MATH 20410 (Analysis in $\mathbb{R}^n$ II – Accelerated) Notes

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Chapter 6

The Riemann-Stieltjes Integral

6.1 Notes

1/28:

- Plan:
  1. Finish up Fundamental Theorem of Calculus proof.
  2. Basic consequences.
  3. Rectifiable curves.
- Recall that we're given $f : [a,b] \to \mathbb{R}$ continuous, $f : [a,b] \to \mathbb{R}$, and $x \mapsto \int_a^x f(t)\,\mathrm{d}t$.
- Goal: Show $F'(x_0) = f(x_0)$.
  - WTS: Find δ such that $|x - x_0| < \delta$ implies

$$\begin{aligned}\left|\frac{1}{x-x_0}\int_{x_0}^x f(t)\,\mathrm{d}t - f(x_0)\right| &= \left|\frac{1}{x-x_0}\int_{x_0}^x f(t)\,\mathrm{d}t - \frac{1}{x-x_0}\int_{x_0}^x f(x_0)\,\mathrm{d}t\right|\\ &= \frac{1}{|x-x_0|}\left|\int_{x_0}^x (f(t)-f(x_0))\,\mathrm{d}t\right|\\ &\leq \frac{1}{|x-x_0|}\int_{x_0}^x |f(t)-f(x_0)|\,\mathrm{d}t\\ &< \epsilon\end{aligned}$$

  - Since f is continuous, there exists δ such that if $|x - x_0| < \delta$, then $|f(x) - f(x_0)| < \epsilon$.
  - Now

$$\begin{aligned}\frac{1}{|x-x_0|}\int_{x_0}^x |f(t)-f(x_0)|\,\mathrm{d}t &< \frac{1}{|x-x_0|}\int_{x_0}^x \epsilon\,\mathrm{d}t\\ &= \epsilon\end{aligned}$$

- Applications:
  1. Theorem (MVT for integration): $f : [a,b] \to \mathbb{R}$ continuous, then there exists $x_0 \in [a,b]$ such that

$$f(x_0) = \frac{1}{b-a}\int_a^b f(x)\,\mathrm{d}x$$

     - Apply MVT to $F(x) = \int_a^x f(t)\,\mathrm{d}t$. Then

$$F'(x_0) = f(x_0) = \frac{F(b)-F(a)}{b-a}$$

       as desired.

2. Theorem (Integration by parts): Let $F, G : [a, b] \to \mathbb{R}$ be differentiable with $F' = f$, $G' = g$ and with f and g both integrable. Then
$$\int_a^b Fg = F(b)G(b) - F(a)G(a) - \int_a^b fG$$
   - Just use the product rule plus the FTC to prove.
   - We have
$$\begin{aligned} \int_a^b (FG)' &= \int_a^b fG + \int_a^b Fg \\ F(b)G(b) - F(a)G(a) &= \int_a^b fG + \int_a^b Fg \\ \int_a^b Fg &= F(b)G(b) - F(a)G(a) - \int_a^b fG \end{aligned}$$
3. Theorem (u-substitution).
   - Follows similarly from the chain rule and FTC.

- Integration of vector-valued functions.
- If $f : [a, b] \to \mathbb{R}^k$, we define $\int_a^b f$ by
$$\int_a^b f = \left(\int_a^b f_1, \dots, \int_a^b f_k \right)$$
- Alternatively, you can define $\int_a^b f$ using P, $U(f, P)$, $L(f, P)$, etc. and then prove that the integral exists iff all f_i are integrable and in this case the above definition holds.
- Rectifiable curves: Let $\gamma : [a, b] \to \mathbb{R}^k$ be a continuous function.
- Plan: Define the length of γ and show that we can compute it with an integral.
  - Idea: For polygonal paths, we know how to define length. So let's approximate γ by polygons and take a limit.
  - Ref: Given a partition P, then define the length of γ with respect to P as $\Lambda(\gamma, P)$. Let the length of γ be $\Lambda(\gamma) = \sup_P \Lambda(\gamma, P)$ if this limit exists in this case, we call γ **rectifiable**.
- Fractals are not rectifiable — their length diverges.
- Theorem: Suppose γ is continuously differentiable (i.e., γ is differentiable and γ' is continuous). Then γ si rectifiable and
$$\Lambda(\gamma) = \int_a^b |\gamma'(t)| \, \mathrm{d}t$$
  - Notice: If $P \leq P'$, then $\Lambda(\gamma, P) \leq \Lambda(\gamma, P')$. (Prove with triangle inequality.)
  - WTS: For all partitions P, $\Lambda(\gamma, P) \leq \int_a^b |\gamma'(t)| \, \mathrm{d}t$ and thus $\Lambda(\gamma) \leq \int_a^b |\gamma'(t)| \, \mathrm{d}t$.
  - We have that
$$\begin{aligned} \Lambda(\gamma, P) &= \sum_{i=1}^n |\gamma(x_i) - \gamma(x_{i-1}) \\ &= \sum_{i=1}^n \left| \int_{x_{i-1}}^{x_i} \gamma'(t) \, \mathrm{d}t \right| \\ &\leq \sum_{i=1}^n \int_{x_{i-1}}^{x_i} |\gamma'(t)| \, \mathrm{d}t \\ &= \int_a^b |\gamma'(t)| \, \mathrm{d}t \end{aligned}$$

- Catch up.
  - I should make up PSets 1-2.
  - Exams have less than Rudin-strength problems.
  - Exams are mostly true/false (and of that, mostly false, provide a counterexample).

6.2 Exam 1 Additional Topics

- A continuous function that is not always differentiable.

$$f(x) = |x|$$

- A differentiable function with a discontinuous derivative.

$$f(x) = x^2 \sin \frac{1}{x}$$

- A vector-valued function that doesn't satisfy the MVT.

$$\mathbf{f}(x) = \mathrm{e}^{ix}$$

  - Between 0 and 2π.
- A pair of vector-valued functions that don't satisfy L'Hôpital's rule.

$$f(x) = x \qquad\qquad g(x) = x + x^2 \mathrm{e}^{i/x^2}$$

Chapter 7

Sequences and Series of Functions

7.1 Notes

1/31:

- Midterm on differentiation and integration, and a bit of stuff from this week.
- Plan:
  - Talk about sequences of functions, all with the same domain and range, converging.
  - Address what properties of f_n remain in the limit (e.g., continuity, differentiability, integrability).
    - The answer depends on what we mean by "convergence."
    - $f_n \to f$ pointwise implies basically nothing.
    - $f_n \to f$ uniformly implies that basically everything works out nicely.
- We'll restrict ourselves to real functions because those have all the properties (integrability, differentiability, etc.) that we care about.
- **Pointwise** (convergent sequence $\{f_n\}$ to f): A sequence of functions $\{f_n\}$ such that for all $x \in X$, the sequence $\{f_n(x)\}$ converges to $f(x)$, where $f_n : X \to \mathbb{R}$ for all $n \in \mathbb{N}$ and $f : X \to \mathbb{R}$. *Denoted by* $f_n \to f$.
- Bad functions.
  - Consider $f_n : [0,1] \to \mathbb{R}$ defined by $x \mapsto x^n$. Each f_n is continuous, but f is not (zero everywhere except $f(1) = 1$)[1].
  - Consider $f_n : \mathbb{R} \to \mathbb{R}$ defined by $f_n(x) = x^2/(1+x^2)^n$, and $f(x) = \sum_{n=0}^{\infty} f_n(x)$. As a geometric series, $f(x) = 1 + x^2$ when $x \neq 0$ but $f(0) = 0$. Thus, the limit exists but is not continuous once again.
  - Consider $f_m : \mathbb{R} \to \mathbb{R}$ defined by $x \mapsto \lim_{n\to\infty} \cos^{2n}(m!\pi x)$. Each f_m is integrable, but the limit f is the function that's 1 for rationals and zero for irrationals. In particular, f is not integrable.
    - We take even powers of the cosine to make it always positive.
    - We use $\cos^2(x)$ just because its always between $[0,1]$, and we know when it is equal to 1.
    - In particular, $\cos^2(\pi x)$ is equal to 1 at every integer, $\cos^2(2\pi x)$ is equal to 1 at every half integer. $\cos^2(6\pi x)$ is equal to 1 at every one-sixth of an integer.
    - Then raising it to the n^{th} power just makes it spiky.
- Aside: Interchanging limits.
  - If all f_n are continuous, then $\lim_{x\to x_0} f_n(x) = f_n(x_0)$.

[1] Questions that require counterexamples like this could show up on the midterm!

- – The question "is f continuous" is equivalent to being able to interchange limits:

$$\lim_{x\to x_0}\lim_{n\to\infty} f_n(x) = f(x_0) = \lim_{n\to\infty}\lim_{x\to x_0} f_n(x)$$

  – Sequence example showing we need to be careful interchanging limits: $s_{n,m} = m/(m+n)$.
- All of this pathology goes away with the right definition, though.
- **Uniformly** (convergent sequence $\{f_n\}$ to f): A sequence of functions $\{f_n\}$ such that for all $\epsilon > 0$, there exists an N such that if $n \geq N$, then $|f_n(x) - f(x)| < \epsilon$ for all $x \in X$, where $f_n : X \to \mathbb{R}$ for all $n \in \mathbb{N}$ and $f : X \to \mathbb{R}$.
- Proposition (Cauchy criterion for uniform convergence): $f_n \to f$ uniformly iff for all $\epsilon > 0$, there exists N such that for all $m, n \geq N$ and for all $x \in X$, $|f_n(x) - f_m(x)| < \epsilon$.
  – Forward direction: Let $\epsilon > 0$. Suppose $f_n \to f$ uniformly. Choose N such that the functions are within $\epsilon/2$. Then

$$|f_n(x) - f_m(x)| \leq |f_n(x) - f(x)| + |f(x) - f_m(x)| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

2/2:
- Office hours tomorrow 4-5 PM.
- Plan:
  1. More on uniform convergence.
     – Limit of continuous functions is continuous.
     – Limit of the integral of functions is the integral of the limit.
  2. $\mathcal{C}(X)$ perspectives on uniform convergence.
- Corollary (Weierstraß M-test): If there exist constants $M_n \in \mathbb{R}$ such that $|f_n(x)| \leq M_n$ for all x and $\sum_{n=1}^{\infty} M_n$ converges, then $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly.
- Theorem: $f_n : X \to \mathbb{R}$, f_n continuous at $x_0 \in X$ for all n, and $f_n \to f$ uniformly imply f continuous at x_0.
  – Idea:
    - "$\epsilon/3$ trick": Find δ such that if $|x - x_0| < \delta$, then

$$|f(x) - f(x_0)| \leq |f(x) - f_N(x)| + |f_N(x) - f_N(x_0)| + |f_N(x_0) - f(x_0)| < \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3} = \epsilon$$

  – Proof:
    - $f_n \to f$ uniformly implies there exists $N \in \mathbb{N}$ such that $|f_N(x) - f(x)| < \epsilon/3$ for all $x \in X$.
    - f_N continuous at x_0: There exists δ such that if $d(x, x_0) < \delta$, then $|f_N(x) - f_N(x_0)| < \epsilon/3$.
    - Thus, by the $\epsilon/3$ trick, we have the continuity of f.
- Defining a norm on $\mathcal{C}(X)$.

$$\|f\| = \sup_{x\in X} |f(x)|$$

  – This makes $\mathcal{C}(X)$ into a vector space.
  – We can now define our metric $d(f,g)$ by $d(f,g) = \|f - g\|$.
- $f_n \to f \iff f$ is bounded.
  – $f_n \to f$ uniformly $\iff \lim_{n\to\infty} \sup |f_n(x) - f(x)| = 0 \iff f_n \to f$ is $\mathcal{C}(X)$.
- Corollary to the Weierstraß M-test: $\mathcal{C}(X)$ is complete (i.e., all uniformly Cauchy sequences converge).

- Assume $\{f_n\}$ is Cauchy. Then by the Cauchy criterion for uniform convergence, f_n converges uniformly to some f. But this f must be continuous, too, meaning $f \in \mathcal{C}(X)$.

2/4:

- Plan.
  1. $\int \lim f_n = \lim \int f_n$.
  2. $\mathrm{d}x \lim f_n = \lim \mathrm{d}x\, f_n$.
  3. Definitions: Pointwise/uniform boundedness, equicontinuity.
- Theorem: $f_n : [a,b] \to \mathbb{R}$ integrable and $f_n \to f$ uniformly implies f is integrable and

$$\int_a^b f = \lim_{n\to\infty} \int_a^b f_n$$

  - Plan:
    1. Show f is integrable.
    2. Show $\int f = \lim \int f_n$.
  - Proof:
    - Let $\epsilon_n = \sup_{x\in[a,b]} |f(x) - f_n(x)|$.
    - Since $f_n \to f$ uniformly, $\epsilon_n \to 0$ as $n \to \infty$.
    - By definition, $f_n - \epsilon_n \leq f \leq f_n + \epsilon_n$.
    - Thus, by Theorems 6.4 and 6.5,

$$\int_a^b (f_n - \epsilon_n) = \underline{\int} (f_n - \epsilon_n) \leq \underline{\int} f \leq \bar{f} \leq \int_a^b (f_n + \epsilon_n)$$

    - It follows since

$$0 \leq \overline{\int} f - \underline{\int} f \leq \int_a^b (f_n + \epsilon_n) - \int_a^b (f_n - \epsilon_n) = (b-a)...$$

      that f is integrable.
    - Hence,

$$\int_a^b (f_n - \epsilon_n) \leq \int_a^b f \leq \int_a^b (f_n - \epsilon_n)$$

$$\left| \int_a^b f_n - \int_a^b f \right| \leq \epsilon_n$$

$$\lim_{n\to\infty} \int_a^b f_n = \int_a^b f$$

- Theorem: $f_n : [a,b] \to \mathbb{R}$, each f_n differentiable, $f_n \to f$ pointwise, and $(f_n)' \to g$ uniformly implies that f is differentiable and $f' = g$.
  - Note that you can do better: Substituting $f_n(x_0)$ converging for some $x_0 \in [a,b]$ for $f_n \to f$ pointwise still implies the desired result.
  - Idea: We use the $\epsilon/3$ trick; 2/3 will be easy and 1/3 will be tricky.
  - Goal: We want

$$\left| \frac{f(x) - f(x_0)}{x - x_0} - g(x_0) \right| < \epsilon$$

    for some δ with $0 < |x - x_0| < \delta$. We will show that

$$\begin{aligned}
&\left| \frac{f(x) - f(x_0)}{x - x_0} - \frac{f_N(x) - f_N(x_0)}{x - x_0} + \frac{f_N(x) - f_N(x_0)}{x - x_0} - f_N'(x_0) + f_N'(x_0) - g(x_0) \right| \\
&\leq \left| \frac{f(x) - f(x_0)}{x - x_0} - \frac{f_N(x) - f_N(x_0)}{x - x_0} \right| + \left| \frac{f_N(x) - f_N(x_0)}{x - x_0} - f_N'(x_0) \right| + |f_N'(x_0) - g(x_0)|
\end{aligned}$$

- For the middle inequality, use Chapter 5, Exercise 8.
- For the right inequality, use the uniform convergence condition.
- For the left inequality, it will suffice to show the Cauchy condition

$$\left|\frac{f_n(x)-f_n(x_0)}{x-x_0}-\frac{f_m(x)-f_m(x_0)}{x-x_0}\right|<\frac{\epsilon}{3}$$

so, noting that the left term above is equal to

$$\left|\frac{[f_n(x)-f_m(x)]-[f_n(x_0)-f_m(x_0)]}{x-x_0}\right|$$

which is equal to $|f_n'(c)-f_m'(c)|$ by the MVT, from which we can apply the Cauchy form of the uniform convergence of $(f_n)'$ condition.

- **Pointwise bounded** ($\{f_n\}$): A sequence of real functions $\{f_n\}$ such that for all $x \in X$, there exists $M_x \in \mathbb{R}$ such that $|f_n(x)| \leq M_x$ for all $n \in \mathbb{N}$.
- **Uniformly bounded** ($\{f_n\}$): A sequence of real functions $\{f_n\}$ for which there exists $M \in \mathbb{R}$ such that for all $x \in X$ and $n \in \mathbb{N}$, $|f_n(x)| \leq M$.
- Proposition: $f_n : E \to \mathbb{R}$, $\{f_n\}$ is pointwise bounded, and E is countable implies there is a subsequence $\{f_{n_k}\}$ that converges pointwise.
  - Enumerate $E = \{x_1, x_2, \dots\}$.
  - Then since $\{f_n(x_m)\}$ is bounded for all m by hypothesis, it always has a convergent subsequence.
  - The claim is if you look at the sequence of diagonal functions, it is such a subsequence, i.e., if $f_1(x_1)$ is the first term for x_1, $f_3(x_2)$ is the second term for x_2, $f_{11}(x_3)$ is the third term for x_3, and so on, $f_1, f_3, f_{11}, \dots$ is such a subsequence.

2/9:
- Build up to the Arzelà-Ascoli theorem.

2/11:
- The Arzelà-Ascoli theorem.

Chapter 9

Functions of Several Variables

9.1 Notes

2/14: • Plan:

1. Warm-up with matrices.
2. The total derivatives of $f : \mathbb{R}^n \to \mathbb{R}^m$ ($n = m = 2$, i.e., $f : \mathbb{C} \to \mathbb{C}$).
3. Basic properties: Chain rule, relation with partial derivatives, implicit function theorem.

- Let V, W be finite-dimensional vector spaces over $\mathbb{R}$. We let $L(V, W)$ be the vector space of all linear transformations $\phi : V \to W$.
- If we pick bases $\mathbf{v}_1, \dots, \mathbf{v}_n$ of V and $\mathbf{w}_1, \dots, \mathbf{w}_m$ of W, then $V \cong \mathbb{R}^n$ and $W \cong \mathbb{R}^m$. It follows that $L(V, W) \cong \mathbb{R}^{mn}$.
- $L(V, W) \times L(W, U) \xrightarrow{\text{compose}} L(V, U)$, i.e., $\mathbb{R}^{mn} \times \mathbb{R}^{nl} \xrightarrow[\text{mult.}]{\text{matrix}} \mathbb{R}^{ml}$.
- Sup norm: If A is an $m \times n$ real matrix, then $\|A\| = \sup_{\substack{\mathbf{x} \in \mathbb{R}^n \\ |\mathbf{x}|=1}} |A\mathbf{x}|$.
  - Basic properties:
    1. $|A\mathbf{x}| \leq \|A\||x|$.
    2. $\|A\| < \infty$ and all $A : \mathbb{R}^n \to \mathbb{R}^m$ are uniformly continuous.
    3. $\|A\| = 0 \iff A = 0$.
    4. $\|cA\| = |c|\|A\|$.
    5. $\|A + B\| \leq \|A\| + \|B\|$.
    6. $\|AB\| \leq \|A\|\|B\|$.
  - Note that we get a metric space structure on $L(V, W)$ by defining $d(A, B) = \|A - B\|$.
- Proves that 1 and 2 imply the uniform continuity of all A (via Lipschitz continuity).
- **Differentiable** (function $\mathbf{f}$ at $\mathbf{x}_0$): A function $\mathbf{f} : U \to \mathbb{R}^m$ ($U \subset \mathbb{R}^n$) such that to $\mathbf{x}_0 \in U$ there corresponds some linear transformation $A : \mathbb{R}^n \to \mathbb{R}^m$ such that

$$\lim_{\mathbf{h} \to \mathbf{0}} \frac{|\mathbf{f}(\mathbf{x}_0 - \mathbf{h}) - \mathbf{f}(\mathbf{x}_0) - A\mathbf{h}|}{|\mathbf{h}|} = 0$$

- **Total derivative** (of $\mathbf{f}$ at $\mathbf{x}_0$): The linear transformation A in the above definition. *Denoted by* $\mathbf{f'(x_0)}$, $\boldsymbol{D}\mathbf{f}(\mathbf{x_0})$, $\boldsymbol{d}\mathbf{f}(\mathbf{x_0})$.
- "An proof and progress in mathematics" - Thurston.

  - Relating to the old one dimensional derivative.
  - A paper we'd find rather impressionistic right now.
- Propositions ahead of us.
  - Proposition: Suppose that $\mathbf{f}$ is differentiable at $\mathbf{x}_0 \in U$ and A, B are both derivatives of $\mathbf{f}$ at $\mathbf{x}_0$. Then $A = B$.
  - Proposition: Differentiable implies continuous.
  - Proposition: Sum rule, product rule, quotient rule.

2/16:

- Plan: Derivatives of functions $\mathbf{f} : U \to \mathbb{R}^m$ where $U \subset \mathbb{R}^n$.
  - Basic properties: Differentiability implies continuity, $(\mathbf{f}+\mathbf{g})' = \mathbf{f}' + \mathbf{g}'$, $(c\mathbf{f})' = c\mathbf{f}'$, chain rule, $\mathbf{f}' = 0$ iff $\mathbf{f}$ is constant.
  - Relationship with partial derivatives (how we compute everything and anything).
  - When is $\mathbf{f}$ differentiable?
  - Inverse function theorem.
  - Implicit function theorem.
- **Continuously differentiable** (function $\mathbf{f}$): A function $\mathbf{f} : U \to \mathbb{R}^m$ that is differentiable for all $\mathbf{x}_0 \in U$ and such that $\mathbf{f}' : U \to L(\mathbb{R}^n, \mathbb{R}^m)$ is continuous. *Also known as* $\boldsymbol{\mathscr{C}^1}$.
- Proposition: Let $\mathbf{f} : U \to \mathbb{R}^m$ be differentiable at $\mathbf{x}_0 \in U$. Then $\mathbf{f}$ is continuous at $\mathbf{x}_0$.
  - The proof makes use of the fact that $\mathbf{f}(\mathbf{x}_0 + \mathbf{h}) - \mathbf{f}(\mathbf{x}_0) = \mathbf{f}'(\mathbf{x}_0)\mathbf{h} + \mathbf{r}(\mathbf{h})$.
- Proposition: Given $\mathbf{f}, \mathbf{g} : U \to \mathbb{R}^m$ both differentiable at $\mathbf{x}_0 \in U$, then $\mathbf{f}+\mathbf{g}$ is also differentiable at $\mathbf{x}_0$ with

$$(\mathbf{f}+\mathbf{g})'(\mathbf{x}_0) = \mathbf{f}'(\mathbf{x}_0) + \mathbf{g}'(\mathbf{x}_0)$$

  - The proof is immediate via the triangle inequality.
- Theorem (Chain Rule): Given $\mathbf{f} : U \to \mathbb{R}^m$ and $\mathbf{g} : V \to \mathbb{R}^k$, where $U \subset \mathbb{R}^n$ and $\mathbf{f}(U) \subset V \subset \mathbb{R}^m$, with $\mathbf{f}$ differentiable at $\mathbf{x}_0 \in U$ and $\mathbf{g}$ differentiable at $\mathbf{f}(\mathbf{x}_0)$, the composition $\mathbf{g} \circ \mathbf{f}$ is differentiable at $\mathbf{x}_0$ with

$$(\mathbf{g} \circ \mathbf{f})'(\mathbf{x}_0) = \mathbf{g}'(\mathbf{f}(\mathbf{x}_0)) \cdot \mathbf{f}'(\mathbf{x}_0)$$

  - The proof is rather subtle.
- **Partial derivative** (of f_i wrt. x_j at $\mathbf{x}_0$): The following limit, if it exists, where $f_i : \mathbb{R}^n \to \mathbb{R}$, $1 \leq i \leq m$, and $1 \leq j \leq n$. *Denoted by* $\boldsymbol{(\partial f_i / \partial x_j)(\mathbf{x}_0)}$, $\boldsymbol{(D_j f_i)(\mathbf{x}_0)}$. *Given by*

$$\frac{\partial f_i}{\partial x_j}(\mathbf{x_0}) = \lim_{t \to 0} \frac{f_i(\mathbf{x}_0 + t\mathbf{e}_j) - f_i(\mathbf{x}_0)}{t}$$

- **Directional derivative** (of f_i toward $\mathbf{u} \in \mathbb{R}^n$): The following limit, if it exists, where $f_i : \mathbb{R}^n \to \mathbb{R}$ and $1 \leq i \leq m$. *Denoted by* $\boldsymbol{D_{\mathbf{u}} f_i}$. *Given by*

$$D_{\mathbf{u}} f_i = \lim_{t \to 0} \frac{f_i(\mathbf{x}_0 + t\mathbf{u}) - f_i(\mathbf{x}_0)}{t}$$

- **Jacobian**: The following matrix. *Given by*

$$\left[\frac{\partial f_i}{\partial x_j}(\mathbf{x}_0)\right]$$

- Theorem: Let $\mathbf{f} = (f_1, \dots, f_m) : U \to \mathbb{R}^m$, where $U \subset \mathbb{R}^n$, be differentiable at some $\mathbf{x}_0 \in U$. Then the partial derivatives $\partial f_i / \partial x_j$ $(1 \leq i \leq m;\ 1 \leq j \leq n)$ exist at $\mathbf{x}_0$ and, with respect to the usual choice of bases,
$$\mathbf{f}'(\mathbf{x}_0) = \left[\frac{\partial f_i}{\partial x_j}(\mathbf{x}_0)\right]$$

2/18:
  - We have that
$$\mathbf{f}(\mathbf{x}_0 + t\mathbf{e}_j) - \mathbf{f}(\mathbf{x}_0) = \mathbf{f}'(\mathbf{x}_0)(t\mathbf{e}_j) + \mathbf{r}(t\mathbf{e}_j)$$
  - Since $\mathbf{f}$ is differentiable at $\mathbf{x}_0$, $\mathbf{f}(t\mathbf{e}_j)/t \to 0$ as $t \to 0$.
  - Additionally, $\mathbf{f}'(\mathbf{x}_0)(t\mathbf{e}_j)/t = \mathbf{f}'(\mathbf{x}_0)(\mathbf{e}_j)$.
  - Therefore,
$$\lim_{t\to 0} \frac{\mathbf{f}(\mathbf{x}_0 + t\mathbf{e}_j) - \mathbf{f}(\mathbf{x}_0)}{t} = \lim_{t\to 0} \frac{\mathbf{f}'(\mathbf{x}_0)(t\mathbf{e}_j) - \mathbf{r}(t\mathbf{e}_j)}{t} = \mathbf{f}'(\mathbf{x}_0)(\mathbf{e}_j) - \lim_{t\to 0}\frac{\mathbf{r}(t\mathbf{e}_j)}{t} = \mathbf{f}'(\mathbf{x}_0)(\mathbf{e}_j)$$
    as desired.
  - Unpacking the definition of the linear transformation as a matrix gives the rest of the proof.
- Today:
  - More on differentiation (recall the Jacobian).
  - Sufficient condition for differentiability.
  - $\mathbf{f}' = 0$ iff $\mathbf{f}$ is constant.
  - State the inverse function theorem.
- It is not true that having all partials exist implies that $\mathbf{f}$ is differentiable at $\mathbf{x}_0$.
- Theorem: $\mathbf{f}$ continuously differentiable at $\mathbf{x}_0$ iff all partials exist and are continuous at $\mathbf{x}_0$.

2/21:
- Contraction mapping theorem.

2/23:
- Plan.
  1. Proof of the inverse function theorem.
  2. Commuting partials.
- Theorem (Inverse function theorem): If $E \subset \mathbb{R}^n$ open, $\mathbf{f} : E \to \mathbb{R}^n$ is differentiable at $\mathbf{x}_0 \in E$, and $\mathbf{f}'(\mathbf{x}_0)$ is invertible, then there exist $U \subset E$ open with $\mathbf{x}_0 \in U$ and $V \subset \mathbb{R}^n$ open with $\mathbf{f}(\mathbf{x}_0) \in V$ such that $\mathbf{f}|_U : U \to V$ is a bijection and $(\mathbf{f}|_U)^{-1}$ is continuously differentiable.
- Idea.
  1. Find U and prove one-to-one restricted to U.
  2. $\mathbf{f}(U)$ is open.
  3. Prove the inverse is continuously differentiable (left as an exercise to us).
  - There is a trick for 1-2: We introduce an auxiliary function $\varphi_{\mathbf{y}}$ and apply the contraction mapping theorem.
- Proof.
  - Let $A = \mathbf{f}'(\mathbf{x}_0)$.
  - Since $\mathbf{f}'$ is continuous, there is an open ball $U \subset E$ with center $\mathbf{x}_0$ such that $\|\mathbf{f}'(\mathbf{x}) - A\| < \lambda$ for all $\mathbf{x} \in U$.
    - We'll pick $\lambda = 1/(2\|A^{-1}\|)$ without motivation for now.

        - ■ Note that if you need to pick a U (for an example function), this criterion gives you one (not necessarily the best one, but it gives you a one).
    - Trick: For all $\mathbf{y} \in \mathbb{R}^n$, consider $\varphi_{\mathbf{y}} : U \to \mathbb{R}^n$ defined by

$$\varphi_{\mathbf{y}}(\mathbf{x}) = \mathbf{x} + A^{-1}(\mathbf{y} - \mathbf{f}(\mathbf{x}))$$

        - ■ Important property of this function: $\mathbf{f}(\mathbf{x}) = \mathbf{y}$ iff $\varphi_{\mathbf{y}}(\mathbf{x}) = \mathbf{x}$.
    - Plan: Show that for all $\mathbf{y} \in \mathbf{f}(U)$ that $\varphi_{\mathbf{y}}$ is a contraction. Therefore, by the contraction mapping theorem, $\mathbf{f}$ has exactly 1 fixed point, so $\mathbf{f}|_U$ is injective.
    - Proving that $\varphi_{\mathbf{y}}$ is a contraction. Claim: $|\varphi_{\mathbf{y}}(\mathbf{x}_1) - \varphi_{\mathbf{y}}(\mathbf{x}_2)| \leq \frac{1}{2}|\mathbf{x}_1 - \mathbf{x}_2|$. Use the Chain Rule, MVT, and the fact that $\|AB\| \leq \|A\|\|B\|$.
        - ■ Using the chain rule, we have that

$$\begin{aligned}\varphi_{\mathbf{y}}' &= I - A^{-1}\mathbf{f}'(\mathbf{x})\\ &= A^{-1}(A - \mathbf{f}'(\mathbf{x}))\end{aligned}$$

        - ■ Thus,

$$\|\varphi_{\mathbf{y}}(\mathbf{x})\| \leq \left\|A^{-1}\right\|\|A - \mathbf{f}'(\mathbf{x})\| < \frac{1}{2}$$

          for all $\mathbf{x}$.
        - ■ It follows by the MVT that

$$|\varphi_{\mathbf{y}}(\mathbf{x}_1) - \varphi_{\mathbf{y}}(\mathbf{x}_2)| \leq \frac{1}{2}|\mathbf{x}_1 - \mathbf{x}_2|$$

        - ■ Therefore, $\varphi_{\mathbf{y}}$ is a contraction.
    - We now prove that $\mathbf{f}(U)$ is open.
    - Let $\mathbf{y}_0 \in f(U)$ be such that $\mathbf{y}_0 = f(\mathbf{p}_0)$.
    - Pick $B_r(\mathbf{p}_0) \subset U$ such that $\overline{B} \subset U$.
    - Claim: For all $\mathbf{y} \in \mathbb{R}^n$ with $|\mathbf{y} - \mathbf{y}_0| < \lambda r$, we have that $\mathbf{y} \in \mathbf{f}(U)$.
        - ■ We are going to show that $\varphi_{\mathbf{y}}(\overline{B}) \subset \overline{B}$ and therefore $\varphi_{\mathbf{y}} : \overline{B} \to \overline{B}$ is a contraction and therefore by the contraction mapping theorem, there exists a fixed point $\mathbf{x}_{\mathbf{y}}$ of $\varphi_{\mathbf{y}}$ in $\overline{B}$. Therefore, $\mathbf{f}(\mathbf{x}_{\mathbf{y}}) = \mathbf{y}$ and so $\mathbf{f}(U)$ is open.

- φ_y is derived from Newton's method. The contraction mapping thing then is what substitutes for convergence. You have to start in the right area though, the chosen U!

2/25:

- Plan:
    1. A point on the IFT.
    2. Commuting partials.
    3. Implicit function theorem.
- Subtle point: Last time, in the proof of the IFT, we first found the $U \subset E$ and prove that $\mathbf{f}|_U$ is injective, and then we proved that $\mathbf{f}(U)$ is open.
- The properties of $\varphi_{\mathbf{y}}$.
    - $\varphi_{\mathbf{y}}(U) \subset U$.
    - $\varphi_{\mathbf{y}}$ is a contraction since $|\varphi_{\mathbf{y}}(\mathbf{x}_1) - \varphi_{\mathbf{y}}(\mathbf{x}_2)| \leq \frac{1}{2}|\mathbf{x}_1 - \mathbf{x}_2|$.
    - $\mathbf{f}(\mathbf{x}) = \mathbf{y}$ iff $\varphi_{\mathbf{y}}(\mathbf{x}) = \mathbf{x}$ (fixed points for this contraction mapping).
- Commuting partials.

- When does the following hold?
$$\frac{\partial^2 f}{\partial x_j \partial x_i} = \frac{\partial^2 f}{\partial x_j \partial x_i}$$
- Simple answer: Not often, but with enough regularity, yes.

- Theorem: Given $f : E \to \mathbb{R}$ where $E \subset \mathbb{R}^n$, we say that f is C^2 (or of class C^2)
- **Class $\boldsymbol{C^2}$** (function f): A function $f : E \to \mathbb{R}$ (where $E \subset \mathbb{R}^n$) such that all partials $\partial^2 f / \partial x_j \partial x_i$ exist and are continuous for all points in E. *Denoted by* $\boldsymbol{f \in C^2}$.
- Lemma (MVT): If $E \subset \mathbb{R}^2$ open, $f : E \to \mathbb{R}$, $\partial f / \partial x$, $\partial^2 f / \partial y \partial x$ exist for all $(x, y) \in E$, $Q = [a, a + h] \times [b, b + k] \subset E$, and
$$\Delta(f, Q) = f(a + h, b + k) - f(a + h, b) + f(a, b + k) - f(a, b)$$
then there exists $(x_0, y_0) \in Q$ such that
$$\Delta(f, Q) = hk \frac{\partial^2}{\partial y \partial x}(x_0, y_0)$$
  - Proof idea: We reduce to the goal of the 1D MVT.
  - Define $u(t) = f(t, b + k) - f(t, b)$. Then u is differentiable by the sum and scalar multiple rules.
  - It follows that
$$\begin{aligned}
\Delta(f, Q) &= u(a + h) - u(a) \\
&= hu'(x_0) \\
&= h \left[\frac{\partial f}{\partial x} - \frac{\partial f}{\partial x} \right] \\
&= hk \frac{\partial^2}{\partial y \partial x}(x_0, y_0)
\end{aligned}$$
- Theorem: If $f \in C^2$, then
$$\frac{\partial^2 f}{\partial x_j \partial x_i} = \frac{\partial^2 f}{\partial x_j \partial x_i}$$
for all $1 \leq i, j \leq n$.
- Idea.
  - To make life easy, take $n = 2$. Then we just need the right kind of mean value theorem (the one in the lemma).
- Proof.
  - Follows from the lemma as $h, k \to 0$.
  - See Theorem 15.3 in Labalme (2021).

2/28:

- Plan:
  1. Implicit function theorem (end of Chapter 9).
  2. Sharkovsky's theorem.
  3. Go back and talk about Chapter 8 material.

- Theorem (Implicit Function Theorem; informal): Given a nice system of equations

$$\begin{aligned} f_1(c_1,\dots,x_n,y_1,\dots,y_m) &= 0 \\ &\vdots \\ f_n(x_1,\dots,x_n,y_1,\dots,y_m) &= 0 \end{aligned}$$

  and a particular solution $(\mathbf{a},\mathbf{b})$, we can solve for $\mathbf{y}=(y_1,\dots,y_m)$ locally at $(\mathbf{a},\mathbf{b})$.

- Theorem (Implicit Function Theorem): If $E\subset\mathbb{R}^{n+m}$, $\mathbf{f}:E\to\mathbb{R}^n$ continuously differentiable, $(\mathbf{a},\mathbf{b})\in E$ with $\mathbf{f}(\mathbf{a},\mathbf{b})=\mathbf{0}$, $A=\mathbf{f}'(\mathbf{a},\mathbf{b})$, $A_{\mathbf{x}}:\mathbb{R}^n\to\mathbb{R}^n$ defined by $\mathbf{x}\mapsto\mathbf{f}'(\mathbf{a},\mathbf{b})(\mathbf{x},\mathbf{0})$ invertible, and $A_{\mathbf{y}}:\mathbb{R}^m\to\mathbb{R}^n$ defined by $\mathbf{y}\mapsto\mathbf{f}'(\mathbf{a},\mathbf{b})(\mathbf{0},\mathbf{y})$, then there exists $U\subset\mathbb{R}^{n+m}$, $W\subset\mathbb{R}^m$ with $(\mathbf{a},\mathbf{b})\in U$, $\mathbf{b}\in W$ such that:
  1. For every $\mathbf{y}\in W$, there exists a unique $\mathbf{x}\in\mathbb{R}^n$ such that $(\mathbf{x},\mathbf{y})\in U$ and $\mathbf{f}(\mathbf{x},\mathbf{y})=\mathbf{0}$.
  2. There is a continuously differentiable function $\mathbf{g}:W\to\mathbb{R}^n$ such that

$$\mathbf{f}(\mathbf{g}(\mathbf{y}),\mathbf{y})=\mathbf{0}$$

     for all $\mathbf{y}\in W$ and

$$\mathbf{g}'(\mathbf{b})=-(A_{\mathbf{x}})^{-1}A_{\mathbf{y}}$$

- Example: Consider $f:\mathbb{R}^{1+1}\to\mathbb{R}$ defined by $(x,y)\mapsto x^2+y^2-1$.
  - Then $f^{-1}(\{0\})$ is the unit circle.
  - $Df=\begin{bmatrix}2x & 2y\end{bmatrix}$, $A_x=\begin{bmatrix}2x\end{bmatrix}$, and $A_y=\begin{bmatrix}2y\end{bmatrix}$.
- Idea:
  - Use the inverse function theorem, and apply it to $A_{\mathbf{x}}$.
  - Goal: Find U and W; from this, $\mathbf{g}$ follows uniquely (though you also technically need to show continuous differentiability).
  - Define $F:E\to\mathbb{R}^{n+m}$ by $F(\mathbf{x},\mathbf{y})=(\mathbf{f}(\mathbf{x},\mathbf{y}),\mathbf{y})$. Claim: $F'(\mathbf{a},\mathbf{b})$ is invertible. Apply the inverse function theorem to F.
- Proof left to us.
- The goal of Sharkovsky's theorem is to understand the iterates of f, i.e., $x,f(x),f^2(x),f^3(x),\dots$. This fits in thematically with the contraction mapping theorem.
- **Periodic** (point $p\in I$): A point $p\in I$ for which $f^m(p)=p$ for some $m\in\mathbb{N}$.
- **Period** (of $p\in I$ periodic): The least number m such that $f^m(p)=p$.
- **Fixed point**: A periodic point of period 1.
- Example: $f:[0,1]\to[0,1]$ defined by $f(x)=1-x$ has periodic points of period 2 everywhere on its domain save 1/2, which has period 1.
- Theorem: If f has a point p of period 3, then f has points of all other periods.
- **Sharkovsky ordering**: All of the odd numbers, then 2^1 times the odd numbers, then 2^2 times the odd numbers, then continuing for $n\to\infty$, and then 2^n as large as possible all the way down to 1.
  - If n comes before m in the Sharkovsky ordering, we write $n\rhd m$.
- Sharkovsky's theorem: If $A\subset\mathbb{R}$, $f:A\to\mathbb{R}$ continuous satisfies $f(A)\subset A$ and has a period m point with $m\rhd l$, then f has a period l point.
- Example: Logistic maps $g_b:[0,1]\to[0,1]$ defined by $x\mapsto bx(1-x)$ for $b\in[1,4]$.

3/2:

- Theorem (Li & Yorke): If f has a period 3 point, then there exists an uncountable set $S \subset A$ such that for all $p, q \in S$,

$$\liminf_{n\to\infty} |f^n(p) - f^n(q)| = 0 \qquad \limsup_{n\to\infty} |f^n(p) - f^n(q)| > 0$$

- Plan:
  1. Prove the warm-up to Sharkovsky.
- Theorem: If f continuous has a period 3 point, then f has points of all other periods.
- Notation.
  - We say "I covers J" and write $I \to J$ when $I, J \subset A$ are closed intervals with $f(I) \supset J$.
- Lemma 1: If $[a, b] \to [a, b]$, then f continuous has a fixed point in $[a, b]$.
  - Consider $f(x) - x$ on $[a, b]$.
  - Either $f(a) = a$, $f(b) = b$, or we can invoke the IVT.
  - Alternatively, since $[a, b] \subset f([a, b])$, there exist a_0, b_0 with $f(a_0) = a$ and $f(b_0) = b$. Thus, $f(a_0) - a_0 \leq 0$ and $f(b_0) - b_0 \geq 0$, so by the IVT, there is some zero of $f(x) - x$ on $[a, b]$, as desired.
- Lemma 2: p has period m iff p is a fixed point of f^m and not a fixed point of f^i for $i < m$.
- Lemma 3: Suppose we have a loop of intervals $J_0 \to J_1 \to J_2 \to \cdots \to J_{n-1} \to J_0 \to \cdots$. Then there is a fixed point $p \in J_0$ of f^n such that $f^i(p) \in J_i$ for all $0 \leq i < n$.

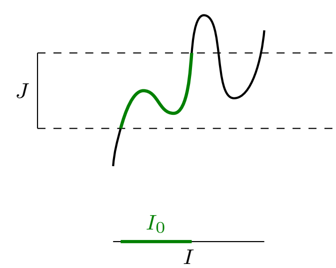

Figure 9.1: Loop mapping.

  - Isn't this obvious? No – there's an issue, namely that $f(J_i) \not\subset J_{i+1}$. We can solve this though by noting that if $I \to J$, then there exists some subinterval $I_0 \subset I$ such that $f(I_0) \subset J$ and $I_0 \to J$ (i.e., $f(I_0) = J$).
  - You can use this idea to pull a J_i' out of each J_i for which set equality holds.
  - Then by the previous lemma, there exists a fixed point p of f^n in J_0'. Then $f(p) \in J_1' \subset J_1, \dots, f^{n-1}(p) \in J_{n-1}' \subset J_{n-1}$.
- Notation.
  - In the case of Lemma 3, we say that p is **following** the cycle $J_0 \to \cdots \to J_{n-1} \to J_0 \to \cdots$.
  - We call $J_0 \to \cdots \to J_{n-1} \to J_0 \to \cdots$ **elementary** if it is only followed by points of period n.
- Lemma: Let q have period m and let $\mathcal{O} = \{q, f(q), \dots, f^{m-1}(q)\}$. Let $J_0 \to \cdots \to J_{n-1} \to J_0 \to \cdots$ and suppose
  (i) all endpoints of the J_i are in $\mathcal{O}$;

(ii) the loop is not followed by any point in $\mathcal{O}$;

(iii) The interior of J_0, $\operatorname{int}(J_0)$ is disjoint from the other J_i.

Then the loop is elementary, and so f has a period n point.

- Suppose p follows the loop.
- Then by (i) and (ii), p is not an endpoint of J_0, so if $f^i(p) = p \in J_0$ for $i < n$, then $\operatorname{int}(J_0) \cap J_i$, contradicting (iii).

9.2 Chapter 9: Functions of Several Variables

From Rudin (1976).

2/15:

- Defines a vector space by the closure of its elements under addition and scalar multiplication.
- Defines a linear combination, span, independence and dependence, dimension, basis, coordinates, and the standard basis.
- Theorem 9.2: If X is spanned by r vectors, $\dim X \leq r$.
- Corollary: $\dim \mathbb{R}^n = n$.
- Theorem 9.3: Let X a vector space with $\dim X = n$.
  (a) $E \subset X$ containing n vectors spans X iff E is independent.
  (b) X has a basis, and every basis contains n vectors.
  (c) If $1 \leq r \leq n$ and $\{\mathbf{y}_1, \dots, \mathbf{y}_r\}$ is independent in X, then X has a basis containing $\{\mathbf{y}_1, \dots, \mathbf{y}_r\}$.
- Defines linear transformation, linear operator.
- Notes that $A\mathbf{0} = \mathbf{0}$ if A is a linear transformation, and that A is completely determined by its action on any basis.
- **Invertible** (linear operator): A linear operator A that is one-to-one and onto.
- Theorem 9.5: A a linear operator on X finite-dimensional is one-to-one iff it is onto.
- Defines $L(X, Y)$, $L(X)$, the product BA of two linear transformations, and the supremum norm of a linear transformation.
- Theorem 9.7:
  (a) $A \in L(\mathbb{R}^n, \mathbb{R}^m)$ implies $\|A\| < \infty$ and $A : \mathbb{R}^n \to \mathbb{R}^m$ uniformly continuous.
  (b) $A, B \in L(\mathbb{R}^n, \mathbb{R}^m)$ and $c \in \mathbb{C}$ implies
  $$\|A + B\| \leq \|A\| + \|B\| \qquad\qquad \|cA\| = |c|\|A\|$$
  Defining $d(A, B) = \|A - B\|$ makes $L(\mathbb{R}^n, \mathbb{R}^m)$ a metric space.
  (c) $A \in L(\mathbb{R}^n, \mathbb{R}^m)$ and $B \in L(\mathbb{R}^m, \mathbb{R}^k)$ implies
  $$\|BA\| \leq \|B\|\|A\|$$
- Theorem 9.8: Let Ω be the set of all invertible linear operators on $\mathbb{R}^n$.
  (a) $A \in \Omega$, $B \in L(\mathbb{R}^n)$, and $\|B - A\| \cdot \left\|A^{-1}\right\| < 1$ implies $B \in \Omega$.

Proof. Let $\|A^{-1}\| = 1/\alpha$, and let $\|B - A\| = \beta$. Then

$$\begin{aligned}\|B-A\|\cdot\|A^{-1}\| &< 1\\ \beta\cdot\frac{1}{\alpha} &< 1\\ \beta &< \alpha\end{aligned}$$

To prove that $B \in \Omega$, the definition of invertibility and Theorem 9.5 tell us that it will suffice to show that B is 1-1. To do so, it will suffice to show that $B\mathbf{x} = \mathbf{0}$ iff $\mathbf{x} = \mathbf{0}$. Let's begin. Let $\mathbf{x} \in \mathbb{R}^n$ be arbitrary. Then

$$\begin{aligned}\alpha|\mathbf{x}| = \alpha|A^{-1}A\mathbf{x}| \leq \alpha\|A^{-1}\|\cdot|Ax| = |A\mathbf{x}| \leq |(A-B)\mathbf{x}| + |B\mathbf{x}| \leq \beta|\mathbf{x}| + |B\mathbf{x}|\\ (\alpha-\beta)|\mathbf{x}| \leq |B\mathbf{x}|\end{aligned}$$

It follows that if $\mathbf{x} \neq \mathbf{0}$, then $|B\mathbf{x}| > 0$. This combined with the fact that $B\mathbf{0} = \mathbf{0}$ implies the desired result. □

(b) Ω is open in $L(\mathbb{R}^n)$ and $A \mapsto A^{-1}$ is continuous on Ω.

Proof. To prove that Ω is open in $L(\mathbb{R}^n)$, it will suffice to show that for all $A \in \Omega$, there exists $N_r(A)$ such that if $\|B - A\| < r$, then $B \in \Omega$. Let's begin. Let $A \in \Omega$ be arbitrary. Choose $N_\alpha(A)$ to be our neighborhood, where α is defined as in part (a). Let $B \in L(\mathbb{R}^n)$ satisfy $\|B - A\| < \alpha$. Then $\|B - A\| \cdot \|A^{-1}\| < 1$, so $B \in \Omega$ by part (a), as desired.

To prove that $A \mapsto A^{-1}$ is continuous, it will suffice to show that $\|B^{-1} - A^{-1}\| \to 0$ as $B \to A$. First off, we have by part (a) and the substitution $\mathbf{x} = B^{-1}\mathbf{y}$ ($\mathbf{y} \in \mathbb{R}^n$) that

$$\begin{aligned}(\alpha-\beta)|B^{-1}\mathbf{y}| &\leq |BB^{-1}\mathbf{y}| = |\mathbf{y}|\\ \left|B^{-1}\left(\frac{\mathbf{y}}{|\mathbf{y}|}\right)\right| &\leq (\alpha-\beta)^{-1}\end{aligned}$$

Thus, since $|B^{-1}\mathbf{u}|$ is bounded by $(\alpha - \beta)^{-1}$ for every unit vector $\mathbf{u} \in \mathbb{R}^n$, $\|B^{-1}\|$ is bounded by $(\alpha - \beta)^{-1}$. This combined with the fact that

$$\begin{aligned}B^{-1} - A^{-1} &= B^{-1}I - IA^{-1}\\ &= B^{-1}AA^{-1} - B^{-1}BA^{-1}\\ &= B^{-1}(A-B)A^{-1}\end{aligned}$$

implies by Theorem 9.7c that

$$\|B^{-1} - A^{-1}\| \leq \|B^{-1}\|\|A-B\|\|A^{-1}\| \leq (\alpha-\beta)^{-1}\cdot\beta\cdot\frac{1}{\alpha} = \frac{\beta}{\alpha(\alpha-\beta)}$$

Therefore, since $\beta \to 0$ as $B \to A$, the above inequality establishes the desired result. □

- Note that the mapping $A \mapsto A^{-1}$ defined in Theorem 9.8b is a 1-1 mapping of Ω onto Ω and its own inverse.
- Defines matrices, column vectors, and matrix multiplication.
- From the Schwarz inequality, we can show that

$$\|A\| \leq \left(\sum_{i,j} a_{i,j}^2\right)^{1/2}$$

- "If S is a metric space, if $a_{11}, \dots, a_{mn}$ are real continuous functions on S, and if for each $p \in S$, A_p is the linear transformation of $\mathbb{R}^n$ into $\mathbb{R}^m$ whose matrix has entries $a_{ij}(p)$, then the mapping $p \to A_p$ is a continuous mapping of S into $L(\mathbb{R}^n, \mathbb{R}^m)$" (Rudin, 1976, p. 211).

- Rudin (1976) spends some time motivating the definition of the total derivative. He also discusses the natural 1-1 correspondence between $\mathbb{R}^1$ and $L(\mathbb{R}^1)$.
- Defines differentiability in $\mathbb{R}^n$.
- Theorem 9.12: A_1, A_2 the derivative of $\mathbf{f}$ at $\mathbf{x}$ implies $A_1 = A_2$.
- If $\mathbf{f} : E \to \mathbb{R}^m$ where $E \subset \mathbb{R}^n$, then $\mathbf{f}' : E \to L(\mathbb{R}^n, \mathbb{R}^m)$.
- $\mathbf{f}$ differentiable implies $\mathbf{f}$ continuous.
- Example ($\mathbf{f}$ is linear):
  - If $A \in L(\mathbb{R}^n, \mathbb{R}^m)$, then $A'(\mathbf{x}) = A$ for all $\mathbf{x} \in \mathbb{R}^n$. Note that this means that $A' : \mathbb{R}^n \to L(\mathbb{R}^n, \mathbb{R}^m)$, as expected.
- Theorem 9.15 (Chain Rule): E open in $\mathbb{R}^n$, $\mathbf{f} : E \to \mathbb{R}^m$ differentiable at $\mathbf{x}_0 \in E$, $I \supset \mathbf{f}(E)$ open in $\mathbb{R}^m$, and $\mathbf{g} : I \to \mathbb{R}^k$ differentiable at $\mathbf{f}(\mathbf{x}_0)$ implies $\mathbf{F} : E \to \mathbb{R}^k$ defined by

  $$\mathbf{F}(\mathbf{x}) = \mathbf{g}(\mathbf{f}(\mathbf{x}))$$

  is differentiable at $\mathbf{x}_0$ with

  $$\mathbf{F}'(\mathbf{x}_0) = \mathbf{g}'(\mathbf{f}(\mathbf{x}_0))\mathbf{f}'(\mathbf{x}_0)$$ [1]

  Proof. Largely symmetric to that of the one-dimensional chain rule in Chapter 5. □

- **Components** (of $\mathbf{f} : \mathbb{R}^n \to \mathbb{R}^m$): The real functions $f_1, \dots, f_m$ defined by

  $$\mathbf{f}(\mathbf{x}) = \sum_{i=1}^{m} f_i(\mathbf{x})\mathbf{u}_i$$

  for all $\mathbf{x} \in E$ or, equivalently, by $f_i(\mathbf{x}) = f(\mathbf{x}) \cdot \mathbf{u}_i$ ($1 \leq i \leq m$), where $\mathbf{u}_1, \dots, \mathbf{u}_m$ is the standard basis of $\mathbb{R}^m$.
- Defines partial derivatives.
- Theorem 9.17: $E \subset \mathbb{R}^n$ open and $\mathbf{f} : E \to \mathbb{R}^m$ differentiable at $\mathbf{x} \in E$ imply the partial derivatives $(D_j f_i)(\mathbf{x})$ exist and

  $$\mathbf{f}'(\mathbf{x})\mathbf{e}_j = \sum_{i=1}^{m} (D_j f_i)(\mathbf{x})\mathbf{u}_i$$

  for $1 \leq j \leq n$.
- It follows that

  $$[\mathbf{f}'(\mathbf{x})] = \begin{bmatrix} (D_1 f_1)(\mathbf{x}) & \cdots & (D_n f_1)(\mathbf{x}) \\ \vdots & & \vdots \\ (D_1 f_m)(\mathbf{x}) & \cdots & (D_n f_m)(\mathbf{x}) \end{bmatrix}$$

- Discusses the gradient and the directional derivative.
- Theorem 9.19: $E \subset \mathbb{R}^n$ convex and open, $\mathbf{f} : E \to \mathbb{R}^m$ differentiable in E, and there exists M such that

  $$\|\mathbf{f}'(\mathbf{x})\| \leq M$$

  for all $\mathbf{x} \in E$ implies

  $$|\mathbf{f}(\mathbf{b}) - \mathbf{f}(\mathbf{a})| \leq M|\mathbf{b} - \mathbf{a}|$$

  for all $\mathbf{a}, \mathbf{b} \in E$.

[1] Note that the right-hand side of this equation contains the product of two linear transformations.

- Corollary: If, in addition, $\mathbf{f}'(\mathbf{x}) = \mathbf{0}$ for all $\mathbf{x} \in E$, then $\mathbf{f}$ is constant.
- **Continuously differentiable** (mapping $\mathbf{f} : E \to \mathbb{R}^m$): A function $\mathbf{f} : E \to \mathbb{R}^m$ such that $\mathbf{f}' : E \to L(\mathbb{R}^n, \mathbb{R}^m)$ is continuous. *Also known as* $\mathscr{C}^1$**-mapping**. *Denoted by* $\mathbf{f} \in \mathscr{C}^1(E)$.
- Theorem 9.21: Let $E \subset \mathbb{R}^n$ open and $\mathbf{f} : E \to \mathbb{R}^m$. Then $\mathbf{f} \in \mathscr{C}^1(E)$ iff the partial derivatives $D_j f_i$ ($1 \le i \le m$; $1 \le j \le n$) exist and are continuous on E.

2/20:

- **Contraction** (of X into X): A function $\varphi : X \to X$ for which there exists a number $c < 1$ such that

$$d(\varphi(x), \varphi(y)) \le c \cdot d(x, y)$$

for all $x, y \in X$, where X is a metric space with metric d.

- Theorem 9.23: X a complete metric space and ϕ a contraction of X into X implies there exists a unique $x \in X$ such that $\varphi(x) = x$.

Proof. Let $x_0 \in X$ be arbitrary. Define $\{x_n\}$ recursively by

$$x_{n+1} = \phi(x_n)$$

for $n = 0, 1, 2, \ldots$. Let $c < 1$ be the number corresponding to the contraction φ. Then for $n \ge 1$, we have

$$d(x_{n+1}, x_n) = d(\varphi(x_n), \varphi(x_{n-1})) \le c \cdot d(x_n, x_{n-1})$$

or, for $n \ge 0$,

$$d(x_{n+1}, x_n) \le c^n d(x_1, x_0)$$

by induction. Now to prove that $\{x_n\}$ is Cauchy, it will suffice to show that for all $\epsilon > 0$, there exists N such that $m \ge n \ge N$ implies $d(x_n, x_m) < \epsilon$. But since

$$\begin{aligned} d(x_n, x_m) &\le \sum_{i=n+1}^{m} d(x_i, x_{i-1}) \\ &\le (c^n + c^{n+1} + \cdots + c^{m-1}) d(x_1, x_0) \\ &\le [(1-c)^{-1} d(x_1, x_0)] c^n \end{aligned}$$

we can simply choose N large enough that $[(1-c)^{-1} d(x_1, x_0)] c^N < \epsilon$. Thus, since $\{x_n\}$ is Cauchy and X is complete, there exists $x \in X$ such that $\lim_{n\to\infty} x_n = x$. Therefore, since φ is Lipschitz continuous, we have that

$$\varphi(x) = \lim_{n\to\infty} \varphi(x_n) = \lim_{n\to\infty} x_{n+1} = x$$

as desired.

Now suppose for the sake of contradiction that there exists $y \ne x$ such that $\varphi(y) = y$. Then since φ is a contraction,

$$d(y, x) = d(\varphi(y), \varphi(x)) \le c \cdot d(y, x) < d(y, x)$$

a contradiction. □

- Theorem 9.24 (Inverse Function Theorem): $E \subset \mathbb{R}^n$ open, $\mathbf{f} : E \to \mathbb{R}^n$ a $\mathscr{C}^1$-mapping, $\mathbf{f}'(\mathbf{a})$ invertible for some $\mathbf{a} \in E$, and $\mathbf{b} = \mathbf{f}(\mathbf{a})$ implies

  (a) There exist $U, V \subset \mathbb{R}^n$ open with $\mathbf{a} \in U$, $\mathbf{b} \in V$ such that $\mathbf{f}$ is 1-1 on U and $\mathbf{f}(U) = V$.

  Proof. Let $A = \mathbf{f}'(\mathbf{a})$. Choose λ such that

$$2\lambda \|A^{-1}\| = 1$$

Define[2] for each $\mathbf{y} \in \mathbb{R}^n$ a function φ by

$$\varphi(\mathbf{x}) = \mathbf{x} + A^{-1}(\mathbf{y} - \mathbf{f}(\mathbf{x}))$$

for all $\mathbf{x} \in E$. (Note that a key property of φ is that as defined, $\mathbf{f}(\mathbf{x}) = \mathbf{y}$ iff $\mathbf{x}$ is a fixed point of $\mathbf{y}$.) Now since $\mathbf{f} \in \mathscr{C}^1$ and hence $\mathbf{f}'$ is continuous at $\mathbf{a}$, there exists an open ball $B_r(\mathbf{a}) \subset E$ such that

$$\|\mathbf{f}'(\mathbf{x}) - A\| < \lambda$$

for all $\mathbf{x} \in B_r(\mathbf{a})$. Let $U = B_r(\mathbf{a})$. Clearly it follows that U is open. Thus, since each $\varphi'(\mathbf{x}) = I - A^{-1}\mathbf{f}'(\mathbf{x}) = A^{-1}(A - \mathbf{f}'(\mathbf{x}))$, we have that

$$\|\varphi'(\mathbf{x})\| \leq \left\|A^{-1}\right\|\|A - \mathbf{f}'(\mathbf{x})\| < \frac{1}{2\lambda} \cdot \lambda = \frac{1}{2}$$

Consequently, we have by Theorem 9.19 that for all $\mathbf{x}_1, \mathbf{x}_2 \in U$,

$$|\varphi(\mathbf{x}_1) - \varphi(\mathbf{x}_2)| \leq \frac{1}{2}|\mathbf{x}_1 - \mathbf{x}_2|$$

Thus, by the uniqueness argument in the proof of Theorem 9.23, φ has at most one fixed point in U, so $\mathbf{f}(\mathbf{x}) = \mathbf{y}$ for at most one $\mathbf{x} \in U$. Therefore, $\mathbf{f}$ is 1-1 on U.
Let $V = \mathbf{f}(U)$. To prove that V is open, it will suffice to show that for all $\mathbf{y}_0 \in V$, there exists an open subset of V containing $\mathbf{y}_0$ such that. Let $\mathbf{y}_0 \in V$ be arbitrary. By the definition of V as the image of U under $\mathbf{f}$, there exists $\mathbf{x}_0 \in U$ such that $\mathbf{f}(\mathbf{x}_0) = \mathbf{y}_0$. As such, choose $B_r(\mathbf{x}_0)$ such that $\overline{B} \subset U$. Pick $\mathbf{y}$ satisfying $|\mathbf{y} - \mathbf{y}_0| < \lambda r$. Then

$$|\varphi(\mathbf{x}_0) - \mathbf{x}_0| = |A^{-1}(\mathbf{y} - \mathbf{y}_0)| < \|A\|\lambda r = \frac{r}{2}$$

so for all $\mathbf{x} \in \overline{B}$,

$$\begin{aligned}
|\varphi(\mathbf{x}) - \mathbf{x}_0| &\leq |\varphi(\mathbf{x}) - \varphi(\mathbf{x}_0)| + |\varphi(\mathbf{x}_0) - \mathbf{x}_0| \\
&< \frac{1}{2}|\mathbf{x} - \mathbf{x}_0| + \frac{r}{2} \\
&\leq \frac{1}{2} \cdot r + \frac{r}{2} \\
&= r
\end{aligned}$$

Thus, $\varphi(\mathbf{x}_0) \in B$. Moreover, since $|\varphi(\mathbf{x}_1) - \varphi(\mathbf{x}_2)| \leq \frac{1}{2}|\mathbf{x}_1 - \mathbf{x}_2|$ naturally holds for all $\mathbf{x}_1, \mathbf{x}_2 \in \overline{B} \subset U$, we have that φ is a contraction of $\overline{B}$ into $\overline{B}$. Additionally, since $\overline{B} \subset \mathbb{R}^n$ is closed, it is a complete metric space under the Euclidean metric. Thus, Theorem 9.23 implies that φ has a fixed point $\mathbf{x} \in \overline{B}$. In particular, $\mathbf{f}(\mathbf{x}) = \mathbf{y}$. Therefore, $\mathbf{y} \in f(\overline{B}) \subset \mathbf{f}(U) = V$, as desired. ☐

(b) If $\mathbf{g}$ is the inverse of $\mathbf{f}$ on V [which exists by (a)], i.e.,

$$\mathbf{g}(\mathbf{f}(\mathbf{x})) = \mathbf{x}$$

for all $\mathbf{x} \in U$, then $\mathbf{g} \in \mathscr{C}^1(V)$.

Proof. We first show that for all $\mathbf{y} \in V$, $\mathbf{g}'(\mathbf{y}) = [\mathbf{f}'(\mathbf{g}(\mathbf{y}))]^{-1}$. Let $\mathbf{y} \in V$ be arbitrary, and choose $\mathbf{k}$ such that $(\mathbf{y} + \mathbf{k}) \in V$. It follows by part (a) that there exist $\mathbf{x}, \mathbf{x} + \mathbf{h} \in U$ such that $\mathbf{y} = \mathbf{f}(\mathbf{x})$ and $\mathbf{y} + \mathbf{k} = \mathbf{f}(\mathbf{x} + \mathbf{h})$. Thus,

$$\varphi(\mathbf{x} + \mathbf{h}) - \varphi(\mathbf{x}) = \mathbf{h} + A^{-1}[\mathbf{f}(\mathbf{x}) - \mathbf{f}(\mathbf{x} + \mathbf{h})] = \mathbf{h} - A^{-1}\mathbf{k}$$

so

$$|\mathbf{h} - A^{-1}\mathbf{k}| = |\varphi(\mathbf{x} + \mathbf{h}) - \varphi(\mathbf{x})| \leq \frac{1}{2}|\mathbf{x} + \mathbf{h} - \mathbf{x}| = \frac{1}{2}|\mathbf{h}|$$

[2] How do we motivate this definition?

Consequently, $|A^{-1}\mathbf{k}| \geq \frac{1}{2}|\mathbf{h}|$, so

$$|\mathbf{h}| \leq 2\|A^{-1}\||\mathbf{k}| = \frac{|\mathbf{k}|}{\lambda}$$

Additionally, we know that $\|\mathbf{f}'(\mathbf{x}) - A\|\|A^{-1}\| = 1/2 < 1$, so Theorem 9.8a implies that $\mathbf{f}'(\mathbf{x})$ is invertible with an inverse that we may call T. Thus, since

$$\begin{aligned}\mathbf{g}(\mathbf{y}+\mathbf{k}) - \mathbf{g}(\mathbf{y}) - T\mathbf{k} &= \mathbf{h} - T\mathbf{k} \\ &= -T[(\mathbf{y}+\mathbf{k}) - \mathbf{y}] + T\mathbf{f}'(\mathbf{x})\mathbf{h} \\ &= -T[\mathbf{f}(\mathbf{x}+\mathbf{h}) - \mathbf{f}(\mathbf{x}) - \mathbf{f}'(\mathbf{x})\mathbf{h}]\end{aligned}$$

we have that

$$\frac{|\mathbf{g}(\mathbf{y}+\mathbf{k}) - \mathbf{g}(\mathbf{y}) - T\mathbf{k}|}{|\mathbf{k}|} \leq \frac{\|T\||\mathbf{f}(\mathbf{x}+\mathbf{h}) - \mathbf{f}(\mathbf{x}) - \mathbf{f}'(\mathbf{x})\mathbf{h}|}{\lambda|\mathbf{h}|}$$

Consequently, $\mathbf{k} \to \mathbf{0}$ implies that $\mathbf{h} \to \mathbf{0}$, which implies that the right side of the above inequality goes to zero, which implies that the left side of the above inequality goes to zero. Thus, $\mathbf{g}'(\mathbf{y}) = T$, so

$$\mathbf{g}'(\mathbf{y}) = [\mathbf{f}'(\mathbf{g}(\mathbf{y}))]^{-1}$$

for all $\mathbf{y} \in V$, as desired.

To prove that $\mathbf{g}'$ is continuous on V, Theorem 4.7 and the above equation tell us that it will suffice to show that $\mathbf{g} : V \to U$ is continuous, $\mathbf{f}' : U \to L(\mathbb{R}^n)$ is continuous, and $M \mapsto M^{-1} : L(\mathbb{R}^n) \to L(\mathbb{R}^n)$ is continuous. But we have the first condition since differentiability implies continuity and $\mathbf{g}$ is differentiable, we have the second condition since $\mathbf{f} \in \mathscr{C}^1$ by hypothesis, and we have the third condition by Theorem 9.8b, as desired. $\square$

- Theorem 9.25: $E \subset \mathbb{R}^n$ open, $\mathbf{f} :: E \to \mathbb{R}^n$ a $\mathscr{C}^1$-mapping, and $\mathbf{f}'(\mathbf{x})$ invertible for all $\mathbf{x} \in E$ implies $\mathbf{f}(W)$ open in $\mathbb{R}^n$ for every open $W \subset E$.
  - Note that the hypotheses of this theorem guarantee that $\mathbf{f}$ is locally 1-1 at each $\mathbf{x} \in E$, but it may not be 1-1 in E under these conditions (see Exercise 9.17).

References

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