

Properties of Derivatives

Definition The derivative of a function $f(x)$ is defined as the limit

$$f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}.$$

Derivative Rules

(i) Constant $f(x) = c \Rightarrow f'(x) = 0.$

(ii) Coefficient $f(x) = c g(x) \Rightarrow f'(x) = c g'(x).$

(iii) Addition $f(x) = g(x) + h(x) \Rightarrow f'(x) = g'(x) + h'(x).$

(iv) Power $f(x) = x^n, n \neq 0 \Rightarrow f'(x) = nx^{n-1}.$

(v) Product $f(x) = g(x)h(x) \Rightarrow f'(x) = g'(x)h(x) + h'(x)g(x).$

(vi) Chain $f(x) = g(h(x)) \Rightarrow f'(x) = g'(h) h'(x).$

(vii) Exponent $f(x) = e^x \Rightarrow f'(x) = e^x.$

(viii) Logarithm $f(x) = \ln x \Rightarrow f'(x) = \frac{1}{x}.$

Proofs

(i) Constant $f(x) = c \Rightarrow f'(x) = 0.$

Proof $f(x) = c \Rightarrow f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$
 $= \lim_{h \rightarrow 0} \frac{c - c}{h}$
 $= \lim_{h \rightarrow 0} \frac{0}{h} = 0. \square$

(ii) Coefficient $f(x) = c g(x) \Rightarrow f'(x) = c g'(x).$

Proof $f(x) = c g(x) \Rightarrow f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$
 $= \lim_{h \rightarrow 0} \frac{c g(x+h) - c g(x)}{h}$
 $= \lim_{h \rightarrow 0} c \left[\frac{g(x+h) - g(x)}{h} \right]$
 $= c \lim_{h \rightarrow 0} \frac{g(x+h) - g(x)}{h}$
 $= c g'(x). \square$

(iii) Addition $f(x) = g(x) + h(x) \Rightarrow f'(x) = g'(x) + h'(x).$

Proof $f(x) = g(x) + h(x) \Rightarrow f'(x) = \lim_{\Delta x \rightarrow 0} \frac{f(x+\Delta x) - f(x)}{\Delta x}$
 $= \lim_{\Delta x \rightarrow 0} \frac{[g(x+\Delta x) + h(x+\Delta x)] - [g(x) + h(x)]}{\Delta x}$
 $= \lim_{\Delta x \rightarrow 0} \frac{[g(x+\Delta x) - g(x)] + [h(x+\Delta x) - h(x)]}{\Delta x}$
 $= \lim_{\Delta x \rightarrow 0} \left(\frac{g(x+\Delta x) - g(x)}{\Delta x} + \frac{h(x+\Delta x) - h(x)}{\Delta x} \right)$
 $= \lim_{\Delta x \rightarrow 0} \frac{g(x+\Delta x) - g(x)}{\Delta x} + \lim_{\Delta x \rightarrow 0} \frac{h(x+\Delta x) - h(x)}{\Delta x}$
 $= g'(x) + h'(x). \square$

(IV) Power $f(x) = x^n, n \in \mathbb{N} \Rightarrow f'(x) = nx^{n-1}$.

Proof for $n \in \mathbb{N}$ $f(x) = x^n, n \in \mathbb{N} \Rightarrow f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$

$$= \lim_{h \rightarrow 0} \frac{(x+h)^n - x^n}{h}$$

by binomial theorem

$$= \lim_{h \rightarrow 0} \frac{\sum_{k=0}^n \frac{n!}{k(n-k)!} h^k x^{n-k} - x^n}{h}$$

$$= \lim_{h \rightarrow 0} \sum_{k=1}^n \frac{n!}{k(n-k)!} h^{k-1} x^{n-k}$$

since $\lim_{h \rightarrow 0} h^{k-1} = \begin{cases} 1 & \text{if } k=1 \\ 0 & \text{if } k>1 \end{cases}$

$$= \frac{n}{1!(n-1)!} x^{n-1}$$

$$= nx^{n-1}. \square$$

Proof for $n \in \mathbb{R} \setminus \{0\}$ let $y = f(x) = x^n, n \in \mathbb{R} \setminus \{0\}$.

$$y = x^n \Rightarrow \ln y = n \ln x.$$

$$\ln y = n \ln x \Rightarrow \frac{d \ln y}{dx} = \frac{d n \ln x}{dx} = nx^{-1}. \quad (4.1)$$

2 by (i) coefficient and (iii) logarithm.

$$(4.1) \Rightarrow \frac{d \ln y}{dx} = \frac{d \ln y}{dy} \frac{dy}{dx} = y^{-1} \frac{dy}{dx} = nx^{-1}$$

by (vi) chain. $\Rightarrow \frac{dy}{dx} = f'(x) = nx^{-1}y$

$$= nx^{-1}x^n$$

$$= nx^n. \square$$

(V) Product $f(x) = g(x)h(x) \Rightarrow f'(x) = g'(x)h(x) + g(x)h'(x)$.

Proof $f(x) = g(x)h(x) \Rightarrow f'(x) = \lim_{\Delta x \rightarrow 0} \frac{f(x+\Delta x) - f(x)}{\Delta x}$

$$= \lim_{\Delta x \rightarrow 0} \frac{g(x+\Delta x)h(x+\Delta x) - g(x)h(x)}{\Delta x}$$

$$= \lim_{\Delta x \rightarrow 0} \frac{g(x+\Delta x)h(x+\Delta x) - g(x)h(x) + (g(x+\Delta x)h(x) - g(x+\Delta x)h(x))}{\Delta x}$$

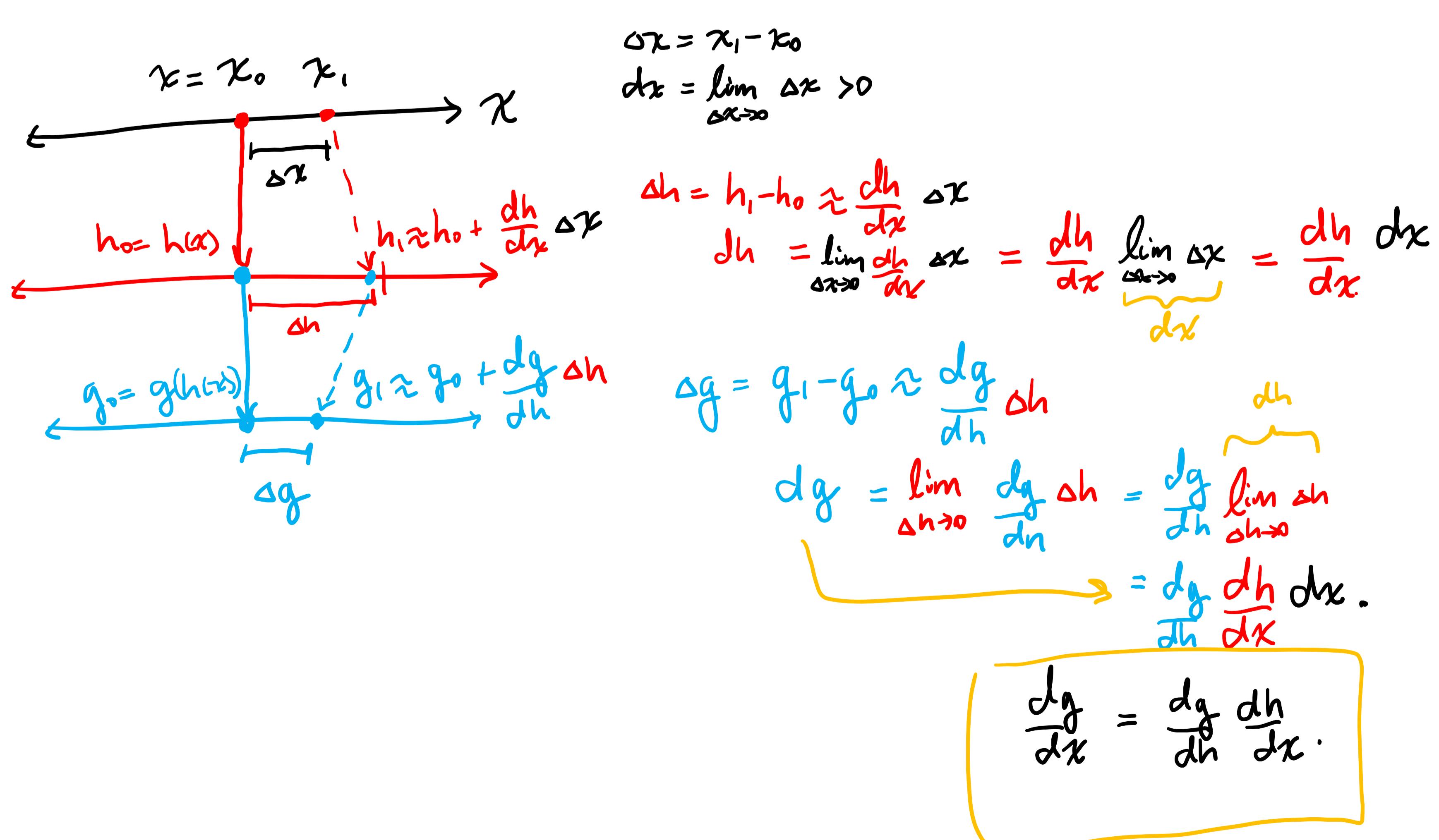
$$= \lim_{\Delta x \rightarrow 0} \frac{g(x+\Delta x)[h(x+\Delta x) - h(x)] + h(x)[g(x+\Delta x) - g(x)]}{\Delta x}$$

$$= \lim_{\Delta x \rightarrow 0} g(x+\Delta x) \frac{h(x+\Delta x) - h(x)}{\Delta x} + \lim_{\Delta x \rightarrow 0} h(x) \frac{g(x+\Delta x) - g(x)}{\Delta x}$$

$$= g(x)h'(x) + h(x)g'(x). \square$$

(vi) Chain $f(x) = g(h(x)) \Rightarrow f'(x) = g'(h)h'(x)$

Illustration



Corollary: Quotient $f(x) = \frac{g(x)}{h(x)} \Rightarrow f'(x) = \frac{g'(x)h(x) + h'(x)g(x)}{h(x)^2}$.

Proof $f(x) = \frac{g(x)}{h(x)} = g(x)[h(x)]^{-1} \Rightarrow f'(x) = \frac{dg(x)}{dx} \frac{1}{h(x)} + \frac{d(h(x)^{-1})}{dx} g(x)$ by (v) Product

$$= \frac{g'(x)}{h(x)} + \frac{\overbrace{d(h(x))}^{\text{by (vi) Chain}}}{dh} \frac{1}{\overbrace{dx}^{d(h(x))}} g(x)$$

$$= \frac{g'(x)h(x)}{h(x)^2} + (-1)[h(x)]^{-2} h'(x) g(x)$$

$$= \frac{g'(x)h(x) + h'(x)g(x)}{h(x)^2}. \square$$

Definition $e = \lim_{n \rightarrow \infty} (1 + \frac{1}{n})^n = \lim_{m \rightarrow 0} (1 + m)^{\frac{1}{m}}$.

$$\log_a(x) = y \Leftrightarrow y = a^x.$$

Properties (LP1) $\log_a(a^x) = x$.

(LP2) $\log_a(x^n) = n \log_a(x)$.

(LP3) $a^{\log_a(x)} = x$.

(LP4) $\log_a(x) = \frac{\log_b(x)}{\log_b(a)}$

Continuous Compounding:

- r: period interest rate
- n: interest payment/period
- t: number of periods

Compounded interest: $r_n = (1 + \frac{r}{n})^{nt}$

Continuous compounding: $r_c = \lim_{n \rightarrow \infty} (1 + \frac{r}{n})^{nt} = \lim_{x \rightarrow \infty} (1 + \frac{1}{x})^{xrt} = \left[\lim_{x \rightarrow \infty} (1 + \frac{1}{x})^x \right]^{rt}$

$$= e^{rt}.$$

(LP1) $\log_a(a^x) = x$.

Proof $y = a^x \Rightarrow \log_a(y) = x$
 $\Rightarrow \log_a(a^x) = x. \square$

Corollary: $\log_a(a) = 1, \log_a(1) = 0$.

Proof Set $x = 1$, then $\log_a(a^x) = x$
 $= \log_a(a^1) = \log_a(a) = 1. \square$

Set $x = 0$, then $\log_a(a^x) = x$
 $= \log_a(a^0) = \log_a(1) = 0. \square$

(LP2) $\log_a(x^n) = n \log_a(x)$.

Proof $\log_a(x) = y \Rightarrow x = a^y$
 $\Rightarrow x^n = (a^y)^n = a^{ny}$
 $\Rightarrow \log_a(x^n) = \log_a(a^{ny}) = ny$
 $\Rightarrow \log_a(x^n) = ny$

$$\log_a(x) = y \Rightarrow ny = n \log_a(x)$$

$$\Rightarrow \log_a(x^n) = n \log_a(x). \square$$

(LP3) $a^{\log_a(x)} = x$.

Proof $\log_a(x) = y \Rightarrow a^y = x$
 $\Rightarrow a^{\log_a(x)} = x. \square$

(LP4) $\log_a(x) = \frac{\log_b(x)}{\log_b(a)}$.

Proof $\log_a(x) = y \Rightarrow a^y = x \Rightarrow \log_b(x) = y \log_b(a)$
 $\Rightarrow y = \log_a(x) = \frac{\log_b(x)}{\log_b(a)}$

(vii) Exponential $f(x) = e^x \Rightarrow f'(x) = e^x.$

Proof $f(x) = e^x \Rightarrow f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$

$$= \lim_{h \rightarrow 0} \frac{e^{x+h} - e^x}{h}$$

$$= \lim_{h \rightarrow 0} \frac{e^x e^h - e^x}{h}$$

$$= \lim_{h \rightarrow 0} \frac{e^x (e^h - 1)}{h}$$

$$= e^x \lim_{h \rightarrow 0} \frac{(e^h - 1)}{h}$$

$$= e^x \lim_{y \rightarrow \infty} \left\{ \begin{array}{l} y \\ \hline \ln(1+y) \end{array} \right\}$$

$$= e^x \lim_{y \rightarrow \infty} \frac{1}{\frac{1}{y} \ln(1+y)}$$

$$= e^x \lim_{y \rightarrow \infty} \frac{1}{\ln((1+y)^{\frac{1}{y}})}$$

$$= e^x \frac{1}{\lim_{y \rightarrow \infty} \ln((1+y)^{\frac{1}{y}})}$$

$$= e^x \frac{1}{\ln(e)} = 1$$

$$= e^x (1) = e^x. \square$$

Let $y = e^h - 1$
 $h = \ln(1+y)$
 $\lim_{h \rightarrow 0} y = 0 = \lim_{h \rightarrow 0} h = \lim_{y \rightarrow 0} y$

(viii) Logarithm $f(x) = \ln(x) \Rightarrow f'(x) = \frac{1}{x}.$

Proof $f(x) = y = \ln(x) \Rightarrow e^y = x$

$$\Rightarrow \frac{de^y}{dx} = \frac{dx}{dx} = 1$$

$$\Rightarrow \frac{de^y}{dy} \frac{dy}{dx} = e^y \frac{dy}{dx} = 1$$

(vi) Chain Rule

$$\Rightarrow \frac{dy}{dx} = \frac{1}{e^y} = \frac{1}{x}. \square$$

Corollary: $f(x) = a^x \Rightarrow f'(x) = a^x \ln(a).$

Proof $f(x) = y = a^x \Rightarrow \ln(y) = x \ln(a)$

$$\Rightarrow \frac{d \ln(y)}{dx} = \frac{d}{dx} x \ln(a) = \ln(a)$$

$$\Rightarrow \frac{d \ln(y)}{dy} \frac{dy}{dx} = \frac{1}{y} \frac{dy}{dx} = \ln(a)$$

$$\Rightarrow \frac{dy}{dx} = y \ln(a) = a^x \ln(a).$$

Corollary: $f(x) = \log_a(x) \Rightarrow f'(x) = \frac{1}{x \ln(a)}.$

Proof $f(x) = \log_a(x) = \frac{\ln(x)}{\ln(a)} \Rightarrow f'(x) = \frac{1}{\ln(a)} \frac{d \ln(x)}{dx}$

$$= \frac{1}{x \ln(a)}. \square$$