temperatures to Kelvin:

$$T_{env} = -3.9^{\circ}\text{C} + 273.15 = 269.25 \text{ K}, T_o = 37^{\circ}\text{C} + 273.15 = 310.15 \text{ K}$$

Now we can work to apply the Stephan-Boltzmann Law for net radiation power:

$$P_{net} = \sigma \epsilon A (T_{env}^4 - T_o^4)$$

Using the methods in Chapter 17 we estimate the surface of the upper body to be $\approx 1 \text{ m}^2$. The typical emissivity of human skin is 0.985^4

$$P_{net} = (5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4))(0.985)(1 \text{ m}^2)(269.25^4 - 310.15^4) \approx 200 \text{ W}$$

We find that the rate of radiative heat loss would be approximately 200 W without a space blanket. Therefore the space blanket saves you 200 W of radiative heat loss and 1100 W of convective heat loss, leaving only the 160 W of conductive heat loss. We see that a space blanket can significantly reduce heat loss rate in some situations. Considering this benefit compared to its small weight and volume, a space blanket seems like a reasonable addition to a survival kit. However, *a space blanket will not serve as a substitute for appropriate clothing*. A typical person has a resting thermal power of roughly 100 W, therefore the person in our example would still have a 60 W thermal power deficit. Over time resulting energy loss would lower the body temperature until hypothermia triggered a shivering response, which could boost the thermal power by up to 2.5 times, or up to 250 W.⁵ This strategy would only work short term, until the person was too tired to shiver. Alternatively, if the person in this example had gotten wet while wearing cotton then the resulting rate of heat loss by conduction would be roughly 1100 W (calculated in the *Cotton Kills* chapter) and shivering would not be able to make up

4. "Table of Emissivity of Various Surfaces" by Mikron Instrument Company, Inc.

5. "Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations" by Andrew J. Young, Michael N. Sawka and Kent B. Pandolf, National Center for Biotechnology Information, National Institutes of Health

for the thermal power deficit, even in the short term. Even shivering would not significantly delay a dangerously low body temperature in the wet cotton situation.

Reinforcement Exercises: Space Walk

Space suits appear thick compared to everyday clothes, but considering that the effective temperature of space is 2.7 K (-455 °F; -270 °C), it seems like they would not be able to keep astronauts warm during a space walk, such as the one pictured below.



Astronaut Sunita L. Williams, Expedition 14 flight engineer, participates in the mission's third planned session of extravehicular activity (EVA) as construction resumes on the International Space Station. Astronaut Robert L. Curbeam, (out of frame), STS-116 mission specialist, also participated in the 7-hour, 31-minute spacewalk. Image Credit: "Sunita Williams astronaut spacewalk" by NASA, via Wikimedia Commons

Space suits do not need thick insulation because there is no material in space through which conduction, natural convection or forced convection could occur. Therefore radiation is the only possible heat transfer method to contend with. As long as the suits reflect the infrared radiation emitted by the astronaut's bodies, they should stay warm.

Calculate the rate of heat loss from a person in space if they wore a space suit that was transparent to thermal radiation (like wearing no suit at all). [Hint: Use the human skin emissivity value from the previous example.]

We have a complication to mention: many materials have different emissivity at different frequency, which is the property of light that we perceive as colors. If the fraction of electromagnetic radiation reflected by an object is the same at all visible frequencies, the object is gray; if the fraction depends on the frequency, the object has some other color. For instance, a red or reddish object reflects red light more strongly than other visible frequencies and because it absorbs less red, it radiates less red when hot. Therefore its emissivity would be lower at frequencies we see as red. Differential reflection and absorption of frequencies outside the visible range have no effect on what we see, but they may have physically important effects with regard to thermal radiation. Skin is a very good absorber and emitter of infrared radiation, having an emissivity of 0.97 in the infrared. This high infrared emissivity is why we can so easily feel infrared radiation from a campfire warming our skin, but also why our

6. "Sunita Williams astronaut spacewalk" by NASA, via Wikimedia Commons is in the public domain

bodies readily lose thermal energy by infrared radiation.

⁷OpenStax University Physics, University Physics Volume 2. OpenStax CNX. Nov 12, 2018 <http://cnx.org/contents/>

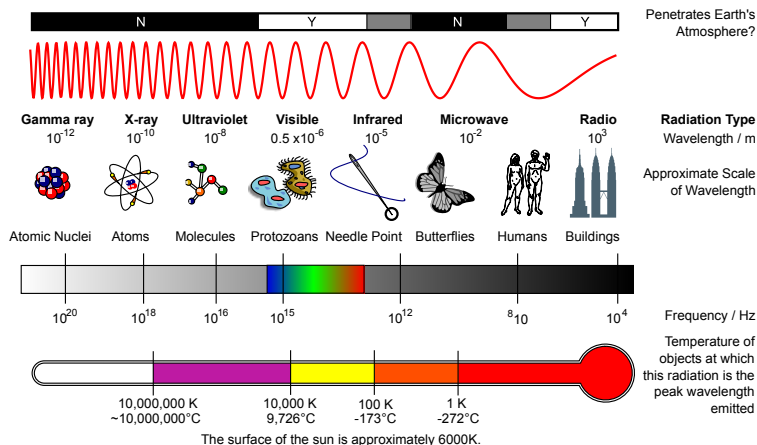
7a0f9770-1c44-4acd-9920-1cd9a99f2a1e@14.10[/footnote]

CHAPTER 94.

THERMAL RADIATION SPECTRA

THE ELECTROMAGNETIC SPECTRUM

Different names are used for electromagnetic radiation (light waves) with various ranges of frequency: radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. Collectively these ranges of frequencies make up the electromagnetic spectrum shown in the following diagram. The range frequencies that we can see is known as the visible spectrum, and we perceive the different frequencies within the visible spectrum as different colors. The wavelength of light, or any wave, is the distance between successive crests (peaks) of the wave. The frequency and wavelength of light waves are directly related and we can sometimes more easily relate to wavelength by comparing it to the length of familiar objects, so we often use wavelength instead of frequency to describe colors and the electromagnetic spectrum as a whole.



The electromagnetic spectrum. "EM Spectrum Properties reflected" by Inductiveload, via Wikimedia Commons

1

We can summarize the previous diagram in tabular form:

The previous diagram in tabular form

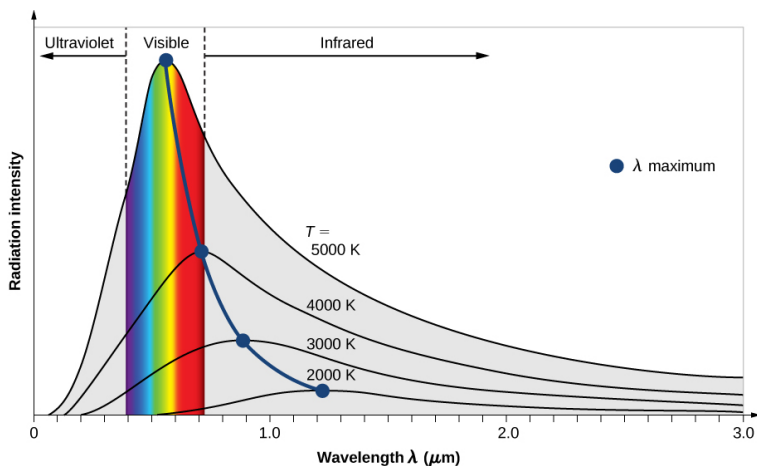
Radiation Type	Wavelength (m)	Approximate Wavelength Scale	Frequency (Hz)	Temperature of object with thermal radiation peak at this wavelength (K)	Significant penetration through atmosphere ?
Gamma Ray	10^{-12}	Atomic Nucli	10^{20}		No
X-ray	10^{-10}	Atoms	10^{18}	10,000,000	No
Ultraviolet (UV)	10^{-8}	Molecules	10^{16}		No (more at longer wavelength)
Visible	0.5^{-6}	Protozoans	10^{15}	10,000	Yes

1. "EM Spectrum Properties reflected" by Inductiveload [CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>)], via Wikimedia Commons

Infrared (IR)	10^{-5}	Needle Point	10^{12}	100	Yes (less at longer wavelength)
Microwave	10^{-2}	Butterflies	10^8	1	No
Radio	10^3	Humans to Buildings	10^4		Yes (less at shorter wavelength)

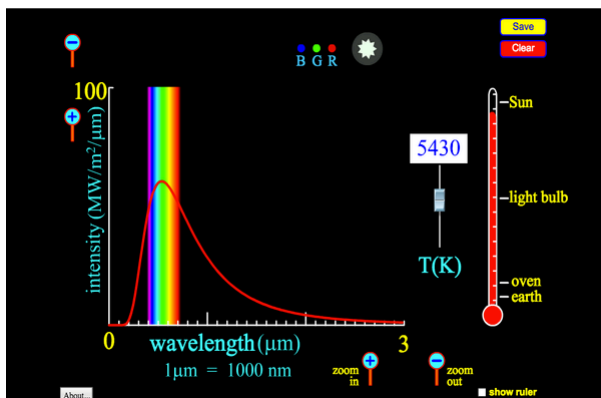
BLACK BODY RADIATION

A theoretically perfect emitter for which the emissivity is one ($\epsilon = 1$) is known as black body emitter, because such an emitter would also be a perfect absorber and would thus appear completely black. The shape and amount of light emitted at each wavelength defines the emission spectrum of the black body, which depends only on temperature in a well-defined way:



The intensity of black body radiation plotted against the wavelength of the emitted radiation. Each curve corresponds to a different black body temperature, starting with a low temperature (the lowest curve) to a high temperature (the highest curve). Image Credit: OpenStax University Physics Volume 3.

This simulations allows you to see how the black body emission spectrum depends on temperature:



We are often able to approximate the temperature of objects by assuming they are black body emitters and matching up their emission spectrum with that of a black body with a known temperature. This is the basic principle behind thermal imaging cameras and handheld infrared (IR) thermometers such as the one in the following image. (Note that IR thermometers are often include a low power laser to improve aim, but contrary to popular belief, the laser is not involved in the temperature measurement).

2. OpenStax University Physics, University Physics Volume 3. OpenStax CNX. Nov 12, 2018 <http://cnx.org/contents/af275420-6050-4707-995c-57b9cc13c358@10.14>.



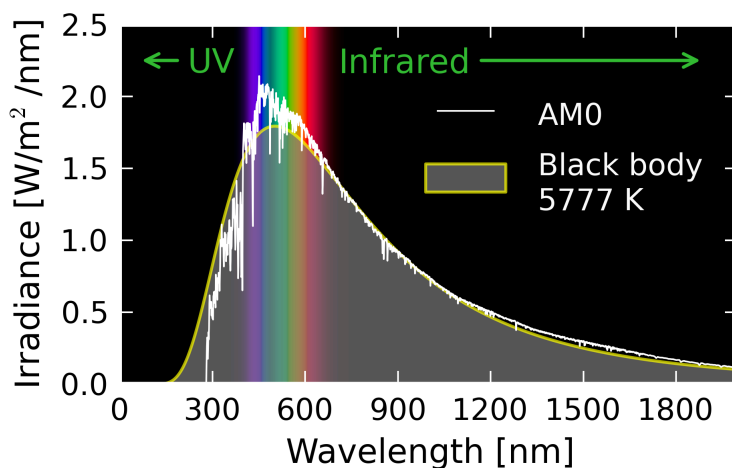
Contact tracers at a hospital in Conakry, Guinea demonstrate how to use a ThermoFlash infrared thermometer to monitor the temperatures of people who have come in contact with Ebola patients. Contacts are monitored for 21 days so that they can be isolated and treated as soon as possible if they develop symptoms. Image Credit: Infrared thermometer training by CDC Global via Wikimedia Commons.

3

For example, we can estimate the surface temperature of the sun to be roughly 6000 K ($10,000\text{ }^{\circ}\text{F}$) because the actual emission spectrum of the Sun best matches the black body emission spectrum of an object at 6000 K , as seen in the following graph. Notice that the peak of the Sun's emission spectrum is in the visible range, but that significant radiation power is found in the UV and

3. Infrared thermometer training by CDC Global [CC BY 2.0 (<https://creativecommons.org/licenses/by/2.0>)], via Wikimedia Commons

IR regions. The UV light is capable of penetrating the dead out layer of skin (epidermis) and breaking some molecular bonds in your cells, including those in DNA, which can lead to sunburn and increased risk of skin cancer.



Emission spectrum of the sun as measured above the Earth's atmosphere (AMO) compared to the black body spectrum of an object at 5777 K. Image Credit: Solar AMO spectrum with visible spectrum background (en) by Danmichaelo [Public domain], from Wikimedia Commons

Everyday Example: Incandescent vs LED and Fluorescent Light Bulbs

Incandescent light bulbs use thermal radiation to generate light. In order for their emission spectrum to contain significant visible light their temperature must be several thousand Kelvin, as seen from the previous graph showing black body emission spectra at several temperatures. Temperatures of 3000 K to 4000 K are achieved by

running electric current through the narrow filaments of inside the bulbs to cause resistive heating (conversion of electric potential energy to thermal energy). The filaments are made of high temperature tolerant metals like tungsten to prevent melting. Additionally, the majority of air within the bulb has been removed to prevent conduction and natural convection from heating the glass and to prevent the filaments from quickly oxidizing (rusting). The emission spectra for objects at 3000 K to 4000 K show us that much of their radiated power is in the IR range rather than the visible range, and thus doesn't provide useful illumination. Consequently, much of the electrical energy used to power incandescent light bulbs goes to waste. In fact, glass does absorb IR radiation so much of the wasted energy simply goes into making the bulb glass hot, in some cases dangerously so. Fluorescent and LED bulbs don't use thermal radiation to generate light. Instead they apply voltages to energize electric charges trapped in atoms or in semi-conductor materials. When the electrons de-energize they emitted light at specific wavelengths, reducing the wasteful production of non-visible light. However, light from incandescent bulbs is sometimes considered more pleasing because it more closely resembles the emission spectrum of fire.

DANGEROUSLY HOT CARS

Some materials are transparent to visible light, but readily absorb IR light (notice how glasses prevent IR light from reaching the camera in this thermal image). Liquid water, water vapor, carbon dioxide (CO₂) gas and most types of glass behave this way. The emission spectrum of the sun shown above has significant emission in the UV, visible, and IR parts of the electromagnetic spectrum. The visible light gets through the glass, which is why the glass

appears transparent to you. The majority of UV is absorbed or reflected, preventing you from getting sunburn inside the car. The glass absorbs much of the IR light, which is re-radiated in both directions, in and out of the car. The visible light that gets through is partially absorbed by the interior of the car (especially if the interior is dark). That absorbed visible light is then re-radiated as IR light because the interior of the car is not nearly hot enough to radiate visible light like the sun. That re-radiated IR light is absorbed by the glass and re-radiated again in both directions, in and out of the car. Therefore a significant portion of the incoming visible light energy gets trapped inside the car and the interior temperature can rise quickly, even if the outside air temperature is cool. Green houses use this same phenomenon to keep plants warm in cool weather, so this phenomenon is commonly known as the green house effect. It's never a good idea to leave children or pets in cars. Even if you perform thoughtful calculations to predict the interior temperature for a given set of conditions such as air temperature, wind speed, and cloudiness, those conditions can change quickly. It's best not to risk injury to loved ones.

THE GREENHOUSE GAS EFFECT

The Earth's atmosphere acts like a car's windshield. The atmosphere lets most UV and visible light through, but significant IR light is absorbed, primarily by water vapor and carbon dioxide gas. With respect to the Earth, this green-house effect is known as the Green House Gas Effect because the phenomenon is caused by gasses in the atmosphere instead of glass or plastic.

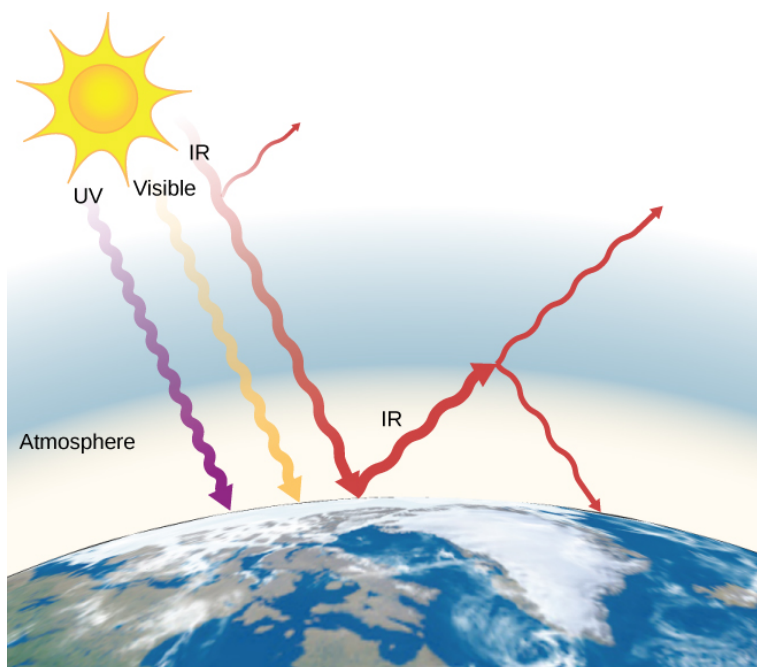
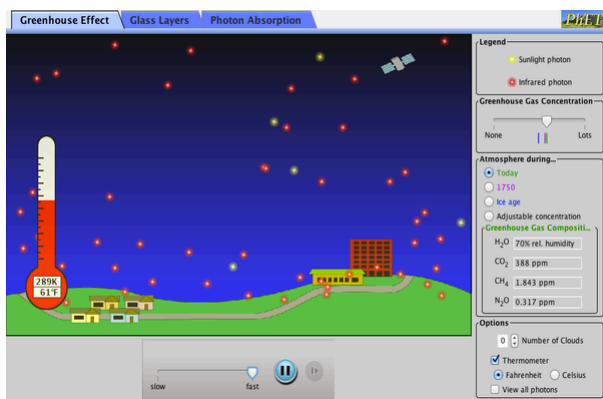


Illustration of the green house gas effect. UV, visible, and some IR light pass through the atmosphere. The UV and visible light are largely transformed to IR light. Only some of that IR light is able to escape back into space, the rest is trapped and the energy it contains increases the Earth's average temperature. Image Credit: OpenStax University Physics.

4

The green house gas effect helps to keep the Earth's temperature about 40 °C warmer than it would be without an atmosphere, which is a generally a good thing for us because most water on Earth would be frozen otherwise. Humans have established our modern infrastructure in accordance with the global climate that

was present over the last few hundred years, but emission of carbon dioxide and methane (and other greenhouse gases) into Earth's atmosphere from human activities strengthens the green house gas effect and increases the average temperature of the Earth. Higher temperature means more thermal energy is available to drive more powerful convection cells and other thermodynamic processes that define weather and climate. The resulting changes in global climate are likely to cause a variety of dangerous and expensive consequences such as higher storm intensity, rising sea levels, and increased flooding in certain areas with prolonged drought in others.⁵⁶ The following simulation allows you to examine how the green house gas effect works.



5. "Fourth National Climate Assessment" by U.S. Global Change Research Program
6. OpenStax University Physics, University Physics. OpenStax CNX. Oct 6, 2016
<http://cnx.org/contents/74fd2873-157d-4392-bf01-2fccab830f2c@1.585>

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CHAPTER 95.

COLD WEATHER SURVIVAL TIME

Stages of Hypothermia		
Stage	Core Body Temperature °C	Symptoms
Mild Hypothermia	35°-33°	shivering, poor judgment, amnesia and apathy, increased heart and respiratory rate, cold and/or pale skin
Moderate Hypothermia	32.9°-27°	progressively decreasing levels of consciousness, stupor, shivering stops, decreased heart and respiratory rate, decreased reflex and voluntary motion, paradoxical undressing.
Severe Hypothermia	< 26.9°	low blood pressure and bradycardia, no reflex, loss of consciousness, coma, death

1

Throughout this unit we have analyzed the rate of heat loss during a cold weather survival situation in which a person is wearing a single layer of thin clothing against an

1. Adapted from "Web-based hypothermia information: a critical assessment of Internet resources and a comparison to peer-reviewed literature" by M Spencer, Jeremy & Sheridan, Scott, Perspectives in public health, 135(2) · February 2014

10 **mph** wind and a $-3\text{ }^{\circ}\text{C}$ air temperature. Our analysis shows that collectively the person would experience a 200 **W** heat loss rate due to thermal radiation and a 1100 **W** heat loss rate due to forced convection. We also found that using a space blanket to reduce the wind chill and thermal radiation would leave only 160 **W** of heat loss rate due to conduction across the clothing. The typical person has a thermal power of 100 **W**, but shivering can increase that to 250 **W**.² It would be interesting to know, given these values for thermal power and heat loss rate, how quickly body temperature would actually change. In order to answer that question we need to learn about specific heat and heat capacity.

HUMAN HEAT CAPACITY

In the fight to maintain body temperature the human body gets assistance from the fact that the body is primarily made of water. The amount of thermal energy required to change the temperature of the body is relatively high compared to other objects of the same mass because water has a very high specific heat (c). Specific heat is a material property that defines the amount of thermal energy removed from one unit mass of the material when its temperature changes by one unit of temperature. For example, water has a specific heat of $4186\text{ J}/(\text{kg } ^{\circ}\text{C})$ so 4186 **J** of thermal energy must be removed from 1 **kg** of water in order for the temperature to drop by $1\text{ }^{\circ}\text{C}$. Multiplying the specific heat of a material by the mass of the material gives the heat capacity (C) of

2. "Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations" by Andrew J. Young, Michael N. Sawka and Kent B. Pandolf, National Center for Biotechnology Information, National Institutes of Health

the object. For example, the heat capacity for 80 **kg** of water would be: $4186 \text{ J}/(\text{kg } ^\circ\text{C}) \times 80 \text{ kg} = 334,880 \text{ J}/(^\circ\text{C})$, meaning that 334,880 **J** must be removed to drop the temperature of 80 **kg** of water by 1 $^\circ\text{C}$.

Reinforcement Exercises

Calculate the heat capacity of 150 **kg** of water.

Now that we know how to calculate heat capacity we are ready to calculate the amount of energy required to change the temperature of the body by a dangerous amount. We just multiply the mass (m) by the specific heat (c) to get heat capacity, which we then multiply by a dangerous temperature change ($\Delta T = T_f - T_i$) to get the heat required (Q). This entire process can be summed up by the equation:

$$(1) \quad Q = mc\Delta T$$

Notice that if the temperature is dropping then final temperature is less than the initial temperature so ΔT will be negative, which makes heat negative, indicating that thermal energy is leaving the object. The equation works for heating as well as cooling because in that case ΔT and Q will be positive indicating that thermal energy is entering the material.

Reinforcement Exercises

Calculate the heat required to raise the temperature of 150 **kg** of water from 14 $^\circ\text{C}$ to 40 $^\circ\text{C}$, as is necessary for a typical bath.

Calculate the cost of one bath when using an electric water heater and energy is sold at 12 cents per $\text{kW} \cdot \text{hr}$. Assume the water heater is 100% efficient at converting electrical energy into thermal energy and transferring that to the water as heat.

One bath per day would cost how much each month?

The following chart provides specific heat values for various substances. Notice the relatively high specific heat of water.

Table of Specific Heat Values

substances	specific heat (c)	
	J/kg·°C	kcal/kg·°C
Solids		
Aluminum	900	0.215
Asbestos	800	0.19
Concrete, granite (average)	840	0.20
Copper	387	0.0924
Glass	840	0.20
Gold	129	0.0308
Human body (average at 37 °C)	3500	0.83
Ice (average, -50°C to 0°C)	2090	0.50
Iron, steel	452	0.108
Lead	128	0.0305
Silver	235	0.0562
Wood	1700	0.4
Liquids		
Benzene	1740	0.415
Ethanol	2450	0.586
Glycerin	2410	0.576
Mercury	139	0.0333

substances	specific heat (c)	
Water (15.0 °C)	4186	1.000
<i>Gases</i>		
Air (dry)	721 (1015)	0.172 (0.242)
Ammonia	1670 (2190)	0.399 (0.523)
Carbon dioxide	638 (833)	0.152 (0.199)
Nitrogen	739 (1040)	0.177 (0.248)
Oxygen	651 (913)	0.156 (0.218)
Steam (100°C)	1520 (2020)	0.363 (0.482)

3

Everyday Examples: Cold Weather Survival Time

Applying the previous equation to the human body we can estimate how long it would take body temperature to drop from a normal 37 °C down to the edge of moderate hypothermia at 33 °C in the example survival situations discuss so far in this unit. Let's use relatively common human mass of about 80 kg and the average specific heat of human tissue of 3470 J/(kg C°). ⁴First we find the heat loss required for the temperature drop:

$$Q = mc\Delta T = (80 \text{ kg}) \left(3470 \frac{\text{J}}{\text{kg C}^\circ} \right) (33 \text{ C}^\circ - 37 \text{ C}^\circ) \approx 1,000,000 \text{ J}$$

We know that in our example of a 10 mph wind and a -3 °C air temperature we found that a person with thin clothing and no space

3. OpenStax, College Physics. OpenStax CNX. Nov 8, 2018 <http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.4>

4. Engineering ToolBox, (2001). [online] Available at: <https://www.engineeringtoolbox.com> [Accessed 27 1 2019]

blanket experienced **1100 W** of convective heat loss and **200 W** of radiative heat loss for a total of **1300 W**. If the person was shivering then their thermal power would be roughly **250 W**. This person would have a **1150 W** thermal power deficit meaning that they lose 1150 Joules of thermal energy each second. Dividing the dangerous heat loss we calculated above, by the thermal power deficit gives us the time required to lose that much heat:

$$t = \frac{1,000,000 \text{ J}}{1150 \text{ J/s}} \approx 900 \text{ s}$$

Dividing the **900 s** by **60 (s/min)**, we see that hypothermia would be reached in only 14 minutes. In reality, the rate of heat loss depends on the temperature difference so the heat loss rate would not be constant, but instead it would slow a bit as body temperature decreased. In our example case the **40.9 C°** difference between the body temperature and environment temperature changed by only about **3 C°** (seven percent). Ignoring this effect gives a reasonable approximation for the time until moderate hypothermia. The next two sections will address this approximation and allow us to calculate the time required for more significant temperature changes.

Exercises

We found previously that a person in wet cotton, but with a space blanket would experience an **1100 W** heat loss rate, giving an **850 W** deficit. Calculate the time to moderate hypothermia in this situation, in minutes.

Calculate the time in minutes to moderate hypothermia for an **80 kg** person wearing wet down in the mountain climbing example at the start of this chapter, for which the rate of heat loss was **5600 W**.

Calculate the time in minutes to reach severe hypothermia body temperature (see hypothermia chart) for a person in the same situation as the previous everyday example, but with a mass of only 60 kg.

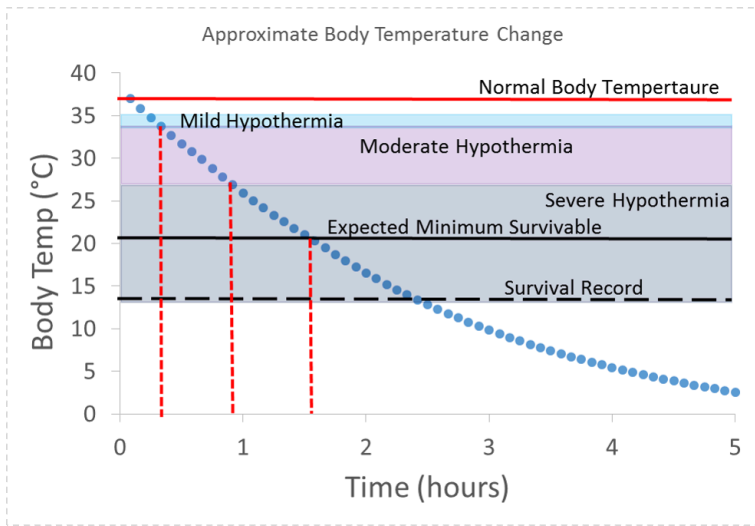
RATES OF BODY TEMPERATURE CHANGE

The rate at which thermal energy is transferred out of the body depends on the difference in temperature between the body and the environment. As the body cools closer to the environmental temperature the rate will decrease. In the previous example we ignored this reality and assumed that the cooling rate was constant, which was reasonable because we only examined a very small temperature change. For our example situation we found that mild hypothermia would be reached in only twenty minutes. The graph below was produced by calculating the body temperature while accounting for a cooling rate that depends on the temperature difference. This was done using a numerical model:

1. calculating a heat transfer rate for the initial body temperature due to both thermal radiation and forced convection
2. using that heat transfer rate to calculate the amount of heat transferred over a relatively short time interval
3. using the amount of heat transferred to calculate a resulting reduction in body temperature
4. calculating a new body temperature by subtracting the reduction in body temperature
5. repeat 1-5 until temperature was well beyond

survival temperature, keeping track of the temperatures and times to make the graph

We see that the time to mild hypothermia is actually more like 30 mins. We also see that severe hypothermia could set in after less than an hour and the minimum survivable temperature could be reached in under two hours. For the purpose of these calculations we assumed a thermal power of 250 **W** while shivering, and that shivering stops when the body reaches 30 °C, at which point thermal power returns to 100 **W**. We also assumed the that thermal power dropped to zero when body temperature reached 21 °C.



Predicted body temperature during a simplified example survival situation.

Approximate body temperature vs. time for an 80 **kg** person in 25 °F air temperature and 10 mph wind (-3 °C , 4.5 **m/s**). For the purpose of these calculations we

assumed a thermal power of 250 W while shivering, that shivering stops at 30 °C at which point thermal power returns to 100 W, and that thermal power dropped to zero below 21 °C. Minimum survivable body temperature and record low body temperature survived were found at “How Cold Can a Body Get” by Ali Venosa, Medical Daily and “Frozen Alive” by Peter Stark, Outside Magazine.

Modeling how body temperature changes with time under different insulation and temperature conditions allows forensic investigators to measure a body's temperature and work backwards to determine the time at which body temperature started to drop from normal. In this way time of death can be determined (unless of course the person was hypothermic or hyperthermic before death).

CHAPTER 96.

PREVENTING HYPERTHERMIA



Whole body hyperthermia is a method to raise a patient's body temperature for the treatment of advanced cancer. This technique is based on laboratory studies that show cancer cells are more sensitive to heat injury than normal cells. Physicians induce hyperthermia using a high-flow water suit controlled by a microprocessor, a machine which closely monitors body temperature. The

patient's body temperature is raised by the insulated build-up of metabolic (body) heat, plus by the heat delivered by the warm-water suit. Image Credit: Hyperthermia Patient by Mike Mitchell (photographer) [Public domain], via Wikimedia Commons

1

Hyperthermia, as opposed to hypothermia, occurs when body temperature increases as thermal energy builds up the body because heat is not transferred out of the body fast enough to keep up with the body's thermal power. We can try to avoid such a situation by minimizing our work output to reduce overall thermal power (remember, the body has low efficiency so doing work means generating thermal energy). We can also use our understanding of the conduction, convection, and thermal radiation to ensure maximum heat transfer away from the body. For example, we can minimize the thickness of clothing to increase conduction, wear light colored clothing to reduce radiation absorbed from the sun, and encourage air circulation (convection).

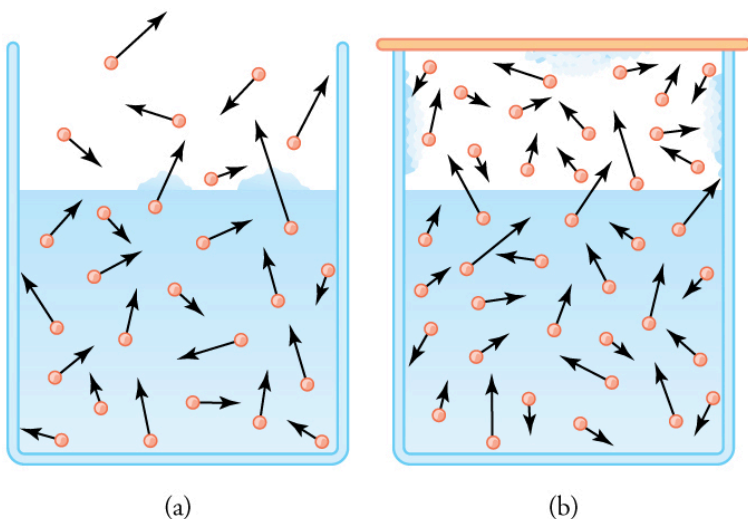
1. Hyperthermia Patient by Mike Mitchell (photographer) [Public domain], via Wikimedia Commons



The clothing worn by the people in this image was designed to minimize energy absorbed from the sun (light colors), not hinder conduction (thin), and allow convection (open, breathable). Image credit: OpenStax University Physics.

SWEATING

In some cases our thermal power outpaces the rate at which we exhaust heat by conduction, convection and radiation. Our strategy to deal with this situation is sweating. When we sweat some of the water on our skin evaporates into a water vapor. Only the molecules with the most kinetic energy are able to escape the attraction of their fellow water molecules and enter the air. Therefore the evaporating molecules remove more than a fair share of the thermal energy (thermal energy is just molecular kinetic energy remember). The remaining liquid water molecules then have less thermal energy on average, so they are at a lower temperature and must absorb more energy from your body as they come to thermal equilibrium with your body again. This evaporation process allows the body to dump thermal energy even when the environment is too warm for significant heat loss by conduction, convection, and radiation. The amount of energy removed by evaporation is quantified by the latent heat of vaporization (L_v). For water $L_v = 2,260 \text{ kJ/kg}$, which means that for every kilogram of sweat evaporated, 2260 kiloJoules of energy is transferred away from the skin.



The liquid temperature is determined by the average of the kinetic energy of atoms and molecules. At any moment the molecules will have a range of individual kinetic energies, some will have greater energy than the average and some less. (a) Those molecules with sufficiently large kinetic energy can break away to the vapor phase even at temperatures below the ordinary boiling point. (b) If the container is sealed, evaporation will continue until the space above the water reaches 100% Relative Humidity, meaning there is so many water molecules in the vapor phase that they re-enter the liquid phase just as often as they evaporate. At 100% humidity evaporation will no longer provide a net cooling effect. Image Credit: OpenStax, Humidity, Evaporation, and Boiling

Everyday Example

A person working in an environment that happens to be very close to body temperature (about 100 °F) would not be able to get rid of thermal energy by conduction, convection, or radiation. If the person was working hard and generating about 250 W of thermal power (similar to the thermal power while shivering) then how much sweat would need to be evaporated each hour to keep their body temperature from rising?

In order to keep the body temperature from rising the person needs to get rid of 250 **W** of thermal energy, that's 250 **J/s**. Let's convert that to Joules per hour:

$$(1) \quad (250 \text{ J/s}) = (250 \text{ J/s})(60 \text{ s/min})(60 \text{ min/hr}) = 900,000 \text{ J/hr}$$

Each kilogram of water that evaporates removes 2,260,000 J of energy, so only a fraction of a kilogram will need to be evaporated every hour:

$$(2) \quad \frac{\text{mass}}{\text{second}} = \frac{900,000 \text{ J/hr}}{2,260,000 \text{ J/kg}} = 0.4 \text{ kg/hr}$$

The body would need to evaporate 0.4 **kg** per hour. Water has a density of about 1 kg/L, so that would be a volume of 0.4 **L/hr**, or roughly 1.7 **cups/hr**, or 13.5 **fluid oz/hr**.

Exercises

The visitor center at Zion National Park uses evaporative cooling towers to condition the inside air⁴. During the day, the center receives heat from the environment through conduction, convection,

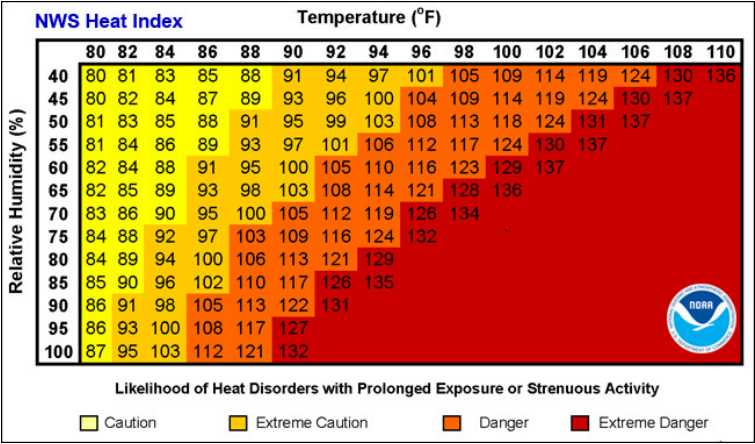
and radiation. In order to maintain a constant temperature that heat must be removed, typically by an air conditioning system. At the visitor center, evaporation of water in the cooling towers removes heat so the air conditioning system doesn't have to.

If the visitor center receives average of **45 MJ/hr** of heat from the environment, what mass of water would need to be evaporated each hour (**kg/hr**) in order to counter-balance all **45 MJ/hr** of incoming heat?

How many liters per hour of water would that be?

4. "Zion National Park Visitor Center" by National Renewable Energy Laboratory, U.S. Department of Energy is in the Public Domain

HEAT INDEX



The Heat Index is a measure of how hot it really feels when relative humidity is factored in with the actual air temperature. To find the Heat Index temperature, look at the Heat Index Chart above or check our Heat Index Calculator. As an example, if the air temperature is 96°F and the relative humidity is 65%, the heat index-how hot it feels-is 121°F. The red area without numbers indicates extreme danger. Image Credit: "Heat Index" by National Weather Service, NOAA is in the Public Domain

5

The rate at which water will evaporate depends on the liquid temperature and the relative humidity of the surrounding air. The relative humidity is a measure of how many water molecules are in the vapor phase relative to the maximum number that could possibly be in the vapor phase at a given temperature. A relative humidity of 100% means that no more water molecules can be added to the vapor phase. If the humidity is high, then

5. "Heat Index" by National Weather Service, NOAA is in the Public Domain

evaporation will be slow and may not provide sufficient cooling. The heat index takes into account both air temperature and the relative humidity to determine how difficult it will be for your body to exhaust heat. Specifically, the heat index provides the theoretical air temperature that would be required at 20% humidity to create the same difficulty in exhausting heat as the actual temperature and humidity. Heat index values were devised for shady conditions with a light wind. Exposure to full sun or stagnant air can increase values by up to 15 degrees!

Exercises

Which of the following situations has a greater heat index temperature, or “feels-like” temperature:

- 90 % Relative Humidity and 85 °F
- 40 % Relative Humidity and 96 °F

BOILING AND THE BENDS

We have learned that evaporation takes place even when a liquid isn't boiling, so we may be wondering what causes boiling and how is it different from normal evaporation? Water ordinarily contains significant amounts of dissolved air and other impurities, which are observed as small bubbles of air in a glass of water. The bubbles formed within the water so the relative humidity inside the bubbles is 100%, meaning the maximum possible number of water molecules are inside the bubble as vapor. Those molecules collide with the walls of the

bubble causing an outward pressure. The speed of the water molecules increases with temperature, so the pressure they exert does as well. At 100 °C the internal pressure exerted by the water vapor is equal to the atmospheric pressure trying to collapse the bubbles, so rather than collapse they will expand and rise, causing boiling. Once water is boiling, any additional thermal energy input goes into changing liquid water to water vapor, so the water will not increase temperature. Turning up the burner on the stove will not cook the food faster, it will just more quickly boil away (evaporate) the water.

Everyday Examples: The Bends

At high altitude the atmospheric pressure is lower, so molecules of water vapor don't need to create as much pressure within bubbles to maintain boiling. Therefore, boiling will occur at a lower temperature and cooking foods by boiling will take longer. (Food packaging often gives alternative cook times for high altitude).

The same process is responsible for *the bends*, which refers to the formation of nitrogen bubbles within the blood upon rapid ascent while SCUBA diving. You might imagine that you could hang out underwater by breathing through a hose, and that would work in very shallow water. However, the high pressure exerted by water at depths below roughly 2 m (6 ft) would prevent the diaphragm and rib cage from expanding to pull air into the lungs. At greater depths you need to breathe from a pressurized container which helps to force air into your lungs against the additional hydrostatic pressure. Of course if you breathed from the container at shallow depth then the pressure would be too high and would cause damage to your lungs. A

pressure regulator that outputs the appropriate pressure according to the water depth is the core of the SCUBA system.

There is always some gas dissolved in your blood, including carbon dioxide, oxygen, and nitrogen. The amount of dissolved gas is determined by the temperature and the pressure. If temperature is high enough, and pressure is low enough, then boiling will occur. Breathing high pressure air from a SCUBA system while at depth forces these gases to dissolve into your blood in the amounts determined by your body temperature and the high pressure.

When ascending, the pressure drops quickly, but the body temperature stays constant, so the blood gases can begin to boil, starting with Nitrogen. There is not issue with blood temperature here, blood is still at body temperature, but the bubbles are a problem for the cardiovascular system. To prevent *the bends*, you must ascend slowly, allowing the gasses to slowly escape from the blood and be expelled in the breath, without forming large bubbles in the blood.

To treat the bends a patient is placed in a hyperbaric (high pressure) chamber. The high pressure collapses the bubbles and prevents new ones from forming. The pressure is then slowly decreases to allow the blood gasses to escape slowly, simulating a gradual ascent.



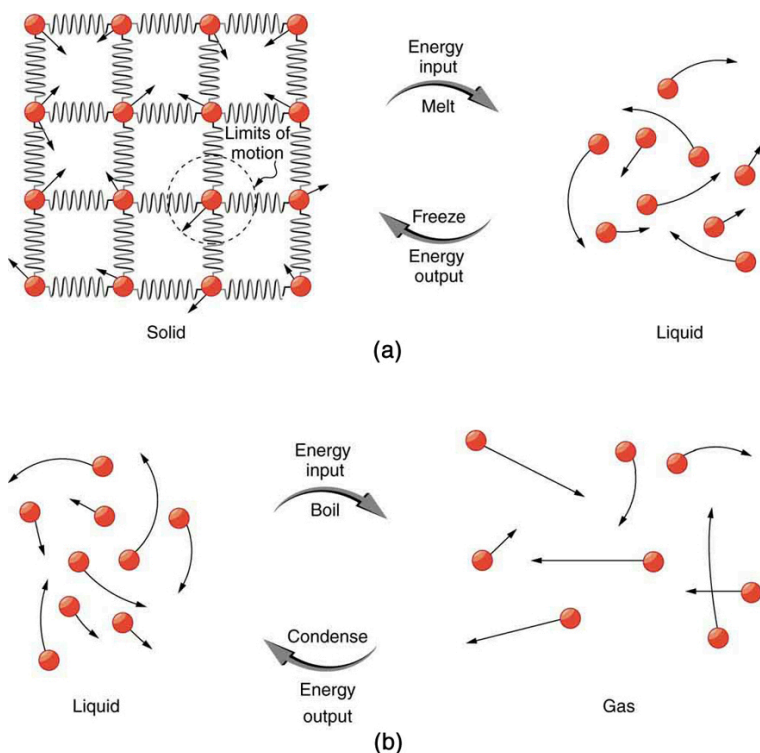
Students at the Naval Diving and Salvage Training Center undergo various training scenarios to prepare them for duties involving underwater emergencies and procedures. Image Credit: "Decompression Chamber" by U.S. Navy Mass Communication Specialist 2nd Class Jayme Pastoric, via Wikimedia Commons.

6

LATENT HEATS

We have learned that evaporation of liquid molecules removes thermal energy from the liquid. An exchange of thermal energy will accompany any such change of phase. The reverse process of condensation, in which vapor molecules stick together to form a liquid, will bring thermal energy into the liquid. The latent heat of vaporization also quantifies the energy exchanged during condensation.

6. "Decompression Chamber" by U.S. Navy Mass Communication Specialist 2nd Class Jayme Pastoric, is in the Public Domain.



Energy is required to partially overcome the attractive forces between molecules in a solid to form a liquid. That same energy must be removed for freezing to take place. (b) Molecules are separated by large distances when going from liquid to vapor, requiring significant energy to overcome molecular attraction. The same energy must be removed for condensation to take place. When causing a phase change by adding or removing thermal energy, there is no temperature change until the phase change is complete. Image Credit: OpenStax CNX

Changing from solid to liquid, known as melting, requires energy just as evaporation does. The thermal energy required to melt a solid will be pulled from the surrounding environment, thus lowering the

environment temperature. In similar fashion to vaporization, the amount of energy removed by melting is quantified by a latent heat, in this case the latent heat of fusion (L_f). For water, $L_f = 334 \text{ kJ/kg}$, which means that for every kilogram of ice melted, 334 kilojoules of energy input is needed. Freezing releases the same amount of energy into the environment that melting requires as input. The temperature at which melting occurs (within a given pressure) is known as the melting point. The melting and boiling points and latent heats of various substances at standard atmospheric pressure are shown in the following chart:

Melting and Boiling points, and Latent Heats at Standard Atmospheric Pressure⁷[footnote]

Substance	L_f	L_v		Boiling point (°C)	kJ/kg	kcal/kg
	Melting point (°C)	kJ/kg	kcal/kg			
Helium	-269.7	5.23	1.25	-268.9	20.9	4.99
Hydrogen	-259.3	58.6	14.0	-252.9	452	108
Nitrogen	-210.0	25.5	6.09	-195.8	201	48.0
Oxygen	-218.8	13.8	3.30	-183.0	213	50.9
Ethanol	-114	104	24.9	78.3	854	204
Ammonia	-75		108	-33.4	1370	327
Mercury	-38.9	11.8	2.82	357	272	65.0
Water	0.00	334	79.8	100.0	2256 ⁵	539 ⁶
Sulfur	119	38.1	9.10	444.6	326	77.9
Lead	327	24.5	5.85	1750	871	208
Antimony	631	165	39.4	1440	561	134
Aluminum	660	380	90	2450	11400	2720
Silver	961	88.3	21.1	2193	2336	558
Gold	1063	64.5	15.4	2660	1578	377

7. [footnote]OpenStax CNX. Feb 27, 2019 <http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.44>.

	L_f			L_v		
Copper	1083	134	32.0	2595	5069	1211
Uranium	1133	84	20	3900	1900	454
Tungsten	3410	184	44	5900	4810	1150

Reinforcement Exercises

Does it take more energy to melt 1 kg of ice or evaporate 1 kg of water? Explain how you know.

Everyday Examples: Melting Ice for Drinking Water

Spending more than a day in frozen landscapes (high altitude, high latitude, or both), will require melting ice/snow to make drinking water. Let's determine the thermal energy required to melt 10 kg of ice that started at 0 °C.

First we look up the latent heat of fusion for water in the previous chart and find $L_f = 334 \text{ kJ/kg}$, or $334,000 \text{ J/kg}$. Using this value in the latent heat formula:

$$Q = mL_f = (10 \text{ kg})(334,000 \frac{\text{J}}{\text{kg}}) = 3,340,000 \text{ J}$$

Now that we are familiar with the idea of latent heat, let's combine that with our understanding of the energy required to change temperature, to get a full approximation of the minimum amount of stove fuel required for a three-person, round-trip expedition to the summit of Denali, North America's highest mountain, at 20,380 ft (6495 m). Allowing for gradual acclimatization to altitude will reduce the likelihood of acquiring high altitude pulmonary edema and/or

high altitude cerebral edema, so we will plan 21 days on the mountain.

First, let's figure out how much water we need. The combination of acclimatization and climbing effort will require at least 4 liters of water per person per day. The total volume we need is then:

$$V = (21\text{days})(3\text{people})(4 \frac{\text{L}}{\text{day} \cdot \text{person}}) = 252 \text{ L}$$

The density of water is 1 kg/L so we will also need 252 kg of water. To get that mass of water we will need to warm and melt that mass of snow each day. The average temperature on the mountain will be -20 °C and we will assume the snow to be melted starts off at this temperature. Let's find the energy required to warm that mass of -20 °C snow up to 0 °C. We use a chart of specific heats to find $c_{\text{ice}} = 2 \text{ kJ/kg} = 2,000 \text{ J/kg}$. Using that value in our equation relating heat and temperature change:

$$Q = mc\Delta T = (252 \text{ kg})(2,000 \frac{\text{J}}{\text{kg} \text{ } ^\circ\text{C}})(20 \frac{^\circ\text{C}}{\text{}}) = 10,080,000 \text{ J}$$

Next we need the energy to melt the snow:

$$Q = mL_f = (252 \text{ kg})(334,000 \frac{\text{J}}{\text{kg}}) = 8,4168,000 \text{ J}$$

So far we need 10,080,000 J + 8,4168,000 J = 94,248,000 J to get ourselves enough water at 0 °C.

Typically the snow is brought to a boil to prevent sickness due to contamination by previous expeditions, and because a hot drink is great for mind and body after hauling a heavy pack and sled through deep snow for 12 hours in sub-zero temperatures at high altitude.

At altitude, the water will boil before reaching 100 °C. According

to boiling point vs. altitude graph the boiling point of water at a mountain height of 13,000 ft will be about 190 °F (88 °C) rather than 212 °F (100°C). We will only need to raise the water temperature from 0 °C to 88 °C to achieve boiling. Water has a specific heat of 4186 J/(kg C°), so we have:

$$Q = mc\Delta T = (252 \text{ kg})(4186 \frac{\text{J}}{\text{kg C}^\circ})(88 \frac{\text{C}^\circ}{}) = 92,828,736 \text{ J}$$

All told, we need that 92,828,736 J plus our previous 94,248,000 J for a total of 187,076,736 J.

According to data on energy densities in fuel, typical liquid fuels (white gas, gasoline, etc.) will provide roughly 40 MJ (40,000,000 J) of net heating energy per kg of fuel burned. To make our rough estimate the *minimum* fuel requirement we will assume all of the thermal energy released by burning the fuel is transferred to the water:

$$Fuel\ Mass = \frac{187,076,736 \text{ J}}{40,000,000 \text{ J/kg}} = 4.7 \text{ kg}$$

The density of liquid fuels is less than water at roughly 0.75 kg/L, so this minimum 4.7 kg of fuel comes out to about 6 liters, or 1.5 gallons. Accounting for heat loss from stove and pot to the environment (especially in windy conditions) the actual requirement could end up substantially greater, depending on conditions. On an actual 3-person, 21-day expedition to the summit of Denali in May of 2012 we used just under 2 gallons of fuel, so our estimate was pretty reasonable.

Reinforcement Exercises

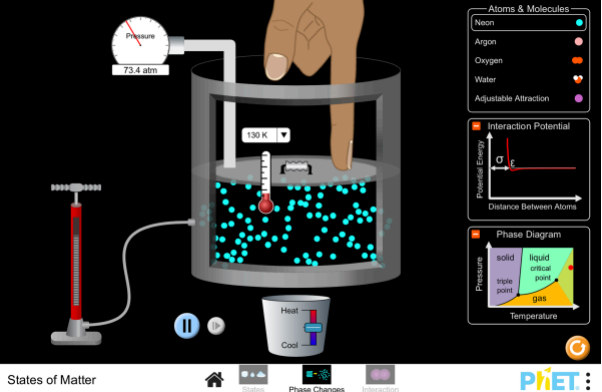
A person having a heat stroke is placed in an ice bath with 3.0 kg of ice at 0.0°C .

How much thermal energy would be removed from the body in order to melt all the ice?

How much would body temperature decrease do to the heat loss you calculated? (Assume an 80 kg body and ignore the fact that the body will be producing about 100 W of thermal power because that rate is very small compared to the overall rate of heat loss to the ice).

Check out the following simulations allows you to play with phase changes.





CHAPTER 97.

HEAT DEATH

THE SECOND LAW OF THERMODYNAMICS REVISITED

The Second Law of Thermodynamics introduced in the previous chapters states that *thermal energy will always spontaneously transfer from higher temperature to lower temperature*. In order to aid in our study of other thermodynamic processes, such as phase changes, a more general version of the Second Law can be stated in terms of energy concentration and dispersion: *any spontaneous process must move an isolated system toward a state of more uniform dispersion of energy throughout the system*. By isolated system we mean one for which energy does not leave or enter. For example, we know that higher temperature means a greater average thermal energy per molecule, so we can think of temperature as a measure of the concentration of thermal energy in an object. If we consider a hot object in a cold room as our complete system, then the thermal energy in our system is not very well dispersed because it's more concentrated in the hot object. The Second Law of thermodynamics predicts that energy should move from the hot object to the cold

environment to better disperse the energy, and that is what we observe. However, the heat transfer will only occur until the thermal energy is maximally dispersed, which corresponds to thermal equilibrium, and is indicated by the object and environment having the same temperature.

Everyday Examples: Sweating, Dew, and Rain

When we sweat to exhaust thermal energy by evaporation we aren't actively grabbing the hottest water molecules, pulling them away from their neighbors, and throwing them into the gas phase. The evaporation happens *spontaneously* because thermal energy stored in water molecules that are stuck together is relatively concentrated compared to thermal energy stored in water molecules zipping around in the air and free to disperse. The transfer of thermal energy to sweat (by conduction), followed by evaporation is a spontaneous process because it increases the dispersion of energy throughout the system made up of you, the sweat, and the surrounding air. Therefore, evaporation of sweat is a spontaneous process.

When the relative humidity reaches 100% then evaporation has maximally dispersed the available thermal energy. Any additional evaporation would begin to over-concentrate energy in the air and decrease the overall level of energy dispersion. Therefore, we don't see evaporation occurring once 100% humidity is reached. In fact if the humidity gets pushed above 100% (by a drop in air temperature without a loss of water vapor) then energy is over-concentrated in the air and thus increasing dispersion of energy requires that water molecules come out of the vapor phase and condensation occurs spontaneously. When the liquid condenses on surfaces we call

it dew, when the liquid condenses on particles in the air and falls to the ground we call it rain.

Reinforcement Exercise

You place $-10\text{ }^{\circ}\text{C}$ ice in warm room. Will thermal energy flow from room air to ice, or from ice to warm air? Explain in terms of thermal energy concentration and dispersion and the Second Law of Thermodynamics.

When the ice warms up to $0\text{ }^{\circ}\text{C}$ it begins to melt instead of increase temperature. Based on the Second Law of Thermodynamics, which of the following processes provides more ways of dispersing thermal energy through the ice and air?

1. Thermal energy is removed from the warm room and stored as kinetic energy (vibrations) in ice molecules, which increases the ice temperature.
2. Thermal energy is removed from the warm room and stored as kinetic energy in vibrations *and rotations* of liquid water molecules, which requires melting the ice instead of raising its temperature.

ENTROPY

Entropy (S) is a measure of energy dispersion within a system. An increase in the entropy corresponds to an increase in dispersion of energy. A decrease in entropy would correspond to energy being less dispersed, or increasing energy concentration. Therefore the Second Law of Thermodynamics can also be stated as: *a process*

will happen spontaneously if it increases the total entropy of an isolated system. The change in entropy for a constant-temperature process can be calculated from the heat transferred (Q) and the temperature at which the transfer occurs (T) as:

$$(1) \quad \Delta S = Q/T$$

Notice that we definitely need to use the Kelvin absolute temperature scale when working with the change in entropy equation, or else we might find ourselves attempting to divide by zero. Let's apply this equation and the entropy version of the Second Law of Thermodynamics to the second part of the previous Reinforcement Exercise.

Everyday Example: Entropy Change of Melting

If you place ice in a warm room and leave it alone, it will melt. The ice melting would be a spontaneous process because it will happen all on its own, so we should find that melting increases the total entropy ($\Delta S > 0$). Let's check that out. We'll keep it simple and calculate change in entropy of one kilogram of ice, which melts at 0°C , or 273 K .

$$\Delta S_{ice} = Q/T = \frac{mL_f}{T} = \frac{(1\text{ kg})(334,000\text{ J/kg})}{273\text{ K}} = 1223\text{ J/K}$$

Next we calculate the change in entropy for the room. The same heat that went *into* melting the ice came *out* of the room, so the Q for the room is the same as for the ice, only negative. Let's pick a typical room temperature of 20°C for our example, which is 293 K :

$$\Delta S_{room} = Q/T = \frac{-mL_f}{T} = \frac{-(1 \text{ kg})(334,000 \text{ J/kg})}{293 \text{ K}} = -1140 \text{ J/K}$$

Now we just add up the two entropy changes to get the total:

$$\Delta S_T = \Delta S_{ice} + \Delta S_{room} = 1223 \text{ J/K} + (-1140) \text{ J/K} = 83 \text{ J/K}$$

Our entropy change is greater than zero, so the Second Law states that ice melting in warm room is a spontaneous process, which we observe it to be.

MAXIMUM EFFICIENCY

Spontaneous processes are inherently irreversible. For example, we could not reverse the spontaneous process of thermal energy transfer from your body to sweat and then to the environment by evaporation. Imagine trying to run around and grab all the water vapor molecules and shove them back into the liquid on our skin and then make those water molecules collide with skin molecules in just the right way to conduct thermal energy back into your body! Good luck. If the process could be reversed, the net entropy change would be zero, but that is not a real possibility. Any *real process* increases the entropy because irreversible at some level, meaning energy is further dispersed throughout the system without a realistic opportunity to put it back where it was. We have arrived at yet another version of the Second Law of Thermodynamics: *any real process increases the total entropy of the universe*. For example, even if you could reverse the evaporation process we described above, the exhaust heat you released during that running around would decrease the concentration of energy in your body and disperse

it throughout the room. The system, which includes you, would not cause have returned to the original conditions at all. In fact, the total entropy would have increased by even more than before you tried to reverse the process. For example, as you ran around, more sweat would have evaporated and you would have to chase those molecules down as well, and so on—you could never win! We can't keep the entropy of the universe from increasing.

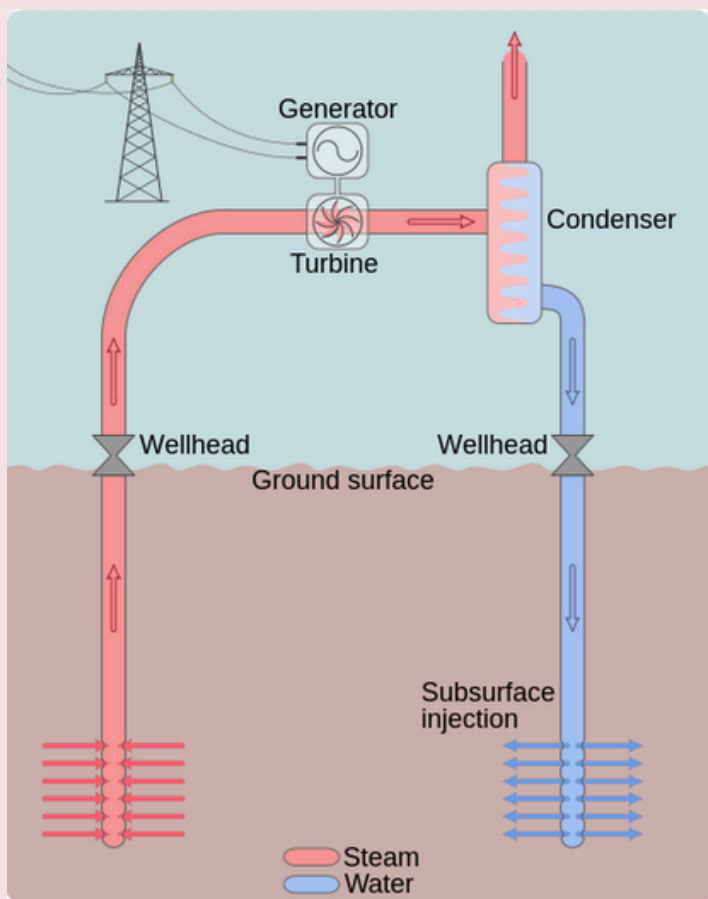
Everyday Examples: Human Mechanical Efficiency

Muscle contraction relies on the release of chemical potential energy stored in ATP molecules. Before contraction, that energy is concentrated into certain molecules in certain areas of a muscle cell. When that energy is released, the entropy of the molecules decreases, so the entropy of their environment must increase by more, and this is achieved because most of the energy released from the ATP molecules is degraded to heat and distributed to the environment. After contraction, a muscle cell must be reorganized, which decreases entropy, but we know overall entropy must increase for any real process, so some additional thermal energy must be dispersed to the environment during reorganization in order to provide the necessary entropy increase. All of this thermal energy is "wasted" because it is came from stored chemical potential energy, but is not available for use by the body to do work. Therefore, entropy and the Second Law of Thermodynamics limit the efficiency of the human body.¹

1. "Thermodynamics of Skeletal Muscle Fiber: Do We Need to Redefine "Active" and "Resting" States?" by I. Y. Cristlieb and E. Cesarman, Cardiovascular and Pulmonary Research Center, The Medical College of Pennsylvania/Hahnemann University

Everyday Example: Geothermal Heat Engine

Let's imagine molten rock from the Earth's mantle pushes partway through the Earth's crust, and keeps a region of bedrock at a constant temperature of $300\text{ }^{\circ}\text{C}$. If the rock was not too deep, we could install pipes in the rock, and then boil water by running it through the pipes. We would basically have a giant pressure cooker! Rather than cook food, we could release the pressurized steam to push on a piston or spin a turbine. After releasing the pressure and getting some work out, we would be left with lower pressure steam. We could condense the steam back to water by running it through pipes exposed to the $20\text{ }^{\circ}\text{C}$ air above ground. Thermal energy would transfer from the steam to the air as exhaust heat, the steam would condense into liquid water, and we could start again.



The dry steam cycle from "Geothermal power plants" by Energy Education, University of Calgary

Machines like the one described that convert thermal energy into mechanical energy are called a heat engines. Your car is powered by an internal combustion heat engine. Let's see how entropy and

the Second Law of Thermodynamics determine the efficiency of our geothermal heat engine.

First we calculate the entropy change when 1000 J of thermal energy transfers out of the rock to the water to run the engine, remembering to convert the 300 °C rock temperature to Kelvin by adding 273 K:

$$\Delta S_{rock} = \frac{Q_{rock}}{T_{rock}} = \frac{-1000 \text{ J}}{573 \text{ K}} = -1.75 \text{ J/K}$$

If our engine is real, then so are its processes, which means that running the engine must increase the total entropy of the universe, according to the Second Law of Thermodynamics. We need to find out how much thermal energy must be transferred from the low pressure steam into the air at 30 °C (293 K) in order for the entropy of the air to increase by at least as much as the rock entropy decreased (1.75 J/K). We can find this by rearranging the change in entropy equation and inserting a positive entropy change that is equal in size to the the negative change experienced by the hot rock:

$$Q_{air} = \frac{T_{air}}{\Delta S_{air}} = \frac{293 \text{ K}}{1.75 \text{ J/K}} = 511 \text{ J}$$

Transferring the 511 J of thermal energy into the air leaves only 489 J of the original 1000 J input energy available for doing work. Therefore the maximum possible efficiency of our engine is limited, no matter how well designed, even if all mechanical inefficiencies like friction could some how be eliminated. The maximum theoretical efficiency is:

$$e = \frac{Work}{Input \text{ Energy}} = \frac{489 \text{ J}}{1000 \text{ J}} = 0.49$$

Multiplying by 100 % would give us the efficiency as a percentage: 49 %. This is a maximum possible efficiency. Any engine we actually built would be less efficient.

The First Law of Thermodynamics told us that you cannot build an engine that is more than 100 % efficient because energy cannot be created. Even worse, the Second Law tells us that even if we managed to eliminate all mechanical inefficiencies, such as friction, we still can't get up to 100 % because all engines must exhaust some energy in order to increase entropy overall. The theoretical maximum efficiency, which is always less than 100 %, is known as the Carnot efficiency (e_c) and depends only on the high and low operating temperatures (T_H and T_L), as we saw in the previous example. Most of the work we did in the previous example can be short-cut by the equation for Carnot Efficiency (e_c):

$$(2) \quad e_c = 1 - \frac{T_L}{T_H}$$

The theoretical engine which could actually produce that theoretically maximum efficiency is known as the Carnot Engine. The operating principles of the Carnot Engine are well known, having been developed by Nicolas Léonard Sadi Carnot in 1824, but the engine cannot be realistically designed or built.²

Reinforcement Exercise: Carnot Efficiency

Check that the previous short-cut equation gives the correct maximum efficiency for our geothermal heat engine.

What is the Carnot efficiency of our geothermal heat engine if the hot rock was actually at 550 C° instead of 300 C° ?

2. "Carnot heat engine" by Wikipedia

You will find that this engine is more efficient just because the hot operating temperature is higher, even though it still works in the same way and nothing else has changed. The efficiency increased because the input energy started out more concentrated and less dispersed (indicated by higher temperature), so less of that energy had to become dispersed in the environment, or wasted, in order to ensure that entropy increased by a sufficient amount to satisfy the Second Law of Thermodynamics. Thermal energy that starts out concentrated (at high temperature) is known as *high quality* energy.

Reinforcement Exercise:

A particular internal combustion engine in a car operates between the temperature of the hot combustion gasses immediately after combustion, and the outside air temperature. These are typically 1000 K and 290 K. What is the theoretical maximum efficiency of such engines?

Actual automobile engines have efficiencies that are about 75 % of the maximum theoretical efficiency. Roughly how efficient are actual automobile engines?

HEAT DEATH

In addition to limiting our efficiency in doing mechanical work, the Second Law drives our bodies toward higher entropy, which means thermal equilibrium with the environment. Unless the environmental temperature happens to be near body temperature, reaching thermal equilibrium means death. Life also requires concentration of chemical potential energy, but due to the the Second Law we tend toward chemical

equilibrium, which is not survivable. Concentrations of electrical energy drive your nervous system, but due to the Second Law we are constantly at risk of reaching an internal electrical equilibrium with no electrical activity. Life is a constant battle against various types of equilibrium that would correspond to maximum entropy, but also to death. The work necessary to fight off our own entropy increase is what we consider basic metabolism. Doing that work, and even taking in the energy required to do that work, involves real processes that provide even more opportunity for entropy increases in a seemingly viscous cycle. You can't beat the Second Law of Thermodynamics! Even as we manage to prevent our own entropy increase we cause the entropy of the environment to increase by a greater amount than what we prevented in ourselves. In fact, a complete dispersion of energy, so that all matter is at equilibrium, and no processes remain which would increase the entropy, and nothing really happens all, is one possible fate of the universe which has been dubbed *heat death*. At least we don't expect heat death of the universe to occur for at least 10^{100} years. ³

3. OpenStax, College Physics. OpenStax CNX. Mar 6, 2019 <http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.78>

CHAPTER 98.

UNIT 10 REVIEW

Key Terms and Concepts

Temperature
Thermal expansion
Thermal energy
Heat
Conduction
Forced Convection
Natural Convection
Thermal Radiation
Heat capacity
Phase change
Latent heat
Entropy
Second Law of Thermodynamics
Heat Engines

Efficiency

Learner Objectives

1. Compare, contrast, and convert between absolute and relative temperature scales.[1]
2. Evaluate the effectiveness of various types of insulation against different mechanisms of heat transfer.[3]
3. Apply the concepts of temperature, thermal expansion, specific heat, heat capacity, and latent heat, to analyze how physical objects respond to heat transfer.[3]
4. Apply the Second Law of Thermodynamics to predict the outcome of physical scenarios.[2]

CHAPTER 99.

UNIT 10 PRACTICE AND ASSESSMENT EXERCISES

Outcome 2

Babies, and especially premature babies, have particularly large surface area relative to their body mass as compared with adults. That makes them especially susceptible to hypothermia. Incubators are used to help reduce the heat loss rate in such cases. What are the basic features of an incubator and how do they reduce heat loss by each of the following:

Thermal Radiation

Conduction

Forced Convection

Evaporation

Outcome 1

Human body temperature is 98.6 °F. Convert this to Celsius.

Convert body temperature to Kelvin.

Outcome 3

The surface area of a premature baby can be calculated according to the formula of Haycock *et. al.*¹

$$\text{Surface Area} = M^{0.5378} \times L^{0.3964} \times 0.024265$$

The result give are in **m²**, but length (L) is input in **cm** and mass (M) is input in **kg**

Calculate the surface area for a premature baby with weight of 3.5 **lbs** (a mass of 1.8 **kg**) and length 42 **cm**.

Use the surface area and body temperature you found above to calculate the rate at which the baby loses thermal energy to the environment by thermal radiation if the room is at a temperature of 75 °F (23.9 °C). The emissivity of human skin is typically 0.98. Don't forget convert the room temperature to Kelvin.

Calculate the heat loss rate by conduction to the table if the baby is laying on a mattress 5 **cm** thick with thermal conductivity of .04 **W/ (m °C)**. Use the same body temperature and room temperature as in the previous calculations. Assume only the back half of the body is experiencing conduction (use half the surface area).

1. "Body Surface Area Calculator" by , NICU Tools

Calculate the heat loss rate by forced convection for an air speed of 0.5 m/s is caused by the ventilation system and movement of people in the room etc. Use the same body temperature and room temperature as in the previous calculations. Assume only the front half of the body is experiencing forced convection (use half the surface area).

If the room is at 50 % relative humidity the air speed of 0.5 m/s will result in an evaporation from the baby's moist skin at a rate described by the equation below (we didn't talk about determining evaporation rate so if you want to understand this equation talk with you instructor, but for now just use it).

Rate of evaporation in $\text{kg/s} = 0.000097 \times \text{surface area}$.

Calculate the rate of evaporation of water from the baby's skin.

What is the rate at which this evaporation removes thermal energy from the baby? (Hint: How much energy is lost for each kg of water that evaporates?)

Add up all of these heat loss rates to get the total rate of heat loss.

Assuming the baby is mostly water, (use the specific heat of water) calculate the rate at which the temperature of the baby will change in $^{\circ}\text{C}$ per second. Use the baby mass from above.

How many degrees would the baby's body temperature lower in 10 minutes at this rate?

Connecting Concepts: Metabolism, Thermal Power, Heat

Let's imagine that we thought the baby could handle generating the thermal energy needed to replace the heat loss you calculate above by simply converting food Calories into thermal energy. In that case we wouldn't need an incubator, we would just need to keep the baby well fed. How much breast milk would the baby need to drink each day? Let's find out.

Breast milk has 700 Calories (**kcal**) per **kg**.² How many **kg/s** of milk would the baby need to drink to intake the same energy as what is lost?

How many **kg**/hour is this?

How many **kg**/day is that?

2. "Basic Report: 01107, Milk, human, mature, fluid" by Food Composition Database, US Department of Agriculture

How does that compare to the baby's mass?

Does this seem reasonable? Explain.

PART XI.

LABORATORY ACTIVITIES

General Design

The labs provided here are designed to create a lab-based or “work-shop” type of experience even when scheduling limitations force a standard lecture + lab course format, as is the case for many community colleges. As such, the labs follow a heavily guided inquiry format, which allows for inquiry based learning by inexperienced students while ensuring leaner outcomes are practiced and assessed. Students will make predictions, work hands on with equipment to acquire and analyze data, and compare predictions to results. Students are not asked to design large portions of experiments themselves, though they may be asked to suggest possible ways to test predictions or explain how they would make improvements to methods. Most students will require significant assistance in completing the labs, especially the analysis portions. As

such, these labs may be best suited for courses in which the primary instructor is also the lab instructor.

Timing

The labs are designed to be completed in a 2 **hr** and 50 **min** lab session, but in some cases additional analysis work might carry over into classroom sessions. This helps to connect the lecture and lab components of the course and brings hands-on activities into the lecture environment.

Mix and Match

Of course instructors edit the labs to match content and cognitive level with their own course outcomes and/or should mix their favorite parts of the labs with other activities they find useful.

CHAPTER 100.

UNIT 2/3 LAB: TESTING A TERMINAL SPEED HYPOTHESIS

TERMINAL SPEED

Materials:

- lab sheet and writing utensil
- calculator
- 10 Coffee filters
- step ladder allowing you (or a partner) to reach 2 **m**
- ruler with **cm** units
- scale with at least 0.1 gram precision
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- one of the following equipment sets:
 - motion sensor + computer with control and analysis software

- video motion analysis app (example)
- camera (slow motion mode preferred) + stopwatch with 0.01

Course Outcome 5, Unit Outcome 2-1

Observation

We observe that when a body falls through the air it eventually reaches a maximum speed, known as terminal speed, which is roughly 200 **mph**.

Question

This phenomenon raises the question: What determines the value of the terminal speed?

Search Existing Knowledge

Find an answer for what determines the value of the terminal speed. Write the answer below and also list your source.

Hypothesis

Our search of existing knowledge told us that one factor affecting terminal speed was the mass of the object.

Provide a qualitative hypothesis on how the terminal speed depends on the mass of an object. That means to state if you think the terminal speed will increase or decrease when mass increases. Explain your reasoning.

Test

To test your hypotheses, without jumping out of airplanes, we will measure the terminal speed of coffee filters with varying mass. The terminal speed for coffee filters is much slower than for bodies and they will typically reach terminal speed in less than 2 meters of drop distance. These properties will make our experiment reasonable to perform in the lab. Your hypothesis was about an object's terminal speed and mass in general, not about bodies specifically, so a coffee filter experiment will still test your hypothesis.

Measure the mass of the coffee filter and record here:_____

Our method will be to drop coffee filters from a height of at least 2 **m** and measure the terminal speed. You will need a step ladder and a partner to make the measurements. You can measure the terminal speed using photogates or acoustic or laser based motion sensor if you have access to those in your lab. If not, you can measure the terminal speed by using a video motion analysis app, or by simply filming the last 0.1 **m** (10 **cm**) of the fall while holding a ruler and a running stopwatch to be visible in the video frame.

If using the motion sensor, be sure to only use the section of the speed data after the speed has become constant and before impact. Your instructor will help you find this section of data. Record your terminal speed here:_____

If using the filming method, be sure to film straight on to the ruler, which should be standing up straight on the floor. Read off the time off the stopwatch in the video when the filter passes the 10 **cm** mark and again when it hits the floor. Subtract the first time from the second to find the difference between these times. Divide 0.10 **m** by the time difference to get the terminal speed. Record your terminal speed here:_____

Repeat this experiment for two nested (one inside another) coffee filters. Nesting the coffee filters increases the mass, but doesn't change the shape of the filters, allowing us to change only one variable at a time. Record your terminal speed for two filters in the chart. Also measure the mass of the two filters and record in the chart as well.

Repeat the experiment until you have measured terminal speed and mass for at least 5 nested coffee filters. Record the number of filters and terminal speed for each in the table below:

Number of Filters	Terminal speed (m/s)	Mass (g)
1		
2		
3		
4		
5		
6		
7		
8		
9		

Analyze

Enter your data into a spreadsheet and create an x-y graph of terminal speed vs. mass. Mass should be on the horizontal (x-axis) because mass is the independent variable (what you are purposefully changing). Speed should be on the vertical axis (y-axis), because speed is the dependent variable (what is changing in response to the independent variable).

Be sure to give your graph a title and label the axes with the variable names and the units of measure.

Check with your instructor to find out if they want you to enter your group's data into the class-data spreadsheet.

Conclusion

Was your qualitative hypothesis supported by the data? Explain.

Be sure to save your spreadsheet and graph. We may use them again during this course.

Hypothesis Testing Including Uncertainty*

In order to really answer the question about whether or not the experimental results support the hypothesis we need to think about uncertainty. (Unit outcome 3-4)

Let's do a little experiment to determine how random error affects the precision of your results. Repeat the final filter set measurement 6 more times and record the results, including the first value you found above, in a chart:

Use your spreadsheet software (or some other method) to take the average and the standard deviation of the seven values. Record both below:

The standard deviation value will serve as an estimate of the precision in our experiment. A new measurement should be within the standard deviation of the average value 68 % of the time. We will use the precision provided by the standard deviation as our estimate of the uncertainty in our final measurement. Ideally we would base our average and standard deviation on more than seven values, but we will use only seven in this learning situation for the sake of time.

Add error bars to the terminal speed data in your graph, setting the size equal to the standard deviation you calculated.

Considering the error bars, does the data support your qualitative hypothesis? Explain your reasoning.

So far we have ignored systematic error. Systematic errors can be difficult to recognize and even more difficult to quantify. We must always be on the look-out for sources of systematic error.

Can you provide a possible source of systematic error in your experiment? Explain. (Unit outcome 3-2)

Can you estimate how large the error might be (provide an upper bound) Explain. (Unit outcome 3-3)

Modeling

As a class we will fit a curve to our data of terminal speed vs. mass of filters and use the equation of that curve to predict the terminal speed for a higher number of filters. (Outcome 2-2)

What type of model is this? Explain.

Write the fit equation we found here:

Record the number of filters and mass of the filter set you will predict/test:

Show your work in calculating the predicted terminal speed for additional filters.

Drop your new filter set and record the terminal velocity you measure:

Did the prediction agree with the experimental test within your uncertainty? Does your result add validity to your model? Explain.

CHAPTER 101.

UNIT 4 LAB: HYDROSTATIC WEIGHING

HYDROSTATIC WEIGHING

Materials:

- graduated cylinder (required for displacement method, but not required for hydrostatic weighing method)
- plastic bin to contain spills
- object to submerge
- calculator
- scale with at least 0.1 gram precision
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- force sensor + computer with control and analysis software OR spring scale with 0.1 gram precision (required for hydrostatic weighing method, but not for required for displacement method)

Objective

The objective of our lab is to determine the density of an object in the same way we would for a person. We will determine body density in two ways, one being the displacement method and the other being hydrostatic weighing.

You might want to watch this video to refresh your memory regarding the general process for hydrostatic weighing:



A YouTube element has been excluded from this version of the text. You can view it online here: <https://openoregon.pressbooks.pub/bodyphysics/?p=1370>

General Methods

The video above does not explain how to actually calculate the body fat percentage ($BF\%$) from the hydrostatic weighing data. The $BF\%$ calculation is done using rather a complex empirical model that requires body density, D_b , as an input. Hydrostatic weighing allows us to determine density to use in the model. The model looks like this.

Siri Equation **Schutte Equation**

$$\%BF = \frac{495}{D_b} - 450 \quad \text{or} \quad \%BF = \frac{437}{D_b} - 393$$

$D_b = \frac{BW}{\frac{BW - UWW}{D_{H2O}} - (RV + 0.1)}$

$RV = (0.0115 \times Age_{(yrs)}) + (0.019 \times Ht_{(cm)}) - 2.24$ For Men
 $RV = (0.009 \times Age_{(yrs)}) + (0.032 \times Ht_{(cm)}) - 3.90$ For Women

Formulas for calculating body fat percentage from body density and other body measurements. Image Credit: MattVerlinich via Instructables

1

Body density is calculated from body weight (BW), under water weight (UWW), water density (D_{H_2O}) and

1. "MEASURE BODY FAT % VIA UNDERWATER WEIGHING" by MattVerlinich, Instructables, Autodesk

residual lung volume (RV). The hydrostatic weighing process provides BW , UWW , and D_{H_2O} . Residual lung volume can be calculated from empirical equations that depend on age, height, and gender. We will not need to account for RV or residual intestinal gasses (the 0.1 value in the D_b equation) today because our object is solid.

For fun we will use the body density value we find as an input to calculate the “body fat percentage” of our object, but of course this number will not be meaningful because the final BF % formula we are using is an empirical model based only on data from people.

Displacement Method (requires graduated cylinder)

Outcome 4-1

Measure the body mass of your object and record here:_____

If your measurement device only provided you with body weight, then calculate the body mass. You may need to look up the equation relating mass and weight of an object near the surface of the Earth. Show your work.

Submerge your object in the graduated cylinder and measure the change in volume. This is the volume of water displaced by the object.

Record displaced volume here:_____

How does the volume of displaced water compare to the volume of the object? Explain your reasoning (remember, the object was completely submerged).

Outcome 4-4

Use your recorded mass and volume to calculate the density of your object. Show your work.

Hydrostatic Weighing Method (requires force sensor or spring scale)

Measure the body weight of your object in air and record here:_____

If your measurement device provided you with mass instead of weight, then calculate the object weight. You may need to look up the equation relating mass and weight of an object near the surface of the Earth. Show your work.

Submerge the object and measure the under water weight, also known as the apparent weight. Record here:_____

Again, if your measurement device provided you with mass instead of weight, then calculate the object weight. Show your work.

Based on your measured weight and apparent weight, what must be the size of the buoyant force?

Use Archimedes' Principle to determine the weight of the water displaced by the object. Explain your reasoning.

Calculate the mass of the water displaced. You may need to look up the equation relating mass and weight of an object near the surface of the Earth. Show your work.

Look up the density of water and record here:_____

Now use the definition of density to find the volume of the displaced water. Show your work.

How does the volume of displaced water compare to the volume of the object? Explain your reasoning (remember, the object was completely submerged).

Now you know the body volume of the object, so if you know its body mass then you can calculate its body density. Calculate the body mass from body weight you found earlier, and then calculate body density. Show all work.

Does the formula result agree with your result from the mass/(displaced volume) method?

The work you just did recreated the complicated

formula for D_b shown at the front of the lab (except for the residual body gasses part)! Now that we know how it works, from now on we can just use the formula instead of going through the extra steps. Just to make sure, use the D_b formula to calculate density of your object, (only leaving out the part accounting for residual body gasses). Show your work.

Does the formula result agree with your result from hydrostatic weighing and mass/ (displaced volume)?

Body Fat Percentage

Use the body fat percentage formula at the start of the lab to calculate the body fat percentage of your object. Show your work. Does the result seem reasonable? Explain. If not, any thoughts on why?

CHAPTER 102.

UNIT 5 LAB: FRICTION FORCES AND EQUILIBRIUM

FRICTION FORCES AND EQUILIBRIUM

Materials:

- lab sheet and writing utensil
- calculator
- small board, box, book, or other object to slide across the table
- string
- pulley with clamp
- set of known masses
- spreadsheet and graphing software
- force sensor + computer with control and analysis software

Course Outcomes 4, 5

Unit Outcome 2-1

Observation

Is it more difficult to start an object sliding than it is to keep it sliding? Give it a try and state your observation.

Question

Finish generating a question about your observation:

Why _____ is _____ it
that_____

Search Existing Knowledge

Find an equation that shows what factors the frictional force depends on. Write it down below and list your source. The equation you found represents what type of model? (Quantitative or Qualitative and Empirical or Physical)

Hypothesis

Based on what you found above and your observation/question, provide a hypothesis about which is larger between the static friction coefficient and the kinetic friction coefficient. Explain how your observation and the information you found above were used to create the hypothesis.

Test

To test your hypotheses we determine the static and

kinetic friction coefficients between an object and the table.

Our method will be to use the force sensor to measure the weight of the object. Then use the force sensor to measure the force needed to slide the object, and keep it sliding at the same speed. Be sure to **zero the force probe** in the orientation you will use it before making each one of your measurements.

Use the string to hang your object from the force probe and record the weight of your object here:_____.

Unit Outcomes 5-1, 5-4

Use the concepts of tension force and static equilibrium to explain how you know that the reading on the force probe was equal to the weight of the object.

What is the normal force on the object from the table when it is sitting on the table? Explain how you know using the concept of static equilibrium.

Does the normal force change if the book is sliding across the table? [Hint: Does the book ever start moving vertically?]

Now you will use the string to connect the object to the force probe and then gradually increase how hard you pull horizontally on the object until it finally begins to

slide. After it begins to slide, keep pulling the object at a constant speed for at least five seconds. Practice this a few times before you begin taking data.

Now that you have practiced, zero the force probe in the horizontal orientation that you will pull, and record the force measured by the probe while you pull horizontally on the object until it finally begins to slide and continues at a constant speed for at least five seconds.

Record the maximum force registered by the force probe:_____

This is the size of the maximum frictional force applied before the object started to move, or the static frictional force. Explain how the concept of static equilibrium tells us that the maximum reading on the probe is the static frictional force.

Use the static friction force and your known normal force from above to calculate a static friction coefficient. Show your work.

Record the average force registered by the force probe after the object started to slide:_____

You pulled the book with a constant speed and direction so it was in dynamic equilibrium and the forces must be balanced. Therefore the pull force you measured with the force probe must have been equal to the kinetic frictional force.

Use the kinetic friction force and your known normal force from above to calculate a kinetic friction coefficient. Show your work.

Repeat the experiment 6 more times, calculating a static and kinetic friction coefficient each time. Create a chart to keep track of your data. You may want to create a spreadsheet to calculate the coefficients from the force measurements so that you don't need to do it by hand each time and because you will be calculating average and standard deviations of your measurements.

Calculate the average static friction coefficient and average kinetic friction coefficient and record these below:

Unit Outcomes 3-4

Also calculate a standard deviation for each set of coefficient measurements. Record this below:

Using the standard deviation as the uncertainty in your measurements, do the average static and kinetic coefficients differ by more than the uncertainty? Explain.

Unit Outcome 2-1

Conclusion

Do you conclude that the static coefficient is larger, the kinetic coefficient is larger, or they are the same? Explain.

Was your qualitative hypothesis correct? Explain.

CHAPTER 103.

UNIT 6 LAB: ELASTIC MODULUS AND ULTIMATE STRENGTH

ELASTICITY

Materials:

- lab sheet and writing utensil
- calculator
- thin (roughly 1 **mm** x 1 **mm**) rubber band and place to hang it (e.g. cabinet handle)
- Ruler with **mm** precision
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- one of the following equipment sets:
 - force sensor + computer with sensor control and analysis software
 - collection of weights with hooks, from 0.01 **kg** to 1 **kg**

Observation

Rubber bands behave elastically and they also appear to have a “crimping” behavior similar to tendons. When relaxed the bands tend to curl up and it takes a small force to straighten them out, then once straight, they provide more resistance to being stretched.

Question

Are rubber bands a good model for tendons?

Search Existing Knowledge

Find an example stress-strain curve for a tendon. What is the name of the region caused by “crimping” behavior? What is the elastic modulus of human tendon? What is the ultimate strength of human tendon? List your sources for this information.

Hypothesis

Provide a qualitative hypothesis that compares the stress-strain behavior of rubber bands and tendons. That means state which parts of the stress-strain curve for a tendon you expect will also appear in the rubber band curve. Explain your reasoning.

Also state whether you expect rubber bands or tendons to have a larger elastic modulus and ultimate strength. Explain your reasoning.

Test

To test your hypotheses you will create a stress-strain curve for the rubber band.

Our method will be measure the stretch distance as additional force is added to the band. In order to determine stress and strain we will need to know the original length and cross-sectional area of the rubber band.

Hang the rubber band from a cabinet handle, ring stand, or other feature capable of supporting about 20 **lbs** (or enough force to rupture your rubber band). If you are using a rubber band larger than 1 **mm** x 1 **mm**, then you may have a difficult reaching the ultimate strength of the rubber band:



Photograph of a 1 mm x 3 mm rubber band during stress testing. The band runs through the slots in the gray weights and the hook attached to the bottom of the band is just visible through the slot in the lowest group of smaller (0.98 N) weights. The 119 N of force is applying 1.3×10^{13} Pa of stress, causing a strain of 660 %. Photo credit: Umpqua Community College student Samuel Marsters.

Use your ruler to measure the relaxed length of the hanging rubber band and record here:_____

Measure the width and thickness of the rubber band and multiply to get the cross-sectional area. Record the measurements here: Width_____

Thickness_____ Show your work in calculating the cross-sectional area below:

Convert your area to square meters (m^2), show your work below:

If you are using a force sensor, be sure to zero the sensor in the vertical orientation. If you are using pennies, determine the weight of a single penny in units of Newtons, if you are using known masses then remember to calculate their weights as you go.

Now we will pull on the band with the force sensor (or pennies or weights) and measure the force and length, then use the initial length and area to calculate stress and strain. Start with your smallest weight and work up so that you can determine if there is crimping behavior. Be sure to pull hard enough or add enough weight so that the length changes by at least 2 **mm**, (so the change is not obscured by the uncertainty in your length measurement). Continue until the rubber band begins to rupture. Record the results in the chart below.

Hanging Mass (Kg)	Force (N) (from force sensor, or weight of pennies)	Length (mm)	Stress (N/m^2)

Analyze

Enter your data into a spreadsheet and create an x-y graph of stress vs. strain.

Be sure to give your graph a title and label the axes with the variable names and the units of measure.

Conclusion

Was your qualitative hypothesis about the shapes of stress-strain curves for tendons and rubber bands correct? Explain.

Analyze

What was the ultimate strength of the rubber band?
Record here:_____

Conclusion

Was your hypothesis about the ultimate strength of rubber bands compared to tendons supported by your data? Explain.

Analyze

We need to find the elastic modulus, which tells us how the material resists strain. The elastic modulus is defined as the slope of the elastic region of the stress-strain curve. You can find the slope two ways: 1) slope is defined as rise over run. Find the how much the stress changes across the elastic region, then divide this by how much the strain changes across the elastic region. 2) graph only the data from the elastic region and use the spreadsheet to fit a line to the data. Don't forget to ask your instructor or TA for help if you need it.

Write the change in stress across the elastic region here:_____

Write the change in strain across the elastic region here:_____

Show your work in calculating the slope below:

Write your slope here:_____. The slope of the elastic region is the elastic modulus.

Conclusion

Was your hypothesis about the elastic modulus of rubber bands and tendons supported by your data? Explain.

CHAPTER 104.

UNIT 7 LAB: ACCELERATED MOTION

MOTION

Materials:

- lab sheet and writing utensil
- calculator
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- string
- 20 g mass with hook
- “frictionless” track + cart
- motion sensor + computer with sensor control and analysis software (self-tracking motion cart optional).

Preparation

Before we begin creating and testing a hypothesis regarding forces and motion, we need to familiarize

ourselves with basic motion concepts and the equipment we will use to measure motion.

First set up the motion sensor and analysis program so that it displays the position, velocity, and acceleration vs. time graphs of your motion as you move in front of the sensor.

Next, create each of the following graphs by moving in front of the motion sensor. Have your instructor sign off on each graph as you progress.

Constant Position

Create a constant position graph. Instructor signature:_____

Describe how you had to move to create this graph.

Describe the velocity and acceleration graphs created by your motion.

Constant Velocity

Create a constant velocity graph. Instructor signature:_____

Describe how you had to move to create this graph.

Describe the position and acceleration graphs created by your motion.

Constant Acceleration

Create a constant acceleration graph. Instructor signature:_____

Describe how you had to move to create this graph.

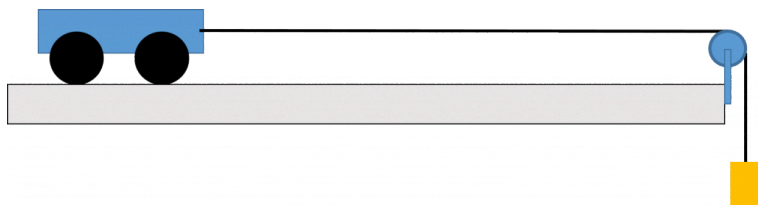
Describe the position and velocity graphs created by your motion.

ACCELERATED MOTION

Now we will use the cart and track to test a hypothesis about how position, velocity, acceleration and net force are related. Setup the cart and track and motion sensor (or the self-tracking cart) to measure the position, velocity, and acceleration of the cart as it moves down the track.

Test Method

Now build the following setup in in order to use the force of gravity on a hanging weight to accelerate the cart. Use a hanging mass roughly $1/5$ of the cart mass. The cart will run on a smooth track to minimize friction. (We know the track/cart setup is not completely frictionless, so we are making the assumption that the friction is small enough not to significantly affect our results).



Measure the cart mass and record here (in **Kg**):

Measure the hanging mass and record here (in **Kg**):

Observation

Gravity is acting on both the cart and hanging mass, but when the hanging mass isn't there the cart doesn't accelerate. Therefore it seems like only gravity on the hanging mass contributes to causing acceleration.

Question

If only the hanging mass contributes to the gravitational force causing acceleration of the system, does the cart's mass even matter at all?

Hypothesis

If we include only the hanging mass in calculating the force causing acceleration, but include both masses in calculating the acceleration caused by that force, then we will (circle one):

Correctly predict the acceleration of the cart

Incorrectly predict the acceleration of the cart

Test

According to our hypothesis, how big is the force causing acceleration of the system?

Use the force you found above and Newton's Second Law to calculate the expected acceleration of the cart + hanging mass, using their combined mass as the system mass.

Use the force you found above and Newton's Second Law to calculate the expected acceleration of the cart + hanging mass, using only the hanging mass as the system mass.

Using the same amount of hanging mass as in your calculations above, release the hanging weight + cart while measuring the position, velocity, and acceleration of the cart.

Analyze

The force that is accelerating the cart + hanging mass system is the force of gravity on the hanging mass, which is constant. Should the measured acceleration also be constant? Is it constant? Explain.

Use the software to find the average value of the acceleration and record here:

Conclusions

Which of your predictions is correct, the one that uses the combined mass for the system mass, or only the hanging mass as the system mass?

Does your experiment support or refute your hypothesis?
Explain.

CHAPTER 105.

UNIT 8 LAB: ANALYSIS OF HUMAN JUMP

JUMP LAUNCH VELOCITY FROM IMPULSE

Materials:

- lab sheet and writing utensil
- calculator
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- tape
- Digital Force Plate + computer with sensor control and analysis software
- Camera with slow-motion capability

Data Acquisition

Place a piece of tape on the jumper's center of mass so that you can use a camera with slow-motion capability to record the change in height of the their center of mass

during the jump. You may need to look up some information on where to locate your center of mass. Cite your sources here:

We will use a force plate to measure the normal force applied to the jumper's feet. Have the jumper stand on the force plate and push the zero button. Now the force plate will read the difference between the normal force and their weight, which is the net force acting on them. It should be zero when they are at rest.

Have the jumper practice jumping and landing on the force plate while trying to keep their arms in the same position during the jump so that the location of their center of mass doesn't change much throughout the jump.

Now record the height of the center of mass throughout a jump and landing while recording the normal force on the person.

Record the change in height here, we will use that later:_____. Keep your video recording for later use as well.

Applying Impulse-Momentum to the Entire Jump

What was change in momentum for the person over the entire jump, from starting at rest, through launch phase, air phase, landing phase, and finishing at rest.

Based on your answer above and the impulse-momentum theorem, what should the total impulse on the person have been for the overall jump?

Based on your previous answer what should the average force on the person be for the entire jump?

Use the lab software to calculate the average force applied to the person throughout the entire jump. Does the result agree with your answer? Explain.

Applying Impulse-Momentum During Launch Phase

Use the force data to calculate the average force applied to the person from the start of their jumping movement until they leave the platform. Record here:

Also record the peak force during this launch phase of the jump (for later use):

Record the time interval used in this average. (The time over which the launch phase lasted.)

Calculate the impulse applied to the person during the launch phase of the jump.

According to the impulse-momentum theorem, what change in momentum should the person experience during the launch phase?

Their initial momentum was zero, so what should their final momentum be at the end of launch phase?

Applying Impulse-Momentum During Air Phase

The only force acting on the person during the air phase is gravity. You already know the size of that force (it's

their weight as measured by the force plate). Use the impulse-momentum theorem to calculate how long it will take the gravitational force to change their momentum from the initial launch value to zero.

The momentum of the jumper is zero at the very top of the jump, so the time you found is half of the total hang time.

Based on your answer above, what will the hang time be?

Does that answer agree with the hang time recorded by your force plate? Explain, including values from your data.

Calculating Launch Velocity

Based on the level of agreement between expected and observed hang time, do you think that using the impulse-momentum theorem to analyze the jump is reasonable? Explain.

Use your previous result for the launch momentum, along with the definition of momentum, to calculate the velocity of the person as they leave the platform at the end of the launch phase.

CHAPTER 106.

UNIT 9 LAB: ENERGY IN EXPLOSIONS

SIMULATED EXPLOSION

Materials:

- lab sheet and writing utensil
- calculator
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- “frictionless” track + two carts with velcro bumpers and at least one with integrated spring
- force probe
- two motion sensors + computer with sensor control and analysis software (or one motion sensor and one self-tracking motion cart).
- force probe

Explosions

During an explosion, such as that which occurs within the cylinders of internal combustion engines, _____energy is converted into _____energy and _____energy.

Observation

Typically after an explosion things are moving which were not moving before. Therefore, it seems like kinetic energy and momentum might not be conserved during explosions.

Questions

Do explosions conserve kinetic energy?

Do explosions conserve momentum?

Search Existing Knowledge

Find information about whether or not momentum and kinetic energy are each conserved during an explosion. Cite your sources.

New Question

If the “explosion” is caused by a release of elastic potential energy instead of chemical potential energy, does that change any of the answers you found above?

Hypotheses

An “explosion” can be simulated by releasing a spring that was compressed between the two objects, causing them to separate. Form two hypotheses, one regarding conservation of momentum and conservation of kinetic energy during the simulated explosion. As part of your hypotheses, draw diagrams of this situation before and after the “explosion” occurs.

Test

Place the two carts together with the loaded spring in the first cart facing the second cart. Record the motion of both carts while pushing the spring release button. Use a ruler to tap the button from directly above, making sure not to put any horizontal force on the button/cart.

Use your velocity data to determine the velocity of each cart immediately after the explosion has finished, but before the carts begin to slow down due to friction. Be sure to consider that the velocities should have opposite directions, but that your motion sensors will not

necessarily record the correct directions. You will need to choose a positive and negative direction for your experiment and correct the directions recorded by your sensors accordingly. Record your final velocities for each cart below.

Measure the mass of each cart and record below:

Momentum Analysis

What was the total momentum of the system before the “explosion?”

Calculate the total momentum after the explosion.

Momentum Conclusions

Does your experiment support or refute your hypothesis on momentum conservation?

Kinetic Energy Analysis

What was the kinetic energy of the system before the explosion?

Calculate the total kinetic energy after the explosion.

Kinetic Energy Conclusion

Was kinetic energy conserved in this explosion?

Does your result support or refute your hypothesis?

If kinetic energy was not conserved in this experiment, did it increase or decrease?

What type of energy was converted into kinetic energy during this experiment?

Efficiency Analysis

Let's find out the efficiency of this "explosion" at converting elastic potential energy into kinetic energy. First we need to know how much elastic potential energy was contained in the spring and to calculate that we need to know the spring constant and compression distance.

Measure the compression distance with a ruler and record here:

Use a force probe to measure the force required to

compress the spring to half of the compression distance.
Record the distance and force here:

Calculate the spring constant of the spring.

Calculate the elastic potential energy stored in spring
when fully compressed.

Calculate the efficiency of the “explosion” at converting
spring potential energy into elastic potential energy.

CHAPTER 107.

UNIT 10 LAB: MECHANISMS OF HEAT TRANSFER

COOLING IN A CUP

Materials:

- foam cups (8 oz)
- plastic or paper cups (8 oz)
- Aluminum foil
- Hot water (80-99) °C
- syringe or graduated cylinder
- thermometer or digital temperature sensor + computer with sensor control and analysis software

Observation

We observe that the cooling of hot liquid in a cup is affected by the cup material (foam, paper, plastic, metal) and by using a lid.

Question

Which raises the question: Among a metal lining, an insulating cup material, or a lid, which features are most important to keeping a hot beverage from cooling too quickly?

Search Existing Knowledge

Find information about how different mechanisms of heat transfer would be affected by using a lid and various combinations of materials. Record what you learn below.

Hypotheses

Use the information you found above to fill in the blank for each hypothesis below.

Starting with a plastic cup as our baseline,

If _____ does not contribute much heat loss, then changing to a foam cup will not significantly decrease the cooling rate.

If _____ does not contribute much heat loss, then adding a lid to the foam cup will not significantly decrease the cooling rate.

If _____ does not contribute much heat loss, then adding a foil lining to the foam cup and lid will not significantly decrease the cooling rate.

Test

We will test the rate at which a liquid cools in each of the situations above.

We will use the following procedure to control for the amount of water used in each test well as for possible differences temperature of the water and the room:

1. Set up a thermometer to continuously measure the room temperature.
2. Use a high precision instrument, such as a syringe or graduated cylinder, to measure the water volume for each test. Measure out enough hot water to fill the plastic cup about $1/2$ way.
3. Place a thermometer in the water and wait ten seconds.
4. Start a timer and record the temperature of the room and the water simultaneously, leave the thermometers in place.
5. Calculate the initial difference between the water temperature and the room temperature.
6. Calculate half of the initial temperature difference.
7. Calculate the temperature the water will be when the temperature difference has dropped to half of its initial value.
8. Record the time when water temperature reached the value you calculated in the previous step. This is the half-life of the temperature difference.
9. Repeat the experiment to determine the half-life when foam cup is used.
10. Repeat the experiment to determine the half-life when a lid is used on the foam cup.

11. Repeat the experiment to determine the half-life when a foil lining is added to the foam cup and lid.

Analysis

Compared to the plastic cup, by what factor did changing to a foam cup increase the half-life of the temperature difference?

Compared to the foam cup, by what factor did adding a lid increase the half-life of the temperature difference?

Compared to the foam with a lid, by what factor did adding foil lining increase the half-life of the temperature difference?

Which feature increased the half-life by the largest factor?

Which feature decreased the half-life by the largest factor?

Conclusions

Which feature is most important to preventing hot liquids from cooling: quality insulation, metal lining, or lid? Explain.

Does radiation contribute much heat loss to hot water in a cup?

Does conduction contribute much heat loss to hot water in a cup?

Do convection and evaporation contribute much heat loss to hot water in a cup?

PART XII.

DESIGN-BUILD-TEST PROJECTS

Design-Build-Test projects give students hands-on experience with scientific concepts and the scientific process in general. The projects were originally designed to be tackled over the course of three one-hour lectures and one three-hour lab, or roughly one week of instructional time. Providing intermediate feedback during various phases of the project improves student outcomes. For example, you might break the projects into phases such as: problem introduction and initial design phase (1 hour), a building, testing, and re-design phase (3 hours), and a re-build and final touches phase (1 hour).

CHAPTER 108.

BIOPHYSICAL MODEL OF THE ARM

PROJECT GOALS

- Use hands-on experience to reinforce physics concepts covered so far
- Jump cognition levels to *create*
- Practice critical thinking and the scientific process
- Have fun

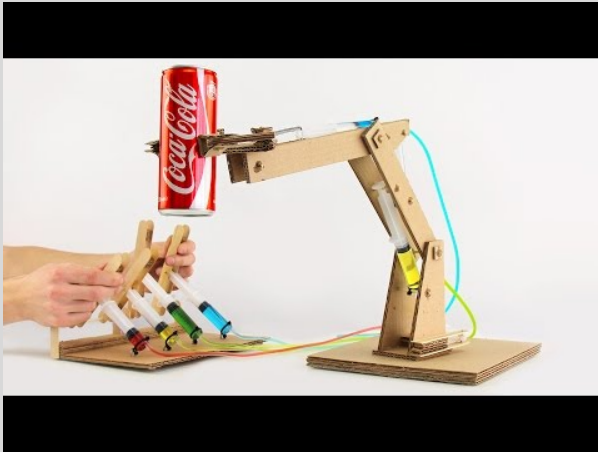
PROJECT DESCRIPTION

Build a scale articulating model of the human arm from the shoulder to the wrist. The model will include the lower arm, upper arm, elbow joint, biceps and triceps muscles and associated tendons. The model will be made out of cardboard, glue, twist ties and wooden dowels. The articulation of muscles will be done using syringes and tubing to form hydraulic actuators and twist ties will serve as tendons in similar fashion to the process seen in the following video:

Your project assess the concepts listed below and your

project grade will be determined according to the criteria listed under each concept. The project is worth 15 points overall, and the distribution of points among the criteria are listed under each concept.

1. Scientific Method: Creation process is well documented in a typed project report with the sections listed in bold below:
 - **DESIGN**



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- Neat documentation of design considerations and how they relate to concepts covered in class = 1pt
 - Neat scale diagram of your design before building begins. Must include labels and dimensions. = 1pt
 - **BUILD**
 - Neat documentation of issues encountered during build = 1pt
 - Neat documentation of solutions to build issues and changes to design = 1pt
 - **TEST**
 - Neat documentation of issues encountered during testing of design = 1pt
 - **REDESIGN**
 - Neat documentation of solutions to testing issues and changes to design = 1pt
 - Neat final updated scale diagram = 1pt
2. Unit Conversion: The model is a 2:3 scale size of a human arm.
- Scaled 2:3 = 2pts
 - Proportionally scaled, but not 2:3 = 1pt
3. Forces and Torques: The model is capable of curling at least 1:100 the weight that a human arm can curl.
- Curls at least 1:100 scale weight = 2 pts
 - Curls weight, but not 1:100 scale weight = 1pt

4. Levers: The model actuates with the same range of motion (in terms of elbow angle) as the human arm.
 - Articulates full human range of motion = 2 pts
 - Articulates, but not full human range of motion = 1pt
5. Stability: The model does not tip over under the 1:100 scale load.
 - Remains standing = 1pt
6. Strength of Materials: The model materials do not fracture, rupture, or otherwise fail under the 1:100 load.
 - No failure, fracture or rupture = 1pt

Additional Information to Consider:

- You may use any resource you like for guidance, however only students in your group may work on your model or add to the documentation AND ***you must cite your sources in your project report.***
- You don't have to build the control levers, you can just hold and operate your two control syringes.
- Your model does not need to rotate like the one in the example video.
- Do not build a hand, we will hang a weight from the end of your model's forearm for the testing phase.
- You do not have to generate your diagrams on the computer unless you want to. You can draw them by hand and attach them to your report as long as they

are still neat, well labeled, properly scaled, and the dimensions are indicated.

- Your project will receive a group score, however students not actively participating and contributing will not receive credit for the project.
- You will be able to go through as many rounds of design/build/test as you would like within the time allotted for this project.
- All projects must have their final evaluation on or before the last day of the period allotted for the project.
- Don't hesitate to ask your instructor for help or ask clarification question regarding the project expectations.

CHAPTER 109.

MARS LANDER

PROJECT GOALS

- Use hands-on experience to reinforce physics concepts covered so far
- Jump cognition levels to *create*
- Practice critical thinking and the scientific process
- Have fun

PROJECT DESCRIPTION

LANDER DELIVERY

Welcome to the first briefing for the touchdown redundancy team. Please pay close attention because I am going to throw a lot of information at you.

Now, as you are aware the sky crane has emerged as the most practical method of delivering relatively massive payloads to the Martian surface. For a brief recap of that system watch the following video:

As we know, the sky crane system successfully delivered the curiosity rover to Mars, an important step in getting

this historic point, where we are now in mission design phase for the Human Exploration of Mars. Several sky crane systems will be used to deliver supplies, equipment and the return rocket ahead of the human mission.

YOUR TASK

We calculate a low failure probability for the sky crane, but we also estimate that the large majority of that probability is concentrated during the time when the crane is within 14 **m** of the surface.

We know humans and equipment can only survive forces up to a certain threshold. Therefore, this team will



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design a lander which will prevent accelerations above the safety threshold for drops up to 14 **m** on Mars. This will ensure that the humans and critical equipment survive an unexpected drop to the Martian surface with no adverse effects.

The system you design to accomplish this must not rely on any other system, which would create a redundancy spiral, and that includes any electronics systems. (Therefore a parachute deployment system is not acceptable). The system must be built into the structure of the lander itself. You will be designing a Mechanical Acceleration Suppression System, or M.A.S.S.

DESIGN AND TESTING PARAMETERS:

In order to generate a diversity of design ideas the team will be split into groups. I want hands-on contributions from all members, so groups cannot be bigger than three. I also want us checking and double-checking each other's work, so no groups smaller than two.

Each group will design a system, build a model, and we will test them in our free-fall facility here in the building. The model test subjects and equipment we will use will be three raw eggs.

We must recognize that g on mars is only about 3.8 **m/s/s** compared to 9.8 **m/s/s** on Earth so you will calculate a new drop height for testing our models here on Earth.

The model lander must fall straight down from the calculated height and land within a 25 **cm** x 25 **cm** area to ensure that it lands in the safe location identified by the sky crane imaging system. (Therefore a parachute system is not acceptable).

Due to the fuel requirements and cost of launching mass into space, you are limited to a total mass of 500 **g**

for your model lander system, including the payload (eggs).

Due to the size limitations of the spacecraft you are limited to a total size of 20 **cm** wide x 20 **cm** long by 30 **cm** high for your model lander system.

You are also limited on your design budget. In order to maximize the efficiency of taxpayer dollars for space exploration you are limited to the following materials, with associated costs and your total cost cannot go above 500 **USD**.

Glue: No cost

Paper: 4 **USD/gram**

Cardboard: 6 **USD/gram**

Wood (Popsicle sticks) 10 **USD/gram**

Aluminum Foil: 25 **USD/gram**

PRESENTATION AND TESTING:

You will give the class an **8 minute** presentation on your model that will include the following sections:

1. Model design features
2. Physics concepts and reasoning behind your design
3. Materials cost breakdown for your model
4. Difficulties and solutions/redesigns during your project

MODEL EVALUATION (GRADING)

C-grades will be earned by:

1. correctly completing and submitting the guide calculations worksheet
2. fully participating in the design-build process
3. keeping your design within budget limitations

4. contributing to your group presentation.

B-Grades will be earned by doing the above plus:

1. landing completely within the designated area
2. preventing damage to the test subject (egg).

A-Grades will be earned by doing all of the above plus:

1. keeping within mass and size limitations

GUIDE CALCULATIONS:

DROP HEIGHT, SPEED, AND ACCELERATION

Using our knowledge of conservation of mechanical energy determine the Earth drop height we need to provide the same impact speed as a 14 **m** drop on Mars:

We want to limit the peak acceleration felt by the cargo to 10 **g**. The humans and equipment will be strapped tightly to the lander frame so the lander frame must not accelerate at more than 10 **g**. What is this acceleration in m/s/s?

IMPACT FORCE

Assuming your lander + payload have the maximum 300 **g** mas, calculate the maximum net force that can be applied to the lander on touchdown without exceeding the threshold acceleration:

Draw a free body diagram of the lander during impact

Determine the peak normal force that can be applied to your model by the ground in order to prevent such an acceleration. This is your safety threshold force.

You may use force plate to test version of your models and see how they react to forces of various sizes.

IMPACT DURATION

Use the lander mass and impact speed to calculate the change in momentum of the lander upon impact.

If you design your lander to keep the average net force applied on impact to be less than $1/3$ of the safety threshold, then the peak force will likely not exceed the safety threshold. Draw a F vs. t curve for the impact that illustrates this idea.

If you were to achieve this average force value of $1/3$ the peak force threshold, then over what time would you need to spread the impact?

What design features will you implement to spread out the impact duration?

TESTING

Record the dimensions of your lander here:

Width:_____Length:_____Height:_____

Record the mass of the lander here:_____

Record the masses and total cost of various materials used:

Record the total cost of your lander here:_____

Did your payload survive without damage?

GLOSSARY

1st Law of Thermodynamics

Any change in the internal energy of a system must in the process of exchanging heat, doing work, or both.

3rd class lever

a lever with the effort between the load and the fulcrum.

absolute zero

A lower limit of temperature corresponding to the minimum possible average kinetic energy of atoms and molecules.

acceleration

the change in velocity per unit time, the slope of a velocity vs. time graph

acceleration due to gravity

the rate at which an object changes velocity when gravity is the only force acting on the object

accelerations

accurate

refers to the closeness of a measured value to a standard or known value

Achilles tendon

a tough band of fibrous tissue that connects the calf muscles to the heel bone

air resistance

a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid

analyze

examine methodically and in detail the constitution or structure of information for purposes of explanation and interpretation

anisotropic

having a physical property that has a different value when measured in different directions

apparent weigh
apparent weight

the reading on a scale that is used to measure the weight of an object that is submerged in a fluid

approximation

a rough value obtained without making a measurement by using prior knowledge and assumptions.

Archimedes' Principle

The upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially submerged, is equal to the weight of the fluid being displaced by the body

assumption

ignoring some complication of the in order to simplify the analysis or proceed even though information is lacking

at rest

not moving

atmospheric pressure

the pressure exerted by the gasses in the atmosphere

average acceleration

average change in velocity per unit time, calculated as

change in velocity during a time interval divided by the time interval

average speed

average rate at which distance was traversed, equal to total distance traveled within a time interval, divided by the time interval

average velocity

the average of all instantaneous velocities that occurred within a certain time interval, equal to the displacement divided by the time interval

Barriers

Objects, events, or conditions that hinder access.

bedrock

hard rock exposed or buried at the earth's surface

biased

prejudice in favor of or against one thing, person, or group compared with another, usually in a way considered to be unfair or inaccurate.

bipedal

(of an animal) using only two legs for walking

black body emitter

an ideal object which absorbs all radiation that strikes it, with no reflection, and releases that energy as thermal radiation in a way that depends only on its temperature

Bloom's Taxonomy

Bloom's Taxonomy

A framework for categorizing educational goals.

Blooms Taxonomy

BMI

Body Mass Index (BMI) is a person's weight in kilograms divided by the square of height in meters. BMI can be used to screen for weight categories that may lead to health problems but it is not diagnostic of the body fatness or health of an individual

brittle

liable to break or shatter due to relatively inability to deform under stress (not ductile)

buoyant force

buoyant force

the upward force exerted by any fluid upon a body placed in it

calibrated

defining the values of an instrument's readings by comparison to a standard

calories

unit of energy equivalent to 4.184 Joules

cantilevered

any rigid structure projecting from a support, especially one in which the projection is great in relation to the depth of the structure

cardiovascular system

heart, blood and blood vessels

Carnot efficiency

the maximum theoretical efficiency that a heat engine could achieve when operating between two set temperatures, as permitted by the Second Law of Thermodynamics

Celsius

the most common relative temperature scale

center of gravity

a point at which the force of gravity on body or system (weight) may be considered to act. In uniform gravity it is the same as the center of mass.

center of mass

a point representing the mean (average) position of the matter in a body or system

centripetal acceleration

component of the acceleration directed toward the center of a circular motion

centripetal force

a name given to the component of the net force acting perpendicular to an objects motion and causing to take a circular path

chain-link method

a specific method for unit conversion that is designed to aid in reducing mistakes.

change of phase

the change of a substance between states of being solid, liquid, or gas (or other more exotic phases)

chemical potential energy

energy stored in the chemical bonds of a substance

class of lever

coefficient of friction

coefficient of restitution

the fraction of relative velocity remaining after a

collision, for collision with a stationary object equal to the ratio of final speed to initial speed

Cognition

The mental action or process of acquiring knowledge and understanding through thought, experience, and the senses

combustion

the process of burning, the rapid chemical combination of a substance with oxygen, involving the production of heat and light

compression

reduction in size caused by application of compressive forces (opposing forces applied inward to the object).

Computer modeling

using a computer program that is designed to simulate what might or what did happen in a situation

concentration

relative amount of one substance or quantity contained or stored within another substance or quantity, such as thermal energy per molecule

conclusion

a judgment or decision reached by reasoning and logic based on results provided by analysis of data

condensation

Process of vapor changing phase into a liquid.

conduction

the process by which heat is directly transmitted through a substance when there is a difference of temperature between adjoining regions, without movement of the material

conservative forces

forces that do work which converts energy between forms of mechanical energy (potential energy and kinetic energy)

conservative work

work that converts energy between mechanical forms of energy (potential energy and kinetic energy)

conserved

a physical quantity is said to be conserved when its total value does not change

constant

not changing, having the same value within a specified interval of time, space, or other physical variable

convection cell

cyclic fluid flow caused by natural convection

conversion factor

a number that relates two different units of measure for the same quantity and allows conversion between the two units

Coriolis Effect

an effect whereby a mass moving in a rotating system behaves as though experiencing a force (the Coriolis force) that acts perpendicular to the direction of motion. On the earth, the effect tends to deflect moving objects to the right in the northern hemisphere and to the left in the southern and is important in the formation of cyclonic weather systems

cross sectional area

cross-sectional area

The cross-sectional area is the area of a two-dimensional shape that is obtained when a three-dimensional object - such as a cylinder - is sliced perpendicular to some specified axis at a point. For example, the cross-section of a cylinder - when sliced parallel to its base - is a circle

crust

the relatively thin layer of rock that makes up the outermost solid shell of our planet

data

collection of values measured during an experiment

density

relation between the amount of a material and the space it takes up, calculated as mass divided by volume.

dependent variable

a factor, condition, or property that changes in response to purposeful changes in the independent variable

derivation

a sequence of steps, logical, mathematical, or computational, combining one or more results to obtain another result

dew

water that condenses on cool surfaces at night, when decreasing temperature forces humidity to 100% or higher

dispersion

the action or process of distributing a quantity over a wide space

displaced

pushed out of original position, typically in reference to fluid pushed out of the way by an object placed in the fluid, or an object being displaced from its equilibrium position

displacement

change in position, typically in reference to a change away from an equilibrium position or a change occurring over a specified time interval

displacement method

method for determining the volume of an object by measuring how much water it displaces

drag coefficient

a number characterizing the effect of object shape and orientation on the drag force, usually determined experimentally

drag force

a force applied by a fluid to any object moving with respect to the fluid, which acts opposite to the relative motion of the object relative to the fluid

ductile

able to be deformed without failure, pliable, not brittle

dynamic equilibrium

a state of being in motion, but having no net force, thus the motion is constant

efficiency

ratio of useful work performed to total energy expended

efficient

effort

referring to a lever system, the force applied in order to hold or lift the load

effort arm

in a lever, the distance from the line of action of the effort to the fulcrum or pivot

elastic collision

collision in which no permanent deformation occurs, and kinetic energy is conserved

Elastic Limit

the maximum stress that can be applied to a material before it leaves the linear region

elastic modulus

measures of resistance to being deformed elastically under applied stress, defined as the slope of the stress vs. strain curve in the elastic region

elastic potential energy

energy stored in the deformation of a material

elastic region

the range of values for stress and strain values over which a material returns to its original shape after deformation

Electromagnetic radiation

light waves, or coupled oscillating electric and magnetic fields that can travel through empty space and carry both energy and momentum without moving mass

electromagnetic spectrum

the range of wavelengths or frequencies over which electromagnetic radiation extends

emission spectrum

data which describes the relative amount of electromagnetic radiation emitted by an object across a range of wavelengths, or conversely frequencies.

emissivity

measure of a material's effectiveness at emitting energy as thermal radiation

Empirical models

mathematical explanation of the relation between measured values that is used for making predictions

Energy

A quantity representing the capacity of an object or system to do work.

Energy pathway

the process of transferring chemical potential energy stored in food to useful work and thermal energy

Entropy

A measure of energy dispersion in a system.

equilibrium

a state of having no unbalanced forces or torques

evaporation

vaporization that occurs on the surface of a liquid as it changes into the gas phase

exhaust heat

heat transferred to the environment rather than being used to do useful work

Fahrenheit

a relative temperature scale commonly used in the U.S.

Feedback

1) information about reactions to a product, a person's performance of a task, etc. which is used as a basis for improvement.

2) the modification or control of a process or system by its results or effects, e.g., in a biochemical pathway or behavioral response

final position

position at the end of the time interval over which motion is being analyzed

final velocity

the value of velocity at the end of the time interval over which motion is being analyzed

First class levers

levers with the fulcrum placed between the effort and load

First Law of Thermodynamics

the change in internal energy of a system is equal to the heat added to the system minus the work done by the system

force

any interaction that causes objects with mass to change

speed and/or direction of motion, except when balanced by other forces. We experience forces as pushes and pulls.

force of gravity

attraction between two objects due to their mass as described by Newton's Universal Law of Gravitation

forced convection

transfer of heat due to the movement of fluid molecules driven by external factors other than thermal expansion.

form drag

that part of the drag on an object that arises from its shape and angle at which it moves the fluid and which can be decreased by streamlining

fracture

the separation of an object or material into two or more pieces under the action of stress and associated strain

free body diagram

a graphical illustration used to visualize the forces applied to an object

free body diagrams

free fall

the motion experienced by an object when gravity is the only force acting on the object.

frequency

the number of cycles or oscillations occurring per second, as in the frequency of the electromagnetic oscillations in a light wave

friction

a force that acts on surfaces in opposition to sliding motion between the surfaces

friction coefficient

coefficient describing the combined roughness of two surfaces and serving as the proportionality constant between friction force and normal force

fulcrum

the point on which a lever rests or is supported and on which it pivots

Glossary

The glossary feature includes rollover definition capability.

gravitational potential energy

potential energy stored in objects based on their relative position within a gravitational field

gravitational potential energy

gravity

gravity passes

Green House Gas Effect

Elevation of Earth's temperature relative to the atmosphere-free condition caused differential absorption of UV, visible, and IR light by specific gases and particles present in the atmosphere.

Heat

An amount of thermal energy transferred due to a difference in temperature.

heat capacity

The amount of energy required to raise the temperature of an object by one temperature unit.

Heat death

the degradation of energy quality associated with a spontaneous processes.

heat engines

devices for converting thermal energy to useful work and exhaust heat

heat index

a measure of how hot feels (according to difficult in exhausting heat) when relative humidity is factored in with the actual air temperature

heat loss rate

the amount of heat (thermal energy transferred due to a temperature difference) that leaves an object per unit time

heat transfer coefficient

a measure how well thermal energy is transferred as heat for a given temperature and contact area

histogram

A graph of relating how often a value falls within a certain range.

homeostasis

is the state of steady internal physical and chemical conditions maintained by living systems

Hooke's Law

the restoring force exerted by a spring is equal to the displacement multiplied by spring constant

horsepower

a unit for power equal to 746 Watts

hydrostatic weighing

a technique for measuring the mass per unit volume of a living person's body. It is a direct application of

Archimedes' principle, that an object displaces its own volume of water

Hyperthermia

The condition of having a body temperature well above the normal range.

hypothermia

The condition of having a body temperature well below the normal range.

hypothesis

a proposed explanation made on the basis evidence that can be supported or refuted by the result of experimentation

impulse

the average force applied during a time interval multiplied by the time interval

impulse-momentum theorem

the change in momentum experienced by an object is equal to the net impulse applied to the object

independent variable

the factor, property, or condition that is purposefully changed within an experiment

inelastic collision

a collision for which kinetic energy is not conserved

inertia

the tenancy of an object to resist changes in motion

infrared

having a frequency just lower than visible red light but higher microwaves.

initial position

position at the start of the time interval over which motion is being analyzed

initial velocity

the value of velocity at the start of the time interval over which motion is being analyzed

instantaneous

existing or measured at a particular instant

internal energy

the total of a systems thermal energy and chemical potential energy, the total energy stored microscopically within the system

irreversible

a process that is not a reversible process in which the system and environment can be restored to exactly the same initial states that they were in before the process

Isolated system

a system for which neither thermal energy or particles are allowed to leave or enter.

isotropic

having a physical property which has the same value when measured in different directions

iterative

relating to or involving repetition of a mathematical or computational procedure applied to the result of a previous application

Joule

International standard (SI) unit of Energy

kelvin

SI unit of temperature

kinetic energy

energy which a body possesses by virtue of being in motion, energy stored by an object in motion

kinetic friction

a force that resists the sliding motion between two surfaces

Latent heat

the thermal energy required to change the phase of a substance (or released by the substance when it changes phase)

latent heat of fusion

the thermal energy required to melt a unit mass of a substance

latent heat of vaporization

Thermal energy input required to change a unit mass of liquid into vapor.

law

a statement, usually in the form of a mathematical equation, that summarizes, but not explains, the results of repeated experiments or observations that describe some aspect of the natural, usually within a certain range of application.

Law of Conservation of Energy

the net work on a system must be equal to the sum of the changes in kinetic, potential, and thermal energies

Law of Conservation of Momentum

the combined total momentum of all objects in system immediately prior to a collision be the same as the total momentum of all objects in the system immediately after the collision

Learning management system

a software application for the administration, documentation, tracking, reporting, and delivery of educational courses, training programs, or learning and development programs

lever

a rigid structure rotating on a pivot and acting on a load, used multiply the effect of an applied effort (force) or enhance the range of motion

lever arm

perpendicular distance between the line of action of a force causing a torque and the pivot about which the torque occurs

lever classes

There are three types or classes of levers, according to where the load and effort are located with respect to the fulcrum

line of action

an imaginary line that is parallel to a force and extends in both directions from the point of application of the force

linear region

region of the stress vs. strain curve for which stress is proportional to strain and the material follows Hooke's Law

linear thermal expansion coefficient

Material property that relates the fractional change in length experienced by an object due to a unit change in temperature.

load

a weight or other force being moved or held by a structure such as a lever

locomotion

movement or the ability to move from one place to another

longitudinal

running lengthwise rather than across

magnitude

the size or extent of a vector quantity, regardless of direction

malleable

able to be hammered or pressed permanently out of shape without breaking or cracking

mantle

the mantle is the mostly-solid bulk of Earth's interior. The mantle lies between Earth's dense, super-heated core and its thin outer layer, the crust.

mass

a measurement of the amount of matter in an object made by determining its resistance to changes in motion (inertial mass) or the force of gravity applied to it by another known mass from a known distance (gravitational mass). The gravitational mass and an inertial mass appear equal.

measurement error

Measurement Error (also called Observational Error) is the difference between a measured quantity and its true value. It includes random error (naturally occurring errors that are to be expected with any experiment) and systematic error (caused by a mis-calibrated instrument that affects all measurements)

measurement units

a unit of measurement is a definite magnitude of a quantity, defined and adopted by convention or by law, that is used as a standard for measurement of the same kind of quantity. Any other quantity of that kind can be expressed as a multiple of the unit of measurement.

mechanical advantage

ratio of the output and input forces of a machine

mechanical efficiency

the effectiveness of a machine in transforming the energy input to the device to mechanical energy output

mechanical energy

the sum of potential and kinetic energy

Melting

changing phase from solid to liquid.

Metacognition

awareness and understanding of one's own thought processes

metastable equilibrium

a state in which a slight disturbance results in a restoring force that maintains stability, but a sufficiently large disturbance moves the system into an unstable region (or different metastable region)

method of significant figures

using the number of digits provided in a measurement value to indicate the measurement uncertainty

metric prefix

a unit prefix that precedes a basic unit of measure to indicate a multiple or fraction of the unit

model

a representation of something that is often too difficult (or impossible) to observe or display directly

momentum

the combined effect of mass and velocity, defined as mass multiplied by velocity

Motion graphs

graphs or plots with time on the horizontal axis and position or velocity or acceleration on the vertical axis

Multitasking

Splitting attention between more than one task at a time.

Natural convection

Transfer of heat due to fluid movement caused by thermal expansion of the fluid

negligible

small enough as to not push the results of an analysis outside the desired level of accuracy

nervous system

the network of nerve cells and fibers which transmits nerve impulses between parts of the body

net force

the total amount of remaining unbalanced force on an object

net torque

remaining unbalanced torque on an object

net work

total work done on an object, equal to the addition of all separate works done on the object, or the work done by the net force

Newton

the SI unit of force. It is equal to the force that would give a mass of one kilogram an acceleration of one meter per second per second

Newton's 3rd Law

Newton's First Law

an object's motion will not change unless it experiences a net force

Newton's Law of Cooling

Observation that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the environmental temperature

Newton's Second Law

the acceleration experienced by an object is equal to the net force on the object divided by the object's mass

Newton's Third Law

for every force applied by an object on a second object, a force equal in size, but opposite in direction, will be applied to the first object by the second object

Newtons

non-conservative forces

forces that do non-conservative work, which is work that does not transfer energy only among kinetic and potential forms (mechanical energy)

normal force

the outward force supplied by an object in response to being compressed from opposite directions, typically in reference to solid objects.

null hypothesis

default position that there is no relation between two measured quantities

numerical simulation

a calculation that is run on a computer following a program that implements a mathematical model for a physical system

order of magnitude

designating which power of 10 (e.g. 1,10,100,100)

order of magnitude estimation

the process of approximating a value to obtain a result you expect to at least be within one order of magnitude of the correct answer.

origin

location where the position is zero

oscillatory

repetitive variation, typically in time, of some measure about a central value

parallel

side by side, pointing in exactly the same direction, or having the same distance continuously between them

Pascals

the SI derived unit of pressure used to quantify internal pressure, stress, Young's modulus and ultimate tensile strength. It is defined as one newton per square meter

perfectly elastic collision

a collision for which initial and final values of the total kinetic energy of all objects in the system are the same

perfectly inelastic collisions

collisions in which the colliding objects stick together (explosions are perfectly inelastic collisions in reverse)

perpendicular

at an angle of 90° to a given line, plane, or surface

perpendicular distance

Physical models

mechanistic explanation of how a physical system works

piezoelectric effect

the ability of certain materials to generate an electric charge in response to applied mechanical stress

pivot

the central point, pin, or shaft on which a mechanism turns or oscillates

plastic region

the range of values for stress and strain over which a material experiences permanent deformation

position

location in space defined relative to a chosen origin, or location where the value of position is zero

potential energy

the energy stored within an object, due to the object's position, arrangement or state. Examples are gravitational potential energy due to the relative position of masses and elastic potential energy caused by being under stress

pounds

a unit of force equal to 4.44822 Newtons, or the the weight of a 0.4536 kg mass on Earth's surface

power

the rate at which work is done, the rate at which energy is converted from one form to another

precision

refers to the closeness of two or more measurements to each other

preponderance

the quality or fact of being greater in number, quantity, or importance

pressure

force per unit area

principle

principles summarize rules created and followed by scientists when formulating hypotheses, designing experiments, analyzing results.

Principle of Conservation of Energy

Energy cannot be created or destroyed, only transferred from one type to another and/or from one object to another

Principle of Conservation of Momentum

the momentum of an object or collection of objects (system) remains constant if the net impulse on the system is zero

prone

lying horizontally with the face and torso facing down

proportional

having a constant ratio to another quantity

qualitative

describing what happens, but not how much happens

quantitative

describing what and how much happens

radians

radians (rads)

a unit of angle, equal to an angle at the center of a circle that produces an arc length equal to the radius

random error

random errors are fluctuations (in both directions) in the measured data due to the precision limitations of the measurement device. Random errors usually result from the experimenter's inability to take the same measurement in exactly the same way to get exact the same number

range of motion

distance or angle traversed by a body part

rate of heat transfer

amount of thermal energy transferred into or, out of an object as heat, per unit time

reactive force

a type of force supplied by an object in response to

application of a different force on the object. Friction is a reactive force

Relative humidity

a measure of how many water molecules are in the vapor phase relative to the maximum number that could possibly be in the vapor phase at a given temperature. A relative humidity of 100% means that no more water molecules can be added to the vapor phase.

resistance

the force working against the rotation of a lever that would be caused by the effort

resistance arm

shortest distance from the line of action of the resistance to the fulcrum

restoring force

a force that tends to move a system back toward the equilibrium position

results

information acquired by analyzing data

rotational equilibrium

a state of having not net torque and no change in rotational motion

rupture

the sudden and complete failure of a material under stress

scientific method

a method of procedure that has characterized natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses

scientific notation

a way of writing very large or very small numbers. A number is written in scientific notation when a number between 1 and 10 is multiplied by a power of 10.

SCUBA

self-contained underwater breathing apparatus

Second class levers

levers with the resistance (load) in-between the effort and the fulcrum

Second Law of Thermodynamics

the total entropy of an isolated system can never decrease over time, meaning objects left to themselves will always trend toward thermal equilibrium, meaning that thermal energy will always spontaneously transfer from hot system to cold system

Sentinel Event

an unexpected occurrence involving death or serious physical or psychological injury, or the risk thereof. Serious injury specifically includes loss of limb or function.

significant figures

each of the digits of a number that are used to express it to the required degree of accuracy, starting from the first nonzero digit

skin drag

friction caused by the viscous nature of fluids

skinfold method

method for measuring body fat percentage using specially designed calipers to measure the thickness of skinfolds that are pinched from several specific locations on the body as inputs to empirical equations

slope

the steepness of a line, defined as vertical change between two points (rise), divided by the horizontal change between the same two points (run)

sonic boom

the sound associated with the shock waves created

whenever an object travelling through the air travels faster than the speed of sound

sound barrier

sudden increase in aerodynamic drag and other undesirable effects experienced by an object when it approaches the speed of sound

specific gravity

the ratio of the density of a substance to the density of a standard, usually water for a liquid or solid, and air for a gas

specific heat

A material property that determines the amount of energy required to raise the temperature one mass unit of the material by one temperature unit.

speed

distance traveled per unit time

speeds

Spontaneous process

a process which occurs naturally on its own, without the need for work to be done in forcing it to happen.

spring constant

measure of the stiffness of a spring, defined as the slope of the force vs. displacement curve for a spring

stability

a measure of the displacement from equilibrium an object can experience and still move back toward equilibrium

stable equilibrium

a state in which a body tends to return to its original position after being disturbed

standard deviation

is a measure that is used to quantify the amount of variation or dispersion of a set of data values

standard scientific (SI) units

a system of physical units (SI units) based on the meter, kilogram, second, ampere, kelvin, candela, and mole

static equilibrium

the state being in equilibrium (no unbalanced forces or torques) and also having no motion

static friction

a force that resists the tenancy of surfaces to slide across one another due to a force(s) being applied to one or both of the surfaces

Stephan-Boltzmann Law

The total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature.

strain

the measure of the relative deformation of the material

stress

a physical quantity that expresses the internal forces that neighboring particles of material exert on each other

Study strategy

a thoughtful and specific process for self-directed learning.

support base

region defined by lines connecting points of contact with the supporting surface

Systematic errors

an error having a nonzero mean (average), so that its effect is not reduced when many observations are averaged. Usually occurring because there is something wrong with the instrument or how it is used.

temperature

a measure of the average kinetic energy of the particles (e.g., atoms and molecules) in an object, which determines how relatively hot or cold an object feels

tension

the force that is provided by an object in response to being pulled tight by forces acting from opposite ends, typically in reference to a rope, cable or wire

terminal speed

the speed at which restive forces such as friction and drag balance driving forces and speed stops increasing, e.g. the gravitational force on a falling object is balanced by air resistance

test conditions

an item or event of a component or system that could be verified by one or more test cases, e.g., a function, transaction, feature, quality, attribute, or structural element

theory

an explanation of an aspect of the natural world that can be repeatedly tested and verified in accordance with the scientific method using accepted standard protocols

thermal conductivity

a measure of a material's ability to conduct heat

thermal energy

energy stored in the microscopic motion of atoms and molecules (microscopic kinetic energy)

thermal equilibrium

a two systems are in thermal equilibrium when they do not exchange heat, which means they must be at the same temperature

thermal expansion

The increase change in volume of an object resulting from a change in temperature.

thermal image

image created by substituting visible color variations for temperature variations determined by measuring variations in thermal radiation intensity and/or wavelengths

thermal insulation

materials designed to slow the rate of heat transfer

Thermal power

rate at which chemical potential energy is converted to thermal energy by the body, batteries, or heat engines.

Also, rate at which thermal energy is converted to electrical energy by a thermal power plant.

thermal radiation

Electromagnetic radiation spontaneously emitted by all objects with temperature above absolute zero.

thermometer

a device that measures temperature

third law pair forces

a pair of equal and opposite forces applied between two different objects as described by Newton's Third Law of Motion

tipping point

the point at which an object is displaced from a region of stable equilibrium

toe region

range of values for stress and strain over which a material experiences large strain for relatively small stress due to un-crimping

torque

the result of a force applied to an object in such a way that the object would change its rotational speed, except when the torque is balanced by other torques

torques

translational equilibrium

a state of having no net force and thus no change in translational motion, though the net torque may be non-zero

translational motion

motion by which a body shifts from one point in space to another (up-down, back-forth, left-right)

transparent

allow light to pass through with minimal absorption

transverse

situated or extending across something, (crosswise)

ultimate strength

the maximum stress a material can withstand

uncertainty

Amount by which a measured, calculated, or approximated value could be different from the actual value

uncrimp

non-permanent re-alignment of substructures (fibers) in

a material that results in non-linear behavior at stress values less than the yield stress.

under water weight

apparent weight when submerged in water

uniform circular motion

motion of an object traveling at a constant speed on a circular path

uniformly

in a way that is the same in all cases, across a defined set of space and times

unit analysis

act of ensuring that the units resulting from a calculation match the type of quantity calculated.

Universal Law of Gravitation

every particle attracts every other particle in the universe with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers

unstable equilibrium

a state of equilibrium such that when the body is slightly displaced it departs further from the original position

useful work

work done on the external environment, such as moving objects, as apposed to work done internally, such as pumping blood

variable

a factor, property, or condition that can change during an experiment

vectors

a quantity having direction as well as magnitude

velocity

a quantity of speed with a defined direction, the change in speed per unit time, the slope of the position vs. time graph

viscous

a fluid that exhibits a large degree of internal friction (between sections of the fluid moving with different speed or direction)

visible spectrum

the portion of the electromagnetic spectrum that is visible to the human eye

volume

a quantity of space, such as the volume within a box or the volume taken up by an object.

Watts

international standard unit of power, equal to one Joule per second

wavelength

the distance between successive crests of a wave, such as a sound wave or electromagnetic wave

weight

the force of gravity on an object, typically in reference to the force of gravity caused by Earth or another celestial body

wind chill effect

Increase in rate of heat loss from objects that are warmer than air caused by the flow of air across the object surface.

Work

A quantity representing the effect of applying a force to an object or system while it moves some distance.

work-energy principle

the change in kinetic energy of an object or system is equal to the net work done on the object or system

yield point

the value of the stress (yield stress) and strain (yield strain) beyond which a material will maintain some permanent deformation