# Lecture 9 Physics 101

Welcome to the beginning of week four of classes! Please turn in homework!

This week, we are really going to start in earnest attempting to describe <u>why</u> physical phenomena happen. The first few weeks of the course were setting the stage, introducing the language of vectors, kinematics, position, velocity, and acceleration, but now we have a complete enough vocabulary, we can use it to construct new sentences. So with that in mind, today we are going to introduce <u>forces</u>, and their consequences.

Let's go back, as we often have, to our thought experiment of the train moving at constant velocity on a very smooth track. As mentioned many times, there is no experiment we can do on the train to determine if it is actually moving or just at rest. The laws of physics are independent of one's velocity, or, more precisely, independent of one's frame of reference. Balls fall when dropped with acceleration $-g$, water is still in a cup, etc., and this is (one) consequence of independence of the physics in different dimensions. By contrast, if the train accelerated, the driver put on the brakes to avoid colliding with cows on the tracks, you will know it. You will feel <u>pulled</u> forward dramatically.

Pull is an action word and specifically what a pull does is <u>change</u> your motion. You were happily traveling at a constant rate, ne'er the wiser, and then the driver changed your motion/velocity by slamming on the brakes. A change in velocity is acceleration and a <u>pull</u>, precisely but even colloquially, is a <u>force</u>. That is, forces (things/actions that enact change) are responsible for acceleration.

This is a profound observation and its mathematical consequence is encapsulated in Newton's second law, which we will get to in a second. If a force ~~are~~ imparts acceleration, then you can exert a force on your friend to make them fall over. That is, a push (= force) can change their idle standing (= at rest) to falling over (= moving). Thus, you made them accelerate by pushing them. ~~Further, there's clearly an~~ Further, there's clearly a difference between pushing a friend and pushing an elephant. With the same exerted push, your friend will fall over, but the elephant may not even know you are there! That is, though a force is the same, the corresponding acceleration (= change of motion) can be very different. So what differs between your friend and a pachyderm that could be responsible for the different acceleration? Well, other than four legs and a trunk, an elephant is <u>much</u> more massive than your friend. With more mass, an equivalent push/force changes motion less.

These considerations and thought experiments motivate Newton's Second Law, which essentially encapsulates all of mechanics we will learn in this course. Newton's Second law is:

$$\boxed{\vec{F}_{net} = m\vec{a}.}$$

Here, m is the mass of the object of interest, $\vec{a}$ is its acceleration (a vector, recall) and $\vec{F}_{net}$ is the <u>total</u>/<u>net</u> force acting on that object. Force is a vector: you can push harder or softer and affect the magnitude of force, and you can also push in different directions. Thus, Newton's second law enables you to predict the motion of an object based on the forces acting on it.

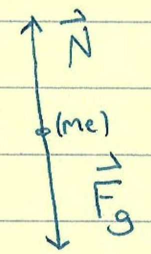
Before we make sense of this, the phrase "Newton's Second Law" begs the question of if there is a Newton's First Law, and for that matter how many laws are there? Is it just laws all the way down? Well, there are three "Newton's Laws" and the first and third can be thought of as consequences of the second. So, we really won't specifically talk about them, like we will for the second law. (There's also a Monte Python joke here: "Thou shalt count to three, no more, no less. Five is right out!")

So let's see how Newton's second law works in some examples. First, and most simply, let's analyze the forces on me, just standing here. Am I accelerating? Nope, so therefore what is the <u>net</u> force that is action on me? If $\vec{a}=0$, $\vec{F}_{net}=0$, too! We can break this apart some more to make sense of how $\vec{F}_{net}=0$. What forces are acting on me; that is, what individual pushes and pulls are exerted on me? First, gravity is <u>pulling</u> me toward the center of the earth. This gravitational force is also called "weight" and its magnitude is just equal to my mass times our old friend, acceleration $g$:

$$|\vec{F}_{grav}| = mg.$$

What other forces are acting on me? That is, am I feeling another push? Actually, you can ask yourself this question. Simply by sitting in your seat, do you feel something <u>pushing</u> on you? I feel the floor pushing on my feet! In your case, you should feel the chair pushing, um, somewhere else! So there is also a force from a surface keeping us upright. Such a force is called a "normal force" because it acts normal, or perpendicular to the surface. I can't think of or feel other forces (other than the weight of the world on my shoulders...) so this is all we have.

Let's draw a picture to represent the forces on me:



Such a picture is called a "free-body diagram" and it represents all forces acting on an object. The dot at the center is me, but I ignore all spatial extent in such a diagram. Gravity, $\vec{F}_g$, pulls me down while the floor's normal force pushes me up. The net force, $\vec{F}_{net}$, is just the vector sum of the forces acting on me:

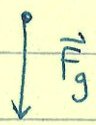
$$\vec{F}_{net} = \vec{N} + \vec{F}_g = N\hat{j} + (-mg)\hat{j} = (N - mg)\hat{j}, \text{ where } N$$

is the magnitude of normal force. By Newton's second law, this is equal to my mass times acceleration, $m\vec{a}$. But what is acceleration? $\vec{a} = 0$, so $\vec{F}_{net} = 0$ which then implies that

$$N = mg.$$

That is, the floor pushes me up juuuust enough to counteract the force of gravity.

What if there's no floor? Not that we blow it up or something, but if we jump out of a plane (ignoring air resistence)? Now, there is no normal force acting on me, so my free-body diagram is:




. Newton's second law then says that:

$$\vec{F}_g = (-mg)\hat{j} = m\vec{a} \quad \text{or that} \quad \vec{a} = -g\hat{j}.$$

Of course this is consistent with what we've been playing with this whole time: every object accelerates at the same rate under the effects of gravity, independent of its mass.

I want to labor this point a little bit. First, we are only able to make this claim if the mass that multiplies $\vec{a}$ in Newton's second law (inertial mass) is the <u>same</u> as the mass that multiplies $g$ (gravitational mass). In principle, these two quantities could be different, but we have 0 experimental evidence to suggest that. The claim/axiom that inertial mass is equivalent to gravitational mass is called the "equivalence principle", and its assumption provides a deep and profound prediction. Actually, let's think about these two systems we just discussed a bit more. When I am standing here, or you are sitting in your chair, do you actively "feel" a push? Well, yes, as argued earlier, I feel a push on my feet. However, and this is odd, while I actually feel a push, my acceleration is 0. By contrast, imagine jumping out of a plane. ~~Ig~~ Ignoring air resistance, do you actually feel anything pulling you? Nope, you feel like you are floating, or in "free fall". Nevertheless, while you feel no pull, you are accelerating!

This is very weird, and the equivalence principle suggests that gravity, as we typically think about it, is not a force in the same way that a push or pull is. Actually, gravity is not a "true" force at all; it is simply the manifestation of the curvature of space and time under the influence of massive objects. This is completely described by Einstein's theory of general relativity, but for this class, we'll just assume that gravity acts like a force, which is good enough for our study.

Let's get back to the topic at hand and think about another system: an accelerating elevator. Let's say that you are in an elevator that is accelerating upward by a. How does the magnitude of the normal force of the floor on you compare to your weight?

Is the normal force:

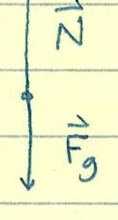
a) larger than weight b) same as weight
c) less than weight?

I'll give you a second to talk to your neighbors!

To solve this problem, let's use Newton's second law and draw a free-body diagram. First, unless you jumped up, you are accelerating at the same rate as the elevator, a. By Newton's second law, the net force is then,

$$\vec{F}_{net} = m\vec{a} = (ma)\hat{j}$$ , where the acceleration is upward.

Now, to a free-body diagram. What are the forces that act on you? There's aways gravity, and we would feel the normal force from the floor of the elevator pushing upward. Anything else, acting <u>directly</u> on you? Nope! So, the free-body diagram is:




and so the net force is

$$\vec{F}_{net} = \vec{N} + \vec{F}_g = (N - mg)\hat{j}.$$

By Newton's second law this is supposed to equal:

$$\vec{F}_{net} = m\vec{a} \Rightarrow (N - mg)\hat{j} = (ma)\hat{j}$$

or that $N = m(a+g)$. Assuming that $a > 0$, the normal force must be larger than your weight.

That's it for today, see you wednesday!