

# MATH 20800 (Honors Analysis in $\mathbb{R}^n$ II) Notes

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# Chapter 1

## The Algebra and Topology of $\mathbb{R}^n$

### 1.1 Notes

- 1/10:
- Syllabus.
    - In his mind, homework is the main setting where learning takes place.
  - We're going to be studying analysis, or calculus, on **manifolds** this quarter.
  - **Manifold**: A “space” that looks like Euclidean space  $\mathbb{R}^n$  locally.
    - The surfaces of a sphere and torus are common examples of 2-dimensional manifolds.
    - With regard to the above definition, think about how people in ancient times didn't think the Earth was a sphere because it looked like a plane locally.
  - This class will look much like a calculus course, in that we first talk about limits, then differentiation, then integration, and culminating in the fundamental theory of calculus.
  - Last quarter, we primarily developed linear algebra and basic topology on metric spaces.
    - Chapter 1 of Munkres (1991) is a review of what's needed from last quarter.
    - This is all basically continuity.
  - Thus, we can start right up with differentiation.

### 1.2 The Algebra and Topology of $\mathbb{R}^n$

*From Munkres (1991).*

- 1/17:
- “In the first part of this book,  $\mathbb{R}^n$  and its subspaces are the only vector spaces with which we shall be concerned. In later chapters, we shall deal with more general vector spaces” (Munkres, 1991, p. 2).
  - **Inner product**: Denoted by  $\langle \mathbf{x}, \mathbf{y} \rangle$ .
  - **Euclidean norm**: The following norm. Denoted by  $\|\mathbf{x}\|$ . Given by

$$\|\mathbf{x}\| = \sqrt{x_1^2 + \cdots + x_n^2}$$

- **Sup norm** (of  $n$ -tuples): The following norm. Denoted by  $|\mathbf{x}|$ . Given by

$$|\mathbf{x}| = \max\{|x_1|, \dots, |x_n|\}$$

- Note that the Euclidean norm and sup norm satisfy the inequalities

$$|\mathbf{x}| \leq \|\mathbf{x}\| \leq \sqrt{n}|\mathbf{x}|$$

for all  $\mathbf{x} \in \mathbb{R}^n$ .

- **Sup norm** (of matrices): The following norm. *Denoted by  $|\mathbf{A}|$ . Given by*

$$|\mathbf{A}| = \max\{|a_{ij}| : i \in [n], j \in [m]\}$$

- Theorem 1.3: If  $A$  has size  $n$  by  $m$  and  $B$  has size  $m$  by  $p$ , then

$$|\mathbf{A} \cdot \mathbf{B}| \leq m|\mathbf{A}| |\mathbf{B}|$$

- **Echelon form**: *Also known as **stairstep form**.*

- **Transpose** (of  $A$ ): *Denoted by  $\mathbf{A}^{\text{tr}}$ .*

- Theorem 2.1: Let  $A$  be an  $n$ -by- $m$  matrix. Any elementary row operation on  $A$  may be carried out by premultiplying  $A$  by the corresponding elementary matrix.

– “We will use this result later on when we prove the change of variables theorem for a multiple integral” (Munkres, 1991, p. 12).

- **Determinant** (of  $A$ ): *Denoted by  $\det \mathbf{A}$ . Not denoted by  $|\mathbf{A}|$ .*

- **Determinant function**: A function that assigns to each  $n$ -by- $n$  matrix  $A$  a real number denoted  $\det A$  and satisfies the following axioms.

1. If  $B$  is the matrix obtained by exchanging any two rows of  $A$ , then  $\det B = -\det A$ .
2. Given  $i$ , the function  $\det A$  is linear as a function of the  $i^{\text{th}}$  row alone.
3.  $\det I_n = 1$ .

- Corollary 2.9: The determinant function is uniquely characterized by its three axioms.

- **$\epsilon$ -neighborhood** (of  $x_0$ ): The following set, where  $X$  is a metric space with metric  $d$ ,  $x_0 \in X$ , and  $\epsilon > 0$ . *Also known as  **$\epsilon$ -neighborhood centered at  $x_0$** . Denoted by  $U(\mathbf{x}_0; \epsilon)$ . Given by*

$$U(x_0; \epsilon) = \{x \mid d(x, x_0) < \epsilon\}$$

- **Topological property** (of  $X$ ): A property of a metric space  $X$  that depends only on the collection of open sets of  $X$ , rather than on the specific metric involved.

– Examples include limits, continuity, and compactness.

- **Interior** (of  $A \subset \mathbb{R}^n$ ): The union of all open sets of  $\mathbb{R}^n$  that are contained in  $A$ . *Denoted by  $\text{Int } \mathbf{A}$ .*

- **Exterior** (of  $A \subset \mathbb{R}^n$ ): The union of all open sets of  $\mathbb{R}^n$  that are disjoint from  $A$ . *Denoted by  $\text{Ext } \mathbf{A}$ .*

- **Boundary** (of  $A \subset \mathbb{R}^n$ ): The set of all points of  $\mathbb{R}^n$  that are contained in neither  $\text{Int } A$  nor  $\text{Ext } A$ . *Denoted by  $\text{Bd } \mathbf{A}$ .*

–  $\mathbf{x} \in \text{Bd } A$  iff every open set containing  $\mathbf{x}$  intersects both  $A$  and  $\mathbb{R}^n \setminus A$ .

# Chapter 2

## Differentiation

### 2.1 Notes

1/10:

- Since manifolds look like Euclidean spaces locally, we basically only need to study differentiation on Euclidean spaces.
- Set up: Let  $U \subset \mathbb{R}^n$  be open, and  $f : U \rightarrow \mathbb{R}^m$  be a function.
- Idea: The derivative of  $f$  at some point  $\mathbf{a} \in U$  is “the best linear approximation” to  $f$  at  $\mathbf{a}$ .
- **Differentiable** (function  $f$  at  $\mathbf{a}$ ): A function  $f$  for which there exists a linear transformation  $A : \mathbb{R}^n \rightarrow \mathbb{R}^m$  such that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} = \mathbf{0}$$

- **Total derivative** (of  $f$  at  $\mathbf{a}$ ): The linear transformation  $A$  corresponding to a differentiable function  $f$ . Denoted by  $Df(\mathbf{a})$ .
- Questions to ask:
  1. When does the total derivative exist?
  2. When it does exist, can there be multiple?
  3. When it exists and is unique, how do I calculate it?
- Proposition: If  $A, B$  are linear transformations that both satisfy the definition, then  $A = B$ .
  - We have

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} = \mathbf{0} \qquad \lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - B\mathbf{h}}{\|\mathbf{h}\|} = \mathbf{0}$$

- It follows by subtracting the right equation above from the left one that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{A\mathbf{h} - B\mathbf{h}}{\|\mathbf{h}\|} = \mathbf{0}$$

- Apply linearity: For an arbitrary  $\mathbf{v} \in \mathbb{R}^n$  and  $t \in \mathbb{R}, t > 0$ , we have

$$\frac{A(t\mathbf{v}) - B(t\mathbf{v})}{t} = A\mathbf{v} - B\mathbf{v}$$

- Therefore, since  $t\mathbf{v} \rightarrow 0$  as  $t \rightarrow 0$ , we have by the above that

$$\begin{aligned} \mathbf{0} &= \lim_{t \rightarrow 0} \frac{A(t\mathbf{v}) - B(t\mathbf{v})}{\|t\mathbf{v}\|} \\ &= \lim_{t \rightarrow 0} \frac{A\mathbf{v} - B\mathbf{v}}{\|\mathbf{v}\|} \\ \mathbf{0} \cdot \|\mathbf{v}\| &= \lim_{t \rightarrow 0} (A\mathbf{v} - B\mathbf{v}) \\ \mathbf{0} &= A\mathbf{v} - B\mathbf{v} \\ B\mathbf{v} &= A\mathbf{v} \end{aligned}$$

- Example: Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be linear, i.e.,  $f(\mathbf{v}) = A\mathbf{v}$  for some linear transformation  $A$ . Then for all  $\mathbf{a} \in \mathbb{R}^n$ ,  $Df(\mathbf{a}) = A$  is constant.

- We have from the definition that

$$\begin{aligned} \lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} &= \lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a}) + f(\mathbf{h}) - f(\mathbf{a}) - f(\mathbf{h})}{\|\mathbf{h}\|} \\ &= \lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{\mathbf{0}}{\|\mathbf{h}\|} \\ &= \mathbf{0} \end{aligned}$$

- Theorem: If  $f$  is differentiable at  $\mathbf{a}$ , then  $f$  is continuous at  $\mathbf{a}$ .

- By definition, there exists a linear transformation  $A$  such that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} = \mathbf{0}$$

- Additionally, we have that

$$f(\mathbf{a} + \mathbf{h}) = f(\mathbf{a}) + A\mathbf{h} + \|\mathbf{h}\| \left( \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} \right)$$

- As  $\mathbf{h} \rightarrow \mathbf{0}$ , the right-hand side of the above equation goes to  $f(\mathbf{a})$ .

- As a linear transformation,  $A\mathbf{h} \rightarrow \mathbf{0}$  as  $\mathbf{h} \rightarrow \mathbf{0}$ .
  - Clearly  $\|\mathbf{h}\| \rightarrow 0$  as  $\mathbf{h} \rightarrow \mathbf{0}$ .
  - And we have by definition that the last term goes to  $\mathbf{0}$  as  $\mathbf{h} \rightarrow \mathbf{0}$ .

- Therefore,  $f$  is continuous at  $\mathbf{a}$ .

- Observation: A function  $f : U \rightarrow \mathbb{R}^m$  is given by an  $m$ -tuple of functions  $f_1 : U \rightarrow \mathbb{R}$  known as components.  $f = (f_1, \dots, f_m)$ .

- Proposition:  $f$  is differentiable at  $\mathbf{a} \in U$  iff each component function  $f_i$  is differentiable at  $\mathbf{a}$ . In this case,

$$Df(\mathbf{a}) = (Df_1(\mathbf{a}), \dots, Df_m(\mathbf{a}))$$

- We know that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} \in \mathbb{R}^m$$

- Thus, the limit is zero iff the limit of each component is zero.

- We have that the  $i^{\text{th}}$  component of the vector on the left below is equal to the number on the right; we call the common value  $L_i(\mathbf{h})$ .

$$\left( \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} \right)_i = \frac{f_i(\mathbf{a} + \mathbf{h}) - f_i(\mathbf{a}) - (A\mathbf{h})_i}{\|\mathbf{h}\|}$$

- The upshot is that  $f$  is differentiable at  $\mathbf{a}$  iff  $\lim_{\mathbf{h} \rightarrow \mathbf{0}} L_i(\mathbf{h}) = \mathbf{0}$  iff the linear transformation  $\mathbf{h} \mapsto (A\mathbf{h})_i : \mathbb{R}^m \rightarrow \mathbb{R}$  is the total derivative of  $f_i$ .

- Now, each  $f_i$  is a function of  $n$  variables, i.e.,  $f_i(x_1, \dots, x_n)$  where  $x_1, \dots, x_n$  are coordinates on  $\mathbb{R}^n$ .

1/12:

- **Partial derivative** (of  $f$  wrt.  $x_i$  at  $\mathbf{a} \in U$ ): The following quantity. Denoted by  $\partial f / \partial x_i$ . Given by

$$\frac{\partial f}{\partial x_i} = \lim_{h \rightarrow 0} \frac{f(a_1, \dots, a_{i-1}, a_i + h, a_{i+1}, \dots, a_n) - f(\mathbf{a})}{h}$$

- The partial derivative is easy to calculate if you're good at calculating single-variable derivatives.

- Questions:

1. If the partial derivatives all exist, does the total derivative also exist?
2. If partial derivatives exist, is  $f$  continuous?

- The answer is no to both — it's too weak a condition.

- Counter example: Consider  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  given by

$$f(x, y) = \begin{cases} \frac{x^2 y}{x^4 + y^4} & (x, y) \neq \mathbf{0} \\ 0 & (x, y) = \mathbf{0} \end{cases}$$

- All partial derivatives exist at  $(0, 0)$  but  $f$  is not continuous at  $(0, 0)$ .

- We'll consider this in the homework.

- Now we try taking derivatives in infinitely many directions, as opposed to just  $n$  many.

- **Directional derivative** (of  $f$  at  $\mathbf{a}$  in the direction of  $\mathbf{v} \in \mathbb{R}^n$ ): The following quantity. Denoted by  $D_{\mathbf{v}}f(\mathbf{a})$ ,  $\partial f / \partial \mathbf{v}$ . Given by

$$D_{\mathbf{v}}f(\mathbf{a}) = \frac{\partial f}{\partial \mathbf{v}} = \lim_{h \rightarrow 0} \frac{f(\mathbf{a} + h\mathbf{v}) - f(\mathbf{a})}{h}$$

- We always take  $\|\mathbf{v}\| = 1$ .

- The partial derivative is just a directional derivative along the standard basis vectors. Alternatively, the directional derivative is just a generalization of the partial derivatives.

- This still isn't a strong enough condition — the above counterexample has all directional derivatives at  $(0, 0)$  but still isn't continuous.

- Proposition: Suppose  $f$  is differentiable at  $\mathbf{a} \in U$ . Then all directional derivatives of  $f$  at  $\mathbf{a}$  exist and for all  $\mathbf{v} \in \mathbb{R}^n$ ,

$$\frac{\partial f}{\partial \mathbf{v}} = Df(\mathbf{a})(\mathbf{v})$$

- The total derivative says that the derivative exists from all sequences of approach. We're just going to pick a particular vector direction of approach.

- Mathematically, by the definition of the total derivative,

$$\begin{aligned} \mathbf{0} &= \lim_{h \rightarrow 0} \frac{f(\mathbf{a} + h\mathbf{v}) - f(\mathbf{a}) - Df(\mathbf{a})(h\mathbf{v})}{h} \\ &= \lim_{h \rightarrow 0} \frac{f(\mathbf{a} + h\mathbf{v}) - f(\mathbf{a})}{h} - Df(\mathbf{a})(\mathbf{v}) \\ Df(\mathbf{a})(\mathbf{v}) &= \frac{\partial f}{\partial \mathbf{v}} \end{aligned}$$

- A particular consequence is that

$$\frac{\partial f}{\partial x_i} = Df(\mathbf{a})(e_i)$$

- But the total derivative, as a linear transformation, is completely defined by its behavior on the basis vectors.
- Thus, it is defined by the  $m$ -by- $n$  matrix

$$Df(\mathbf{a}) = \left( \frac{\partial f_j}{\partial x_i} \right)_{\substack{1 \leq j \leq m \\ 1 \leq i \leq n}}$$

- **Jacobian matrix** (of  $f$  at  $\mathbf{a}$ ): The above matrix, representing the total derivative of  $f$  at  $\mathbf{a}$ .
- Theorem: Suppose  $f : U \rightarrow \mathbb{R}^m$  is a function on an open set  $U \subset \mathbb{R}^n$ . If all partial derivatives of  $f$  exist and are continuous on  $U$ , then  $f$  is differentiable on  $U$ .

- Recall the mean value theorem (MVT): Suppose  $g : [a, b] \rightarrow \mathbb{R}$  is a continuous function which is differentiable on  $(a, b)$ . Then there exists  $c \in (a, b)$  such that  $g'(c) = [g(b) - g(a)]/[b - a]$ .
- WLOG let  $m = 1$  (if we prove this case, we can use the proposition relating  $f$  to its components to prove the general case).
- Rewrite

$$\begin{aligned} f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) &= f(a_1 + h_1, a_2 + h_2, a_3 + h_3, \dots, a_n + h_n) - f(a_1, a_2 + h_2, a_3 + h_3, \dots, a_n + h_n) \\ &\quad + f(a_1, a_2 + h_2, a_3 + h_3, \dots, a_n + h_n) - f(a_1, a_2, a_3 + h_3, \dots, a_n + h_n) \\ &\quad + \dots \\ &\quad + f(a_1, \dots, a_{n-1}, a_n + h_n) - f(\mathbf{a}) \end{aligned}$$

where  $\mathbf{a} = (a_1, \dots, a_n)$  and  $\mathbf{h} = (h_1, \dots, h_n)$ .

- Apply the MVT to each term to get

$$f(a_1, \dots, a_i + h_i, \dots, a_n + h_n) - f(a_1, \dots, a_i, \dots, a_n + h_n) = h_i \frac{\partial f}{\partial x_i}(a_1, \dots, c_i(\mathbf{h}), \dots, a_n + h_n)$$

for some  $c_i(\mathbf{h}) \in (a_i, a_i + h_i) \cup (a_i + h_i, a_i)$ .

- Now let  $A$  be the Jacobian matrix of  $f$  at  $\mathbf{a}$ .
- WTS:

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} = \mathbf{0}$$

- We have

$$f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) = \sum_{i=1}^n h_i \frac{\partial f}{\partial x_i}(a_1, \dots, c_i(\mathbf{h}), \dots, a_n + h_n)$$

- Let  $\pi_i : \mathbb{R}^n \rightarrow \mathbb{R}^n$  be the linear map  $(x_1, \dots, x_n) \mapsto (0, \dots, x_i, \dots, 0)$ . Clearly,  $\mathbf{x} = \sum_{i=1}^n \pi_i \mathbf{x}$ .
- Thus,  $A\mathbf{h} = \sum_{i=1}^n A\pi_i \mathbf{h}$  and  $A\pi_i \mathbf{h} = \frac{\partial f}{\partial x_i}(\mathbf{a}) \cdot h_i$ .
- Applying, we have

$$\begin{aligned} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - A\mathbf{h}}{\|\mathbf{h}\|} &= \sum_{i=1}^n \frac{1}{\|\mathbf{h}\|} \left( h_i \frac{\partial f}{\partial x_i}(a_1, \dots, a_{i-1}, c_i(\mathbf{h}), a_{i+1} + h_{i+1}, \dots, a_n + h_n) - \frac{\partial f}{\partial x_i}(\mathbf{a}) \cdot h_i \right) \\ &= \sum_{i=1}^n \frac{h_i}{\|\mathbf{h}\|} \left( \frac{\partial f}{\partial x_i}(a_1, \dots, a_{i-1}, c_i(\mathbf{h}), a_{i+1} + h_{i+1}, \dots, a_n + h_n) - \frac{\partial f}{\partial x_i}(\mathbf{a}) \right) \end{aligned}$$

- We know that  $-1 \leq h_i/\|\mathbf{h}\| \leq 1$ , so we need only show that the difference above goes to zero as  $\mathbf{h} \rightarrow \mathbf{0}$ . But we know this by the continuity of the partial derivatives.



- Note that this theorem gives a sufficient condition but not a necessary condition for  $f$  to be differentiable.

1/14:

- Theorem (Chain Rule): Suppose  $f : U \rightarrow \mathbb{R}^m$  and  $g : V \rightarrow \mathbb{R}^p$  are functions defined on open sets  $U \subset \mathbb{R}^n$ ,  $V \subset \mathbb{R}^m$  with  $f(U) \subset V$ . Suppose that  $f$  is differentiable at  $\mathbf{a} \in U$  and  $g$  is differentiable at  $\mathbf{b} = f(\mathbf{a}) \in V$ . Then the composite function  $g \circ f : U \rightarrow \mathbb{R}^p$  is differentiable at  $\mathbf{a}$  and  $D(g \circ f)(\mathbf{a}) = Dg(\mathbf{b}) \circ Df(\mathbf{a}) : \mathbb{R}^n \rightarrow \mathbb{R}^p$ .

- Note that  $f : U \rightarrow \mathbb{R}^m$  is differentiable at  $\mathbf{a} \in U$  with derivative  $A$  iff  $f(\mathbf{a} + \mathbf{h}) = f(\mathbf{a}) + A\mathbf{h} + \tilde{f}(\mathbf{h})$  such that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{\tilde{f}(\mathbf{h})}{\|\mathbf{h}\|} = \mathbf{0}$$

where  $\tilde{f}$  is an error function.

- We're just rearranging terms here.
- If you like,  $\tilde{f}$  is the numerator from the definition of the total derivative.
- Let  $A = Df(\mathbf{a})$ ,  $B = Dg(\mathbf{b})$ . Then

$$f(\mathbf{a} + \mathbf{h}) = f(\mathbf{a}) + A\mathbf{h} + \tilde{f}(\mathbf{h})$$

so

$$\begin{aligned} (g \circ f)(\mathbf{a} + \mathbf{h}) &= g(f(\mathbf{a} + \mathbf{h})) \\ &= g(f(\mathbf{a}) + A\mathbf{h} + \tilde{f}(\mathbf{h})) \\ &= g(f(\mathbf{a})) + B(A\mathbf{h} + \tilde{f}(\mathbf{h})) + \tilde{g}(A\mathbf{h} + \tilde{f}(\mathbf{h})) \\ &= g(f(\mathbf{a})) + BA\mathbf{h} + B\tilde{f}(\mathbf{h}) + \tilde{g}(A\mathbf{h} + \tilde{f}(\mathbf{h})) \end{aligned}$$

- WTS:  $\lim_{\mathbf{h} \rightarrow \mathbf{0}} [B\tilde{f}(\mathbf{h}) + \tilde{g}(A\mathbf{h} + \tilde{f}(\mathbf{h}))]/\|\mathbf{h}\| = \mathbf{0}$ .
- For the first half of the fraction,

$$\frac{B\tilde{f}(\mathbf{h})}{\|\mathbf{h}\|} = B \left( \frac{\tilde{f}(\mathbf{h})}{\|\mathbf{h}\|} \right) \rightarrow \mathbf{0}$$

as  $\mathbf{h} \rightarrow \mathbf{0}$  since the argument goes to  $\mathbf{0}$  as  $\mathbf{h} \rightarrow \mathbf{0}$  and  $B$  is a linear transformation (in particular,  $B(\mathbf{0}) = \mathbf{0}$ ).

- For the second half of the fraction,

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{\tilde{g}(A\mathbf{h} + \tilde{f}(\mathbf{h}))}{\|\mathbf{h}\|} = \lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{\tilde{g}(A\mathbf{h} + \tilde{f}(\mathbf{h}))}{\|A\mathbf{h} + \tilde{f}(\mathbf{h})\|} \cdot \frac{\|A\mathbf{h} + \tilde{f}(\mathbf{h})\|}{\|\mathbf{h}\|}$$

- The left fraction on the right side of the equality goes to zero as  $\mathbf{h} \rightarrow \mathbf{0}$  by the definition of  $\tilde{g}$ .
- The right fraction on the right side of the equality is bounded since

$$\frac{\|A\mathbf{h} + \tilde{f}(\mathbf{h})\|}{\|\mathbf{h}\|} \leq \frac{\|A\mathbf{h}\|}{\|\mathbf{h}\|} + \frac{\|\tilde{f}(\mathbf{h})\|}{\|\mathbf{h}\|} \leq \|A\| + \frac{\|\tilde{f}(\mathbf{h})\|}{\|\mathbf{h}\|}$$

where  $\|A\|$  is the operator norm and  $\|\tilde{f}(\mathbf{h})\|/\|\mathbf{h}\| \rightarrow 0$  as  $\mathbf{h} \rightarrow \mathbf{0}$  by the definition of  $\tilde{f}$ .

- Thus, the second half of the fraction goes to zero as well.
- Theorem: Let  $U \subset \mathbb{R}^m$  be an open subset.

1. Suppose  $f, g : U \rightarrow \mathbb{R}^m$  are functions that are differentiable at  $\mathbf{a} \in U$ . Then  $f + g$  is also differentiable at  $\mathbf{a} \in U$  and

$$D(f + g)(\mathbf{a}) = Df(\mathbf{a}) + Dg(\mathbf{a})$$

2. Suppose  $f, g : U \rightarrow \mathbb{R}$  are both differentiable at  $\mathbf{a} \in U$ . Then  $f \cdot g$  is also differentiable at  $\mathbf{a}$ , and

$$D(f \cdot g)(\mathbf{a}) = Df(\mathbf{a}) \cdot g(\mathbf{a}) + f(\mathbf{a}) \cdot Dg(\mathbf{a})$$

3. Suppose  $f : U \rightarrow \mathbb{R}$  is differentiable at  $\mathbf{a} \in U$  and  $f(\mathbf{a}) \neq 0$ . Then  $1/f$  is differentiable at  $\mathbf{a} \in U$  and

$$D(1/f)(\mathbf{a}) = -\frac{Df(\mathbf{a})}{f(\mathbf{a})^2}$$

- Proof of 1: Consider the functions  $F : U \rightarrow \mathbb{R}^{2m}$  and  $G : \mathbb{R}^m \times \mathbb{R}^m \rightarrow \mathbb{R}^m$  defined by

$$F(\mathbf{x}) = (f(\mathbf{x}), g(\mathbf{x})) \qquad G(\mathbf{y}, \mathbf{z}) = \mathbf{y} + \mathbf{z}$$

so that

$$f + g = G \circ F$$

- $F$  is differentiable because its components are differentiable.
- $G$  is differentiable because it's linear. This also implies that  $DG(\mathbf{x}) = G$ .
- Apply the chain rule to learn that  $G \circ F$  is differentiable with derivative

$$\begin{aligned} D(f + g)(\mathbf{a}) &= D(G \circ F)(\mathbf{a}) \\ &= DG(F(\mathbf{a})) \circ DF(\mathbf{a}) \\ &= G(DF(\mathbf{a})) \\ &= G(Df(\mathbf{a}), Dg(\mathbf{a})) \\ &= Df(\mathbf{a}) + Dg(\mathbf{a}) \end{aligned}$$

- Prove the others the same way.

- Theorem (Mean Value Theorem): Suppose  $f : U \rightarrow \mathbb{R}$  is differentiable for all  $\mathbf{a} \in U$  and that  $U$  contains the line segment joining  $\mathbf{a}, \mathbf{a} + \mathbf{h} \in U$ . Then there exists  $t_0 \in (0, 1)$  such that

$$f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) = Df(\mathbf{a} + t_0\mathbf{h})(\mathbf{h})$$

- Define  $\phi(t) = f(\mathbf{a} + t\mathbf{h})$  for  $t \in [0, 1]$ .
- Apply the usual MVT to  $\phi$  to learn that there exists  $t_0 \in (0, 1)$  such that  $\phi(1) - \phi(0) = \phi'(t_0)$ .
- Then using the chain rule,  $\phi'(t_0) = Df(\mathbf{a} + t_0\mathbf{h})(\mathbf{h})$ .
- We now discuss higher order derivatives.
- **Differentiable** ( $f$  on  $U$ ): A function  $f$  that is differentiable at every  $\mathbf{a} \in U$ .
- If  $f$  is differentiable on  $U$ , then the total derivative gives a map  $Df : U \rightarrow \mathcal{L}(\mathbb{R}^n, \mathbb{R}^m)$ .
  - Note that  $\mathcal{L}(\mathbb{R}^n, \mathbb{R}^m)$  is isomorphic to the set of all  $m$ -by- $n$  matrices, and  $\mathbb{R}^{mn}$ .

- We can ask for  $Df$  to itself be differentiable. We define

$$D^2f = D(Df)$$

if it exists and, more generally,

$$D^k f = D(D^{k-1} f)$$

- **Class  $C^k$**  (function): A function  $f : U \rightarrow \mathbb{R}^m$  for which  $Df, \dots, D^k f$  all exist and are continuous on  $U$ .

- Note that we technically need only require that  $D^k f$  exist, as this implies the existence of  $Df, \dots, D^{k-1}f$ .
- A function  $f : U \rightarrow \mathbb{R}^m$  is of class  $C^k$  iff all partial derivatives  $\partial f / \partial x_i : U \rightarrow \mathbb{R}^m$  exist and are of class  $C^{k-1}$  (this follows from the theorem relating partial derivatives and differentiability).

• **Smooth** (function): A function of class  $C^\infty$ .

1/19: • Theorem: Let  $U \subset \mathbb{R}^n$  be open, and let  $f : U \rightarrow \mathbb{R}^m$  be a  $C^2$  function. Then for any  $i, j$ ,

$$\frac{\partial}{\partial x_i} \left( \frac{\partial f}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \frac{\partial f}{\partial x_i} \right)$$

- WLOG, let  $n = 2$  (because only two variables play a role in this theorem; we don't need the others) and  $m = 1$  (we can do this for each component separately).
- See the figure/proof associated with Theorem 15.3 in Labalme (2021).
- Note that there is a homework problem giving an example of a function for which the above quantities are defined but not equal. This doesn't violate the theorem, though, because the function isn't  $C^2$ .
- Next goal: One of the most important theorems in this class — the inverse function theorem.
- Theorem (Inverse function theorem): Suppose  $U \subset \mathbb{R}^n$  is open,  $f : U \rightarrow \mathbb{R}^n$  is a  $C^k$  function for  $k \geq 1$ , and  $\mathbf{a} \in U$  such that  $Df(\mathbf{a}) : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is invertible. Then there exist open neighborhoods  $V \subset U$  of  $\mathbf{a}$  and  $W$  of  $\mathbf{b} = f(\mathbf{a}) \in \mathbb{R}^n$  and a  $C^k$  function  $g : W \rightarrow V$  such that  $f(V) = W$ ,  $g(W) = V$ ,  $g(f(\mathbf{x})) = \mathbf{x}$  for all  $\mathbf{x} \in V$ , and  $f(g(\mathbf{y})) = \mathbf{y}$  for all  $\mathbf{y} \in W$ . Moreover,  $Dg(\mathbf{y}) = Df(g(\mathbf{y}))^{-1}$  for all  $\mathbf{y} \in W$ .
  - The proof will be reasonably involved because we have to deal with the construction of the open neighborhoods. The proof will be reasonably nonconstructive?
  - Intuition: If  $n = 1$ ,  $f'(\mathbf{a}) \neq 0$  implies that  $f$  is increasing or decreasing in a neighborhood of  $\mathbf{a}$ ; in either case, there's a local inverse.
    - In higher dimensions, the derivative won't be up or down but will look like a linear transformation.
  - Idea of proof: Given  $\mathbf{y} \in \mathbb{R}^n$  near  $\mathbf{b} = f(\mathbf{a})$ , we want to find  $\mathbf{x} \in U$  near  $\mathbf{a}$  such that  $f(\mathbf{x}) = \mathbf{y}$ .
    - First guess: Take  $\mathbf{x}_0 = \mathbf{a} - A^{-1}(\mathbf{b} - \mathbf{y})$  where  $A = Df(\mathbf{a})$ .
    - Hope:  $f(\mathbf{x}_0)$  is closer to  $\mathbf{y}$  than  $\mathbf{b} = f(\mathbf{a})$ .
    - Then we iterate; do this again and again to get a sequence that converges to the point we want. In particular,  $\mathbf{x}_1 = \mathbf{x}_0 - A^{-1}(f(\mathbf{x}_0) - \mathbf{y})$ , and on and on.
    - We're going to formalize this idea of iteration using the **contraction mapping theorem** (aka the Banach fixed point theorem).
    - Let  $\mathbf{y} \in \mathbb{R}^n$  be fixed near  $\mathbf{b} = f(\mathbf{a})$ .  $F_{\mathbf{y}}(\mathbf{x}) = \mathbf{x} - A^{-1}(f(\mathbf{x}) - \mathbf{y})$ . Note:  $f(\mathbf{x}) = \mathbf{y}$  iff  $F_{\mathbf{y}}(\mathbf{x}) = \mathbf{x}$ .
    - Goal: Find a fixed point of  $F_{\mathbf{y}}(\mathbf{x})$  (another way of iterating the sequence is that at some point you will get a fixed point, i.e., a point that you can plug into the recursion relation and get the same point back out).
- Theorem (Contraction mapping theorem): Let  $X$  be a complete metric space, and suppose  $T : X \rightarrow X$  is a function for which there exists a constant  $r < 1$  such that for all  $\mathbf{x}, \mathbf{y} \in X$ ,  $d(T(\mathbf{x}), T(\mathbf{y})) \leq r \cdot d(\mathbf{x}, \mathbf{y})$ . Then  $T$  has a unique fixed point.
- The way you find a fixed point is by starting with an arbitrary point and then just iterating  $T$  to it. Then show that in the limit it converges to something, and that something is a fixed point.
- You can't have more than one fixed point.

## 2.2 Chapter 2: Differentiation

From Munkres (1991).

- 1/18: • **Directional derivative** (of  $f$  at  $\mathbf{a}$  with respect to  $\mathbf{u}$ ): The following limit, where  $A \subset \mathbb{R}^m$  contains a neighborhood of  $\mathbf{a}$ ,  $f : A \rightarrow \mathbb{R}^n$ , and  $\mathbf{u} \in \mathbb{R}^m$  is nonzero. Denoted by  $\mathbf{f}'(\mathbf{a}; \mathbf{u})$ . Given by

$$\mathbf{f}'(\mathbf{a}; \mathbf{u}) = \lim_{t \rightarrow 0} \frac{f(\mathbf{a} + t\mathbf{u}) - f(\mathbf{a})}{t}$$

- Note that it is not necessary for  $\mathbf{u}$  to be a unit vector.
- If we choose as our definition of differentiability “ $f$  is differentiable at  $\mathbf{a}$  if  $\mathbf{f}'(\mathbf{a}; \mathbf{u})$  exists for every  $\mathbf{u} \neq \mathbf{0}$ ,” we would not have results such as differentiability implies continuity and the chain rule.
  - Thus, we need a stronger definition.
- As an alternate definition of differentiability in the one-variable case, consider the following.
- **Differentiable** (single-variable real function at  $a$ ): A function  $\phi : A \rightarrow \mathbb{R}$ , where  $A \subset \mathbb{R}$  contains a neighborhood of  $a$ , for which there exists a number  $\lambda$  such that

$$\frac{\phi(a+t) - \phi(a) - \lambda t}{t} \rightarrow 0 \quad \text{as } t \rightarrow 0$$

- **Derivative** (of a single-variable real function at  $a$ ): The unique number  $\lambda$  in the above definition. Denoted by  $\phi'(a)$ .
- “This formulation of the definition makes explicit the fact that if  $\phi$  is differentiable, then the linear function  $\lambda t$  is a good approximation to the **increment function**  $\phi(a+t) - \phi(a)$ ; we often call  $\lambda t$  the **first-order approximation** or **linear approximation** to the increment function” (Munkres, 1991, p. 43).
- **Increment function**: The function  $\phi(a+t) - \phi(a)$ .
- **First-order approximation**: The function  $\lambda t$ . Also known as **linear approximation**.
- To generalize the idea of a first-order/linear approximation to the increment function  $f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a})$ , we take a function that is linear in the sense of linear algebra.
- Note that either the sup norm or the Euclidean norm can be used in the definition of the total derivative.
- Theorem 5.1: Let  $A \subset \mathbb{R}^m$ , and let  $f : A \rightarrow \mathbb{R}^n$ . If  $f$  is differentiable at  $\mathbf{a}$ , then all the directional derivatives of  $f$  at  $\mathbf{a}$  exist, and

$$\mathbf{f}'(\mathbf{a}; \mathbf{u}) = Df(\mathbf{a}) \cdot \mathbf{u}$$

- Theorem 5.2: Let  $A \subset \mathbb{R}^m$ , and let  $f : A \rightarrow \mathbb{R}^n$ . If  $f$  is differentiable at  $\mathbf{a}$ , then  $f$  is continuous at  $\mathbf{a}$ .
- **$j^{\text{th}}$  partial derivative** (of  $f$  at  $\mathbf{a}$ ): The directional derivative of  $f$  at  $\mathbf{a}$  with respect to the vector  $\mathbf{e}_j$ , provided this derivative exists. Denoted by  $D_j f(\mathbf{a})$ .
- Theorem 5.3. Let  $A \subset \mathbb{R}^m$ , and let  $f : A \rightarrow \mathbb{R}$ . If  $f$  is differentiable at  $\mathbf{a}$ , then

$$Df(\mathbf{a}) = [D_1 f(\mathbf{a}) \quad \cdots \quad D_m f(\mathbf{a})]$$

- Theorem 5.4: Let  $A \subset \mathbb{R}^m$ , and let  $f : A \rightarrow \mathbb{R}^n$ . Suppose  $A$  contains a neighborhood of  $\mathbf{a}$ . Let  $f_i : A \rightarrow \mathbb{R}$  be the  $i^{\text{th}}$  component function of  $f$  so that

$$f(\mathbf{x}) = \begin{bmatrix} f_1(\mathbf{x}) \\ \vdots \\ f_n(\mathbf{x}) \end{bmatrix}$$

- (a) The function  $f$  is differentiable at  $\mathbf{a}$  if and only if each component function  $f_i$  is differentiable at  $\mathbf{a}$ .
- (b) If  $f$  is differentiable at  $\mathbf{a}$ , then its derivative is the  $n$ -by- $m$  matrix whose  $i^{\text{th}}$  row is the derivative of the function  $f_i$ , i.e.,

$$Df(\mathbf{a}) = \begin{bmatrix} Df_1(\mathbf{a}) \\ \vdots \\ Df_n(\mathbf{a}) \end{bmatrix}$$

or, in other words,  $Df(\mathbf{a})$  is the matrix whose entry in row  $i$  and column  $j$  is  $D_j f_i(\mathbf{a})$ .

- “It is possible for the partial derivatives, and hence the Jacobian matrix, to exist *without* it following that  $f$  is differentiable at  $\mathbf{a}$ ” (Munkres, 1991, p. 47).

- As per the example outlined in class.

- Special cases ( $m = 1$  or  $n = 1$ ).

- If  $f : \mathbb{R}^1 \rightarrow \mathbb{R}^3$ ,  $f$  is often interpreted as a parameterized curve and

$$Df(t) = \begin{bmatrix} f'_1(t) \\ f'_2(t) \\ f'_3(t) \end{bmatrix}$$

is the velocity vector of the curve.

- If  $g : \mathbb{R}^3 \rightarrow \mathbb{R}^1$ ,  $g$  is often interpreted as a scalar field, and the vector field

$$Dg(\mathbf{x}) = [D_1g(\mathbf{x}) \quad D_2g(\mathbf{x}) \quad D_3g(\mathbf{x})]$$

is called the gradient of  $g$ .

- In this case, the directional derivative of  $g$  with respect to  $\mathbf{u}$  is written in calculus as the dot product of the vectors  $\vec{\nabla} g$  and  $\mathbf{u}$ .

- Theorem 6.1 (Mean Value Theorem): If  $\phi : [a, b] \rightarrow \mathbb{R}$  is continuous at each point of the closed interval  $[a, b]$ , and differentiable at each point of the open interval  $(a, b)$ , then there exists a point  $c$  of  $(a, b)$  such that

$$\phi(b) - \phi(a) = \phi'(c)(b - a)$$

- Theorem 6.2: Let  $A$  be open in  $\mathbb{R}^m$ . Suppose that the partial derivatives  $D_j f_i(\mathbf{x})$  of the component functions of  $f$  exist at each point  $\mathbf{x}$  of  $A$  and are continuous on  $A$ . Then  $f$  is differentiable at each point of  $A$ .

- **Continuously differentiable** (function on  $A$ ): A function  $f$  for which the partial derivatives  $D_j f_i(\mathbf{x})$  of the component functions of  $f$  exist at each point  $\mathbf{x} \in A$  and are continuous on  $A$ , where  $A \subset \mathbb{R}^m$  is open. *Also known as class  $C^1$*  (function on  $A$ ).

- There are differentiable functions that are not of class  $C^1$ , but we will not concern ourselves with them.
- Theorem 6.3<sup>[1]</sup>: Let  $A$  be open in  $\mathbb{R}^m$ , and let  $f : A \rightarrow \mathbb{R}$  be a function of class  $C^2$  on  $A$ . Then for each  $\mathbf{a} \in A$ ,

$$D_k D_j f(\mathbf{a}) = D_j D_k f(\mathbf{a})$$

- Theorem 7.1 (Chain Rule): Let  $A \subset \mathbb{R}^m$ ,  $B \subset \mathbb{R}^n$ ,  $f : A \rightarrow \mathbb{R}^n$ ,  $g : B \rightarrow \mathbb{R}^p$ ,  $f(A) \subset B$ , and  $\mathbf{b} = f(\mathbf{a})$ . If  $f$  is differentiable at  $\mathbf{a}$  and  $g$  is differentiable at  $\mathbf{b}$ , then the composite function  $g \circ f$  is differentiable at  $\mathbf{a}$ . Furthermore,

$$D(g \circ f)(\mathbf{a}) = Dg(\mathbf{b}) \cdot Df(\mathbf{a})$$

where the indicated product is matrix multiplication.

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<sup>1</sup>See Theorem 15.3 in Labalme (2021).

- Corollary 7.2: Let  $A$  be open in  $\mathbb{R}^m$ , and let  $B$  be open in  $\mathbb{R}^n$ . Let  $f : A \rightarrow \mathbb{R}^n$  and  $g : B \rightarrow \mathbb{R}^p$  with  $f(A) \subset B$ . If  $f$  and  $g$  are of class  $C^r$ , so is the composite function  $g \circ f$ .
- Theorem 7.3 (Mean Value Theorem): Let  $A$  be open in  $\mathbb{R}^m$ , and let  $f : A \rightarrow \mathbb{R}$  be differentiable on  $A$ . If  $A$  contains the line segment with end points  $\mathbf{a}$  and  $\mathbf{a} + \mathbf{h}$ , then there is a point  $\mathbf{c} = \mathbf{a} + t_0 \mathbf{h}$  with  $0 < t_0 < 1$  of this line segment such that

$$f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) = Df(\mathbf{c}) \cdot \mathbf{h}$$

- Theorem 7.4: Let  $A$  be open in  $\mathbb{R}^n$ ,  $f : A \rightarrow \mathbb{R}^n$ , and  $\mathbf{b} = f(\mathbf{a})$ . Suppose that  $g$  maps a neighborhood of  $\mathbf{b}$  into  $\mathbb{R}^n$ , that  $g(\mathbf{b}) = \mathbf{a}$ , and  $g(f(\mathbf{x})) = \mathbf{x}$  for all  $\mathbf{x}$  in a neighborhood of  $\mathbf{a}$ . If  $f$  is differentiable at  $\mathbf{a}$  and if  $g$  is differentiable at  $\mathbf{b}$ , then

$$Dg(\mathbf{b}) = [Df(\mathbf{a})]^{-1}$$

*Proof.* Let  $i : \mathbb{R}^n \rightarrow \mathbb{R}^n$  be the identity function. It has total derivative  $I_n$ . But since  $g(f(\mathbf{x})) = i(\mathbf{x})$  for all  $\mathbf{x}$  in a neighborhood of  $\mathbf{a}$ , the Chain Rule implies that

$$\begin{aligned} Dg(\mathbf{b}) \cdot Df(\mathbf{a}) &= I_n \\ Dg(\mathbf{b}) &= [Df(\mathbf{a})]^{-1} \end{aligned}$$

as desired. □

- It follows from Theorem 7.4 that for  $f^{-1}$  to be differentiable at  $\mathbf{a}$ , it is *necessary* that  $Df(\mathbf{a})$  is invertible.
  - We will later prove that this condition is also *sufficient* for a function  $f$  of class  $C^1$  to have a differentiable inverse.
- **Functional notation:** Notation such as  $\phi'$  for a derivative.
- **Operator notation:** Notation such as  $D\phi$  for a derivative.
- Munkres (1991) argues that Leibniz notation is a relic of a “time when the focus of every physical and mathematical problem was on the *variables* involved, and when *functions* as such were hardly even thought about” (p. 60).

# References

- Labalme, S. (2021). *Calculus and Analytic Geometry (Thomas) notes*. Retrieved January 18, 2022, from <https://github.com/shadypuck/CAAGThomasNotes/blob/master/main.pdf>
- Munkres, J. R. (1991). *Analysis on manifolds*. Addison-Wesley.