Calculus I
Lecture 10
Trigonometric Derivatives

Todor Milev
https://github.com/tmilev/freecalc

2020

Outline

1 Derivatives of Trigonometric Functions

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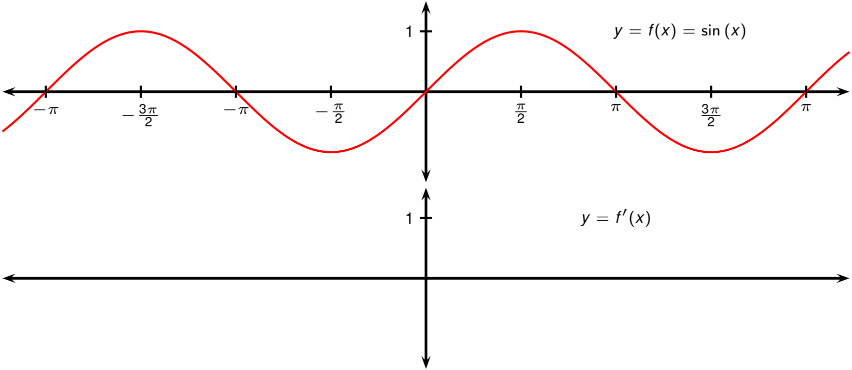
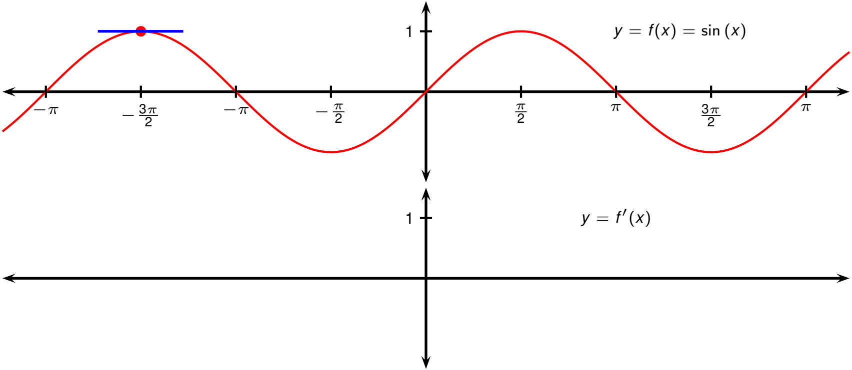
Derivatives of Trigonometric Functions



What is the derivative of $f(x) = \sin x$?

Derivatives of Trigonometric Functions



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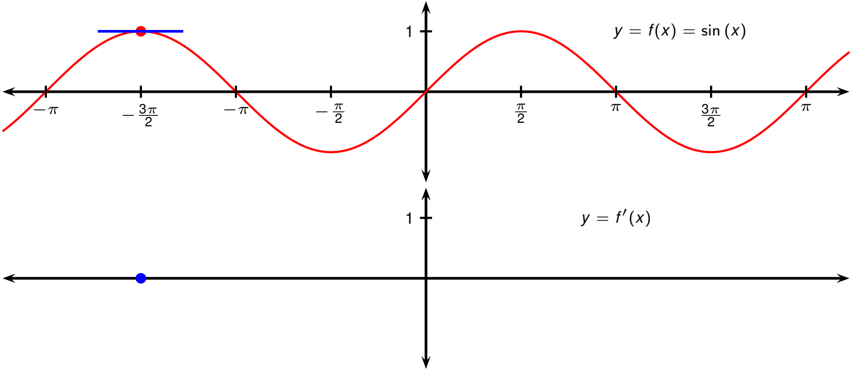

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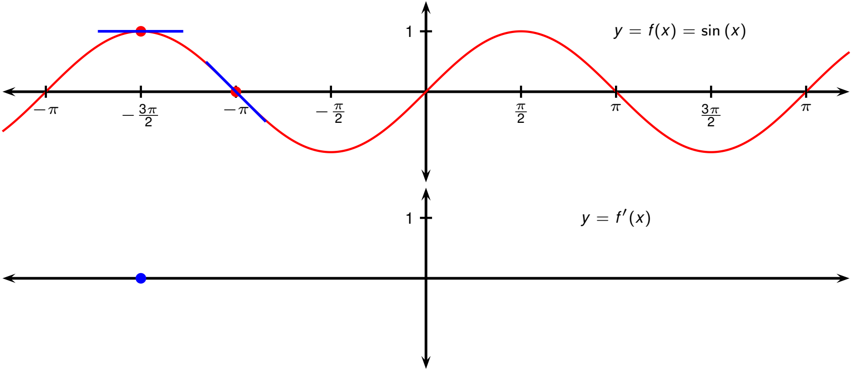

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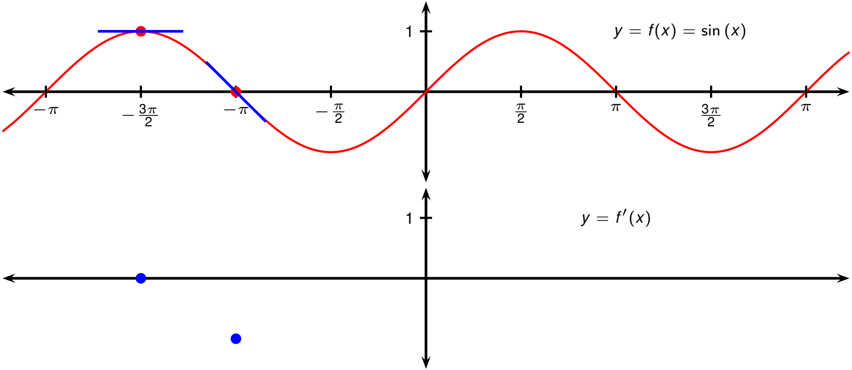

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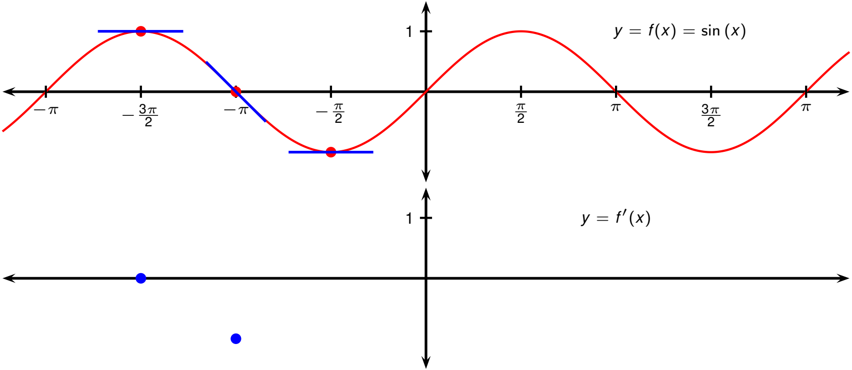

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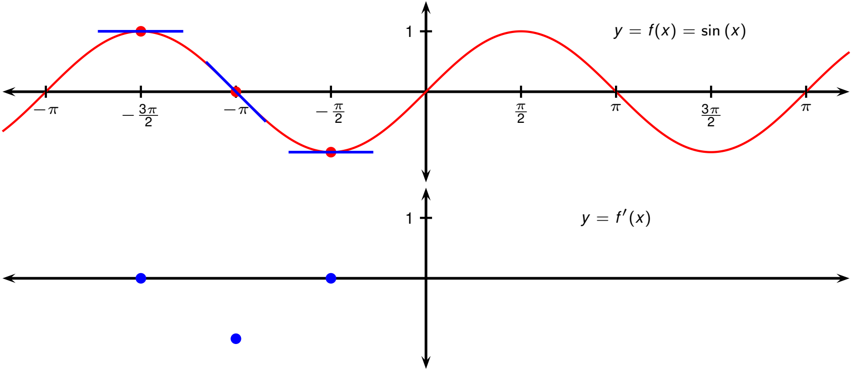

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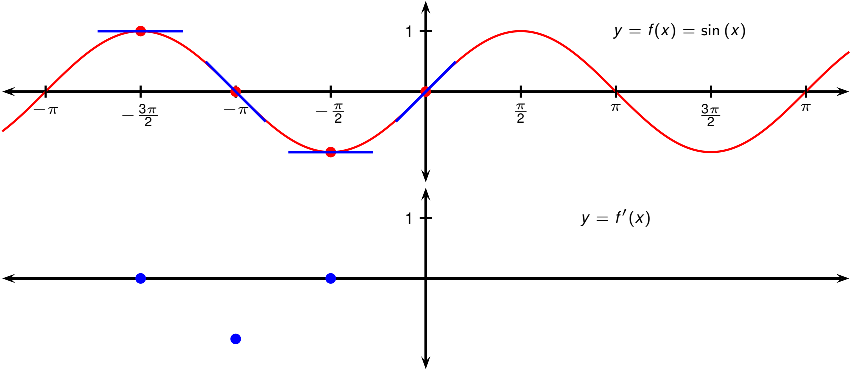

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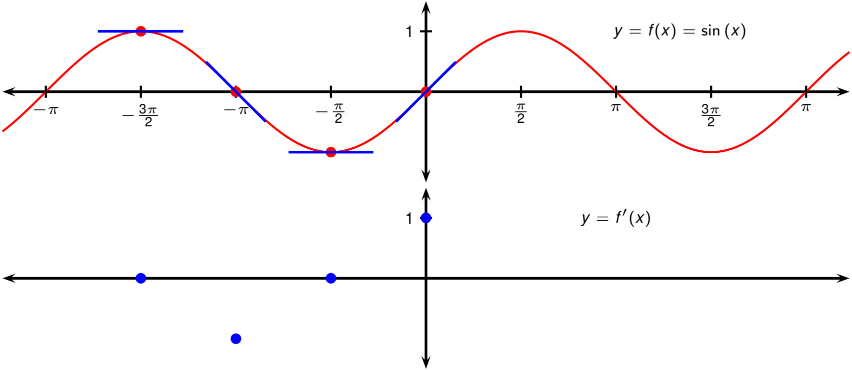

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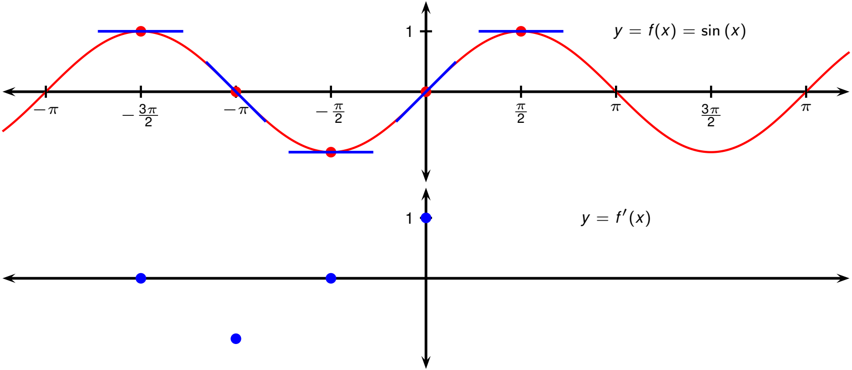

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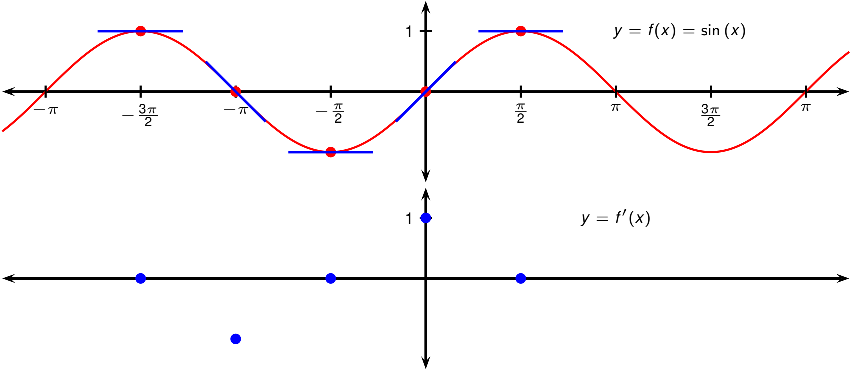

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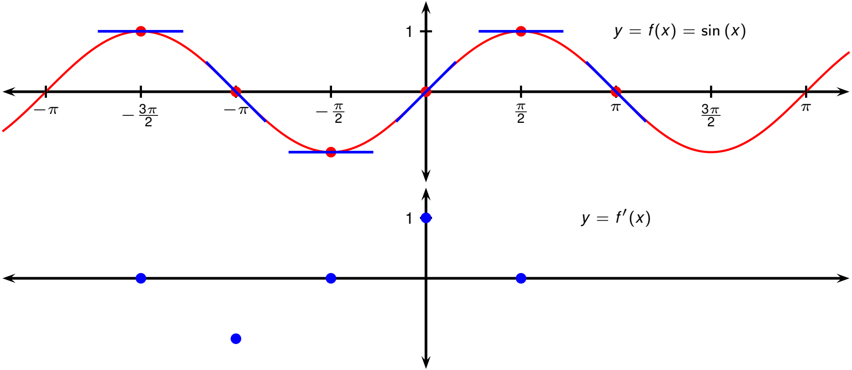

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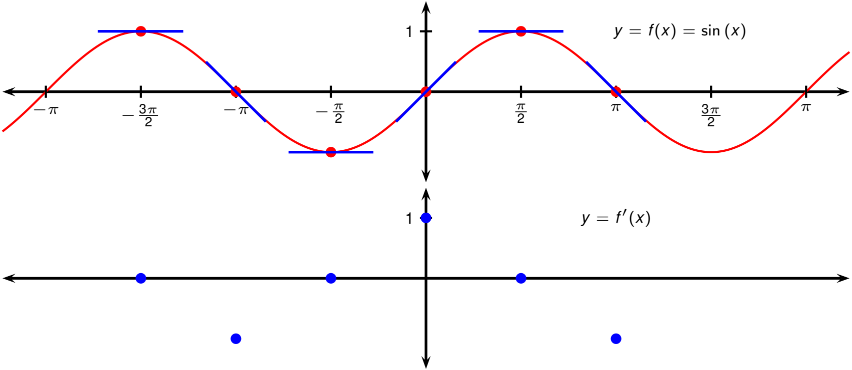

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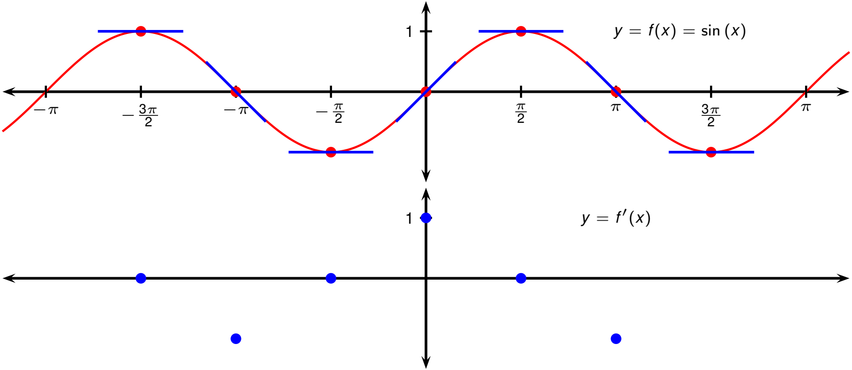

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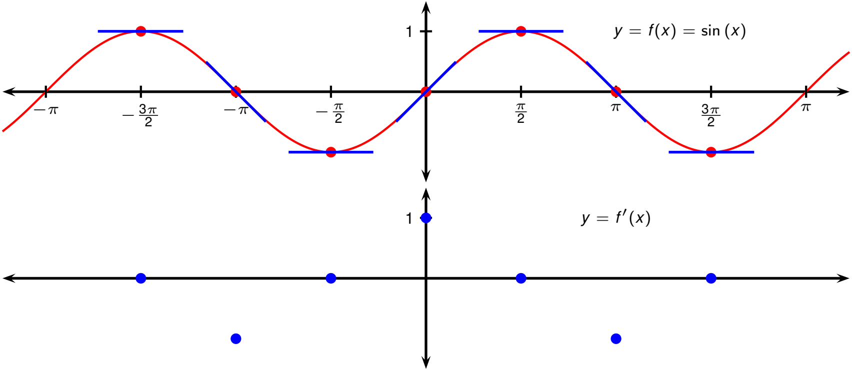

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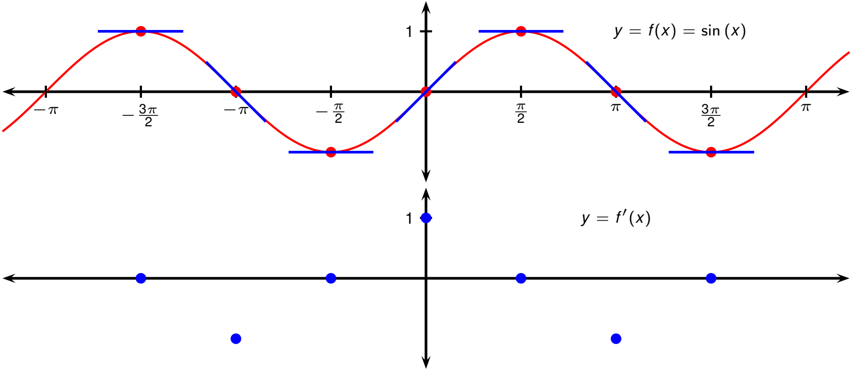
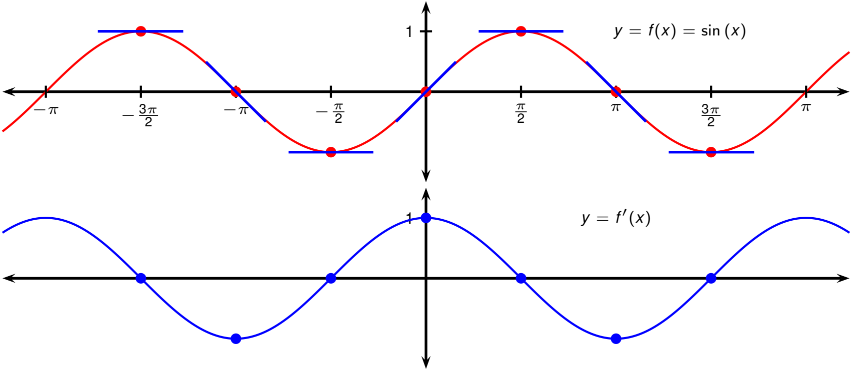


What is the derivative of $f(x) = \sin x$? It looks like $\cos x$.

Derivatives of Trigonometric Functions



What is the derivative of $f(x) = \sin x$? It looks like $\cos x$.

Let $f(x) = \sin x$.

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Then $\quad f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}$

Let $\quad f(x) = \sin x.$

Then $\quad f'(x) = \lim_{h\to 0} \dfrac{f(x+h) - f(x)}{h} = \lim_{h\to 0} \dfrac{\sin(x+h) - \sin x}{h}$

Let $f(x) = \sin x$.

Then
$$f'(x) = \lim_{h\to 0} \frac{f(x+h) - f(x)}{h} = \lim_{h\to 0} \frac{\sin(x+h) - \sin x}{h}$$
$$= \lim_{h\to 0} \frac{\sin x \cos h + \cos x \sin h - \sin x}{h}$$

Let $f(x) = \sin x$.

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$$= \lim_{h\to 0} \left(\frac{\sin x \cos h - \sin x}{h} + \frac{\cos x \sin h}{h} \right)$$

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Let $\quad f(x) = \sin x.$

Then $\quad f'(x) = \lim_{h\to 0} \frac{f(x+h)-f(x)}{h} = \lim_{h\to 0} \frac{\sin(x+h)-\sin x}{h}$

$$= \lim_{h\to 0} \frac{\sin x\cos h + \cos x \sin h - \sin x}{h}$$

$$= \lim_{h\to 0} \left(\frac{\sin x \cos h - \sin x}{h} + \frac{\cos x \sin h}{h} \right)$$

$$= \lim_{h\to 0} \left(\sin x \left(\frac{\cos h - 1}{h} \right) + \cos x \left(\frac{\sin h}{h} \right) \right)$$

Let $f(x) = \sin x$.

Then
$$
\begin{aligned}
f'(x) &= \lim_{h\to 0} \frac{f(x+h)-f(x)}{h} = \lim_{h\to 0} \frac{\sin(x+h)-\sin x}{h}\\
&= \lim_{h\to 0} \frac{\sin x\cos h + \cos x \sin h - \sin x}{h}\\
&= \lim_{h\to 0} \left(\frac{\sin x\cos h - \sin x}{h} + \frac{\cos x\sin h}{h}\right)\\
&= \lim_{h\to 0} \left(\sin x\left(\frac{\cos h - 1}{h}\right) + \cos x\left(\frac{\sin h}{h}\right)\right)\\
&= \lim_{h\to 0}\sin x \cdot \lim_{h\to 0}\left(\frac{\cos h - 1}{h}\right) + \lim_{h\to 0}\cos x \cdot \lim_{h\to 0}\left(\frac{\sin h}{h}\right)
\end{aligned}
$$

Let $f(x) = \sin x.$

Then
$$
\begin{aligned}
f'(x) &= \lim_{h\to 0} \frac{f(x+h) - f(x)}{h} = \lim_{h\to 0} \frac{\sin(x+h) - \sin x}{h} \\
&= \lim_{h\to 0} \frac{\sin x \cos h + \cos x \sin h - \sin x}{h} \\
&= \lim_{h\to 0} \left(\frac{\sin x \cos h - \sin x}{h} + \frac{\cos x \sin h}{h} \right) \\
&= \lim_{h\to 0} \left(\sin x \left(\frac{\cos h - 1}{h} \right) + \cos x \left(\frac{\sin h}{h} \right) \right) \\
&= \lim_{h\to 0} \sin x \cdot \lim_{h\to 0} \left(\frac{\cos h - 1}{h} \right) + \lim_{h\to 0} \cos x \cdot \lim_{h\to 0} \left(\frac{\sin h}{h} \right) \\
&= \textbf{?} \cdot \lim_{h\to 0} \left(\frac{\cos h - 1}{h} \right) + \textbf{?} \cdot \lim_{h\to 0} \left(\frac{\sin h}{h} \right)
\end{aligned}
$$

Let $f(x) = \sin x$.

Then
$$
\begin{aligned}
f'(x) &= \lim_{h\to 0} \frac{f(x+h)-f(x)}{h} = \lim_{h\to 0} \frac{\sin(x+h)-\sin x}{h}\\
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&= \lim_{h\to 0} \sin x \cdot \lim_{h\to 0}\left(\frac{\cos h - 1}{h}\right) + \lim_{h\to 0} \cos x \cdot \lim_{h\to 0}\left(\frac{\sin h}{h}\right)\\
&= \sin x \cdot \lim_{h\to 0}\left(\frac{\cos h - 1}{h}\right) + \textbf{?} \quad \cdot \lim_{h\to 0}\left(\frac{\sin h}{h}\right)
\end{aligned}
$$

Let $f(x) = \sin x.$

$$
\begin{aligned}
\text{Then}\quad f'(x) &= \lim_{h\to 0}\frac{f(x+h)-f(x)}{h} = \lim_{h\to 0}\frac{\sin(x+h)-\sin x}{h}\\
&= \lim_{h\to 0}\frac{\sin x\cos h+\cos x\sin h-\sin x}{h}\\
&= \lim_{h\to 0}\left(\frac{\sin x\cos h-\sin x}{h}+\frac{\cos x\sin h}{h}\right)\\
&= \lim_{h\to 0}\left(\sin x\left(\frac{\cos h-1}{h}\right)+\cos x\left(\frac{\sin h}{h}\right)\right)\\
&= \lim_{h\to 0}\sin x\cdot\lim_{h\to 0}\left(\frac{\cos h-1}{h}\right)+\lim_{h\to 0}\cos x\cdot\lim_{h\to 0}\left(\frac{\sin h}{h}\right)\\
&= \sin x\cdot\lim_{h\to 0}\left(\frac{\cos h-1}{h}\right)+\textbf{?}\qquad\cdot\lim_{h\to 0}\left(\frac{\sin h}{h}\right)
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Let $f(x) = \sin x$.

Then
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f'(x) &= \lim_{h\to 0} \frac{f(x+h)-f(x)}{h} = \lim_{h\to 0} \frac{\sin(x+h)-\sin x}{h}\\
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&= \sin x \cdot \lim_{h\to 0} \left(\frac{\cos h - 1}{h}\right) + \cos x \cdot \lim_{h\to 0} \left(\frac{\sin h}{h}\right)
\end{aligned}
$$

$$
\begin{aligned}
\text{Let}\quad f(x) &= \sin x.\\
\text{Then}\quad f'(x) &= \lim_{h\to 0}\frac{f(x+h)-f(x)}{h} = \lim_{h\to 0}\frac{\sin(x+h)-\sin x}{h}\\
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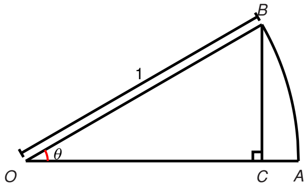
&= \sin x\cdot\lim_{h\to 0}\left(\frac{\cos h-1}{h}\right)+\cos x\cdot\lim_{h\to 0}\left(\frac{\sin h}{h}\right)
\end{aligned}
$$

We need to do more work to find the other two limits.

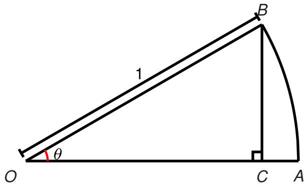
Claim: $\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$

Suppose $0 < \theta < \frac{\pi}{2}$.



Claim: $\lim_{\theta \to 0} \frac{\sin \theta}{\theta} = 1$

Suppose $0 < \theta < \frac{\pi}{2}$. Write $\sin \theta$ using ratios of side lengths of a triangle.



$\sin \theta = $ **?**

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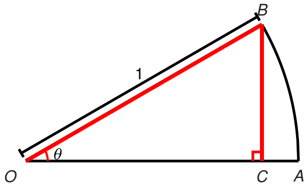
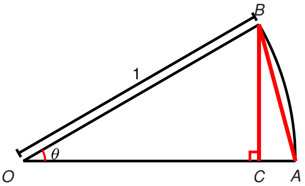


Suppose $0 < \theta < \frac{\pi}{2}$. Write $\sin\theta$ using ratios of side lengths of a triangle.

$$\sin\theta = \frac{|BC|}{|OB|} = |BC|$$

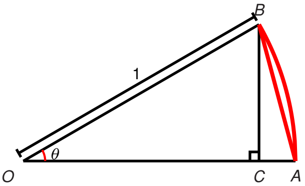
Claim: $\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$



Suppose $0 < \theta < \frac{\pi}{2}$. Write $\sin\theta$ using ratios of side lengths of a triangle.

$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB|$$

Claim: $\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$



Suppose $0 < \theta < \frac{\pi}{2}$. Write $\sin\theta$ using ratios of side lengths of a triangle.

$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \text{arc}AB$$

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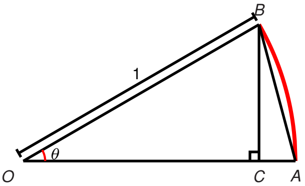
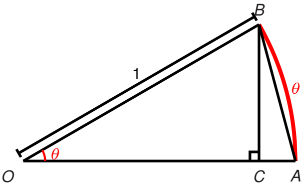


$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \text{arc}AB = \textbf{?}$$

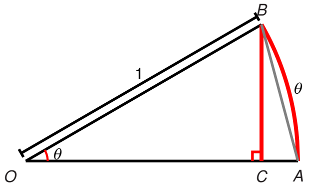
Claim: $\lim_{\theta \to 0} \frac{\sin \theta}{\theta} = 1$



Suppose $0 < \theta < \frac{\pi}{2}$. Write $\sin \theta$ using ratios of side lengths of a triangle.

$$\sin \theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \text{arc}AB = \theta$$

Claim: $\lim\limits_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$



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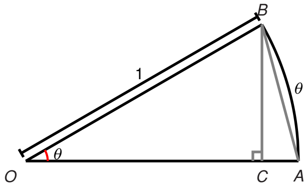
$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \text{arc}AB = \theta$$

Therefore $\sin\theta < \theta$

Claim: $\lim_{\theta\to 0} \frac{\sin\theta}{\theta} = 1$



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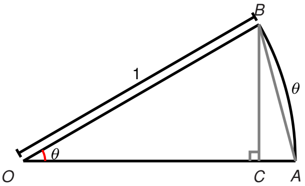
$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \mathrm{arc}AB = \theta$$

Therefore $\sin\theta < \theta$ and therefore $\frac{\sin\theta}{\theta} < 1$.

Claim: $\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$



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$\theta = \mathrm{arc}AB$

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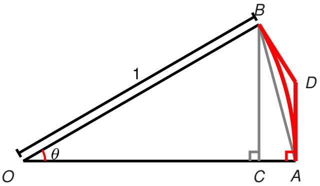

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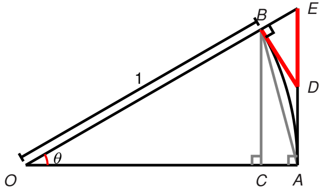
$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \mathrm{arc}AB = \theta$$

Therefore $\sin\theta < \theta$ and therefore $\frac{\sin\theta}{\theta} < 1$.

$$\theta = \mathrm{arc}AB < |AD| + |DB|$$

Claim: $\lim_{\theta \to 0} \frac{\sin \theta}{\theta} = 1$



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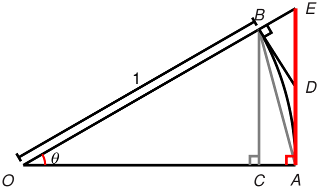
$$\sin \theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \mathrm{arc} AB = \theta$$

Therefore $\sin \theta < \theta$ and therefore $\frac{\sin \theta}{\theta} < 1$.

$$\theta = \mathrm{arc} AB < |AD| + {\color{red}|DB|} < |AD| + {\color{red}|DE|}$$

Claim: $\lim_{\theta \to 0} \frac{\sin \theta}{\theta} = 1$



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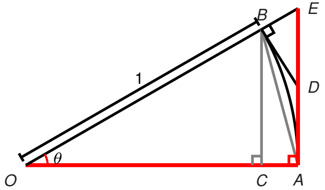
$$\sin \theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \mathrm{arc} AB = \theta$$

Therefore $\sin \theta < \theta$ and therefore $\frac{\sin \theta}{\theta} < 1$.

$$\theta = \mathrm{arc} AB < |AD| + |DB| < |AD| + |DE|$$

$$= |AE|$$



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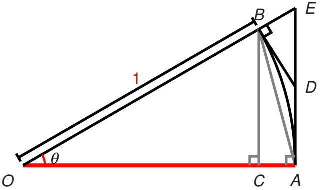
Therefore $\sin \theta < \theta$ and therefore $\frac{\sin \theta}{\theta} < 1$.

$$\theta = \mathrm{arc} AB < |AD| + |DB| < |AD| + |DE|$$
$$= |AE| = |OA| \tan \theta$$



Claim: $\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$

Suppose $0 < \theta < \frac{\pi}{2}$. Write $\sin\theta$ using ratios of side lengths of a triangle.

$$\sin\theta = \frac{|BC|}{|OB|} = |BC| < |AB| < \mathrm{arc}AB = \theta$$

Therefore $\sin\theta < \theta$ and therefore $\frac{\sin\theta}{\theta} < 1$.

$$\begin{aligned}\theta = \mathrm{arc}AB &< |AD| + |DB| < |AD| + |DE| \\ &= |AE| = |OA| \tan\theta = \tan\theta\end{aligned}$$

Claim: $\lim_{\theta\to 0}\frac{\sin\theta}{\theta} = 1$

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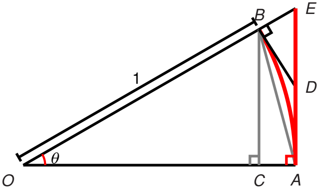

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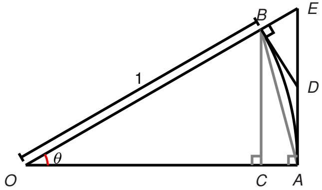

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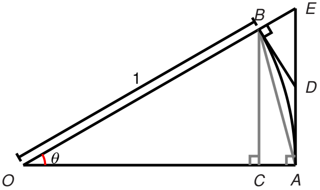

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Therefore $\theta < \tan\theta = \frac{\sin\theta}{\cos\theta}$, so $\cos\theta < \frac{\sin\theta}{\theta}$.

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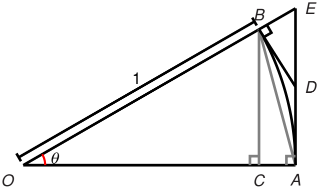

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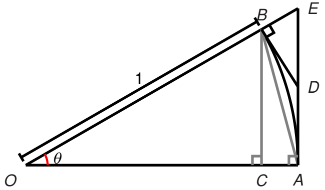

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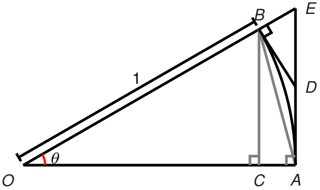

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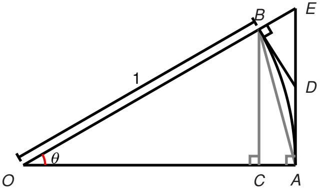

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$\lim\limits_{\theta\to 0}\cos\theta = \textbf{?}$

Claim: $\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$

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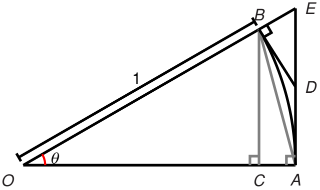

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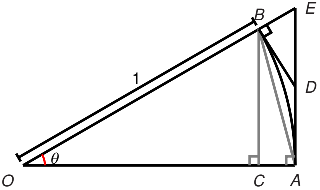

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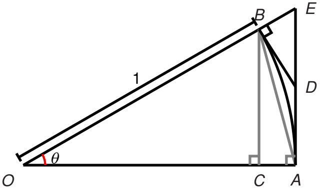
Claim: $\lim\limits_{\theta\to 0} \dfrac{\sin\theta}{\theta} = 1$



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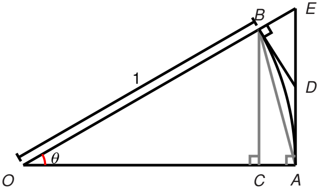
$$\cos\theta < \frac{\sin\theta}{\theta} < 1$$

$\lim\limits_{\theta\to 0} \cos\theta = 1$ and $\lim\limits_{\theta\to 0} 1 = 1$, so by the Squeeze Theorem $\lim\limits_{\theta\to 0^+} \frac{\sin\theta}{\theta} = 1$.

Claim: $\lim_{\theta\to 0} \frac{\sin\theta}{\theta} = 1$



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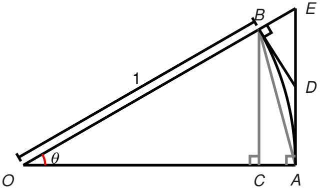

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Let $f(x) = \sin x.$

Then $f'(x) = \lim_{h\to 0} \sin x \cdot \lim_{h\to 0} \left(\frac{\cos h - 1}{h} \right) + \lim_{h\to 0} \cos x \cdot \lim_{h\to 0} \left(\frac{\sin h}{h} \right)$

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$$= \mathbf{?} \quad \cdot \mathbf{?} \qquad + \mathbf{?} \quad \cdot \mathbf{?}$$

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\end{aligned}
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&= \sin x \cdot \lim_{h\to 0}\left(\frac{\cos h - 1}{h}\right) + \cos x \cdot 1
\end{aligned}
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We need to find

$$\lim_{h\to 0} \frac{\cos h - 1}{h}$$

Let $f(x) = \sin x.$

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$$\lim_{h\to 0} \frac{\cos h - 1}{h} = \lim_{h\to 0} \frac{(\cos h - 1)}{h} \cdot \frac{(\cos h + 1)}{(\cos h + 1)}$$

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$$= -\lim_{h\to 0}\frac{\sin h}{h}\cdot\lim_{h\to 0}\frac{\sin h}{\cos h + 1} = -1\cdot\left(\frac{0}{1+1}\right)$$

Let $f(x) = \sin x.$

Then $$f'(x) = \lim_{h\to 0} \sin x \cdot \lim_{h\to 0}\left(\frac{\cos h - 1}{h}\right) + \lim_{h\to 0}\cos x \cdot \lim_{h\to 0}\left(\frac{\sin h}{h}\right)$$
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$$\begin{aligned}\lim_{h\to 0}\frac{\cos h - 1}{h} &= \lim_{h\to 0}\frac{(\cos h - 1)}{h}\cdot\frac{(\cos h + 1)}{(\cos h + 1)} = \lim_{h\to 0}\frac{\cos^2 h - 1}{h(\cos h + 1)}\\ &= \lim_{h\to 0}\frac{-\sin^2 h}{h(\cos h + 1)} = -\lim_{h\to 0}\left(\frac{\sin h}{h}\cdot\frac{\sin h}{\cos h + 1}\right)\\ &= -\lim_{h\to 0}\frac{\sin h}{h}\cdot\lim_{h\to 0}\frac{\sin h}{\cos h + 1} = -1\cdot\left(\frac{0}{1+1}\right) = 0\end{aligned}$$

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We need to find

$$\lim_{h\to 0}\frac{\cos h - 1}{h} = \lim_{h\to 0}\frac{(\cos h - 1)}{h}\cdot\frac{(\cos h + 1)}{(\cos h + 1)} = \lim_{h\to 0}\frac{\cos^2 h - 1}{h(\cos h + 1)}$$
$$= \lim_{h\to 0}\frac{-\sin^2 h}{h(\cos h + 1)} = -\lim_{h\to 0}\left(\frac{\sin h}{h}\cdot\frac{\sin h}{\cos h + 1}\right)$$
$$= -\lim_{h\to 0}\frac{\sin h}{h}\cdot\lim_{h\to 0}\frac{\sin h}{\cos h + 1} = -1\cdot\left(\frac{0}{1+1}\right) = 0$$

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Differentiate $f(x) = x \sin x.$

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Example (Quotient Rule, Natural Exponential Function and Sine)

Differentiate $y = \dfrac{e^x}{2 + \sin x}$.

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&= \frac{2e^x + e^x \sin x - e^x \cos x}{(2+\sin x)^2} \\
&= \frac{e^x(2+\sin x - \cos x)}{(2+\sin x)^2}.
\end{aligned}$$

Example (Trigonometric limit)

Find $\lim_{x\to 0} \frac{2x}{\sin(9x)}$

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Let $\theta = 9x.$

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Theorem (The Derivative of $\cos x$)

$$\frac{d}{dx}(\cos x) = -\sin x$$

- This can be proved in a similar fashion as the formula for $\sin x$.
- Alternatively, this can be proved using the derivative of $\sin x$ and (the not yet studied) Implicit Differentiation and Chain Rule.

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Theorem (The Derivative of Tangent)

$$\frac{\mathrm{d}}{\mathrm{d}x}(\tan x) = \sec^2 x.$$

Proof.

$\square$

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&= \frac{\cos^2 x + \sin^2 x}{\cos^2 x} = \frac{1}{\cos^2 x} \\
&= \sec^2 x.
\end{aligned}$$

□

Derivatives of Trigonometric Functions

$$\frac{d}{dx}(\sin x) = \cos x \qquad \frac{d}{dx}(\csc x) = -\csc x \cot x$$

$$\frac{d}{dx}(\cos x) = -\sin x \qquad \frac{d}{dx}(\sec x) = \sec x \tan x$$

$$\frac{d}{dx}(\tan x) = \sec^2 x \qquad \frac{d}{dx}(\cot x) = -\csc^2 x$$

Example (Quotient Rule, Trig)

Differentiate $y = \dfrac{\sec x}{1 + \tan x}$.

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\frac{dy}{dx} &= \frac{\frac{d}{dx}(\sec x)(1+\tan x) - (\sec x)\frac{d}{dx}(1+\tan x)}{(1+\tan x)^2} \\
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&= \frac{\sec x(\tan x + \tan^2 x - \sec^2 x)}{(1+\tan x)^2} \\
&= \frac{\sec x(\tan x + (-1))}{(1+\tan x)^2} \qquad .
\end{aligned}$$

Example (Quotient Rule, Trig)

Differentiate $y = \dfrac{\sec x}{1+\tan x}$.

Quotient Rule:

$$\begin{aligned}
\frac{dy}{dx} &= \frac{\frac{d}{dx}(\sec x)(1+\tan x) - (\sec x)\frac{d}{dx}(1+\tan x)}{(1+\tan x)^2}\\
&= \frac{(\sec x \tan x)\,(1+\tan x) - (\sec x)\left(\sec^2 x\right)}{(1+\tan x)^2}\\
&= \frac{\sec x(\tan x + \tan^2 x - \sec^2 x)}{(1+\tan x)^2}\\
&= \frac{\sec x(\tan x + (-1))}{(1+\tan x)^2} = \frac{\sec x(\tan x - 1)}{(1+\tan x)^2}.
\end{aligned}$$

Example (Using the Product Rule twice)

Differentiate:

$$y = \theta e^{\theta}(\tan\theta + \sec\theta).$$

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$$= \left(\textbf{?} \qquad\qquad\qquad\qquad \right)(\tan\theta + \sec\theta) + \theta e^{\theta}\left(\textbf{?} \qquad\qquad\qquad\qquad \right)$$

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Example

Find the 27th derivative of $f(x) = \cos x$.

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$$f'(x) =$$

$$f''(x) =$$

$$f'''(x) =$$

$$f^{(4)}(x) =$$

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Find the 27th derivative of $f(x) = \cos x$.

$$f'(x) = -\sin x$$

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Example

Find the 27th derivative of $f(x) = \cos x$.

$$\begin{aligned} f'(x) &= -\sin x \\ f''(x) &= -\cos x \\ f'''(x) &= \sin x \\ f^{(4)}(x) &= \cos x \\ f^{(5)}(x) &= -\sin x \end{aligned}$$

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- The derivatives repeat in a cycle of length 4.

Example

Find the 27th derivative of $f(x) = \cos x$.

$$
\begin{aligned}
f'(x) &= -\sin x\\
f''(x) &= -\cos x\\
f'''(x) &= \sin x\\
f^{(4)}(x) &= \cos x\\
f^{(5)}(x) &= -\sin x
\end{aligned}
$$

- The derivatives repeat in a cycle of length 4.
- $f^{(24)}(x) = \mathbf{?}$.

Example

Find the 27th derivative of $f(x) = \cos x$.

$$f'(x) = -\sin x$$
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- $f^{(24)}(x) = \cos x$.

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- The derivatives repeat in a cycle of length 4.
- $f^{(24)}(x) = \cos x$.
- Differentiate three more times: $f^{(27)}(x) = \textbf{?}$.

Example

Find the 27th derivative of $f(x) = \cos x$.

$$f'(x) = -\sin x$$
$$f''(x) = -\cos x$$
$$f'''(x) = \sin x$$
$$f^{(4)}(x) = \cos x$$
$$f^{(5)}(x) = -\sin x$$

- The derivatives repeat in a cycle of length 4.
- $f^{(24)}(x) = \cos x$.
- Differentiate three more times: $f^{(27)}(x) = \sin x$.