Announcements

- Assignment 3 is posted (and complete).
  Due Tuesday 22 October 2019 at 2:25pm via crowdmark.
- **Math 3A03 Test #1**
  Tuesday 29 October 2019, 5:30–7:00pm, in JHE 264
  (room is booked for 90 minutes; you should not feel rushed)
- Math 3A03 **Final Exam**: Fri 6 Dec 2019, 9:00am–11:30am
  Location: `MDCL 1105`

Continuous Functions

McMaster University

Mathematics and Statistics

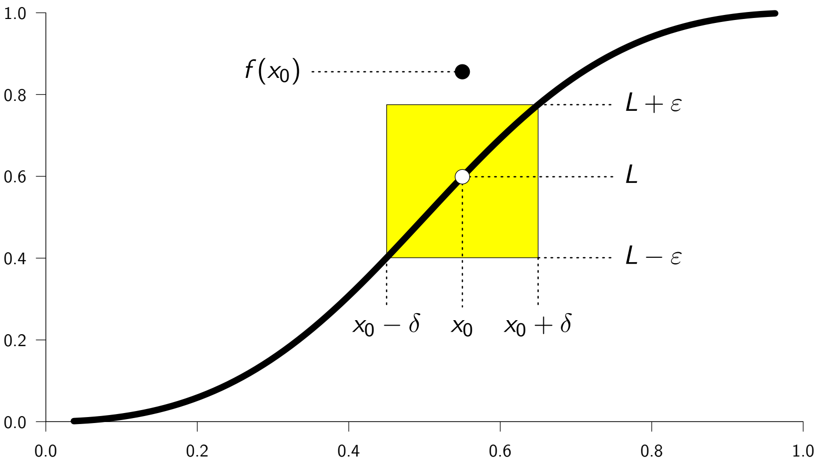
$$\int_M d\omega = \int_{\partial M} \omega$$

Mathematics 3A03
Real Analysis I

Instructor: David Earn

Lecture 18
Continuity
Friday 11 October 2019

Limits of functions



Limits of functions

Definition (Limit of a function on an interval (a, b))

Let $a < x_0 < b$ and $f : (a, b) \to \mathbb{R}$. Then f is said to ***approach the limit*** L ***as*** x ***approaches*** x_0, often written "$f(x) \to L$ as $x \to x_0$" or

$$\lim_{x \to x_0} f(x) = L\,,$$

iff for all $\varepsilon > 0$ there exists $\delta > 0$ such that if $0 < |x - x_0| < \delta$ then $|f(x) - L| < \varepsilon$.

Shorthand version:

$\forall \varepsilon > 0 \; \exists \delta > 0 \ni 0 < |x - x_0| < \delta \implies |f(x) - L| < \varepsilon$.

limitdefinterval

Limits of functions

The function f need not be defined on an entire interval. It is enough for f to be defined on a set with at least one accumulation point.

Definition (Limit of a function with domain $E \subseteq \mathbb{R}$)

Let $E \subseteq \mathbb{R}$ and $f : E \to \mathbb{R}$. Suppose x_0 is a point of accumulation of E. Then f is said to ***approach the limit*** L ***as*** x ***approaches*** x_0, *i.e.*,

$$\lim_{x \to x_0} f(x) = L\,,$$

iff for all $\varepsilon > 0$ there exists $\delta > 0$ such that if $x \in E$, $x \neq x_0$, and $|x - x_0| < \delta$ then $|f(x) - L| < \varepsilon$.

Shorthand version:

$$\forall \varepsilon > 0 \; \exists \delta > 0 \ni \; (x \in E \;\wedge\; 0 < |x - x_0| < \delta) \implies |f(x) - L| < \varepsilon.$$

Limits of functions

Example

Prove directly from the definition of a limit that

$$\lim_{x \to 3} (2x + 1) = 7 \,.$$

Proof that $2x + 1 \to 7$ as $x \to 3$.

We must show that $\forall \varepsilon > 0 \; \exists \delta > 0$ such that $0 < |x - 3| < \delta \implies |(2x + 1) - 7| < \varepsilon$. Given ε, to determine how to choose δ, note that

$$|(2x + 1) - 7| < \varepsilon \iff |2x - 6| < \varepsilon \iff 2\,|x - 3| < \varepsilon \iff |x - 3| < \frac{\varepsilon}{2}$$

Therefore, given $\varepsilon > 0$, let $\delta = \frac{\varepsilon}{2}$. Then $|x - 3| < \delta \implies |(2x + 1) - 7| = |2x - 6| = 2\,|x - 3| < 2\frac{\varepsilon}{2} = \varepsilon$, as required. $\square$

Limits of functions

Example

Prove directly from the definition of a limit that

$$\lim_{x \to 2} x^2 = 4\,.$$

(Solution on next slide)

Limits of functions

Proof that $x^2 \to 4$ as $x \to 2$.

We must show that $\forall \varepsilon > 0\ \exists \delta > 0$ such that $0 < |x-2| < \delta \implies |x^2 - 4| < \varepsilon$. Given ε, to determine how to choose δ, note that

$$\left|x^2 - 4\right| < \varepsilon \iff |(x-2)(x+2)| < \varepsilon \iff |x-2|\,|x+2| < \varepsilon.$$

We can make $|x-2|$ as small as we like by choosing δ sufficiently small. Moreover, if x is close to 2 then $x+2$ will be close to 4, so we should be able to ensure that $|x+2| < 5$. To see how, note that

$$\begin{aligned} |x+2| < 5 &\iff -5 < x+2 < 5 \iff -9 < x-2 < 1 \\ &\impliedby -1 < x-2 < 1 \iff |x-2| < 1\,. \end{aligned}$$

Therefore, given $\varepsilon > 0$, let $\delta = \min(1, \frac{\varepsilon}{5})$. Then $|x^2 - 4| = |(x-2)(x+2)| = |x-2|\,|x+2| < \frac{\varepsilon}{5}5 = \varepsilon$. □

Poll

- Go to https://www.childsmath.ca/childsa/forms/main_login.php
- Click on Math 3A03
- Click on Take Class Poll
- Fill in poll **Lecture 18: ε-δ definition of limit**
- `Submit`.

Limits of functions

Rather than the ε-δ definition, we can exploit our experience with sequences to define "$f(x) \to L$ as $x \to x_0$".

Definition (Limit of a function via sequences)

Let $E \subseteq \mathbb{R}$ and $f : E \to \mathbb{R}$. Suppose x_0 is a point of accumulation of E. Then

$$\lim_{x \to x_0} f(x) = L$$

iff for every sequence $\{e_n\}$ of points in $E \setminus \{x_0\}$,

$$\lim_{n\to\infty} e_n = x_0 \quad \Longrightarrow \quad \lim_{n\to\infty} f(e_n) = L\,.$$

Mathematics
and Statistics

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

Mathematics 3A03
Real Analysis I

Instructor: David Earn

Lecture 19
Continuity II
Tuesday 22 October 2019

Announcements

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  Tuesday 29 October 2019, 5:30–7:00pm, in JHE 264
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Last time...

- ε-δ definition of limit of a function
- Sequence definition of limit of a function

Poll

- Go to https://www.childsmath.ca/childsa/forms/main_login.php
- Click on Math 3A03
- Click on Take Class Poll
- Fill in poll **Lecture 19: ε-δ vs sequence definition of a limit**
- Submit.

Limits of functions

Lemma (Equivalence of limit definitions)

The ε-δ definition of limits and the sequence definition of limits are equivalent.

(proof on next two slides)

Note: The definition of a limit via sequences is sometimes easier to use than the ε-δ definition.

Proof of Equivalence of ε-δ definition and sequence definition of limit.

Proof (ε-$\delta \implies$ seq).

Suppose the ε-δ definition holds and $\{e_n\}$ is a sequence in $E \setminus \{x_0\}$ that converges to x_0. Given $\varepsilon > 0$, there exists $\delta > 0$ such that if $0 < |x - x_0| < \delta$ then $|f(x) - L| < \varepsilon$. But since $e_n \to x_0$, given $\delta > 0$, there exists $N \in \mathbb{N}$ such that, for all $n \geq N$, $|e_n - x_0| < \delta$. This means that if $n \geq N$ then $x = e_n$ satisfies $0 < |x - x_0| < \delta$, implying that we can put $x = e_n$ in the statement $|f(x) - L| < \varepsilon$. Hence, for all $n \geq N$, $|f(e_n) - L| < \varepsilon$. Thus,

$$e_n \to x_0 \implies f(e_n) \to L\,,$$

as required. □

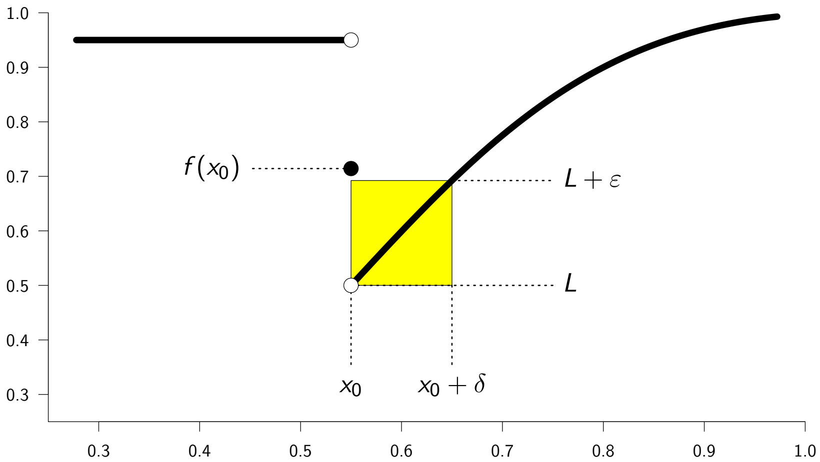
Proof of Equivalence of ε-δ definition and sequence definition of limit.

Proof (seq $\implies$ ε-δ) via contrapositive.

Suppose that as $x \to x_0$, $f(x) \not\to L$ according to the ε-δ definition. We must show that $f(x) \not\to L$ according to the sequence definition.

Since the ε-δ criterion does not hold, $\exists \varepsilon > 0$ such that $\forall \delta > 0$ there is some $x_\delta \in E$ for which $0 < |x_\delta - x_0| < \delta$ and yet $|f(x_\delta) - L| \geq \varepsilon$. This is true, in particular, for $\delta = 1/n$, where n is any natural number. Thus, $\exists \varepsilon > 0$ such that: $\forall n \in \mathbb{N}$, there exists $x_n \in E$ such that $0 < |x_n - x_0| < 1/n$ and yet $|f(x_n) - L| \geq \varepsilon$. This demonstrates that there is a sequence $\{x_n\}$ in $E \setminus \{x_0\}$ for which $x_n \to x_0$ and yet $f(x_n) \not\to L$. Hence, $f(x) \not\to L$ as $x \to x_0$ according to the sequence criterion, as required. □

One-sided limits



One-sided limits

Definition (Right-Hand Limit)

Let $f : E \to \mathbb{R}$ be a function with domain E and suppose that x_0 is a point of accumulation of $E \cap (x_0, \infty)$. Then we write

$$\lim_{x \to x_0^+} f(x) = L$$

if for every $\varepsilon > 0$ there is a $\delta > 0$ so that

$$|f(x) - L| < \varepsilon$$

whenever $x_0 < x < x_0 + \delta$ and $x \in E$.

One-sided limits

One-sided limits can also be expressed in terms of sequence convergence.

Definition (Right-Hand Limit – sequence version)

Let $f : E \to \mathbb{R}$ be a function with domain E and suppose that x_0 is a point of accumulation of $E \cap (x_0, \infty)$. Then we write

$$\lim_{x \to x_0^+} f(x) = L$$

if for every <u>decreasing</u> sequence $\{e_n\}$ of points of E with $e_n > x_0$ and $e_n \to x_0$ as $n \to \infty$,

$$\lim_{n \to \infty} f(e_n) = L\,.$$

Infinite limits

Definition (Right-Hand Infinite Limit)

Let $f : E \to \mathbb{R}$ be a function with domain E and suppose that x_0 is a point of accumulation of $E \cap (x_0, \infty)$. Then we write

$$\lim_{x \to x_0^+} f(x) = \infty$$

if for every $M > 0$ there is a $\delta > 0$ such that $f(x) \geq M$ whenever $x_0 < x < x_0 + \delta$ and $x \in E$.

Properties of limits

There are theorems for limits of functions of a real variable that correspond (and have similar proofs) to the various results we proved for limits of sequences:

- Uniqueness of limits
- Algebra of limits
- Order properties of limits
- Limits of absolute values
- Limits of Max/Min

See Chapter 5 of textbook for details.

Limits of compositions of functions

When is $\lim_{x\to x_0} g(f(x)) = g\Big(\lim_{x\to x_0} f(x)\Big)$?

Theorem (Limit of composition)

Suppose

$$\lim_{x\to x_0} f(x) = L\,.$$

If g is a function defined in a neighborhood of the point L and

$$\lim_{z\to L} g(z) = g(L)$$

then

$$\lim_{x\to x_0} g(f(x)) = g\Big(\lim_{x\to x_0} f(x)\Big) = g(L)\,.$$

(Textbook (TBB) §5.2.5)

Limits of compositions of functions – more generally

Note: It is a little more complicated to generalize the statement of this theorem so as to minimize the set on which g must be defined but the proof is no more difficult.

Theorem (Limit of composition)

Let $A, B \subseteq \mathbb{R}$, $f : A \to \mathbb{R}$, $f(A) \subseteq B$, and $g : B \to \mathbb{R}$. Suppose x_0 is an accumulation point of A and

$$\lim_{x \to x_0} f(x) = L\,.$$

Suppose further that g is defined at L. If L is an accumulation point of B and

$$\lim_{z \to L} g(z) = g(L)\,,$$

or $\exists \delta > 0$ *such that $f(x) = L$ for all $x \in (x_0 - \delta, x_0 + \delta) \cap A$, then*

$$\lim_{x \to x_0} g\big(f(x)\big) = g\Big(\lim_{x \to x_0} f(x)\Big) = g(L)\,.$$

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Mathematics and Statistics

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

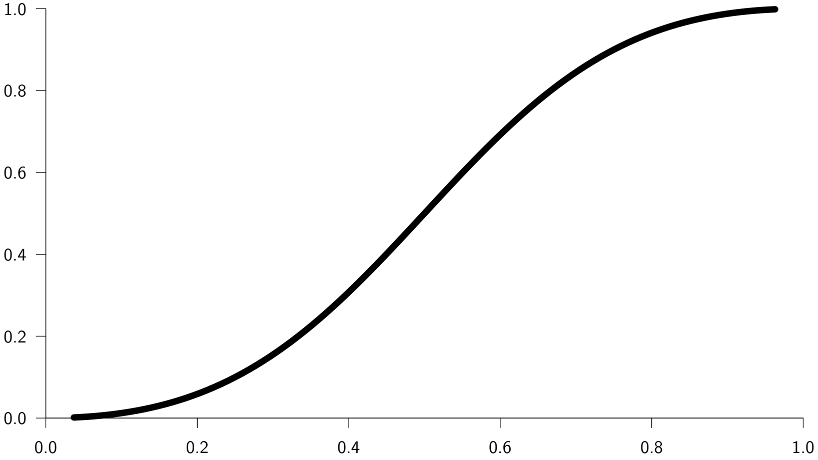
Mathematics 3A03
Real Analysis I

Instructor: David Earn

Lecture 20
Continuity III
Thursday 24 October 2019

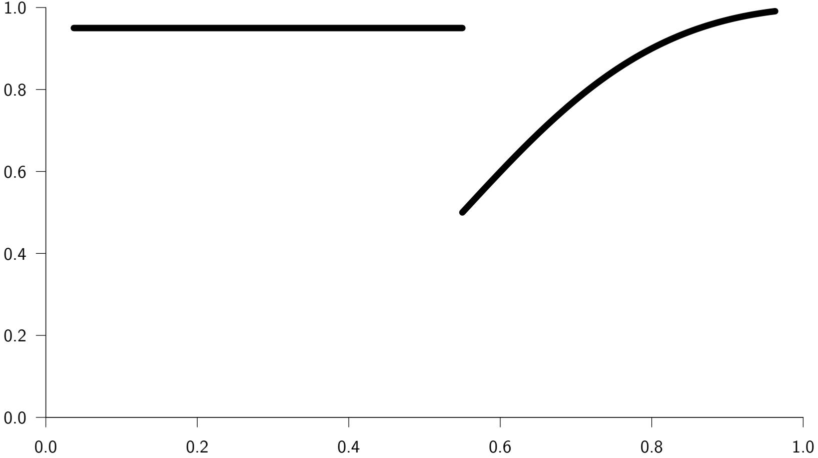
Continuity

Intuitively, a function f is ***continuous*** if you can draw its graph without lifting your pencil from the paper. . .



Continuity

and ***discontinuous*** otherwise. . .



Continuity

In order to develop a rigorous foundation for the theory of functions, we need to be more precise about what we mean by "continuous".

The main challenge is to define "continuity" in a way that works consistently on sets other than intervals (and generalizes to spaces that are more abstract than $\mathbb{R}$).

We will define:

- continuity at a single point;
- continuity on an open interval;
- continuity on a closed interval;
- continuity on more general sets.

Pointwise continuity

Definition (Continuous at an interior point of the domain of f)

If the function f is defined in a neighbourhood of the point x_0 then we say f is ***continuous at x_0*** iff

$$\lim_{x \to x_0} f(x) = f(x_0)\,.$$

This definition works more generally provided x_0 is a point of accumulation of the domain of f (notation: $\mathrm{dom}(f)$).

We will also consider a function to be continuous at any isolated point in its domain.

Pointwise continuity

Definition (Continuous at any $x_0 \in \mathrm{dom}(f)$ – limit version)

If $x_0 \in \mathrm{dom}(f)$ then f is ***continuous at*** x_0 iff x_0 is either an isolated point of $\mathrm{dom}(f)$ or x_0 is an accumulation point of $\mathrm{dom}(f)$ and $\lim_{x \to x_0} f(x) = f(x_0)$.

Definition (Continuous at any $x_0 \in \mathrm{dom}(f)$ – sequence version)

If $x_0 \in \mathrm{dom}(f)$ then f is ***continuous at*** x_0 iff for any sequence $\{x_n\}$ in $\mathrm{dom}(f)$, if $x_n \to x_0$ then $f(x_n) \to f(x_0)$.

Definition (Continuous at any $x_0 \in \mathrm{dom}(f)$ – ε-δ version)

If $x_0 \in \mathrm{dom}(f)$ then f is ***continuous at*** x_0 iff for any $\varepsilon > 0$ there exists $\delta > 0$ such that if $x \in \mathrm{dom}(f)$ and $|x - x_0| < \delta$ then $|f(x) - f(x_0)| < \varepsilon$.

Pointwise continuity

Example

Suppose $f : A \to \mathbb{R}$. In which cases is f continuous on A?

- $A = (0,1) \cup \{2\}, \quad f(x) = x;$
- $A = \{0\} \cup \{\frac{1}{n} : n \in \mathbb{N}\} \cup \{2\}, \quad f(x) = x;$
- $A = \{\frac{1}{n} : n \in \mathbb{N}\} \cup \{2\}, \quad f(x) =$ whatever you like.

Example

Is it possible for a function f to be discontinuous at every point of $\mathbb{R}$ and yet for its restriction to the rational numbers ($f|_{\mathbb{Q}}$) to be continuous at every point in $\mathbb{Q}$?

Extra Challenge Problem:

Prove or disprove: There is a function $f : \mathbb{R} \to \mathbb{R}$ that is continuous at every irrational number and discontinuous at every rational number.

Continuity on an interval

Definition (Continuous on an open interval)

The function f is said to be ***continuous on*** (a, b) iff

$$\lim_{x \to x_0} f(x) = f(x_0) \qquad \text{for all } x_0 \in (a, b)\,.$$

Definition (Continuous on a closed interval)

The function f is said to be ***continuous on*** $[a, b]$ iff it is continuous on the open interval (a, b), and

$$\lim_{x \to a^+} f(x) = f(a) \qquad \text{and} \qquad \lim_{x \to b^-} f(x) = f(b)\,.$$

Continuity on an arbitrary set $E \subseteq \mathbb{R}$

Definition (Continuous on a set E)

The function f is said to be ***continuous on*** E iff f is continuous at each point $x \in E$.

Example

- Every polynomial is continuous on $\mathbb{R}$.
- Every rational function is continuous on its domain (*i.e.*, avoiding points where the denominator is zero).

These facts are painful to prove directly from the definition.
But they follow easily if from the theorem on the algebra of limits.

Continuity of compositions of functions

Theorem (Continuity of $f \circ g$ at a point)

If g is continuous at x_0 and f is continuous at $g(x_0)$ then $f \circ g$ is continuous at x_0.

Consequently, if g is continuous at x_0 and f is continuous at $g(x_0)$ then

$$\lim_{x \to x_0} f(g(x)) = f\Big(\lim_{x \to x_0} g(x)\Big).$$

Theorem (Continuity of $f \circ g$ on a set)

If g is continuous on $A \subseteq \mathbb{R}$ and f is continuous on $g(A)$ then $f \circ g$ is continuous on A.

Continuity of compositions of functions

Example

Use the theorem on continuity of $f \circ g$, and the theorem on the algebra of limits, to prove that

1. the polynomial $x^8 + x^3 + 2$ is continuous on $\mathbb{R}$;
2. the rational function $\dfrac{x^2+2}{x^2-2}$ is continuous on $\mathbb{R} \setminus \{-\sqrt{2}, \sqrt{2}\}$.
3. the function $\sqrt{\dfrac{x^2+2}{x^2-2}}$ is continuous on its domain.

Mathematics and Statistics

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

Mathematics 3A03
Real Analysis I

Instructor: David Earn

Lecture 21
Continuity IV
Friday 25 October 2019

Announcements

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  Location: `MDCL 1105`

Last time. . .

- Continuity at a point and on a set.
- Continuity of compositions.

Uniform continuity

In the ε-δ definition of continuity, the δ that must exist depends on ε **AND** on the point x_0, *i.e.,* $\delta = \delta(f, \varepsilon, x_0)$.

Definition (Uniformly continuous)

If $f : A \to \mathbb{R}$ then f is said to be ***uniformly continuous on A*** iff for every $\varepsilon > 0$ there exists $\delta > 0$ such that if $x, y \in A$ and $|x - y| < \delta$ then $|f(x) - f(y)| < \varepsilon$.

Note: This is a stronger form of continuity: Given any $\varepsilon > 0$, there is a single $\delta > 0$ that works for the entire set A.
(δ still depends on f and ε.)

Uniform continuity

Example

Prove that $f(x) = 2x + 1$ is uniformly continuous on $\mathbb{R}$.

Proof.

We must show that $\forall \varepsilon > 0$, $\exists \delta > 0$ such that if $x, y \in \mathbb{R}$ and $|x - y| < \delta$ then $|(2x + 1) - (2y + 1)| < \varepsilon$. But note that

$$|(2x+1) - (2y+1)| = |2x - 2y| = 2\,|x - y| \;,$$

so if we choose $\delta = \varepsilon/2$ then we have

$$|(2x+1) - (2y+1)| = 2\,|x - y| < 2 \cdot \frac{\varepsilon}{2} = \varepsilon\,,$$

as required. □

Uniform continuity

Example

Prove that $f(x) = \sqrt{x}$ is uniformly continuous on $[\frac{1}{8}, 1]$.

Proof.

We must show that $\forall \varepsilon > 0$, $\exists \delta > 0$ such that if $x, y \in [\frac{1}{8}, 1]$ and $|x - y| < \delta$ then $\left|\sqrt{x} - \sqrt{y}\right| < \varepsilon$. But note that

$$\left|\sqrt{x} - \sqrt{y}\right| = \left|\left(\sqrt{x} - \sqrt{y}\right)\frac{\sqrt{x}+\sqrt{y}}{\sqrt{x}+\sqrt{y}}\right|$$

$$= \left|\frac{x-y}{\sqrt{x}+\sqrt{y}}\right| \leq \left|\frac{x-y}{\sqrt{\frac{1}{8}}+\sqrt{\frac{1}{8}}}\right| = \left|\frac{x-y}{\frac{1}{\sqrt{2}}}\right| = \sqrt{2}\,|x-y| \,,$$

so taking $\delta = \varepsilon/\sqrt{2}$, we have $\quad \left|\sqrt{x} - \sqrt{y}\right| < \sqrt{2} \cdot \frac{\varepsilon}{\sqrt{2}} = \varepsilon.$ □

Uniform continuity

Example

Is $f(x) = \sqrt{x}$ uniformly continuous on $[0, 1]$?

Note: The proof on the previous slide fails if the lower limit is 0, but that doesn't establish that the function is not uniformly continuous.
Either we must find a different proof that works for the whole interval $[0, 1]$, or we must show that $\exists\varepsilon > 0$ such that $\forall\delta > 0$, $\exists x, y \in [0, 1]$ such that $|x - y| < \delta$ and yet $\left|\sqrt{x} - \sqrt{y}\right| \geq \varepsilon$.

Poll

- Go to https://www.childsmath.ca/childsa/forms/main_login.php
- Click on Math 3A03
- Click on Take Class Poll
- Fill in poll **Lecture 21: Is $f(x) = \sqrt{x}$ uniformly continuous on $[0,1]$?**
- Submit.

Uniform continuity

Theorem (Cont. on a closed interval $\implies$ unif. cont.)

If $f : [a, b] \to \mathbb{R}$ is continuous then f is uniformly continuous.

(Textbook (TBB) Theorem 5.48, p. 323)

Theorem (Unif. cont. on a bounded interval $\implies$ bounded)

If f is uniformly continuous on a bounded interval I then f is bounded on I.

Corollary (Continuous on a closed interval $\implies$ bounded)

If $f : [a, b] \to \mathbb{R}$ is continuous then f is bounded.

Proof.

Combine the above two theorems. □