IOP Concise Physics

Physics is ...

The Physicist explores attributes of physics

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Chapter 5

Physics is frivolous

5.1 Introduction

I often get questions which seek to find the physics of 'frivolous' situations, situations involving superheroes, video games, science fiction, etc. These are fun, and they often lead to outrageously impossible physics from the viewpoint of practicality.

5.2 Frivolous physics

Question: Two of us disagree on part of a solution given by two people with physics backgrounds, and I want to know if I am correct, or if I am missing something in the analysis of the problem, in case I have to explain it to a student. The question concerns forces/impulse. A 50 kg person falling with a speed of 15 m s^{-1} is caught by a superhero, and the final velocity up is 10 m s^{-1}. Find the change in velocity. Find the change in momentum. It takes 0.1 s to catch them. What was the average force? The answers are: Person A says the change in velocity = 25 m s^{-1}, the change in momentum = 1250 kg · m s^{-1}, and the average force is 12 500 N. Here's where we disagree. Person B says that 12 500 N is equivalent to 25*g*. They try to explain that 250 m s^{-2} acceleration corresponds to 25*g*. I said this makes no sense at all—I know the acceleration is 250 m s^{-2}, but that doesn't in any way imply a 25*g* 'equivalence' to me. Person B then went further to 'prove' their point. Here is their argument. 500 N/g = 12 500 N/ng. I agree with the $n = 25$, but say there is no justification for the 500 N/g in the first place. Do you have any ideas about where it comes from, or how to justify that value? By the way, I teach physics on and off at the high school level. Person B is an engineer, I think.

Answer: Person B is wrong but has the right idea. (As you and your friend have apparently done, I will approximate $g \approx 10$ m s^{-2}.) We can agree that the acceleration is $a = 250$ m s^{-2} and that is undoubtedly 25*g*. Now, we need to write Newton's second law for the person, $-mg + F = ma = -500 + F = 12\,500$, so $F = 13\,000$ N. This is the average force by the superhero on the person as she is

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stopped, so the answer that the average force is 12 500 N is wrong. When one expresses a force as 'gs of force', this is a comparison of the force F to the weight of the object mg, $F(\text{in } g\text{s}) = F(\text{in N})/mg = 13\,000/500 = 26g$; this simply means that the force on the object is 26 times the object's weight. So neither of you is completely right, but if there is any money riding on this, your friend should be the winner because the only error he made was to forget about the contribution of the weight to the calculation of the force. I am hoping that superman knows enough physics to make the time be at least 0.3 s, so that Lois does not get badly hurt!

The following question is a perfect example of how totally impossible something can be, from a 'where is the required energy going to come from?' point of view.

Question: In some of the more realistic space combat in science fiction there is a concept called a 'BFR' (big fast rock), in which matter is mined from a dead world or asteroid, melted to molten and then reformed to a near-perfect density distribution with collars of ferrous metal impressed in it, before being shot at some fraction of light speed from a large EML cannon running down the long axis of mile-long ships. I would like to know how to calculate the impact force release for a 2 000 lb BFR moving at 0.10, 0.15, and 0.30 c. I'm assuming it's going to be in the high megaton range and I don't know what the translative per ton equivalence is in TNT.

Answer: What you want is the energy your projectile has when it hits. ('Impact force release' has no meaning in physics.) The energy in joules is $E = m\gamma c^2$, where $\gamma = \sqrt{(1 - (v/c)^2)}$. In your case, 2000 lb = 907 kg, $c = 3 \times 10^8$ m s^{-1}, $\gamma = 1.005$, 1.011, and 1.048. The energies in joules are $E = 8.204 \times 10^{19}$, 8.253×10^{19}, and 8.555×10^{19} J. There are about 4×10^9 J per ton of TNT, so the energies are 20.51, 20.63, and 21.39 megatons of TNT. I might add that this is not actually very 'realistic'. Where are you going to get that much energy (you have to supply it somehow) in the middle of empty space? Or, look at it this way: I figure that for a mile-long gun the time to accelerate the BFR to $0.1c$ is about $t = 10^{-4}$ s. During that time the required power is about $8 \times 10^{19}/10^{-4} = 8 \times 10^{23}$ W $= 8 \times 10^{14}$ GW; the largest power plant on the Earth is about 6 GW! Also, don't forget about the recoil of the ship, which would likely destroy it. I am afraid that I would have to label your BFR as completely unrealistic! Are you sure that BFR stands for big fast rock?

The next question addresses an important question that is often ignored in science fiction—the effect of acceleration on humans. The maximum acceleration which can be endured, and only for short times, is approximately $8g$. In other words, 'jump to light speed, Scotty' would crush everybody on the *Enterprise*. So, getting up to speeds near c would take a pretty long time because we can only really be comfortable near g. How long is long? The positive side of this is that the acceleration of the ship will provide artificial gravity.

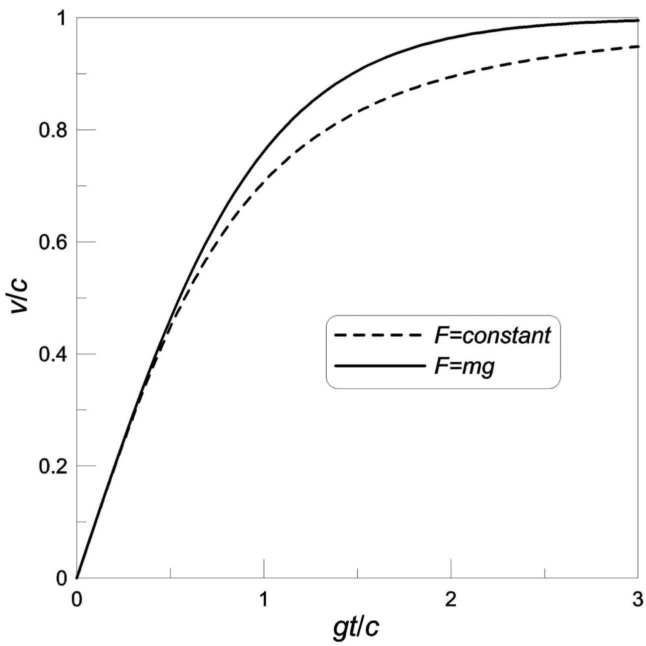

Figure 5.1. Speed as a function of time for a constant force and for a force *mg* using the velocity-dependent mass.

Question: A starship pilot wants to set her spaceship to light speed, but the crew and passengers can only endure a force up to 1.2 times their weight. Assuming the pilot can maintain a constant rate of acceleration, what is the minimum time she can safely achieve light speed?

Answer: This question completely ignores special relativity. It is impossible to go as fast as the speed of light. Furthermore, acceleration is not really a useful quantity in special relativity and you must use special relativity when speeds become comparable to the speed of light. I have previously worked out the velocity of something which would correspond to the occupants of your spaceship experiencing a force equal to their own weight due to the acceleration, which I will adapt to your case later (see figure 5.1.) First, though, I will work out the (incorrect) Newtonian calculation that is presumably what you want. The appropriate equation would be $v = at$, where $v = 3 \times 10^8$ m s^{-1}, $a = 1.2g = 11.8$ m s^{-2}, and t is the time to reach v; the solution is 2.5×10^7 s = 0.79 years. For the correct calculation, you cannot reach the speed of light; from figure 5.1 (full-drawn curve), though, you can see that you would reach more than 99% of c when $gt/c = 3$. To make this your problem, we simply replace g by $1.2g$ and solve for t. I find that $t = 7.7 \times 10^7$ s = 2.4 years, about three times longer than the classical calculation. (Note: the calculations for figure 5.1 are explained in *From Newton to Einstein*, the first volume in the *Ask The Physicist* series.)

The next question is short and sweet and the answer is even shorter! When we reach 'transgalactic civilization status', we will have to seek some other energy source!

Question: Would it be possible physically to encapsulate a black hole with solar panel type devices and use its energy to power a civilization? Like when we reach transgalactic civilization status and run across a black hole and want to utilize it.
Answer: Well, that is a pretty crazy idea because a black hole is an energy sink, not an energy source!

The next question is about how fast the superhero Flash can run in the real world. Flash is a character(s) in DC comics who has somehow acquired the superpower to run really fast; I had never heard of him, but there are limitations in the real world, even for superheroes! (I think this was probably a homework question, a no-no at AskThePhysicist.com! I guess this one slipped past me.)

Question: Using real-world estimates for the coefficient of friction between his feet and the ground, how fast could the Flash run a quarter-mile? Assume that the limiting factor for his acceleration is the force parallel to the ground that his feet can apply.
Answer: Suppose he is running on a dry asphalt road with rubber-sole shoes. Then the coefficient of static friction is approximately $\mu \approx 0.8$. The maximum force of friction on level ground would be $f_{\max} \approx \mu N = \mu mg \approx 8\ m$, where m is his mass. So, his acceleration would be $a = f_{\max}/m = 8\ \mathrm{m\ s^{-2}}$. A quarter mile is about 400 m, so assuming uniform acceleration, the appropriate kinematic equation would be $400 = \frac{1}{2}at^2 = 4t^2$, so $t = 10$ s. His final speed would be $v = at = 80\ \mathrm{m\ s^{-1}} =$ 179 mph.

The next question is not really so ‘frivolous’, but also involves static friction. We tend to think that the limit to how hard we can push something depends on how strong we are. But the real limit is friction. For example, pushing a stuck car on an icy day often ends with you down on the ground, having slipped on the icy road while pushing.

Question: How strong would a man have to be to push a 16 000 lb bus on a flat surface?
Answer: That depends on how much friction there is. And not just the friction on the bus, but, more importantly, the friction between the man’s feet and the ground. Newton’s third law says that the force the man exerts on the bus is equal and opposite the force which the bus exerts on the man ($\boldsymbol{B}$ in figure 5.2). Other forces on the man are his weight ($\boldsymbol{W}$), the friction the road exerts on his feet ($\boldsymbol{f}$), and the force that the road exerts up on him ($\boldsymbol{N}$). If the bus is not moving, $N = W$ and $f = B$, equilibrium. The biggest that the frictional force can be without the man’s feet slipping is $f = \mu N$, where μ is the coefficient of the static friction between the shoe soles and the road surface. A typical value of μ for rubber on

Figure 5.2. Strong man pushing a bus. Copyright: Jennifer Gottschalk/Anabela88 Shutterstock.

asphalt, for example, is $\mu \approx 1$, so the biggest f could be is approximately his weight W; this means that the largest force he could exert on the bus without slipping would be about equal to his weight. Taking $W \approx 200$ lb, if the frictional force on the bus is taken to be zero, the bus would accelerate forward with an acceleration of $a = Bg/16\ 000 = 200 \times 32/16\ 000 = 0.4$ ft s^{-2}, where $g = 32$ ft s^{-2} is the acceleration due to gravity; this means that after 10 s the bus would be moving forward with a speed 4 ft s^{-1}. If there were a 100 lb frictional force acting on the bus, the acceleration would only be $a = 0.2$ ft s^{-2}. If there were a frictional force greater than 200 lb acting on the bus, the man could not move it.

I have no idea where this next question came from, but it has the added interesting aspect that we need to calculate the total energy to gravitationally disassociate a uniform sphere.

Question: What would the yield of a 5000 ton iron slug accelerated at 95% of c by, say, a bored omnipotent be? Would it be enough to mass scatter a planet?
Answer: I get the strangest questions sometimes! So, 5000 metric tons = 5×10^6 kg. The kinetic energy would be $K = E - mc^2 = mc^2[(1/\sqrt{(1 - .95^2)}) - 1] \approx 10^{24}$ J. The energy U required to totally disassemble a uniform mass M of radius R is $U = 3GM^2/(5\ R)$, where $G = 6.67 \times 10^{-11}$ is the universal gravitational constant. So, taking the Earth as a 'typical' planet, $U = 3 \times 6.67 \times 10^{-11}(6 \times 10^{24})^2/(5 \cdot 6.4 \times 10^6) \approx 2 \times 10^{32}$ J. So your god's slug is far short of supplying enough energy to totally blast apart the Earth.

The next question again illustrates how, so often, the awesome weapons which play such an important role in video games have as their biggest problem the impossibility of the power source.

Question: I was playing a game known as *Fallout* 3 and in the game there are laser weapons. The laser weapons are powered by Marshmallow sized micro-fusion cells that are basically miniature nuclear reactors that fuse hydrogen

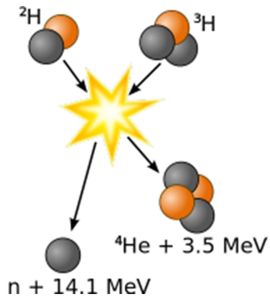

Figure 5.3. A fusion reaction.

atoms. In the game they produce enough power to turn a 500 kilogram bear into ash in one second. So, could a reactor that small produce enough power for the gun and how much energy would a Marshmallow-sized blob of fused hydrogen produce? A normal microfusion cell in the game has enough energy to fire 24 of these shots. Would it be possible in any way for these laser weapons to be able to be this powerful with an energy source like the microfusion cell?
Answer: I have no way to estimate the 'power to turn a 500 kilogram bear into ash in one second'. I am sure you realize that, with today's technology, the possibility of there being such a power supply is zilch. Let's just do a few estimates to show how hard this is. One gram of hydrogen fuel (deuterium + tritium), if fully fused into helium + neutrons, figure 5.3, releases something on the order of 300 GJ of energy; so, if released in 24 one second pulses, each pulse would be about 10 GW. That is probably way more than your bear burning would need, so let's say 100 MW would do it; so, we would need about 10^{-2} g of fuel. I calculate that to confine that amount of gas in a volume of 10^{-5} m^3 (about 1 in^3) would require a pressure of about 5 000 000 atmospheres! That, in itself, should be enough to convince you that this machine could probably never be possible. If you need more convincing, consider shielding: 80% of the energy produced is in the kinetic energy of neutrons. How are you going to harvest that energy in such a small volume and how are you going to protect yourself from the huge neutron flux? And surely there needs to be some sort of mechanism to control the process and convert the energy into usable electrical energy to power the laser; all that is supposed to fit into 1 in^3? This truly is a fantasy game with no connection to reality!

The next question, from a sci-fi screenwriter, proposes using linear acceleration to create artificial gravity during a trip from the Earth to the Moon. This will get you there very quickly!

Question: I am a writer putting together a science fiction screenplay. Those who know me say I have an attention to detail—to a fault. There is one particular element I would like to be as accurate as possible. I'm hoping you might be able to help me. Here is the scenario. A spacecraft leaves Earth on course to the Moon. In order to create an Earth-like gravity inside the ship, the ship accelerates at a constant rate, exerting a force on the occupants equal to one g. Halfway through the trip the craft will flip, then decelerate for the remainder of the journey. This would give the same sensation of false gravity to the occupants of the craft. So here is the question: if this were possible; how long would it take to actually reach the Moon?

Answer: Since you are such a stickler for detail, I will give you detail, probably far more than you want! Your scheme of having an acceleration with 'constant rate' would work in empty space, but not between the Earth and the Moon because the force causing the acceleration is not the only force on you, the Earth's and the Moon's gravity are also acting. As you go away from the Earth, the Earth's gravity gets smaller like $1/r^2$, where r is the distance from the Earth's center, and the Moon's gets bigger as you get closer. So, it becomes a complicated problem as to how much force must be applied to keep the acceleration just right for where you are. Let's call your mass M. Then there are two forces on you, your weight $\boldsymbol{W}$ down and the force the scale you are standing on exerts on you, $\boldsymbol{F}$. $\boldsymbol{W}$ gets smaller as you get farther and farther away and you want F to always be what your weight would be on the Earth's surface, Mg. So, Newton's second law says that $F - W = Ma = Mg - W$, where a is the acceleration you must have. Note that, for the time being, I am ignoring the Moon; that would just complicate things and its force is much smaller than the Earth's, at least for the first half of the trip. I want you to understand the complication caused by the fact that W changes as you go farther away. Now, how does W change? $W = MM_EG/r^2 = Mg(R/r)^2$, where R is the radius of the Earth and M_E is the mass of the Earth. We can now solve for the acceleration the spacecraft would have to have: $a = g(1 - (R/r)^2)$. I have plotted this in red in figure 5.4. (The distance to the Moon is about 60 Earth radii.) Note that for most of the trip the acceleration is just about g. I also calculated the effect the Moon would have (blue dashed line) and, except for the very end of the trip, it is pretty negligible. Now that we have taken care of the always-important details, we can try to answer your question. To calculate the time exactly would be very complicated, but, since the required acceleration is g for almost the whole trip, it looks like we can get a really good approximation

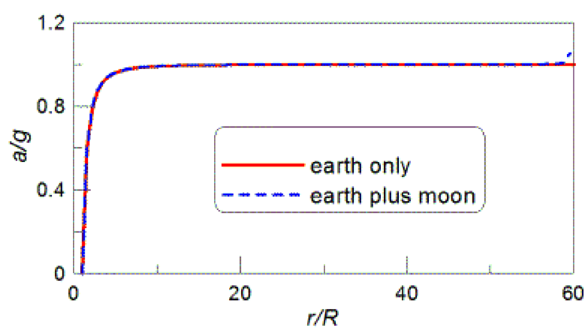

Figure 5.4. Required acceleration for the net force to be equal to W on Earth's surface.

by just assuming $a = g$ for the first half and $a = -g$ for the second half; your perceived weight (F) will just decrease from twice its usual value when you take off to about normal when you get to about five Earth radii in altitude. The symmetry of the situation is such that I need only calculate the time for the first half of the trip and double it. The appropriate equation to use is $r = r_0 + v_0 t + \frac{1}{2}at^2$, where $r_0 = R$ is where you start and $v_0 = 0$ is the speed you start with. Halfway to the Moon is about $r = 30\ R = R + \frac{1}{2}at^2$ and so, putting in the numbers, I find $t \approx 1.69$ hours, and so the time to the Moon would be about 3.4 hours. You can also calculate the maximum speed, you would have to be about 140 000 mph halfway.

Note that the calculation I did above to generate figure 5.4 was the acceleration if you continued speeding up the whole way. I should have had the acceleration switch to (approximately) $-9.8\ \mathrm{m\ s^{-2}}$ halfway so as to slow down. But the important takeaway here is that once you are more than a few Earth radii on your way, you can ignore the Earth altogether as the questioner did for the whole trip.