

Math 140B Lecture Notes (Professor: Brandon Seward)

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Lecture 1: 4/1/2024

Let $f : E \longrightarrow \mathbb{R}$ where $E \subseteq \mathbb{R}$.

Since E is the domain of f , we shall also refer to it as $\text{dom}(f)$.

Fix a point $x \in E \cap E'$. Then consider the function $\frac{f(t)-f(x)}{t-x}$ for $t \in \text{dom}(f) \setminus \{x\}$ and define the derivative of f at x to be $f'(x) = \lim_{t \rightarrow x} \left(\frac{f(t)-f(x)}{t-x} \right)$ provided that this limit exists. When the above limit exists, we say f is differentiable at x .

We say f is differentiable on $D \subseteq E$ if f is differentiable at every point in D , and if f is differentiable on its entire domain, then we call f differentiable.

The function $f'(x) = \lim_{t \rightarrow x} \left(\frac{f(t)-f(x)}{t-x} \right)$ is called the derivative of f .

Proposition 83: If f is differentiable at x , then f is continuous at x .

Proof:

Note that $\lim_{t \rightarrow x} (f(t)) = \lim_{t \rightarrow x} \left((t-x) \frac{f(t)-f(x)}{t-x} + f(x) \right)$.

Now $\lim_{t \rightarrow x} (t-x) = 0$ and we know $\lim_{t \rightarrow x} \frac{f(t)-f(x)}{t-x} = f'(x)$ exists because f is differentiable at x . Also, obviously $\lim_{t \rightarrow x} f(x) = f(x)$.

Thus by proposition 66 (check 140A notes), we know that:

$$\begin{aligned} \lim_{t \rightarrow x} \left((t-x) \frac{f(t)-f(x)}{t-x} + f(x) \right) &= \lim_{t \rightarrow x} (t-x) \lim_{t \rightarrow x} \left(\frac{f(t)-f(x)}{t-x} \right) + \lim_{t \rightarrow x} f(x) \\ &= 0 \cdot f'(x) + f(x) \\ &= f(x) \end{aligned}$$

Thus, f is continuous at x .

Notes:

1. The above proposition says that differentiability is stronger than continuity.
2. The converse of this proposition is false. For example, the function $f(x) = |x|$ is continuous at $x = 0$ but not differentiable at $x = 0$.

Proposition 84: Suppose f and g are real valued functions with $\text{dom}(f), \text{dom}(g) \subseteq \mathbb{R}$. Also suppose f and g are differentiable at x . Then $f + g$, fg , and (when $g(x) \neq 0$) $\frac{f}{g}$ are differentiable at x with:

- (A) $(f + g)'(x) = f'(x) + g'(x)$ (sum rule)
 (B) $(fg)'(x) = f'(x)g(x) + f(x)g'(x)$ (product rule)
 (C) $\left(\frac{f}{g}\right)'(x) = \frac{f'(x)g(x) - f(x)g'(x)}{(g(x))^2}$ (quotient rule)

Proof:

(A) Since both f and g are differentiable, we know that both $f'(x) = \lim_{t \rightarrow x} \frac{f(t) - f(x)}{t - x}$ and $g'(x) = \lim_{t \rightarrow x} \frac{g(t) - g(x)}{t - x}$ exist. So by proposition 66:

$$(f + g)'(x) = \lim_{t \rightarrow x} \frac{f(t) + g(t) - f(x) - g(x)}{t - x} = \lim_{t \rightarrow x} \frac{f(t) - f(x)}{t - x} + \lim_{t \rightarrow x} \frac{g(t) - g(x)}{t - x}$$

This means $(f + g)'(x) = f'(x) + g'(x)$.

(B) Note that:

$$\begin{aligned} (fg)'(x) &= \lim_{t \rightarrow x} \frac{f(t)g(t) - f(x)g(x)}{t - x} \\ &= \lim_{t \rightarrow x} \frac{f(t)g(t) - f(x)g(t) + f(x)g(t) - f(x)g(x)}{t - x} \\ &= \lim_{t \rightarrow x} \left(g(t) \frac{f(t) - f(x)}{t - x} + f(x) \frac{g(t) - g(x)}{t - x} \right) \end{aligned}$$

By proposition 83, $g(t) \rightarrow g(x)$ as $t \rightarrow x$. Also, since both f and g are differentiable, we know $f'(x) = \lim_{t \rightarrow x} \frac{f(t) - f(x)}{t - x}$ and $g'(x) = \lim_{t \rightarrow x} \frac{g(t) - g(x)}{t - x}$ exist. So by proposition 66:

$$\lim_{t \rightarrow x} \left(g(t) \frac{f(t) - f(x)}{t - x} + f(x) \frac{g(t) - g(x)}{t - x} \right) = f'(x)g(x) + f(x)g'(x).$$

(C) Note that:

$$\begin{aligned} \left(\frac{f}{g}\right)'(x) &= \lim_{t \rightarrow x} \frac{\frac{f(t)}{g(t)} - \frac{f(x)}{g(x)}}{t - x} \\ &= \lim_{t \rightarrow x} \left(\frac{1}{g(x)g(t)} \frac{f(t)g(x) - f(x)g(t)}{t - x} \right) \\ &= \lim_{t \rightarrow x} \left(\frac{1}{g(x)g(t)} \frac{f(t)g(x) - f(x)g(x) + f(x)g(x) - f(x)g(t)}{t - x} \right) \\ &= \lim_{t \rightarrow x} \left(\frac{1}{g(x)g(t)} \left(g(x) \frac{f(t) - f(x)}{t - x} - f(x) \frac{g(t) - g(x)}{t - x} \right) \right) \end{aligned}$$

Now, for the same reasons as before, we can use propositions 83 and 66 to separate the parts of the above limit to get that the above limit equals:

$$\frac{1}{(g(x))^2} (g(x)f'(x) - f(x)g'(x))$$

If $f(x) = \alpha$ where $\alpha \in \mathbb{R}$ is constant, then trivially $f'(x) = 0$ for all x .
 Meanwhile, if $f(x) = x$, then we can trivially find that $f'(x) = 1$.

Claim 1: For all $n \in \mathbb{Z}^+$, if $f(x) = x^n$, then $f'(x) = nx^{n-1}$.

Proof: (we proceed by induction)

Base Case:

If $n = 1$, then for $f(x) = x^1$, we have that $f'(x) = 1 \cdot x^0$.

Induction:

Now assume $n > 1$, and for $f(x) = x^{n-1}$, we have that $f'(x) = (n-1)x^{n-2}$.

For the rest of this proof, I'll abbreviate the derivative of x^n as $(x^n)'$ and the derivative of x^{n-1} as $(x^{n-1})'$. Then using product rule, we know that:

$$(x^n)' = x(x^{n-1})' + 1 \cdot x^{n-1} = x \cdot (n-1)x^{n-2} + x^{n-1} = ((n-1) + 1)x^{n-1} = nx^{n-1}$$

Claim 2: If f is differentiable at x and $\alpha \in \mathbb{R}$, then $(\alpha f)'(x) = \alpha f'(x)$.

Proof:

By the product rule: $(\alpha f)'(x) = \alpha f' + (\alpha)'f = \alpha f' + 0 \cdot f = \alpha f'$.

These combined with proposition 84 tells us that both polynomials and rational functions are differentiable over their domains.

Proposition 85: (chain rule)

Let f and g be real-valued functions with $\text{dom}(f), \text{dom}(g) \subseteq \mathbb{R}$. Let $x \in \mathbb{R}$.

Suppose that f is differentiable at x and that g is differentiable at $f(x)$. Then

$g \circ f$ is differentiable at x and $(g \circ f)'(x) = g'(f(x))f'(x)$.

Intuition:

$$\lim_{t \rightarrow x} \left(\frac{g(f(t)) - g(f(x))}{f(t) - f(x)} \cdot \frac{f(t) - f(x)}{t - x} \right) = g'(f(x)) \cdot f'(x).$$

That said, the issue with this intuition is that we need to address the possibility that $f(t) - f(x) = 0$.

Proof:

Set $y = f(x)$ and define $v(s) = \begin{cases} \frac{g(s) - g(y)}{s - y} - g'(y) & \text{if } s \neq y \\ 0 & \text{if } s = y \end{cases}$

Note that v is continuous at y . This is because g being differentiable at $f(x) = y$ means that:

$$\lim_{s \rightarrow y} v(s) = \lim_{s \rightarrow y} \left(\frac{g(s) - g(y)}{s - y} - g'(y) \right) = g'(y) - g'(y) = 0 = v(y).$$

Also, since f is differentiable at x , we know that f is continuous at x . Therefore, $v \circ f$ is continuous at x by proposition 68. Additionally, setting $s = f(t)$, we know that $s \rightarrow y$ as $t \rightarrow x$ because f is continuous at x . Thus:

$$\lim_{t \rightarrow x} v(f(t)) = \lim_{s \rightarrow y} v(s) = 0$$

Finally, note that $g(s) - g(y) = (s - y)(g'(y) + v(s))$ for all s . Thus by substituting that into our limit:

$$\begin{aligned} (g \circ f)'(x) &= \lim_{t \rightarrow x} \frac{g(f(t)) - g(f(x))}{t - x} \\ &= \lim_{t \rightarrow x} \frac{f(t) - f(x)}{t - x} (g'(f(x)) + v(f(t))) \\ &= f'(x) (g'(f(x)) + 0) \quad (\text{by proposition 66}) \end{aligned}$$

Lecture 2: 4/3/2024

To start off lecture, here is some intuition about the behavior of derivatives. We'll formally define sine and cosine later (on page __) but for this section please take for granted that $(\sin(x))' = \cos(x)$. Additionally, please take for granted that the power rule holds for non-positive integer exponents.

1. Define $f(x) = \begin{cases} x \sin(\frac{1}{x}) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$

When $x \neq 0$, we have by chain rule that $f'(x) = \sin(\frac{1}{x}) - \frac{1}{x} \cos(\frac{1}{x})$.

Meanwhile if $x = 0$, then $\frac{f(t) - f(0)}{t - 0} = \frac{t \sin(\frac{1}{t})}{t} = \sin(\frac{1}{t})$ when $t \neq 0$.

So $\lim_{t \rightarrow 0} \left(\frac{f(t) - f(0)}{t - 0} \right)$ does not exist, meaning f is not differentiable at x .

This shows that $\text{dom}(f')$ can be a proper subset of $\text{dom}(f)$.

2. Define $g(x) = \begin{cases} x^2 \sin(\frac{1}{x}) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$

When $x \neq 0$, we have by chain rule that $g'(x) = 2x \sin(\frac{1}{x}) - \cos(\frac{1}{x})$.

Meanwhile when $t \neq 0$:

$$\left| \frac{g(t) - g(0)}{t - 0} \right| = \left| \frac{t^2 \sin(\frac{1}{t})}{t} \right| = |t \sin(\frac{1}{t})| \leq |t|.$$

Thus $0 = \lim_{t \rightarrow 0} (-t) \leq \lim_{t \rightarrow 0} \left(\frac{g(t) - g(0)}{t - 0} \right) \leq \lim_{t \rightarrow 0} (t) = 0$, meaning $g'(0) = 0$.

So $\text{dom}(g') = \text{dom}(g)$. That said, note that g' has a discontinuity of the second kind at 0. Therefore, because g is continuous, this shows that the derivative of a continuous function does not have to be continuous.

Let X be a metric space. A function $f : X \rightarrow \mathbb{R}$ has a local maximum at $p \in X$ if $\exists \delta > 0$ s.t. $\forall x \in B_\delta(p)$, $f(x) \leq f(p)$. Similarly, f has a local minimum if $\exists \delta > 0$ s.t. $\forall x \in B_\delta(p)$, $f(x) \geq f(p)$.

Proposition 86: Let $f : (a, b) \rightarrow \mathbb{R}$. If f has a local maximum at x and f is differentiable at x , then $f'(x) = 0$.

Proof:

Let $\delta > 0$ so that $\forall t \in B_\delta(x)$, $f(t) \leq f(x)$. Then for all $t \in (x - \delta, x)$, $\frac{f(t) - f(x)}{t - x} \geq 0$. So $f'(x) \geq 0$. Similarly for all $t \in (x, x + \delta)$, we have $\frac{f(t) - f(x)}{t - x} \leq 0$. Thus $f'(x) \leq 0$.

Hence $f'(x) = 0$.

Note that analogous reasoning can show that if f has a local minimum at x and f is differentiable at x , then $f'(x) = 0$.

Proposition 87: If $f, g : [a, b] \rightarrow \mathbb{R}$ are continuous on $[a, b]$ and differentiable on (a, b) , then there exists $x \in (a, b)$ with:

$$(f(b) - f(a))g'(x) = (g(b) - g(a))f'(x).$$

Proof:

Define $h : [a, b] \rightarrow \mathbb{R}$ by $h(x) = (f(b) - f(a))g(x) - (g(b) - g(a))f(x)$. Then $h(a) = f(b)g(a) - g(b)f(a) = h(b)$.

Notice that h is continuous on $[a, b]$ and differentiable on (a, b) because of propositions 70 and 84. Since $h'(x) = (f(b) - f(a))g'(x) - (g(b) - g(a))f'(x)$, for all $x \in (a, b)$ it now suffices to show that there exists $x \in (a, b)$ with $h'(x) = 0$.

Since h is continuous on a compact set $[a, b]$, we know that h attains a maximum value and a minimum value over the interval $[a, b]$.

Case 1: If h is constant on $[a, b]$, then $h'(x) = 0$ for all $x \in (a, b)$.

Case 2: If there is $t \in (a, b)$ with $h(t) > h(a) = h(b)$, then $h(a)$ and $h(b)$ can't be the max. value that h attains on $[a, b]$. So h has a maximum at some point $x \in (a, b)$. Then by the last theorem, $h'(x) = 0$.

Case 3: If there is $t \in (a, b)$ with $h(t) < h(a) = h(b)$, then $h(a)$ and $h(b)$ can't be the min. value that h attains on $[a, b]$. So h has a minimum at some point $x \in (a, b)$. Then by the last theorem, $h'(x) = 0$.

Proposition 88: (Mean Value Theorem)

If $f : [a, b] \rightarrow \mathbb{R}$ is continuous on $[a, b]$ and differentiable on (a, b) , then there is $x \in (a, b)$ with $f(b) - f(a) = (b - a)f'(x)$.

To prove this, apply the previous proposition with $g(x) = x$.

Proposition 89: Suppose $f : (a, b) \rightarrow \mathbb{R}$ is differentiable. Then:

- If $f'(x) \geq 0$ for all $x \in (a, b)$, then f is monotone increasing.
- If $f'(x) \leq 0$ for all $x \in (a, b)$, then f is monotone decreasing.
- If $f'(x) = 0$ for all $x \in (a, b)$, then f is constant.

Proof:

For all $a < x_1 < x_2 < b$, we know by the mean value theorem that there exists $t \in (x_1, x_2)$ with $f(x_2) - f(x_1) = (x_2 - x_1)f'(t)$. Then since $x_2 - x_1 > 0$, the sign of $f(x_2) - f(x_1)$ depends entirely on $f'(t)$.

Lecture 3: 4/5/2024

Even though derivatives are not necessarily continuous, we can show they always satisfy the conclusion of the intermediate value theorem.

Proposition 90: Suppose $f : [a, b] \rightarrow \mathbb{R}$ is differentiable and $\lambda \in \mathbb{R}$ satisfies that $f'(a) < \lambda < f'(b)$. Then there is $x \in (a, b)$ with $f'(x) = \lambda$.

Proof:

Define $g : [a, b] \rightarrow \mathbb{R}$ by the rule $g(t) = f(t) - \lambda t$. Then g is differentiable with $g'(t) = f'(t) - \lambda$. So, it suffices to find $x \in (a, b)$ with $g'(x) = 0$.

Since g is differentiable, we know that g is continuous. Adding in the fact that $[a, b]$ is compact, we know that g achieves a minimum value. So, let $x \in [a, b]$ be such that $g(x)$ is the minimum value of g .

Now consider that $f'(a) < \lambda < f'(b) \implies g'(a) < 0 < g'(b)$. Since $g'(a) < 0$, there is some $t_1 > a$ near a such that $g(x) \leq g(t_1) < g(a)$.

Explanation:

Set $\varepsilon = |g'(a)|$. Then by the definition of limits:

$$\exists \delta > 0 \text{ s.t. } \forall t \in (a, a + \delta), \left| \frac{g(t) - g(a)}{t - a} - g'(a) \right| < \varepsilon.$$

Then because $g'(a)$ is negative, we must have that $\frac{g(t) - g(a)}{t - a} < 0$.

But as $t - a > 0$, we must have that $g(t) - g(a) < 0$.

This will be a common trick so get used to it.

Similarly, since $g'(b) > 0$, there is some $t_2 < b$ near b such that $g(x) \leq g(t_2) < g(b)$. Hence, we have shown that $x \neq a$ and $x \neq b$, meaning that $x \in (a, b)$. Then, by applying proposition 86 we know that $g'(x) = 0$.

We can prove an analogous theorem for when $f'(b) < \lambda < f'(a)$.

Corollary: If $f : [a, b] \rightarrow \mathbb{R}$ is differentiable, then f' has no simple discontinuities.

Proof:

Assume that $x \in [a, b)$ and $f'(x+)$ exists. Then let $\varepsilon > 0$. By the definition of $f'(x+)$:

$$\exists \delta > 0 \text{ s.t. } \forall t \in (x, x + \delta), |f'(t) - f'(x+)| < \varepsilon/2.$$

If $f'(t) = f'(x)$ for all $t \in (x, x + \delta)$, then we automatically have that $f'(x+) = f'(x)$. So assume there exists $t \in (x, x + \delta)$ such that $f'(t) \neq f'(x)$. Then by the previous proposition, there exists $s \in (x, t)$ such that $f'(s)$ is between $f'(x)$ and $f'(t)$, and that $|f'(s) - f'(x)| < \varepsilon/2$.

Finally:

$$|f'(x) - f'(x+)| \leq |f'(x) - f'(s)| + |f'(s) - f'(x+)| < \varepsilon/2 + \varepsilon/2 = \varepsilon.$$

So $f'(x)$ must equal $f'(x+)$. Similarly, we can show that if $x \in (a, b]$ and $f'(x-)$ exists, then $f'(x) = f'(x-)$. Thus, it is impossible for f' to have a simple discontinuity.

However, we already saw that f' can have discontinuities of the second kind.

Proposition 91: (L'Hôpital's rule)

A List of How The Proposition Numbering in my Notes Lines up With Our Textbook:

Proposition Number	Label in Textbook	Proposition Number	Label in Textbook
83	5.2	84	5.3
85	5.5	86	5.8
87	5.9	88	5.10
89	5.11	90	5.12
91	5.13	92	

Our textbook is *Principles of Mathematical Analysis* by Walter Rudin.

Homework 1:

Exercise 5.2: Let $f : (a, b) \longrightarrow \mathbb{R}$ be differentiable with $f'(x) > 0$. Then f is strictly increasing.

For all $a < x_1 < x_2 < b$, we know by the mean value theorem that there exists $t \in (x_1, x_2)$ with $f(x_2) - f(x_1) = (x_2 - x_1)f'(t)$. Since $(x_2 - x_1)$ and $f'(t)$ are positive, we thus have that $f(x_2) - f(x_1) > 0$.

As a consequence of f being strictly increasing, we know f is injective. Thus if we restrict the codomain of f to its image, then f is bijective, meaning there exists a function $g = f^{-1}$ such that $(g \circ f)(x) = x = (f \circ g)(x)$. Now we show that for all $y \in \text{dom}(g)$, $y \in \text{dom}(g)'$ and $g(z) \rightarrow g(y)$ as $z \rightarrow y$.

Let $y \in \text{dom}(g)$. Then there exists $x \in \text{dom}(f)$ such that $f(x) = y$ and $g(y) = x$. But, since $\text{dom}(f)$ is an open set, we know that x is an interior point of $\text{dom}(f)$. Hence, there exists r such that $[x - r, x + r] \subseteq \text{dom}(f)$. Let \hat{f} be the restriction of f whose domain is $[x - r, x + r]$ and whose codomain is the image of $[x - r, x + r]$ with respect to f .

Because f is differentiable, we know f is continuous. Then, note that $\forall x_0 \in \text{dom}(\hat{f}) \cap \text{dom}(\hat{f})'$, $\lim_{t \rightarrow x_0} \hat{f}(t) = \lim_{t \rightarrow x_0} f(t) = f(x_0) = f(x_0) = \hat{f}(x_0)$. So, \hat{f} is a continuous function over its domain. Also, note that \hat{f} is still bijective.

Meanwhile $[x - r, x + r] = \text{dom}(\hat{f})$ is compact and connected. Firstly, this means that \hat{f}^{-1} is continuous. Secondly, this tells us that the image of $[x - r, x + r]$ is connected. Because f and thus \hat{f} is strictly increasing, we know that: $\hat{f}(x - r) < \hat{f}(x) = f(x) = y < \hat{f}(x + r)$. So, $[\hat{f}(x - r), \hat{f}(x + r)]$ is a subset of the domain of \hat{f}^{-1} and y is an interior point of that subset of the domain.

$[\hat{f}(x - r), \hat{f}(x + r)]$ is perfect, meaning y is a limit point of $[\hat{f}(x - r), \hat{f}(x + r)]$. In turn, this means y is a limit point of $\text{dom}(\hat{f})$ and $\text{dom}(g)$ because:

$$[\hat{f}(x - r), \hat{f}(x + r)] \subseteq \text{dom}(\hat{f}) \subseteq \text{dom}(g).$$

Then as \hat{f}^{-1} is continuous, we know that $\lim_{z \rightarrow y} \hat{f}^{-1}(z) = \hat{f}^{-1}(y)$. Additionally, because y is an interior point of $[\hat{f}(x - r), \hat{f}(x + r)]$, there exists $R > 0$ so that $B_R(y) \subset [\hat{f}(x - r), \hat{f}(x + r)]$.

Finally, we show that $g(z) \rightarrow g(y)$ as $z \rightarrow y$.

Let $\varepsilon > 0$. Then there exists $\delta > 0$ such that $|z - y| < \delta \implies |\hat{f}^{-1}(z) - \hat{f}^{-1}(y)| < \varepsilon$. Set $\delta' = \min(\delta, R)$. Then $|z - y| < \delta' \implies |g(z) - g(y)| = |\hat{f}^{-1}(z) - \hat{f}^{-1}(y)| \leq \varepsilon$.

Finally, we show that g is differentiable.

Note that $z = f(g(z))$ and $y = f(g(y))$. So, we can write that:

$$\lim_{z \rightarrow y} \frac{g(z) - g(y)}{z - y} = \lim_{z \rightarrow y} \frac{g(z) - g(y)}{f(g(z)) - f(g(y))}.$$

Now let (z_n) be any sequence in the domain of g converging to y such that $z_n \neq y$ for any y . Since $\lim_{z \rightarrow y} g(z) = g(y)$ for all $y \in \text{dom}(g)$, we know that $g(z_n) \rightarrow g(y)$.

Meanwhile, note that since $f'(x) \neq 0$ for all $x \in \text{dom}(f)$, we can evaluate that:

$$\lim_{t \rightarrow g(y)} \frac{t - g(y)}{f(t) - f(g(y))} = \frac{1}{f'(g(y))}.$$

So, given any sequence (t_n) in the domain of f converging to $g(y)$, we have that $\frac{t_n - g(y)}{f(t_n) - f(g(y))} \rightarrow \frac{1}{f'(g(y))}$. $(g(z_n))$ is one such sequence. Hence:

$$\frac{g(z_n) - g(y)}{f(g(z_n)) - f(g(y))} \rightarrow \frac{1}{f'(g(y))}.$$

Since this is true for all relevant (z_n) , we conclude that:

$$\lim_{z \rightarrow y} \frac{g(z) - g(y)}{z - y} = \lim_{z \rightarrow y} \frac{g(z) - g(y)}{f(g(z)) - f(g(y))} = \frac{1}{f'(g(y))}$$

Thus, $g'(y)$ exists and equals $\frac{1}{f'(g(y))}$.

Plugging in $y = f(x)$, we get that $g'(f(x)) = \frac{1}{f'(x)}$.