

Continuous Functions

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1 Continuous Functions

Text excerpts remixed from Vladimir A. Zorich - Mathematical Analysis I as well as Stephen Abbott - Understanding Analysis.

“Let f be a real-valued function defined in a neighborhood of a point $a \in \mathbb{R}$. In intuitive terms, the function f is continuous at a if its value $f(x)$ approaches the value $f(a)$ that it assumes at the point a itself as x gets nearer to a .” (V. A. Zorich)

Definition 1 (Continuity of a function). A function $f : D \subseteq \mathbb{R} \rightarrow \mathbb{R}$ is *continuous at the point* $a \in D$ if

$$\boxed{\forall \epsilon > 0 \quad \exists \delta > 0 \quad \forall x \in D : \quad (|x - a| < \delta \Rightarrow |f(x) - f(a)| < \epsilon)}$$

If f is continuous at every point in the domain D , then we say that f is *continuous on* D .

2 Examples

Here, we give a few examples of continuous functions alongside the respective proofs.

2.1 The constant function is continuous

Theorem 1. *Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a function given by $f(x) := c$, where $c \in \mathbb{R}$. That is, f is a constant function. Then f is continuous at every point $a \in \mathbb{R}$.*

Proof. Let $a \in \mathbb{R}$ be an arbitrary point where we want to show that $f : \mathbb{R} \rightarrow \mathbb{R}, x \mapsto c$ is continuous. Let $\varepsilon > 0$. We choose $\delta := 1 > 0$. Let $x \in \mathbb{R}$. Then:

$$|f(x) - f(a)| = |c - c| = |0| = 0 < \varepsilon$$

With that, the implication also holds true since its conclusion is always true (as shown above) irregardless of the premise.

$$|x - a| < \delta \Rightarrow |f(x) - f(a)| = 0 < \varepsilon$$

Therefore, f is continuous at a . □

2.2 Functions $x \mapsto mx + y_0$ are continuous

Theorem 2. *Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a function given by $f(x) := m \cdot x + y_0$, where $m, y_0 \in \mathbb{R}$. Then f is continuous at every point $a \in \mathbb{R}$.*

Proof. Let $a \in \mathbb{R}$ be an arbitrary point where we want to show that $f : \mathbb{R} \rightarrow \mathbb{R}, x \mapsto m \cdot x + y_0$ is continuous.

We first consider the simpler case where the slope is 0, that is $\mathbf{m} = \mathbf{0}$. Then our function is given by $f(x) = y_0$ for all $x \in \mathbb{R}$. This is a constant function and we have already shown that constant functions are continuous. Therefore, f is continuous at a when $m = 0$.

Now to the more interesting case where $\mathbf{m} \neq \mathbf{0}$. Let $\varepsilon > 0$. We choose $\delta := \frac{\varepsilon}{|m|}$. Since $\varepsilon > 0$ and $|m| > 0$, we have $\delta > 0$.

Let $x \in \mathbb{R}$ and $|x - a| < \delta$. Then:

$$\begin{aligned} |f(x) - f(a)| &= |(m \cdot x + y_0) - (m \cdot a + y_0)| \\ &= |m \cdot x - m \cdot a| \\ &= |m \cdot (x - a)| \\ &= |m| \cdot |x - a| \\ &< |m| \cdot \delta = |m| \cdot \frac{\varepsilon}{|m|} = \varepsilon \end{aligned}$$

In the last line, we have used the fact that $|x - a| < \delta$ and then used our definition of δ .

The argument shows that $|f(x) - f(a)| < \varepsilon$, which proves the continuity of f at a . □

2.3 The parabola is continuous

Theorem 3. *Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by $f(x) := x^2$. That is, f is a parabola. Then f is continuous at every point $a \in \mathbb{R}$.*

Proof. Let $a \in \mathbb{R}$ be an arbitrary point where we want to show that $f : \mathbb{R} \rightarrow \mathbb{R}$, $x \mapsto x^2$ is continuous.

Let $\epsilon > 0$. We choose $\delta := \min\left(\frac{\epsilon}{2|a|+1}, 1\right)$. Since $\epsilon > 0$ and $2|a|+1 > 0$ and $1 > 0$, we have $\delta > 0$.

Let $x \in \mathbb{R}$ and $|x - a| < \delta$. Then:

$$\begin{aligned}
 |f(x) - f(a)| &= |x^2 - a^2| = |(x+a)(x-a)| \\
 &= |x+a| \cdot |x-a| && \left. \begin{array}{l} \downarrow |x+a| \leq |x|+|a| \\ \downarrow |x-a| < \delta \\ \downarrow |x| < |a|+\delta \text{ (*)} \end{array} \right\} \\
 &\leq (|x|+|a|) \cdot |x-a| \\
 &\leq (|x|+|a|) \cdot \delta \\
 &< ((|a|+\delta)+|a|) \cdot \delta \\
 &= (2|a|+\delta) \cdot \delta && \left. \begin{array}{l} \downarrow \delta \leq 1 \text{ and } \delta \leq \frac{\epsilon}{2|a|+1} \end{array} \right\} \\
 &\leq (2|a|+1) \cdot \frac{\epsilon}{2|a|+1} \\
 &= \epsilon
 \end{aligned}$$

(*) is true because $|x| = |a + (x - a)| \leq |a| + |x - a| < |a| + \delta$. Therefore, $|x| < |a| + \delta$.

The argument shows that $|f(x) - f(a)| < \epsilon$, which proves the continuity of f at a . \square

2.4 The hyperbola is continuous

Theorem 4. Let $f: \mathbb{R} \setminus \{0\} \rightarrow \mathbb{R}$ be defined by $f(x) := \frac{1}{x}$. Then f is continuous at every point $a \in \mathbb{R} \setminus \{0\}$.

Proof. Let $a \in \mathbb{R} \setminus \{0\}$ be an arbitrary point where we want to show that $f: \mathbb{R} \setminus \{0\} \rightarrow \mathbb{R}$, $x \mapsto \frac{1}{x}$ is continuous.

Let $\epsilon > 0$. We choose $\delta := \min\left(\frac{\epsilon|a|^2}{2}, \frac{|a|}{2}\right)$. Since $\epsilon > 0$ and $|a| > 0$ ($a \in \mathbb{R} \setminus \{0\}$), we have $\delta > 0$.

Let $x \in D := \mathbb{R} \setminus \{0\}$ and $|x - a| < \delta$. Then:

$$\begin{aligned}
 |f(x) - f(a)| &= \left| \frac{1}{x} - \frac{1}{a} \right| = \left| \frac{a - x}{ax} \right| \\
 &= \frac{|a - x|}{|ax|} = \frac{|a - x|}{|a||x|} \quad \left. \begin{array}{l} |a - x| = |x - a| < \delta \\ |x| > \frac{|a|}{2} \quad (*) \end{array} \right\} \\
 &< \frac{\delta}{|a||x|} \\
 &< \frac{\delta}{|a|\frac{|a|}{2}} \\
 &\leq \frac{\epsilon|a|^2}{2} \frac{1}{|a|\frac{|a|}{2}} \\
 &= \epsilon
 \end{aligned}$$

(*) is true because

$$\begin{aligned}
 |x| &= |a + (x - a)| \\
 &\geq |a| - |x - a| \quad \left. \begin{array}{l} \text{Reverse triangle inequality} \\ |x - a| < \delta \end{array} \right\} \\
 &> |a| - \delta \\
 &\geq |a| - \frac{|a|}{2} \quad \left. \right\} \delta \leq \frac{|a|}{2} \\
 &= \frac{|a|}{2} \Rightarrow |x| > \frac{|a|}{2}
 \end{aligned}$$

The reverse triangle inequality used in the first step can also be derived. Let $m, n, u, v \in \mathbb{R}$.

$$\begin{aligned}
 |m + n| &\leq |m| + |n| \\
 \Rightarrow |m + n| - |n| &\leq |m| \\
 \Rightarrow |u| - |v| &\leq |u + v| \quad \left. \right\} m := u + v, \quad n := -v
 \end{aligned}$$

The argument shows that $|f(x) - f(a)| < \epsilon$, which proves the continuity of f at a .

□

2.5 The exponential function is continuous

We assume that the exponential function is defined by its power series:

$$e^x := \sum_{k=0}^{\infty} \frac{x^k}{k!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

Theorem 5. *Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by $f(x) := e^x$. Then f is continuous at $a = 0$.*

Proof. ¹ We want to show that $f : \mathbb{R} \rightarrow \mathbb{R}$, $x \mapsto e^x$ is continuous at $a = 0$.

Let $\epsilon > 0$. We choose $\delta := \frac{\epsilon}{\epsilon + 1}$. Since $\epsilon > 0$ we have $0 < \delta < 1$.

Let $x \in \mathbb{R}$ and $|x - a| = |x - 0| = |x| < \delta$. Then:

$$\begin{aligned}
 |f(x) - f(0)| &= |e^x - e^0| = |e^x - 1| && \left. \begin{array}{l} \\ \end{array} \right\} \text{definition of } e^x \\
 &= \left| \sum_{k=0}^{\infty} \frac{x^k}{k!} - 1 \right| \\
 &= \left| \sum_{k=1}^{\infty} \frac{x^k}{k!} \right| \\
 &\leq \sum_{k=1}^{\infty} \frac{|x|^k}{k!} && \left. \begin{array}{l} \\ \end{array} \right\} |x| < \delta \\
 &< \sum_{k=1}^{\infty} \frac{\delta^k}{k!} && \left. \begin{array}{l} \\ \end{array} \right\} k > 0 \\
 &< \sum_{k=1}^{\infty} \delta^k \\
 &= \left(\sum_{k=0}^{\infty} \delta^k \right) - 1 && \left. \begin{array}{l} \\ \end{array} \right\} \text{Geometric series, } 0 < \delta < 1 \\
 &= \frac{1}{1 - \delta} - 1 \\
 &= \frac{1}{1 - \frac{\epsilon}{\epsilon + 1}} - 1 && \left. \begin{array}{l} \\ \end{array} \right\} \delta := \frac{\epsilon}{\epsilon + 1} \\
 &= \frac{1}{\frac{1}{\epsilon + 1}} - 1 = \epsilon + 1 - 1 = \epsilon
 \end{aligned}$$

The argument shows that $|f(x) - f(0)| < \epsilon$, which proves the continuity of f at 0. \square

¹This proof is adapted from [this video](#).

Theorem 6. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by $f(x) := e^x$. Then f is continuous at every point $a \in \mathbb{R}$.

*Proof.*² Let $a \in \mathbb{R}$ be an arbitrary point where we want to show that $f : \mathbb{R} \rightarrow \mathbb{R}$, $x \mapsto e^x$ is continuous.

Let $\epsilon > 0$. We let the choice of $\delta > 0$ open for now.

Let $x \in \mathbb{R}$ and $|x - a| < \delta$. Then:

$$\begin{aligned}
 |f(x) - f(a)| &= |e^x - e^a| \\
 &= |e^a \cdot (e^{x-a} - 1)| \quad \left. \begin{array}{l} e^{x'} e^{y'} = e^{x'+y'} \quad \forall x', y' \in \mathbb{R} \\ e^{x'} > 0 \quad \forall x' \in \mathbb{R} \end{array} \right\} \\
 &= e^a \cdot |e^{x-a} - 1| \\
 &= e^a \cdot |e^{x-a} - e^0| \\
 &= e^a \cdot |e^z - e^0|
 \end{aligned}$$

We substituted $z := x - a$ and therefore $|x - a| = |z| < \delta$ (and still $\delta > 0$). This was done to **reduce the problem**. Should $f : \mathbb{R} \rightarrow \mathbb{R}$, $z \mapsto e^z$ be continuous at 0, then by definition of continuity in [1](#), we know:

$$\forall \epsilon' > 0 \quad \exists \delta > 0 \quad \forall z \in \mathbb{R} : \left(|z - 0| < \delta \Rightarrow |f(z) - f(0)| = |e^z - e^0| < \epsilon' \right)$$

And indeed $|z| < \delta$. Let's choose $\epsilon' := \frac{\epsilon}{e^a}$. Then continuing the above argument:

$$|f(x) - f(a)| = e^a \cdot |e^z - e^0| < e^a \cdot \epsilon' = e^a \cdot \frac{\epsilon}{e^a} = \epsilon$$

By [Theorem 5](#), we know that $f : \mathbb{R} \rightarrow \mathbb{R}$, $z \mapsto e^z$ is continuous at 0. With the reasoning above, this implies that $|f(x) - f(a)| < \epsilon$ for all $x \in \mathbb{R}$ with $|x - a| < \delta$. Therefore, f is continuous at every point $a \in \mathbb{R}$.

□

²This proof is adapted from [this video](#).

3 Sum and Product of Continuous Functions

Theorem 7. *If f and g are continuous functions on a set $D \subseteq \mathbb{R}$, then $f + g$ is continuous on D .*

Proof. Assume f and g are continuous on D . We need to show that $f + g$ is continuous at any $a \in D$. Let $a \in D$ and $\epsilon > 0$. By the continuity of f and g , we have:

- There $\exists \delta_1 > 0$ such that $\forall x \in D$, if $|x - a| < \delta_1$, then $|f(x) - f(a)| < \frac{\epsilon}{2}$.
- There $\exists \delta_2 > 0$ such that $\forall x \in D$, if $|x - a| < \delta_2$, then $|g(x) - g(a)| < \frac{\epsilon}{2}$.

Choose $\delta := \min(\delta_1, \delta_2)$. Then $\delta > 0$ since both $\delta_1 > 0$ and $\delta_2 > 0$.

Let $x \in D$. If $|x - a| < \delta$, we have:

$$\begin{aligned} |f(x) - f(a)| &< \frac{\epsilon}{2} \\ |g(x) - g(a)| &< \frac{\epsilon}{2} \end{aligned}$$

Putting it together:

$$\begin{aligned} |(f + g)(x) - (f + g)(a)| &= |f(x) + g(x) - f(a) - g(a)| \\ &= |f(x) - f(a) + g(x) - g(a)| \\ &\leq |f(x) - f(a)| + |g(x) - g(a)| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon \end{aligned}$$

Hence, $f + g$ is continuous at a . Since a was arbitrary, $f + g$ is continuous on D . \square

Theorem 8. *If f and g are continuous functions on a set $D \subseteq \mathbb{R}$, then $f \cdot g$ is continuous on D .*

Proof. Assume f and g are continuous on D . We need to show that $f \cdot g$ is continuous at any $a \in D$. Let $a \in D$ and $\epsilon > 0$. By the continuity of f and g , we have:

- There $\exists \delta_1 > 0$ such that $\forall x \in D$, if $|x - a| < \delta_1$, then $|f(x) - f(a)| < \frac{\epsilon}{2|g(a)| + 1}$.

The 1 in the denominator is just to ensure we don't divide by 0.

- There $\exists \delta_2 > 0$ such that $\forall x \in D$, if $|x - a| < \delta_2$, then $|g(x) - g(a)| < \frac{\epsilon}{2(\epsilon + |f(a)|)}$.

Choose $\delta := \min(\delta_1, \delta_2)$. Then $\delta > 0$ since both $\delta_1 > 0$ and $\delta_2 > 0$.

Let $x \in D$. If $|x - a| < \delta$, we have:

$$\begin{aligned} |f(x) - f(a)| &< \frac{\epsilon}{2|g(a)| + 1} \\ |g(x) - g(a)| &< \frac{\epsilon}{2(\epsilon + |f(a)|)} \end{aligned}$$

Putting it together:

$$\begin{aligned} |(f \cdot g)(x) - (f \cdot g)(a)| &= |f(x) \cdot g(x) - f(a) \cdot g(a)| \\ &= |f(x) \cdot g(x) - f(x) \cdot g(a) + f(x) \cdot g(a) - f(a) \cdot g(a)| \\ &= |f(x) \cdot (g(x) - g(a)) + (f(x) - f(a)) \cdot g(a)| \\ &\leq |f(x) \cdot (g(x) - g(a))| + |(f(x) - f(a)) \cdot g(a)| \\ &= |f(x)| \cdot |g(x) - g(a)| + |f(x) - f(a)| \cdot |g(a)| \\ &\leq |f(x)| \cdot \frac{\epsilon}{2(\epsilon + |f(a)|)} + \frac{\epsilon}{2|g(a)| + 1} \cdot |g(a)| \\ &\stackrel{(1)}{<} \frac{\epsilon}{2} \cdot \frac{\epsilon + |f(a)|}{\epsilon + |f(a)|} + \frac{\epsilon}{2} \cdot \frac{|g(a)|}{|g(a)| + 1/2} \\ &\leq \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon \end{aligned}$$

In step (1), we made use of the triangle inequality:

$$|f(x) - f(a)| < \frac{\epsilon}{2|g(a)| + 1} \leq \epsilon \quad \Rightarrow \quad |f(x)| < \epsilon + |f(a)| \quad (1)$$

Hence, $f \cdot g$ is continuous at a . Since a was arbitrary, $f \cdot g$ is continuous on D . \square

4 Left- and Right-Continuous Functions

4.1 Definitions

Definition 2. A function $f : D \rightarrow \mathbb{R}$ is *left-continuous at a point* $a \in D$ if

$$\boxed{\forall \epsilon > 0 \quad \exists \delta > 0 \quad \forall x \in D, x < a : \left(|x - a| < \delta \Rightarrow |f(x) - f(a)| < \epsilon \right)}$$

If f is left-continuous at every point in D , then we say that f is *left-continuous on* D .

Definition 3. A function $f : D \rightarrow \mathbb{R}$ is *right-continuous at a point* $a \in D$ if

$$\boxed{\forall \epsilon > 0 \quad \exists \delta > 0 \quad \forall x \in D, x > a : \left(|x - a| < \delta \Rightarrow |f(x) - f(a)| < \epsilon \right)}$$

If f is right-continuous at every point in D , then we say that f is *right-continuous on* D .

4.2 Heaviside function as example

Definition 4. The Heaviside function $\Theta : \mathbb{R} \rightarrow \{0, 1\}$ is defined as

$$\Theta(x) := \begin{cases} 0 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$$

Theorem 9. Let $\Theta : \mathbb{R} \rightarrow \mathbb{R}$ denote the Heaviside function. Θ is right-continuous at 0.

Proof. We consider the point 0. Let $\epsilon > 0$. Choose $\delta := 1 > 0$.

Let $x \in \mathbb{R}$, $x > 0$ and $|x - 0| < \delta$, i. e. $|x| < 1$. In summary, $x \in (0, 1)$. Then $\Theta(x) = 1$.

We find: $|\Theta(x) - \Theta(0)| = |1 - 1| = 0 < \epsilon$. This proves that Θ is right-continuous at 0. \square

Theorem 10. Let $\Theta : \mathbb{R} \rightarrow \mathbb{R}$ denote the Heaviside function. Θ is not continuous at 0.

Proof. Assume, for contradiction, that Θ is continuous at 0. Let $\epsilon = 1/2$. Then there $\exists \delta > 0$, such that $\forall x \in D$, if $|x - 0| < \delta$, then $|\Theta(x) - \Theta(0)| < \epsilon = 1/2$. Consider $x = -\delta/2$, which fulfills $|x| < \delta$ since $|\delta/2| = \delta/2 < \delta$.

For our choice of x , we find $\Theta(x) = 0$ since $x < 0$. Therefore:

$$|\Theta(x) - \Theta(0)| = |0 - 1| = 1$$

This is a contradiction to $|\Theta(x) - \Theta(0)| < 1/2$. Therefore, Θ is not continuous at 0. \square

4.3 Left- and right-continuous is the same as continuous

Theorem 11. *A function $f : D \rightarrow \mathbb{R}$ is continuous at a point $a \in D$ if and only if it is both left-continuous and right-continuous at a .*

Proof. Let $a \in D$ and consider a function $f : D \rightarrow \mathbb{R}$. That is,

(\Rightarrow) Assume f is continuous at a .

$$\forall \epsilon > 0 \quad \exists \delta > 0 \quad \forall x \in D : \left(|x - a| < \delta \Rightarrow |f(x) - f(a)| < \epsilon \right)$$

This implies both left- and right-continuity at a due to $x < a$ and $x > a$ being stronger conditions than $x \in D$.

(\Leftarrow) Assume f is both left- and right-continuous at a .

Since f is left-continuous: $\exists \delta_1 > 0 \quad \forall x \in D, x < a : (|x - a| < \delta_1 \Rightarrow |f(x) - f(a)| < \epsilon)$

Since f is right-continuous: $\exists \delta_2 > 0 \quad \forall x \in D, x > a : (|x - a| < \delta_2 \Rightarrow |f(x) - f(a)| < \epsilon)$

Choose $\delta := \min(\delta_1, \delta_2)$. Let $x \in D$ and $|x - a| < \delta$. Due to our choice of δ , we also have $|x - a| < \delta_1$ and $|x - a| < \delta_2$.

Now consider these cases:

- If $x < a$, then $|f(x) - f(a)| < \epsilon$ by left-continuity.
- If $x > a$, then $|f(x) - f(a)| < \epsilon$ by right-continuity.
- If $x = a$, then $|f(x) - f(a)| = 0 < \epsilon$.

Hence, f is continuous at a .

□