

7 Integration

8 Integration II

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Mathematics
and Statistics

$$\int_M d\omega = \int_{\partial M} \omega$$

Mathematics 3A03 Real Analysis I

Instructor: David Earn

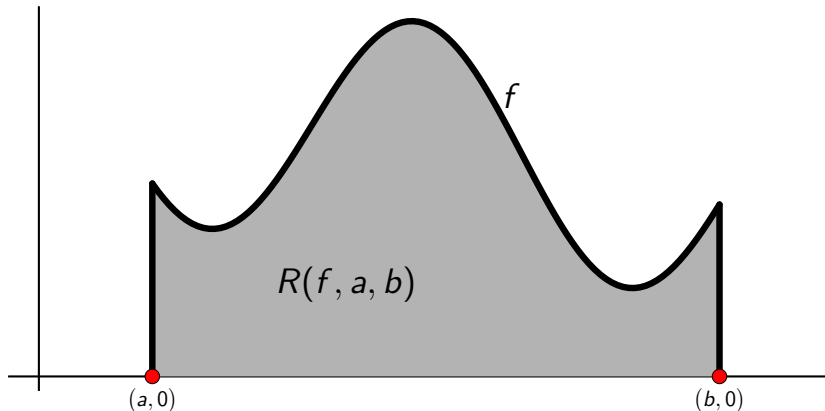
Lecture 7
Integration
Wednesday 22 January 2025

Announcements

- Solutions to [Assignment 1](#) were posted last night.
- Kieran will have office hours tomorrow (Thursday) for two hours, 12:30–2:30 pm. (He will not have a Friday office hour this week.)

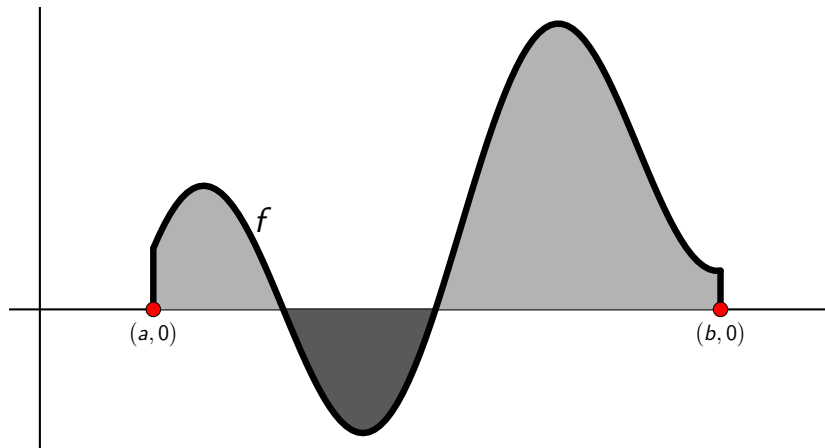
Integration

Integration



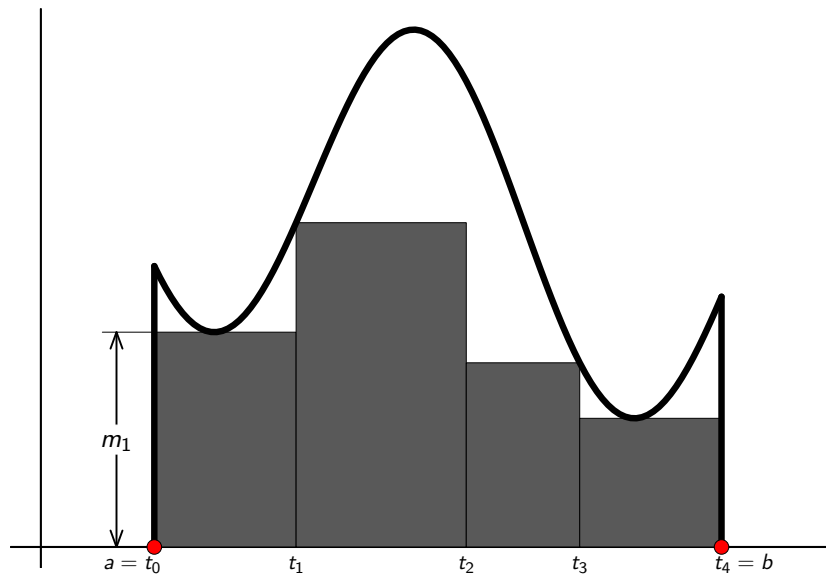
- “Area of region $R(f, a, b)$ ” is actually a very subtle concept.
- We will only scratch the surface of it (greater depth in Math 4A).
- Our treatment is similar to that in Michael Spivak’s “Calculus” (2008); BS refer to this approach as the Darboux integral (BS §7.4, p. 225).
- The Darboux and Riemann approaches to the integral are equivalent.

Integration

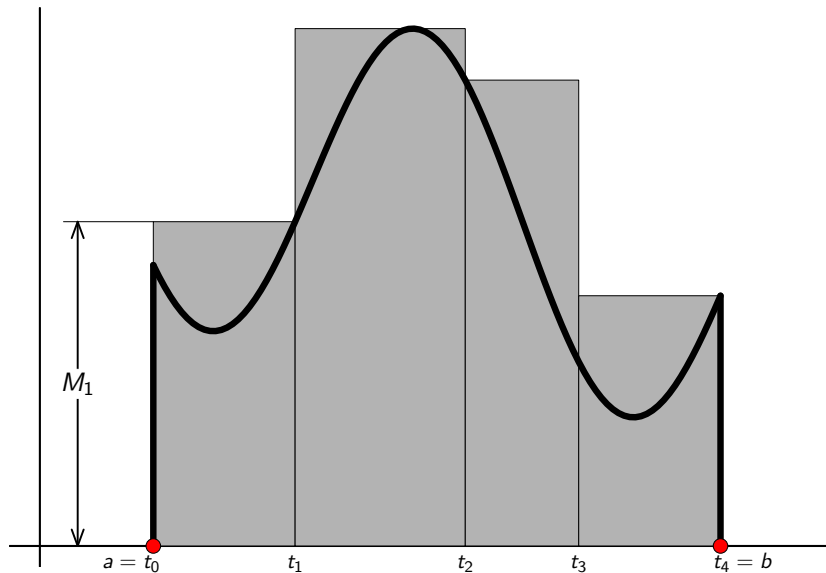


- Contribution to “area of $R(f, a, b)$ ” is positive or negative depending on whether f is positive or negative.

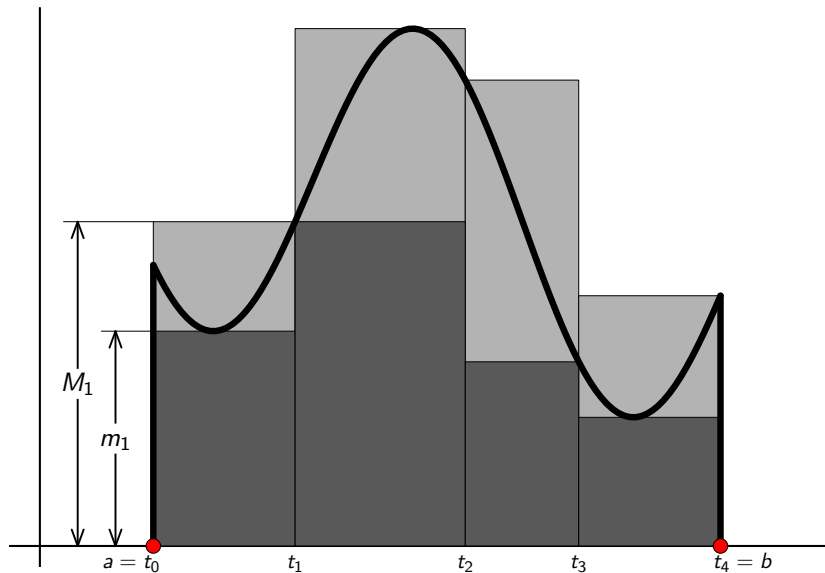
Lower sum



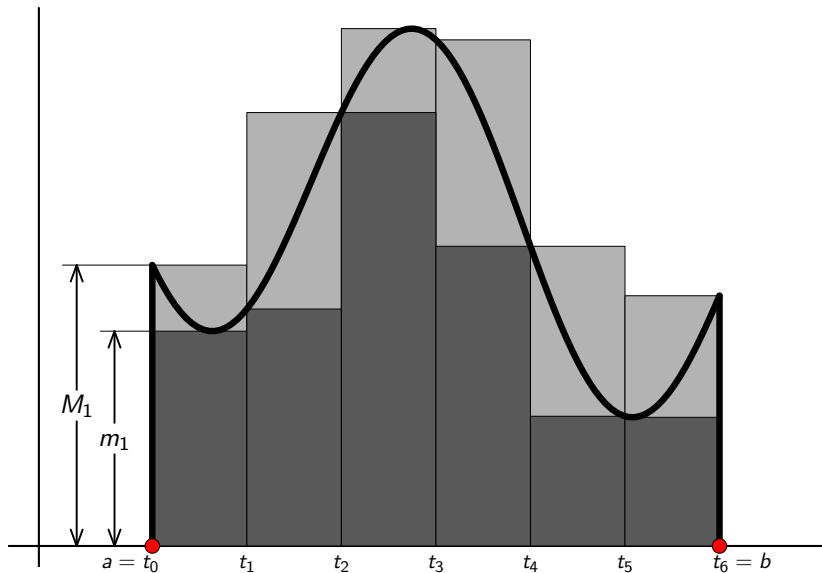
Upper sum



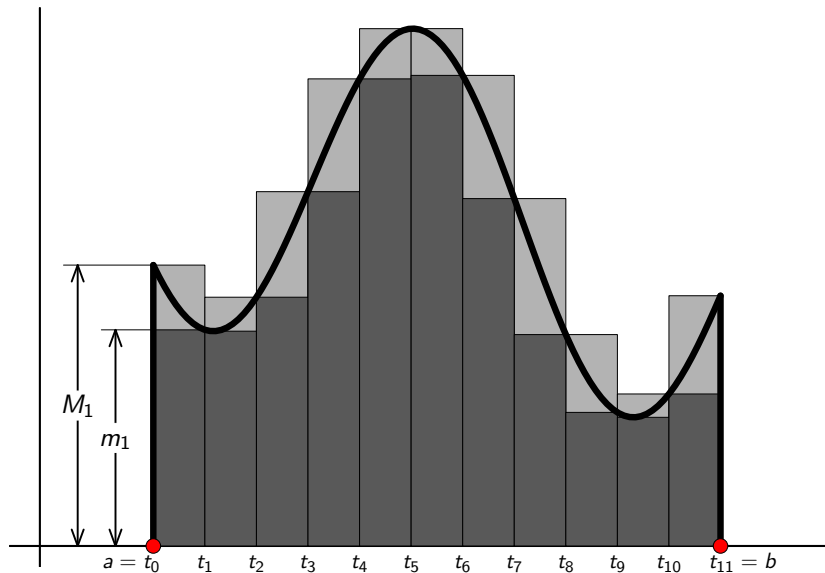
Lower and upper sums



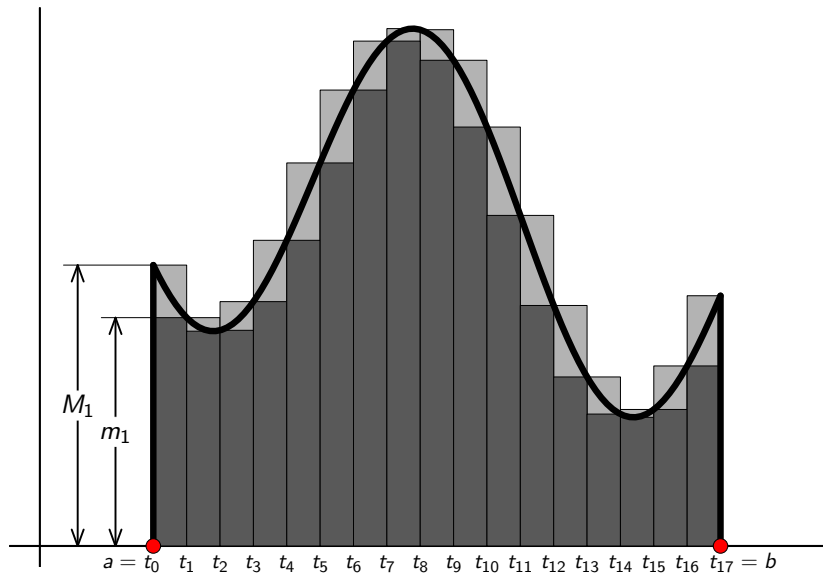
Lower and upper sums



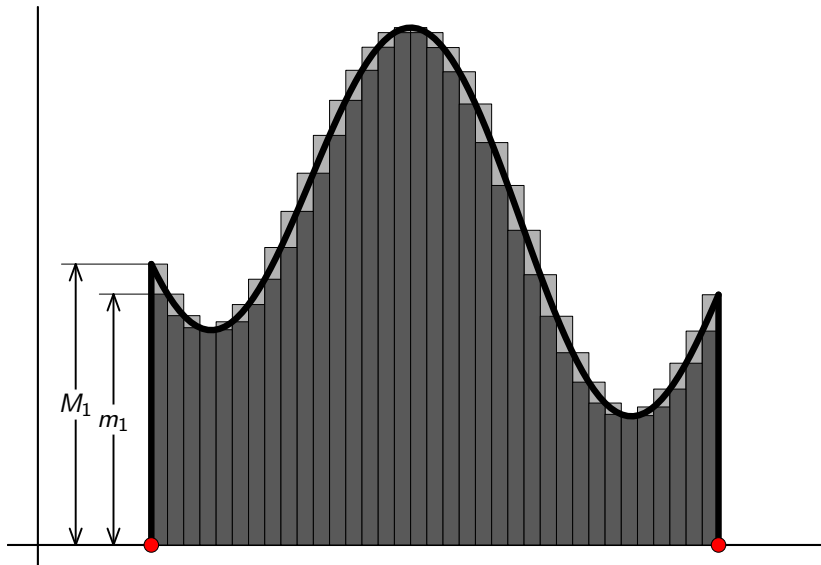
Lower and upper sums



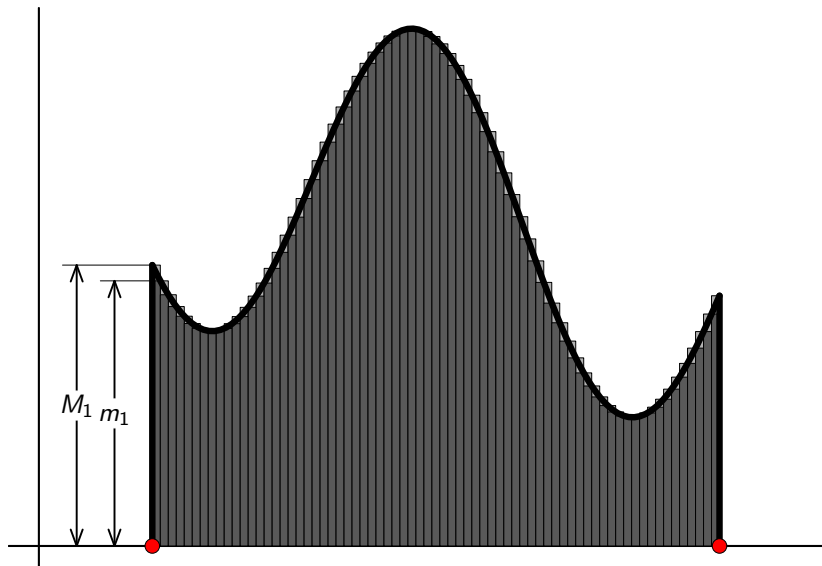
Lower and upper sums



Lower and upper sums



Lower and upper sums



Rigorous development of the integral

Definition (Partition)

Let $a < b$. A **partition** of the interval $[a, b]$ is a finite collection of points in $[a, b]$, one of which is a , and one of which is b .

We normally label the points in a partition

$$a = t_0 < t_1 < \cdots < t_{n-1} < t_n = b,$$

so the i^{th} subinterval in the partition is

$$[t_{i-1}, t_i].$$

Rigorous development of the integral

Definition (Lower and upper sums)

Suppose f is bounded on $[a, b]$ and $P = \{t_0, \dots, t_n\}$ is a **partition** of $[a, b]$. Recalling the **motivating sketch**, let

$$m_i = \inf \{ f(x) : x \in [t_{i-1}, t_i] \},$$

$$M_i = \sup \{ f(x) : x \in [t_{i-1}, t_i] \}.$$

The **lower sum** of f for P , denoted by $L(f, P)$, is defined as

$$L(f, P) = \sum_{i=1}^n m_i(t_i - t_{i-1}).$$

The **upper sum** of f for P , denoted by $U(f, P)$, is defined as

$$U(f, P) = \sum_{i=1}^n M_i(t_i - t_{i-1}).$$

Rigorous development of the integral

Relationship between motivating sketch and rigorous definition of lower and upper sums:

- The **lower and upper sums** correspond to the total areas of rectangles lying below and above the graph of f in our **motivating sketch**.
- However, these sums have been defined precisely without any appeal to a concept of “area”.
- The requirement that f be bounded on $[a, b]$ is essential in order to be sure that all the m_i and M_i are well-defined.
- It is also essential that the m_i and M_i be defined as inf's and sup's (rather than maxima and minima) because f was not assumed to be continuous.

Rigorous development of the integral

Relationship between motivating sketch and rigorous definition of lower and upper sums:

- Since $m_i \leq M_i$ for each i , we have

$$m_i(t_i - t_{i-1}) \leq M_i(t_i - t_{i-1}), \quad i = 1, \dots, n.$$

∴ For any partition P of $[a, b]$ we have

$$L(f, P) \leq U(f, P),$$

because

$$L(f, P) = \sum_{i=1}^n m_i(t_i - t_{i-1}),$$
$$U(f, P) = \sum_{i=1}^n M_i(t_i - t_{i-1}).$$

Poll

- Go to
https://www.childsmath.ca/childsa/forms/main_login.php
- Click on **Math 3A03**
- Click on **Take Class Poll**
- Fill in poll **Integrals: Lower and Upper Sums**
- .

Rigorous development of the integral

Relationship between motivating sketch and rigorous definition of lower and upper sums:

- More generally, if P_1 and P_2 are any two partitions of $[a, b]$, it ought to be true that

$$L(f, P_1) \leq U(f, P_2),$$

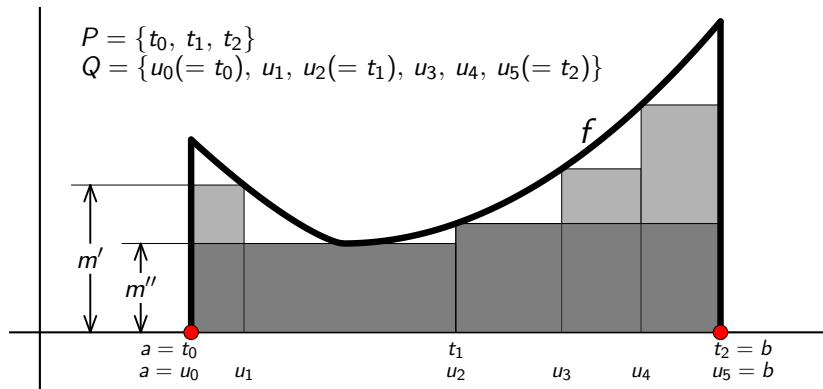
because $L(f, P_1)$ should be \leq area of $R(f, a, b)$, and $U(f, P_2)$ should be \geq area of $R(f, a, b)$.

- But “ought to” and “should be” prove nothing, especially since we haven’t yet even defined “area of $R(f, a, b)$ ”.
- Before we can *define* “area of $R(f, a, b)$ ”, we need to prove that $L(f, P_1) \leq U(f, P_2)$ for any partitions $P_1, P_2 \dots$

Rigorous development of the integral

Lemma (Partition Lemma)

If *partition* $P \subseteq$ *partition* Q (i.e., if every point of P is also in Q), then $L(f, P) \leq L(f, Q)$ and $U(f, P) \geq U(f, Q)$.



Rigorous development of the integral

Proof of Partition Lemma

As a first step, consider the special case in which the finer partition Q contains only one more point than P :

$$P = \{t_0, \dots, t_n\},$$

$$Q = \{t_0, \dots, t_{k-1}, u, t_k, \dots, t_n\},$$

where

$$a = t_0 < t_1 < \dots < t_{k-1} < u < t_k < \dots < t_n = b.$$

Because $[t_{k-1}, t_k]$ is split by u , we have two lower bounds:

$$m' = \inf \{ f(x) : x \in [t_{k-1}, u] \},$$

$$m'' = \inf \{ f(x) : x \in [u, t_k] \}.$$

... continued ...

Rigorous development of the integral

Proof of Partition Lemma (cont.)

Then
$$L(f, P) = \sum_{i=1}^n m_i(t_i - t_{i-1}),$$

and
$$\begin{aligned} L(f, Q) &= \sum_{i=1}^{k-1} m_i(t_i - t_{i-1}) + m'(u - t_{k-1}) \\ &\quad + m''(t_k - u) + \sum_{i=k+1}^n m_i(t_i - t_{i-1}). \end{aligned}$$

\therefore To prove $L(f, P) \leq L(f, Q)$, it is enough to show

$$m_k(t_k - t_{k-1}) \leq m'(u - t_{k-1}) + m''(t_k - u).$$

... continued ...

Rigorous development of the integral

Proof of Partition Lemma (cont.)

Now note that since

$$\{f(x) : x \in [t_{k-1}, u]\} \subseteq \{f(x) : x \in [t_{k-1}, t_k]\},$$

the RHS might contain some additional smaller numbers, so we must have

$$\begin{aligned} m_k &= \inf \{f(x) : x \in [t_{k-1}, t_k]\} \\ &\leq \inf \{f(x) : x \in [t_{k-1}, u]\} = m'. \end{aligned}$$

Thus, $m_k \leq m'$, and, similarly, $m_k \leq m''$.

$$\begin{aligned} \therefore m_k(t_k - t_{k-1}) &= m_k(t_k - u + u - t_{k-1}) \\ &= m_k(u - t_{k-1}) + m_k(t_k - u) \\ &\leq m'(u - t_{k-1}) + m''(t_k - u), \end{aligned}$$

... continued ...

Rigorous development of the integral

Proof of Partition Lemma (cont.)

which proves (in this special case where Q contains only one more point than P) that $L(f, P) \leq L(f, Q)$.

We can now prove the general case by adding one point at a time.

If Q contains ℓ more points than P , define a sequence of partitions

$$P = P_0 \subset P_1 \subset \cdots \subset P_\ell = Q$$

such that P_{j+1} contains exactly one more point than P_j . Then

$$L(f, P) = L(f, P_0) \leq L(f, P_1) \leq \cdots \leq L(f, P_\ell) = L(f, Q),$$

so $L(f, P) \leq L(f, Q)$.

(Proving $U(f, P) \geq U(f, Q)$ is similar: check!)



Rigorous development of the integral

Theorem (Partition Theorem)

Let P_1 and P_2 be any two partitions of $[a, b]$. If f is bounded on $[a, b]$ then

$$L(f, P_1) \leq U(f, P_2).$$

Proof.

This is a straightforward consequence of the [partition lemma](#).

Let $P = P_1 \cup P_2$, i.e., P is the partition obtained by combining all the points of P_1 and P_2 .

Then

$$L(f, P_1) \leq L(f, P) \leq U(f, P) \leq U(f, P_2).$$



Rigorous development of the integral

Important inferences that follow from the **partition theorem**:

- For any partition P' , the upper sum $U(f, P')$ is an upper bound for the set of all lower sums $L(f, P)$.

$$\therefore \sup \{L(f, P) : P \text{ a partition of } [a, b]\} \leq U(f, P') \quad \forall P'$$

$$\therefore \sup \{L(f, P)\} \leq \inf \{U(f, P)\}$$

\therefore For any partition P' ,

$$L(f, P') \leq \sup \{L(f, P)\} \leq \inf \{U(f, P)\} \leq U(f, P')$$

- If $\sup \{L(f, P)\} = \inf \{U(f, P)\}$ then we can define “**area of $R(f, a, b)$** ” to be this number.

- Is it possible that $\sup \{L(f, P)\} < \inf \{U(f, P)\}$?

Poll

- Go to https://www.childsmath.ca/childsa/forms/main_login.php
- Click on **Math 3A03**
- Click on **Take Class Poll**
- Fill in poll **Integrals: $\sup \{L(f, P)\} < \inf \{U(f, P)\} ?$**
- .



Mathematics
and Statistics

$$\int_M d\omega = \int_{\partial M} \omega$$

Mathematics 3A03 Real Analysis I

Instructor: David Earn

Lecture 8
Integration II
Friday 24 January 2025

Announcements

- **Assignment 2** will be posted either during, or soon after, the weekend.
- Kieran's office hours going forward are as follows:
 - Thursday 12:30–1:30 (Math Café)
 - Friday 12:30–1:30 (HH 207)

Poll

- Go to https://www.childsmath.ca/childsa/forms/main_login.php
- Click on **Math 3A03**
- Click on **Take Class Poll**
- Fill in poll **Integrals: $\sup \{L(f, P)\} < \inf \{U(f, P)\} ?$
(AGAIN!)**
- .

Rigorous development of the integral

Example

$\exists? f : [a, b] \rightarrow \mathbb{R}$ (bounded) $\nexists \sup \{L(f, P)\} < \inf \{U(f, P)\}$

$$\text{Let } f(x) = \begin{cases} 1 & x \in \mathbb{Q} \cap [a, b], \\ 0 & x \in \mathbb{Q}^c \cap [a, b]. \end{cases}$$

Consider any partition P of $[a, b]$.

If $P = \{t_0, \dots, t_n\}$ then $m_i = 0 \forall i$ ($\because [t_{i-1}, t_i] \cap \mathbb{Q}^c \neq \emptyset$),
and $M_i = 1 \forall i$ ($\because [t_{i-1}, t_i] \cap \mathbb{Q} \neq \emptyset$).

$\therefore L(f, P) = 0$ and $U(f, P) = b - a$ for **any** partition P .

$\therefore \sup \{L(f, P)\} = 0 < b - a = \inf \{U(f, P)\}$. □

Can we define “area of $R(f, a, b)$ ” for such a weird function?

Yes, but not in this course!

Rigorous development of the integral

Definition (Integrable)

A function $f : [a, b] \rightarrow \mathbb{R}$ is said to be *integrable* on $[a, b]$ if it is bounded on $[a, b]$ and

$$\begin{aligned} & \sup\{L(f, P) : P \text{ a partition of } [a, b]\} \\ & = \inf\{U(f, P) : P \text{ a partition of } [a, b]\}. \end{aligned}$$

In this case, this common number is called the *integral* of f on $[a, b]$ and is denoted

$$\int_a^b f$$

Note: If f is integrable then for any partition P we have

$$L(f, P) \leq \int_a^b f \leq U(f, P),$$

and $\int_a^b f$ is the unique number with this property.

Rigorous development of the integral

■ Notation:

$$\int_a^b f(x) dx \quad \text{means precisely the same as} \quad \int_a^b f.$$

- The symbol “ dx ” has no meaning in isolation just as “ $x \rightarrow$ ” has no meaning except in $\lim_{x \rightarrow a} f(x)$.
- It is not clear from the definition which functions are **integrable**.
- The definition of the **integral** does not itself indicate how to compute the integral of any given **integrable** function. So far, without a lot more effort, we can't say much more than these two things:
 - 1 If $f(x) \equiv c$ then f is **integrable** on $[a, b]$ and $\int_a^b f = c \cdot (b - a)$.
 - 2 The **weird example** function is not **integrable**.

Rigorous development of the integral

- Bartle and Sherbert refer to functions that are **integrable** according to our definition as ***Darboux integrable*** (BS §7.4, p. 225).
- BS develop the integral using one value of the function within each subinterval of a partition, rather than starting with upper and lower sums. They refer to functions that are integrable in this sense as ***Riemann integrable***.
- BS also prove (BS **Theorem 7.4.11**, p. 232) that a function is Riemann integrable if and only if it is Darboux integrable. So the two definitions are, in fact, equivalent.
- In Math 4A03 you will define ***Lebesgue integrable***, a more subtle concept that makes it possible to attach meaning to “area of $R(f, a, b)$ ” for the **weird example** function (among others), and to precisely characterize functions that are Riemann integrable.

Rigorous development of the integral

Theorem (Equivalent " ε - P " criterion for integrability)

A bounded function $f : [a, b] \rightarrow \mathbb{R}$ is *integrable* on $[a, b]$ iff for all $\varepsilon > 0$ there is a partition P of $[a, b]$ such that

$$U(f, P) - L(f, P) < \varepsilon.$$

(BS Theorem 7.4.8, p. 229)

Note: This theorem is just a restatement of the definition of *integrability*. It is often more convenient to work with $\varepsilon > 0$ than with sup's and inf's.

Rigorous development of the integral

Proof of equivalence of “sup = inf” and “ ε - P ” definitions of integrability.

(\implies) Suppose the bounded function f is integrable, i.e.,

$$\begin{aligned} & \sup\{L(f, P) : P \text{ a partition of } [a, b]\} \\ &= \inf\{U(f, P) : P \text{ a partition of } [a, b]\} = \int_a^b f \end{aligned}$$

Given $\varepsilon > 0$, since $\int_a^b f$ is the least upper bound of the lower sums, there is a partition P_1 such that

$$\int_a^b f = \sup_{P'}\{L(f, P')\} < L(f, P_1) + \frac{\varepsilon}{2},$$

i.e., such that
$$-L(f, P_1) < -\int_a^b f + \frac{\varepsilon}{2}. \quad (\heartsuit)$$

... continued...

Rigorous development of the integral

Proof of equivalence of “ $\sup = \inf$ ” and “ ε - P ” definitions of integrability.

Similarly, there is a partition P_2 such that

$$U(f, P_2) < \inf_{P'} \{U(f, P')\} + \frac{\varepsilon}{2} = \int_a^b f + \frac{\varepsilon}{2}. \quad (\diamond)$$

Therefore, putting together inequalities (\diamond) and (\heartsuit) , we have

$$U(f, P_2) - L(f, P_1) < \int_a^b f + \frac{\varepsilon}{2} - \int_a^b f + \frac{\varepsilon}{2} = \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon.$$

But that's not quite **what we need**. We need, for a *single* partition P ,

$$U(f, P) - L(f, P) < \varepsilon.$$

How should we proceed?

Hint: Recall the **partition lemma** ...

... continued...

Rigorous development of the integral

Proof of equivalence of “ $\sup = \inf$ ” and “ ε - P ” definitions of integrability.

Let $P = P_1 \cup P_2$. Then the **partition lemma** implies that $L(f, P) \geq L(f, P_1)$, and $U(f, P) \leq U(f, P_2)$, so

$$\begin{aligned} U(f, P) - L(f, P) &\leq U(f, P_2) - L(f, P_1) \\ &< \int_a^b f + \frac{\varepsilon}{2} - \int_a^b f + \frac{\varepsilon}{2} = \varepsilon, \end{aligned}$$

which completes the proof that $\sup = \inf \implies \varepsilon$ - P .

(\Leftarrow) We now need to show that if a bounded function f satisfies the ε - P definition of integrability then it also satisfies the $\sup = \inf$ definition of integrability.

Given $\varepsilon > 0$, we can choose a partition P (depending on ε) such that

$$U(f, P) - L(f, P) < \varepsilon.$$

... continued ...

Rigorous development of the integral

Proof of equivalence of "sup = inf" and " ε - P " definitions of integrability.

Now, for any partition, and in particular for P , we have

$$L(f, P) \leq \sup_{P'} \{L(f, P')\} \leq \inf_{P'} \{U(f, P')\} \leq U(f, P),$$

We can temporarily write this more simply as

$$L \leq S \leq I \leq U$$

Subtracting S from this chain of inequalities implies

$$L - S \leq 0 \leq I - S \leq U - S$$

Now note that $L \leq S$ implies $U - S \leq U - L$, so we have

$$0 \leq I - S \leq U - L$$

i.e., $0 \leq \inf_{P'} \{U(f, P')\} - \sup_{P'} \{L(f, P')\} \leq U(f, P) - L(f, P) < \varepsilon$.

But by hypothesis, such a partition P can be found for any given $\varepsilon > 0$.

Therefore, $\inf_{P'} \{U(f, P')\} = \sup_{P'} \{L(f, P')\}$. □

Rigorous development of the integral

Example

Suppose $b > 0$ and $f(x) = x$ for all $x \in \mathbb{R}$. Prove, using only the definition of the integral via $\sup = \inf$ or ε - P , that

$$\int_0^b f = \frac{b^2}{2}.$$

(This exercise should help you appreciate the Fundamental Theorem of Calculus.)

Note: If working through the above example doesn't convince you of the power of the Fundamental Theorem of Calculus, try computing $\int_0^b x^2 dx$ directly from the definition of the integral.



Mathematics
and Statistics

$$\int_M d\omega = \int_{\partial M} \omega$$

Mathematics 3A03 Real Analysis I

Instructor: David Earn

Lecture 9
Integration III
Monday 27 January 2025

Announcements

- **Assignment 2** has been posted on the course web site.
 - The participation deadline is Monday 3 Feb 2025 @ 11:25am.
- On Friday this week, the class will be a Q&A session with the TA. It's a great opportunity to ask questions about Assignment 2, or anything else.

Last time . . .

Rigorous development of the integral:

- Definition: **integrable**.
- Example: **non-integrable function**.
- Theorem: Equivalent “ ϵ - P ” definition of integrable.
- Note: The different equivalent definitions are most convenient in different contexts, e.g.,
 - Proving non-integrability of the **weird example** was easiest using the **sup-inf** definition.
 - Computing the value of $\int_0^b x \, dx$ is easiest using the ϵ - P definition.

Poll

- Go to https://www.childsmath.ca/childs/math/forms/main_login.php
- Click on **Math 3A03**
- Click on **Take Class Poll**
- Fill in poll **Integrals: Integrable vs Continuous vs Differentiable**
- .

Integral theorems

Theorem (continuous \implies integrable)

If f is continuous on $[a, b]$ then f is *integrable* on $[a, b]$.

Rough work to prepare for proof:

$$U(f, P) - L(f, P) = \sum_{i=1}^n (M_i - m_i)(t_i - t_{i-1})$$

Given $\varepsilon > 0$, choose a partition P that is so fine that $M_i - m_i < \varepsilon$ for all i (possible because f is continuous and bounded). Then

$$U(f, P) - L(f, P) < \varepsilon \sum_{i=1}^n (t_i - t_{i-1}) = \varepsilon(b - a).$$

Not quite what we want. So choose the partition P such that $M_i - m_i < \varepsilon/(b - a)$ for all i . To get that, choose P such that

$$|f(x) - f(y)| < \frac{\varepsilon}{2(b - a)} \quad \text{if } |x - y| < \max_{1 \leq i \leq n} (t_i - t_{i-1}),$$

which we can do because f is uniformly continuous on $[a, b]$.

Integral theorems

Proof that continuous \implies integrable (cont.)

Since f is continuous on the closed interval $[a, b]$, it is bounded on $[a, b]$ (which is the first requirement to be integrable on $[a, b]$).

Also, since f is continuous on $[a, b]$, it is uniformly continuous on $[a, b]$. $\therefore \forall \varepsilon > 0 \exists \delta > 0$ such that $\forall x, y \in [a, b]$,

$$|x - y| < \delta \implies |f(x) - f(y)| < \frac{\varepsilon}{2(b - a)}.$$

Now choose a partition of $[a, b]$ such that the length of each subinterval $[t_{i-1}, t_i]$ is less than δ , i.e., $t_i - t_{i-1} < \delta$. Then, for any $x, y \in [t_{i-1}, t_i]$, we have $|x - y| < \delta$ and therefore

... continued ...

Integral theorems

Proof that continuous \implies integrable (cont.)

$$|f(x) - f(y)| < \frac{\varepsilon}{2(b-a)} \quad \forall x, y \in [t_{i-1}, t_i].$$

$$\therefore M_i - m_i \leq \frac{\varepsilon}{2(b-a)} < \frac{\varepsilon}{b-a} \quad i = 1, \dots, n.$$

Since this is true for all i , it follows that

$$\begin{aligned} U(f, P) - L(f, P) &= \sum_{i=1}^n (M_i - m_i)(t_i - t_{i-1}) \\ &< \frac{\varepsilon}{b-a} \sum_{i=1}^n (t_i - t_{i-1}) = \frac{\varepsilon}{b-a} (b-a) = \varepsilon. \end{aligned}$$

□

Properties of the integral

Theorem (Integral segmentation)

Let $a < c < b$. If f is *integrable* on $[a, b]$, then f is *integrable* on $[a, c]$ and on $[c, b]$. Conversely, if f is *integrable* on $[a, c]$ and $[c, b]$ then f is *integrable* on $[a, b]$. Finally, if f is *integrable* on $[a, b]$ then

$$\int_a^b f = \int_a^c f + \int_c^b f. \quad (\heartsuit)$$

(a good exercise)

This theorem motivates these definitions:

$$\int_a^a f = 0 \quad \text{and} \quad \text{if } a > b \quad \text{then} \quad \int_a^b f = - \int_b^a f.$$

Then (\heartsuit) holds for any $a, b, c \in \mathbb{R}$.

Properties of the integral

Theorem (Algebra of integrals – a.k.a. \int_a^b is a linear operator)

If f and g are *integrable* on $[a, b]$ and $c \in \mathbb{R}$ then $f + g$ and cf are *integrable* on $[a, b]$ and

$$\mathbf{1} \quad \int_a^b (f + g) = \int_a^b f + \int_a^b g;$$

$$\mathbf{2} \quad \int_a^b cf = c \int_a^b f.$$

(proofs are relatively easy; good exercises) (BS [Theorem 7.1.5](#), p. 204)

Properties of the integral

Theorem (Integral of a product)

If f and g are *integrable* on $[a, b]$ then fg is *integrable* on $[a, b]$.

(compared to *integral of a sum*, proof is much harder; tough exercise)

Note:

- There is no “product rule” for integrals. While f and g integrable does imply fg integrable, we cannot write the integral of the product fg in terms of the integrals of the factors f and g .
- The closest we can come to a product formula is integration by parts, which arises from the Fundamental Theorem of Calculus together with the product rule for *derivatives*.

Properties of the integral

Lemma (Integral bounds)

Suppose f is integrable on $[a, b]$. If $m \leq f(x) \leq M$ for all $x \in [a, b]$ then

$$m(b - a) \leq \int_a^b f \leq M(b - a).$$

Proof.

For any partition P , we must have $m \leq m_i \forall i$ and $M \geq M_i \forall i$.

$$\therefore m(b - a) \leq L(f, P) \leq U(f, P) \leq M(b - a) \quad \forall P$$

$$\begin{aligned} \therefore m(b - a) &\leq \sup\{L(f, P)\} = \int_a^b f = \inf\{U(f, P)\} \\ &\leq M(b - a). \end{aligned}$$



Properties of the integral

Theorem (Integrals are continuous)

If f is *integrable* on $[a, b]$ and F is defined on $[a, b]$ by

$$F(x) = \int_a^x f,$$

then F is continuous on $[a, b]$.

Proof

Let's first consider $x_0 \in [a, b)$ and show F is continuous from above at x_0 , i.e., $\lim_{x \rightarrow x_0^+} F(x) = F(x_0)$. If $x \in (x_0, b]$ then

$$(\heartsuit) \quad \implies \quad F(x) - F(x_0) = \int_a^x f - \int_a^{x_0} f = \int_{x_0}^x f. \quad (*)$$

... continued ...

Properties of the integral

Proof that integrals are continuous (cont.)

Since f is **integrable** on $[a, b]$, it is bounded on $[a, b]$, so $\exists M > 0$ such that

$$-M \leq f(x) \leq M \quad \forall x \in [a, b],$$

from which the **integral bounds lemma** implies

$$-M(x - x_0) \leq \int_{x_0}^x f \leq M(x - x_0),$$

$$\therefore (*) \implies -M(x - x_0) \leq F(x) - F(x_0) \leq M(x - x_0).$$

\therefore For any $\varepsilon > 0$, we can ensure $|F(x) - F(x_0)| < \varepsilon$ by requiring $0 \leq x - x_0 < \varepsilon/M$, which proves $\lim_{x \rightarrow x_0^+} F(x) = F(x_0)$.

A similar argument starting from $x_0 \in (a, b]$ and $x \in [a, x_0)$ yields $\lim_{x \rightarrow x_0^-} F(x) = F(x_0)$. Thus, “integrals are continuous”. \square



Mathematics
and Statistics

$$\int_M d\omega = \int_{\partial M} \omega$$

Mathematics 3A03 Real Analysis I

Instructor: David Earn

Lecture 10
Integration IV
Wednesday 29 January 2025

Announcements

- **Assignment 2** has been posted on the course web site.
 - The participation deadline is Monday 3 Feb 2025 @ 11:25am.
- On Friday this week, the class will be a Q&A session with the TA. It's a great opportunity to ask questions about Assignment 2, or anything else.
- The poll for Assignment 2 participation will open after class today until 11:25am on Monday.
- I have an office hour today, 2:00-3:00 pm.

Last time...

Rigorous development of the integral:

- continuous \implies integrable.
- Integral segmentation.
- Algebra of integrals.
- Integral bounds lemma.
- Integrals are continuous.

Fundamental Theorem of Calculus

Theorem (First Fundamental Theorem of Calculus – FFTC)

Let f be *integrable* on $[a, b]$, and define F on $[a, b]$ by

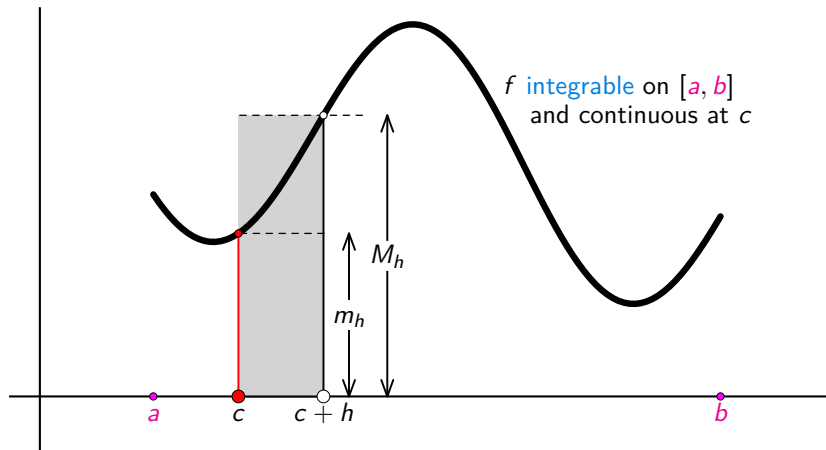
$$F(x) = \int_a^x f.$$

If f is continuous at $c \in [a, b]$, then F is differentiable at c , and

$$F'(c) = f(c).$$

- If $c = a$ or $c = b$, then $F'(c)$ is understood to mean the right- or left-hand derivative of F .
- The “*integrals are continuous*” theorem implies that F is continuous on all of $[a, b]$. The FFTC says, in addition, that F is differentiable at the single point c .
- The FFTC implies that if f is continuous on all of $[a, b]$ then F is differentiable on all of $[a, b]$.

Fundamental Theorem of Calculus

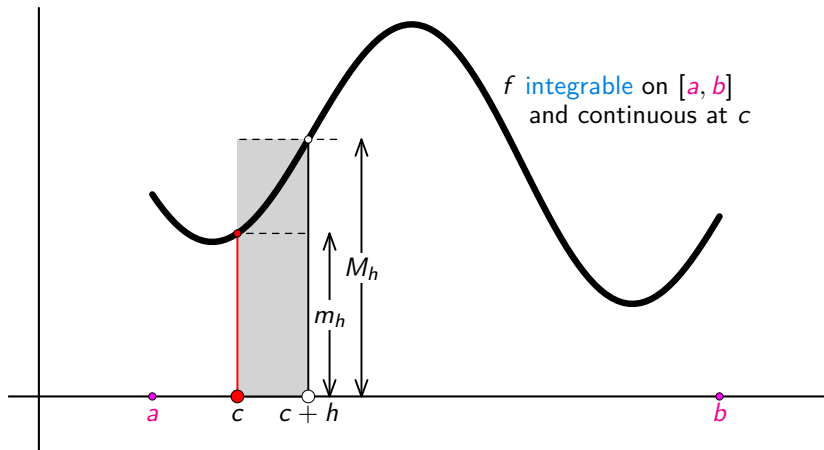


$$F(c+h) - F(c) \simeq f(c+h) \cdot h$$

$$\text{and } \lim_{h \rightarrow 0} f(c+h) = f(c)$$

$$\implies \lim_{h \rightarrow 0} \frac{F(c+h) - F(c)}{h} = f(c)$$

Fundamental Theorem of Calculus

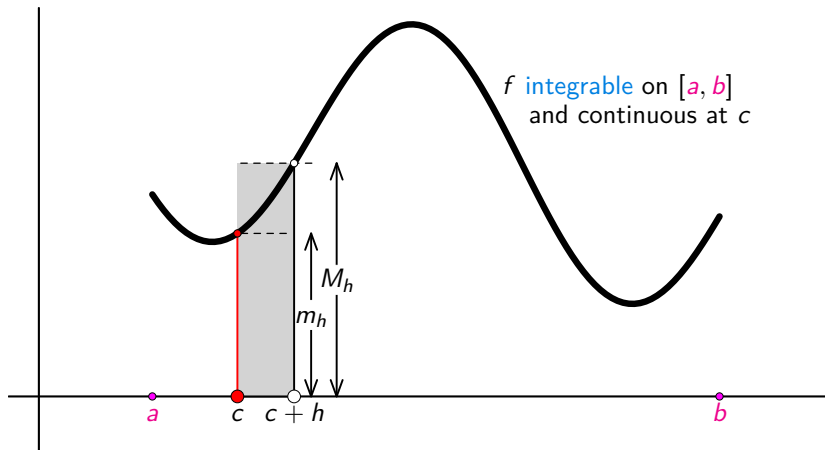


$$F(c+h) - F(c) \simeq f(c+h) \cdot h$$

$$\text{and } \lim_{h \rightarrow 0} f(c+h) = f(c)$$

$$\implies \lim_{h \rightarrow 0} \frac{F(c+h) - F(c)}{h} = f(c)$$

Fundamental Theorem of Calculus

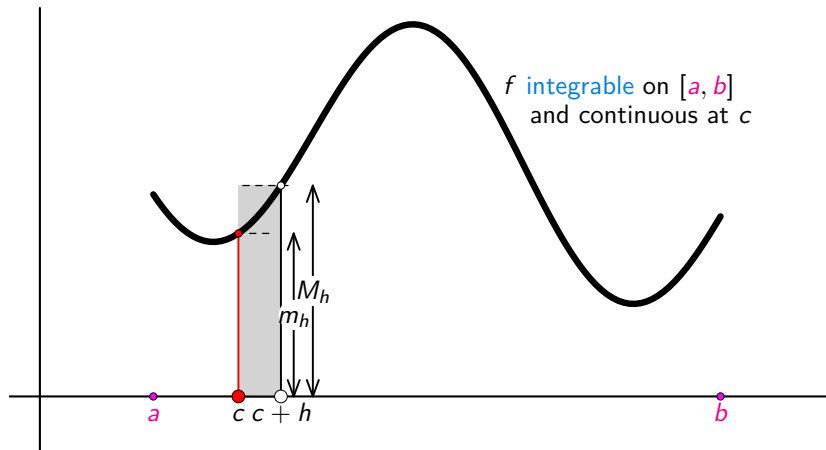


$$F(c+h) - F(c) \simeq f(c+h) \cdot h$$

$$\text{and } \lim_{h \rightarrow 0} f(c+h) = f(c)$$

$$\implies \lim_{h \rightarrow 0} \frac{F(c+h) - F(c)}{h} = f(c)$$

Fundamental Theorem of Calculus



$$F(c+h) - F(c) \simeq f(c+h) \cdot h$$

$$\text{and } \lim_{h \rightarrow 0} f(c+h) = f(c)$$

$$\implies \lim_{h \rightarrow 0} \frac{F(c+h) - F(c)}{h} = f(c)$$

Fundamental Theorem of Calculus

Proof of First Fundamental Theorem of Calculus

Suppose $c \in [a, b)$, and $0 < h \leq b - c$. Then the [integral segmentation theorem](#) implies that

$$F(c+h) - F(c) = \int_a^{c+h} f - \int_a^c f = \int_c^{c+h} f.$$

Motivated by the [sketch](#), define

$$m_h = \inf \{ f(x) : x \in [c, c+h] \},$$

$$M_h = \sup \{ f(x) : x \in [c, c+h] \}.$$

Then the [integral bounds lemma](#) implies

$$m_h \cdot h \leq \int_c^{c+h} f \leq M_h \cdot h,$$

... continued ...

Fundamental Theorem of Calculus

Proof of First Fundamental Theorem of Calculus (cont.)

and hence

$$m_h \leq \frac{F(c+h) - F(c)}{h} \leq M_h.$$

This inequality is true for any integrable function. However, because f is continuous at c , we have

$$\lim_{h \rightarrow 0^+} m_h = f(c) = \lim_{h \rightarrow 0^+} M_h,$$

so the squeeze theorem (BS Theorem 4.2.6, p. 114) implies

$$F'_+(c) = \lim_{h \rightarrow 0^+} \frac{F(c+h) - F(c)}{h} = f(c).$$

A similar argument for $c \in (a, b]$ and $-(c-a) \leq h < 0$ yields $F'_-(c) = f(c)$. □

Fundamental Theorem of Calculus

Corollary

If f is continuous on $[a, b]$ and $f = g'$ for some function g , then

$$\int_a^b f = g(b) - g(a).$$

Proof.

Let $F(x) = \int_a^x f$. Then $\forall x \in [a, b]$, $F'(x) = f(x)$ (by FFTC).
 $\implies F' = f = g'$.

$\therefore \exists c \in \mathbb{R}$ such that $F = g + c$ (Assignment 1).

$\therefore F(a) = g(a) + c$. But $F(a) = \int_a^a f = 0$, so $c = -g(a)$.

$\therefore F(x) = g(x) - g(a)$.

This is true, in particular, for $x = b$, so $\int_a^b f = g(b) - g(a)$. \square

Poll

- Go to
https://www.childsmath.ca/childsa/forms/main_login.php
- Click on **Math 3A03**
- Click on **Take Class Poll**
- Fill in poll **Integrals: Fundamental Theorem of Calculus**
- .

Fundamental Theorem of Calculus

Theorem (Second Fundamental Theorem of Calculus)

If f is *integrable* on $[a, b]$ and $f = g'$ for some function g , then

$$\int_a^b f = g(b) - g(a).$$

Notes:

- This looks like the *corollary* to the *first fundamental theorem*, except that f is assumed only to be *integrable*, not continuous.
- Recall from *Darboux's theorem* that if $f = g'$ for some g then f has the *intermediate value property*, but f need not be continuous.
- g' exists on $[a, b] \implies$ applies to g .
- The proof of the *second fundamental theorem* is completely different from the *corollary* to the first, because we cannot use the *first fundamental theorem* (which assumed f is continuous).

Fundamental Theorem of Calculus

Proof of Second Fundamental Theorem of Calculus

Let $P = \{t_0, \dots, t_n\}$ be any partition of $[a, b]$. By the Mean Value Theorem, for each $i = 1, \dots, n$, $\exists x_i \in [t_{i-1}, t_i]$ such that

$$g(t_i) - g(t_{i-1}) = g'(x_i)(t_i - t_{i-1}) = f(x_i)(t_i - t_{i-1}).$$

Define m_i and M_i as usual. Then $m_i \leq f(x_i) \leq M_i \forall i$, so

$$m_i(t_i - t_{i-1}) \leq f(x_i)(t_i - t_{i-1}) \leq M_i(t_i - t_{i-1}),$$

$$\text{i.e., } m_i(t_i - t_{i-1}) \leq g(t_i) - g(t_{i-1}) \leq M_i(t_i - t_{i-1}).$$

$$\therefore \sum_{i=1}^n m_i(t_i - t_{i-1}) \leq \sum_{i=1}^n (g(t_i) - g(t_{i-1})) \leq \sum_{i=1}^n M_i(t_i - t_{i-1})$$

$$\text{i.e., } L(f, P) \leq g(b) - g(a) \leq U(f, P)$$

for any partition P . $\therefore g(b) - g(a) = \int_a^b f.$ □

What useful things can we do with integrals?

- Compute areas of complicated shapes: find anti-derivatives and use the [second fundamental theorem of calculus](#).
- Define trigonometric functions (rigorously).
- Define logarithm and exponential functions (rigorously).



Mathematics
and Statistics

$$\int_M d\omega = \int_{\partial M} \omega$$

Mathematics 3A03 Real Analysis I

Instructor: David Earn

Lecture 11
Integration V
Monday 3 February 2025

Announcements

- The participation deadline for [Assignment 2](#) is today, Monday 3 Feb 2025 @ 11:25am.
- If you haven't participated yet, do the poll **now**.

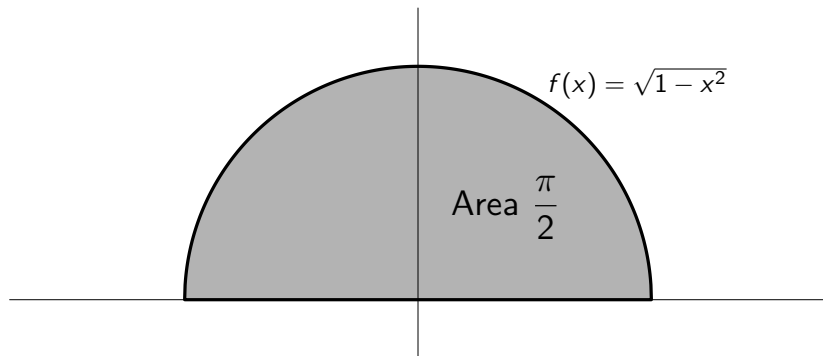
Last time...

Rigorous development of the integral

- First Fundamental Theorem of Calculus.
- Corollary to FFTC.
- Second Fundamental Theorem of Calculus.
- What can we do with the integral?

Poll

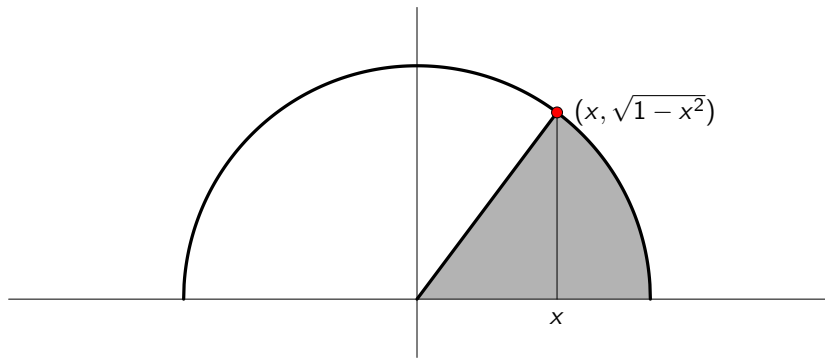
- Go to
https://www.childsmath.ca/childsa/forms/main_login.php
- Click on **Math 3A03**
- Click on **Take Class Poll**
- Fill in poll **What is π ?**
- .

What is π ?

Definition

$$\pi \equiv 2 \int_{-1}^1 \sqrt{1-x^2} \, dx .$$

What are cos and sin ?

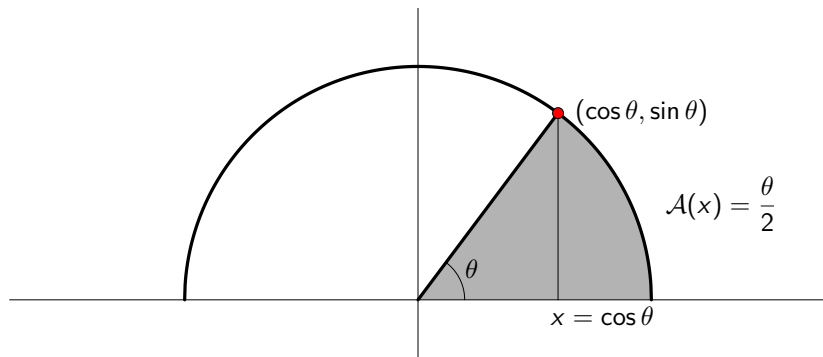


Definition (Sectoral area)

If $x \in [-1, 1]$ then
$$\mathcal{A}(x) = \frac{x\sqrt{1-x^2}}{2} + \int_x^1 \sqrt{1-t^2} dt.$$

Note: $\mathcal{A}(-1) = \pi/2$, $\mathcal{A}(1) = 0$.

What are cos and sin ?



Length of circular arc swept out by angle θ : θ

Area of sectoral region swept out by angle θ : $\theta/2$

So, if $\theta \in [0, \pi]$ then we define $\cos \theta$ to be the unique number in $[-1, 1]$ such that $\mathcal{A}(\cos \theta) = \theta/2$, and we define $\sin \theta$ to be $\sqrt{1 - (\cos \theta)^2}$.

We must prove: given $x \in [0, \pi] \exists! y \in [-1, 1]$ such that $\mathcal{A}(y) = x/2$.

What are cos and sin ?

Proof that $\forall x \in [0, \pi] \exists! y \in [-1, 1]$ such that $\mathcal{A}(y) = x/2$:

Existence: $\mathcal{A}(1) = 0$, $\mathcal{A}(-1) = \pi/2$, and \mathcal{A} is continuous. Hence by the **intermediate value theorem** $\exists y \in [-1, 1]$ such that $\mathcal{A}(y) = x/2$.

Uniqueness: \mathcal{A} is differentiable on $(-1, 1)$ and $\mathcal{A}'(x) < 0$ on $(-1, 1)$.
 \therefore On $(-1, 1)$, \mathcal{A} is decreasing, and hence one-to-one.

Definition (cos and sin)

If $x \in [0, \pi]$ then $\cos x$ is the unique number in $[-1, 1]$ such that $\mathcal{A}(\cos x) = x/2$, and $\sin x = \sqrt{1 - (\cos x)^2}$.

These definitions are easily extended to all of \mathbb{R} :

- For $x \in [\pi, 2\pi]$, define $\cos x = \cos(2\pi - x)$ and $\sin x = -\sin(2\pi - x)$.
- Then, for $x \in \mathbb{R} \setminus [0, 2\pi]$ define $\cos x = \cos(x \bmod 2\pi)$ and $\sin x = \sin(x \bmod 2\pi)$.

Trigonometric theorems

Given the **rigorous definition of cos and sin**, we can prove:

- 1 **cos** and **sin** are differentiable on \mathbb{R} . Moreover, $\cos' = -\sin$ and $\sin' = \cos$.
- 2 **sec**, **tan**, **csc** and **cot** can all be defined in the usual way and have all the usual properties.
- 3 The **inverse function theorem** allows us to define, and compute the derivatives of, all the inverse trigonometric functions.
- 4 If f is twice differentiable on \mathbb{R} , $f'' + f = 0$, $f(0) = a$ and $f'(0) = b$, then $f = a \cos + b \sin$.
- 5 For all $x, y \in \mathbb{R}$,

$$\sin(x + y) = \sin x \cos y + \cos x \sin y,$$

$$\cos(x + y) = \cos x \cos y - \sin x \sin y.$$

Something deep that you know enough to prove

Extra Challenge Problem: Prove that π is irrational.

Hint: Suppose $\pi^2 = \frac{a}{b}$, for $a, b \in \mathbb{N}$.

Show that the smallest positive root of \sin is irrational.

What are log and exp ?

Consider the function

$$f(x) = 10^x .$$

What exactly is this function?

In our mathematically naïve previous life, we just assumed that $f(x)$ is well-defined $\forall x \in \mathbb{R}$, and that f has a well-defined inverse function,

$$f^{-1}(x) = \log_{10}(x) .$$

But how are 10^x and $\log_{10}(x)$ defined for irrational x ?

Let's review what we know...

What are log and exp ?

$$n \in \mathbb{N} \implies 10^n = \underbrace{10 \cdots 10}_{n \text{ times}}$$

$$n, m \in \mathbb{N} \implies 10^n \cdot 10^m = 10^{n+m}$$

When we extend 10^x to $x \in \mathbb{Q}$, we want this product rule to be preserved:

$$10^0 \cdot 10^n = 10^{0+n} = 10^n \implies 10^0 = 1$$

$$10^{-n} \cdot 10^n = 10^0 = 1 \implies 10^{-n} = \frac{1}{10^n}$$

$$\underbrace{10^{1/n} \cdots 10^{1/n}}_{n \text{ times}} = 10^{\underbrace{1/n \cdots 1/n}_{n \text{ times}}} = 10^1 = 10 \implies 10^{1/n} = \sqrt[n]{10}$$

What are log and exp ?

Finally, to define 10^q for all $q \in \mathbb{Q}$, note that we must have

$$\left(10^{\frac{1}{n}}\right)^m = \underbrace{10^{\frac{1}{n}} \cdots 10^{\frac{1}{n}}}_{m \text{ times}} = 10^{\underbrace{\frac{1}{n} + \cdots + \frac{1}{n}}_{m \text{ times}}} = 10^{\frac{m}{n}} \quad \implies \quad 10^{\frac{m}{n}} \stackrel{\text{def}}{=} \left(\sqrt[n]{10}\right)^m$$

Now we're stuck. *How do we extend this scheme to irrational x ?*

We need a more sophisticated idea.

Let's try to find a function on all of \mathbb{R} that satisfies

$$f(x + y) = f(x) \cdot f(y), \quad \forall x, y \in \mathbb{R},$$

and $f(1) = 10.$

It then follows that $f(0) = 1$ and, $\forall x \in \mathbb{Q}$, $f(x) = [f(1)]^x.$

What additional properties can we impose on $f(x)$ that will lead us to a sensible definition of $f(x)$ for all $x \in \mathbb{R}$?