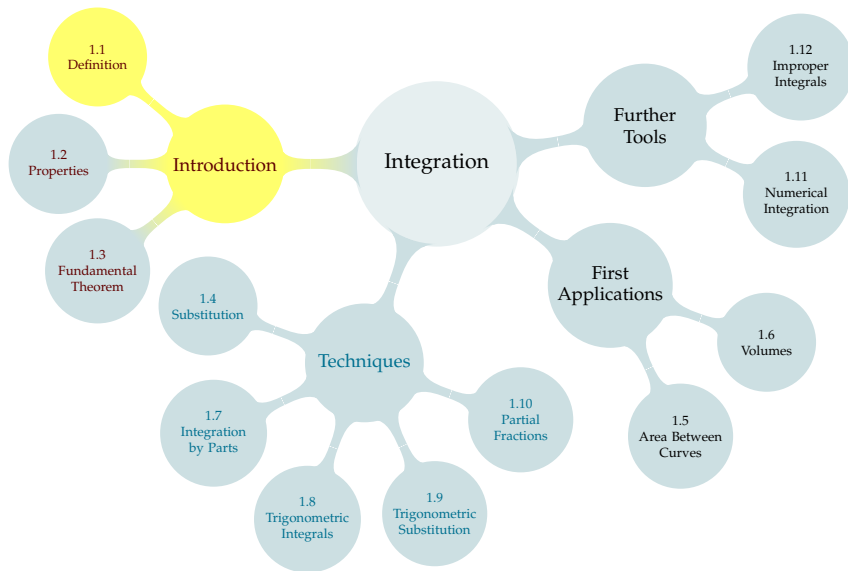


# TABLE OF CONTENTS



We defined the definite integral as

$$\int_a^b f(x) \, dx = \lim_{N \rightarrow \infty} \sum_{i=1}^N \Delta x \cdot f(x_{i,N}^*)$$

where  $\Delta x = \frac{b-a}{N}$  and  $x_{i,N}^*$  is a point in the interval  $[a + (i-1)\Delta x, a + i\Delta x]$ .

We have seen in previous classes that limits don't always exist. We will verify that this limit does indeed exist, and is equal to the desired area (at least in the most common cases).

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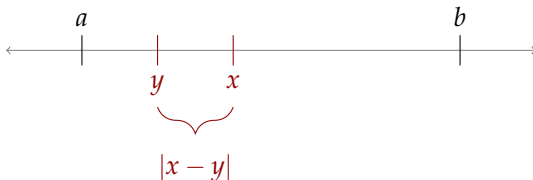
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We'll start with some general ideas that appear in the proof.

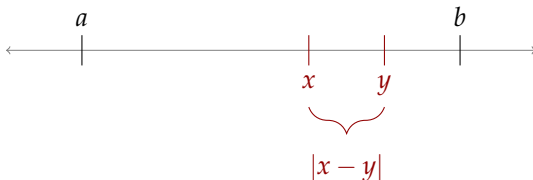
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If  $a \leq x \leq b$  and  $a \leq y \leq b$ , then

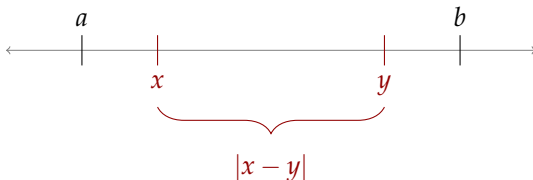
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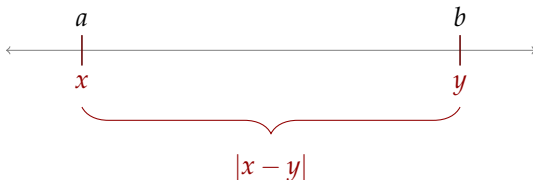
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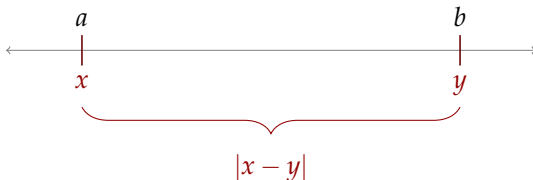
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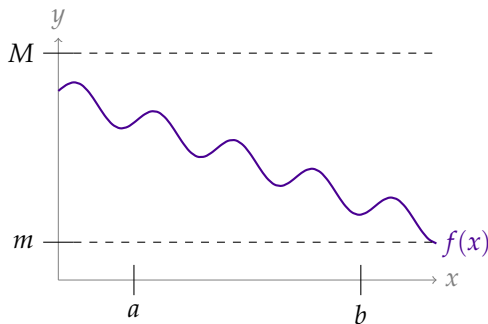
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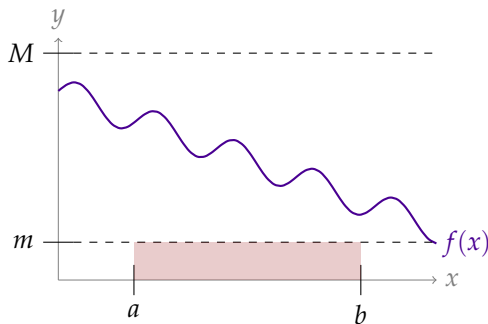
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Let  $f(x)$  be a function, defined over the interval  $[a, b]$ . If  $m \leq f(x) \leq M$  over the entire interval  $[a, b]$ , then the (signed) area between the curve  $y = f(x)$  and the  $x$ -axis, from  $a$  to  $b$ , is between  $m(b - a)$  and  $M(b - a)$ .



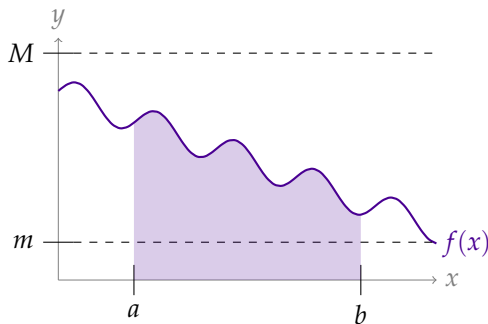
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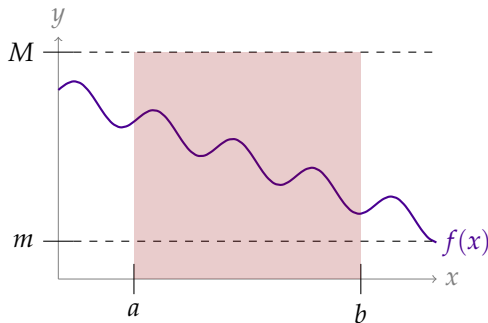
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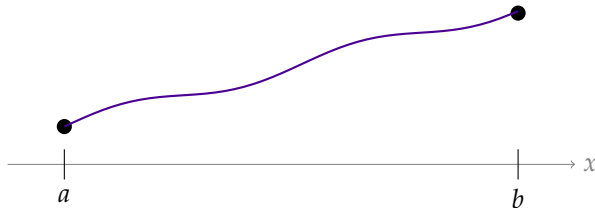


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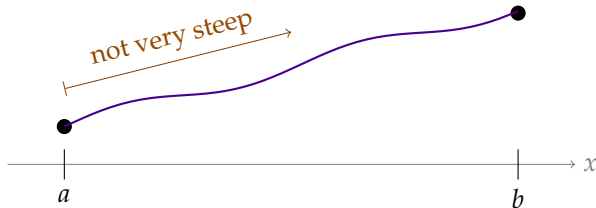
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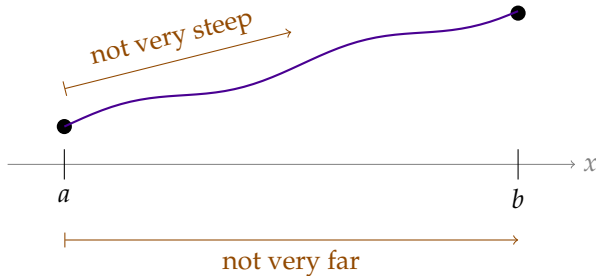
Intuition: If  $f'(x)$  is bounded on  $(a, b)$  and  $b - a$  is small, then  $f(b) - f(a)$  is also small.



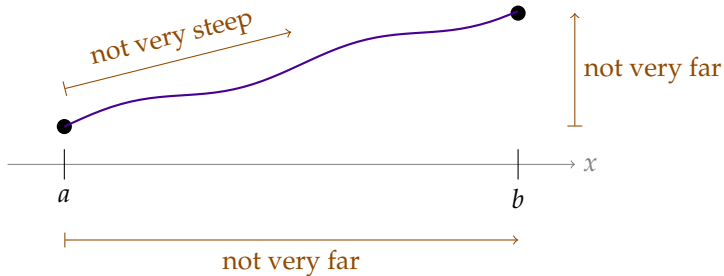
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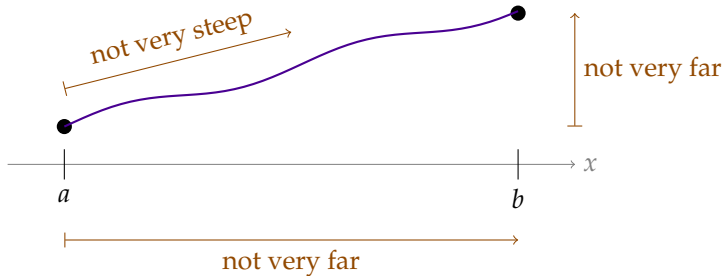


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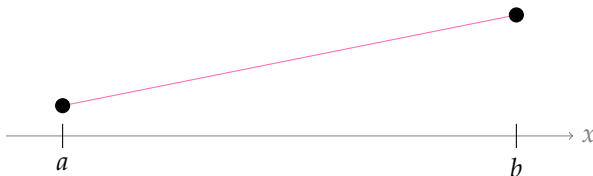




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The Mean Value Theorem provides a more explicit connection between these quantities.



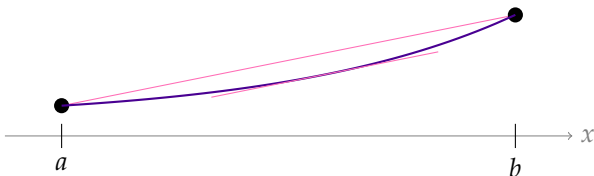
## Mean Value Theorem

Let  $a$  and  $b$  be real numbers with  $a < b$ . Let  $f$  be a function such that

- ▶  $f(x)$  is continuous on the closed interval  $a \leq x \leq b$ , and
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Then there is a  $c$  in  $(a, b)$  such that

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## Mean Value Theorem

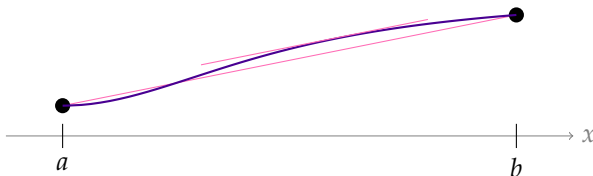
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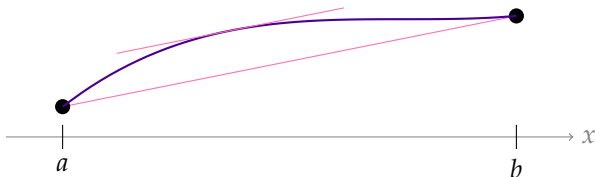
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## Triangle Inequality

For any real numbers  $x_1, x_2, \dots, x_n$ :

$$\left| \sum_{i=1}^n x_i \right| \leq \sum_{i=1}^n |x_i|$$

Intuition: If some terms are positive and some are negative, they “cancel each other out” and make the overall sum smaller.

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$$|1 + 2|$$

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$$|1| + |-2|$$

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Proof outline:



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Proof outline:

Let  $x$  and  $y$  be any real numbers.

- ▶  $x \leq |x|$  and  $y \leq |y|$ , so  $x + y \leq |x| + |y|$
- ▶  $-x \leq |x|$  and  $-y \leq |y|$ , so  $-(x + y) = (-x) + (-y) \leq |x| + |y|$
- ▶  $|x + y| = \begin{cases} x + y & \text{if } x + y \geq 0 \\ -(x + y) & \text{if } x + y < 0 \end{cases} \leq |x| + |y|$
- ▶ Then  $|x + y + z| = |(x + y) + z| \leq |x + y| + |z| \leq |x| + |y| + |z|$ , etc.

# REQUIREMENTS

We will consider

$$\int_a^b f(x) \, dx$$

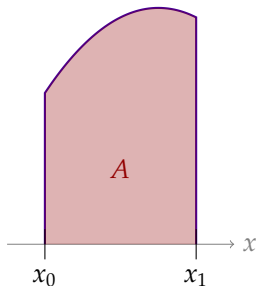
where:

- ▶  $a < b$
- ▶  $f(x)$  is continuous over the interval  $[a, b]$
- ▶  $f(x)$  is differentiable over the interval  $(a, b)$
- ▶  $f'(x)$  is bounded over the interval  $(a, b)$ . That is, there exists a positive constant number  $F$  such that  $|f'(x)| \leq F$  for all  $x$  in the interval  $(a, b)$ .

# ERROR IN A SINGLE SLICE

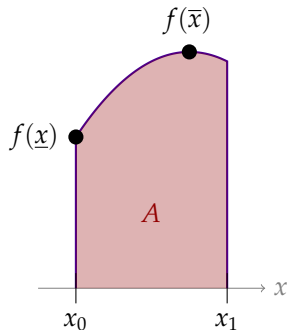
Consider approximating the area of single slice, from  $x_0$  to  $x_1$ .

►  $A$  is the actual area of the slice



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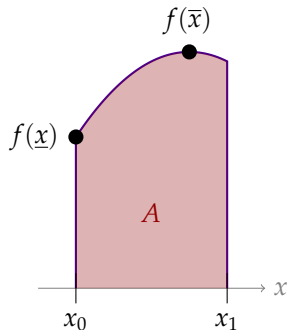


- ▶  $A$  is the actual area of the slice
- ▶  $f(\bar{x})$  and  $f(\underline{x})$  are the largest and smallest function values over the slice



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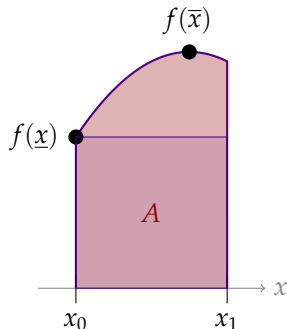
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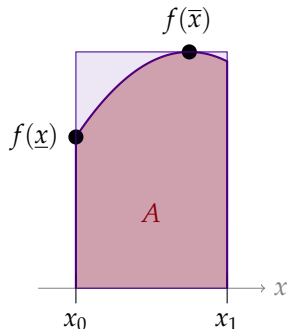
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$$f(x) \cdot (x_1 - x_0) \leq A \leq f(\bar{x}) \cdot (x_1 - x_0)$$

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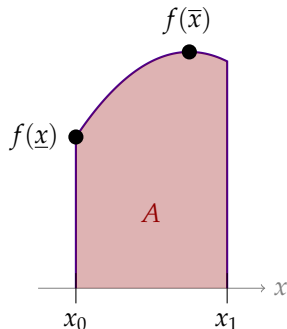
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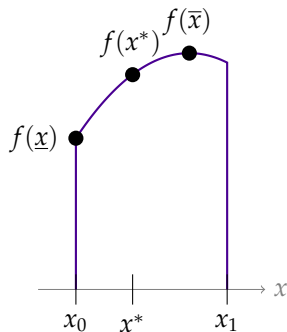
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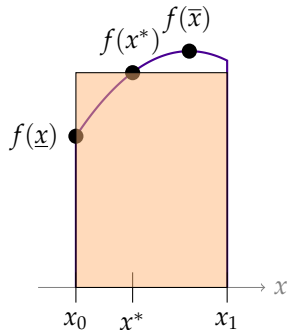
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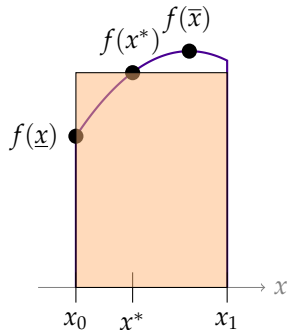


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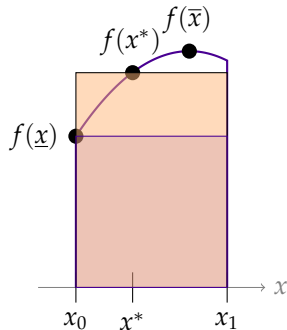


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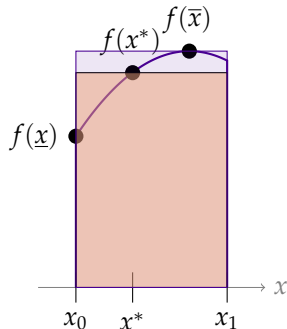
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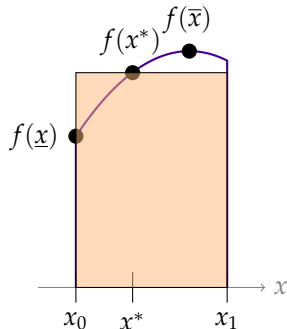
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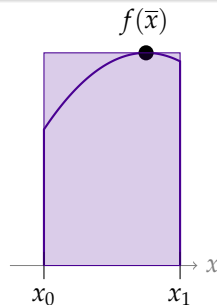
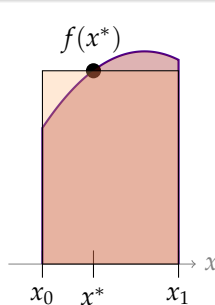
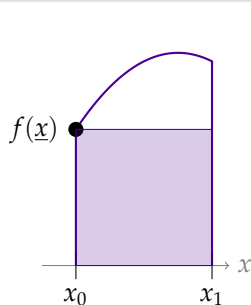
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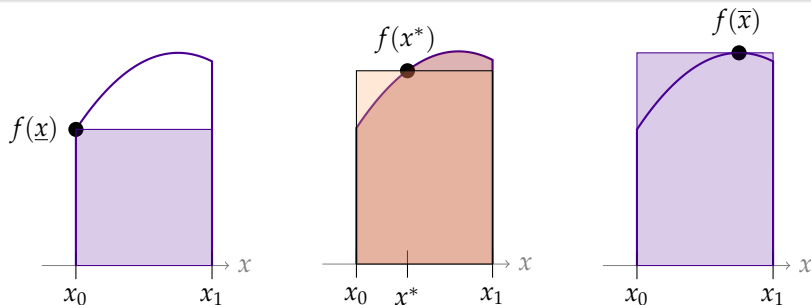


# ERROR IN A SINGLE SLICE



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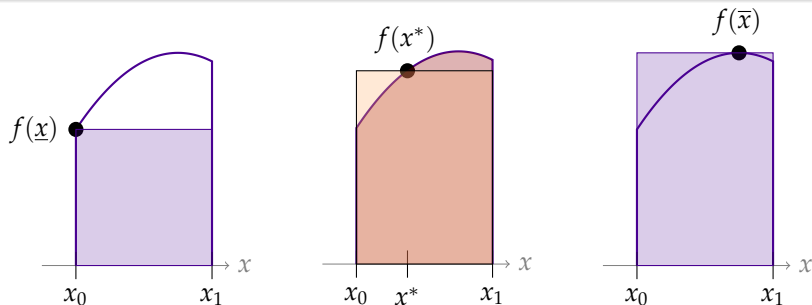


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# ERROR IN A SINGLE SLICE

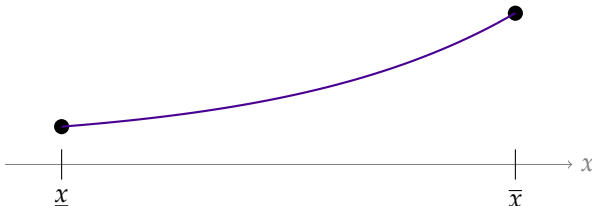
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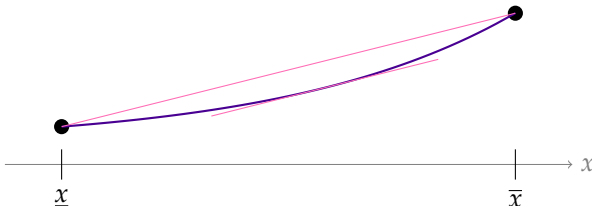
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# ERROR IN A SINGLE SLICE

## Mean Value Theorem

Let  $a$  and  $b$  be real numbers with  $a < b$ . Let  $f$  be a function such that

- ▶  $f(x)$  is continuous on the closed interval  $a \leq x \leq b$ , and
- ▶  $f(x)$  is differentiable on the open interval  $a < x < b$ .

Then there is a  $c$  in  $(a, b)$  such that

$$f(b) - f(a) = f'(c)(b - a)$$

There exists some  $c$  in  $(x_0, x_1)$  such that

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Since  $|f'(x)|$  is never larger than the positive constant  $F$  in  $(a, b)$ ,

$$|f(\bar{x}) - f(\underline{x})| \leq F \cdot |\bar{x} - \underline{x}| \leq F \cdot |x_1 - x_0|$$

# ERROR IN A SINGLE SLICE

All together,

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 \underbrace{|A - f(x^*) \cdot (x_1 - x_0)|}_{\text{error in slice}} &\leq [f(\bar{x}) - f(\underline{x})] \cdot (x_1 - x_0) \\
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 &\leq F \cdot (x_1 - x_0) \cdot (x_1 - x_0)
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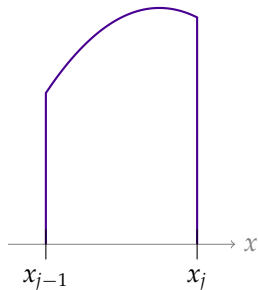
So,

$$\underbrace{|A - f(x^*) \cdot (x_1 - x_0)|}_{\text{error in slice}} \leq F \cdot (x_1 - x_0)^2$$

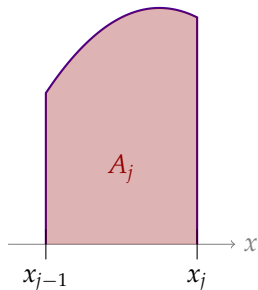
We have shown that the error on a **single** slice can't be worse than some amount.

Now let's consider adding up slices.

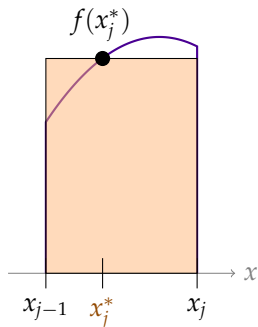
What we did for a single slice, we now do for all slices.  
Updated notation for slice  $j$ :



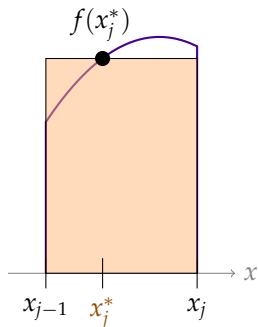
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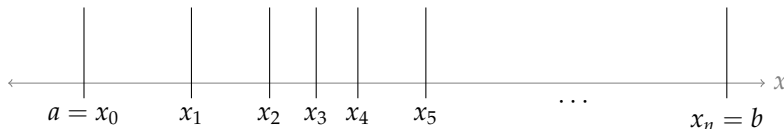


Slice error bound:

$$\left| A_j - f(x_j^*) \cdot (x_j - x_{j-1}) \right| \leq F \cdot (x_j - x_{j-1})^2$$

# (POSSIBLY IRREGULAR) PARTITIONS

Consider partitioning the interval  $[a, b]$  into  $n$  subintervals, not necessarily the same size. Let the points at the edges of the slices be  $a = x_0, x_1, x_2, \dots, x_{n-1}, x_n = b$ .

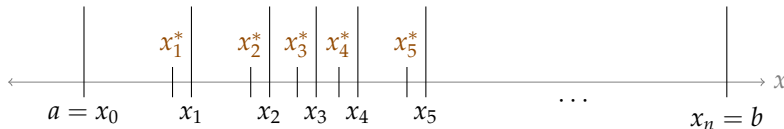




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In each part, choose a vertex  $x_i^*$  to sample the height of the function.

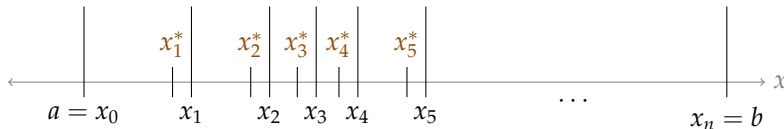




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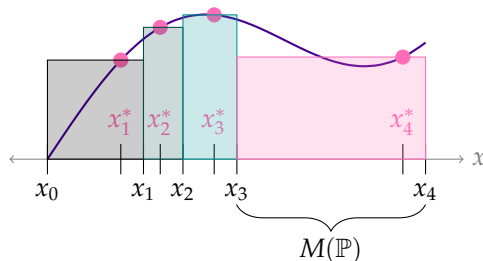
The approximation of  $\int_a^b f(x) \, dx$  depends on how you choose your subintervals, and where you choose your sample points. Let

$$\mathbb{P} = (n, x_1, x_2, \dots, x_{n-1}, x_1^*, x_2^*, \dots, x_n^*)$$

denote these choices.

Let  $\mathcal{I}(\mathbb{P})$  be the approximation that arises from  $\mathbb{P}$ :

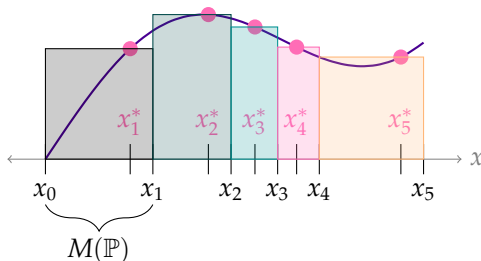
$$\mathcal{I}(\mathbb{P}) = \sum_{i=1}^n f(x_i^*)(x_i - x_{i-1})$$



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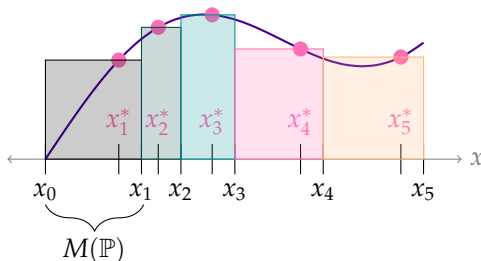
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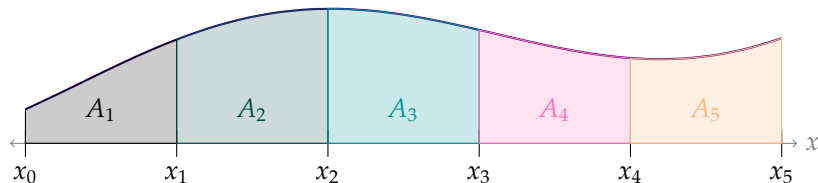
Let  $M(\mathbb{P})$  be the maximum width of any subinterval.  
If  $M(\mathbb{P})$  is small, then *every* subinterval is small (narrow).

Define the integral as the limit

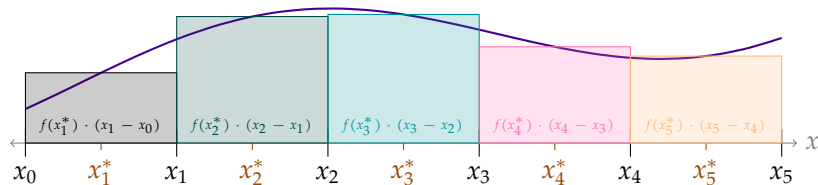
$$\int_a^b f(x) \, dx = \lim_{M(\mathbb{P}) \rightarrow 0} \mathcal{I}(\mathbb{P})$$

(Compare to our previous Riemann sum definition.)

We will show that the limit exists and is equal to the signed area under the curve.



Actual area:  $\int_a^b f(x) \, dx = \sum_{i=1}^n A_i$



Approximation:  $\mathcal{I}(\mathbb{P}) = \sum_{i=1}^n f(x_i^*) \cdot (x_i - x_{i-1})$

$$\begin{aligned}
 \underbrace{\left| \int_a^b f(x) \, dx - \mathcal{I}(\mathbb{P}) \right|}_{\text{overall error}} &= \left| \sum_{i=1}^n A_i - \sum_{i=1}^n f(x_i^*) \cdot (x_i - x_{i-1}) \right| \\
 &= \left| \sum_{i=1}^n [A_i - f(x_i^*) \cdot (x_i - x_{i-1})] \right|
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 &= \sum_{i=1}^n F \cdot (x_i - x_{i-1}) \cdot (x_i - x_{i-1}) \\
 &\leq \sum_{i=1}^n F \cdot M(\mathbb{P}) \cdot (x_i - x_{i-1})
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 &= F \cdot M(\mathbb{P}) \cdot \sum_{i=1}^n (x_i - x_{i-1}) \\
 &= F \cdot M(\mathbb{P}) \cdot (b - a)
 \end{aligned}$$

$$0 \leq \underbrace{\left| \int_a^b f(x) \, dx - \mathcal{I}(\mathbb{P}) \right|}_{\text{overall error}} \leq F \cdot M(\mathbb{P}) \cdot (b - a)$$

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$$\lim_{M(\mathbb{P}) \rightarrow 0} [F \cdot M(\mathbb{P}) \cdot (b - a)] = 0$$

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So, by the squeeze theorem,

$$\lim_{M(\mathbb{P}) \rightarrow 0} \underbrace{\left| \int_a^b f(x) \, dx - \mathcal{I}(\mathbb{P}) \right|}_{\text{overall error}} = 0$$

That is,

$$\lim_{M(\mathbb{P}) \rightarrow 0} \mathcal{I}(\mathbb{P}) = \int_a^b f(x) \, dx$$



# COMPARING DEFINITIONS

Here, we defined

$$\int_a^b f(x) \, dx = \lim_{M(\mathbb{P}) \rightarrow 0} \mathcal{I}(\mathbb{P})$$

for “nice” functions  $f(x)$ .

Originally, we used a slightly different definition:

## Definition 1.1.9 (abridged)

For “nice” functions  $f(x)$ :

$$\int_a^b f(x) \, dx = \lim_{n \rightarrow \infty} \sum_{i=1}^n f(x_{i,n}^*) \cdot \frac{b-a}{n}$$

when the limit exists and takes the same value for all choices of the  $x_{i,n}^*$ 's.

# COMPARING DEFINITIONS

We showed that **all** families of partitions “work,” as long as their largest subintervals shrink to length 0.

If all families of partitions “work,” then we might as well choose a simple one. The (arguably) simplest choices are regular partitions, cutting the interval  $[a, b]$  into  $n$  subintervals of length  $\frac{b-a}{n}$ .