Contents

Chapter 1

Buoyancy

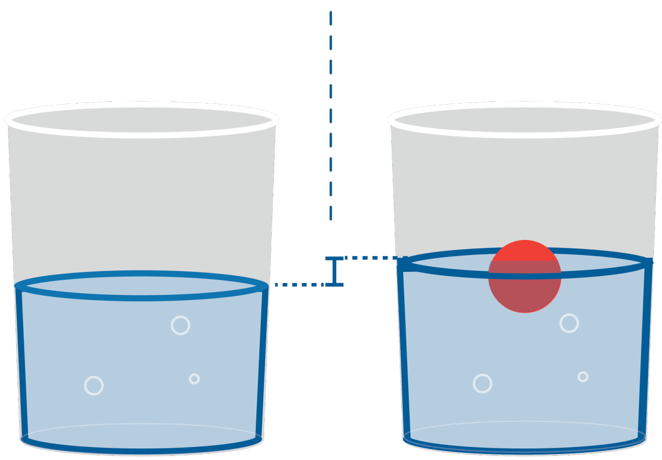
The word buoyancy probably brings to mind images of floating in water. Before we dive in, let's zoom out for a better understanding of everything buoyancy entails. You may be thinking: I want to be a computer programmer, why do I need to know about buoyancy? You might be surprised! This topic is much bigger than it seems at first glance.

Buoyancy concerns the ways in which liquids and gasses interact with gravity. The concept of buoyancy is connected to fundamental concepts about how the universe works. The *buoyant force*, as it is known in engineering, is an important concept that has wide ranging applications. A big part of engineering is moving stuff around, and understanding buoyancy helps us solve problems where we need to move things in and through fluids. Even if you don't have plans to build a robotic submarine, these are incredibly useful ideas to be familiar with. We will start exploring the topic with familiar scenarios around boats and water.

When you put a boat into water, it will sink into the water until the mass of the water it displaces is equal to the mass of the boat. We think of this in terms of forces. Gravity pulls the mass of the boat down; the *buoyant force* pushes the boat up. A boat dropped into the water will bob up and down at first before reaching an *equilibrium* where the two forces are equal.

The buoyant force pushes things up, fighting against the force of gravity. The force is equal to the weight of the fluid being replaced. For example, a cubic meter of freshwater has a mass of about 1000kg. If you submerge anything with a volume of one meter in freshwater on earth, the buoyant force will be about 9800 newtons.

For some things, like a block of styrofoam, this buoyant force will be sufficient to carry it to the surface. Once it reaches the surface, it will continue to rise (displacing less water) until the mass of the water it displaces is equal to its mass. And then we say "It floats!"



For some things, like a block of lead, the buoyant force is not sufficient to lift it to the surface, and then we say "It sinks!"

This is why a helium balloon floats through the air. The air that it displaces weighs more than the balloon and the helium itself. (It is easy to forget that air has a mass, but it does.)

Exercise 1 Buoyancy

You have an aluminum box that has a heavy base, so it will always float upright. The box and its contents weigh 10 kg. Its base is 0.3 m x 0.4 m. It is 1m tall.

When you drop it into freshwater ($1000 kg/m^3$), how far will it sink before it reaches equilibrium?

Working Space

Answer on Page 31

1.1 The Mechanism of Buoyancy: Pressure

As you dive down in the ocean, you will experience greater and greater pressure from the water. And if you take a balloon with you, you will gradually see it get smaller as the water pressure compresses the air in the balloon.

Let's say you are 3 meters below the surface of the water. What is the pressure in Pascals (newtons per square meter)? You can think of the water as a column of water crushing down upon you. The pressure over a square meter is the weight of 3 cubic meters of water pressing down.

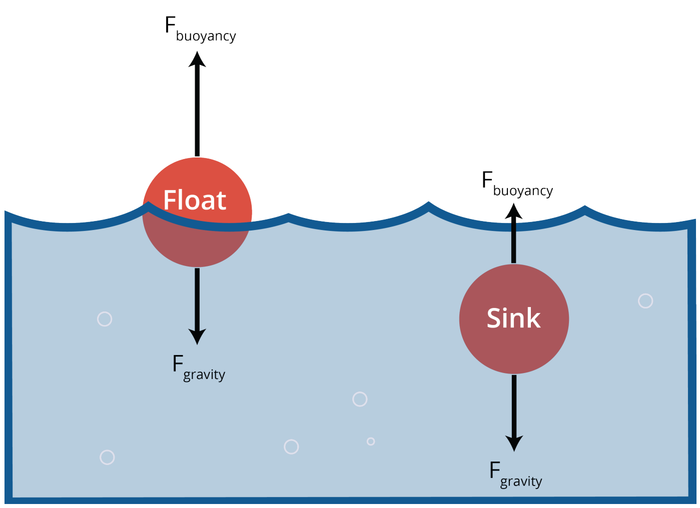
$$p = (3)(1000)(9.8) = 29,400 \text{ Pa}$$

This is called *hydrostatic pressure*. The general rule for hydrostatic pressure in Pascals p is

$p = dgh$

where d is the density of the fluid in kg per cubic meter, g is the acceleration due to gravity in m/s^2, and h is the height of the column of fluid above you.

So where does buoyant force come from? Basically, the pressure pushing up on the deepest part of the object is higher than the pressure pushing down on the shallowest part of the object. That is where bouyancy comes from.



Exercise 2 Hydrostatic Pressure

Working Space

You dive into a tank of olive oil on Mars. How much more hydrostatic pressure does your body experience at 5 meters deep than it did at the surface?

The density of olive oil is about 900 kg per square meter. The acceleration due to gravity on Mars is 3.721 m/s^2.

Answer on Page 31

1.2 The Mechanism of Buoyancy: Density

Keep in mind that although the pressure is increasing as you go deeper, the buoyant force will *not increase*, because the buoyant force is always equal to the weight of the fluid that is displaced, regardless whether that is 1 meter or 100 meters underwater.

Due to the added minerals, saltwater is denser than freshwater. This causes objects to float better in the sea than they do in a river. Lipids, like fats and oils, are less dense than water, allowing them to float on top of a glass of water. When you're facing a grease fire, you're told not to put water on it. That's because the water sinks below the grease, then boils, throwing burning grease everywhere.

Chapter 2

Heat

All mass in the universe has heat, whether you're looking at a block of dry ice (frozen CO_2, -78.5° C) or the surface of the sun ($5,600^\circ$ C). As long as the mass is above absolute zero — the coldest possible temperature in the universe — there is some amount of heat in it.

2.1 How Heat Works

As you heat up an object, you are imparting energy into it. Where does this energy go? The atoms take this energy and they begin to move, vibrating and bumping into each other, causing the heat to spread throughout. Everytime the atoms collide and bounce off of each other, they emit a tiny amount of energy as light. In most cases, that light is in the infrared spectrum, but in extreme cases can be visible, such as with molten lava or hot metal.

As objects interact, they either put heat into colder objects or take heat from warmer objects. That's what allows you to heat up anything in the first place. The hot air from a stove or bunsen burner interacts with the pan or test tube you're heating, passing the air's heat on. How could you model this?

2.2 Specific Heat Capacity

If you are heating something, the amount of energy you need to transfer to it depends on three things: the mass of the thing you are heating, the amount of temperature change you want, and the *specific heat capacity* of that substance.

Energy in Heat Transfer

The energy moved in a heat transfer is given by

$$E = mc\Delta_T$$

where m is the mass, Δ_T is the change in temperature, and c is the specific heat capacity of the substance.

(Note that this assumes there isn't a phase change. For example, this formula works nicely on warming liquid water, but it gets more complicated if you warm the water past its boiling point.)

Can we guess the specific heat capacity of a substance? It is very, very difficult to guess the specific heat of a substance, so we determine it by experimentation.

For example, it takes 0.9 joules to raise the temperature of solid aluminum one degree Celsius. So we say "The specific heat capacity of aluminum is 0.9 J/g °C."

The specific heat capacity of liquid water is about 4.2 J/g °C.

Let's say you put a 1 kg aluminum pan that is 80° C into 3 liters of water that is 20° C. Energy, in the form of heat, will be transferred from the pan to the water until they are at the same temperature. We call this "thermal equilibrium".

What will the temperature of the water be?

To answer this question, the amount of energy given off by the pan must equal the amount of energy absorbed by the water. They also need to be the same temperature at the end. Let T be the final temperature of both.

3 liters of water weighs 3,000 grams, so the change in energy in the water will be:

$$E_W = mc\Delta_T = (3000)(4.2)(T - 20) = 12600T - 252000 \text{ joules}$$

The pan weighs 1000 grams, so the change in energy in the pan will be::

$$E_P = mc\Delta_T = (1000)(0.9)(T - 80) = 900T - 72000 \text{ joules}$$

The total energy stays the same, so $E_W + E_P = 0$. This means you need to solve

$$(12600T - 252000) + (900T - 72000) = 0$$

And find that the temperature at equilibrium will be

$$T = 24°C$$

Exercise 3 Thermal Equilibrium

Working Space

Just as you put the aluminium pan in the water as described above, someone also puts a 1.2 kg block of copper cooled to 10 ° C. The specific heat of solid copper is about 0.4 J/g °C.

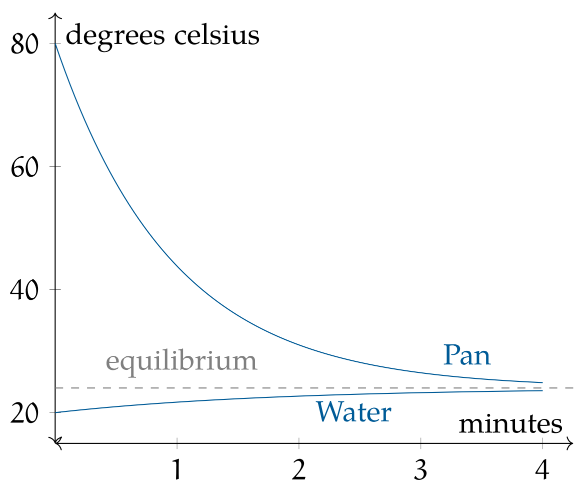
What is the new temperature at equilibrium?

Answer on Page 31

2.3 Getting to Equilibrium

When two objects with different temperatures are touching, the speed at which they exchange heat is proportional to the differences in their temperatures. As their temperatures get closer together, the heat exchange slows down.

In our example, the pan and the water will get close to equilibrium quickly, but they may never actually reach equilibrium.



Exercise 4 Cooling Your Coffee

You have been given a ridiculously hot cup of coffee and a small pitcher of chilled milk.

You need to start chugging your coffee in three minutes, and you want it as cool as possible at that time. When should you add the milk to the coffee?

Working Space

Answer on Page 31

2.4 Specific Heat Capacity Details

For any given substance, the specific heat capacity often changes a great deal when the substance changes state. For example, ice is 2.1 J/g °C, whereas liquid water is 4.2 J/g°C.

Even within a given state, the specific heat capacity varies a bit based on the temperature and pressure. If you are trying to do these sorts of calculations with great accuracy, you will want to find the specific heat capacity that matches your situation. For example, I might look for the specific heat capacity for water at 22°C at 1 atmosphere of pressure (atm).

Chapter 3

Cognitive Biases 1

In this section, we are going to take a look at research findings about *cognitive biases*. These are universal quirks found in the human thought process. Cognitive biases are a bit different from other kinds of biases, such as racial biases. Everyone, regardless of nationality, race, or gender is subject to these cognitive traps. You might be wondering, why do I need to learn about cognitive science in order to be an engineer? The most important tool we have as problem solvers is our own minds. We are going to be looking at ways that our minds can trip us up.

Our brains were designed over millions of years by the evolutionary process. The resulting mind is an amazing and powerful tool, but it is not flawless. The human brain has tendencies (or biases) that nudge us toward bad judgment and poor decisions.

When someone first gave you a hammer they handed it over with a warning: ”Don't hit your thumb!” No matter how careful you are with the hammer, at some point you will still hit your thumb. It's the same with cognitive biases. In the course of life, all of us will fall prey to these cognitive biases. Knowing about them is the first step in protecting ourselves.

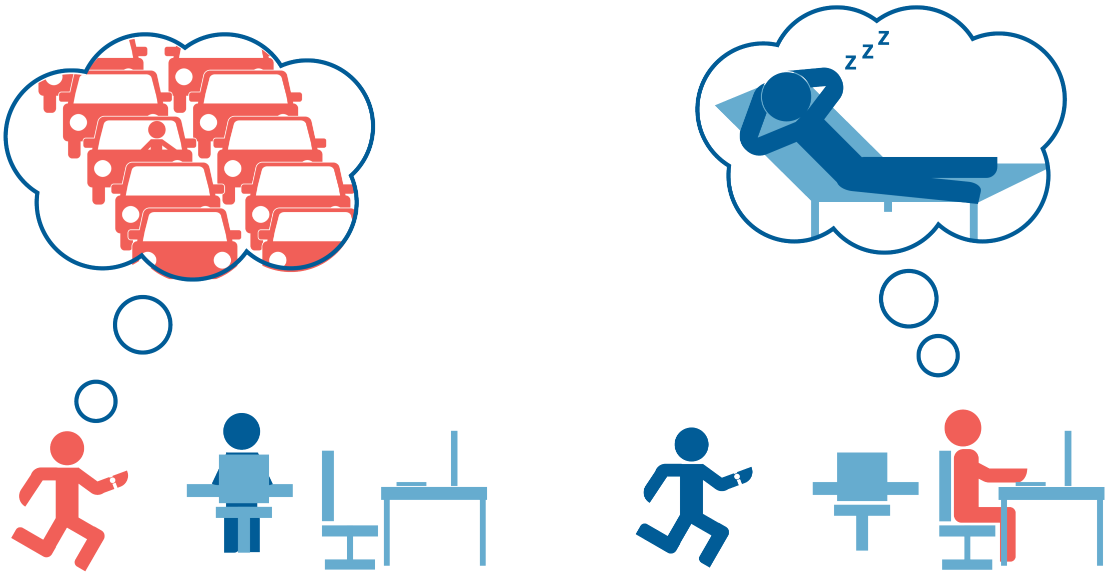
It would be irresponsible to teach you powerful ideas without also teaching you about the cognitive biases that follow them. There are about 50 that you should know about, but let's start with only a few.

3.1 Fundamental Attribution Error

You tend to attribute the mistakes of another person to their character, but attribute your own mistakes to the situation.

If someone asks you "Why were you late for work today?" you are likely to have an excuse, such as "I got stuck in a crazy traffic jam."

However, if you notice your coworker is late for work, you are likely to think "My coworker is lazy."



The solution? Cut people some slack. You probably don't know the whole story, so assume that their character is as strong as yours.

Or maybe you also need to hold yourself to a higher standard? Do you find yourself frequently rationalizing your bad judgment, lateness, or rudeness? This could be an opportunity for you to become a better person whose character is stronger regardless of the situation.

3.2 Self-Serving Bias

Self-serving bias is when you blame the situation for your failures, but attribute your successes to your strengths.

For example, when asked "Why did you lose the match?" you are likely to answer "The referee wasn't fair." When you are asked "Why did you win the match?" you are likely to answer "Because I have been training for weeks, and I was very focused."

This bias tends to make us feel better about ourselves, but it makes it difficult for us to be objective about our strengths and weaknesses.

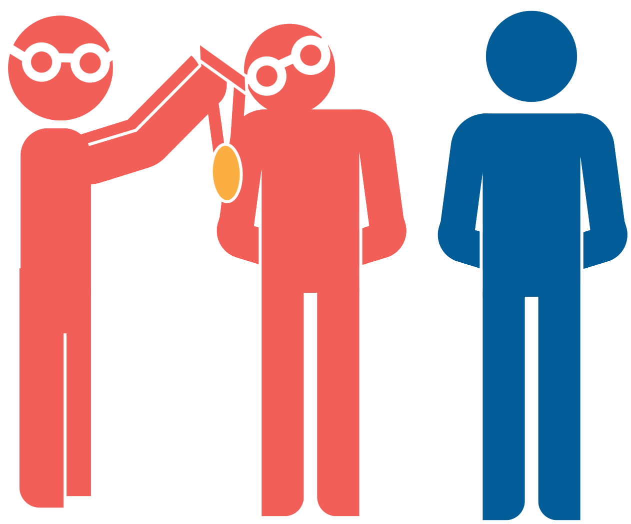
3.3 In-group favoritism

In-group favoritism: We tend to favor people who are in a group with us over people who are not in groups with us.

When asked “Who is the better goalie, Ted or John?”

If Ted is a Star Trek fan like you, you are likely to think he is also a good goalie.

As you might imagine, this unconscious tendency is the source of a lot of subtle discrimination based on race, gender, age, and religion. As we mentioned earlier, racial bias isn’t a cognitive bias, but one can still feed into the other.



3.4 The Bandwagon Effect and Groupthink

The bandwagon effect is our tendency to believe the same things that the people around us believe. This is how fads spread so quickly: one person buys in, and then the people they know have a strong tencdency to buy in as well.

Groupthink is similar: To create harmony with the people around us, we go along with things we disagree with.

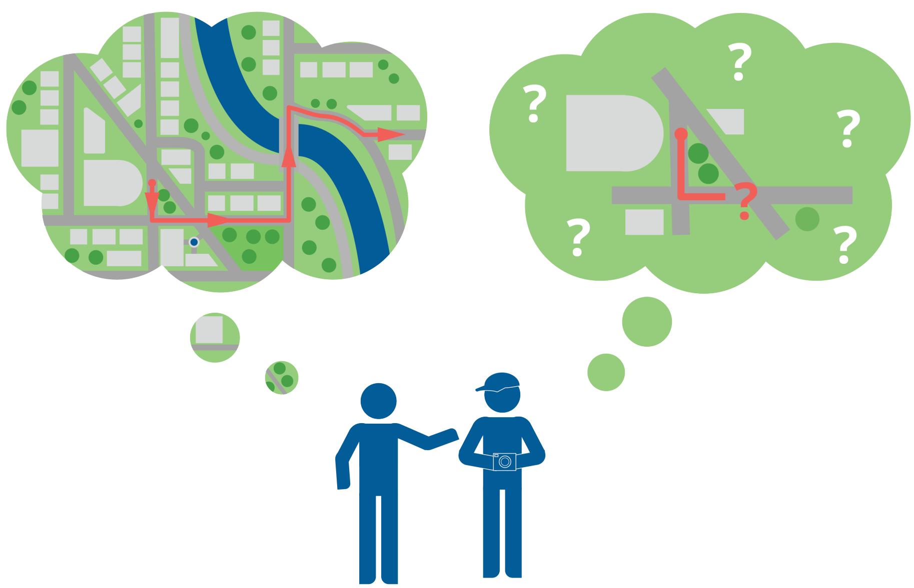
It takes a lot of perspective to recognize when those around us are wrong. And it takes even more courage to openly disagree with them.

3.5 The Curse of Knowledge

Once you know something, you tend to assume everyone else knows it too.

This is why teaching is sometimes difficult; a teacher will assume that everyone in the audience already knows the same things the teacher knows.

For example, imagine a local who has lived in a city for years giving directions to a tourist. The local has an in-depth understanding of the city, and gives overly quick and detailed instructions. The tourist politely smiles and nods, but stopped following after the local began listing unfamiliar street names and landmarks.



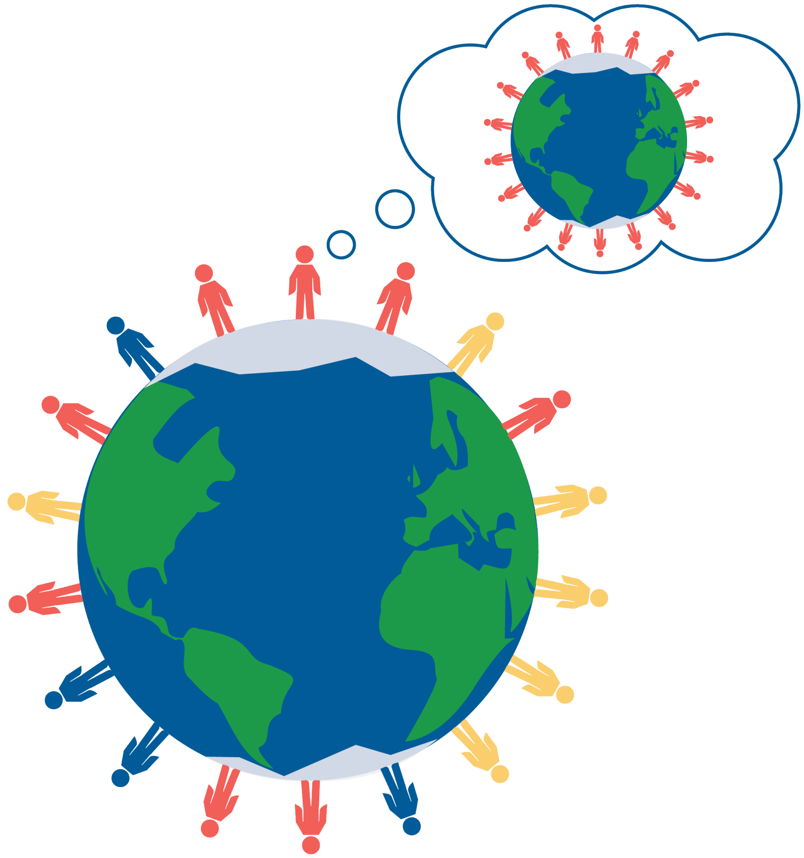
When we learn that a friend doesn't know something that we know, we are often very surprised. This surprise can sometimes manifest as hurtful behavior.

When we find a gap in our friend's knowledge, we try to remind ourselves that the friend certainly knows many things that we don't. We also try to imagine how it would feel if they teased us for our ignorance.

3.6 False Consensus

We tend to believe that more people agree with us than is actually the case. For example, if you are a member of a particular religion, you tend to overestimate the percentage of people in the world who are members of that religion.

When people vote in elections, they are often surprised when their preferred candidate loses. "Everyone, and I mean EVERYONE, voted for Smith!" they yell. "There must have been a mistake in counting the votes."

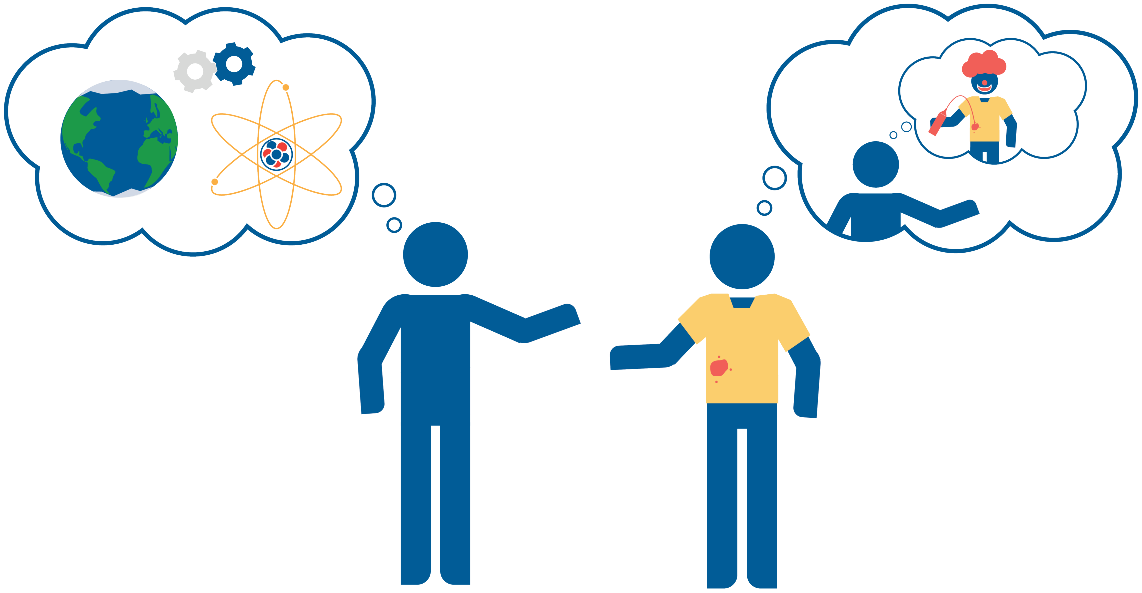


3.7 The Spotlight Effect

You tend to overestimate how much other people are paying attention to your behavior and appearance.

Think of six people that you talked to today. Can you even remember what shoes most of them were wearing? Do you care? Do you think any of them remember which shoes you wore today?

There is an old saying, “You would worry a lot less about how people think of you, if you realized how rarely they do.”



3.8 The Dunning-Kruger Effect

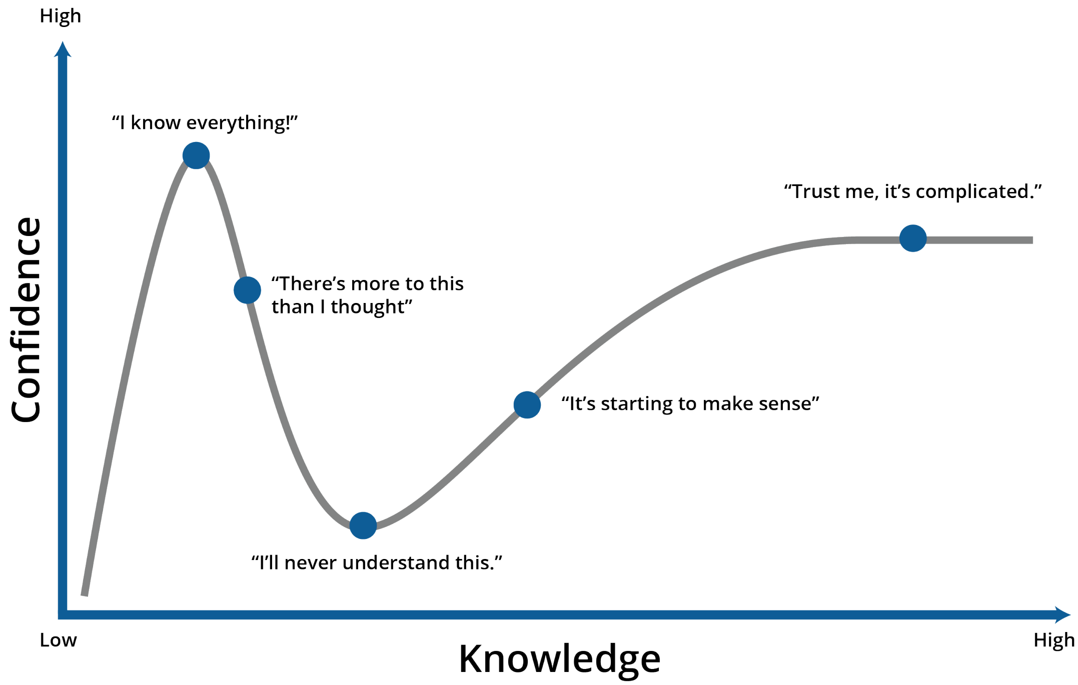
The less you know, the more confident you are.

When a person doesn't know all the nuance and context in which a question is asked, the question seems simple. Thus, person tends to be confident in their answer. As they learn more about the complexity of the space in which the question lives, they often realize the answer is not nearly so obvious.

For example, a lot of people will confidently proclaim "Taxes are too high! We need to lower taxes." An economist who has studied government budgets, deficits, history, and monetary policy, might say something like "Maybe taxes *are* too high. Or maybe they are too low. Or maybe we are taxing the wrong things. It is a complex question."

When we are talking with people about a particular topic, we do our best to defer to the person in the conversation who we think has the most knowledge in the area. If we disagree with the person, we try to figure out why our opinions are different.

Similarly, you should assume that any opinion that is voiced in an internet discussion is, at best, wildly over-simplified. If you really care about the subject, read a book by a respected expert. Yes, a whole book — there are few interesting topics that can be legitimately explained in under 100 pages.

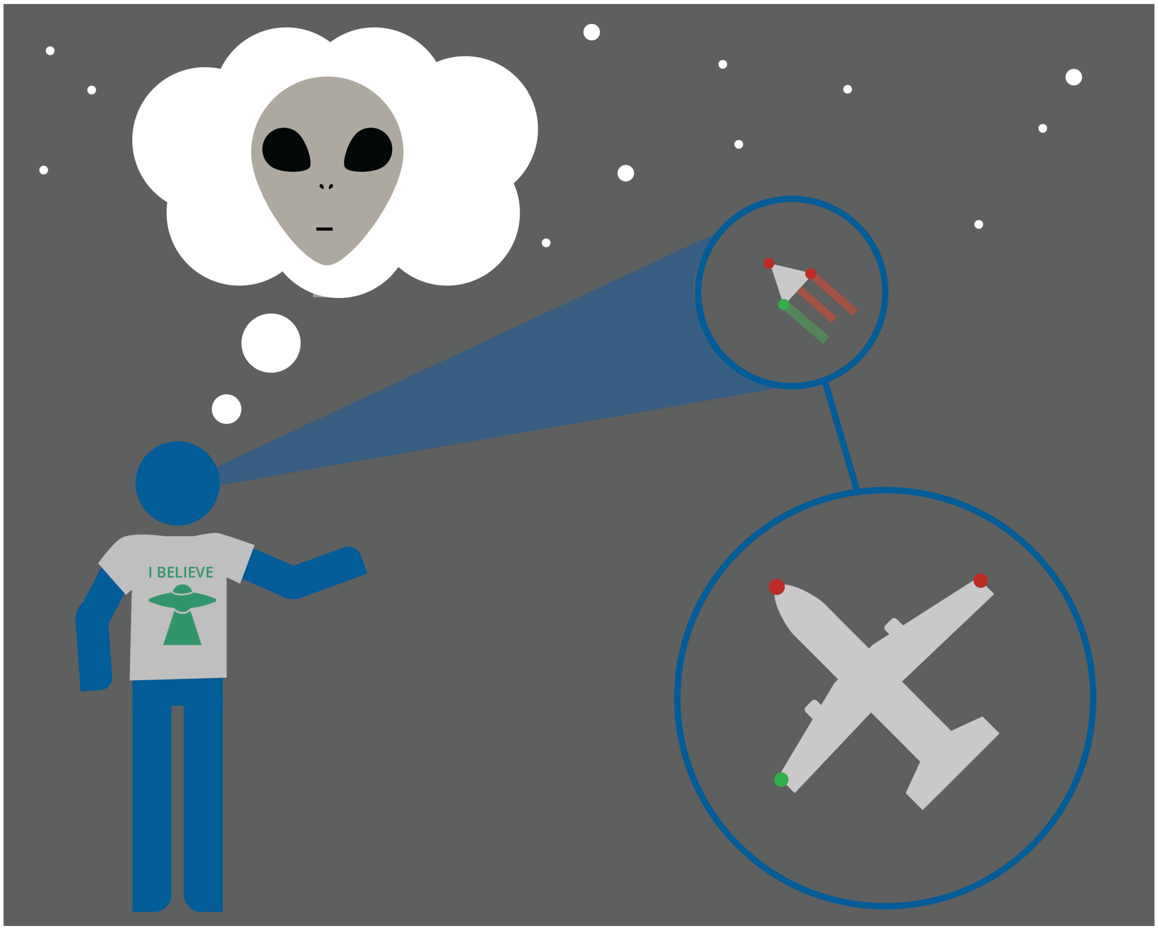


3.9 Confirmation Bias

You tend to find and remember information that supports beliefs you already have. You also tend to avoid and dismiss information that contradicts your beliefs.

If you believe that intelligent creatures have visited from other planets, you will tend to look for data to support your beliefs. When you find data that shows that it is just too far for any creature to travel, you will try to find a reason why the data is incorrect.

Confirmation bias is one reason why people don't change their beliefs more often.



Confirmation bias wrecks many, many studies. The person doing the study often has a hypothesis that they believe and very much want to prove true. It is very tempting to discard data that doesn't support the hypothesis. A person may even throw all the data away and experiments again and again until they get the result they want.

When you design an experiment, you must describe it explicitly before you start. You must tell someone: "If the hypothesis I love is incorrect, the results will look like this. If the hypothesis I love is correct, the results will look like that. And if the results look any other way, I have neither proved nor disproved the hypothesis."

Once the experiment is underway, you must not change the plan and you must not discard any data.

This is scientific integrity. You should demand it from yourself, and you should expect it from others.

Watch a TED Talk and Learn More About Confirmation Bias: What shapes our perceptions (and misperceptions) about science? In an eye-opening talk, meteorologist J. Marshall Shepherd explains how confirmation bias, the Dunning-Kruger effect and cognitive dissonance impact what we think we know – and shares ideas for how we can replace them with something much more powerful: knowledge.

https://www.ted.com/talks/j_marshall_shepherd_3_kinds_of_bias_that_shape_your_worldview

3.10 Survivorship bias

You will pay more attention to those that survived a process than those who failed.

After looking at several old houses, you might say "In the 1880s, they built great houses." However, you haven't seen the houses that were built in the 1880s and didn't survive. Which houses tended to survive for a long time? Only the great houses – you are basing your opinion on a very skewed sample.

Chapter 4

Friction

Imagine there is a large and heavy steel box resting in the middle of a floor, and you push it hard enough to get it moving. If you stop pushing, will it continue to glide gracefully across the floor?

Probably not. Unless the floor is very slippery for some reason, the box will come to a halt immediately after you stop pushing. We would say that it is stopped by the force of *friction*.

What is really happening? The kinetic energy of the box is being converted into heat between the bottom of the box and floor. As the bottom of the box and the floor get warmer, the speed of the box decreases.

The amount of friction is proportional to the force with which the box is pressing against the floor — so you should expect a box that is twice as heavy to experience twice as much frictional force.

In other words, the frictional force is proportional to the normal force. (FIXME: picture here)

The amount of friction is also determined by the materials that are sliding against each other. For example, if the floor is ice, the frictional force will be less than if the floor is made of wood.

If you are pushing the box with a force of F and it is moving but neither accelerating nor decelerating, then the force you are applying is exactly balanced by the frictional force. If the box is pressing against the floor with a force of N, then we say the *coefficient of friction* between the steel box and the floor is given by

$$\mu = \frac{F}{N}$$

Exercise 5 Bicycle Stopping

Working Space

You are riding your bicycle at 11 meters per second when you suddenly slam on the brakes and lock up the wheels.

You weigh 55 kg.

When any piece of rubber is skidding across a dry road, the coefficient of friction will be about 0.7.

Answer the following questions:

- How much kinetic energy do you have when you engage the brakes?
- As you skid, how much frictional force is decelerating you?
- For how many meters will you slide?

Answer on Page 32

Notice that the force of friction is not determined by how much of the tire is touching the ground. The coefficient of friction of the two materials and the normal force is all you need to compute the friction.

4.1 Static vs Kinetic Friction Coefficients

Let's return to the box on the floor we discussed earlier. As you start to push it, it will sit still until your force is greater than the force of friction. However, once it starts moving, the force of friction seems to be less.

Between the two materials, there are actually two different friction coefficients:

- Kinetic friction coefficient: The coefficient you use once the box is sliding against the floor.

- Static friction coefficient: The coefficient you use to figure out how much force you need to get the box to start to move.

The kinetic friction coefficient is always less than the static friction coefficient:

- *Kinetic*, μ_k: For a car skidding on a dry road, the friction coefficient is about 0.7.
- *Static*, μ_s: When the car is parked with its brakes on, it has a friction coefficient of about 1.0.

Exercise 6 Rocket Sled

Working Space

You are built a rocket sled with steel runners on a flat, level wooden floor. The sled weighs 50 kg and you weigh 55 kg.

Before you get on the sled, you try pushing it around the floor. You find that you can get it to move from a standstill if you push it with a force of 270 N. Once it is moving, you can keep it moving at the same speed using a force of 220 N.

What are μ_s and μ_k of your sled's runners on your wooden floor?

Next, you get on the sled and gradually increase the thrust of the rocket mounted on the sled until it starts to move. You then keep the thrust constant.

How much force was the rocket exerting on you and the sled when it started to move?

How how fast do you accelerate now that the sled is moving?

Answer on Page 32

4.2 Skidding and Anti-Lock Braking Systems

When a car goes through a curve, the friction of the tire on the road is what changes the direction of the car's travel. Even though the wheel is turning, this is the static friction coefficient because the surface of the tire is not sliding across the road.

If you go into the curve too fast, the tire may not have enough friction to turn the car. In this case the car will start to slide sideways. Now the friction between the tire and road uses the kinetic coefficient. In other words, you have significantly less friction than you had before you started to skid.

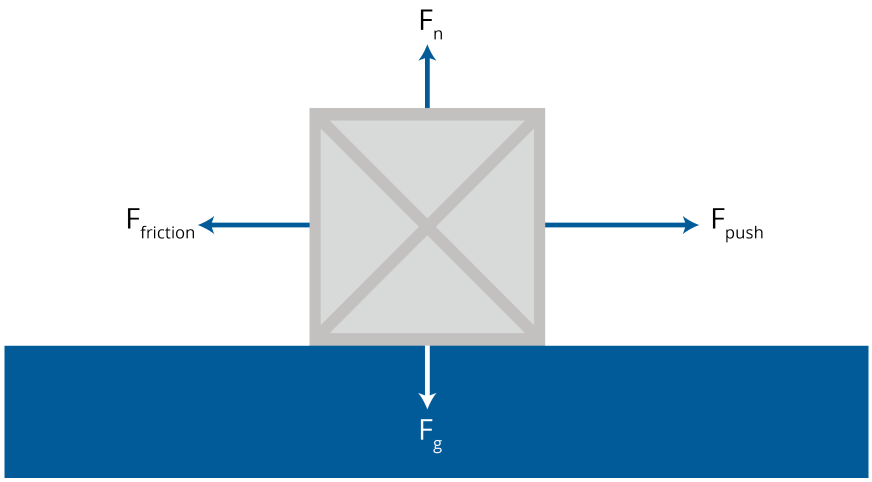
When you are driving a car, the force of friction that your tires create is your friend. It lets you steer, accelerate, and stop.

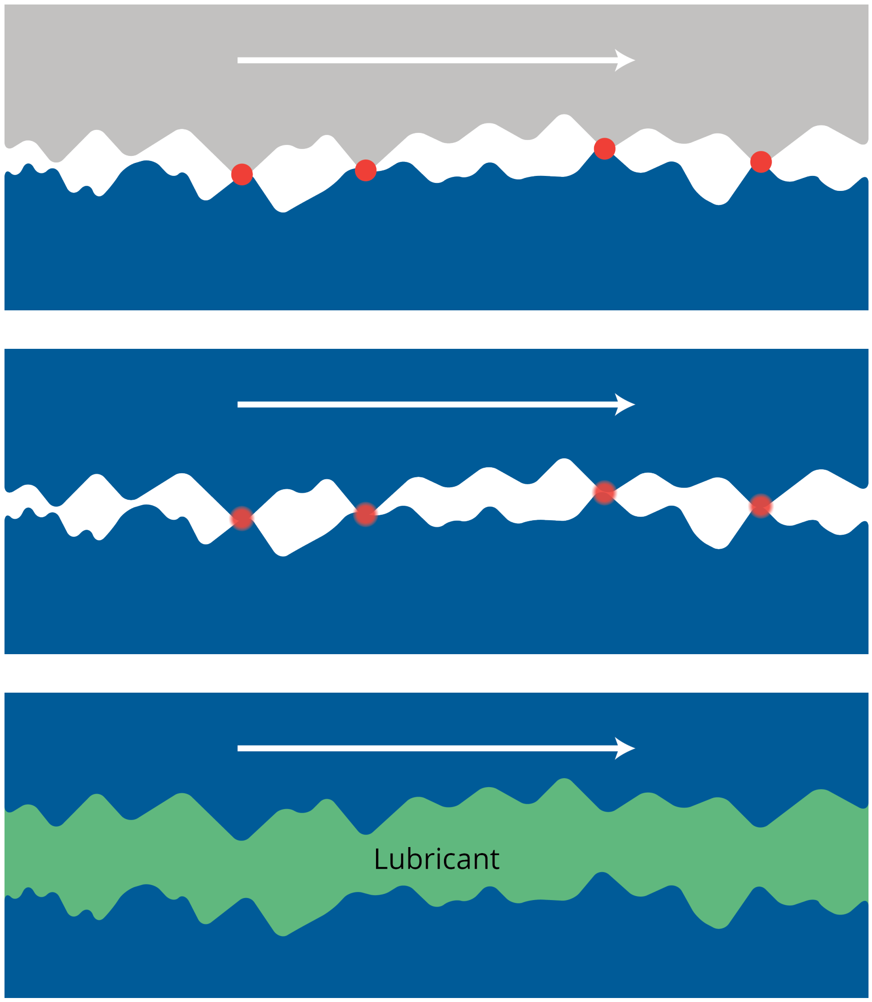
In older cars, if you would panicked and slammed on the brakes, you would probably lock up the wheels: they would stop turning suddenly. And the surface of the tire would begin to slide across the pavement. At that moment, two problems occurred:

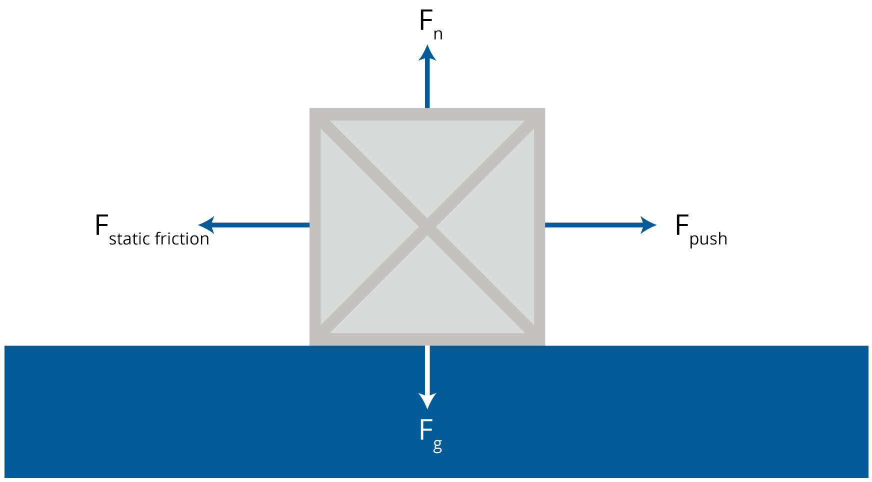
- You don't stop as quickly, because now the friction between your tires and the road is based on the kinetic friction coefficient instead of the static friction coefficient.
- You can't steer the car. Steering only happens because the wheels are turning in a particular direction.

To prevent this problem, car companies developed the anti-lock brake system, or ABS.

FIXME: More here.


F n
F friction
F push
F g


Lubricant


F n
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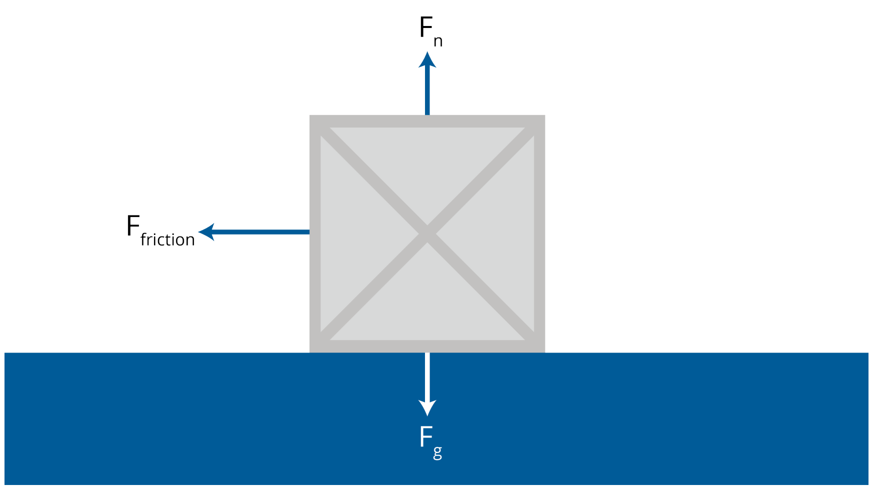
F push
F g


F n
F friction
F g

Chapter 5

The Greek Alphabet

If you do anything involving math or physics, you will be encountering Greek letters on a regular basis. Here is a table for your reference:

Capital	Lower	Pronounced	Capital	Lower	Pronounced
A	α	Alpha	N	ν	Nu
B	β	Beta	Ξ	ξ	Xi (”ku-ZY”)
Γ	γ	Gamma	O	o	Omicron
Δ	δ	Delta	Π	π	Pi
E	ϵ	Epsilon	P	ρ	Rho
Z	ζ	Zeta	Σ	σ	Sigma
H	η	Eta	T	τ	Tau
Θ	θ	Theta	Υ	υ	Upsilon
I	ι	Iota	Φ	ϕ	Phi
K	κ	Kappa	X	χ	Chi (”Kai”)
Λ	λ	Lambda	Ψ	ψ	Psi (”Sigh”)
M	μ	Mu	Ω	ω	Omega

Appendix A

Answers to Exercises

Answer to Exercise 1 (on page 4)

Equilibrium will be achieved when the box has displaced 10 kg of water. In other words, when it has displaced 0.01 cubic meters.

The area of the base of the box is 0.12 square meters. So if the box sinks x meters into the water it will displace $0.12x$ cubic meters.

Thus at equilibrium $x = \frac{0.01}{0.12} \approx 0.083$ m. So the box will sink 8.3 cm into the water before reaching equilibrium.

Answer to Exercise 2 (on page 6)

$$p = dgh = (900)(3.721)(5) = 16,744.5 \text{ Pa}$$

Answer to Exercise 3 (on page 9)

$$E_C = (1200)(0.4)(T - 10) = 480T - 4800$$

Total energy stays constant:

$$0 = (12600T - 252000) + (900T - 72000) + (480T - 4800)$$

Solving for T gets you $T = 23.52°$ C.

Answer to Exercise 4 (on page 10)

During the 3 minutes, you want the coffee to give off as much of its heat as possible, so you want to maximize the difference between the temperature of the coffee and the temperature of the room around it.

You wait until the last moment to put the milk in.

Answer to Exercise 5 (on page 22)

Kinetic energy? $E = mv^2 = (55)(11^2) = 6,655\frac{kgm^2}{s^2} = 6,655$ joules.

Frictional force? $F = \mu N = (0.7)(55)(9.8) = 377.3$ newtons.

Distance? $D = \frac{6,655}{377.3} = 17.6$ seconds.

Answer to Exercise 6 (on page 23)

The empty sled is pushing directly down on the floor with a force of $(50)(9.8) = 490$ N.

The force to overcome the static friction is:

$$270 = 490\mu_s$$

Thus, $\mu_s = 0.551$

The force to match kinetic friction is:

$$220 = 490\mu_k$$

Thus, $\mu_k = 0.449$

Once you are on the sled, it is pressing directly down on the floor with a force of $(50 + 55)(9.8) = 1,029$ N.

The force to overcome the static friction is:

$$F = (1,029)(0.551) = 567 \text{ N}$$

Once the sled is moving, friction is counteracting some of your force. How much?

$$F_f = (1,029)(0.449) = 462 \text{ N}$$

All of your acceleration is due to the remaining $567 - 492 = 75$ N.

We know that $F = ma$. In this case $F = 75$ N and $m = 105$ kg. So

$$a = \frac{75}{105} = 0.714 \text{ meters per second per second}$$

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