Integration of Exponential Functions :

Recall : $\int e^{kx}\,dx = \frac{1}{k}e^{kx} + C$

In general : $\int a^x\,dx = ?$ for $a > 0$

Recall : $a^x = e^{\ln a^x} = e^{(\ln a)x}$

$$\therefore \int a^x\,dx = \int e^{(\ln a)x}\,dx$$

$$= \frac{1}{\ln a}e^{(\ln a)x} + C$$

$$= \frac{a^x}{\ln a} + C$$

OR : Recall that $\frac{d}{dx}a^x = a^x \ln a$

so $\frac{d}{dx}\frac{a^x}{\ln a} = a^x$, and $\int a^x\,dx = \frac{a^x}{\ln a} + C$

Integration of Logarithmic Functions :

$\int \ln x\,dx = ?$ for $x > 0$

Ex : $\frac{d}{dx}\, x\ln x - x$

Ans : $\ln x$!

Therefore , $\int \ln x\,dx = x\ln x - x + C$

Problem : How do we know $\frac{d}{dx}\, x\ln x - x = \ln x$ in advance ?

(Make a guess of antiderivative of $\ln x$ directly)

Any direct way to find an antiderivative of $\ln x$? (Yes, later !)

e.g. (Constant issue)

$\int (x+1)^2\,dx$ let $u = x+1$

$= \int u^2\,du$ $du = dx$

$= \frac{1}{3}u^3 + C$

$= \frac{1}{3}(x+1)^3 + C$

$= \frac{1}{3}x^3 + x^2 + x + \frac{1}{3} + C$

$\int (x+1)^2\,dx$

$= \int x^2 + 2x + 1\,dx$

$= \frac{1}{3}x^3 + x^2 + x + C$

seems to be different !

Ans : This C is NOT that C !

Integration by Parts

Recall: Let $u(x)$ and $v(x)$ be differentiable functions.

Product rule: $\frac{d}{dx}(uv) = u\frac{dv}{dx} + v\frac{du}{dx}$

$$u\frac{dv}{dx} = \frac{d}{dx}(uv) - v\frac{du}{dx}$$

Integrate both sides with respect to x:

$$\int u\frac{dv}{dx}\,dx = \int \frac{d}{dx}(uv)\,dx - \int v\frac{du}{dx}\,dx$$

$$\int u\frac{dv}{dx}\,dx = uv - \int v\frac{du}{dx}\,dx$$

OR: $\int u\,dv = uv - \int v\,du$

Integration by Parts: $\int u\frac{dv}{dx}\,dx = uv - \int v\frac{du}{dx}\,dx$

e.g. $\int x^2 \ln x\,dx = \int (\ln x)\, x^2\,dx$

$$= \int (\ln x)\frac{d}{dx}\left(\frac{x^3}{3}\right)dx \qquad (\text{Now, } u = \ln x,\ v = \frac{x^3}{3})$$

$$= \int \ln x\, d\frac{x^3}{3}$$

$$= \frac{x^3}{3}\ln x - \int \frac{x^3}{3}\, d(\ln x)$$

$$= \frac{x^3}{3}\ln x - \int \frac{x^3}{3}\frac{1}{x}\,dx$$

$$= \frac{x^3}{3}\ln x - \int \frac{x^2}{3}\,dx$$

$$= \frac{x^3}{3}\ln x - \frac{x^3}{9} + C$$

(Verify the answer by differentiation!)

e.g. $\int xe^x dx$

Note : $\frac{d}{dx}e^x = e^x$

$e^x dx = de^x$

Now, $u = x$, $v = e^x$

$$\int x e^x dx$$
$$= \int x\, de^x$$
$$= xe^x - \int e^x dx$$
$$= xe^x - e^x + C$$
$$= e^x(x-1) + C$$

e.g. $\int x^2 e^x dx$

$$= \int x^2 de^x$$
$$= x^2e^x - \int e^x dx^2$$
$$= x^2e^x - \underbrace{\int 2xe^x dx}$$

Ex : Apply Integration by parts again!

Ans : $e^x(x^2-2x+2)+C$

Challenge : $\int x^n e^x dx = ?$

Ans : $e^x[x^n - nx^{n-1} + n(n-1)x^{n-2} - n(n-1)(n-2)x^{n-3} + \cdots + (-1)^n n!] + C$

Question : How to make a guess of $u(x)$ and $v(x)$?

Integration by Parts : $\int u\frac{dv}{dx}dx = uv - \int v\frac{du}{dx}dx$

e.g. $\int x^2 \ln x\, dx = \int (\ln x)\, x^2\, dx$

$$= \int (\ln x)\frac{d}{dx}\left(\frac{x^3}{3}\right) dx$$

Realize the integrand as a product of parts and make a guess of $u(x)$ and $v(x)$ such that one part can be realized as a function $u(x)$, another part is $v'(x)$

Integration of Logarithmic Functions :

$\int \ln x \, dx = ?$ for $x > 0$

Using Integration by part :

$\int \ln x \, dx$ $u = \ln x$ $v = x$

$= x \ln x - \int x \, d \ln x$

$= x \ln x - \int x \cdot \frac{1}{x} dx$

$= x \ln x - \int dx$

$= x \ln x - x + C$

Ex: $\int \log_a x \, dx = ?$

Hints : $\log_a x = \dfrac{\ln x}{\ln a}$

$\int \log_a x \, dx = \frac{1}{\ln a} \int \ln x \, dx$

$= \frac{1}{\ln a} (x \ln x - x + C)$

$= x \frac{\ln x}{\ln a} - \frac{x}{\ln a} + \frac{C}{\ln a}$

$= x \log_a x - \frac{x}{\ln a} + C'$ $C' = \frac{C}{\ln a}$ just a constant !

Sequences of Real Numbers

e.g. $a_1 = 2,\ a_2 = \pi,\ a_3 = 1,\ \cdots$

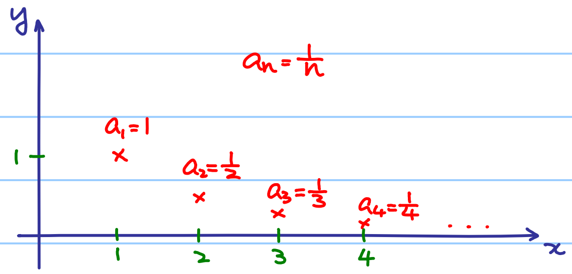
OR write as $\{2, \pi, 1, \cdots\}$ (No pattern)

e.g. Sequences having patterns.

$a_1 = 1,\ a_2 = 2,\ a_3 = 4,\ \cdots$ In general, $a_n = 2^{n-1}$

$a_1 = 1,\ a_2 = \frac{1}{2},\ a_3 = \frac{1}{3},\ \cdots$ In general, $a_n = \frac{1}{n}$

$a_1 = -1,\ a_2 = 1,\ a_3 = -1,\ \cdots$ In general, $a_n = (-1)^n$



Any observation?

When n is getting larger and larger, a_n is getting closer and closer to 0.

Limits of Sequences

Informal definition:

Let a_n be a sequence of real numbers.

If n is getting larger and larger, a_n is getting closer and closer to $L \in \mathbb{R}$, then we say L is the limit of the sequence a_n and we denote it by

$$\lim_{n\to\infty} a_n = L.$$

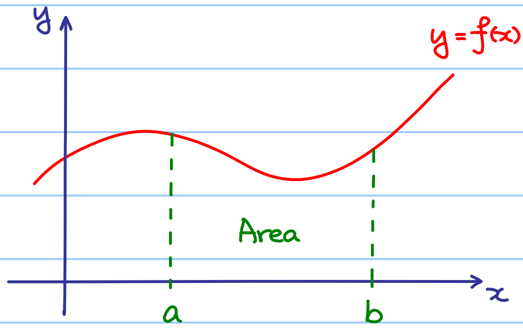
e.g. $\lim_{n\to\infty} \frac{1}{n} = 0$.

$\lim_{n\to\infty} (-1)^n$ does NOT exist.

$\lim_{n\to\infty} 2^{n-1}$ does NOT exist.

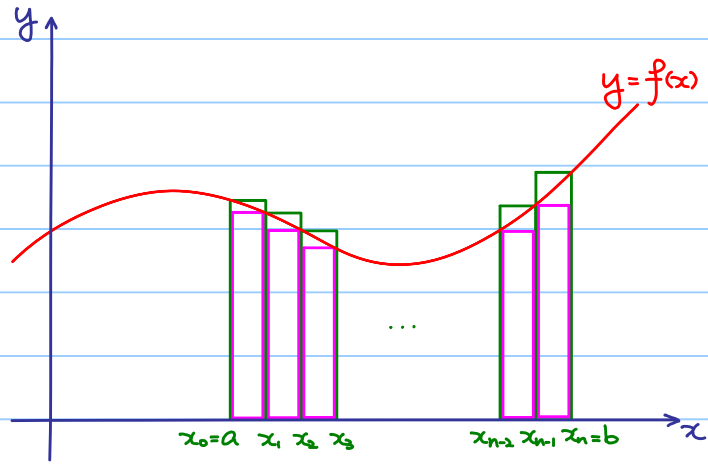
Definite Integration

Goal : Find the area of the region under the curve $y=f(x)$ over an interval $[a,b]$.



Riemann Sum

Area as the limit of a sum



Subdivide $[a,b]$ into n equal subintervals , $x_i - x_{i-1} = \Delta x$, $i = 1,2,3,\cdots,n$

Upper sum $= \max\limits_{x_0 \le \xi_1 \le x_1} f(\xi_1)\Delta x + \max\limits_{x_1 \le \xi_2 \le x_2} f(\xi_2)\Delta x + \cdots + \max\limits_{x_{n-1} \le \xi_n \le x_n} f(\xi_n)\Delta x$

$$U_n = \sum_{i=1}^{n} \max_{x_{i-1} \le \xi_i \le x_i} f(\xi_i)\Delta x$$

Lower sum $= \min\limits_{x_0 \le \xi_1 \le x_1} f(\xi_1)\Delta x + \min\limits_{x_1 \le \xi_2 \le x_2} f(\xi_2)\Delta x + \cdots + \min\limits_{x_{n-1} \le \xi_n \le x_n} f(\xi_n)\Delta x$

$$L_n = \sum_{i=1}^{n} \min_{x_{i-1} \le \xi_i \le x_i} f(\xi_i)\Delta x$$

Note : $L_n \le \text{Area} \le U_n$

Rough idea : $n \to \infty$, more rectangles , better approximation !

If $\lim\limits_{n\to\infty} L_n = \lim\limits_{n\to\infty} U_n = A$, we define the area to A. —— (*)

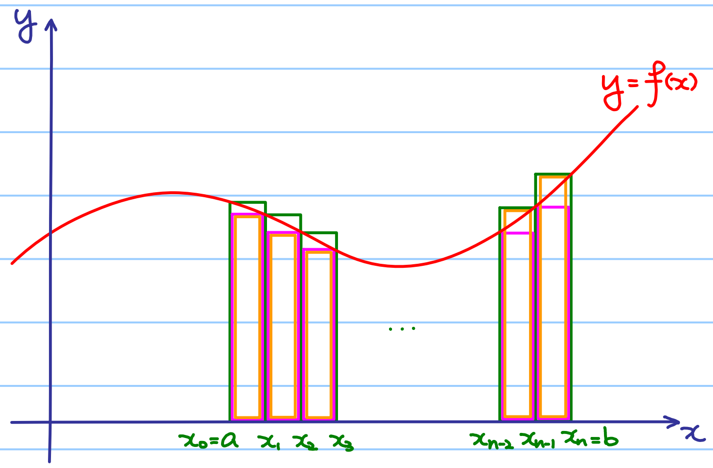
Remark:

1) If the area is defined, we denote it by $\int_a^b f(x)\,dx$.

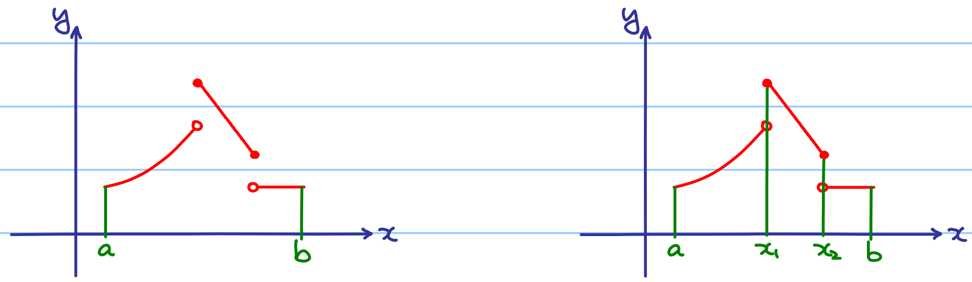
2) If $f(x)$ is a continuous function, $\int_a^b f(x)\,dx$ is well-defined for any $a \le b$.

3) Let $a_n = \sum_{i=1}^{n} f(x_i)\Delta x = \sum_{i=1}^{n} f(a+(b-a)\frac{i}{n}) \cdot \frac{b-a}{n}$, then $L_n \le a_n \le U_n$.

Now, we know $\lim_{n\to\infty} L_n = \lim_{n\to\infty} U_n = A$, so $\lim_{n\to\infty} a_n = A$

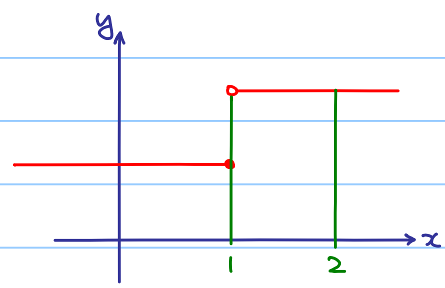


4) If f is a piecewise continuous on $[a,b]$, i.e. discontinuous only at finitely many points, then $\int_a^b f(x)dx$ is defined as the following:



$$\int_a^b f(x)dx = \int_a^{x_1} f(x)dx + \int_{x_1}^{x_2} f(x)dx + \int_{x_2}^{b} f(x)dx$$

e.g. Let $f(x) = \begin{cases} 1 & \text{if } x \le 1 \\ 2 & \text{if } x > 1 \end{cases}$



$$\int_0^2 f(x)dx = \int_0^1 f(x)dx + \int_1^2 f(x)dx$$
$$= 1\times 1 + 2\times 1$$
$$= 3$$

Note: width of a point = 0

Rules for Definite Integrals :

Let $f(x)$, $g(x)$ be continuous (or piecewise continuous) functions.

Suppose $a \le b$.

1) If k is a constant , $\int_a^b k f(x)\,dx = k \int_a^b f(x)\,dx$

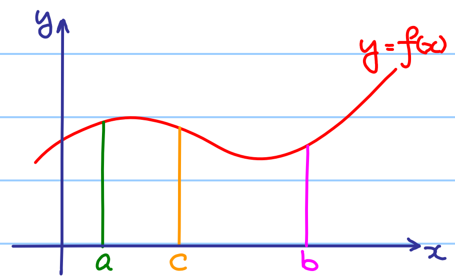
2) $\int_a^b f(x) \pm g(x)\,dx = \int_a^b f(x)\,dx \pm \int_a^b g(x)\,dx$

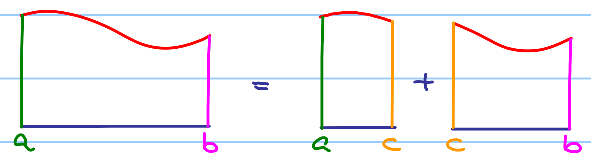
3) $\int_a^a f(x)\,dx = 0$

4) $\int_b^a f(x)\,dx$ is defined to be $-\int_a^b f(x)\,dx$ (reverse direction)

5) $\int_a^b f(x)dx = \int_a^c f(x)dx + \int_c^b f(x)dx$ for any c (subdivision)

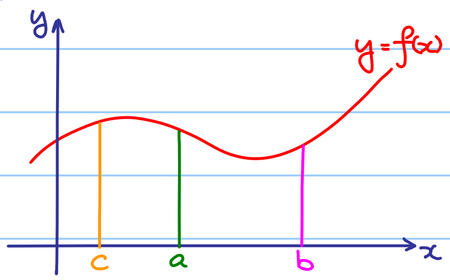
If $a \le c \le b$,

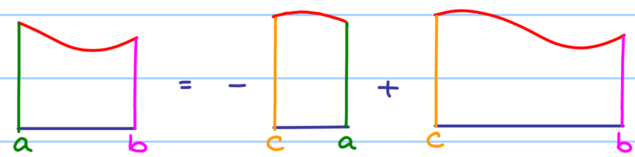




$$\int_a^b f(x)dx = \int_a^c f(x)dx + \int_c^b f(x)dx$$

If $c < a \le b$,





$$\int_a^b f(x)dx = \underbrace{\int_a^c f(x)dx}_{= -\int_c^a f(x)dx} + \int_c^b f(x)dx$$

Ex : Think why (5) is true if $a \le b < c$!

These properties are followed the definition (*) .

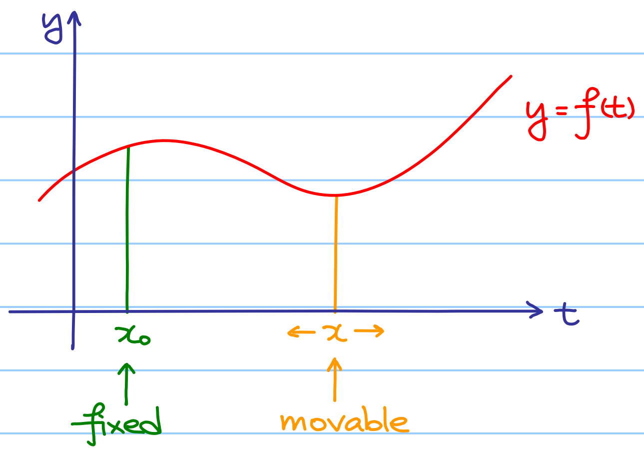
Computation of area :

NOT rely on the above limit, but Fundamental Theorem of Calculus !

Fundamental Theorem of Calculus :

Preparation :

Let $f(t)$ be a continuous function.



1) $\int_{x_0}^{x} f(t)\,dt$ is well defined for all $x \in \mathbb{R}$

2) What is a function? Roughly speaking, input x, output y.

Now, construct a new function $F(x)$ defined by

$$F(x) = \text{Area under the curve } y = f(t) \text{ over } [x_0, x]$$
$$= \int_{x_0}^{x} f(t)\,dt$$

3) How about choosing another fixed point ?

Let $\tilde{F}(x) = \int_{x_1}^{x} f(t)\,dt$, what is the difference between $F(x)$ and $\tilde{F}(x)$?

In fact,

$$F(x) - \tilde{F}(x) = \int_{x_0}^{x} f(t)\,dt - \int_{x_1}^{x} f(t)\,dt$$
$$= \int_{x_0}^{x} f(t)\,dt + \int_{x}^{x_1} f(t)\,dt$$
$$= \int_{x_0}^{x_1} f(t)\,dt \quad \text{which is a constant.}$$

Fundamental Theorem of Calculus :

Let $f(t)$ be a continuous function, x_0 be a fixed point.

Suppose $F(x)$ is a function defined by

$$F(x) = \int_{x_0}^{x} f(t)\,dt ,$$

then $F(x)$ is a differentiable function and $F'(x) = f(x)$.

(i.e. $F(x)$ is an antiderivative of $f(x)$.)

1) Direct consequence : $\displaystyle\int_a^b f(x)\,dx = \int_{x_0}^{b} f(x)\,dx - \int_{x_0}^{a} f(x)\,dx$

$$= F(b) - F(a)$$

i.e. if we know how to compute antiderivative of $f(x)$,

then we know how to find $\int_a^b f(t)\,dt$.

2) Wait ! Antiderivative of $f(x)$ is NOT unique, but unique up to a constant.

Which one should we pick ?

If $\tilde{F}(x) = \int_{x_1}^{x} f(t)\,dt$, then $\tilde{F}(x)$ is another antiderivative of $f(x)$.

In fact, it is NOT surprising, we know $F(x) - \tilde{F}(x)$ is a constant.

Also, $\displaystyle\int_a^b f(x)\,dx = \int_{x_1}^{b} f(x)\,dx - \int_{x_1}^{a} f(x)\,dx$

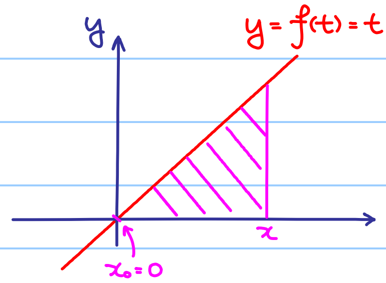
$$= \tilde{F}(b) - \tilde{F}(a)$$

Therefore, we can pick anyone !

e.g. (Verification of Fundamental Theorem of Calculus)

$f(t) = t$, $x_0 = 0$

$f(x) = x$



$$F(x) = \int_{x_0}^{x} f(t)\,dt$$

$$= \text{Area of the shaded triangle}$$

$$= \frac{1}{2}x^2$$

Note : We have $F'(x) = f(x)$.

e.g. $f(x) = x+1$

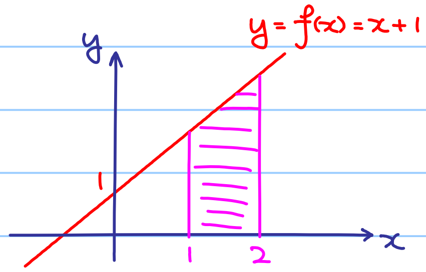
Antiderivative of $f(x) = \int x+1\,dx = \frac{x^2}{2} + x + C$

Choose $C = 0$, let $F(x) = \frac{x^2}{2} + x$

Area of the shaded region $= \int_1^2 f(x)\,dx = F(2) - F(1)$

$= 4 - \frac{3}{2}$

$= \frac{5}{2}$



What we write :

$$\int_1^2 f(x)\,dx = \left[\frac{x^2}{2} + x\right]_1^2$$

$$= \underbrace{\left(\frac{2^2}{2} + 2\right)}_{F(2)} - \underbrace{\left(\frac{1^2}{2} + 1\right)}_{F(1)} = 4 - \frac{3}{2} = \frac{5}{2}$$

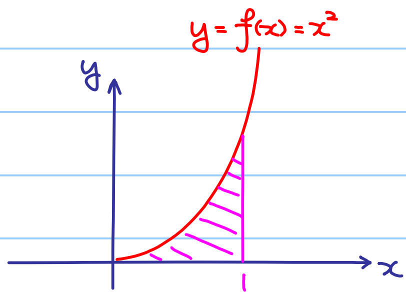
e.g. $f(x) = x^2$

Area of the shaded region $= \int_0^1 f(x)\,dx$

$= \left[\frac{x^3}{3}\right]_0^1$

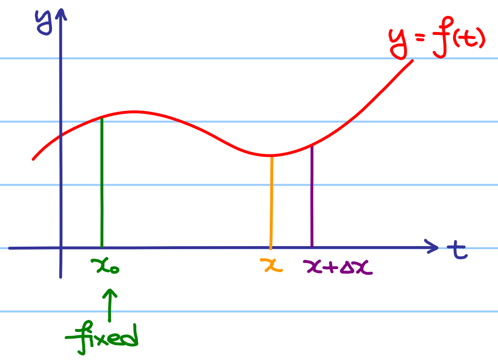
$= \left(\frac{1^3}{3}\right) - \left(\frac{0^3}{3}\right)$

$= \frac{1}{3}$



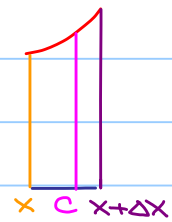
Sketch of the proof Fundamental Theorem of Calculus

Claim: If $F(x) = \int_{x_0}^{x} f(t)\,dt$, $\lim\limits_{\Delta x \to 0} \frac{F(x+\Delta x) - F(x)}{\Delta x} = f(x)$, i.e. $F'(x) = f(x)$



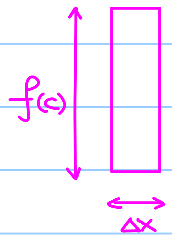
$F(x+\Delta x) - F(x)$

= Area of



By continuity of f, there exists $c \in (x, x+\Delta x)$ such that

=



$$\lim_{\Delta x \to 0} \frac{F(x+\Delta x) - F(x)}{\Delta x}$$

$$= \lim_{\Delta x \to 0} \frac{f(c)\,\Delta x}{\Delta x}$$

$$= \lim_{\Delta x \to 0} f(c)$$

$$= \lim_{c \to x} f(c) \qquad \text{(As } \Delta x \text{ tends to } 0\text{, } c \text{ tends to } x\text{)}$$

$$= f(x) \qquad \text{(By continuity of } f\text{)}$$