

# Problem Solving I: Mathematical Techniques

For the basics of dimensional analysis and limiting cases, see chapter 1 of Morin or chapter 2 of Order of Magnitude Physics. Many more examples are featured in The Art of Insight; some particularly relevant sections are 2.1, 5.5, 6.3, 8.2, and 8.3. Other sections will be mentioned throughout the course. There is a total of **81** points.

## 1 Dimensional Analysis

### Idea 1

The dimensions of all physical equations should match on both sides. Sometimes, this constraint alone can determine the answers to physical questions.

Even a statement such as “the speed  $v$  is slow” does not make sense, since we need to compare it to something else with dimensions of speed. A more meaningful statement would be “ $v$  is slow compared to the speed of light”, which would correspond to  $v/c \ll 1$ .

### Example 1: $F = ma$ 2018 B11

A circle of rope is spinning in outer space with an angular velocity  $\omega_0$ . Transverse waves on the rope have speed  $v_0$ , as measured in a rotating reference frame where the rope is at rest. If the angular velocity of the rope is doubled, what is the new speed of transverse waves?

### Solution

To solve this problem by dimensional analysis, we reason about what could possibly affect the speed of transverse waves. The result could definitely depend on the rope’s length  $L$ , mass per length  $\lambda$ , and angular velocity  $\omega_0$ . It could also depend on the tension, but since this tension balances the centrifugal force, it is determined by all of the other quantities. Thus the quantities we have are

$$[L] = \text{m}, \quad [\lambda] = \text{kg/m}, \quad [\omega_0] = 1/\text{s}.$$

Since  $\lambda$  is the only thing with dimensions of mass, it can’t affect the speed, because there is nothing that could cancel out the mass dimension. So the only possible answer is

$$v_0 \sim L\omega_0$$

where the  $\sim$  indicates equality up to a dimensionless constant, which cannot be found by dimensional analysis alone. In practice, the constant usually won’t be too big or too small, so  $L\omega_0$  is a decent estimate of  $v_0$ . But even if it isn’t, the dimensional analysis tells us the scaling: if  $\omega_0$  is doubled, the new speed is  $2v_0$ .

### Example 2

Find the dimensions of the magnetic field.

**Solution**

To do this, we just think of some simple equation involving  $B$ , then solve for its dimensions. For example, we know that  $\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$ , so

$$[B] = \frac{[F]}{[q][v]} = \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \frac{1}{\text{C} \cdot \text{m/s}} = \frac{\text{kg}}{\text{C} \cdot \text{s}}.$$

- [2] **Problem 1.** Find the dimensions of power, the gravitational constant  $G$ , the permittivity of free space  $\epsilon_0$ , and the ideal gas constant  $R$ .

**Solution.** The units are

$$[P] = \frac{\text{kg m}^2}{\text{s}^3}, \quad [G] = \frac{\text{m}^3}{\text{kg s}^2}, \quad [\epsilon_0] = \frac{\text{C}^2 \text{s}^2}{\text{kg m}^3}, \quad [R] = \frac{\text{J}}{\text{mol K}} = \frac{\text{kg m}^2}{\text{mol K s}^2}.$$

The easiest way to get these results is to use formulas containing the desired quantity, such as  $P = Fv$ ,  $F = GMm/r^2$ ,  $F = q^2/(4\pi\epsilon_0 r^2)$ , and  $PV = nRT$ , where the units of the other quantities are already known.

- [2] **Problem 2.** Some questions about vibrations.

- (a) The typical frequency  $f$  of a vibrating star depends only on its radius  $R$ , density  $\rho$ , and the gravitational constant  $G$ . Use dimensional analysis to find an expression for  $f$ , up to a dimensionless constant. Then estimate  $f$  for the Sun, looking up any numbers you need.
- (b) The typical frequency  $f$  of a small water droplet freely vibrating in zero gravity could depend on its radius  $R$ , density  $\rho$ , surface tension  $\gamma$ , and the gravitational constant  $G$ . Argue that at least one of these parameters doesn't matter, and find an expression for  $f$  up to a dimensionless constant.

**Solution.** (a) We just do the usual dimensional analysis,

$$[f] = \text{s}^{-1} \quad [R] = \text{m} \quad [\rho] = \text{kg/m}^3 \quad [G] = \frac{\text{m}^3}{\text{kg} \cdot \text{s}^2}$$

To cancel out  $\text{kg}$ , multiplying  $G$  and  $\rho$  will yield  $[\rho G] = \text{s}^{-2}$ . Then to get  $[f] = \text{s}^{-1}$ ,

$$f \sim \sqrt{G\rho} \sim 3 \times 10^{-3} \text{ Hz}$$

which is in the right range. These oscillations are measured in the field of helioseismology.

Another application of this result is that the time needed for a ball of gas of density  $\rho$  to collapse is of order  $1/\sqrt{G\rho}$ , called the free fall time. This timescale plays an important role in structure formation in the early universe.

- (b) In this case the surface tension force dominates; the gravitational forces of the droplet on itself are negligible, so we can drop  $G$ . Performing dimensional analysis with  $R$ ,  $\rho$ , and  $\gamma$  gives

$$f \sim \sqrt{\frac{\gamma}{\rho R^3}}.$$

Of course, part (a) is equivalent to starting with the same set of four parameters and dropping  $\gamma$ , which makes sense since the objects considered are huge.

**[3] Problem 3.** Some questions about the speed of waves. For all estimates, you can look up any numbers you need.

- (a) The speed of sound in an ideal gas depends on its pressure  $p$  and density  $\rho$ . Explain why we don't have to use the temperature  $T$  or ideal gas constant  $R$  in the dimensional analysis, and then estimate the speed of sound in air.
- (b) The speed of sound in a fluid depends only on its density  $\rho$  and bulk modulus  $B = -V dP/dV$ . Estimate the speed of sound in water, which has  $B = 2.1$  GPa.

The speed of waves on top of the surface of water can depend on the water depth  $h$ , the wavelength  $\lambda$ , the density  $\rho$ , the surface tension  $\gamma$ , and the gravitational acceleration  $g$ .

- (c) Find the speed of capillary waves, i.e. water waves of very short wavelength, up to a dimensionless constant.
- (d) Find the speed of long-wavelength waves in very deep water, up to a dimensionless constant.

**Solution.** (a) We don't have to use  $R$  or  $T$  because all that matters is the restoring force, determined by  $p$ , and the inertia, determined by  $\rho$ . So we have

$$[p] = \frac{kg s^2}{m}, \quad [\rho] = \frac{kg}{m^3}$$

and a routine dimensional analysis gives

$$v \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{10^5 \text{ Pa}}{1 \text{ kg/m}^3}} \sim 300 \text{ m/s}$$

which is reasonably close. (Actually, the exact answer is  $v = \sqrt{\gamma p / \rho}$ , as we'll derive in **T3** and **W3**, so thermodynamics actually does play a role through the dimensionless constant.)

- (b) We have

$$[B] = \frac{kg}{m \cdot s^2} \quad [\rho] = \frac{kg}{m^3}.$$

A routine dimensional analysis gives

$$v \sim \sqrt{\frac{B}{\rho}} \sim 1500 \text{ m/s}.$$

This is actually very close to the true answer; here there is no dimensionless constant.

- (c) In this case, the surface tension force dominates, just as it did for a small water droplet in a previous problem, which also means that  $g$  doesn't matter. The wavelength is so short that the waves can't "see" the depth of the water, so  $h$  doesn't matter. Doing dimensional analysis with the remaining three parameters gives

$$v \sim \sqrt{\frac{\gamma}{\rho \lambda}}.$$

- (d) In this case, the wave is big enough for surface tension not to matter; the restoring force is gravity, so we keep  $g$  and toss out  $\gamma$ . Since the water is even deeper than the wavelength, we again toss out  $h$ . Doing dimensional analysis with the remaining parameters gives

$$v \sim \sqrt{g\lambda}.$$

We will derive this in **W3**. The fact that  $\rho$  also dropped out makes sense: when gravity is the only force,  $\rho$  usually doesn't matter because scaling it up scales all the forces and all the masses up the same way, keeping accelerations the same.

**[3] Problem 4** (Morin 1.5). A particle with mass  $m$  and initial speed  $v$  is subject to a velocity-dependent damping force of the form  $bv^n$ .

- (a) For  $n = 0, 1, 2, \dots$ , determine how the stopping time and stopping distance depend on  $m$ ,  $v$ , and  $b$ .
- (b) Check that these results actually make sense as  $m$ ,  $v$ , and  $b$  are changed, for a few values of  $n$ . You should find something puzzling going on. (Hint: to resolve the problem, it may be useful to find the stopping time explicitly in a few examples.)

**Solution.** (a) The dimensions of  $b$  can be found with  $[b] = [F/v^n] = kg \cdot m^{1-n} \cdot s^{-2+n}$ . To get a stopping time or distance, the mass term must be canceled out. So we're working with

$$\left[ \frac{b}{m} \right] = m^{1-n} s^{-2+n} \quad [v] = \frac{m}{s}$$

The stopping time  $t$  can be found by canceling out the length dimension. If  $t \propto (b/m)^\alpha v^\beta$ , then:

$$\alpha(1-n) + \beta = 0 \quad \alpha(-2+n) - \beta = 1$$

Solving yields

$$\alpha = -1 \quad \beta = 1 - n, \quad t \propto \frac{mv^{1-n}}{b}.$$

The distance  $x$  traveled has dimensions of  $vt$ , so

$$x \propto \frac{mv^{2-n}}{b}.$$

- (b) The results don't seem to make sense. At  $n = 1$ , it appears that the time it takes to stop no longer depends on  $v$ , which doesn't seem correct since the stopping time should always increase with velocity. And for  $n > 1$ , the stopping time *decreases* with velocity, which is even worse. Similar issues happen for the stopping distance for  $n \geq 2$ .

The resolution is that in these cases, the stopping time/distance are actually infinite, as you can check explicitly. In other words, dimensional analysis worked, but the hidden dimensionless prefactor was *infinity*.

**Idea 2**

Dimensional analysis applies everywhere. The argument of any function that is not a monomial, such as  $\sin x$ , must have no dimensions. The derivative  $d/dx$  has the opposite dimensions to  $x$ , and the  $dx$  in an integral has the same dimensions as  $x$ .

**Example 3**

We are given the integral

$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}.$$

Find the value of the integral

$$\int_{-\infty}^{\infty} e^{-ax^2} dx.$$

**Solution**

In the first equation,  $x$  must be dimensionless, so both sides are dimensionless. The second equation would also be consistent if both  $x$  and  $a$  were dimensionless, but we can do better. Suppose we arbitrarily assign  $x$  dimensions of length,  $[x] = \text{m}$ . Then to make the argument of the exponential dimensionless,  $a$  must have dimensions  $[a] = \text{m}^{-2}$ . The dimensions of the left-hand side are  $[dx] = \text{m}$ . In order to make the dimensions work out on the right-hand side, we must have

$$\int_{-\infty}^{\infty} e^{-ax^2} dx \propto \frac{1}{\sqrt{a}}.$$

To find the value of the constant, treat  $x$  and  $a$  as dimensionless again. Then we know the answer must reduce to  $\sqrt{\pi}$  when  $a = 1$ , so

$$\int_{-\infty}^{\infty} e^{-ax^2} dx = \sqrt{\frac{\pi}{a}}.$$

This procedure is completely equivalent to using  $u$ -substitution to nondimensionalize everything, but may be faster to see. In general, for all integrals except for the simplest ones, you should use either dimensional analysis or  $u$ -substitution to reduce the integral to a dimensionless one.

**Remark**

Consider the value of the definite integral

$$\int_{-\infty}^y e^{-x^2} dx.$$

You can try all day to compute the value of this integral, using all the integration tricks you know, but nothing will work. The function  $e^{-x^2}$  simply doesn't have an antiderivative in terms of the functions you already know, i.e. in terms of polynomials, exponents and logarithms, and trigonometric functions (for more discussion, see [here](#)).

If you ask a computer algebra system like Mathematica, it'll spit out something like  $\text{erf}(x)$ , which is defined by being an antiderivative of  $e^{-x^2}$ . But is this really an “analytic” solution? Isn't that just saying “the integral of  $e^{-x^2}$  is equal to the integral of  $e^{-x^2}$ ”? Well, like many things in math, it depends on what the meaning of the word “is” is.

The fact is, the set of functions we regard as “elementary” is arbitrary; we just choose a set that's big enough to solve most of the problems we want, and small enough to attain fluency with. (Back in the days before calculators, it just meant all the functions whose values were tabulated in the references on hand.) If you're uncomfortable with  $\text{erf}(x)$ , note that a similar thing would happen if a middle schooler asked you what the ratio of the opposite to adjacent sides of a right triangle is. You'd say  $\tan(x)$ , but they could say it's tautological, because the only way to define  $\tan(x)$  at the middle school level is the ratio of opposite to adjacent sides. Similarly,  $1/x$  has no elementary antiderivative – unless you count  $\log(x)$  as elementary, but  $\log(x)$  is simply *defined* to be such an antiderivative. It's all tautology, but it's still useful.

- [1] **Problem 5** (SFM 1.11). Find the integral

$$\int \frac{dx}{x^2 + 1}$$

using a trigonometric substitution. Using dimensional analysis, find the integral

$$\int \frac{dx}{x^2 + a^2}.$$

**Solution.**

$$\int \frac{dx}{x^2 + 1} = \int \frac{\sec^2 \theta d\theta}{1 + \tan^2 \theta} = \arctan(x) + C$$

Since  $x^2$  is added to  $a^2$ , they must have the same dimensions, so the integral has dimensions of  $1/a$  ( $dx$  also has dimensions!). The argument of  $\arctan$  must be dimensionless. Thus

$$\int \frac{dx}{x^2 + a^2} = \frac{1}{a} \arctan\left(\frac{x}{a}\right)$$

- [2] **Problem 6** (SFM 1.15). Derive Kepler's Third Law using only dimensional analysis. Why do you think people didn't figure out this argument 2000 years ago?

**Solution.** They should depend on  $G$  and  $M$ , whose dimensions can be found with the gravitation law:  $GMm/r^2 = F$ , so  $[GM] = \text{m}^3\text{s}^{-2} = [a^3/T^2]$ . Thus

$$GM \sim \frac{a^3}{T^2}$$

2000 years ago, no one would've known about  $G$ !

- [2] **Problem 7.** In particle physics, it is conventional to set  $\hbar = c = 1$ , resulting in equations with seemingly incorrect units. For example, it is said that the mass of the Higgs boson is about 125 GeV, where 1 eV is the energy gained by an electron accelerated through a voltage difference of 1 V. Energy doesn't have the same units as mass, but the units can be fixed by adding appropriate factors of  $\hbar$  and  $c$ . Do this, and find the mass of the Higgs boson in kilograms.

**Solution.** One easy way to start out dimensional analysis is with famous equations:  $E = mc^2$ , or  $E = \frac{1}{2}mv^2$  to get  $m \sim E/c^2$ . Thus the mass of the Higgs boson is  $m = 125 \text{ GeV}/c^2 = 2.22 \times 10^{-25} \text{ kg}$ .

[3] **Problem 8.** ⌚ USAPhO 2002, problem A3.

#### Example 4

The Schrodinger equation for an electron in the electric field of a proton is

$$-\frac{\hbar^2}{2m}\nabla^2\psi - \frac{e^2}{4\pi\epsilon_0 r}\psi = E\psi.$$

Estimate the size of the hydrogen atom.

#### Solution

This is yet another dimensional analysis problem: there is only one way to form a length using the quantities given above. We have

$$[m] = \text{kg}, \quad [\hbar] = \text{J} \cdot \text{s} = \text{kg m}^2 \text{s}^{-1}, \quad [e^2/4\pi\epsilon_0] = \text{J} \cdot \text{m} = \text{kg m}^3 \text{s}^{-2}.$$

Doing dimensional analysis, the only length scale is the Bohr radius,

$$a_0 = \frac{4\pi\hbar^2\epsilon_0}{me^2} \sim 10^{-10} \text{ m}.$$

I've thrown in a  $4\pi$  above because  $\epsilon_0$  always appears in the equations as  $4\pi\epsilon_0$ . The dimensional analysis would be valid without this factor, but as you'll see in problem 11, if you don't include it then annoying compensating factors of  $4\pi$  will appear elsewhere.

Classically (i.e. without  $\hbar$ ), there is no way to form a length, and hence there should be no classically stable radius for the atom. (This was one of the arguments used by Bohr to motivate quantum mechanics; it appears in the beginning of his paper introducing the Bohr model.) Once we introduce  $\hbar$ , there are three dimensionful parameters in the problem, as listed above. And there are exactly three fundamental dimensions. So there is only one way to create a length, which we found above, one way to create a time, one way to create an energy, and so on. This means that the solutions to the Schrodinger equation above look qualitatively the same no matter what these parameters are; all that changes are the overall length, time, and energy scales. In problem 11, you'll investigate how this conclusion changes when we add more dimensionful parameters.

Dimensional analysis is especially helpful with scaling relations. For example, a question might ask you how the radius of the hydrogen atom would change in a world where the electron mass was twice as large. You would solve this problem in the exact same way as the example above, using dimensional analysis to show that  $a_0 \propto 1/m$ .

[3] **Problem 9.** In this problem we'll continue the dimensional analysis of the Schrodinger equation.

- (a) Estimate the typical energy scale of quantum states of the hydrogen atom, as well as the typical “velocity” of the electron, using dimensional analysis.

- (b) Do the same for one-electron helium, the system consisting of a helium nucleus (containing two protons) and one electron.
- (c) Estimate the electric field needed to rip the electron off the hydrogen atom.

**Solution.** (a) Recall the electrostatic potential energy formula,  $E = kq^2/r$ . We have a length scale,  $a_0$  to replace  $r$ . For velocity, we use  $E \sim mv^2$ , giving

$$E \sim \frac{me^4}{(4\pi\epsilon_0)^2\hbar^2}, \quad v \sim \frac{e^2}{4\pi\epsilon_0\hbar}.$$

In fact, the binding energy of the hydrogen atom in its ground state is

$$E = \frac{me^4}{2(4\pi\epsilon_0)^2\hbar^2} = 13.6 \text{ eV}$$

which is a constant known as the Rydberg. So the dimensional argument (keeping the factors of  $4\pi$ ) gets the answer right to a factor of 2.

- (b) Adding the second proton would double the charge inside the nucleus, so the expressions for energy and velocity should stay the same except  $e^2$  would be replaced with  $2e^2$  (not 4, since the electron charge stays the same) and thus the energy would be  $4e^4$ . In general, with  $Z$  as the atomic number,

$$E \sim \frac{mZ^2e^4}{(4\pi\epsilon_0)^2\hbar^2}, \quad v \sim \frac{Ze^2}{4\pi\epsilon_0\hbar}.$$

- (c) Physically, the work the electric field does by moving the electron across the radius of its orbit should be enough to overcome its binding energy to the proton. This also tells us how to set up the dimensional analysis; we have electric field

$$|\mathbf{E}| \sim \frac{E}{ea_0} \sim \frac{m_e^2e^5}{(4\pi\epsilon_0)^3\hbar^4} \sim 10^{12} \text{ V/m}.$$

This is a tremendously large electric field!

All of the results above are not that accurate, but they become much more accurate if we replace  $\epsilon_0$  with  $4\pi\epsilon_0$ . That in turn makes sense because these factors always appear together in electromagnetism.

### Idea 3: Buckingham Pi Theorem

Dimensional analysis can't always pin down the form of the answer. If one has  $N$  quantities with  $D$  independent dimensions, then one can form  $N - D$  independent dimensionless quantities. Dimensional analysis can't say how the answer depends on them.

A familiar but somewhat trivial example is the pendulum: its period depends on  $L$ ,  $g$ , and the amplitude  $\theta_0$ , three quantities which contain two dimensions (length and time). Hence we can form one dimensionless group, which is clearly just  $\theta_0$  itself. The period of a pendulum is  $T = f(\theta_0)\sqrt{L/g}$ .



**Example 5:  $F = ma$  2014 12**

A paper helicopter with rotor radius  $r$  and weight  $W$  is dropped from a height  $h$  in air with a density of  $\rho$ . Assuming the helicopter quickly reaches terminal velocity, use dimensional analysis to analyze the total flight time  $T$ .

**Solution**

The answer can only depend on the parameters  $r$ ,  $W$ ,  $h$ , and  $\rho$ . There are four quantities in total, but three dimensions (mass, length, and time), so by the Buckingham Pi theorem we can form one independent dimensionless quantity. In this case, it's clearly  $r/h$ . Continuing with routine dimensional analysis, we find

$$T = f(r/h) h^2 \sqrt{\frac{\rho}{W}}.$$

The form of this expression is a bit arbitrary; for instance, we could also have written  $f(r/h)r^2$  in front, or even  $f(r/h)r^{37}h^{-35}$ . These adjustments just correspond to pulling factors of  $r/h$  out of  $f$ , not to changing the actual result.

This is as far as we can get with dimensional analysis alone, but we can go further using physical reasoning. If the helicopter quickly reaches terminal velocity, then it travels at a constant speed. So we must have  $T \propto h$ , which means that  $f(x) \propto x$ , and

$$T \propto rh \sqrt{\frac{\rho}{W}}.$$

**Example 6**

An hourglass is constructed with sand of density  $\rho$  and an orifice of diameter  $d$ . When the sand level above the orifice is  $h$ , what is the mass flow rate  $\mu$ ?

**Solution**

The answer can only depend on  $\rho$ ,  $d$ ,  $h$ , and  $g$ . The Buckingham Pi theorem gives

$$\mu = f(h/d) \rho \sqrt{gd^5}.$$

That's as far as we can get with dimensional analysis; to go further we need to know more about sand. If we were dealing with an ideal fluid, then the flow speed would be  $v = \sqrt{2gh}$  by Torricelli's law, which means the flow rate has to be proportional to  $\sqrt{h}$ . Then  $f(x) \propto \sqrt{x}$ , giving the result  $\mu \propto \rho d^2 \sqrt{gh}$ . This is a good estimate as long as the orifice isn't so small that viscosity starts to dominate.

But this isn't how sand works. Sand is a granular material, whose motion is dominated by the friction between sand grains. So the higher pressure doesn't actually propagate to the orifice, and the flow rate is independent of  $h$ , which is apparent from watching an hourglass run. Then  $f(x)$  is a constant, giving  $\mu \propto \rho \sqrt{gd^5}$ , which is [experimentally verified](#).

**Remark**

One has to be a little careful with the Buckingham Pi theorem. For example, if all we had were 3 speeds  $v_i$ , we can form two dimensionless quantities:  $v_1/v_2$  and  $v_1/v_3$ . (The quantity  $v_2/v_3$  is not independent, since it is the quotient of these two.) But there are 3 quantities with 2 dimensions (length and time), so we expect only 1 dimensionless quantity.

The problem is that the two dimensions really aren't independent: for any quantity built from the  $v_i$ , a power of length always comes with an inverse power of time, so there's only one independent dimension. These considerations can be put on a more rigorous footing in linear algebra, where the Buckingham Pi theorem is merely a special case of the rank-nullity theorem. If you're ever in doubt, you can just forget about the theorem and play with the equations directly.

**Remark**

Dimensional analysis is an incredibly common tool in Olympiad physics because it lets you say a lot even without much advanced knowledge. If a problem ever says to find some quantity "up to a constant/dimensionless factor", or how that quantity scales as another quantity changes, or what that quantity is proportional to, it's almost certainly asking you to do dimensional analysis. Another giveaway is if the problem *looks* extremely technical and advanced, because they can't actually be.

- [3] **Problem 10** (Insight). In this problem we'll do one of the most famous dimensional analyses of all time: estimating the yield of the first atomic bomb blast. Such a blast will create a shockwave of air, which reaches a radius  $R$  at time  $t$  after the blast. The air density is  $\rho$ , and we want to estimate the blast energy  $E$ .

- Declassified photographs of the blast indicate that  $R \approx 100$  m at time  $t \approx 15$  ms. The density of air is  $\rho \approx 1$  kg/m<sup>3</sup>. Estimate the blast energy  $E$ .
- How much mass-energy (in grams) was used up in this blast?
- If we measure the entire function  $R(t)$ , what general form would we expect it to have, if this dimensional analysis argument is correct?

**Solution.** (a) The only way to write an expression with the right dimensions is

$$E \sim \frac{R^5 \rho}{t^2}.$$

Plugging in the numbers gives  $E \sim 4 \times 10^{13}$  J.

- The mass-energy equivalent is  $m = E/c^2 \sim 0.5$  g. This is quite reasonable, as fission can only release a small fraction of the mass-energy (about 0.1%) of a sample, and the critical mass is typically on the order of a few pounds.
- Let's do the dimensional analysis in reverse: we know  $E$  is fixed, so the only way to write an expression with the right dimensions for  $R$  is

$$R \sim (Et^2/\rho)^{1/5} \sim t^{2/5}.$$

So  $R(t)$  must have this power-law dependence. If it doesn't, then it means some other quantity with dimensions is intervening, so our dimensional analysis is suspect. Luckily, around this range of time the relation above is true, and indeed the answer of part (a) is pretty close.

### Remark

The British physicist G. I. Taylor performed the dimensional analysis in problem 10 upon seeing a picture of the first atomic blast in a magazine. The result was so good that the physicists at the Manhattan project thought their security had been breached!

During World War II, the exact value of the critical mass needed to set off a nuclear explosion was important and nontrivial information. The Nazi effort to make a bomb had been stopped by Werner Heisenberg's huge overestimation of this quantity, and after the war, the specific value was kept a closely guarded secret. That is, it was until 1947, when a Chinese physicist [got the answer](#) using a rough estimate that took four lines of algebra.

- [5] **Problem 11.** We now consider the Schrodinger equation for the hydrogen atom in greater depth. We begin by switching to dimensionless variables, which is useful for the same reason that writing integrals in terms of dimensionless variables is: it highlights what is independent of unit choices.

- (a) Define a dimensionless length variable  $\tilde{r} = r/a_0$ , where  $a_0$  is the length scale found in example 4. The  $\nabla^2$  term in the Schrodinger equation is a second derivative, the 3D generalization of  $d^2/dx^2$ . Using the chain rule, argue that

$$\tilde{\nabla}^2 = a_0^2 \nabla^2$$

where  $\tilde{\nabla}$  is the gradient with respect to  $\tilde{r}$ .

- (b) Similarly define a dimensionless energy  $\tilde{E} = E/E_0$ , using the energy scale  $E_0$  found in problem 9. Show that the Schrodinger equation can be written in a form like

$$-\tilde{\nabla}^2 \psi - \frac{1}{\tilde{r}} \psi = \tilde{E} \psi$$

Here I've suppressed all dimensionless constants, like factors of 2, because they depend on how you choose to define  $E_0$  and don't really matter at this level of precision.

The result of this part confirms what we concluded above: solutions to the Schrodinger equation don't qualitatively depend on the values of the parameters, because they all come from scaling a solution to this one dimensionless equation appropriately.

- (c) This is no longer true in relativity, where the total energy is

$$E = \sqrt{p^2 c^2 + m^2 c^4}.$$

Assuming  $p \ll mc$ , perform a Taylor expansion to show that the next term is  $A p^4$ , and find the coefficient  $A$ . (If you don't know how to do this, work through the next section first.)

- (d) In quantum mechanics, the momentum is represented by a gradient,  $p \rightarrow -i\hbar \nabla$ . (We will see why in **X1**.) Show that the Schrodinger equation with the first relativistic correction is

$$-\frac{\hbar^2}{2m} \nabla^2 \psi - \frac{e^2}{4\pi\epsilon_0 r} \psi + \hbar^4 A \nabla^4 \psi = E \psi.$$

- (e) Since there is now one more dimensionful quantity in the game, it is possible to combine the quantities to form a dimensionless one. Create a dimensionless quantity  $\alpha$  that is proportional to  $e^2/4\pi$ , then numerically evaluate it. This is called the fine structure constant. It serves as an “objective” measure of the strength of the electromagnetic force, because it is dimensionless, and hence its value doesn’t depend on an arbitrary unit system.
- (f) As the number of protons in the nucleus increases, the relativistic correction becomes more important. Estimate the atomic number  $Z$  where the correction becomes very important.

**Solution.** (a) For the first derivative,

$$\frac{d\psi}{dr_x} = \frac{d\psi}{dx} \frac{dx}{dr_x}.$$

With the length scale,  $dx/dr_x = a_0$  which is a constant. The second derivative does the same, which gives two factors of  $a_0$ . This holds true for all the other dimensions, so

$$\tilde{\nabla}^2 = a_0^2 \nabla^2.$$

- (b) Ignoring all numerical factors and dividing by  $E_0 = e^2/\epsilon_0 a_0$ , we get

$$-\frac{\hbar^2 \epsilon_0 a_0}{m e^2} \left( \frac{1}{a_0^2} \tilde{\nabla}^2 \right) \psi - \frac{a_0}{r} \psi = (E/E_0) \psi$$

which simplifies to

$$-\tilde{\nabla}^2 \psi - \frac{1}{\tilde{r}} \psi = \tilde{E} \psi.$$

- (c) Since  $\sqrt{1+x} \approx 1 + x/2 + (1/2)(-1/4)x^2$ ,

$$E = mc^2 \sqrt{1 + \frac{p^2 c^2}{m^2 c^4}} \approx mc^2 + \frac{p^2}{2m} - \frac{1}{8} \frac{p^4 c^4}{m^3 c^6}$$

which implies

$$A = -\frac{1}{8m^3 c^2}.$$

- (d) With  $p^4 = \hbar^4 \nabla^4$ , this is simply added to the left hand side of the equation as a correction of the first order momentum term  $p^2/2m = -\hbar^2/2m$ ,

$$-\frac{\hbar^2}{2m} \nabla^2 \psi - \frac{e^2}{4\pi \epsilon_0 r} \psi + \hbar^4 A \nabla^4 \psi = E \psi.$$

- (e) Just like in part (b), divide both sides by  $E_0$ . The dimensionless quantity in the added term should be

$$\frac{\hbar^4}{m^3 c^2 a_0^4} \frac{\epsilon_0 a_0}{e^2} = \frac{e^4}{\hbar^2 c^2 \epsilon_0^2}.$$

To make it proportional to  $e^2$ , take the square root to get


$$\alpha \sim \frac{e^2}{4\pi \epsilon_0 \hbar c} \approx \frac{1}{137}.$$

- (f) The relativistic correction is important when the above term is of order 1, and since there's an electron charge  $e$  and a nucleus with charge  $+Ze$ , replace  $e^2$  with  $Ze^2$ . It's order one when

$$Z\alpha \approx 1.$$

So the atomic number when the correction becomes very important is around 137. Actually, even when  $Z \approx 30$  the corrections are noticeable and must be accounted for in chemistry.

You probably won't see any differential equations as complex as the ones in the above problem anywhere in Olympiad physics, but the key idea of using dimensionless quantities to simplify and clarify the physics can be used everywhere.

- [5] **Problem 12.**  IPhO 2007, problem "blue". This problem applies thermodynamics and dimensional analysis in some exotic contexts.

### Example 7

Estimate the Young's modulus for a material with interatomic separation  $a$  and typical atomic bond energy  $E_b$ . Use this to estimate the spring constant of a rod of area  $A$  and length  $L$ , as well as the speed of sound, if each atom has mass  $m$ .

### Solution

This example is to get you comfortable with the Young's modulus  $Y$ , which occasionally comes up. It is defined in terms of how much a material stretches as it is pulled apart,

$$Y = \frac{\text{stress}}{\text{strain}} = \frac{\text{restoring force/cross-sectional area}}{\text{change in length/length}}.$$

The Young's modulus is a useful way to characterize materials, because unlike the spring constant, it doesn't depend on the shape of the material. For example, putting two identical springs side-by-side doubles the spring constant, because they both contribute to the force. But since the stress is the force per area, it's unchanged. Similarly, putting two identical springs end-to-end halves the spring constants, because they both stretch, but since the strain is change in length per length, it's unchanged. So you would quote a material's Young's modulus instead of its spring constant, for the same reason you would quote a material's resistivity instead of its resistance.

We note that  $Y$  has the dimensions of energy per length cubed, so

$$Y \sim \frac{E_b}{a^3}$$

solely by dimensional analysis. (Of course, for this dimensional analysis to work, one has to understand why  $E_b$  and  $a$  are the only relevant quantities. It's because  $Y$ , or equivalently the spring constant  $k$ , determines the energy stored in a stretched spring. But microscopically this comes from the energy stored in interatomic bonds when they're stretched. So the relevant energy scale is the bond energy  $E_b$ , and the relevant distance scale is  $a$ , because that determines how many bonds get stretched, and by how much.)

To relate  $Y$  to the spring constant of a rod, note that

$$Y = \frac{F/A}{\Delta L/L} = \frac{L}{A} \frac{F}{\Delta L} = k \frac{L}{A}$$

for a rod, giving the estimate  $k \sim AE_b/La^3$ . This is correct to within an order of magnitude!

To relate  $Y$  to the speed of sound, note that the sound speed, like most wave speeds, depends on the material's inertia and its restoring force against distortions. Since the speed of sound doesn't depend on the extrinsic features of a metal object, such as a length, both of these should be measured intrinsically. The intrinsic measure of inertia is the mass density  $\rho \sim m/a^3$ , while the intrinsic measure of restoring force is just  $Y$ . By dimensional analysis,

$$v \sim \sqrt{\frac{Y}{\rho}} \sim \sqrt{\frac{E_b/a^3}{m/a^3}} \sim \sqrt{\frac{E_b}{m}}.$$

This is also reasonably accurate. For example, in diamond,  $E_b \sim 1 \text{ eV}$  (a typical atomic energy scale), while a carbon nucleus contains 12 nucleons, so to the nearest order of magnitude,  $m \sim 10m_p$ , where a useful fact is  $m_p \sim 1 \text{ GeV}/c^2$ . Thus,

$$v \sim \sqrt{\frac{1 \text{ eV}}{10^{10} \text{ eV}}} c \sim 10^{-5} c \sim 3 \text{ km/s}$$

which is roughly right. (The true answer is 12 km/s.)

Amazingly, we can get an even rougher estimate of  $v$  for any solid in terms of nothing besides fundamental constants. To be very rough, the binding energy is on the order of that of hydrogen. As you found in problem 9, this is, by dimensional analysis,

$$E_b \sim \frac{1}{4\pi\epsilon_0} \frac{e^2}{a_0} \sim m_e \left( \frac{e^2}{4\pi\epsilon_0\hbar} \right)^2.$$

We take the nuclear mass to be very roughly the proton mass  $m_p$ , which gives

$$\frac{v}{c} \sim \sqrt{\frac{m_e}{m_p} \left( \frac{e^2}{4\pi\epsilon_0\hbar c} \right)^2} \sim \alpha \sqrt{\frac{m_e}{m_p}}$$

where  $\alpha$  is as found in problem 11. This expresses the speed of sound in terms of the dimensionless strength of electromagnetism  $\alpha$ , the electron to proton mass ratio, and the speed of light. Of course, the approximations we have made here have been so rough that now the answer is off by *two* orders of magnitude, but now we know how the answer would change if the fundamental constants did.

Estimates as simple as these can be surprising to even seasoned physicists: in 2020, the simple estimate above was rediscovered and [published](#) in one of the top journals in science. If you want to learn how to do more of these estimates, [this paper](#) is a good starting point.

**Remark**

A warning: from these examples, you could get the idea that dimensional analysis gives you nearly godlike powers, and the ability to write down the answer to most physics problems instantly. In reality, it only works if you're pretty sure your physical system depends on only about 3 or 4 variables – and the hard part is often finding *which* variables matter. For example, as we saw above, you can't get Kepler's third law for free because that requires knowing the dimensions of  $G$ , which require knowing that gravity is an inverse square law in the first place, a luxury Kepler didn't have. And as another example, we couldn't have figured out  $E = mc^2$  long before Einstein, as who would have thought that the speed of light had anything to do with the energy of a lump of matter? Without the framework of relativity, it seems as irrelevant as the speed of sound or the speed of water waves. To illustrate this point, we consider two contrasting examples below.

In reality, dimensional analysis is best for problems where it's easy to see which variables matter, problems where you're explicitly told what variables matter, and for checking your work, which you should get in the habit of doing all the time!

**Example 8**

Archaeologists and biologists have discovered that the famed T. Rex was essentially a gigantic chicken. Suppose that a T. Rex is about  $N = 20$  times larger in scale than a chicken. Compared to a chicken, how much larger is its weight, cross-sectional area of bone, walking speed, and maximum jump height?

**Solution**

These kinds of biological scaling questions are fun to think about, though the accuracy of the results is questionable. Here's the typical reasoning:

- Since the densities should match, the weight should scale with the volume, so as  $N^3$ .
- Since the maximum compressive pressure that bone can take should be the same, the bone area should scale with the weight, so also as  $N^3$ . That is, the width of the bones scales as  $N^{3/2}$ , while their length  $L$  scales only as  $N$ . This is one of the reasons it's impractical to have huge land animals; the biggest animals now are all whales.
- As a very crude model of walking, we can think of the legs as swinging like a free pendulum. The length of one step is proportional to  $L$ , while the period of the steps is proportional to  $\sqrt{L}$ . Thus, the walking speed scales as  $\sqrt{L} \propto \sqrt{N}$ .
- The energy stored in the muscle cells scales with the volume, but the mass also scales with the volume. Since the jump height satisfies  $E = mgh$  where  $E$  is the energy stored by the muscles,  $h \propto N^0$ . And indeed, a flea can jump nearly as high as a human!

**Example 9**

A person with density  $\rho$  and total energy  $E$  stored in their muscles can jump to a height  $h$  in gravity  $g$ . How high would they be able to jump in gravity  $10g$ ?

**Solution**

By dimensional analysis, the only possible answer is

$$h \propto \left( \frac{E}{\rho g} \right)^{1/4}$$

which means that in gravity  $10g$ , they can jump to height  $h/10^{1/4}$ .

But this is completely wrong! In gravity  $10g$ , a person wouldn't be able to jump at all; they'd be so crushed by their own weight that they wouldn't even be able to stand. The actual answer depends on details of the biomechanics of muscles and bone, which involve more dimensionful quantities than just the total energy  $E$ . So, as remarked above, you can't solve literally any problem by just listing a few relevant quantities and doing dimensional analysis – you need to make sure those are the *only* relevant quantities.

## 2 Approximations

**Idea 4: Taylor Series**

For small  $x$ , a function  $f(x)$  may be approximated as

$$f(x) = f(0) + xf'(0) + \frac{x^2}{2}f''(0) + \dots + \frac{x^n}{n!}f^{(n)}(0) + O(x^{n+1})$$

where  $O(x^{n+1})$  stands for an error term which grows at most as fast as  $x^{n+1}$ .

There are a few Taylor series that are essential to know. The most important are

$$\exp x = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + O(x^4), \quad \log(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - O(x^4)$$

and the small angle approximations

$$\sin x = x - \frac{x^3}{6} + O(x^5), \quad \cos x = 1 - \frac{x^2}{2} + O(x^4).$$

Another Taylor series you learned long before calculus class is

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + O(x^4)$$

Usually you'll only need the first one or two terms, but for practice we'll do an example with more. If any of these results aren't familiar, you should rederive them!



**Example 10**

Find the Taylor series for  $\tan x$  up to, and including the fourth order term.

**Solution**

By the fourth order term, we mean the term proportional to  $x^4$ . (Not the fourth nonzero term, which would be  $O(x^7)$ .) Of course,  $\tan x$  is an odd function, so the  $O(x^4)$  term is zero, which means we only need to expand up to  $O(x^3)$ . That means we can neglect  $O(x^4)$  terms and higher everywhere in the computation, subject to some caveats we'll point out later.

By definition, we have

$$\tan x = \frac{\sin x}{\cos x} = \frac{x - x^3/6 + O(x^5)}{1 - x^2/2 + O(x^4)}.$$

However, it's a little tricky because we have a Taylor series in a denominator. There are two ways to deal with this. We could multiply both sides by  $\cos x$ , and expand  $\tan x$  in a Taylor series with unknown coefficients. Then we would get a system of equations that will allow us to solve for the coefficients recursively.

A faster method is to use the Taylor series for  $1/(1 - x)$ . We have

$$\frac{1}{1 - u} = 1 + u + O(u^2)$$

and substituting  $u = x^2/2 - O(x^4)$  gives

$$\frac{1}{\cos x} = 1 + \frac{x^2}{2} + O(x^4).$$

Therefore, we conclude

$$\tan x = (x - x^3/6 + O(x^5))(1 + x^2/2 + O(x^4)) = x + x^3/3 + O(x^5).$$

Here I was fairly careful with writing out all the error terms and intermediate steps, but as you get better at this process, you'll be able to do it faster. (Of course, one could also have done this example by just directly computing the Taylor series of  $\tan x$  from its derivatives. This is possible, but for more complicated situations it's generally not a good idea, because computing high derivatives of a complex expression tends to get very messy. It's better to just Taylor expand the individual pieces and combine the results, as we did here.)

**Remark**

Finding series up to a given order can be subtle. For example, if you want to compute an  $O(x^4)$  term, it is *not* always enough to expand everything up to  $O(x^4)$ , because powers of  $x$  might cancel. To illustrate this, the last step here is wrong:

$$\tan x = \frac{x^3 \sin x}{x^3 \cos x} = \frac{x^4 + O(x^6)}{x^3 + O(x^5)} = x + O(x^5).$$

- [2] **Problem 13.** Find the Taylor series for  $1/\cos x$  up to and including the fourth order ( $O(x^4)$ ) term.

**Solution.** The derivatives of  $\cos(x)$  at  $x = 0$  are 0,  $-1$ , 0, 1, so

$$\cos x = 1 - \frac{x^2}{2} + \frac{x^4}{4!} + O(x^6).$$

To expand the inverse, note that

$$\frac{1}{1-u} = 1 + u + u^2 + O(u^3)$$

where in our case,  $u = x^2/2 - x^4/24$ . Plugging this in gives

$$\frac{1}{\cos x} = 1 + (x^2/2 - x^4/24) + (x^2/2 - x^4/24)^2 + O(x^6) = 1 + x^2/2 + \frac{5x^4}{24}.$$

- [2] **Problem 14.** Extend the computation above to get the  $x^5$  term in the Taylor series for  $\tan x$ .

**Solution.** From this point on we will start omitting the explicit  $O(x^n)$  error terms. We have

$$(x - x^3/6 + x^5/120)(1 + x^2/2 + 5x^4/24) = x + x^3/2 + 5x^5/24 - x^3/6 - x^5/12 + x^5/120$$

giving the answer,

$$\tan(x) = x + \frac{x^3}{3} + \frac{2x^5}{15}.$$

- [3] **Problem 15.** For small  $x$ , approximate the quantity

$$\frac{x^2 e^x}{(e^x - 1)^2} - 1$$

to lowest order. That is, find the first nonzero term in the Taylor series. If you don't take enough terms in the Taylor series to begin with, you'll get an answer of zero, indicating you approximated too loosely. But if you take too many, the computation will get extremely messy. Your final answer should contain a 12, which is actually the same 12 as in the classic result  $1 + 2 + 3 + \dots = -1/12$ .

**Solution.** Again suppressing the error terms, we have

$$\begin{aligned} \frac{x^2(1+x+x^2/2)}{(x+x^2/2+x^3/6)^2} - 1 &= \frac{1+x+x^2/2}{1+x+7x^2/12} - 1 \\ &= (1+x+x^2/2)(1-x+5x^2/12) - 1 \\ &= -\frac{x^2}{12}. \end{aligned}$$

Note that we have been careful to keep the manipulations as simple as possible, e.g. by canceling factors of  $x/x$  as early as possible. If you don't do this, everything gets very messy and it's unclear what is contributing at what order, because of the subtlety pointed out in the above remark.

- [2] **Problem 16.** The function  $\cos^{-1}(1-x)$  does not have a Taylor series about  $x = 0$ . However, it does have a series expansion about  $x = 0$  in a different variable. What is this variable, and what's the first term in the series? (Optionally, can you find higher order terms in the series?)

**Solution.** We have

$$\frac{d}{dx} \arccos(1-x) = \frac{-1}{\sqrt{1-(1-x)^2}}$$

which is unfortunately undefined at  $x = 0$ , so there is no Taylor series. But note that if we let  $y = \cos^{-1}(1-x)$  and take the cosine of both sides, we have

$$\cos y = 1 - x.$$

Now  $y$  does have a good Taylor series near  $y = 0$ , which corresponds to where  $x = 0$ . At lowest order, we have

$$1 - y^2/2 \approx 1 - x$$

which implies that

$$y \approx \sqrt{2x}.$$

More generally, the answer is a series in  $\sqrt{x}$ . Since cosine is even, the next term is  $O(x^{3/2})$ .

In order to get higher order terms, we can write

$$\cos^{-1}(1-x) = \cos^{-1}(1-u^2)$$

where  $u = \sqrt{x}$ , and directly compute a Taylor series in  $u$ , using the usual rule for a derivative of an inverse function. There is also an alternative route that uses the Taylor series for cosine directly. Let's suppose we just want the  $O(x^{3/2})$  term, so let

$$y = \sqrt{2}x^{1/2} + Ax^{3/2} + O(x^{5/2}).$$

We also know that

$$1 - x = \cos y = 1 - \frac{y^2}{2} + \frac{y^4}{24} + O(y^6).$$

Now, the lowest order term in the series found above is what matches to  $1 - x$ . The next term in the series can be found by demanding that the right-hand side contain  $x^2$  with zero coefficient. Thus, we are only interested in expanding up to  $O(x^2)$ , and since  $y^6 = O(x^3)$  we can drop it, so

$$\begin{aligned} 1 - x &= 1 - \frac{1}{2} \left( \sqrt{2}x^{1/2} + Ax^{3/2} \right)^2 + \frac{1}{24} \left( \sqrt{2}x^{1/2} + Ax^{3/2} \right)^4 + O(x^3) \\ &= 1 - \frac{1}{2} (2x + 2\sqrt{2}Ax^2) + \frac{1}{24} \left( \sqrt{2}x^{1/2} \right)^4 + O(x^3) \\ &= 1 - x - \sqrt{2}Ax^2 + \frac{x^2}{6} + O(x^3) \end{aligned}$$

from which we conclude  $A = 1/6\sqrt{2}$ . This method, of taking a series expression for  $x$  in terms of  $y$ , and reversing it to a series for  $y$ , is called reversion of series.

### Idea 5: Binomial Theorem

When the quantity  $xn$  is small, it is useful to use the binomial theorem,

$$(1+x)^n = 1 + xn + O(x^2n^2).$$

It applies even when  $n$  is not an integer. In particular,  $n$  can be very large, very small, or even negative. The extra terms will be small as long as  $xn$  is small. If desired, one can find

higher terms using binomial coefficients,

$$(1+x)^n = \sum_{m=0}^{\infty} \binom{n}{m} x^m$$

where the definition of the binomial coefficient is formally extended to arbitrary real  $n$ .

The binomial theorem is one of the most common approximations in physics. It's really just taking the first two terms in the Taylor series of  $(1+x)^n$ , but we give it a name because it's so useful.

- [1] **Problem 17.** Suppose the period of a pendulum is one second, and recall that

$$T = 2\pi\sqrt{\frac{L}{g}}.$$

If the length is increased by 3% and  $g$  is increased by 1%, use the binomial theorem to estimate how much the period changes. This kind of thinking is extremely useful when doing experimental physics, and you should be able to do it in your head.

**Solution.**  $L$  is raised to the power of  $1/2$ , and for  $g$  it is  $-1/2$ . Thus  $T = T_0(1 + \delta L/2L)(1 - \delta g/2g)$ . Putting in the numbers yield  $T \approx 1.01T_0$  so the period should be 1% longer.

- [2] **Problem 18.** Consider an electric charge  $q$  placed at  $x = 0$  and a charge  $-q$  placed at  $x = d$ . The electric field along the  $x$  axis is then

$$E(x) = \frac{q}{4\pi\epsilon_0} \left( \frac{1}{x^2} - \frac{1}{(x-d)^2} \right).$$

For large  $x$ , use the binomial theorem to approximate the field.

**Solution.** Use the binomial theorem with  $d/x \ll 1$  to get

$$\frac{1}{(x-d)^2} = \frac{1}{x^2} \left( 1 + \frac{2d}{x} \right).$$

Then

$$E(x) = -\frac{2qd}{4\pi\epsilon_0 x^3} = -\frac{qd}{2\pi\epsilon_0 x^3}.$$

This is the field of an electric dipole.

- [3] **Problem 19.** Some exercises involving square roots.

- Manually find the Taylor series for  $\sqrt{1+x}$  up to second order, and verify they agree with the binomial theorem.
- Approximate  $\sqrt{1+2x+x^2}$  for small  $x$  using the binomial theorem. Does the result match what you expect? If not, how can you correct it?

**Solution.** (a) The binomial theorem gives  $1 + x/2$ . By differentiating, we get  $1/(2\sqrt{1+x})$  and  $-1/(4(1+x)^{3/2})$ . Then

$$\sqrt{1+x} = 1 + \frac{1}{2}x - \frac{1}{8}x^2 + O(x^3).$$

The first two terms agree with the usual form of the binomial theorem. For the third term, note that the coefficient should be

$$\binom{1/2}{2} = \frac{(1/2)(-1/2)}{2} = -\frac{1}{8}$$

which is indeed what we find.

- (b) Of course, the result is  $1 + x$ , so we want the  $O(x^2)$  term to vanish. On the other hand, applying the binomial theorem gives

$$\sqrt{1 + 2x + x^2} \approx 1 + \frac{1}{2}(2x + x^2) = 1 + x + \frac{x^2}{2}$$

which is wrong! The reason is that the first order binomial theorem isn't good enough, because the second order term in the binomial theorem will also contribute a second order term to the answer. Using the result of part (a),

$$\begin{aligned} \sqrt{1 + 2x + x^2} &= 1 + \frac{1}{2}(2x + x^2) - \frac{1}{8}(2x + x^2)^2 + O((2x + x^2)^3) \\ &= 1 + x + \frac{x^2}{2} - \frac{1}{8}(2x + x^2)^2 + O(x^3) \\ &= 1 + x + \frac{x^2}{2} - \frac{1}{8}(2x)^2 + O(x^3) \\ &= 1 + x + O(x^3) \end{aligned}$$

as desired.

### Example 11: Birthday Paradox

If you have  $n$  people in a room, around how large does  $n$  have to be for there to be at least a 50% chance of two people sharing the same birthday?

### Solution

Imagine adding people one at a time. The second person has a  $1/365$  chance of sharing a birthday with the first. If they don't share a birthday, the third person has a  $2/365$  chance of sharing a birthday with either, and so on. So a decent estimate for  $n$  is the  $n$  where

$$\left(1 - \frac{1}{365}\right) \left(1 - \frac{2}{365}\right) \cdots \left(1 - \frac{n}{365}\right) \approx \frac{1}{2}.$$

The surprising point of the birthday paradox is that  $n \ll 365$ . So we can use the binomial theorem in reverse, approximating the left-hand side as

$$\left(1 - \frac{1}{365}\right) \left(1 - \frac{1}{365}\right)^2 \cdots \left(1 - \frac{1}{365}\right)^n \approx \left(1 - \frac{1}{365}\right)^{n^2/2}$$

which is valid since  $n/365$  is small. It's tempting to use the binomial theorem again to write

$$\left(1 - \frac{1}{365}\right)^{n^2/2} \approx 1 - \frac{n^2}{2 \cdot 365} = \frac{1}{2}$$

which gives  $n = 19$ . However, this is a bad approximation, because the binomial theorem only works if  $(n^2/2)(1/365)$  is very small, but here we've set it to  $1/2$ , which isn't particularly small. Since the series expansion variable is  $1/2$ , each term in the series expansion is *roughly*  $1/2$  as big as the last (ignoring numerical coefficients), so we expect to be off by about  $(1/2)^2 = 25\%$ .

The binomial theorem is an expansion for  $(1+x)^y$  which works when  $xy$  is small. Here  $xy$  isn't small, and we instead want an approximation that works when only  $x$  is small. One trick to dealing with an annoying exponent is to take the logarithm, since that just turns it into a multiplicative factor. Note that

$$\log((1+x)^y) = y \log(1+x) \approx yx$$

by Taylor series, which implies that

$$(1+x)^y \approx e^{yx}$$

when  $x$  is small, an important fact which you should remember. So we have

$$\left(1 - \frac{1}{365}\right)^{n^2/2} \approx e^{-n^2/2(365)} = \frac{1}{2}$$

and solving gives  $n = 22.5$ . We should round up since  $n$  is actually an integer, giving  $n = 23$ , which is indeed the exact answer.

### Remark

Precisely how accurate is the approximation  $(1+x)^y \approx e^{yx}$ ? Note that the only approximate step used to derive it was taking  $\log(1+x) \approx x$ , which means we can get the corrections by expanding to higher order. If we take the next term,  $\log(1+x) \approx x - x^2/2$ , then we find

$$(1+x)^y \approx e^{yx} e^{-x^2 y/2}.$$

Note that because we are approximating the logarithm of the quantity we want, the next correction is multiplicative rather than additive; we'll see a similar situation with Stirling's approximation in **T2**. So, while we motivated the approximation by imagining  $x \ll 1$ , the real condition we need to have a good approximation is  $x^2 y \ll 1$ . For instance, in the previous example we had  $x^2 y/2 = (22.5/365)^2/4 = 0.1\%$ , so our answer was quite accurate.

- [2] **Problem 20.** Find a series approximation for  $x^y$ , given that  $y$  is small and  $x$  is neither small nor exponentially huge. (Hint: to check if you have it right, you can try concrete numbers, such as  $y = 0.01$  and  $x = 10$ . The series expansion variable may look a bit unusual.)

**Solution.** We have

$$x^y = e^{y \log(x)}.$$

If  $y$  is small, then for any reasonable  $x$  (i.e.  $x$  not exponentially huge),  $y \log(x)$  is also small. So we can use the Taylor series for the exponential to get

$$x^y \approx 1 + y \log(x) + O((y \log(x))^2)$$

with further terms easily computed.

[3] **Problem 21.** Sometimes, transcendental equations can be solved numerically by “iteration”. This is especially useful in Olympiad contexts where only basic calculators are allowed.

- (a) Take a scientific calculator (in radians), put in any number, and press the “cos” button many times. Convince yourself that the final number you get is the unique solution to  $x = \cos x$ .
- (b) What are the key features of the graphs of  $x$  and  $\cos x$  that made this work? For example, why doesn’t pressing  $\cos^{-1}$  repeatedly give the same result? As another example, since  $x = \sin x$  has a unique solution, why does repeatedly pressing sin not work so well?
- (c) Find a nonzero solution for  $x = \tan(x/2)$ .
- (d) Find a nonzero solution for  $e^x - 1 = 2x$ .
- (e) Find a positive solution for  $x^x = e$ .

If you ever have trouble getting iteration to work, another useful technique is ordinary binary search. It’s not as flashy or fast as iteration, but it’s easy and reliable. Numeric solutions like these will appear in future problem sets.

**Solution.** (a) Well, just try it!

- (b) What makes  $\cos x$  work and  $\arccos x$  fail is that near the Dottie number (the solution to  $x = \cos x$ ), the slope of  $\cos(x)$  (call it  $m_1$ ) is greater than  $-1$ , and the slope of  $\arccos(x)$  ( $m_2$ ) is less than  $-1$ . This means that when one starts with  $x + \epsilon$ , to the first order  $\cos(x)$  will map it to  $x + m_1\epsilon$ , and for  $\arccos x$  it will be  $x + m_2\epsilon$ . The repeated factors of  $m_1$  with absolute value less than 1 will make iterations of  $\cos x$  converge to the Dottie number exponentially, but with  $|m_2| > 1$ , the iterations will result in numbers getting farther away from the Dottie number.

Another, more global reason that  $\cos x$  works so well is that it’s bounded. So whatever your initial guess is, at the next stage it’ll be mapped to within  $[-1, 1]$ , and from then on it’ll close into the answer. For general functions, you usually have to choose the initial guess more carefully, or else you’ll get the wrong solution, or diverge to infinity.

The solution to  $\sin x = x$  is  $x = 0$ , but near zero, the slope of sine is gets closer and closer to 1. This makes convergence excruciatingly slow! If you play around a bit with series, you can show that after  $n$  iterations, your answer starts shrinking as  $1/\sqrt{n}$ , which is much worse than the exponential convergence. This is a pretty weird case though; you probably won’t see it in practice.

In general, iteration can “go wrong” in far weirder ways. For example, suppose you tried to iterate  $x \rightarrow rx(1 - x)$  for a constant  $r$ . This is called the [logistic map](#), and it turns out that if  $r$  is in the right range, the result is chaotic! The result bounces around in an unpredictable way, never repeating itself, and you get a completely different result after a few iterations if you start with a very slightly different number.

- (c) Note that iterating  $\tan(x/2)$  will lead to  $x = 0$ . In this case, the solution  $x = 0$  is stable, while the solution we actually want is unstable. Thus to get the other solution, try the inverse:  $x = 2 \arctan(x)$ . So type in a guess in your calculator like 3, and then enter  $2 \arctan(\text{Ans})$ , and keep pressing “=”. Eventually you’ll get  $x = 2.331$ . There’s also a negative solution,  $x = -2.331$ , and which one you get depends on your initial guess.

- (d) Iterating  $(e^{\text{Ans}} - 1)/2$  will also yield  $x = 0$ , so iterate  $x = \ln(1 + 2x)$ . Type in a guess like 2, and type in  $\ln(1 + 2\text{Ans})$ . Eventually you'll get to  $x = 1.256$ .
- (e) Taking the log of both sides gives  $x \log x = 1$ . The iteration from  $x = 1/\log(x)$  is unstable, so instead iterate  $x = e^{1/x}$ . That is, type in a guess close to 1.8 or so, and iterate  $e^{1/\text{Ans}}$ . You'll get  $x = 1.7632$ .

### Example 12

In units where  $c = 1$ , the Lorentz factor is defined as

$$\gamma = \frac{1}{\sqrt{1 - v^2}}.$$

Suppose that a particle traveling very close to the speed of light has  $\gamma = 10^8$ . Find the difference  $\Delta v$  between its speed and the speed of light.

### Solution

This problem looks easy; by some trivial algebra we find

$$\Delta v = 1 - \sqrt{1 - 1/\gamma^2}.$$

But when you plug this into a cheap scientific calculator, you get *zero*, or something that's quite far from the right result. The problem is that we are trying to find a small quantity  $\Delta v$  by subtracting two nearby, much larger quantities. But the calculator has limited precision, and it ends up rounding  $1 - 1/\gamma^2 = 1 - 10^{-16}$  a bit, giving a completely wrong answer!

Instead, we can apply the binomial theorem to find

$$\Delta v \approx \frac{1}{2\gamma^2} + O(1/\gamma^4).$$

This is no longer the exact answer, but it's a great approximation, because the error term is around  $1/\gamma^2 \sim 10^{-16}$  times as small as the answer, and it's easy for a calculator to evaluate. The lesson is that it's better to be accurate in practice than to be precise in theory.

- [1] **Problem 22.** Find the solutions of the equation  $x^2 - 10^{20}x + 1 = 0$  to reasonable accuracy.

**Solution.** Applying the quadratic formula, the solutions are

$$x = \frac{10^{20} \pm \sqrt{10^{40} - 4}}{2}.$$

Of course you can't just plug this into a calculator and expect a reasonable result. Instead, we need to approximate. For the larger root, an excellent approximation is

$$x \approx \frac{10^{20} + \sqrt{10^{40}}}{2} = 10^{20}.$$

Then by Vieta's formula, an excellent approximation for the other root is  $10^{-20}$ .



- [4] **Problem 23.** Consider the equation  $\epsilon x^3 - x^2 + 1 = 0$ , where  $\epsilon$  is small. Find approximate expressions for all three roots of this equation, up to and including terms of order  $\epsilon$ .

**Solution.** If we set  $\epsilon = 0$ , then the roots of the resulting quadratic equation are  $\pm 1$ . Thus, two of the roots should be near  $\pm 1$ . To calculate the  $O(\epsilon)$  correction, let  $x = 1 + A\epsilon + O(\epsilon^2)$ . Then plugging this into the equation gives

$$\epsilon(1 + A\epsilon)^3 - (1 + A\epsilon)^2 + 1 = \epsilon - 2A\epsilon + O(\epsilon)^2 = 0.$$

Thus, we find  $A = 1/2$ . A similar calculation can be done for the root near  $x = -1$ , giving roots

$$x = 1 + \frac{\epsilon}{2} + O(\epsilon^2), \quad x = -1 + \frac{\epsilon}{2} + O(\epsilon^2).$$

However, the third root is nowhere to be found in this analysis, because the quadratic only has two roots. Upon graphing the function, you can see that the third root is at very large  $x$ , once the cubic term catches up in size to the quadratic term. This happens when  $x \approx 1/\epsilon$ . This appearance of an inverse power of  $\epsilon$  makes this a “singular perturbation series”.

Here’s a general way to conceptualize what’s going on here. The equation in this problem has three terms, and it’s easy to find a root if any one of the terms is negligible compared to the others. For example, for the first two roots, we assumed the  $\epsilon x^3$  term was negligible, and then found  $x = \pm 1$ . Then, adding on the  $\epsilon x^3$  term produces  $O(\epsilon)$  and higher corrections to the left-hand side, which can be used to compute  $O(\epsilon)$  and higher corrections to the root itself. Now, this third root we’ve just found occurs when the 1 term is negligible. In this case, both of the first two terms are of order  $1/\epsilon^2$ , and the 1 creates small corrections to the root (relative to its huge size).

Since 1 is two orders in  $\epsilon$  smaller than  $1/\epsilon^2$ , we expect these terms only appear two orders down in the root. That is, we expect the root has the form

$$x = \frac{1}{\epsilon} (1 + A\epsilon^2 + O(\epsilon^3))$$

with no  $O(\epsilon)$  term in parentheses. (If you don’t believe this, check this term vanishes for yourself!) Plugging this into the equation gives

$$\frac{1}{\epsilon^2}(1 + A\epsilon^2 + O(\epsilon^3))^3 - \frac{1}{\epsilon^2}(1 + A\epsilon^2 + O(\epsilon^3))^2 + 1 = 0$$

which is equivalent to

$$3A - 2A + 1 + O(\epsilon) = 0$$

from which we conclude  $A = -1$ , and hence the third root is

$$x = \frac{1}{\epsilon} - \epsilon + O(\epsilon^2).$$

Finally, you might be wondering what happens if the  $x^2$  term is the negligible one. However, this never happens. If we assume it’s negligible, then we need  $x \approx -\epsilon^{-1/3}$ , so that both the other terms are about 1. But then the  $x^2$  term is  $1/\epsilon^{2/3} \gg 1$ . So we can’t assume the  $x^2$  term is negligible self-consistently, so it doesn’t give any new roots.

The idea used above, of supposing two of the terms are large, using that to solve a simpler equation, and then checking for consistency, is known as the method of dominant balance. You can read more about it in the first few chapters of the draft book *Physical Mathematics*.

**Remark**

If these questions seem complicated, rest assured that 90% of approximations on the USAPhO and IPhO boil down to using

$$\sin x \approx x, \quad \cos x \approx 1 - x^2/2, \quad (1+x)^n \approx 1 + nx, \quad e^x \approx 1 + x, \quad \log(1+x) \approx x.$$

I've given you a lot of subtle situations above, but it's these that you have to know by heart. Almost all situations where you will use these will look like problem 17 or problem 18.

**3 Limiting Cases****Idea 6**

Limiting cases can be used to infer how the answer to a physical problem depends on its parameters. It is primarily useful for remembering the forms of formulas, but can also be powerful enough to solve multiple choice questions by itself.

**Example 13**

What is the horizontal range of a rock thrown with speed  $v$  at an angle  $\theta$  to the horizontal?

**Solution**

This result is easy to derive, but dimensional analysis and extreme cases can be used to recover the result too. The answer can only depend on  $v$ ,  $g$ , and  $\theta$ , so by dimensional analysis it is proportional to  $v^2/g$ . This is sensible, since the range increases with  $v$  and decreases with  $g$ . Now, the range is zero in the extreme cases  $\theta = 0$  and  $\theta = \pi/2$ , but not anywhere in between, so if we remember the range contains a simple trigonometric function, it must be  $\sin(2\theta)$ , so

$$R \propto \frac{v^2}{g} \sin(2\theta).$$

We can also get the prefactor by a simple limiting case, the case  $\theta \ll 1$ . In this case, by the small angle approximation,

$$v_x \approx v, \quad v_y \approx v\theta.$$

The time taken is  $t = 2v_y/g$ , so the range is

$$R \approx v_x t = \frac{2v^2}{g} \theta.$$

Thus there is no proportionality constant; the answer is

$$R = \frac{v^2}{g} \sin(2\theta).$$

In reality, it's probably faster to go through the full derivation than all of this reasoning, but if you're just not sure about whether it's a sine or a cosine, or what the prefactor is, then

limiting cases can be quickly used to recover that piece. Also note that the approximations we used above are frequently useful for evaluating limiting cases.

### Example 14

Consider an [Atwood's machine](#) with masses  $m$  and  $M$ , and a massless pulley. Find the tension in the string.

### Solution

Since the equations involved are all linear equations, we expect the answer should also be simple. It can only depend on  $g$ ,  $m$ , and  $M$ , so by dimensional analysis, it must be proportional to  $g$ . By dimensional analysis, this must be multiplied by something with one net power of mass. Since the answer remains the same if we switch the masses, it should be symmetric in  $m$  and  $M$ .

Given all of this, the simplest possible answer would be

$$T \propto g(m + M).$$

To test this, we consider some limiting cases. If  $M \gg m$ , the mass  $M$  is essentially in freefall, so the mass  $m$  accelerates upward with acceleration  $g$ . Then the tension is approximately  $2mg$ . Similarly, in the case  $M \ll m$ , the tension is approximately  $2Mg$ . These can't be satisfied by the form above.

The next simplest option is a quadratic divided by a linear expression. Both of these must be symmetric, so the most general possibility is

$$T = g \frac{A(m^2 + M^2) + BmM}{m + M}.$$

Then the limiting cases can be satisfied if  $A = 0$  and  $B = 2$ , giving

$$T = \frac{2gmM}{m + M}.$$

- [1] **Problem 24.** Find the perimeter of a regular  $N$ -gon, if  $L$  is the distance from the center to any of the sides. By considering a limiting case, use this to derive the circumference of a circle.

**Solution.** By basic trigonometry, the perimeter is  $2NL \sin(\pi/N)$ . Then the circumference of a circle is

$$\lim_{N \rightarrow \infty} 2NL \sin(\pi/N) = 2NL \frac{\pi}{N} = 2\pi L$$

as expected. We can see that the limit of  $N \sin(\pi/N)$  is  $\pi$  through the small angle approximation. If you want more rigor, you could also say that this is an indeterminate form  $\infty \times 0$ , and use l'Hospital's rule.

- [1] **Problem 25.** Use similar reasoning to find the acceleration of the Atwood's machine. (We will show an even easier way to do this, using "generalized coordinates", in **M4**.)

**Solution.** We know from dimensional analysis that the acceleration is  $gf(m, M)$  where  $f(m, M)$  is dimensionless. Thus it should be a fraction.

If either of the masses is much more massive than the other mass, then the acceleration should be  $g$ . Thus the coefficients of  $m, M$  should be  $\pm 1$ . If the masses are equal, then the acceleration should be 0. This leads to a  $M - m$  term in the numerator. Since the denominator should be different but still have factors of  $\pm 1$ , a reasonable answer is

$$a = \frac{m - M}{m + M}g.$$

which is indeed the real answer.

- [2] **Problem 26** (Morin 1.6). A person throws a ball (at an angle of her choosing, to achieve the maximum distance) with speed  $v$  from the edge of a cliff of height  $h$ . Which of the below could be an expression for the maximal range?

$$\frac{gh^2}{v^2}, \quad \frac{v^2}{g}, \quad \sqrt{\frac{v^2 h}{g}}, \quad \frac{v^2}{g} \sqrt{1 + \frac{2gh}{v^2}}, \quad \frac{v^2}{g} \left(1 + \frac{2gh}{v^2}\right), \quad \frac{v^2/g}{1 - 2gh/v^2}.$$

If desired, try Morin problems 1.13, 1.14, and 1.15 for additional practice.

**Solution.** First check if they're all dimensionally correct (they are). When  $h = 0$ , the maximum range as found above with  $\sin(2\theta) = 1$  is  $v^2/g$ . Also the maximum range obviously depends on the height of the edge of the cliff, and there shouldn't be a case of a finite height or velocity where the range becomes infinite. This leaves 2 options:

$$\frac{v^2}{g} \sqrt{1 + \frac{2gh}{v^2}}, \quad \frac{v^2}{g} \left(1 + \frac{2gh}{v^2}\right)$$

When  $h$  is small, the extra distance at the end of the trajectory from dipping down a vertical distance  $h$  can be found with binomial theorem:  $h$ , and  $2h$  respectively. Since the trajectory is symmetric, when  $h \approx 0$  (to be more concise,  $h \ll v^2/g$ ) the optimal launch angle is 45 deg, so by geometry the extra distance should also be  $h$ . Thus the correct formula is

$$\frac{v^2}{g} \sqrt{1 + \frac{2gh}{v^2}}.$$

- [2] **Problem 27.** Consider a triangle with side lengths  $a, b$ , and  $c$ . It turns out the area of its incircle can be expressed purely by multiplying and dividing combinations of these lengths. Moreover, the answer is the simplest possible one consistent with limiting cases, scaling, and symmetry. Guess it!

**Solution.** In the limiting case  $a = b + c$ , the triangle collapses and the area must be zero, which means the answer must be proportional to  $b + c - a$ . But the answer should also be symmetric between exchanging  $a, b$ , and  $c$ , so it must be proportional to  $(b + c - a)(c + a - b)(a + b - c)$ . The dimension of this quantity is one too high, so we need to divide by a length, and the only possibility consistent with symmetry is  $a + b + c$ . Finally, the overall constant can be fixed using the special case of an equilateral triangle, giving the result

$$A = \frac{\pi}{4} \frac{(a + b - c)(b + c - a)(c + a - b)}{a + b + c}.$$

Incidentally, the area of the excircle is  $\pi(abc)^2/((a+b+c)(a+b-c)(b+c-a)(c+a-b))$ . While most of the denominator makes sense from limiting cases, the overall expression is certainly harder to guess, since powers of  $abc$  and  $a+b+c$  could cancel while preserving all the limiting cases and symmetry. That just goes to show that limiting cases can only get you so far. In some sense, “real” math starts once all the easy information accessible to methods like these has been accounted for.

While we won’t have more questions that are explicitly about dimensional analysis or limiting cases, these are not techniques but ways of life. For all future problems you solve, you should be constantly checking the dimensions and limiting cases to make sure everything makes sense.

## 4 Manipulating Differentials

You might have been taught in math class that manipulating differentials like they’re just small, finite quantities, and treating derivatives like fractions is “illegal”. But it’s also very useful.

### Idea 7

Derivatives can be treated like fractions, if all functions have a single argument.

The reason is simply the chain rule. The motion of a single particle only depends on a single parameter, so the chain rule is just the same as fraction cancellation. For example,

$$\frac{dv}{dt} = \frac{d}{dt}v(x(t)) = \frac{dv}{dx} \frac{dx}{dt}$$

which show that “canceling a  $dx$ ” is valid. Similarly, you can show that

$$\frac{dy}{dx} \frac{dx}{dy} = 1$$

by considering the derivative with respect to  $x$  of the function  $x(y(x)) = x$ .

### Remark

Math students tend to get very upset about the above idea – you can read thousands of rants online from people who have spent whole days mad at it, and at physics in general. The crux of their objection is that we shouldn’t use convenient notation if it hides what’s “really” going on. But that attitude is unhelpful.

For example, the “rigorous” definition of the number 2 is  $S(1)$ , where  $S$  is the successor function. And 4 is just a shorthand for  $S(S(S(1)))$ . So if you want to do arithmetic the “right” way, you shouldn’t even write  $2 + 2 = 4$ , because that hides the true definition of the natural numbers. You should at minimum expand it out to

$$S(1) + S(1) = S(S(S(1))).$$

Or really, if you want to go all the way to the set-theoretic foundations, you should use the “real” definition of the successor function in terms of sets, where for example,

$$S(S(S(1))) = \{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}, \{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}.$$

People have actually advocated for 1<sup>st</sup> grade math to be taught this way – to a certain type of mathematician, an equation becomes more elegant, and more true, the longer it is. For them, inventing and then following many steps of elaborate logic is inherently enjoyable, even if they know it won't lead to anything they didn't already know. But in physics we have no time to luxuriate in such rigor, because we want to figure out how specific things work. The point of notation is to help us do that by suppressing mathematical clutter, not inventing more of it.

However, the mathematicians are right in one sense: this trick won't work for functions with multiple arguments. For example, for a function  $f(x(t), y(t))$ , the chain rule says

$$\frac{df}{dt} = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}$$

where there are two terms, representing the change in  $f$  from changes only in  $x$ , and only in  $y$ . Luckily, in mechanics we'll usually consider functions with one argument. We'll come back to the multivariable chain rule in **T1**.

### Example 15

Derive the work-kinetic energy theorem,  $dW = F dx$ .

### Solution

Canceling the mass from both sides, we wish to show

$$\frac{1}{2}d(v^2) = a dx.$$

To do this, note that

$$\frac{1}{2}d(v^2) = v dv = \frac{dx}{dt} dv = \frac{dv}{dt} dx = a dx$$

as desired. If you're not satisfied with this derivation, because of the bare differentials floating around, we can equivalently prove that  $F = dW/dx$ , by noting

$$\frac{dW}{dx} = mv \frac{dv}{dx} = mv \frac{dv}{dt} \frac{dt}{dx} = m \frac{dv}{dt} = F.$$

**[2] Problem 28.** Some more about power.

- (a) Use similar reasoning to derive  $P = Fv$ .
- (b) An electric train has a power line that can deliver power  $P(x)$ , where  $x$  is the distance along the track. If the train starts at rest at  $x = 0$ , find its speed at point  $x_0$  in terms of an integral of  $P(x)$ . (Hint: try to get rid of the  $dt$ 's to avoid having to think about the time-dependence.)

**Solution.** (a) First, let's use differentials. Since  $P = dW/dt$ , we have

$$dW = Fv dt.$$

Using the same reasoning as before,  $dW = md(v^2)/2 = mv dv$ , so

$$mv dv = mav dt.$$

Canceling on both sides, this simplifies to  $dv = a dt$ , which is clearly true. Alternatively, we can use derivatives directly. We have

$$P = \frac{dW}{dt} = mv \frac{dv}{dt} = mva = Fv$$

as desired.

(b) We note that

$$dW = mv dv$$

but we also have

$$dW = P dt = P \frac{dt}{dx} dx = \frac{P}{v} dx$$

where we introduced the power of  $v$  to convert  $dt$  (which we don't want to deal with) to  $dx$ . Doing some rearrangement,

$$\int mv^2 dv = \int P dx.$$

Performing the integral, we have

$$v = \left( \frac{3}{m} \int P dx \right)^{1/3}.$$

- [2] **Problem 29** (Kalda). The deceleration of a boat in water due to drag is given by a function  $a(v)$ . Given an initial velocity  $v_0$ , write the total distance the boat travels as a single integral.

**Solution.** We have

$$\int dx = \int dv \frac{dx}{dv} = \int dv \frac{dx}{dt} \frac{dt}{dv} = \int \frac{v dv}{a(v)}$$

which is a single integral in terms of the function  $a(v)$ , as desired. Putting the bounds in, the total distance is

$$\Delta x = \int_{v_0}^0 \frac{v dv}{a(v)}.$$

The signs are correct here, since both  $dv$  and  $a(v)$  are negative.

- [5] **Problem 30.** A particle in a potential well.

- Consider a particle of mass  $m$  and energy  $E$  with potential energy  $V(x)$ , which performs periodic motion. Write the period of the motion in terms of a single integral over  $x$ .
- Suppose the potential well has the form  $V(x) = V_0(x/a)^n$  for  $n > 0$ . If the period of the motion is  $T_0$  when it has amplitude  $A_0$ , find the period when the amplitude is  $A$ , by considering how the integral you found in part (a) scales with  $A$ .
- Find a special case where you can check your answer to part (b). (In fact, there are two more special cases you can check, one which requires negative  $n$  and negative  $V_0$ , and one which requires  $V(x)$  to be replaced with its absolute value.)

- (d) Using a similar method to part (a), write down an integral over  $\theta$  giving the period of a pendulum with length  $L$  in gravity  $g$ , without the small angle approximation. Using this, compute the period of the pendulum with amplitude  $\theta_0$ , up to and including order  $\theta_0^2$ .
- (e) [A] Part (d) is the kind of involved computation you might see in a graduate mechanics course. But if you think you're *really* tough, you can go one step further. Consider a mass  $m$  oscillating on a spring of spring constant  $k$  with amplitude  $A$ . Calculate its period of oscillation up to terms of order  $A^2$ , accounting for special relativity. (Hint: in relativistic dynamics, force can be defined so that  $F = dp/dt$  and  $F = -dU/dx$  still hold.)

**Solution.** (a) The statement of conservation of energy is

$$E = \frac{1}{2}mv^2 + V(x), \quad v = \sqrt{\frac{2(E - V(x))}{m}}.$$

Therefore, the period is

$$T = \int dt = \int \frac{dt}{dx} dx = \int \frac{dx}{\sqrt{2(E - V(x))/m}}.$$

To be more precise, we should put the bounds of integration back in. If the lowest and highest values of  $x$  are  $x_{\min}$  and  $x_{\max}$ , then

$$T = 2 \int_{x_{\min}}^{x_{\max}} \frac{dx}{\sqrt{2(E - V(x))/m}}$$

where the factor of two is because this is just half of the oscillation.

- (b) The particle can perform periodic motion if at  $x = \pm A$ ,  $v = 0$  so  $V_0(A/a)^n = E$ . Thus

$$T = 2 \int_{-A}^A \frac{dx}{\sqrt{2(V_0(A/a)^n - V_0(x/a)^n))/m}} \propto \int_{-A}^A \frac{dx}{\sqrt{A^n - x^n}}$$

By dimensional analysis, the integral (a function of  $A$ ) is proportional to  $A^{1-n/2}$ , so

$$T = T_0 \left( \frac{A}{A_0} \right)^{1-n/2}$$

Incidentally, you can also do this problem by dimensional analysis directly on the parameters. At first glance, this is impossible because there are too many dimensionful quantities:  $E$ ,  $m$ ,  $a$ ,  $V_0$ , and  $T$ , which permit  $5 - 3 = 2$  dimensionless groups. (Recall from an earlier problem that one can usually get a scaling relation only if there's only 1 dimensionless group.) However, the situation can be saved by noting that  $V_0$  and  $a$  only ever appear together in the combination  $V_0/a^n$ . So there are only 4 independent dimensionful parameters, and a standard dimensional analysis yields the same result.

- (c) Simple harmonic motion occurs for  $n = 2$ , and indeed here the period is independent of amplitude. (Incidentally, can you think of any potentials that aren't simple harmonic, but also have this property?)

For  $n = -1$  we have an inverse square force,  $T \propto A^{3/2}$  which is Kepler's third law. Finally with  $n = 1$  ( $V(x) = V_0|x/a|$  so periodic motion is possible), it's similar to free fall with  $x = \frac{1}{2}gt^2$ , so  $T \propto \sqrt{A}$  which is also consistent.



(d) Conservation of energy states

$$\frac{1}{2}I\omega^2 = mgL(\cos\theta - \cos\theta_0), \quad I = mL^2$$

which means

$$T = 4 \int_0^{\theta_0} \frac{d\theta}{\omega} = 4 \int_0^{\theta_0} \frac{d\theta}{\sqrt{(2g/L)(\cos\theta - \cos\theta_0)}}.$$

Now the trick is figuring out how far to expand the cosines. To zeroth order in  $\theta$  and  $\theta_0$ , the denominator is simply zero, but this is too weak of an approximation. If we expand to second order, however, we get

$$T = 4\sqrt{\frac{L}{g}} \int_0^{\theta_0} \frac{d\theta}{\sqrt{\theta_0^2 - \theta^2}} = 2\pi\sqrt{\frac{L}{g}}$$

after using a trigonometric substitution, which is the leading order result for the period. This illustrates the point that it can be nontrivial which order of approximation in one quantity (the denominator) corresponds to the same order of approximation in another (the period).

The  $O(\theta_0)$  correction to the period simply vanishes, because the period should not depend on the sign of  $\theta_0$ . Thus, we only need to compute the  $O(\theta_0^2)$  correction, which corresponds to expanding the cosine to  $O(\theta_0^4)$ . This gives

$$T = 4\sqrt{\frac{L}{g}} \int_0^{\theta_0} \frac{d\theta}{\sqrt{\theta_0^2 - \theta^2 + (\theta^4 - \theta_0^4)/12}}.$$

The scaling is clearer if we substitute  $x = \theta/\theta_0$ , giving

$$T = 4\sqrt{\frac{L}{g}} \int_0^1 \frac{dx}{\sqrt{1 - x^2 + \theta_0^2(x^4 - 1)/12}} = 4\sqrt{\frac{L}{g}} \int_0^1 \frac{dx}{\sqrt{1 - x^2}} \frac{1}{\sqrt{1 - \theta_0^2(x^2 + 1)/12}}.$$

This form makes it clear that to get the period to  $O(\theta_0^2)$ , we just need to expand the square root with the binomial theorem, giving

$$T = 4\sqrt{\frac{L}{g}} \int_0^1 \frac{dx}{\sqrt{1 - x^2}} \left( 1 + \frac{\theta_0^2}{24}(1 + x^2) \right).$$

The new term can also be integrated straightforwardly with a trigonometric substitution  $u = \sin^{-1}(x)$ , giving the final result

$$T = 2\pi\sqrt{\frac{L}{g}} \left( 1 + \frac{\theta_0^2}{16} + O(\theta_0^4) \right).$$

(e) This is a taste of the kind of problem you'll see in **R2**. It can get quite messy, but it's not too bad if you work in the right variables. First, note that since  $F = -dU/dx$ , we still have energy conservation, but with the relativistic energy expression,

$$\gamma mc^2 + \frac{1}{2}m\omega^2 x^2 = mc^2 + \frac{1}{2}m\omega^2 A^2$$

where  $\omega^2 = k/m$  as usual. Solving for  $\gamma$ , we find

$$\gamma = 1 + \frac{\omega^2}{2c^2}(A^2 - x^2).$$

Next, using the definition of  $\gamma$ , we have

$$T = 4 \int_0^A \frac{dx}{v} = \frac{4}{c} \int_0^A \frac{\gamma}{\sqrt{\gamma^2 - 1}} dx.$$

To simplify the integrand, we must use the fact that  $\gamma - 1$  is of order  $A^2$ . By carefully applying the binomial theorem, noting that  $\gamma - 1$  is the small quantity, we find

$$T = \frac{4}{c} \int_0^A \frac{c}{\omega} \frac{1}{\sqrt{A^2 - x^2}} + \frac{3}{8} \frac{\omega}{c} \sqrt{A^2 - x^2} + O(A^4) dx.$$

The first term simply recovers the nonrelativistic result  $T = 2\pi/\omega$ , and the second term is straightforward to integrate, yielding

$$T = \frac{2\pi}{\omega} \left( 1 + \frac{3}{16} \frac{\omega^2 A^2}{c^2} + O(A^4) \right).$$

We also find along the way that the dimensionless expansion parameter is  $\omega A/c$ . In other words, the relativistic corrections are small as long as the peak speed is much less than the speed of light, which makes sense.

## 5 Multiple Integrals

It's also useful to know how to set up multiple integrals. This is fairly straightforward, though technically an "advanced" topic, so we'll demonstrate it by example. For further examples, see chapter 2 of Wang and Ricardo, volume 1, or [MIT OCW 18.02](#), lectures 16, 17, 25, and 26.

### Idea 8

In most Olympiad problems, multiple integrals can be reduced to single integrals by symmetry.

### Example 16

Calculate the area of a circle of radius  $R$ .

### Solution

The area  $A$  is the integral of  $dA$ , i.e. the sum of the infinitesimal areas of pieces we break the circle into. As a first example, let's consider using Cartesian coordinates. Then the pieces will be the rectangular regions centered at  $(x, y)$  with sides  $(dx, dy)$ , which have area  $dx dy$ . The area is thus

$$A = \int dA = \int dx \int dy.$$

The only tricky thing about setting up the integral is writing down the bounds. The inner integral is done first, so its bounds depend on the value of  $x$ . Since the boundary of the circle

is  $x^2 + y^2 = R^2$ , the bounds are  $y = \pm\sqrt{R^2 - x^2}$ . Thus we have

$$A = \int_{-R}^R dx \int_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}} dy.$$

We then just do the integrals one at a time, from the inside out, like regular integrals,

$$A = \int_{-R}^R 2\sqrt{R^2 - x^2} dx = 2R^2 \int_{-1}^1 \sqrt{1 - u^2} du = 2R^2 \int_{-\pi/2}^{\pi/2} \cos^2 \theta d\theta = \pi R^2$$

where we nondimensionalized the integral by letting  $u = x/R$ , and then did the trigonometric substitution  $u = \sin \theta$ . (To do the final integral trivially, notice that the average value of  $\cos^2 \theta$  along any of its periods is  $1/2$ .)

We can also use polar coordinates. We break the circle into regions bounded by radii  $r$  and  $r + dr$ , and angles  $\theta$  and  $\theta + d\theta$ . These regions are rectangular, with side lengths of  $dr$  and  $r d\theta$ , so the area element is  $dA = r dr d\theta$ . Then we have

$$A = \int_0^R r dr \int_0^{2\pi} d\theta = 2\pi \int_0^R r dr = \pi R^2$$

which is quite a bit easier. In fact, it's so much easier that we didn't even need to use double integrals at all. We could have decomposed the circle into a bunch of thin circular shells, argued that each shell contributed area  $(2\pi r) dr$ , then integrated over them,

$$A = \int_0^R 2\pi r dr = \pi R^2.$$

In Olympiad physics, there's usually a method like this, that allows you to get the answer without explicitly writing down any multiple integrals.

### Example 17

Calculate the moment of inertia of the circle above, about the  $y$  axis, if it has total mass  $M$  and uniform density.

### Solution

The moment of inertia of a small piece of the circle is

$$dI = x^2 dm = x^2 \sigma dA = \frac{x^2 M}{\pi R^2} dA$$

where  $x^2$  appears because  $x$  is the distance to the rotation axis, and  $\sigma$  is the mass density per unit area. Using Cartesian coordinates, we have

$$I = \frac{M}{\pi R^2} \int_{-R}^R dx \int_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}} x^2 dy.$$

The inner integral is still trivial; the  $x^2$  doesn't change anything, because from the perspective of the  $dy$  integral,  $x$  is just some constant. However, the remaining integral becomes a bit nasty. In general, when this happens, we can try flipping the order of integration, giving

$$I = \frac{M}{\pi R^2} \int_{-R}^R dy \int_{-\sqrt{R^2-y^2}}^{\sqrt{R^2-y^2}} x^2 dx.$$

Unfortunately, this is also nasty. Both of these integrals can be done using trigonometric substitutions, but in this case there's a clever symmetry argument.

Notice that  $I$  is also equal to the moment of inertia about the  $x$  axis, by symmetry. So if we add them together, we get

$$2I = \int (x^2 + y^2) dm = \int r^2 dm.$$

The  $r^2$  factor has no dependence on  $\theta$  at all, so the angular integral in polar coordinates is trivial. We end up with

$$2I = \frac{M}{\pi R^2} \int_0^R 2\pi r r^2 dr = \frac{1}{2}MR^2$$

which gives an answer of  $I = MR^2/4$ , as expected.

[2] **Problem 31.** Evaluate  $I$  in the previous example using Cartesian coordinates.

**Solution.** Starting from the second expression in the example,

$$I = \frac{M}{\pi R^2} \int_{-R}^R dy \int_{-\sqrt{R^2-y^2}}^{\sqrt{R^2-y^2}} x^2 dx = \frac{M}{3\pi R^2} \int_{-R}^R 2(R^2 - y^2)^{3/2} dy.$$

Let  $y = R \sin \theta$ . Then we have

$$I = \frac{2MR^2}{3\pi} \int_{-\pi/2}^{\pi/2} \cos^4 \theta d\theta.$$

This integral can be done by repeatedly using the double angle formula,

$$\int_{-\pi/2}^{\pi/2} \cos^4 \theta d\theta = \int \left( \frac{1 + \cos(2\theta)}{2} \right)^2 d\theta = \int_{-\pi/2}^{\pi/2} \left( \frac{1}{4} + \cos(2\theta) + \frac{1}{8} + \frac{1}{8} \cos(4\theta) \right) d\theta = \frac{3}{8}.$$

This gives an answer of

$$I = \frac{MR^2}{4}.$$

[3] **Problem 32.** In this problem we'll generalize some of the ideas above to three dimensions, where we need triple integrals. Consider a ball of radius  $R$ .

- (a) In Cartesian coordinates, the volume element is  $dV = dx dy dz$ . Set up an appropriate triple integral for the volume.

- (b) The inner two integrals might look a bit nasty, but we already have essentially done them. Using the result we already know, perform the inner two integrals in a single step, and then perform the remaining integral to derive the volume of a sphere.
- (c) In cylindrical coordinates, the volume element is  $dV = r dr d\theta dz$ . Set up a triple integral for the volume, and perform it. (Hint: this can either be hard, or a trivial extension of part (b), depending on what order of integration you choose.)
- (d) In spherical coordinates, the volume element is  $dV = r^2 dr \sin \phi d\phi d\theta$ . Set up a triple integral for the volume, and perform it.
- (e) Let the ball have uniform density and total mass  $M$ . Compute its moment of inertia about the  $z$ -axis. (Hint: this can be reduced to a single integral if you use an appropriate trick.)

**Solution.** (a) By analogy to the two-dimensional case,

$$V = \int_{-R}^R dx \int_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}} dy \int_{-\sqrt{R^2-x^2-y^2}}^{\sqrt{R^2-x^2-y^2}} dz.$$

- (b) The inner two integrals just represent the area of a circle, formed by slicing the ball along a plane of constant  $x$ . Thus, the answer has to be  $\pi r^2$  where  $r$  is the radius of that circle (as we derived explicitly in the example), and in this case  $r^2 = R^2 - x^2$ . Thus, we have

$$V = \int_{-R}^R \pi(R^2 - x^2) dx = \pi R^3 \int_{-1}^1 1 - x^2 dx = \frac{4}{3} \pi R^3.$$

- (c) By analogy to the two-dimensional case,

$$V = \int_{-R}^R dz \int_0^{\sqrt{R^2-z^2}} r dr \int_0^{2\pi} d\theta.$$

Again, the inner two integrals look a bit nasty, but they represent nothing more than the area of a circle of radius  $r$ , leaving

$$V = \int_{-R}^R \pi(R^2 - z^2) dz$$

upon which the solution continues just as in part (b).

- (d) The first task is to decide what order the integrals appear in. It's probably best to have the  $dr$  integral be the outermost one, because surfaces of constant  $dr$  are spheres, which are simple; thus the final integral is just an integral over spherical slices, which we know are simple. By comparison, if the last integral were  $d\theta$  we would have hemispherical slices, while if it were  $d\phi$  we would have slices with a really weird shape. We thus have

$$V = \int_0^R r^2 dr \int_0^\pi \sin \phi d\phi \int_0^{2\pi} d\theta.$$

The inner two integrals can be done easily, giving

$$V = 4\pi \int_0^R r^2 dr = \frac{4}{3} \pi R^3.$$

(e) We are looking for

$$I = \int x^2 + y^2 dm.$$

By spherical symmetry, the integrals of  $x^2 dm$ ,  $y^2 dm$ , and  $z^2 dm$  are all equal. Thus,

$$I = \frac{2}{3} \int x^2 + y^2 + z^2 dm$$

but this integral is now easy to do because it has spherical symmetry. We have

$$I = \frac{2}{3} \frac{M}{\frac{4}{3}\pi R^3} \int_0^R 4\pi r^2 r^2 dr = \frac{2}{5} MR^2$$

as expected.

- [2] **Problem 33.** Consider a spherical cap that is formed by slicing a sphere of radius  $R$  by a plane, so that the altitude from the vertex to the base is  $h$ . Find the area of its curved surface using an appropriate integral.

**Solution.** This is a double integral, where it's best to use spherical coordinates. Recall that the volume element in spherical coordinates was  $dV = r^2 dr \sin \phi d\phi d\theta$ . Thus, the area element for a part of this sphere is  $dA = R^2 \sin \phi d\phi d\theta$ . The area integral is

$$A = R^2 \int_0^{\cos^{-1}((R-h)/R)} \sin \phi d\phi \int_0^{2\pi} d\theta = 2\pi h R.$$

After doing the trivial inner integral, this approach is just slicing the surface by  $d\phi$ . You can also equivalently solve it by slicing it in  $dz$ . In that case the integrand is a bit more complicated, but the bounds are simpler.