Review: Our zoo of functions

- polynomials

  x^2, x^3, $7x^4 - x + 2$, ...

- rational functions

  $\frac{1}{x+1}$, $\frac{x^2 - 2x - 3}{x^3 + 7}$, ...

- power functions

  x^2, $x^{1/2} = \sqrt{x}$, $x^{-1/2} = \frac{1}{\sqrt{x}}$, ...

- exponentials

  2^x, e^x, ...

- logarithms

  $\ln(x) = \log_e(x)$, $\log_2(x)$, ...

- trigonometric functions

  $\sin(x)$, $\cos(x)$, $\tan(x) = \frac{\sin(x)}{\cos(x)}$, ...

- inverse trig functions

  $\arcsin(x)$, $\arccos(x)$, $\arctan(x)$, ...

Review: Computing derivatives

Given a function $y(x)$, we learned in Calculus I that its **derivative**

$$y'(x) = \frac{\mathrm{d}y}{\mathrm{d}x} = \lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x}$$

(where $\Delta y = y(x + \Delta x) - y(x)$) has the following two important characterizations:

- $y'(x)$ is the **slope of the tangent line** of the graph of $y(x)$ at x, and
- $y'(x)$ is the **rate of change** of $y(x)$ at x.

Comment. Derivatives were introduced in the late 1600s by Newton and Leibniz who later each claimed priority in laying the foundations for calculus. Certainly both of them contributed mightily to those foundations.

Moreover, we learned simple rules to compute the derivative of functions:

- **(sum rule)** $\frac{\mathrm{d}}{\mathrm{d}x}[f(x) + g(x)] = f'(x) + g'(x)$
- **(product rule)** $\frac{\mathrm{d}}{\mathrm{d}x}[f(x)g(x)] = f'(x)g(x) + f(x)g'(x)$
- **(chain rule)** $\frac{\mathrm{d}}{\mathrm{d}x}[f(g(x))] = f'(g(x))g'(x)$

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Comment. If we write $t = g(x)$ and $y = f(t)$, then the chain rule takes the form $\frac{\mathrm{d}y}{\mathrm{d}x} = \frac{\mathrm{d}y}{\mathrm{d}t} \cdot \frac{\mathrm{d}t}{\mathrm{d}x}$.
In other words, the chain rule expresses the fact that we can treat $\frac{\mathrm{d}y}{\mathrm{d}x}$ (which initially is just a notation for $y'(x)$) as an honest fraction.

- **(basic functions)** $\frac{\mathrm{d}}{\mathrm{d}x} x^r = r x^{r-1}$,
  $\frac{\mathrm{d}}{\mathrm{d}x} e^x = e^x$, $\frac{\mathrm{d}}{\mathrm{d}x} \ln(x) = \frac{1}{x}$,
  $\frac{\mathrm{d}}{\mathrm{d}x}\sin(x) = \cos(x)$, $\frac{\mathrm{d}}{\mathrm{d}x}\cos(x) = -\sin(x)$

These rules are enough to compute the derivative of any function that we can build from the basic functions using algebraic operations and composition. On the other hand, reversing the operation of differentiation (i.e. computing antiderivatives) is much more difficult.

In particular, there exist simple functions (such as e^{x^2}) whose antiderivative cannot be expressed in terms of the basic functions above.

Example 1. Derive the **quotient rule** from the rules above.

Solution. We write $\frac{f(x)}{g(x)} = f(x) \cdot \frac{1}{g(x)}$ and apply the product rule to get

$$\frac{\mathrm{d}}{\mathrm{d}x} f(x) \cdot \frac{1}{g(x)} = f'(x)\frac{1}{g(x)} + f(x)\frac{\mathrm{d}}{\mathrm{d}x}\frac{1}{g(x)}.$$

By the chain rule combined with $\frac{\mathrm{d}}{\mathrm{d}x}\frac{1}{x} = -\frac{1}{x^2}$, we have $\frac{\mathrm{d}}{\mathrm{d}x}\frac{1}{g(x)} = -\frac{1}{g(x)^2} g'(x)$. Using this in the previous formula,

$$\frac{\mathrm{d}}{\mathrm{d}x} f(x) \cdot \frac{1}{g(x)} = f'(x)\frac{1}{g(x)} - f(x)\frac{1}{g(x)^2} g'(x) = \frac{f'(x)}{g(x)} - \frac{f(x)g'(x)}{g(x)^2}.$$

Putting the final two fractions on a common denominator, we obtain the familiar quotient rule

$$\frac{\mathrm{d}}{\mathrm{d}x}\frac{f(x)}{g(x)} = \frac{f'(x)g(x) - f(x)g'(x)}{g(x)^2}.$$

Example 2. Compute the following derivatives:

(a) $\frac{\mathrm{d}}{\mathrm{d}x}(5x^3 + 7x^2 + 2)$

(b) $\frac{\mathrm{d}}{\mathrm{d}x}\sin(5x^3 + 7x^2 + 2)$

(c) $\frac{\mathrm{d}}{\mathrm{d}x}(x^3 + 2x)\sin(5x^3 + 7x^2 + 2)$

Solution.

(a) $\frac{\mathrm{d}}{\mathrm{d}x}(5x^3 + 7x^2 + 2) = 15x^2 + 14x$

(b) $\frac{\mathrm{d}}{\mathrm{d}x}\sin(5x^3 + 7x^2 + 2) = (15x^2 + 14x)\cos(5x^3 + 7x^2 + 2)$

(c) $\frac{\mathrm{d}}{\mathrm{d}x}(x^3 + 2x)\sin(5x^3 + 7x^2 + 2)$
$= (3x^2 + 2)\sin(5x^3 + 7x^2 + 2) + (x^3 + 2x)(15x^2 + 14x)\cos(5x^3 + 7x^2 + 2)$

Example 3. Find $\frac{\mathrm{d}}{\mathrm{d}x}\tan(x)$ using $\tan(x) = \frac{\sin(x)}{\cos(x)}$ and the quotient rule.

Example 4. What is $\frac{\mathrm{d}}{\mathrm{d}x}\ln(x)$?

Why? Can you explain why this is the case?
(One way to see this is to recall that $e^{\ln(x)} = x$ and to differentiate both sides. What do you conclude?)

Review: Integration and areas

If $f(x) \geqslant 0$ for $x \in [a, b]$, then

$$\int_a^b f(x) \mathrm{d}x$$

is defined as the area enclosed by the graph of $f(x)$ and the x-axis between $x = a$ and $x = b$.

Can you explain how the integral $\int_a^b f(x)\, \mathrm{d}x$ is constructed from sums $\sum f(x) \Delta x$?
(Here, we are summing over rectangles of width Δx between a and b; at position x their height is roughly $f(x)$.)

Comment. Σ is a capital sigma, and just means "sum". Don't worry about it for now. We will see it again later.

Review: Fundamental Theorem of Calculus

The Fundamental Theorem of Calculus connects the two operations

(a) differentiation and

(b) integration,

which, at first glance, look like they might be of a rather different nature. Roughly, it shows that these two operations are inverses of each other.

Theorem 5. (Fundamental Theorem of Calculus, part 2)

$$\int_a^b f(x)\, \mathrm{d}x = F(b) - F(a),$$

if $F(x)$ is an antiderivative of $f(x)$.

The "first part" of the Fundamental Theorem of Calculus is the statement that

$$\frac{\mathrm{d}}{\mathrm{d}x} \int_a^x f(t)\, \mathrm{d}t = f(x).$$

Modulo details (such as whether $f(x)$ is continuous or differentiable), can you conclude this "first part" from the "second part" above?
(Hint: in the "second part", replace b by x and differentiate both sides with respect to x.)

Example 6. Compute $\displaystyle\int_1^2 x \mathrm{d}x$ in two ways: first, making a sketch and using the definition as an area; then, using the Fundamental Theorem of Calculus.

Solution.

(a) Make a sketch! The area in question consists of a 1×1 square (area 1) with exactly half a 1×1 square (area $1/2$) on top. Hence, the total area is $1 + \frac{1}{2} = \frac{3}{2}$.

(b) $\displaystyle\int_1^2 x \mathrm{d}x = \left[\frac{1}{2} x^2\right]_1^2 = \frac{1}{2} \cdot 2^2 - \frac{1}{2} \cdot 1^2 = \frac{4}{2} - \frac{1}{2} = \frac{3}{2}$

Example 7. $\displaystyle\int_0^\pi \sin(x)\, \mathrm{d}x =$

Why is $\displaystyle\int_0^{2\pi} \sin(x)\, \mathrm{d}x = 0$? Explain geometrically in terms of areas.

Review: Antiderivatives (or indefinite integrals)

Definition 8. If $f(x) = F'(x)$ then we say that $F(x)$ is an **antiderivative** of $f(x)$.

We write: $\int f(x)\mathrm{d}x = F(x) + C$

This is also called the **indefinite integral** of $f(x)$.

Comment. The notation using the integral sign makes sense because of the Fundamental Theorem of Calculus.

Example 9. $\int x\,\mathrm{d}x = \frac{1}{2}x^2 + C$

Example 10. $\int x^a\,\mathrm{d}x = \frac{1}{a+1}x^{a+1} + C$

Comment. Note that the case $a = -1$ is special. What happens in that case?

Example 11. $\int \frac{1-x}{x^3}\,\mathrm{d}x = \int (x^{-3} - x^{-2})\mathrm{d}x = -\frac{1}{2}x^{-2} + x^{-1} + C$

Example 12. $\int x\sqrt{x}\,\mathrm{d}x = \int x^{3/2}\mathrm{d}x = \frac{2}{5}x^{5/2} + C$

Substitution

The following is a first example for which the antiderivative is not so readily obtained by reversing basic rules of differentiation.

Example 13. Determine $\int x\sqrt{x^2+1}\mathrm{d}x$ by substituting $u = x^2 + 1$.

Solution. We need to substitute all occurences of x in the integral, including the $\mathrm{d}x$.

To substitute the latter, note that if $u = x^2 + 1$ then the derivative with respect to x is

$$\frac{\mathrm{d}u}{\mathrm{d}x} = 2x.$$

Solving for $\mathrm{d}x$, we find $\mathrm{d}x = \frac{1}{2x}\mathrm{d}u$.

Substituting in the integral, we therefore find

$$\int x\sqrt{x^2+1}\mathrm{d}x = \int x\sqrt{u}\,\frac{1}{2x}\mathrm{d}u = \frac{1}{2}\int \sqrt{u}\,\mathrm{d}u = \frac{1}{2}\cdot\frac{2}{3}u^{3/2} + C = \frac{1}{3}(x^2+1)^{3/2} + C.$$

Note how in the final step, we substituted back $u = x^2 + 1$ to get the desired antiderivative in terms of x.

Comment. We could have been slightly more efficient by directly substituting $x\,\mathrm{d}x = \frac{1}{2}\mathrm{d}u$.

Substitution, cont'd

In general, finding the right substitution can be tricky and there are no straightforward rules that work for every integral. However, for our integrals there is usually a natural choice.

On the other hand, there is often more than one way to substitute successfully (see next example).

Example 14. (cont'd) Determine $\int x\sqrt{x^2+1}\mathrm{d}x$

(a) by substituting $u = x^2+1$, and

(b) by substituting $u = \sqrt{x^2+1}$.

(c) Explain why the substitution $u = x^2+1$ is particularly natural.

Solution.

(a) Since $u = x^2+1$, we have $\frac{\mathrm{d}u}{\mathrm{d}x} = 2x$ so that $x\mathrm{d}x = \frac{1}{2}\mathrm{d}u$.
The integral therefore becomes

$$\int x\sqrt{x^2+1}\mathrm{d}x = \int \frac{1}{2}\sqrt{u}\,\mathrm{d}u = \frac{1}{2}\cdot\frac{2}{3}u^{3/2} + C = \frac{1}{3}(x^2+1)^{3/2} + C.$$

(b) Since $u = \sqrt{x^2+1}$, we have $\frac{\mathrm{d}u}{\mathrm{d}x} = \frac{1}{2\sqrt{x^2+1}}\cdot 2x = \frac{x}{u}$ so that $x\mathrm{d}x = u\mathrm{d}u$.
The integral therefore becomes

$$\int x\sqrt{x^2+1}\mathrm{d}x = \int u\cdot u\,\mathrm{d}u = \int u^2\,\mathrm{d}u = \frac{1}{3}u^3 + C = \frac{1}{3}(x^2+1)^{3/2} + C.$$

(c) The $\sqrt{x^2+1}$ in the integrand will become $\sqrt{u}$ (of course) while the remaining x in the integrand is (up to a factor of 2) exactly the derivative of x^2+1 (and so will disappear when we bring in $\mathrm{d}u$ to replace $\mathrm{d}x$). With a bit of practice, this allows us to immediately see that our substitution will be a success.

Substitution in definite integrals

If we want to apply substitution in a definite integral like $\int_a^b f(x)\mathrm{d}x$, we have two options:

(a) We can first compute the indefinite integral $\int f(x)\mathrm{d}x$ using substitution.

If the result is $F(x) + C$, then $\int_a^b f(x)\mathrm{d}x = F(b) - F(a)$.

(b) Or, we can substitute the limits a and b as well to get a new definite integral $\int_c^d g(u)\mathrm{d}u$.

Often you can choose either approach. But for certain problems it might not be possible to compute the indefinite integral explicitly (so the first approach won't work), yet it can be useful obtain a substituted new integral using the second approach.

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Example 15. Determine $\int_0^1 x\sqrt{x^2+1}\mathrm{d}x$.

Solution. Let us illustrate both of the two approaches just mentioned:

(a) In the previous example, we already worked out that $\int x\sqrt{x^2+1}\mathrm{d}x = \frac{1}{3}(x^2+1)^{3/2} + C$. It follows that

$$\int_0^1 x\sqrt{x^2+1}\mathrm{d}x = \left[\frac{1}{3}(x^2+1)^{3/2}\right]_0^1 = \frac{1}{3}2^{3/2} - \frac{1}{3}.$$

(b) As in the previous example, we will substitute $u = x^2+1$. Since $\frac{\mathrm{d}u}{\mathrm{d}x} = 2x$, we get $x\mathrm{d}x = \frac{1}{2}\mathrm{d}u$. Moreover, if $x=0$ (lower limit) then $u = x^2+1 = 0^2+1 = 1$. And if $x=1$ (upper limit) then $u = x^2+1 = 1^2+1 = 2$. The definite integral therefore becomes

$$\int_0^1 x\sqrt{x^2+1}\mathrm{d}x \;=\; \int_1^2 \frac{1}{2}\sqrt{u}\,\mathrm{d}u = \left[\frac{1}{3}u^{3/2}\right]_1^2 = \frac{1}{3}2^{3/2} - \frac{1}{3}.$$

Comment. While it looks like the first approach was much quicker, that's only because we had already computed the indefinite integral in the previous example. In general, if we haven't already done so, the second approach is a bit more direct (but requires us to pay attention to the limits of the integral).

Review 16. $\int \frac{1}{x}\mathrm{d}x = \ln|x| + C$

To verify, use $\ln|x| = \begin{cases} \ln(x), & \text{if } x>0, \\ \ln(-x), & \text{if } x<0, \end{cases}$ to differentiate the right-hand side.

Example 17. Determine $\int_0^\pi \frac{\sin(t)}{2-\cos(t)}\mathrm{d}t$.

Here, a very natural substitution is $u = 2-\cos(t)$.

(Note how we can already anticipate that the derivative will nicely take care of the $\sin(t)$ in the integrand.)

Solution. We again have the choice of either substituting without limits or with limits:

(a) We substitute $u = 2-\cos(t)$. Since $\frac{\mathrm{d}u}{\mathrm{d}t} = \sin(t)$, we get $\sin(t)\mathrm{d}t = \mathrm{d}u$. Hence,

$$\int \frac{\sin(t)}{2-\cos(t)}\mathrm{d}t = \int \frac{1}{u}\mathrm{d}u = \ln|u| + C = \ln|2-\cos(t)| + C.$$

Hence (by the Fundamental Theorem of Calculus)

$$\int_0^\pi \frac{\sin(t)}{2-\cos(t)}\mathrm{d}t = \Big[\ln|2-\cos(t)|\Big]_0^\pi = \ln(3).$$

(b) Alternatively, once we feel comfortable with integration, we can do this substitution in a single step by also adjusting the boundaries. When $t=0$ we have $u = 2-\cos(0) = 1$, and when $t=\pi$ we have $u = 2-\cos(\pi) = 3$. Therefore,

$$\int_0^\pi \frac{\sin(t)}{2-\cos(t)}\mathrm{d}t = \int_1^3 \frac{1}{u}\mathrm{d}u = \Big[\ln|u|\Big]_1^3 = \ln(3).$$

Extra practice

Example 18. Determine $\int x^3\sqrt{x^2+1}\mathrm{d}x$.

Solution. We substitute $u=x^2+1$. Since $\frac{\mathrm{d}u}{\mathrm{d}x}=2x$, we have $x\mathrm{d}x=\frac{1}{2}\mathrm{d}u$.
Note that there will be x^2 left into the integral which we replace with $x^2=u-1$.
The integral therefore becomes:

$$\begin{aligned}\int x^3\sqrt{x^2+1}\mathrm{d}x &= \int \frac{1}{2}x^2\sqrt{u}\,\mathrm{d}u = \int \frac{1}{2}(u-1)\sqrt{u}\,\mathrm{d}\\ &= \frac{1}{2}\int (u^{3/2}-u^{1/2})\,\mathrm{d}u = \frac{1}{5}u^{5/2}-\frac{1}{3}u^{3/2}+C\\ &= \frac{1}{5}(x^2+1)^{5/2}-\frac{1}{3}(x^2+1)^{3/2}+C\end{aligned}$$

Comment. If you prefer, the final answer could be rewritten as $\frac{1}{15}(x^2+1)^{3/2}(3x^2-2)+C$.

Example 19. $\int \frac{\mathrm{d}x}{x\ln(x)}=$

First, use the substitution $u=\ln(x)$. (Can you already see why this is a good choice?)

Then, for practice, use $u=\frac{1}{\ln(x)}$ and see if you can get the same final answer.

(For more complicated integrals, finding the "best" substitution is quite an art form. For the integrals we are concerned with, there is always a natural choice.)

Example 20. $\int_2^4 \frac{\mathrm{d}x}{x\ln(x)}=$

To reduce work, use the previous problem and the fundamental theorem.

Example 21. $\int x\sin(x^2+3)\,\mathrm{d}x=$

Example 22. $\int \frac{1}{x^2}\cos\left(\frac{1}{x}\right)\mathrm{d}x=$

Example 23. $\int 3x^5\sqrt{x^3+1}\,\mathrm{d}x=$

First, use the substitution $u=x^3+1$ (that's the most natural choice).

Then, for practice, use $u=\sqrt{x^3+1}$ and see if you can get the same final answer.

Notes for Lecture 3

Mon, 8/26/2024

Review. There will be a first quiz in lab on Thursday. One of the two problems will be to compute an integral like the following by substitution:

$$\int \cos^5(3t)\sin(3t)\mathrm{d}t$$

Example 24.

(a) Determine $\displaystyle\int_0^\pi \frac{\sin(t)}{2-\cos(t)}\mathrm{d}t$.

(b) Determine $\displaystyle\int_0^\pi \frac{\sin^3(t)}{2-\cos(t)}\mathrm{d}t$.

Solution.

(a) **(again)** We substitute $u=2-\cos(t)$. When $t=0$ we have $u=2-\cos(0)=1$, and when $t=\pi$ we have $u=2-\cos(\pi)=3$. Therefore,

$$\int_0^\pi \frac{\sin(t)}{2-\cos(t)}\mathrm{d}t=\int_1^3 \frac{1}{u}\mathrm{d}u=\Big[\ln|u|\Big]_1^3=\ln(3).$$

(b) We substitute $u=2-\cos(t)$ again. When $t=0$ we have $u=2-\cos(0)=1$, and when $t=\pi$ we have $u=2-\cos(\pi)=3$. This time, there will be $\sin^2(t)$ left over in the integral so we need to rewrite this in terms of u.

Note that $\cos(t)=2-u$. (At this point, we could solve for t to get $t=\arccos(2-u)$ and use this to substitute away any remaining t. However, we would get $\sin^2(t)=\sin^2(\arccos(2-u))$ which is not pleasant and would have to be simplified. We get this simplification for free by proceeding slightly differently.) Recall that $\cos^2(t)+\sin^2(t)=1$ so that $\sin^2(t)=1-\cos^2(t)=1-(2-u)^2=-u^2+4u-3$. Therefore,

$$\int_0^\pi \frac{\sin^3(t)}{2-\cos(t)}\mathrm{d}t=\int_1^3 \frac{\sin^2(t)}{u}\mathrm{d}u=\int_1^3 \frac{-u^2+4u-3}{u}\mathrm{d}u=\int_1^3\left(-u+4-\frac{3}{u}\right)\mathrm{d}u=\ldots=4-3\ln(3).$$

Areas enclosed by curves

Theorem 25. The area enclosed by the curves $y=f(x)$ and $y=g(x)$, between $x=a$ and $x=b$, is given by

$$\int_a^b [f(x)-g(x)]\,\mathrm{d}x$$

provided that $f(x)\geqslant g(x)$ (for all $x\in[a,b]$).

[Note that the area is always $\int_a^b|f(x)-g(x)|\,\mathrm{d}x$ but to work with the absolute value, we need to break the problem into subcases according to whether $f(x)-g(x)\geqslant 0$ or $f(x)-g(x)\leqslant 0$.]

Example 26. What is the area enclosed by the curves $y=\cos(x)$, $y=1$, $x=0$, $x=2\pi$?

First, write down an integral and compute its value, then look at your sketch (always make a quick sketch!) and confirm that your answer makes rough sense.

Solution. Note that $y=1$ describes a horizontal line while $x=0$ and $x=2\pi$ are two vertical lines. For our area, $y=1$ lies above $y=\cos(x)$. Therefore, the area in question is

$$\int_0^{2\pi}(1-\cos(x))\mathrm{d}x=\Big[x-\sin(x)\Big]_0^{2\pi}=(2\pi-\sin(2\pi))-(0-\sin(0))=2\pi.$$

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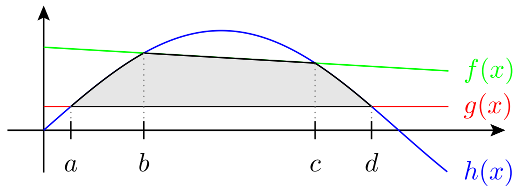
Example 27. Consider the plot below. What is the area enclosed by the curves $y=f(x)$, $y=g(x)$ and $y=h(x)$?



Solution. We split up the area into three smaller regions in which we can apply Theorem 25. The area is

$$\int_a^b [h(x)-g(x)]\mathrm{d}x + \int_b^c [f(x)-g(x)]\mathrm{d}x + \int_c^d [h(x)-g(x)]\mathrm{d}x.$$

Comment. In this case, we can alternatively (and equivalently) write the area as the difference

$$\int_a^d [h(x)-g(x)]\mathrm{d}x - \int_b^c [h(x)-f(x)]\mathrm{d}x.$$

Example 28. What is the area enclosed by the curves $y=2-x^2$, $y=-x$?

(a) First, make a sketch!

(b) Find intersections of the curves.

(c) Write down the integral for the area of interest.

(d) Evaluate the integral.

Solution.

(a) Do it! This should always be our first step.

(b) Since the equations for both curves are of the form $y=\ldots$, we can find the (x coordinates of the) intersections by setting the right-hand sides of the equations equal:

$$2-x^2=-x \quad \Longrightarrow \quad x^2-x-2=0 \quad \Longrightarrow \quad x=-1,2$$

For the final step, we solved the quadratic equation (for instance, using the quadratic formula).

[It's not needed for the remaining parts, but we can get the corresponding y-coordinates from either $y=2-x^2$ or $y=-x$. The latter is simpler and we find that the two intersections are $(-1,1)$ and $(2,-2)$.]

(c) This tells us (look at sketch!) that our area extends from $x=-1$ to $x=2$ and that the curve $y=2-x^2$ is the upper boundary while $y=-x$ is the lower boundary. Therefore, the area is

$$\int_{-1}^2 ((2-x^2)-(-x))\mathrm{d}x.$$

(d) We compute the area as

$$\int_{-1}^2 ((2-x^2)-(-x))\mathrm{d}x = \int_{-1}^2 (2+x-x^2)\mathrm{d}x = \left[2x+\frac{1}{2}x^2-\frac{1}{3}x^3\right]_{-1}^2 = \ldots = \frac{9}{2}.$$

.

Example 29. What is the area enclosed by the curves $y=3-x^2$, $y=2$, $y=-1$?

First, make a sketch like we did in class!

For this problem, we then have a choice of whether we cut up our area into tiny vertical rectangles (with width $\mathrm{d}x$) or into tiny horizontal rectangles (with width $\mathrm{d}y$). Below, we do both. Of course, the final answer will be the same.

Solution. (vertical slicing) We first need to find the intersections of the parabola $y=3-x^2$ with each of $y=2$ and $y=-1$.

- $y=3-x^2$ and $y=2$: solving $3-x^2=2$, we get $x^2=1$ and so $x=\pm 1$.
- $y=3-x^2$ and $y=-1$: solving $3-x^2=-1$, we get $x^2=4$ and so $x=\pm 2$.

The area is therefore given by the following three integrals:

$$\int_{-2}^{-1}((3-x^2)-(-1))\mathrm{d}x+\int_{-1}^{1}(2-(-1))\mathrm{d}x+\int_{1}^{2}((3-x^2)-(-1))\mathrm{d}x$$

You might notice that the first and last integral must be equal, while the second integral is just computing the area of a rectangle of height $2-(-1)=3$ and width $1-(-1)=2$ (and so its area is $3\cdot 2=6$).

Whether or not you use any simplifications, the above integrals evaluate to $\frac{5}{3}+6+\frac{5}{3}=\frac{28}{3}$ (do it!).

Solution. (horizontal slicing) This time we don't need to compute the intersections because the area (see sketch!) clearly extends from $y=-1$ to $y=2$.

Since we are working in y-direction, we rewrite $y=3-x^2$ as $x^2=3-y$ or $x=\pm\sqrt{3-y}$ (note that $x=\sqrt{3-y}$ describes the right half, while $x=-\sqrt{3-y}$ describes the left half).

So the horizontal slice has length $\sqrt{3-y}-(-\sqrt{3-y})=2\sqrt{3-y}$. Accordingly, the total area is

$$\int_{-1}^{2}(\sqrt{3-y}-(-\sqrt{3-y}))\mathrm{d}y=2\int_{-1}^{2}\sqrt{3-y}\,\mathrm{d}y=2\left[-\frac{2}{3}(3-y)^{3/2}\right]_{-1}^{2}=-\frac{4}{3}(1-4^{3/2})=-\frac{4}{3}(1-8)=\frac{28}{3}.$$

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Volumes using cross-sections

We have computed areas of certain regions by cutting them into tiny (typically vertical) pieces of width $\mathrm{d}x$ and some height $h(x)$. If the region extends from $x=a$ to $x=b$, then the total area is the sum of the areas of these pieces (each has area $h(x)\mathrm{d}x$) and therefore given by

$$\text{area} = \int_a^b h(x)\mathrm{d}x.$$

We now use the same idea to compute volumes:

Please have a look at the Section 6.1 in the book for all the pretty pictures and detailed explanations. Below is just a summary which probably doesn't make too much sense unless you have been in class or have read through the beginning of Section 6.1.

- The volume of a cylindrical solid is its base area times its height.
- The idea for computing the volume of more general solids is to cut it into little slices that are approximately cylindrical.
- Suppose that the slice at position x has cross-sectional area $A(x)$. If we are slicing with a width of $\mathrm{d}x$, then this slice has roughly volume $A(x)\mathrm{d}x$.
- Summing the volumes of all these slices leads to the follwing formula of the volume of the general solid:

$$\text{vol} = \int_a^b A(x)\mathrm{d}x$$

Note: It is usually up to us to introduce coordinates for the position x. The formula above assumes that our solid extends from $x=a$ to $x=b$ in these coordinates.

Example 30. Derive the formula for the volume of a pyramid of height h whose base is a square with sides of length a.

You might remember that the volume is $\frac{1}{3}a^2h$ but the point of this example is that we can actually find this formula without knowing it by slicing the pyramid (the easiest way to slice is horizontally, so that each cross-section is again just a square).

Solution. We cut the pyramid into cross-sections parallel to its base. Let x, between 0 and h, denote how far we have gone from the tip $(x=0)$ down to the base of the pyramid $(x=h)$. Then, at x, the cross-section is a square with side length $a\frac{x}{h}$ (make a sketch!). This cross-section has area $A(x)=\left(\frac{a}{h}x\right)^2$. Therefore, the volume is

$$\text{vol} = \int_0^h A(x)\mathrm{d}x = \int_0^h \left(\frac{a}{h}x\right)^2 \mathrm{d}x = \frac{a^2}{h^2}\int_0^h x^2\mathrm{d}x = \frac{a^2}{h^2}\left[\frac{1}{3}x^3\right]_0^h = \frac{a^2}{h^2}\cdot\left(\frac{1}{3}h^3 - 0\right) = \frac{1}{3}a^2h.$$

Comment. Introducing the extra variable x can be done in different ways and it requires some practice to make the easiest choice. For instance, if we had let x, again between 0 and h, denote how far we have gone from the base $(x=0)$ to the tip of the pyramid $(x=h)$, then, at x, the cross-section is a square with side length $a\frac{x-h}{h}$. We would get the same in the end but with a little bit more algebra.

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Solids of revolution

Consider a region (for instance, the region enclosed by a bunch of curves). A solid of revolution is what we obtain when revolving this region about a given line.

Again, Section 6.1 in the book contains lots of helpful illustrations.

- Suppose the region is the area between a curve $R(x)$ and the x-axis, between $x=a$ and $x=b$.
- Further, suppose that we revolve this region about the x-axis. Then, slicing vertically, the cross-sections are disks (circles with the interior) with radius $R(x)$ (so that the cross-sectional area is $A(x)=\pi R(x)^2$).
- Hence, the volume of the resulting solid is

$$\mathrm{vol} = \int_a^b A(x)\mathrm{d}x = \int_a^b \pi R(x)^2\,\mathrm{d}x.$$

Example 31. Consider the region enclosed by the curves $y=\sqrt{x}$, $y=0$, $x=1$, $x=4$. If we revolve this region about the x-axis, what is the volume of the resulting solid?

Solution. Make a sketch! The solid should look roughly like a solid coffee mug (no room for coffee) without handles.

The cross-section at x is a disk with radius $R(x)=\sqrt{x}$ and so has area $\pi R(x)^2=\pi x$. If we give this disk a thickness of $\mathrm{d}x$, then its volume is $\pi R(x)^2\,\mathrm{d}x=\pi x\mathrm{d}x$. The total volume is

$$\mathrm{vol} = \int_1^4 \pi R(x)^2\,\mathrm{d}x = \int_1^4 \pi x\,\mathrm{d}x = \pi\left[\frac{1}{2}x^2\right]_1^4 = \pi\left(8-\frac{1}{2}\right) = \frac{15}{2}\pi.$$

Example 32. Consider the region enclosed by the curves $y=\sqrt{x}$, $y=1$, $x=1$, $x=4$. If we revolve this region about the line $y=1$, what is the volume of the resulting solid?

Solution. Again, make a sketch! This solid should look roughly like a bullet.

The cross-section at x now is a disk with radius $R(x)=\sqrt{x}-1$ and so has area $\pi R(x)^2=\pi(\sqrt{x}-1)^2$. If we give this disk a thickness of $\mathrm{d}x$, then its volume is $\pi R(x)^2\,\mathrm{d}x=\pi x\mathrm{d}x$. The total volume is

$$\mathrm{vol} = \int_1^4 \pi R(x)^2\mathrm{d}x = \int_1^4 \pi(\sqrt{x}-1)^2\,\mathrm{d}x = \int_1^4 \pi(x-2\sqrt{x}+1)\,\mathrm{d}x = \pi\left[\frac{1}{2}x^2-\frac{4}{3}x^{3/2}+x\right]_1^4 = \pi\left(\frac{4}{3}-\frac{1}{6}\right) = \frac{7}{6}\pi.$$

Example 33. Consider (again) the region enclosed by the curves $y=\sqrt{x}$, $y=1$, $x=1$, $x=4$. If we revolve this region about the x-axis, what is the volume of the resulting solid?

The solid should look roughly like the coffee mug from Example 31 with a cylindrical hole drilled out.

What do the cross-sections look like now?

Your final answer should be $\frac{9}{2}\pi$.

Solution. The solid should look roughly like the coffee mug from Example 31 with a cylindrical hole drilled out.

The cross-section at x now is a **washer** with outer radius $R(x)=\sqrt{x}$ and inner radius $r(x)=1$ so that its area is $\pi R(x)^2-\pi r(x)^2=\pi x-\pi=\pi(x-1)$. If we give this washer a thickness of $\mathrm{d}x$, then its volume is $\pi(x-1)\mathrm{d}x$. The total volume is

$$\mathrm{vol} = \int_1^4 \pi(x-1)\,\mathrm{d}x = \pi\left[\frac{1}{2}x^2-x\right]_1^4 = \pi\left(4-\left(-\frac{1}{2}\right)\right) = \frac{9}{2}\pi.$$

Comment. In this simple case, we could also obtain the final answer from Example 31 by simply subtracting the volume of the cylinder (base area $\pi\cdot 1^2$ times height $4-1=3$ gives a volume of 3π) that is “drilled out”.

Volumes using cylindrical shells

See Section 6.2 in our book for nice illustrations of cylindrical shells!

Example 34. Consider the region bounded by the curves $y = x^2$, $y = 0$ and $x = 2$. Determine the volume of the solid generated by revolving this region about the y-axis

(a) using horizontal cross-sections of the region (turning into washers), and

(b) using vertical cross-sections of the region (turning into **cylindrical shells**).

Solution. First, make a sketch as we did in class!

(a) Our region extends from $y = 0$ to $y = 4$. The cross-section at y (a line which extends from $x = \sqrt{y}$ to $x = 2$) turns into a washer with outer radius $R(y) = 2$ and inner radius $r(y) = \sqrt{y}$, which has area $\pi R(y)^2 - \pi r(y)^2 = \pi(4 - y)$. If we give this disk a thickness of $\mathrm{d}y$, then its volume is $\pi(4 - y)\mathrm{d}y$. The total volume is

$$\mathrm{vol} = \int_0^4 \pi(4 - y)\,\mathrm{d}y = \pi\left[4y - \frac{1}{2}y^2\right]_0^4 = 8\pi.$$

(b) Our region extends from $x = 0$ to $x = 2$. The cross-section at x (a line which extends from $y = 0$ to $y = x^2$) turns into a cylindrical shell with radius $r(x) = x$ and height $h(x) = x^2$ and so has area $2\pi r(x) \cdot h(x) = 2\pi x^3$. If we give this shell a thickness of $\mathrm{d}x$, then its volume is $2\pi x^3 \mathrm{d}x$. The total volume is

$$\mathrm{vol} = \int_0^2 2\pi x^3\,\mathrm{d}x = 2\pi\left[\frac{1}{4}x^4\right]_0^2 = 8\pi.$$

The following is a similar but slightly beefed up example.

Example 35. Consider the region bounded by the curves $y = x^2$, $y = 1$ and $x = 2$. Determine the volume of the solid generated by revolving this region about the line $x = -1$.

(a) using horizontal cross-sections of the region (turning into disks), and

(b) using vertical cross-sections of the region (turning into cylindrical shells).

Solution. As always, start with a sketch! Note that $y = 1$ is now describing the bottom: the bottom-left corner of the region is $(1, 1)$, the bottom-right corner is $(2, 1)$, and the top-right corner is $(2, 4)$.

(a) Our region extends from $y = 1$ to $y = 4$. The cross-section at y (a line which extends from $x = \sqrt{y}$ to $x = 2$) turns into a washer with outer radius $R(y) = 2 - (-1) = 3$ and inner radius $r(y) = \sqrt{y} - (-1) = \sqrt{y} + 1$, which has area $\pi R(y)^2 - \pi r(y)^2 = 9\pi - \pi(\sqrt{y} + 1)^2 = \pi(8 - 2\sqrt{y} - y)$. If we give this disk a thickness of $\mathrm{d}y$, then its volume is $\pi(8 - 2\sqrt{y} - y)\mathrm{d}y$. The total volume is

$$\mathrm{vol} = \int_1^4 \pi(8 - 2\sqrt{y} - y)\,\mathrm{d}y = \pi\left[8y - \frac{4}{3}y^{3/2} - \frac{1}{2}y^2\right]_1^4 = \pi\left(\frac{40}{3} - \frac{37}{6}\right) = \frac{43}{6}\pi.$$

(b) Our region extends from $x = 1$ to $x = 2$. The cross-section at x (a line which extends from $y = 1$ to $y = x^2$) turns into a cylindrical shell with radius $r(x) = x - (-1) = x + 1$ and height $h(x) = x^2 - 1$ and so has area $2\pi r(x) \cdot h(x) = 2\pi(x + 1)(x^2 - 1)$. If we give this shell a thickness of $\mathrm{d}x$, then its volume is $2\pi(x + 1)(x^2 - 1)\mathrm{d}x$. The total volume is

$$\mathrm{vol} = \int_1^2 2\pi(x + 1)(x^2 - 1)\,\mathrm{d}x = \int_1^2 2\pi(x^3 + x^2 - x - 1)\,\mathrm{d}x = 2\pi\left[\frac{1}{4}x^4 + \frac{1}{3}x^3 - \frac{1}{2}x^2 - x\right]_1^2 = \frac{43}{6}\pi.$$

Example 36. (extra) Consider the region enclosed by the curves

$$y=\sqrt{x}, \quad y=0, \quad x=0, \quad x=4.$$

Determine the volume of the solid generated by revolving this region about the x-axis

(a) using vertical cross-sections of the region, and

(b) using horizontal cross-sections of the region.

Solution. As always, start with a sketch!

(a) The volume is

$$\int_0^4 \pi(\sqrt{x})^2\,\mathrm{d}x=\pi\int_0^4 x\,\mathrm{d}x=\pi\left[\frac{1}{2}x^2\right]_0^4=8\pi.$$

(b) We operate between $y=0$ and $y=\sqrt{4}=2$. A slice at height y has width $4-y^2$ (note that $y=\sqrt{x}$ implies $x=y^2$). Giving this slice a thickness of $\mathrm{d}y$ and revolving about the x-axis, we obtain a cylindrical shell with approximate volume

$$(\text{circumference})\times(\text{width})\times(\text{thickness})=(2\pi y)(4-y^2)\,\mathrm{d}y.$$

"Summing" all these volumes, we get

$$\int_0^2 2\pi y(4-y^2)\,\mathrm{d}y=2\pi\left[2y^2-\frac{1}{4}y^4\right]_0^2=2\pi(8-4)=8\pi.$$

Sure enough, the volume is exactly what we calculated before.

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Review. Which equation describes the circle of radius r centered at the origin?

Solution. The circle consists of all points (x, y) that satisfy $x^2 + y^2 = r^2$.
This is just the Pythagorean theorem (make a sketch to make sure this is clear to you).

Example 37. We wish to compute the volume of a ball of radius r.

(a) Which region can we revolve to obtain a ball as our solid of revolution?

(b) Setup the appropriate integral for the volume and evaluate it.

For practice, you can compute it using disks/washers as well as using cylindrical shells.

Solution.

(a) We can revolve a half-circle to end up with a ball. A convenient choice is to take the region between $y = \sqrt{r^2 - x^2}$ and revolve it about the x-axis. This is what we will use for the next part.

(b) Taking vertical cross-sections, we get disks after revolving and the total volume is

$$\int_{-r}^{r} \pi \left(\sqrt{r^2 - x^2}\right)^2 \mathrm{d}x = \int_{-r}^{r} \pi (r^2 - x^2)\, \mathrm{d}x = \pi \left[r^2 x - \frac{1}{3} x^3\right]_{-r}^{r} = \frac{4}{3} \pi r^3$$

Sure enough, this is the formula for the volume of a ball that we have seen before (though our memory might be foggy on the exact formula).

Alternatively. It is more complicated here but, for practice, we can also take horizontal cross-sections in which case we get cylindrical shells after revolving. Lets take the cross-section at height y where y is between 0 and r. This cross-section extends from $x = -\sqrt{r^2 - y^2}$ to $x = \sqrt{r^2 - y^2}$ and therefore has width $2\sqrt{r^2 - y^2}$. Giving this slice a thickness of $\mathrm{d}y$ and revolving about the x-axis, we obtain a cylindrical shell with approximate volume

$$(\text{circumference}) \times (\text{width}) \times (\text{thickness}) = (2\pi y)\left(2\sqrt{r^2 - y^2}\right) \mathrm{d}y.$$

"Summing" all these volumes, we get

$$\int_0^r (2\pi y)\left(2\sqrt{r^2 - y^2}\right) \mathrm{d}y = 4\pi \int_0^r y\sqrt{r^2 - y^2}\, \mathrm{d}y = 4\pi \left[-\frac{1}{3}(r^2 - y^2)^{3/2}\right]_0^r = \frac{4}{3}\pi r^3.$$

Here, we substituted $u = r^2 - y^2$ to compute the integral (do it!). The final volume is, of course, the same we calculated before.

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Arc length

Example 38. What is the length of the curve $y=2x$, for $0\leqslant x\leqslant 4$?

Make a sketch and use Pythagoras.

Solution. The curve is the hypothenuse of a right triangle with shorter sides of length 4 (in x-direction) and 8 (in y-direction). Therefore its length is $\sqrt{4^2+8^2}=\sqrt{80}=4\sqrt{5}$.

(arc length) The length of a general curve $y=f(x)$, for $a\leqslant x\leqslant b$, is given by

$$\int_a^b \sqrt{1+(f'(x))^2}\,\mathrm{d}x.$$

Why? To see how we can arrive at this formula, we proceeded as follows:

- We chop the x-axis into little pieces of width $\mathrm{d}x$ and look at the corresponding pieces of our graph.
- Suppose we are looking at our graph near x. If we zoom in plenty, then the tiny portion of the graph we see begins to look roughly like a line with slope $f'(x)$.
- We can compute the length of a segment of this line as we did in Example 38 by using Pythagoras. If the segment extends $\mathrm{d}x$ horizontally, then it extends $f'(x)\mathrm{d}x$ vertically (make a sketch!). [We can also write $f'(x)\mathrm{d}x=\frac{\mathrm{d}y}{\mathrm{d}x}\mathrm{d}x=\mathrm{d}y$.]

  By Pythagoras, our piece of the line has length

  $$\sqrt{(\mathrm{d}x)^2+(f'(x)\,\mathrm{d}x)^2}=\sqrt{1+(f'(x))^2}\,\mathrm{d}x.$$

- "Adding" all these little pieces, we obtain the formula above for the total length of the curve.

Example 39. (again) Using the integral formula, compute the length of the curve $y=2x$, for $0\leqslant x\leqslant 4$, again. Of course, the answer agrees with Example 38.

Solution. Here, $f(x)=2x$ so that $f'(x)=2$. Hence, the length is

$$\int_a^b \sqrt{1+(f'(x))^2}\,\mathrm{d}x=\int_0^4 \sqrt{1+2^2}\,\mathrm{d}x=4\sqrt{5}\approx 8.944.$$

Example 40. Compute the length of the curve $y=x^{3/2}$, for $0\leqslant x\leqslant 4$.

Before you compute the answer, make a sketch. Which curve should be longer: $y=x^{3/2}$ or $y=2x$?

Solution. With $f(x)=x^{3/2}$, we have $f'(x)=\frac{3}{2}\sqrt{x}$. The length is

$$\int_0^4 \sqrt{1+\left(\frac{3}{2}\sqrt{x}\right)^2}\,\mathrm{d}x=\int_0^4 \sqrt{1+\frac{9}{4}x}\,\mathrm{d}x=\int_1^{10}\frac{4}{9}\sqrt{u}\,\mathrm{d}u=\frac{4}{9}\left[\frac{2}{3}u^{3/2}\right]_1^{10}=\frac{8}{27}(\sqrt{1000}-1)\approx 9.073.$$

Here, we substituted $u=1+\frac{9}{4}x$. Make sure that this substitution is clear to you (including the change of boundaries: if $x=4$ then $u=?$).

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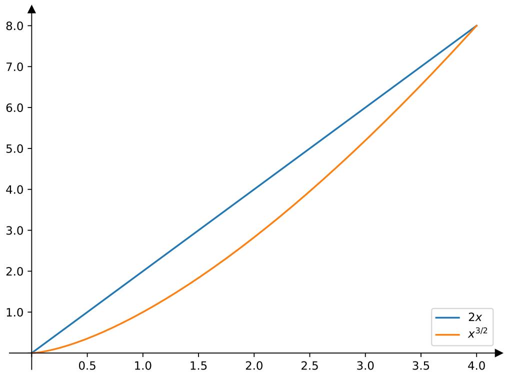
Comparing the lengths. As for comparing the lengths, note that, on the interval $0 \leqslant x \leqslant 4$, both $y = x^{3/2}$ and $y = 2x$ begin at the point $(0, 0)$ and end at the point $(4, 8)$. Since a line is the shortest connection between two points, the arc length for $y = x^{3/2}$ had to be larger.

However, you can see that the difference is not much. This is confirmed by the plot below:



Example 41. Setup an integral for the circumference of a circle of radius r.

Review. The (arc) length of a general curve $y = f(x)$, for $a \leqslant x \leqslant b$, is given by

$$\int_a^b \sqrt{(\mathrm{d}x)^2 + (\mathrm{d}y)^2} = \int_a^b \sqrt{1 + \left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2}\,\mathrm{d}x.$$

Example 42. (extra) Using our new technology, compute the circumference of a circle of radius r.

Solution. Of course, the final answer has to be $2\pi r$.

- First, in order to work with a function, we consider the (upper) half circle.
  That half-circle is described by $y = \sqrt{r^2 - x^2}$ and the length of that curve (from $x = -r$ to $x = r$) is half of the circumference of our circle.
- $\dfrac{\mathrm{d}y}{\mathrm{d}x} = \dfrac{-x}{\sqrt{r^2 - x^2}}$
- Hence, the circumference of our circle is given by the integral

$$2\int_{-r}^r \sqrt{1 + \left(\frac{-x}{\sqrt{r^2 - x^2}}\right)^2}\,\mathrm{d}x = 2\int_{-r}^r \sqrt{1 + \frac{x^2}{r^2 - x^2}}\,\mathrm{d}x = 2\int_{-r}^r \sqrt{\frac{r^2}{r^2 - x^2}}\,\mathrm{d}x.$$

- Now, we substitute $u = x/r$.
  Why? Just looking at the integral, the reason for choosing this substitution might not be obvious. However, thinking about our actual problem, this substitution is very natural: it scales things by $1/r$ so that our circle gets rescaled to a circle of radius 1.

It is very common in applications that we need to change scales or coordinate systems. When dealing with integrals, we then need to perform the corresponding substitution.

Such changes of scale or coordinate systems for practical reasons is a second important reason why we need to be able to substitute. (So far we substituted as a means to mathematically simplify an integral.)

- To substitute, we compute $\dfrac{\mathrm{d}u}{\mathrm{d}x} = \dfrac{1}{r}$, and so $\mathrm{d}x = r\,\mathrm{d}u$ [r is just a number—we can treat it like we would treat 7.]
  For the boundaries of the integral: if $x = -r$, then $u = -1$. If $x = r$, then $u = 1$.
  Since $x = ru$, we therefore get

$$2\int_{-r}^r \sqrt{\frac{r^2}{r^2 - x^2}}\,\mathrm{d}x = 2\int_{-1}^1 \sqrt{\frac{r^2}{r^2 - (ru)^2}} \cdot r\,\mathrm{d}u = 2r\int_{-1}^1 \frac{1}{\sqrt{1 - u^2}}\,\mathrm{d}u.$$

- We can actually evaluate this final integral (more on such integrals later) if we recall that the derivative of $\arcsin(u)$ is $1/\sqrt{1 - u^2}$. Hence,

$$2r\int_{-1}^1 \frac{1}{\sqrt{1 - u^2}}\,\mathrm{d}u = 2r\Big[\arcsin(u)\Big]_{-1}^1 = 2r[\arcsin(1) - \arcsin(-1)] = 2\pi r.$$

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Physical work

Work is **force** times **distance**: $W = Fd$.

- F could be measured in lb and d in ft. Then W is conveniently measured in $\mathrm{ft\text{-}lb}$.
- The SI units for F are N (newton), for d they are m (meter), and W is measured in Nm (newtonmeter) or joule ($1\ \mathrm{Nm} = 1\ \mathrm{joule} \approx 0.738\ \mathrm{ft\text{-}lb}$).

Think about the work necessary to lift an object to a certain height.

Calculus comes in when the force F is not constant!

Example 43. Suppose we wish to lift a $100\ \mathrm{lb}$ piano from the ground to the top of a $20\ \mathrm{ft}$ building (for instance, by standing on the roof and pulling it up using a rope). The work required for that is

$$\mathrm{work} = (100\ \mathrm{lb})(20\ \mathrm{ft}) = 2000\,\mathrm{ft\text{-}lb}.$$

This was easy because the force was constant througout the problem (the piano always weighed $100\ \mathrm{lb}$). It is when the force varies (as in the next example) that we need our calculus skills and mastery of integrals.

Example 44. As before, we wish to lift a $100\ \mathrm{lb}$ piano from the ground to the top of a $20\ \mathrm{ft}$ building. We are doing so by standing on the roof and pulling it up using a rope. However, this time, we are using a rather heavy rope weighing $0.1\ \mathrm{lb/ft}$ and want to take that into account (just pulling up the rope, dangling to the ground, would require some work).

Think about the moment when the piano is $x\ \mathrm{ft}$ off the ground (and we want to pull it up by $\mathrm{d}x\ \mathrm{ft}$):

- We still need to pull up $20 - x\ \mathrm{ft}$.

  So, at that moment, the weight (piano plus rope) to be pulled up is $100 + 0.1(20 - x)\ \mathrm{lb}$.
- Hence, to pull up the piano by a tiny amount of $\mathrm{d}x$ feet, the amount of work needed is (roughly) $[100 + 0.1(20 - x)]\mathrm{d}x$ pound.

  [Assuming that $\mathrm{d}x$ is very small, the change in weight is insignificant, so that we can use $W = Fd$.]

To get the total amount of work (in $\mathrm{ft\text{-}lb}$), we need to "add" up these small contributions from $x = 0$ to $x = 20$:

$$\mathrm{work} = \int_0^{20} [100 + 0.1(20 - x)]\mathrm{d}x.$$

It only remains to calculate this integral (which is very simple in this case):

$$\mathrm{work} = \int_0^{20} [102 - 0.1x]\mathrm{d}x = \left[102x - \frac{0.1}{2}x^2\right]_0^{20} = 2020\ \mathrm{ft\text{-}lb}.$$

Comment. In this simple example, you can get away with not computing any integrals by arguing as follows: the rope weighs a total of $20 \cdot 0.1 = 2\ \mathrm{lb}$. On average, we need to lift it $10\ \mathrm{ft}$ so that the total amount of work needed to pull up the rope is $2\ \mathrm{lb} \cdot 10\ \mathrm{ft} = 20\,\mathrm{ft\text{-}lb}$. Added to the work required for just the piano ($2000\,\mathrm{ft\text{-}lb}$, see previous example), we get the total that we just computed.

Example 45. A conical container of radius 10 ft and height 30 ft is completely filled with water. How much work will it take to pump the water to a level of 2 ft above the cone's rim?

[Water weighs $62.4 \text{ lb}/\text{ft}^3$.]

Solution. Make a sketch! This being a container means that the tip of the cone is at the bottom. Let us denote with y (in ft) the vertical position in such a way that the tip is at $y=0$ and the rim is at $y=30$. We need to pump the water to the level $y=30+2=32$.

We consider a horizontal slice at height y and thickness $\mathrm{d}y$:

- This slice needs to be lifted up $(30-y)+2=32-y$ (ft).

  (If we considered vertical slices, we could not make such a statement and therefore would be stuck here.)

- The slice is (almost) a disk with radius $r=\frac{10}{30}y=\frac{y}{3}$. Hence, its volume is $\pi r^2\,\mathrm{d}y=\frac{\pi}{9}y^2\mathrm{d}y$ (ft^3).

- The weight of the slice is $62.4\frac{\pi}{9}y^2\,\mathrm{d}y$ (lb) and it needs to be lifted up $32-y$ (ft). That takes work of $(32-y)\cdot 62.4\frac{\pi}{9}y^2\mathrm{d}y$ (ft-lb).

- "Adding" up, the total work required is

$$\int_0^{30}(32-y)\cdot 62.4\frac{\pi}{9}y^2\mathrm{d}y=\ldots\approx 1.86\cdot 10^6 \text{ ft-lb}.$$

Comment. Note that we rounded the answer to 3 significant digits, because we cannot expect more precision given that the weight of water per ft^3 is only given to us to 3 digits.

Example 46. Repeat Example 45 if…

(a) …the container is not completely filled with water but only to a height of 15 ft.

(b) …we stop pumping once the container is filled with water to a height of 15 ft.

Can you predict in which case the work required is larger?

Solution.

(a) In that case, the total work required is

$$\int_0^{15}(32-y)\cdot 62.4\frac{\pi}{9}y^2\mathrm{d}y=\ldots\approx 508{,}000 \text{ ft-lb}.$$

(b) In that case, the total work required is

$$\int_{15}^{30}(32-y)\cdot 62.4\frac{\pi}{9}y^2\mathrm{d}y=\ldots\approx 1.35\cdot 10^6 \text{ ft-lb}.$$

Comment. Note that the sum of these two is again $1.86\cdot 10^6 \text{ ft-lb}$. Think about why that makes perfect sense!

Example 47. We want to "lift" a 1600 kg satellite from the ground into orbit, $20{,}000\text{ km}$ above the surface. Let us compute the theoretic amount of work required to do so.

Context. These are actually typical values for a GPS satellite. For comparison, the ISS has an average altitude about 400 km, while the moon is about $384{,}000\text{ km}$ away. Light travels at the speed of about $300{,}000\text{ km/s}$ (sound only at about 340 m/s).

Solution. First, let us gather the necessary background information:

- Initially, the satellite is sitting on the surface, about $d_1 = 6371\text{ km}$ from the center of earth (for gravitation, earth behaves like all its mass is concentrated at its center).
  The goal is to bring the satellite to a distance $d_2 = 26{,}371\text{ km}$ from the center of earth.
- The mass of the earth is about $m_E = 5.972 \cdot 10^{24}\text{ kg}$. The mass of our satellite is $m_S = 1600\text{ kg}$.
- The physical law of attraction is $F = G\frac{m_E m_S}{d^2}$.
  It tells us the force of attraction between two masses (here, the satellite and earth) that are at distance d.
  Here, $G = 6.674 \cdot 10^{-11}\text{ N} \cdot \text{m}^2/\text{kg}^2$ is the gravitational constant.
  Comment. Note that this force is not constant in our problem: the values of d range from $d = d_1$ to $d = d_2$.

Make a sketch! Similar to our approach Example 44, we now think about the moment when the satellite is at distance x from the center of the earth and about the amount of work needed to lift it by $\mathrm{d}x$.

- At that moment, the gravitational force is $G\frac{m_S m_E}{x^2}$.
- To lift up the satellite by a tiny amount of $\mathrm{d}x$, the amount of work needed is (roughly) $G\frac{m_S m_E}{x^2}\mathrm{d}x$ (force times distance).

Hence, the total amount of work is

$$\text{work} = \int_{d_1}^{d_2} G\frac{m_S m_E}{x^2}\mathrm{d}x = G m_S m_E \int_{d_1}^{d_2} \frac{\mathrm{d}x}{x^2} = G m_S m_E \left[-\frac{1}{x}\right]_{d_1}^{d_2} = G m_S m_E \left(\frac{1}{d_1} - \frac{1}{d_2}\right).$$

Plugging in our values for G, m_S, m_E, d_1, d_2, we find

$$\text{work} = (6.674 \cdot 10^{-11}) \cdot (1600) \cdot (5.972 \cdot 10^{24}) \left(\frac{1}{6371000} - \frac{1}{26371000}\right) \approx 7.59 \cdot 10^{10}\text{ joule}.$$

Comment. You could also let x be the distance from the surface. That works as well if you adjust things accordingly. (Do that as an exercise!)

Comment. If you choose $d = 6371\text{ km}$ in the law of attraction, set one mass to be the mass $m_E = 5.972 \cdot 10^{24}\text{ kg}$ of earth and the other to be 1 kg, then the resulting force is $F = 6.674 \cdot 10^{-11} \cdot \frac{5.972 \cdot 10^{24}}{(6.371 \cdot 10^6)^2} \approx 9.820\text{ N}$, which you have surely met in other class before. Note that this force is an approximation and depends on the exact elevation (earth is not perfectly round). Usually, the value 9.81 N is used.

Example 48.

- What happens when we take the **limit** $d_2 \to \infty$ in the previous example? What does that mean physically?
- How does the previous problem change if the physical law of attraction was $F = G\frac{m_S m_E}{d}$? What happens now when we take the limit $d_2 \to \infty$?

Example 49. (extra) The Pyramid of Cheops, built about 2560 BC, has been the tallest man-made structure in the world for over 3800 years. The pyramid was built to a height of 146m. Its base is a square with each side 230m in length.

(a) The pyramid is made out of limestone (1 cubicmeter of limestone has a mass of 2.3 tonnes). Assuming that the pyramid is solid, compute its mass (in tonnes) by using an integral.

(b) What was the mass of the pyramid when it was built to half its final height?

(c) The limestone blocks used usually have a mass of about 2.5 tonnes each. (Roughly) how many limestone blocks does the pyramid consist of?

(d) Compute the (theoretical) total amount of work (in joule) that was required in lifting all the blocks from the ground to their final position.

(e) Of course, the actual amount of work required was much higher; assume it was 50 times as high as the theoretical amount you just calculated. Further, assume that an Egyptian worker could perform work of about 2000 kilojoules per day. Based on these numbers and no holidays, how many workers would have been needed to construct the Pyramid of Cheops in 20 years?
Comment. That's just for the building part! Sourcing and transport of the blocks and all other stuff not included ... For perspective, assume a person consumes 2000 calories a day. That actually means $2000\text{ kcal} \approx 8400\text{ kJ}$, and that is an upper limit on how much work they can perform on a daily basis.

Solution.

(a) Let us denote with x (in m) the vertical position in such a way that the tip is at $x=0$ and the base is at $x=146$. That way, the cross-section at x has a width of $\frac{230}{146}x$ (so that the width is 0 when $x=0$, and the width is 230 when $x=146$). The volume of the pyramid is

$$\int_0^{146}\left(\frac{230}{146}x\right)^2 \mathrm{d}x = \left(\frac{230}{146}\right)^2 \frac{1}{3}x^3\bigg|_0^{146} = \frac{1}{3}230^2\cdot 146 \approx 2.57\cdot 10^6 \quad \mathrm{m}^3$$

and hence its weight is

$$\frac{1}{3}230^2\cdot 146\cdot 2.3 \approx 5.921\cdot 10^6 \quad \mathrm{t}.$$

(b) The volume of the pyramid was

$$\int_{73}^{146}\left(\frac{230}{146}x\right)^2 \mathrm{d}x = \left(\frac{230}{146}\right)^2 \frac{1}{3}x^3\bigg|_{73}^{146} = \frac{7}{24}230^2\cdot 146 \quad \mathrm{m}^3$$

and hence its weight about 5.181 million tonnes.

(c) About $\frac{5.921\cdot 10^6}{2.5} \approx 2.369\cdot 10^6$, or 2.4 million, blocks of limestone.

(d) Recall that on earth's surface, one kg weighs about $9.81\ \mathrm{N}$. The work therefore is

$$\int_0^{146}\left(\frac{230}{146}x\right)^2 (146-x)2300\cdot 9.81\mathrm{d}x \approx 2.120\cdot 10^{12} \quad \mathrm{J}.$$

(e) The building takes

$$\frac{50\cdot 2.120\cdot 10^{12}}{2{,}000{,}000} \approx 5.30\cdot 10^7$$

days of a man's work. To complete the work in 20 years

$$\frac{5.30\cdot 10^7}{20\cdot 365} \approx 7260$$

workers would be needed.