Real Analysis and Multivariable Calculus: Graduate Level Problems and Solutions

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Disclaimer: This handbook is intended to assist graduate students with qualifying examination preparation. Please be aware, however, that the handbook might contain, and almost certainly contains, typos as well as incorrect or inaccurate solutions. I can not be made responsible for any inaccuracies contained in this handbook.

Contents

1 Countability

The number of elements in S is the **cardinality** of S.
S and T have the **same cardinality** ($S \simeq T$) if there exists a bijection $f : S \to T$.
card $S \leq$ card T if $\exists$ **injective**[1] $f : S \to T$.
card $S \geq$ card T if $\exists$ **surjective**[2] $f : S \to T$.
S is **countable** if S is finite, or $S \simeq \mathbb{N}$.

Theorem. *$S, T \neq \phi$. $\exists$ injection $f : S \hookrightarrow T \;\Leftrightarrow\; \exists$ surjection $g : T \twoheadrightarrow S$.*

Theorem. *$\mathbb{Q}$ is countable.*

Proof. Need to show that there is a bijection $f : \mathbb{N} \to \mathbb{Q}$.
Since $\mathbb{N} \subseteq \mathbb{Q}$, card $\mathbb{N} \leq$ card $\mathbb{Q}$, and therefore, $\exists f$ that is *injective.*
To show card $\mathbb{N} \geq$ card $\mathbb{Q}$, construct the following map. The set of all rational numbers can be displayed in a grid with rows $i = 1, 2, 3, \ldots$ and columns $j = 0, -1, 1, -2, 2, -3, 3, \ldots$. Each a_{ij}, the ij'th entry in a table, would be represented as $\frac{j}{i}$. Starting from a_{11}, and assigning it $n = 1$, move from each subsequent row diagonally left-down, updating n. This would give a map $g : \mathbb{N} \to \mathbb{Q}$, which will count all fractions, some of them more than once. Therefore, card $\mathbb{N} \geq$ card $\mathbb{Q}$, and so g is *surjective.* Thus, card $\mathbb{N} =$ card $\mathbb{Q}$, and $\mathbb{Q}$ is countable. $\square$

Theorem. *$\mathbb{R}$ is **not** countable.*

Proof. It is enough to prove that $[0, 1) \subset \mathbb{R}$ is not countable. Suppose that the set of all real numbers between 0 and 1 is countable. Then we can list the decimal representations of these numbers (use the infinite expansions) as follows:
$a_1 = 0.a_{11}a_{12}a_{13} \ldots a_{1n} \ldots$
$a_2 = 0.a_{21}a_{22}a_{23} \ldots a_{2n} \ldots$
$a_3 = 0.a_{31}a_{32}a_{33} \ldots a_{3n} \ldots$
and so on. We derive a contradiction by showing there is a number x between 0 and 1 that is not on the list. For each positive integer j, we will choose jth digit after the decimal to be different than a_{jj}:
$x = 0.x_1x_2x_3 \ldots x_n \ldots$, where $x_j = 1$ if $a_{jj} \neq 1$, and $x_j = 2$ if $a_{jj} = 1$.
For each integer j, x differs in the jth position from the jth number on the list, and therefore cannot be that number. Therefore, x cannot be on the list. This means the list as we chose is not a bijection, and so the set of all real numbers is uncountable.
(Need to worry about not allowing 9 tails in decimal expansion: $0.399\ldots = 0.400\ldots$). $\square$

[1] **injective = 1-1:** $f(s_1) = f(s_2) \Rightarrow s_1 = s_2$.
[2] **surjective = onto:** $\forall t \in T, \exists s \in S$, s.t. $f(s) = t$.

Problem (F'01, #4). *The set of all sequences whose elements are the digits* 0 *and* 1 *is not countable.*

Let S be the set of all binary sequences. We want to show that there does not exist a one-to-one mapping from the set $\mathbb{N}$ *onto* the set S.

Proof. 1) Let A be a countable subset of S, and let A consist of the sequences $s_1, s_2, \ldots$. We construct the sequence s as follows. If the nth digit in s_n is 1, let the nth digit of s be 0, and vice versa. Then the sequence s differs from every member of A in at least one place; thus $s \notin A$. However, $s \in S$, so that A is a proper[3] subset of S.

Thus, every countable subset of S is a proper subset of S, and therefore, S is not countable. □

Proof. 2) Suppose there exists a $f : \mathbb{N} \to S$ that is injective. We can always exhibit an injective map $f : \mathbb{N} \to S$ by always picking a different sequence from the set of sequences that are already listed. (One way to do that is to choose a binary representation for each $n \in \mathbb{N}$).

Suppose $f : \mathbb{N} \to S$ is surjective. Then, all sequences in S could be listed as $s_1, s_2, \ldots$. We construct the sequence s as follows. If the nth digit in s_n is 1, let the nth digit of s be 0, and vice versa. Then the sequence s differs from every member of the list. Therefore, s is not on the list, and our assumption about f being surjective is false. Thus, there does not exist $f : \mathbb{N} \to S$ surjective. □

Theorem. *card* $(A) <$ *card* $(P(A))$[4].

Proof. card $(A) \leq$ card $(P(A))$, since A can be injectively mapped to the set of one-element sets of A, which is a subset of $P(A)$.
We need to show there is no onto map between A and $P(A)$. So we would like to find a thing in $P(A)$ which is not reached by f. In other words, we want to describe a subset of A which cannot be of the form $f(a)$ for any $a \in A$.

Suppose $|A| = |P(A)|$. Then there is a 1-1 correspondence $f : A \to P(A)$. We obtain a contradiction to the fact that f is onto by exhibiting a subset X of A such that $X \neq f(a)$ for any $a \in A$.
For every $a \in A$, either $a \in f(a)$, or $a \notin f(a)$. Let $X = \{a \in A : a \notin f(a)\}$.
Consider $a \in A$. If $a \in f(a)$, then $a \notin X$, so $f(a) \neq X$.
If $a \notin f(a)$, than $a \in X$, so $f(a) \neq X$. Therefore, $X \neq f(a)$, $\forall a \in A$, a contradiction.
Therefore, card $(A) <$ card $(P(A))$. □

Theorem. *Suppose that $f : [0,1] \to \mathbb{R}$ is an increasing function. Show that f can have at most a countable number of discontinuities.*

Proof. Let $E = \{x \in [0,1] : f$ is discontinuous at $x\}$. Given any $x \in E$, we know that

$$\lim_{t \to x^-} f(t) < \lim_{t \to x^+} f(t)$$

and, using this fact, we choose $r(x) \in \mathbb{Q}$ such that $\lim_{t \to x^-} f(t) < r(x) < \lim_{t \to x^+} f(t)$.
$\Rightarrow$ We have defined a $1-1$ function $r : E \to \mathbb{Q}$. □

[3] A is a **proper subset** of B if every element of A is an element of B, and there is an element of B which is not in A.

[4] **Power set** of a set S is the set whose elements are all possible subsets of S, i.e.
$S = \{1,2\}$, $P(S) = 2^S = \{\phi, \{1\}, \{2\}, \{1,2\}\}$. $|P(A)| = 2^n$, if $|A| = n$.

2 Unions, Intersections, and Topology of Sets

Theorem. *Let E_α be a collection of sets. Then*

$$(\bigcup_\alpha E_\alpha)^c = \bigcap_\alpha (E_\alpha^c).$$

Proof. Let $A = (\bigcup E_\alpha)^c$ and $B = (\bigcap E_\alpha^c)$. If $x \in A$, then $x \notin \bigcup E_\alpha$, hence $x \notin E_\alpha$ for any α, hence $x \in E_\alpha^c$ for every α, so that $x \in \bigcap E_\alpha^c$. Thus $A \subset B$.
Conversely, if $x \in B$, then $x \in E_\alpha^c$ for every α, hence $x \notin E_\alpha$ for any α, hence $x \notin \bigcup E_\alpha$, so that $x \in (\bigcup E_\alpha)^c$. Thus $B \subset A$. $\square$

Theorem.
a) For any collection G_α of open sets, $\bigcup_\alpha G_\alpha$ is open.
b) For any collection F_α of closed sets, $\bigcap_\alpha F_\alpha$ is closed.
c) For any finite collection $G_1, \ldots, G_n$ of open sets, $\bigcap_{i=1}^n G_i$ is open.
d) For any finite collection $F_1, \ldots, F_n$ of closed sets, $\bigcup_{i=1}^n F_i$ is closed.

Proof. *a)* Put $G = \bigcup_\alpha G_\alpha$. If $x \in G$, then $x \in G_\alpha$ for some α. Since x is an interior point of G_α, x is also an interior point of G, and G is open.
b) By theorem above,

$$(\bigcup_\alpha F_\alpha)^c = \bigcap_\alpha (F_\alpha^c) \quad \Rightarrow \quad (\bigcap_\alpha F_\alpha)^c = \bigcup_\alpha (F_\alpha^c), \tag{2.1}$$

and F_α^c is open. Hence *a)* implies that the right equation of (2.1) is open so that $\bigcap_\alpha F_\alpha$ is closed.
c) Put $H = \bigcap_{i=1}^n G_i$. For any $x \in H$, there exists neighborhoods N_{r_i} of x, such that $N_{r_i} \subset G_i$ $(i = 1, \ldots, n)$. Put $r = \min(r_1, \ldots, r_n)$. Then $N_r(x) \subset G_i$ for $i = 1, \ldots, n$, so that $N_r(x) \subset H$, and H is open.
d) By taking complements, *d)* follows from *c)*: $(\bigcup_{i=1}^n F_i)^c = \bigcap_{i=1}^n (F_i^c)$. $\square$

Theorem. *$S \subset M \subseteq X$. S open relative to M $\Leftrightarrow$ $\exists$ open $U \subset X$ such that $S = U \bigcap M$.*

Proof. $\Rightarrow$ S open relative to M. To each $x \in S$, $\exists r_x$, $|x - y| < r_x$, $y \in M \Rightarrow y \in S$. Define

$$U = \bigcup_{x \in S} N_{r_x}(x) \qquad \Rightarrow \qquad U \subset X \text{ open.}$$

It is clear that $S \subset U \bigcap M$. By our choice of $N_{r_x}(x)$, we have $N_{r_x}(x) \bigcap M \subset S$, $\forall x \in S$ so that $U \bigcap M \subset S \;\Rightarrow\; S = U \bigcap M$.
$\Leftarrow$ If U is open in X and $S = U \bigcap M$, every $x \in S$ has a neighborhood $N_{r_x}(x) \subset U$. Then $N_{r_x}(x) \bigcap M \subset S$ so that S is open relative to M. $\square$

Theorem. *$K \subset Y \subset X$. K compact relative to X $\Leftrightarrow$ K compact relative to Y.*

Proof. $\Rightarrow$ Suppose K is compact relative to X, and let $\{V_\alpha\}$ be a collection of sets, open relative to Y, such that $K \subset \bigcup_\alpha V_\alpha$. By the above theorem, $\exists U_\alpha$ open relative to X, such that $V_\alpha = Y \bigcap U_\alpha$, $\forall \alpha$; and since K is compact relative to X, we have

$$K \subset U_{\alpha_1} \bigcup \cdots \bigcup U_{\alpha_n} \qquad \circledcirc$$

$$\text{Since } K \subset Y \quad \Rightarrow \quad K \subset V_{\alpha_1} \bigcup \cdots \bigcup V_{\alpha_n}. \qquad \circledast$$

$\Leftarrow$ Suppose K is compact relative to Y. Let $\{U_\alpha\}$ be a collection of open subsets of X which covers K, and put $V_\alpha = Y \bigcap U_\alpha$. Then $\circledast$ will hold for some choice of $\alpha_1, \ldots, \alpha_n$; and since $V_\alpha \subset U_\alpha$, $\circledast$ implies $\circledcirc$. $\square$

Theorem. *Compact subsets of metric spaces are closed.*

Proof. Let $K \subset X$ be a compact subset. We prove K^c is open.
Suppose $x \in X$, $x \notin K$. If $y \in K$, let V_y and W_y be neighborhoods of x and y, respectively, of radius less than $\frac{1}{2}d(x,y)$. Since K is compact, $K \subset W_{y_1} \bigcup \cdots \bigcup W_{y_n} = W$.
If $V = V_{y_1} \bigcap \cdots \bigcap V_{y_n}$, then V is a neighborhood of x which does not intersect W. Hence $V \subset K^c$, so that x is an interior point of K^c. $\square$

Theorem. *Closed subsets of compact sets are compact.*

Proof. Suppose $F \subset K \subset X$, F is closed (relative to X), and K is compact. Let $\{V_\alpha\}$ be an open cover of F. If F^c is adjoined to $\{V_\alpha\}$, we obtain an open cover Ω of K. Since K is compact, there is finite subcollection Φ of Ω which covers K, and hence F. If F^c is a member of Φ, we may remove it from Φ and still retain an open cover of F. We have thus shown that a finite subcollection of $\{V_\alpha\}$ covers F. $\square$

Corollary. *If F is closed and K is compact, then $F \bigcap K$ is compact.*

Proof. K is closed (by a theorem above), and thus $F \bigcap K$ is closed. Since $F \bigcap K \subset K$, the above theorem shows that $F \bigcap K$ is compact. $\square$

Theorem. *If $\{K_\alpha\}$ is a collection of compact subsets of a metric space X such that the intersection of every finite subcollection of $\{K_\alpha\}$ is nonempty, then $\bigcap K_\alpha$ is nonempty.*

Proof. Fix a member K_1 of $\{K_\alpha\}$. Assume that no point of K_1 belongs to every K_α. Then the sets K_α^c form an open cover of K_1; and since K_1 is compact, $K_1 \subset K_{\alpha_1}^c \bigcup \cdots \bigcup K_{\alpha_n}^c$. But this means that $K_1 \bigcap K_{\alpha_1} \bigcap \cdots \bigcap K_{\alpha_n}$ is empty. $\Rightarrow$ contradiction. $\square$

3 Sequences and Series

A sequence $\{p_n\}$ **converges** to $p \in X$ if:
$\forall \epsilon > 0$, $\exists N$: $\forall n \geq N$ $|p_n - p| < \epsilon \quad \Leftrightarrow \quad \lim_{n\to\infty} p_n = p$.
A sequence $\{p_n\}$ is **Cauchy** if:
$\forall \epsilon > 0$, $\exists N$: $\forall n, m \geq N$ $|p_n - p_m| < \epsilon$.
Cauchy criterion: A sequence converges in $\mathbb{R}^k \quad \Leftrightarrow \quad$ it is a Cauchy sequence.
Cauchy criterion: $\sum a_n$ converges $\quad \Leftrightarrow \quad \forall \epsilon > 0, \exists N : |\sum_{k=n}^m a_k| \leq \epsilon$ if $m \geq n \geq N$.
The series $\sum a_n$ is said to **converge absolutely** if $\sum |a_n|$ converges.

Problem (S'03, #2). *If $a_1, a_2, a_3, \ldots$ is a sequence of real numbers with $\sum_{j=1}^\infty |a_j| < \infty$, then $\lim_{N\to\infty} \sum_{j=1}^N a_j$ exists. ($\sum a_n$ converges absolutely $\Rightarrow$ $\sum a_n$ converges).*

Proof. If $s_n = \sum_{j=1}^n a_j$ is a partial sum, then for $m \leq n$ we have

$$|s_n - s_m| = |\sum_{j=1}^n a_j - \sum_{j=1}^m a_j| = |\sum_{j=m}^n a_j| \leq \sum_{j=m}^n |a_j|$$

Since $\sum |a_j|$ converges, given $\epsilon > 0, \exists N$, s.t. $m, n \geq N$ $(m \leq n)$, then $\sum_{j=m}^n |a_j| < \epsilon$.
Thus $\{s_n\}$ is a Cauchy sequence in $\mathbb{R}$, and converges. $\Rightarrow$ $\lim_{N\to\infty} \sum_{j=1}^N a_j$ exists. $\square$

Problem (F'01, #2). *Let $\mathbb{N}$ denote the positive integers, let $a_n = (-1)^n \frac{1}{n}$, and let α be any real number. Prove there is a one-to-one and onto mapping $\sigma : \mathbb{N} \to \mathbb{N}$ such that*

$$\sum_{n=1}^\infty a_{\sigma(n)} = \alpha.$$

Proof. $a_n = (-1)^n \frac{1}{n} \quad \Rightarrow \quad a_1 = -1, a_2 = \frac{1}{2}, a_3 = -\frac{1}{3}, a_4 = \frac{1}{4}, \ldots$.
$a_{2n} > 0, \quad a_{2n-1} < 0, \quad n = 1, 2, \ldots$
$\sum$(*positive terms*) $= \sum_{n=1}^\infty a_{2n} = \sum_{n=1}^\infty \frac{1}{2n} = \frac{1}{2}\sum_{n=1}^\infty \frac{1}{n}$ diverges, and $\lim_{n\to\infty} \frac{1}{2n} = 0$.
$\sum$(*negative terms*) $= \sum_{n=1}^\infty a_{2n-1} = -\sum_{n=1}^\infty \frac{1}{2n-1}$ diverges by comparison with $-\sum_{n=1}^\infty \frac{1}{2n}$, and $\lim_{n\to\infty} \frac{1}{2n-1} = 0$.
Claim: $\forall \alpha \in \mathbb{R}$, there is a one-to-one and onto mapping $\sigma : \mathbb{N} \to \mathbb{N}$ such that $\sum_{n=1}^\infty a_{\sigma(n)} = \alpha$, where $\sigma(n)$ is the rearrangement of indices of the original series.
Given α, choose positive terms in sequential order until their sum exceeds α. At this switch point, choose negative terms until their sum is less than α. Repeat the process.
Note: This process never stops because no matter how many positive and negative terms are taken, there are still infinitely many both positive and negative terms left; the sum of positive terms is ∞, the sum of negative terms is $-\infty$.
Let the sum of terms at the Nth step be denoted by S_N, $S_N = \sum_{n=1}^N a_{\sigma(n)}$. At switch point, $|\alpha - S_N|$ is bounded by the size of the term added:

$$|\alpha - S_N| \to 0, \qquad N \to \infty$$

All terms $\{a_n\}$ will eventually be added to the sum ($\sigma : \mathbb{N} \twoheadrightarrow \mathbb{N}$ is *surjective* (onto)) at different steps ($\sigma : \mathbb{N} \hookrightarrow \mathbb{N}$ is *injective* (1-1)). $\big[\sigma : \{1, 2, 3, \ldots\} \to \{n_1, n_2, n_3, \ldots\}\big]$. $\square$

Root Test. *Given* $\sum a_n$*, put* $\alpha = \limsup_{n\to\infty} \sqrt[n]{|a_n|}$*. Then*
a) if $\alpha < 1$*,* $\sum a_n$ *converges;*
b) if $\alpha > 1$*,* $\sum a_n$ *diverges;*
c) if $\alpha = 1$*, the test gives no information.*

Ratio Test. *The series* $\sum a_n$
a) converges if $\limsup_{n\to\infty} |\frac{a_{n+1}}{a_n}| < 1$*,*
b) diverges if $|\frac{a_{n+1}}{a_n}| \geq 1$ *for all* $n \geq n_0$*, where* n_0 *is some fixed integer.*

Alternating Series. *Suppose*
(a) $|a_1| \geq |a_2| \geq \dots$;
(b) $a_{2m-1} \geq 0$*,* $a_{2m} \leq 0$*,* $m = 1, 2, 3, \dots$;
(c) $\lim_{n\to} a_n = 0$.
Then $\sum a_n$ *converges.*

Geometric Series. $|x| < 1$:

$$\sum_{k=0}^{\infty} x^k = \frac{1}{1-x}.$$

$$\begin{aligned} Proof: \quad S_n &= 1 + x + x^2 + \cdots + x^n & \circledast \\ xS_n &= x + x^2 + x^3 + \cdots + x^{n+1} & \circledcirc \\ \circledast - \circledcirc &= (1-x)S_n = 1 - x^{n+1} & \\ \Rightarrow \quad S_n &= \sum_{k=0}^{n} x^k = \frac{1-x^{n+1}}{1-x} & \end{aligned}$$

Problem (F'02, #4). *By integrating the series*

$$\frac{1}{1+x^2} = 1 - x^2 + x^4 - x^6 + x^8 \cdots$$

prove that

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} \cdots .$$

Justify carefully all the steps (especially taking the limit as $x \to 1$ from below).

Proof. Geometric Series:

$$\frac{1}{1+x^2} = 1 - x^2 + x^4 - x^6 + x^8 \cdots ; \qquad |x| < 1.$$

$$\int \frac{dx}{1+x^2} = \tan^{-1}(x) = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \frac{x^9}{9} \cdots .$$

$$\int_0^1 \frac{dx}{1+x^2} = [\tan^{-1}(x)]_0^1 = \tan^{-1} 1 - \tan^{-1} 0 = \frac{\pi}{4} - 0 = \frac{\pi}{4}.$$

$$\int_0^1 \frac{dx}{1+x^2} = \lim_{\epsilon \to 0} \int_0^{1-\epsilon} \frac{dx}{1+x^2}$$

$$\int_0^{1-\epsilon} \frac{dx}{1+x^2} = \int_0^{1-\epsilon} \underbrace{\overbrace{\boxed{1 - x^2 + x^4 - \cdots}}^{S}}_{\text{converges uniformly for } |x| \le 1-\epsilon} dx = \lim \int_0^{1-\epsilon} S_N(x) dx$$

$$||f_n - f||_\infty \to 0 \quad \Rightarrow \quad \int_a^b f_n(x)dx \to \int_a^b f(x)dx$$

$$\left| \int_a^b f(x)dx - \int_a^b f_n(x)dx \right| \le \int_a^b |f(x) - f_n(x)|dx \le \int_a^b ||f - f_n||_\infty dx = (b-a)||f - f_n||_\infty.$$

$$S \text{ is a uniform limit of } S_N = \sum_{n=1}^{N} (-1)^n x^{2n}.$$

$$|S(x) - S_N(x)| = \left| \sum_{N+1}^{\infty} (-1)^n x^{2n} \right|, \ \forall x \in [0, 1-\epsilon] \ \le \sum_{N+1}^{\infty} |x|^{2n} \le \sum_{N+1}^{\infty} (1-\epsilon)^{2n} = \frac{(1-\epsilon)^{2(N+1)}}{(1-\epsilon)^2} \to 0.$$

Above calculations show $\tan^{-1} x = \sum \frac{(-1)^n x^{2n+1}}{2n+1}, \quad |x| < 1.$

Alternating series test $\Rightarrow$ right side converges.

$$\frac{\pi}{4} = \sum \frac{(-1)^n}{2n+1} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} \cdots .$$

□

Logarithm. $|x| < 1$:

$$\frac{1}{1+x} = 1 - x + x^2 - x^3 + \cdots = \sum_{n=0}^{\infty} (-1)^n x^n$$

$$\log(1+x) = \int_0^x \frac{dt}{1+t} = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^n}{n}$$

$\log(1+x)$ is **not** valid for $|x| > 1$, or $x < -1$. Claim: If $x = 1$, the series converges to $\log 2$. Proof: $\sum_{n=1}^{\infty} (-1)^{n-1} \frac{x^n}{n}$ is uniformly convergent for $x \in [0, 1]$, since the sum of any number of consecutive terms starting with the n^{th} has absolute value at most $\frac{x^n}{n} \le \frac{1}{n}$, since for $0 < x < 1$ we have alternating series.

Binomial Series. $|x| < 1$:

$$\begin{aligned}
(1+x)^\alpha &= 1 + \sum_{n=1}^{\infty} \frac{\alpha(\alpha-1)\cdots(\alpha-n+1)}{n!} x^n = 1 + \alpha x + \binom{\alpha}{2} x^2 + \cdots + \binom{\alpha}{n} x^n + \cdots \\
&= 1 + \alpha x + \frac{\alpha(\alpha-1)}{2!} x^2 + \frac{\alpha(\alpha-1)(\alpha-2)}{3!} x^3 + \cdots
\end{aligned}$$

Problem (F'03, #3). *The sequence $a_1, a_2, \ldots$ with $a_n = \left(1 + \frac{1}{n}\right)^n$ converges as $n \to \infty$.*

Proof. By Binomial Series Theorem with $\alpha = n,\ x = \frac{1}{n}$, we get:

$$\begin{aligned}
\left(1 + \frac{1}{n}\right)^n &= 1 + n \cdot \frac{1}{n} + \frac{n(n-1)}{2!} \cdot \frac{1}{n^2} + \frac{n(n-1)(n-2)}{3!} \cdot \frac{1}{n^3} + \cdots + \frac{n(n-1)(n-2)\cdots 1}{n!} \cdot \frac{1}{n^n} \\
&\le 1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \cdots + \frac{1}{n!} = \sum_{k=0}^{n} \frac{1}{k!} \ \to\ e, \text{ as } n \to \infty.
\end{aligned}$$

$\square$

4 Notes

4.1 Least Upper Bound Property

An ordered set S is said to have the **least upper bound**[5] **property** if:
$E \subset S$, E is not empty, and E is bounded above, then $\sup E$ exists in S.
Completeness axiom: If E is a nonempty subset of $\mathbb{R}$ that is bounded above, then E has a least upper bound.

Problem (F'02, #2). *Show why the Least Upper Bound Property (every set bounded above has a least upper bound) implies the Cauchy Completeness Property (every Cauchy sequence has a limit) of the* ***real numbers****.*

Proof. Suppose $\{x_n\}$ Cauchy. The problem is to show that $\{x_n\}$ converges.
We first show that $\{x_n\}$ is bounded. Fix $\epsilon > 0$ and let N be such that $|x_n - x_m| < \epsilon$ if $n, m > N$. Then for any fixed $n > N$, the entire sequence is contained in the closed ball of center x_n and radius $\max\{d(x_n, x_1), d(x_n, x_2), \ldots, d(x_n, x_N), \epsilon\}$. Thus $\{x_n\}$ is bounded.
Define $z_n = sup\{x_k\}_{k \geq n}$. Since $\{x_n\}$ is bounded, each z_n is a finite real number and is bounded above in absolute value by M. If $m > n$, then z_m is obtained by taking the sup of a smaller set than is z_n; hence $\{z_n\}$ is decreasing. By the greatest lower bound property, $Z = \{z_n | n \in \mathbb{N}\}$ has an infimum. Let $x = \inf Z$. We *claim* that $x_n \to x$.[6]
For each $\epsilon > 0$ there is a corresponding integer N such that $x \leq z_N \leq x + \epsilon$. Since $\{x_n\}$ is Cauchy, by taking a larger N if necessary, we know that $k \geq N \ \Rightarrow \ x_k \in [x_N - \epsilon, x_N + \epsilon]$. It follows that $z_N \in [x_N - \epsilon, x_N + \epsilon]$. Hence for $k \geq N$,

$$|x_k - x| \leq |x_k - x_N| + |x_N - z_N| + |z_N - x| \leq \epsilon + \epsilon + \epsilon = 3\epsilon. \qquad \square$$

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[5] **least upper bound** of $E \equiv \sup E$.

[6] *Idea:* Since $\{x_n\}$ is Cauchy, the terms of this sequence would approach one another. $\{z_n\}$ also approaches $\{x_n\}$. Since $z_n \to x$, $\{z_n\}$ approaches x. It follows that $\{x_n\}$ approaches x.

5 Completeness

A metric space X is **complete** if every Cauchy sequence of elements of X converges to an element of X.

Lemma. *A convergent sequence is a Cauchy sequence.*

Proof. $x_n \to x$ means $\forall \epsilon > 0, \exists N$, such that $\forall n \geq N,\ |x - x_n| < \epsilon$. Hence

$$|x_n - x_m| \leq |x_n - x| + |x - x_m| \leq 2\epsilon$$

when $n, m \geq N$. Thus, x_n is a Cauchy sequence. □

Lemma. *If x_n is Cauchy, then x_n is bounded.*

Proof. If the sequence is $x_1, x_2, x_3, \ldots$, $\epsilon > 0$ and N is such that $|x_n - x_m| < \epsilon$ if $n, m > N$, then for any fixed $m > N$, the entire sequence is contained in the closed ball of center x_m and radius $\max\{d(x_m, x_1), d(x_m, x_2), \ldots, d(x_m, x_N), \epsilon\}$. □

Lemma. *If x_n is Cauchy and $x_{n_k} \to x$, then $x_n \to x$.*

Proof. Let $\epsilon > 0$. Since x_n is Cauchy $\Rightarrow$ choose $k > 0$ so large that $|x_n - x_m| < \epsilon$ whenever $n, m \geq k$. Since $x_{n_k} \to x \Rightarrow$ choose $l > 0$ so large (i.e. n_l large) that $|x_{n_j} - x| < \epsilon$ whenever $j \geq l$. Set $N = \max(k, n_l)$. If $m, n_j > N$, then

$$|x_m - x| \leq |x_m - x_{n_j}| + |x_{n_j} - x| < \epsilon + \epsilon = 2\epsilon.$$

□

Theorem. $[a, b]$ *is complete.*

Proof. Let x_n be a Cauchy sequence in $[a, b]$. Let x_{n_k} be a monotone subsequence. Since $a \leq x_{n_k} \leq b$, x_{n_k} converges (by the Least Upper Bound). $\Rightarrow$ $x_{n_k} \to c$. Since $[a, b]$ is closed, $c \in [a, b]$. $\Rightarrow$ Any x_n that is Cauchy in $[a, b]$, converges in $[a, b]$. $\Rightarrow$ $[a, b]$ is complete. □

The above theorem is a specific case of the following Lemma:

Theorem. *Let x_n be a Cauchy sequence in a compact metric space X. Then x_n converges to some point of X.*

Proof. Since X is (sequentially) compact, then for any sequence $x_n \in X$, there is a subsequence $x_{n_k} \to c,\ c \in X$. Using the above theorem (x_n Cauchy and $x_{n_k} \to c \Rightarrow x_n \to c$), we see that $x_n \to c \in X$. □

Theorem. $\mathbb{R}$ *is complete.*

Proof. Let x_n be a Cauchy sequence in $\mathbb{R}$. x_n is bounded (by the Lemma above). $\Rightarrow$ $\{x_n\} \subseteq [a, b]$, and see above. □

A direct consequence of the above theorem is the following: In $\mathbb{R}^k$, every Cauchy sequence converges.

Theorem. $[0, 1)$ *is **not** complete.*

Bolzano-Weierstrass. *Every **bounded**, infinite subset $S \subset \mathbb{R}$ has a limit point.*

Proof. If I_0 is a closed interval containing S, denote by I_1 one of the closed half-intervals of I_0 that contains infinitely many points of S. Continuing in this way, we define a nested sequence of intervals $\{I_n\}$, each of which contains infinitely many points of S. If $c = \bigcap_{n=1}^{\infty} I_n$, then it is clear that c is a limit point of S. $\square$

Lemma. *Every **bounded** sequence of $\mathbb{R}$ has a convergent subsequence.*

Proof. If a sequence x_n contains only finitely many distinct points, the conclusion is trivial and obvious. Otherwise we are dealing with a bounded infinite set, to which the Bolzano-Weierstrass theorem applies, giving us a limit point x. If, for each integer $k \geq 1$, x_{n_k} is a point of the sequence such that $|x_{n_k} - x| \leq 1/k$, then it is clear that x_{n_k} is a convergent subsequence. $\square$

Theorem. *A closed subspace Y of a complete metrix space X is complete.*

Proof. Let y_n be a Cauchy sequence in Y. Then y_n is also a Cauchy sequence in X. Since X is complete, $\exists\, x \in X$ such that $y_n \to x$ in X. Since Y is closed, $x \in Y$. Consequently, $y_n \to x$ in Y. $\square$

Theorem. *A complete subspace Y of a metric space X is closed in X.*

Proof. Suppose $x \in X$ is a limit point of Y. $\exists y_n$ in Y that converges to x. y_n is a Cauchy sequence in X; hence it is also a Cauchy sequence in Y. Since Y is complete, $y_n \to y \in Y$. Since limits of sequences are unique, $y = x$ and x belongs to Y. Hence Y is closed. $\square$

Theorem. *V is a normed space. If we have the following implication*

$$\sum_{n=1}^{\infty} ||v_n|| < \infty \quad \Rightarrow \quad \sum_{n=1}^{\infty} v_n < \infty,$$

then V is complete (V is a Banach space).

Proof. Say v_n is Cauchy. Choose n_k such that $m, n \geq n_k \;\Rightarrow\; ||v_m - v_n|| < 2^{-k}$. We may assume that $n_1 < n_2 < \ldots$.
$||v_{n_{k+1}} - v_{\underline{n_k}}|| < 2^{-k} \;\Rightarrow\; \sum_{k=1}^{\infty} ||v_{n_{k+1}} - v_{n_k}|| < \infty$. It follows that $\sum_{n=1}^{\infty} (v_{n_{k+1}} - v_{n_k}) < \infty$.

$$s \leftarrow s_K = \sum_{k=1}^{K} (v_{n_{k+1}} - v_{n_k}) = v_{n_{K+1}} - v_{n_1} \quad \Rightarrow \quad v_{n_{k+1}} \text{ converges} \quad \Rightarrow \quad v_n \text{ converges.}$$

$\square$

6 Compactness

M is **(sequentially) compact** if for any sequence $x_n \in M$, there is a subsequence $x_{n_k} \to c,\ \ c \in M$.
M is **(topologically) compact** if any open cover of M, $M \subseteq \bigcup G_\alpha,\ G_\alpha$ open, contains a finite subcover.

Problem (W'02, #2). *$[a, b]$ is* ***compact****.*

Proof. Let x_n be a sequence in $[a, b]$. Let x_{n_k} be a monotone subsequence $\Rightarrow\ a \leq x_{n_k} \leq b \ \Rightarrow\ x_{n_k} \to c$. Since $[a, b]$ is closed, $c \in [a, b]$. $\Rightarrow$ $[a, b]$ is (sequentially) compact. ☐

Lemma. *If M is compact, every open cover of M has a countable subcover.*

Theorem. *If M is* ***sequentially compact****, then it is* ***topologically compact****.*

Proof. Say that $M \subseteq G_1 \bigcup G_2 \bigcup \cdots$ has a countable subcover. Need to show that there is a finite subcover, i.e. $M \subseteq \bigcup_{k=1}^{n} G_k$ for some n.
Suppose that fails for every n; then for every $n = 1, 2, \ldots$, there would exist

$$x_n \in M \setminus \bigcup_{k=1}^{n} G_k.$$

That sequence would have a convergent subsequence $\{x_{n_k}\}$. Let x be its limit, $x_{n_k} \to x$. Then x would be contained in G_m for some m, and thus

$$x_{n_k} \in G_m$$

for all n_k sufficiently large, which is impossible for $n_k > m$ (since $x_{n_k} \in M \backslash G_1 \bigcup \cdots \bigcup G_{n_k}$). We have reached a contradiction. So there must be a finite subcovering. ☐

Problem (S'02, #3). *If M is* ***topologically compact****, then it is* ***sequentially compact****.*

Proof. Let $x_n \in M$ and E be the range of $\{x_n\}$. If E is *finite*, then there is $x \in E$ and a sequence $\{n_i\}$, with $n_1 < n_2 < \ldots$, such that

$$x_{n_1} = x_{n_2} = \cdots = x$$

The subsequence $\{x_{n_i}\}$ converges to x.

If E is *infinite*, E has a limit point x in M (as an infinite subset of a compact set). Every neighborhood of x contains infinitely many points of M. For each k, $B_{\frac{1}{k}}(x)$ contains infinitely many x_n's. Select one and call it x_{n_k}, such that, $n_k > n_{k-1} > \ldots$. We have a subsequence $\{x_{n_k}\}$ so that $d(x, x_{n_k}) < \frac{1}{k} \to 0.\ \Rightarrow\ x_{n_k} \to x.$ ☐

Problem (F'02, #1). *Let K be a compact subset and F be a closed subset in the metric space X. Suppose $K \bigcap F = \phi$. Prove that*

$$0 < \inf\{d(x, y) : x \in K, y \in F\}.$$

Proof. Given $x \in K, x \notin F,\ \ d_x = d(x, F) > 0$. Then, the ball centered at that x with radius $d_x/2$, i.e. $B_{\frac{d_x}{2}}(x)$, satisfies $B_{\frac{d_x}{2}}(x) \bigcap F = \phi$. Since x was taken arbitrary, this is true $\forall x \in K, x \notin F$.
$K \subset \bigcup_{x \in K} B_{\frac{d_x}{2}}(x)$. Since K is compact, $\exists x_1, \ldots, x_n \in K,\ n < \infty$, such that
$K \subset \bigcup_{k=1}^{n} B_{\frac{d_x}{2}}(x_k)$, and $B_{\frac{d_{x_k}}{2}}(x_k) \bigcap F = \phi$. Since $\min_k\{d_{x_k}\} > 0$, we have
$0 < \inf\{d(x, y) : x \in K, y \in F\}$. ☐

7 Continuity

Limits of Functions: $lim_{x\to p} f(x) = q$ if:
$\forall \epsilon > 0$, $\exists\, \delta$ such that $\forall x \in E \;\; 0 < |x-p| < \delta \Rightarrow |f(x) - q| < \epsilon$.
A function f is **continuous** at p: $lim_{x\to p} f(x) = f(p)$ if:
$\forall \epsilon > 0$, $\exists\, \delta$ such that $\forall x \in E \; |x-p| < \delta \Rightarrow |f(x) - f(p)| < \epsilon$.
Negation: f is **not** continuous at p if:
$\exists\, \epsilon > 0$, $\forall \delta$ such that $\exists x \in E \; |x-p| < \delta \Rightarrow |f(x) - f(p)| > \epsilon$.
f is **uniformly continuous** on X if:
$\forall \epsilon > 0$, $\exists\, \delta$ such that $\forall x, z \in X \; |x-z| < \delta \Rightarrow |f(x) - f(z)| < \epsilon$.
Negation: f is **not** uniformly continuous on X if:
$\exists\, \epsilon > 0$, $\forall \delta$ such that $\exists x, z \in X \; |x-z| < \delta \Rightarrow |f(x) - f(z)| > \epsilon$.
Examples: $f(x) = \frac{1}{x}$ on $(0, 1]$ and $f(x) = x^2$ on $[1, \infty)$ are **not** uniformly continuous.

Theorem. *$f : X \to Y$ is continuous $\Leftrightarrow$ $f^{-1}(V)$ is open in X for every open set V in Y.*

Proof. [7] $\Rightarrow$ Suppose f is continuous on X. Let V be an open set in Y. We have to show that every point of $f^{-1}(V)$ is an interior point of $f^{-1}(V)$. Let $x \in f^{-1}(V)$. Choose ϵ such that $B_\epsilon(f(x)) \subset V$. Since f is continuous[8], $\exists\, \delta > 0$ such that $f(B_\delta(x)) \subset B_\epsilon(f(x)) \subset V$. Hence, $B_\delta(x) \subseteq f^{-1}(V)$. Since $f^{-1}(V)$ contains an open ball about each of its points, $f^{-1}(V)$ is open.

$\Leftarrow$ Suppose $f^{-1}(V)$ is open in X for every open set V in Y. Let $x \in X$ and let $\epsilon > 0$. Then $f^{-1}(B_\epsilon(f(x)))$ is open in X. Hence, $\exists\, \delta$ such that $B_\delta(x) \subset f^{-1}(B_\epsilon(f(x)))$. Applying f, we obtain $f(B_\delta(x)) \subset B_\epsilon(f(x))$, and so f is continuous. $\square$

Problem (S'02, #4; S'03, #1). *A function $f : (0, 1) \to \mathbb{R}$ is the restriction to $(0, 1)$ of a continuous function $F : [0, 1] \to \mathbb{R}$ $\Leftrightarrow$ f is uniformly continuous on $(0, 1)$.*

Proof. $\Leftarrow$ We show that if $f : (0, 1) \to \mathbb{R}$ is uniformly continuous, then there is a continuous $F : [0, 1] \to \mathbb{R}$ with $F(x) = f(x)$ for all $x \in (0, 1)$.

Let x_n be a sequence in $(0, 1)$ converging to 0. Since f is uniformly continuous, given $\epsilon > 0$, $\exists \delta$, s.t. $|x - y| < \delta \Rightarrow |f(x) - f(y)| < \epsilon$. Therefore, we have

$$|f(x_n) - f(x_m)| < \epsilon$$

for n, m large enough. $f(x_n)$ is a Cauchy sequence, so it converges to some ξ. Define $F(0) = \lim_{n\to\infty} f(x_n) = \xi$. We want to show that this limit is well defined. Let y_n be another sequence, s.t. $y_n \to 0$, so $f(y_n)$ is Cauchy by the same argument. Since the sequence $(f(x_1), f(y_1), f(x_2), f(y_2), \ldots)$ is Cauchy by still the same argument, and that there is a subsequence $f(x_n) \to \xi$, then the entire sequence converges to ξ. Thus, $F(0) = \lim_{n\to\infty} f(x_n) = \xi$ is well defined.

By the same set of arguments, $F(1) = \eta$. The function $F : [0, 1] \to \mathbb{R}$ given by

$$F(x) = \begin{cases} f(x) & \text{for } x \in (0, 1), \\ \xi & \text{for } x = 0, \\ \eta & \text{for } x = 1. \end{cases}$$

is the unique continuous extension of f to $[0, 1]$.

$\Rightarrow$ $F : [0, 1] \to \mathbb{R}$ is continuous, and $[0, 1]$ is compact. Therefore, F is uniformly continuous on $[0, 1]$. Thus, $f = F|_{(0,1)} : (0, 1) \to \mathbb{R}$ is uniformly continuous. $\square$

[7] Gamelin, Green, p. 26; Edwards, p. 51.
[8] f continuous at $x \;\Rightarrow\; \forall \epsilon > 0, \exists\, \delta$ such that $z \in B_\delta(x) \Rightarrow f(z) \in B_\epsilon(f(x))$, or $f(B_\delta(x)) \subset B_\epsilon(f(x))$.

7.1 Continuity and Compactness

Theorem. *Let $f : X \to Y$ is continuous, where X is compact. Then $f(X)$ is compact.*

Proof. 1) Let $\{V_\alpha\}$ be an open cover of $f(X)$, $(V_\alpha \subset Y)$. Since f is continuous, $f^{-1}(V_\alpha)$ is open. Since X is compact, there are finitely many $\alpha_1, \ldots, \alpha_n$, such that

$$X \subset f^{-1}(V_{\alpha_1}) \bigcup \ldots \bigcup f^{-1}(V_{\alpha_n}).$$

Since $f(f^{-1}(E)) \subset E$ for every $E \subset Y$, then

$$f(X) \subset V_{\alpha_1} \bigcup \ldots \bigcup V_{\alpha_n}.$$

$\Rightarrow \quad f(X)$ is compact. □

Proof. 2) Let $\{y_n\}$ be a sequence in the image of f. Thus we can find $x_n \in X$, such that $y_n = f(x_n)$. Since X is compact the sequence $\{x_n\}$ has a convergent subsequence $\{x_{n_k}\}$ with limit $s \in X$. Since f is continuous,

$$\lim_{k\to\infty} y_{n_k} = \lim_{k\to\infty} f(x_{n_k}) = f(s)$$

Hence, the given sequence $\{y_n\}$ has a convergent subsequence which converges in $f(X)$.
$\Rightarrow \quad f(X)$ is compact. □

Problem (F'01, #1). *Let $K \subset \mathbb{R}$ be compact and $f(x)$ continuous on K. Then f has a maximum on K (i.e. there exists $x_0 \in K$, such that $f(x) \le f(x_0)$ for all $x \in K$).*

Proof. By theorem above, the image $f(K)$ is closed and bounded. Let b be its least upper bound. Then b is adherent to $f(K)$. Since $f(K)$ is closed $\Rightarrow$ $b \in f(K)$, that is $\exists x_0 \in K$, such that $b = f(x_0)$, and thus $f(x_0) \ge f(x)$, $\forall x \in K$. □

Theorem. *Let $f : [a, b] \to \mathbb{R}$ be continuous function. Then:*
1) f is bounded;
2) f assumes its max and min values;
3) $f(a) < p < f(b) \quad \Rightarrow \quad \exists x : f(x) = p$.

Proof. 1) f is continuous $\Rightarrow$ $f([a, b])$ is compact $\Rightarrow$ $f([a, b])$ is closed and bounded.
2) $\phi \ne f([a, b]) \le M$. Let $M_0 = \sup f([a, b]) \;\Rightarrow\; M_0 \in \mathit{closure}(f([a, b])) = f([a, b]) \;\Rightarrow$ $\exists x_0 \in [a, b] : \; f(x_0) = M_0$.
3) $[a, b]$ is connected $\Rightarrow$ $f([a, b])$ is connected $\Rightarrow$ $f([a, b])$ is an interval. □

Theorem. *$f : X \to Y$ **continuous** and X **compact**. Then f is uniformly continuous.*

Proof. [9] Suppose that f is not uniformly continuous. Then there exist $\epsilon > 0$ and (setting $\delta = 1/k$ in the definition) points $x_k, z_k \in X$ [10] such that $|x_k - z_k| < 1/k$ while $|f(x_k) - f(z_k)| \ge \epsilon$. Passing to a subsequence, we can assume that $x_k \to x \in X$.[11] Since $|x_k - z_k| \to 0$, we also obtain $z_k \to x$. Since f is continuous, $f(x_k) \to f(x)$ and $f(z_k) \to f(x)$, so that $|f(x_k) - f(z_k)| \le |f(x_k) - f(x)| + |f(x) - f(z_k)| \to 0$, a contradiction. □

[9] Gamelin, Green, p. 26-27; Rudin, p. 91.
[10] See the technique of negation in the beginning of the section.
[11] Since $\{x_k\}$ is Cauchy, and the convergent subsequence can be constructed, $x_k \to x$.

8 Sequences and Series of Functions

8.1 Pointwise and Uniform Convergence

Suppose $\{f_n\}$, $n = 1, 2, 3, \ldots$, is a sequence of functions defined on a set E, and suppose that the sequence of numbers $\{f_n(x)\}$ converges $\forall x \in E$. Define a function f by

$$f(x) = \lim_{n\to\infty} f_n(x), \qquad (x \in E).$$

$\{f_n\}$ **converges pointwise** to f on E.

A sequence of functions $\{f_n\}$ **converges uniformly** on E to f if $\forall \epsilon > 0$, $\exists N$, such that $\forall n \geq N$,

$$|f_n(x) - f(x)| \leq \epsilon, \qquad \forall x \in E.$$

Example: Consider $f(x) = x^n$ on $[0, 1]$ $\Rightarrow$ convergent, but not uniformly convergent on $[0, 1]$.

Problem (F'01, #3). *If $\{f_n\}$ is a sequence of continuous functions on E, and if $f_n \to f$ uniformly on E, then f is continuous on E.*

Proof. Fix $\epsilon > 0$. Since $f_n \to f$ uniformly, choose N, s.t. $\forall n \geq N$

$$|f_n(x) - f(x)| < \frac{\epsilon}{3}, \qquad \forall x \in E$$

Since f_n is continuous at p, choose δ, s.t. $x \in E$, $|x - p| < \delta$ then

$$|f_n(x) - f_n(p)| < \frac{\epsilon}{3}, \qquad n \geq N$$

Thus, $|f(x) - f(p)| \leq |f(x) - f_n(x)| + |f_n(x) - f_n(p)| + |f_n(p) - f(p)| < \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3} = \epsilon$. Hence, given any ϵ, $\exists\delta$, s.t. $|x - p| < \delta \Rightarrow |f(x) - f(p)| < \epsilon$, and f is continuous at p. $\square$

8.2 Normed Vector Spaces

Problem (F'03, #7). $C^0[a, b]$ *with the metric* $d(f, g) \equiv \sup_{x\in[0,1]} |f(x) - g(x)|$ $= ||f - g||_\infty$ *is complete.*

Proof. Let $\{\varphi_n\}_1^\infty$ be a Cauchy sequence of elements of $C^0[a, b]$. Given $\epsilon > 0$, choose N such that $m, n \geq N$ $\Rightarrow$

$$||\varphi_m - \varphi_n||_\infty < \frac{\epsilon}{2} \qquad \text{(sup norm)}.$$

Then, in particular, $||\varphi_m(x) - \varphi_n(x)||_\infty < \epsilon/2$ for each $x \in [a, b]$. Therefore $\{\varphi_n(x)\}_1^\infty$ is a Cauchy sequence of real numbers, and hence converges to some real number $\varphi(x)$. It remains to show that the sequence of functions $\{\varphi_n\}$ converges uniformly to φ; if so, it will imply that φ is continuous on $[a, b]$, i.e. $\varphi \in C^0[a, b]$.
Claim: For $n \geq N$, (N same as above, n fixed), $|\varphi(x) - \varphi_n(x)| < \epsilon$ for all $x \in [a, b]$.
To see this, choose $m \geq N$ sufficiently large (depending on x) s.t. $|\varphi(x) - \varphi_m(x)| < \epsilon/2$.
$\Rightarrow$ $|\varphi(x) - \varphi_n(x)| \leq |\varphi(x) - \varphi_m(x)| + |\varphi_m(x) - \varphi_n(x)| < \epsilon/2 + ||\varphi_m - \varphi_n|| < \epsilon/2 + \epsilon/2 = \epsilon$.
Since $x \in [a, b]$ was arbitrary, it follows that $||\varphi_n - \varphi|| < \epsilon$ as desired. $\square$

Theorem. *Let $\{f_n\} \in C^1[a,b]$, $f_n \to f$ pointwise, $f_n' \to g$ uniformly. Then $f_n \to f$ uniformly, and f is differentiable, with $f' = g$.*

Proof. By the Fundamental Theorem of Calculus, we have

$$f_n(x) = f_n(a) + \int_a^x f_n' \qquad \forall n,\ \forall x \in [a,b].$$

From this and the Uniform Convergence and Integration theorem, we obtain

$$\begin{aligned} f(x) &= \lim_{n\to\infty} f_n(x) = \lim_{n\to\infty} f_n(a) + \lim_{n\to\infty} \int_a^x f_n', \\ f(x) &= f(a) + \int_a^x g. \end{aligned}$$

Another application of the Fundamental Theorem yields $f' = g$ as desired.
To see that convergence of $f_n \to f$ is uniform, note that

$$\begin{aligned} |f_n(x) - f(x)| &= \Big| \int_a^x f_n' - \int_a^x g \Big| + |f_n(a) - f(a)| \le \int_a^x |f_n' - g| + |f_n(a) - f(a)| \\ &\le (b-a)||f_n' - g||_\infty + |f_n(a) - f(a)|. \end{aligned}$$

The uniform convergence of f_n therefore follows from that of f_n'. □

Theorem. $C^1[a,b]$, *with the C^1-norm defined by*

$$||\varphi|| = \max_{x\in[a,b]} |\varphi(x)| + \max_{x\in[a,b]} |\varphi'(x)|,$$

is complete.

Proof. Let $\{\varphi_n\}_1^\infty$ be a Cauchy sequence of elements of $C^1[a,b]$. Since

$$\max_{x\in[a,b]} |\varphi_m(x) - \varphi_n(x)| \le ||\varphi_m - \varphi_n|| \qquad (C^1 - \text{norm}),$$

φ_n is a uniformly Cauchy sequence of continuous functions. Thus $\varphi_n \to \varphi \in C^0[a,b]$ uniformly. Similarly, since

$$\max_{x\in[a,b]} |\varphi_m'(x) - \varphi_n'(x)| \le ||\varphi_m - \varphi_n|| \qquad (C^1 - \text{norm}),$$

$\varphi_n' \to \psi \in C^0[a,b]$ uniformly. By the above theorem, φ is differentiable with $\varphi' = \psi$, so $\varphi \in C^1[a,b]$. Since

$$\begin{aligned} \max_{x\in[a,b]} |\varphi_n(x) - \varphi(x)| &= ||\varphi_n - \varphi||_\infty \qquad \text{(sup norm)}, \quad \text{and} \\ \max_{x\in[a,b]} |\varphi_n'(x) - \varphi'(x)| &= ||\varphi_n' - \varphi'||_\infty \qquad \text{(sup norm)} \end{aligned}$$

the uniform convergence of φ_n and φ_n' implies that $\varphi_n \to \varphi$ with respect to the C^1-norm of $C^1[a,b]$. Thus every Cauchy sequence in $C^1[a,b]$ converges. □

8.3 Equicontinuity

A family F of functions f defined on a set $E \subset X$ is **equicontinuous** on E if:
$\forall \epsilon > 0$, $\exists\, \delta$, such that $|x - y| < \delta,\ x, y \in E,\ f \in F \quad \Rightarrow \quad |f(x) - f(y)| < \epsilon$.

8.3.1 Arzela-Ascoli Theorem

Suppose $\{f_n(x)\}_{n=1}^{\infty}$ is **uniformly bounded** and **equicontinuous** sequence of functions defined on a **compact** subset K of X. Then $\{f_n\}$ is precompact, i.e. the closure of $\{f_n\}$ is compact, i.e. $\{f_n\}$ contains a **uniformly convergent subsequence**, i.e. $\{f_n\}$ contains a subsequence $\{f_{n_k}\}$ that converges uniformly on K to a function $f \in X$.

9 Connectedness

9.1 Relative Topology

Define the neighborhood of a point in $\mathbb{R}^n$ as $N_\epsilon(x) = \{y : |x - y| < \epsilon\}$. Consider the subset of $\mathbb{R}^n$, $M \subseteq \mathbb{R}^n$. If all we are interested in are just points in M, it would be more natural to define a neighborhood of a point $x \in M$ as $N_{M,\epsilon} = \{y \in M : |x - y| < \epsilon\}$. Thus, the relative neighborhood is just a restriction of the neighborhood in $\mathbb{R}^n$ to M. Relative interior points and relative boundary points of a set, as well as a relative open set and a relative closed set, can be defined accordingly.

Alternative definitions:
$S \subseteq M(\subseteq \mathbb{R}^n)$ is open relative to M if there is an open set U in $\mathbb{R}^n$ such that $S = U \bigcap M$.
$S \subseteq M(\subseteq \mathbb{R}^n)$ is closed relative to M if there is a closed set V in $\mathbb{R}^n$ such that $S = V \bigcap M$.
Example: A set $S = [1, 4)$ is open relative to $M = [1, 10] \subseteq \mathbb{R}$ since for the open set $U = (0, 4)$ in $\mathbb{R}$, we have $S = U \bigcap M$.
Example: A set $S = [1, 3]$ is open relative to $M = [1, 3] \bigcup [4, 6] \subseteq \mathbb{R}$ since for the open set $U = (0, 4)$ in $\mathbb{R}$, we have $S = U \bigcap M$.

9.2 Connectedness

X is **connected** if it cannot be expressed as a disjoint[12] union of two nonempty subsets that are both open and closed. i.e.
M is connected if $M = A \bigcup B$, such that A, B open and $A \bigcap B = \phi$, then A or B is empty; or, M is connected if $M = A \bigsqcup B$, A, B open $\Rightarrow A = \phi$ or $B = \phi$.

Fact: X is connected $\Leftrightarrow$ X and ϕ are the only subsets which are clopen.

X is **disconnected** if there are closed and open subsets A and B of X such that $A \bigcup B = X$, $A \bigcap B = \phi$, $A \neq \phi$, $B \neq \phi$.

Another way of phrasing: X is disconnected if there is a closed and open $U \subset X$, such that $U \neq \phi$ and $U \neq X$. If there is such a U, then the complement $V = X \setminus U$ of U is also both closed and open and X is the disjoint union of the nonempty sets U and V.

A subset of a space is a *connected subset* if it is connected in the relative topology.

[12] $A \bigcap B = \phi$, then A and B are **disjoint**.

Problem (S'02, #1). *The closed interval $[a, b]$ is **connected**.*

Proof. Let $[a, b] = G \bigcup H$, s.t. $G \bigcap H = \phi$. Let $b \in H$. Then claim: $G = \phi$. If not, let $c = \sup G$. Since G is closed, $c \in G$. Since G is open[13], $B_\epsilon(c) \subseteq G$, i.e. $[c, c+\epsilon) \subset G$. That contradicts $c = \sup G$. Thus $G = \phi$. $\square$

Note: Since $[a, b)$ and (a, b) can be expressed as the union of an increasing sequence of compact intervals, these are also connected.

Theorem. *Let $S_\alpha \subseteq M$, S_α connected. Suppose $\bigcap S_\alpha \neq \phi$. Then $\bigcup S_\alpha$ is connected.*

Proof. Let $S = \bigcup S_\alpha = G \bigsqcup H$, G, H are open in $\bigcup S_\alpha$.
Choose $x_0 \in \bigcap S_\alpha$. $S_\alpha = (S_\alpha \bigcap G) \bigsqcup (S_\alpha \bigcap H)$. Assume $x_0 \in G$. Since S_α is connected and $x_0 \in S_\alpha \bigcap G$, we get $S_\alpha \bigcap H = \phi$, $\forall \alpha$. Therefore, $(\bigcup S_\alpha) \bigcap H = \phi$. Since $H \subseteq \bigcup S_\alpha$ $\Rightarrow$ $H = \phi$. Therefore, S is connected. $\square$

Corollary. *$\mathbb{R}$ is **connected**.*

Proof. Let $\mathbb{R} = \bigcup_{n \in \mathbb{N}} [-n, n]$, $\quad 0 \in \bigcap [-n, n]$. Therefore, $\mathbb{R}$ is the union of connected subsets. By the theorem above, $\mathbb{R}$ is connected. $\square$

Theorem. *Let $f : M \to N$ is continuous and M is connected. Then $f(M)$ is connected.*

Proof. Say $f(M) = G \bigsqcup H$, $\;G, H \neq \phi$. $\;G, H$ open. Then $M = f^{-1}(G) \bigcup f^{-1}(H)$, where $f^{-1}(G)$ and $f^{-1}(H)$ are both open and nonempty. Contradicts connectedness of M. $\square$

Theorem. *$a, b \in I$, and $a < c < b$, then $c \in I$, i.e. I is an interval $\Leftrightarrow$ $I \subseteq \mathbb{R}$ is connected.*

Proof. $\Rightarrow$ Assume I an interval.
$S = [a, b]$; $\;S = (a, b]$, $a \geq -\infty$; $\;S = [a, b)$, $b \leq \infty$; $\;S = (a, b)$, $a \geq -\infty$, $b \leq \infty$.
$[a, b) = \bigcup_{n \geq n_0} [a, b - \frac{1}{n}]$. $\;a \in \bigcap [a, b - \frac{1}{n}]$.
$\Leftarrow$ Say I is not an interval. $\exists a < c < b$, $a, b \in I$, $c \notin I$. $I = ((-\infty, c) \bigcap I) \bigsqcup ((c, \infty) \bigcap I)$, i.e. I is not connected. $\square$

Problem (W'02, #3). *The open unit ball in $\mathbb{R}^2$, $\{(x, y) \in \mathbb{R}^2 : x^2 + y^2 < 1\}$ is connected.*

Proof. Let $f_\theta(t) = t(\cos\theta, \sin\theta)$, $\;-1 < t < 1$. We have $f_\theta : (-1, 1) \to (t\cos\theta, t\sin\theta)$. Since f_θ is continuous and $(-1, 1)$ is connected, $f_\theta((-1, 1))$ is connected. The unit ball can be expressed as $\{(x, y) \in \mathbb{R}^2 : x^2 + y^2 < 1\} = \bigcup_{0 \leq \theta < \pi} f_\theta(t)$. We know that the origin is contained in the intersection of f_θ's. Therefore, $\bigcup_{0 \leq \theta < \pi} f_\theta(t)$ is connected by the theorem above. $\square$

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[13] If $M = G \bigcup H$, $G \bigcap H = \phi$ and G, H are open, then G is closed and open, since $G = H^c$.
$M = [0, 1] \bigcup [2, 3]$ is not connected because if $G = [0, 1]$, $H = [2, 3]$, $M = G \bigcup H$, G, H are clopen in M, $G \bigcap H = \phi$, and $G, H \neq \phi$.

9.3 Path Connectedness

A **path** in X from x_0 to x_1 is a continuous function $\gamma : [0,1] \to X$, such that $\gamma(0) = x_0$ and $\gamma(1) = x_1$.

X is **path-connected** if, for every pair of points x_0 and x_1 in X, there is a path γ from x_0 to x_1.

Theorem. *A path-connected space is connected.*

Proof. Fix $x_0 \in X$. For each $x \in X$, let $\gamma_x : [0,1] \to X$ be a path from x_0 to x. By theorems above, i.e.
(1) X connected and $f : X \to Y$ continuous $\Rightarrow$ $f(X)$ connected;
(2) any interval in $\mathbb{R}$ is connected;
each $\gamma_x([0,1])$ is a connected subset of X. Each $\gamma_x([0,1])$ contains x_0 and $X = \bigcup\{\gamma_x([0,1]) : x \in X\}$, so that the theorem above shows that X is connected. $\square$

Theorem. *An open subset of $\mathbb{R}^n$ is connected $\Leftrightarrow$ it is path-connected.*

Problem. *Any subinterval of $\mathbb{R}$ (closed, open, or semiopen) is path-connected.*

Proof. If a, b belong to an interval (of any kind), then $\gamma(t) = (1-t)a + tb,\ 0 \le t \le 1$, defines a path from a to b in the interval. $\square$

Problem. *If X is path-connected and $f : X \to Y$ is a map, then $f(X)$ is path-connected.*

Proof. If $p = f(x)$ and $q = f(y)$, and γ is a path in X from p to q, then $f \circ \gamma$ is a path in $f(X)$ from x to y. $\square$

10 Baire Category Theorem

A subset $T \subset X$ is **dense** in X if $\overline{T} = X$, i.e. every point of X is a limit point of T, or a point of T, or both.
A subset $Y \subset X$ is **nowhere dense** if $\overline{Y}$ has no interior points, i.e. $int(\overline{Y}) = \phi$.
Y is nowhere dense $\Leftrightarrow$ $X \setminus \overline{Y}$ is a dense open subset of X.
The **interior** of E is the largest open set in E, i.e. the set of all interior points of E.
$\overline{\mathbb{Q}} = \mathbb{R}$, $\overline{(\mathbb{R} \setminus \mathbb{Q})} = \mathbb{R}$.
$[0,1] \bigcap \mathbb{Q}$ is **not** closed; $(0,1) \bigcap \mathbb{Q}$ is **not** open in $\mathbb{R}$.

Baire's Category Theorem. *Let $\{U_n\}_{n=1}^{\infty}$ be a sequence of dense open subsets of a complete metric space X. Then $\bigcap_{n=1}^{\infty} U_n$ is also dense in X. (Any countable intersection of dense open sets in a complete metric space is dense.)*

Corollary. *Let $\{E_n\}_{n=1}^{\infty}$ be a sequence of nowhere dense subsets of a complete metric space X. Then $\bigcup_{n=1}^{\infty} E_n$ has empty interior. (In a complete metric space, no nonempty open subset can be expressed as a union of countable collection of nowhere dense sets.)*

Proof. We apply the Baire Category Theorem to the dense open sets $U_n = X \setminus \overline{E}_n$. Then, $\bigcap_{n=1}^{\infty} U_n$ is dense in X.

$$\bigcap_{n=1}^{\infty} U_n = \bigcap_{n=1}^{\infty} (X \setminus \overline{E}_n) = X \setminus \bigcup_{n=1}^{\infty} \overline{E}_n$$

Therefore, $X \setminus \bigcup_{n=1}^{\infty} \overline{E}_n$ is dense, $\Rightarrow$ $\bigcup_{n=1}^{\infty} E_n$ is nowhere dense $\Rightarrow$ $\bigcup_{n=1}^{\infty} E_n$ has empty interior. $\square$

A subset of X is of the **first category** (i.e. $\mathbb{Q}$) if it is the countable union of nowhere dense subsets. A subset (i.e. $\mathbb{I}, \mathbb{R}$) that is not of the first category is said to be of the **second category**.
$S \subseteq \mathbb{R}$ is $\mathbf{F}_\sigma$ set if $S = \bigcup_{n=1}^{\infty} F_n$, F_n closed.
$S \subseteq \mathbb{R}$ is $\mathbf{G}_\delta$ set if $S = \bigcap_{n=1}^{\infty} G_n$, G_n open.

Problem (W'02, #4). *The set of irrational numbers $\mathbb{I}$ in $\mathbb{R}$ is **not** the countable union of closed sets (not an F_σ set).*

Proof. Suppose $\mathbb{I} = \bigcup F_n$, where each F_n is closed.

$$\mathbb{R} = \bigcup_{n \in \mathbb{N}} F_n \bigcup_{q \in \mathbb{Q}} \{q\}$$

Thus $\mathbb{R}$ can be expressed as the countable union of closed sets. By (corollary to) the Baire Category Theorem, since $\mathbb{R}$ is a nonempty open subset, one of these closed sets has a nonempty interior. It cannot be one of q's, and since any nonempty interval contains rational numbers, it cannot be one of F_n's. Contradiction. $\square$

Problem (S'02, #2; F'02, #3). *The set $\mathbb{Q}$ of rational numbers is **not** the countable intersection of open sets of $\mathbb{R}$ (not a G_δ set).*
*Show that there is a subset of $\mathbb{R}$ which is **not** the countable intersection of open subsets.*

Proof. We take complements in the preceding theorem. Suppose $\mathbb{Q} = \bigcap G_n$, where each G_n open. Then,

$$\mathbb{I} = \mathbb{R} \setminus \mathbb{Q} = \mathbb{R} \setminus (\bigcap_{n \in \mathbb{N}} G_n) = \bigcup_{n \in \mathbb{N}} (\mathbb{R} \setminus G_n),$$

and $\mathbb{R} \setminus G_n$ is closed. Thus, $\mathbb{I}$ is a F_σ set, which contradicts the previous theorem. $\square$

Problem (S'03, #3). *Find $S \subset \mathbb{R}$ such that both (i) and (ii) hold for S:*
*(i) S is **not** the countable union of closed sets (not F_σ);*
*(ii) S is **not** the countable intersection of open sets (not G_δ).*

Proof. Let $\mathbf{A} \subseteq [\mathbf{0}, \mathbf{1}]$ **not** $\mathbf{F}_\sigma$, $\mathbf{B} \subseteq [\mathbf{2}, \mathbf{3}]$ **not** $\mathbf{G}_\delta$ $\Rightarrow$ $\mathbf{A} \bigcup \mathbf{B}$ **is neither** $\mathbf{F}_\sigma$ **nor** $\mathbf{G}_\delta$.
If $A \bigcup B$ is F_σ, say $A \bigcup B = \bigcup \underbrace{F_n}_{closed} \quad \Rightarrow$

$$A = A \bigcup B \bigcap [0,1] = \bigcup F_n \bigcap [0,1] = \bigcup \underbrace{(F_n \bigcap [0,1])}_{closed} \equiv F_\sigma \text{ set } \Rightarrow \text{contradiction.}$$

If $A \bigcup B$ is G_δ, say $A \bigcup B = \bigcap \underbrace{G_n}_{open} \quad \Rightarrow$

$$B = A \bigcup B \bigcap (\frac{3}{2}, \frac{7}{2}) = \bigcap G_n \bigcap (\frac{3}{2}, \frac{7}{2}) = \bigcap \underbrace{(G_n \bigcap (\frac{3}{2}, \frac{7}{2}))}_{open} \equiv G_\delta \text{ set } \Rightarrow \text{contradiction.}$$

□

Problem. $\mathbb{Q}$ *is **not** open, is **not** closed, but **is** the countable union of closed sets (F_σ set).*

Proof. Since any neighborhood $(q - \epsilon, q + \epsilon)$ of a rational q contains irrationals, $\mathbb{Q}$ has no inner points. $\Rightarrow$ $\mathbb{Q}$ is **not** open. Since every irrational number i is the limit of a sequence of rationals $\Rightarrow$ $\mathbb{Q}$ is **not** closed. Since every one-point-set $\{x\} \subset \mathbb{R}$ is closed and $\mathbb{Q}$ is countable, say (q_n) is a sequence of all rational numbers, we find that

$$\mathbb{Q} = \bigcup_{n \in \mathbb{N}} \{q_n\}$$

is the countable union of closed sets, i.e. $\mathbb{Q}$ is F_σ. □

Problem. *The set of isolated points of a countable complete metric space X forms a dense subset of X.*

Proof. For each point $x \in X$ that is *not* an isolated point of X, define $U_x = X \setminus \{x\}$. Each such U_x is open and dense in X, and the intersection of the U_x's consists precisely of the isolated points of X. By the Baire Category Theorem, the intersection of the U_x's is dense in X. □

Problem. *Suppose that F is a subset of the first category in a metric space X and E is a subset of F. Prove that E is of the first category in X. Show by an example that E may not be of the first category in the metric space F.*

Proof. If $F = \bigcup F_n$, where each F_n is nowhere dense, then $E = \bigcup (E \bigcap F_n)$, and each $E \bigcap F_n$ is nowhere dense. For example, note the $\mathbb{R}$ is of first category in $\mathbb{R}^2$, but $\mathbb{R}$ is not of first category in itself. □

Problem. *Any countable union of sets of the first category in X is again of the first category in X.*

Proof. A countable union of countable unions is a countable union. □

Problem. *a) If $a, b \in \mathbb{R}$ satisfy $a < b$, then there exists a rational number $q \in (a, b)$.*
b) The set $\mathbb{Q}$ of rational numbers is dense in $\mathbb{R}$.

Problem. *The set of irrational numbers is dense in $\mathbb{R}$.*

Proof. If i is any irrational number, and if q is rational, then $q + i/n$ is irrational, and $q + i/n \to q$. □

Problem. *Regard the rational numbers $\mathbb{Q}$ as a subspace of $\mathbb{R}$. Does the metric space $\mathbb{Q}$ have any isolated points?*

Proof. The rationals have no isolated points. This does not contradict the above, i.e. *"The set of isolated points of countable complete metric space X forms dense subset of X"*
because the rationals are not complete. □

Problem. *Every open subset of $\mathbb{R}$ is a union of disjoint open intervals (finite, semi-infinite, or infinite).*

Proof. For each $x \in U$, let I_x be the union of all open intervals containing x that are contained in U. Show that each I_x is an open interval (possibly infinite or semi-infinite), any two I_x's either coincide or are disjoint, and the union of the I_x's is U. □

11 Integration

11.1 Riemann Integral

Let $[a, b]$ be a given interval. A **partition** P of $[a, b]$ is a finite set of points $x_0, \ldots, x_n$:

$$a = x_0 < x_1 < \ldots < x_{n-1} < x_n = b, \qquad \triangle x_i = x_i - x_{i-1}.$$

A *Riemann sum for f correspoding to the given partition* is

$$S(P, f) = \sum_{i=1}^{n} f(x_i^{'})\triangle x_i, \qquad x_{i-1} \leq x_i^{'} \leq x_i.$$

Definition: f is *Riemann integrable on* $[a, b]$, if $\exists A \in \mathbb{R}$ such that:
$\forall \epsilon > 0,\ \exists\, \delta > 0$ such that whenever S is a Riemann sum for f corresponding to any partition of $[a, b]$ with $\max(\triangle x_i) < \delta \quad \Rightarrow \quad |S - A| < \epsilon$.
In this case A is called the *Riemann integral of f between a and b and is denoted as* $\int_a^b f\, dx$.
Alternative Definition: f is *Riemann integrable on* $[a, b]$ if:
$\forall \epsilon > 0,\ \exists P$ such that $U(P, f) - L(P, f) < \epsilon$.

If f is bounded, there exist m and M, such that $m \leq f(x) \leq M,\ a \leq x \leq b$. Hence, for every P,

$$m(b - a) \leq S(P, f) \leq M(b - a),$$

so that $S(P, f)$ is bounded. This shows that Riemann sums are defined for every bounded function f.

11.2 Existence of Riemann Integral

Theorem. *f is integrable on $[a,b]$ $\Leftrightarrow$ $\forall \epsilon > 0$, $\exists\, \delta > 0$ such that $S_1(P,f)$, $S_2(P,f)$, P with $\max(\triangle x_i) < \delta$, then $|S_1 - S_2| < \epsilon$.*

Proof. $\Rightarrow$ Suppose f is integrable on $[a,b]$. $\forall \epsilon > 0$, $\exists\, \delta > 0$ such that $S(P,f)$, P with $\max(\triangle x_i) < \delta$, then $|S - \int_a^b f(x)dx| < \epsilon/2$. For such S_1 and S_2,

$$|S_1 - S_2| = \left|\left(S_1 - \int_a^b f(x)dx\right) - \left(S_2 - \int_a^b f(x)dx\right)\right| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

$\Leftarrow$ $\forall \epsilon > 0$, $\exists\, \delta > 0$ such that $S_1(P,f)$, $S_2(P,F)$, P with $\max(\triangle x_i) < \delta \Rightarrow |S_1 - S_2| < \epsilon$.
For $n = 1, 2, \ldots$, choose $S^{(n)}(P,f)$, P with $\max(\triangle x_i) < 1/n$. Then,
$\forall \epsilon > 0$, $\exists\, N > 0$ ($\delta = 1/N$), such that $|S^{(n)} - S^{(m)}| < \epsilon$, $n, m \geq N$ $\Rightarrow$ $S^{(n)}$ is a Cauchy sequence of real numbers $\Rightarrow$ $S^{(n)}$ converges to some $A \in \mathbb{R}$ $\Rightarrow$ $|S^{(N)} - A| < \epsilon$, $1/N < \delta$.
Thus for any $S(P,f)$, P with $\max(\triangle x_i) < \delta$, we have
$|S - A| \leq |S - S^{(N)}| + |S^{(N)} - A| < 2\epsilon$. $\square$

Theorem. *If f is continuous on $[a,b]$ then f is integrable on $[a,b]$.*

Proof. Since f is uniformly continuous on $[a,b]$, $\forall \epsilon > 0$, $\exists\, \delta > 0$ such that $\forall x, z \in [a,b]$, $|x - z| < \delta$ $\Rightarrow$ $|f(x) - f(z)| < \epsilon$ $\circledast$. If P is any partition of $[a,b]$ with $\max(\triangle x_i) < \delta$, then $\circledast$ implies that $M_i - m_i \leq \epsilon$, $i = 1, \ldots, n$, and therefore

$$U(P,f) - L(P,f) = \sum_{i=1}^n (M_i - m_i)\triangle x_i \leq \epsilon \sum_{i=1}^n \triangle x_i = \epsilon(b-a).$$

Thus, $\forall \epsilon > 0$, $\exists P$ such that $|U(P,f) - L(P,f)| < C\epsilon$ $\Rightarrow$ f is integrable. $\square$

11.3 Fundamental Theorem of Calculus

Theorem. *If $f : [a,b] \to \mathbb{R}$ is continuous, and $F : [a,b] \to \mathbb{R}$ is defined by*

$$F(x) = \int_a^x f(t)dt,$$

then F is differentiable and $F' = f$.

Proof. Since f is continuous, $F(x) = \int_a^x f(t)dt$ is defined for all $x \in [a,b]$. We have to show that for any fixed $x_0 \in [a,b]$

$$\lim_{x \to x_0} \frac{F(x) - F(x_0)}{x - x_0} = f(x_0).$$

For any $x \in [a,b]$, $x \neq x_0$, we have

$$\left|\frac{F(x) - F(x_0)}{x - x_0} - f(x_0)\right| = \left|\frac{\int_a^x f(t)dt - \int_a^{x_0} f(t)dt}{x - x_0} - f(x_0)\right| = \left|\frac{\int_{x_0}^x f(t)dt}{x - x_0} - f(x_0)\right|$$

$$= \left|\frac{\int_{x_0}^x f(t)dt}{x - x_0} - \frac{\int_{x_0}^x f(x_0)dt}{x - x_0}\right| = \left|\frac{\int_{x_0}^x (f(t) - f(x_0))dt}{x - x_0}\right| \leq \frac{\int_{x_0}^x |f(t) - f(x_0)|dt}{|x - x_0|} \quad \Rightarrow \quad \circledast$$

Since f is continuous at x_0, given $\epsilon > 0$, $\exists \delta$, such that $x \in [a,b]$, $|x - x_0| < \delta$ $\Rightarrow$ $|f(x) - f(x_0)| < \epsilon$. Then for any t between x and x_0, we have $|f(t) - f(x_0)| < \epsilon$.

$$\Rightarrow \quad \circledast \quad < \frac{\int_{x_0}^x \epsilon \, dt}{|x - x_0|} = \epsilon.$$

Thus $F'(x_0) = f(x_0)$. $\square$

Corollary. *If $f : [a, b] \to \mathbb{R}$ is continuous and $F' = f$ on $[a, b]$, then*

$$\int_a^b f(t)dt = F(b) - F(a).$$

Proof. Since $\frac{d}{dx}(\int_a^x f(t)dt - F(x)) = f(x) - f(x) = 0$, $\int_a^x f(t)dt - F(x)$ is constant. Thus $\int_a^x f(t)dt = F(x) + c$, for some $c \in \mathbb{R}$. In particular, $0 = \int_a^a f(t)dt = F(a) + c$, so that $c = -F(a)$. Therefore, $\int_a^x f(t)dt = F(x) - F(a)$. Hence, $\int_a^b f(t)dt = F(b) - F(a)$. □

Integration by Parts. *Suppose f and g are differentiable functions on $[a, b]$, $f', g' \in \mathfrak{R}$. Then*

$$\int_a^b f(x)g'(x)dx = f(b)g(b) - f(a)g(a) - \int_a^b f'(x)g(x)dx.$$

Proof. Let $h(x) = f(x)g(x)$ and apply the Fundamental Theorem of Calculus to h and its derivative.

$$\begin{aligned} \int_a^b h'(x)dx &= h(b) - h(a) \\ \int_a^b (f'(x)g(x) + f(x)g'(x))dx &= f(b)g(b) - f(a)g(a). \end{aligned}$$

Note that $h' \in \mathfrak{R}$. □

Mean Value Theorem for Integrals. *If $f : [a, b] \to \mathbb{R}$ is continuous, then $\int_a^b f(x)dx = f(c)(b - a)$ for some $c \in [a, b]$.*

Proof. Since f is continuous, by the Fundamental Theorem of Calculus, there is a function $F : [a, b] \to \mathbb{R}$ such that $F'(x) = f(x)$ for $x \in (a, b)$, and $\int_a^b f(x)dx = F(b) - F(a)$.
By the Mean Value Theorem for Differentiation, $\exists c \in (a, b)$ such that $F(b) - F(a) = F'(c)(b - a)$. Thus,

$$\int_a^b f(x)dx \underbrace{=}_{FTC} F(b) - F(a) \underbrace{=}_{MVT} F'(c)(b - a) \underbrace{=}_{FTC} f(c)(b - a).$$

Thus, $\exists c \in (a, b)$ such that $\int_a^b f(x)dx = f(c)(b - a)$. □

Generalized Mean Value Theorem for Integrals. *If $f, g : [a, b] \to \mathbb{R}$ are continuous and $g(x) > 0$ for all $x \in [a, b]$, then there exists $c \in [a, b]$ such that*

$$\int_a^b f(x)g(x)dx = f(c)\int_a^b g(x)dx.$$

Proof. Since $g(x) > 0$ for all $x \in [a, b]$ and since g is continuous, $\int_a^b g(x) > 0$.
Suppose $f(x)$ attains its maximum M at x_2 and minimum m at x_1.
Then $m = f(x_1) \leq f(x) \leq f(x_2) = M$ for $x \in [a, b]$, and

$$m\int_a^b g(x)dx \leq \int_a^b f(x)g(x)dx \leq M\int_a^b g(x)dx,$$

and hence

$$m \leq \frac{\int_a^b f(x)g(x)dx}{\int_a^b g(x)dx} \leq M.$$

Since f is continuous on compact $[a, b]$, $\exists c$ such that $f(c) = \frac{\int_a^b f(x)g(x)dx}{\int_a^b g(x)dx}$. □

Uniform Convergence and Integration. *Let $\{f_n\}$ be a sequence of continuous functions on $[a,b]$ and $f_n \to f$ uniformly on $[a,b]$. Then*

$$\int_a^b \underbrace{\lim_{n\to\infty} f_n(x)}_{f(x)}\,dx = \lim_{n\to\infty}\int_a^b f_n(x)dx.$$

Proof. Let $f = \lim_{n\to\infty} f_n$. Since each f_n is continuous and $f_n \to f$ uniformly $\Rightarrow$ f is continuous. In particular, f is integrable on $[a,b]$. By the definition of uniform convergence, $\forall\epsilon > 0, \exists N > 0$ such that $n > N$, $|f(x) - f_n(x)| < \epsilon/(b-a)$, $\forall x \in [a,b]$. Thus,

$$-\frac{\epsilon}{b-a} \le f(x) - f_n(x) \le \frac{\epsilon}{b-a}, \qquad \forall x \in [a,b] \quad \Rightarrow$$

$$\Rightarrow \quad -\epsilon \le \int_a^b (f(x) - f_n(x))dx \le \epsilon$$

$$\text{or} \quad \left|\int_a^b f(x)dx - \int_a^b f_n(x)dx\right| \le \epsilon.$$

The last inequality holds for all $n > N$, and therefore, $\lim_{n\to\infty}\int_a^b f_n(x)dx = \int_a^b f(x)dx$. □

Uniform Convergence and Differentiation. *Let $\{f_n\}$ be a sequence of differentiable functions on $[a,b]$ such that $\{f_n(x_0)\}$ converges for some $x_0 \in [a,b]$. If $f_n' \to f'$ uniformly, then $f_n \to f$ uniformly on $[a,b]$, and*

$$\Big(\lim_{n\to\infty} f_n\Big)' = \lim_{n\to\infty} f_n'$$

Proof. See the section on "Sequences and Series of Functions: Normed Vector Spaces" where the weaker statement is proved, i.e. $\{f_n\} \in C^1$, $f_n \to f$ pointwise on $[a,b]$. □

12 Differentiation

12.1 $\mathbb{R} \to \mathbb{R}$

12.1.1 The Derivative of a Real Function

Let $f : (a, b) \to \mathbb{R}$, $x_0 \in (a, b)$. f is **differentiable** at x_0 if

$$f'(x_0) = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0}$$

exists. f' is the **derivative** of f.

Theorem. *$f : (a, b) \to \mathbb{R}$. f is differentiable at x_0 $\Rightarrow$ f is continuous at x_0.*

Proof.

$$\lim_{x \to x_0} (f(x) - f(x_0)) = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0} \cdot \lim_{x \to x_0} (x - x_0) = f'(x_0) \cdot 0 = 0.$$

Since $\lim_{x \to x_0} f(x) = f(x_0)$, f is continuous at x_0. □

Lemma. *If $f'(c) > 0$, then f is locally strictly increasing at c, i.e., $\exists \delta > 0$ such that:*
$c - \delta < x < c \quad \Rightarrow \quad f(x) < f(c)$,
$c < x < c + \delta \quad \Rightarrow \quad f(c) < f(x)$.

Proof. $\lim_{x \to c} \frac{f(x) - f(c)}{x - c} > 0 \;\Rightarrow\; \exists \delta > 0$: $\frac{f(x) - f(c)}{x - c} > 0$ whenever $0 < |x - c| < \delta$.
Thus since $f(x) - f(c) = \frac{f(x) - f(c)}{x - c}(x - c)$, $(x \neq c)$, we have
$c - \delta < x < c \quad \Rightarrow \quad f(x) - f(c) < 0$,
$c < x < c + \delta \quad \Rightarrow \quad f(x) - f(c) > 0$. □

Corollary. *If f has a max (or a min) at $c \in (a, b)$, i.e. $f(x) \leq f(c)$ (or $f(x) \geq f(c)$) for all x, then $f'(c) = 0$.*

Proof. Say $f'(c) \neq 0$. Say $f'(c) > 0$. Then $x > c \;\Rightarrow\; f(x) \leq f(c)$ (since f has a max at c), contradicting the lemma above. Proofs of other conditions are similar. □

12.1.2 Rolle's Theorem

Theorem. *Let f be continuous on $[a, b]$, differentiable on (a, b), and $f(a) = f(b)$. Then $\exists c \in (a, b) :\; f'(c) = 0$.*

Proof. Let $M = \sup\{f(x) : x \in [a, b]\}$, $m = \inf\{f(x) : x \in [a, b]\}$.
Then $m \leq f(a) = f(b) \leq M$. If $M = m \;\Rightarrow\; f(x) = f(a), \forall x \;\Rightarrow\; f'(c) = 0, \forall c \in (a, b)$.
Say $f(a) = f(b) < M$ $\circledast$. Then choose $c \in [a, b] : f(c) = M$. From $\circledast$, $c \in (a, b)$. We have from corollary, $f'(c) = 0$.
Similarly, say $m < f(a) = f(b)$ $\circledcirc$. Then choose $c \in [a, b] : f(c) = m$. From $\circledcirc$, $c \in (a, b)$. We have from corollary, $f'(c) = 0$. □

12.1.3 Mean Value Theorem

Theorem. *Let f be continuous on $[a, b]$, differentiable on (a, b). Then $\exists c \in (a, b)$:*

$$f'(c) = \frac{f(b) - f(a)}{b - a}.$$

Proof. Let $g(x) = f(x) - \frac{f(b)-f(a)}{b-a}(x-a)$. Then $g(a) = g(b) = f(a)$. By Rolle's Theorem, $\exists c \in (a,b)$, such that $0 = g'(c) = f'(c) - \frac{f(b)-f(a)}{b-a}$. □

Corollary. *Let f be continuous on $[a,b]$, differentiable on (a,b).*
a) $f'(x) = 0$, $\forall x \in (a,b) \;\Rightarrow\; f$ is constant.
b) $f'(x) > 0$, $\forall x \in (a,b) \;\Rightarrow\; f$ is strictly increasing.

Proof. b) $a \le x_1 < x_2 \le b$. By mean value theorem, $f(x_2) - f(x_1) = f'(c)(x_2 - x_1)$ for some $c \in (x_1, x_2)$. Therefore, $f(x_2) - f(x_1) > 0$ for all such x_1, x_2. Proof of a) is similar. □

12.2 $\mathbb{R} \to \mathbb{R}^{\mathbf{m}}$

$f : \mathbb{R} \to \mathbb{R}^m$ is **differentiable** at $c \in \mathbb{R}$ if there exists a linear map $L : \mathbb{R} \to \mathbb{R}^m$ such that

$$\lim_{h \to 0} \frac{||f(c+h) - f(c) - L(h)||}{||h||} = 0.$$

in which case L is defined by $L = df_c = f'(c) = \begin{bmatrix} f_1'(c) \\ \vdots \\ f_m'(c) \end{bmatrix}$.

The linear mapping $df_c : \mathbb{R} \to \mathbb{R}^m$ is called the *differential* of f at c. The matrix of the linear mapping $f'(c)$ is the *derivative*. The differential is the linear mapping whose matrix is the derivative.

12.3 $\mathbb{R}^{\mathbf{n}} \to \mathbb{R}^{\mathbf{m}}$

Let $U \subseteq \mathbb{R}^n$ open, $\mathbf{c} \in U$. $f : U \to \mathbb{R}^m$ is **differentiable** at $\mathbf{c}$ if there exists a linear map $L : \mathbb{R}^n \to \mathbb{R}^m$ such that

$$\lim_{\mathbf{h} \to \mathbf{0}} \frac{||f(\mathbf{c}+\mathbf{h}) - f(\mathbf{c}) - L(\mathbf{h})||}{||\mathbf{h}||} = 0.$$

in which case L is defined by

$$L = df_c = f'(c) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \cdot & \cdots & \cdot \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}_{x=c}$$

Let $\mathbf{v} \in \mathbb{R}^n$, $\mathbf{c} \in G \subseteq \mathbb{R}^n$. The **directional derivative** with respect to $\mathbf{v}$ of f at $\mathbf{c}$ is

$$D_{\mathbf{v}} f(\mathbf{c}) = \lim_{t \to 0} \frac{f(\mathbf{c} + t\mathbf{v}) - f(\mathbf{c})}{t}$$

provided that the limit exists. In particular, the **partial derivatives** of f at $\mathbf{c}$ are

$$\frac{\partial f}{\partial x_j}(\mathbf{c}) = D_{\mathbf{e_j}} f(\mathbf{c}) = \lim_{t \to 0} \frac{f(\mathbf{c} + t\mathbf{e_j}) - f(\mathbf{c})}{t} = \lim_{t \to 0} \frac{f(c_1, \ldots, c_j + t, \ldots, c_n) - f(c_1, \ldots, c_j, \ldots, c_n)}{t}$$

Theorem. *Let f be differentiable at $\mathbf{c}$ (i.e., $df_c : \mathbb{R}^n \to \mathbb{R}^m$ is defined). Then:*
a)[14] *The directional derivative $D_{\mathbf{v}}f(\mathbf{c})$ exists $\forall \mathbf{v} \in \mathbb{R}^n$, and $D_{\mathbf{v}}f(\mathbf{c}) = df_c(\mathbf{v})$ $(= f'(\mathbf{c})\mathbf{v})$.*
b)[15] *The matrix $f'(\mathbf{c})$ of df_c is $df_c = f'(\mathbf{c}) = [\frac{\partial f_i}{\partial x_j}(\mathbf{c})]$.*

Proof. **a)** Since f is differentiable, and letting $\mathbf{h} = t\mathbf{v}$,

$$\lim_{t\to 0} \frac{||f(\mathbf{c}+t\mathbf{v}) - f(\mathbf{c}) - df_c(t\mathbf{v})||}{||t\mathbf{v}||} = 0,$$

$$\frac{1}{||\mathbf{v}||}\Big[\lim_{t\to 0}\Big|\Big|\frac{f(\mathbf{c}+t\mathbf{v}) - f(\mathbf{c})}{t} - df_c(\mathbf{v})\Big|\Big|\Big] = 0,$$

$$\lim_{t\to 0} \frac{f(\mathbf{c}+t\mathbf{v}) - f(\mathbf{c})}{t} = df_c(\mathbf{v}).$$

i.e. $D_{\mathbf{v}}f(\mathbf{c})$ exists, and equals to $df_c(\mathbf{v})$. $\square$

Proof. **b)** $df_c = \begin{bmatrix} \uparrow & & \uparrow \\ df_c(\mathbf{e_1}) & \cdots & df_c(\mathbf{e_n}) \\ \downarrow & & \downarrow \end{bmatrix} = \begin{bmatrix} \uparrow & & \uparrow \\ D_{\mathbf{e_1}}f(\mathbf{c}) & \cdots & D_{\mathbf{e_n}}f(\mathbf{c}) \\ \downarrow & & \downarrow \end{bmatrix} = \begin{bmatrix} \uparrow & & \uparrow \\ \frac{\partial f}{\partial x_1}(\mathbf{c}) & \cdots & \frac{\partial f}{\partial x_n}(\mathbf{c}) \\ \downarrow & & \downarrow \end{bmatrix} = \Big[\frac{\partial f_i}{\partial x_j}(\mathbf{c})\Big]_{m\times n}$. $\square$

$f : \mathbb{R}^n \to \mathbb{R}^m$ is said to be **continuously differentiable** at $\mathbf{c}$ if the partial derivatives $\frac{\partial f_i}{\partial x_j}$ exist on $B_\epsilon(\mathbf{c})$, and are continuous at $\mathbf{c}$.

[14]Edwards, Theorem 2.1
[15]Edwards, Theorem 2.4

Theorem[16]**.** *If $\frac{\partial f_i}{\partial x_j}$ exist and are continuous on G, then at each $\mathbf{c} \in G$,*

$$df_c = f'(\mathbf{c}) = \Big[\frac{\partial f_i}{\partial x_j}(\mathbf{c})\Big]. \qquad (i.e.\ \frac{\partial f_i}{\partial x_j}\ continuous\ \Rightarrow\ f\ differentiable).$$

Proof. Since $f : \mathbb{R}^n \to \mathbb{R}^m$ is differentiable at $\mathbf{c}$ iff each of its component functions $f_1, \ldots, f_m$ is, we may assume $m = 1$; $f : U \to \mathbb{R}$. Given $\mathbf{h} = (h_1, \ldots, h_n)$, let $\mathbf{h_0} = (0, \ldots, 0)$, $\mathbf{h_j} = (h_1, \ldots, h_j, 0, \ldots, 0)$, $j = 1, \ldots, n$. We have

$$f(\mathbf{c}+\mathbf{h}) - f(\mathbf{c}) = \sum_{j=1}^{n}[f(\mathbf{c}+\mathbf{h}_j) - f(\mathbf{c}+\mathbf{h}_{j-1})].$$

$$\begin{aligned} f(\mathbf{c}+\mathbf{h}_j) - f(\mathbf{c}+\mathbf{h}_{j-1}) &= f(c_1+h_1, \ldots, c_{j-1}+h_{j-1}, \underline{c_j+h_j}, c_{j+1}, \ldots, c_n) \\ &- f(c_1+h_1, \ldots, c_{j-1}+h_{j-1}, \underline{c_j}, c_{j+1}, \ldots, c_n) \\ &= \frac{\partial f}{\partial x_j}(c_1+h_1, \ldots, c_{j-1}+h_{j-1}, \underline{c_j+t}, c_{j+1}, \ldots, c_n) \cdot h_j \end{aligned}$$

for some $0 \le t \le h_j$, by mean-value theorem. Thus

$$f(\mathbf{c}+\mathbf{h}_j) - f(\mathbf{c}+\mathbf{h}_{j-1}) = \frac{\partial f}{\partial x_j}(\mathbf{d_j}) \cdot h_j, \qquad \text{for some } \mathbf{d_j},\ ||\mathbf{d_j} - \mathbf{c}|| \le \mathbf{h}.$$

$$\Rightarrow \quad f(\mathbf{c}+\mathbf{h}) - f(\mathbf{c}) = \sum_{j=1}^{n} \frac{\partial f}{\partial x_j}(\mathbf{d_j}) \cdot h_j$$

Also considering $f'(\mathbf{c}) \cdot \mathbf{h} = \begin{bmatrix} \frac{\partial f}{\partial x_1}(c) & \cdots & \frac{\partial f}{\partial x_n}(c) \end{bmatrix} \begin{bmatrix} h_1 \\ \vdots \\ h_n \end{bmatrix}$, we have

$$\begin{aligned} \lim_{\mathbf{h}\to\mathbf{0}} \frac{|f(\mathbf{c}+\mathbf{h}) - f(\mathbf{c}) - f'(\mathbf{c})\cdot\mathbf{h})|}{||\mathbf{h}||} &= \lim_{\mathbf{h}\to\mathbf{0}} \frac{\big|\sum_{j=1}^{n}\big[\frac{\partial f}{\partial x_j}(\mathbf{d_j}) - \frac{\partial f}{\partial x_j}(\mathbf{c})\big]h_j\big|}{||\mathbf{h}||} \\ &\le \lim_{\mathbf{h}\to\mathbf{0}} \sum_{j=1}^{n} \Big|\frac{\partial f}{\partial x_j}(\mathbf{d_j}) - \frac{\partial f}{\partial x_j}(\mathbf{c})\Big| = 0, \end{aligned}$$

since each $\mathbf{d_j} \to \mathbf{c}$ as $\mathbf{h} \to \mathbf{0}$, and each $\frac{\partial f}{\partial x_j}$ is continuous at $\mathbf{c}$. □

[16] Edwards, Theorem 2.5

12.3.1 Chain Rule

Theorem. *$U \subset \mathbb{R}^n$, $V \subset \mathbb{R}^m$. If the mappings $F : U \to \mathbb{R}^m$ and $G : V \to \mathbb{R}^k$ are differentiable at $\mathbf{a} \in U$ and $F(\mathbf{a}) \in V$ respectively, then their composition $H = G \circ F$ is differentiable at $\mathbf{a}$, and*

$$dH_{\mathbf{a}} = dG_{F(\mathbf{a})} \circ dF_{\mathbf{a}} \qquad \textit{(composition of linear mappings)}$$

In terms of derivatives

$$H'(\mathbf{a}) = G'(F(\mathbf{a})) \cdot F'(\mathbf{a}) \qquad \textit{(matrix multiplication)}$$

The differential of the composition is the composition of the differentials;
the derivative of the composition is the product of the derivatives.

Proof. We must show that

$$\lim_{\mathbf{h}\to\mathbf{0}} \frac{H(\mathbf{a}+\mathbf{h}) - H(\mathbf{a}) - dG_{F(\mathbf{a})} \circ dF_{\mathbf{a}}(\mathbf{h})}{||\mathbf{h}||} = \mathbf{0}. \qquad \text{Define}$$

$$\varphi(\mathbf{h}) = \frac{F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a}) - dF_{\mathbf{a}}(\mathbf{h})}{||\mathbf{h}||} \quad \Rightarrow \quad F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a}) = dF_{\mathbf{a}}(\mathbf{h}) + ||\mathbf{h}||\tilde{\varphi}(\mathbf{h}) \quad \text{and} \tag{12.1}$$

$$\psi(\mathbf{k}) = \frac{G(F(\mathbf{a})+\mathbf{k}) - G(F(\mathbf{a})) - dG_{F(\mathbf{a})}(\mathbf{k})}{||\mathbf{k}||} \quad \Rightarrow \quad G(F(\mathbf{a})+\mathbf{k}) - G(F(\mathbf{a})) = dG_{F(\mathbf{a})}(\mathbf{k}) + ||\mathbf{k}||\tilde{\psi}(\mathbf{k}) \tag{12.2}$$

The fact that F and G are differentiable at $\mathbf{a}$ and $F(\mathbf{a})$, respectively, implies that

$$\lim_{\mathbf{h}\to\mathbf{0}} \varphi(\mathbf{h}) = \lim_{\mathbf{k}\to\mathbf{0}} \psi(\mathbf{k}) = \mathbf{0}. \qquad \text{Then}$$

$$\begin{aligned}
H(\mathbf{a}+\mathbf{h}) - H(\mathbf{a}) &= G(F(\mathbf{a}+\mathbf{h})) - G(F(\mathbf{a})) = G(F(\mathbf{a}) + (F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a}))) - G(F(\mathbf{a})) \\
= {}_{[\mathbf{k}=F(\mathbf{a}+\mathbf{h})-F(\mathbf{a}) \ in \ (12.2)]} &= dG_{F(\mathbf{a})}(F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a})) + ||F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a})|| \cdot \tilde{\psi}(F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a})) \\
&= (12.1) = dG_{F(\mathbf{a})}(dF_{\mathbf{a}}(\mathbf{h}) + ||\mathbf{h}||\varphi(\mathbf{h})) + \Big|\Big|dF_{\mathbf{a}}(\mathbf{h}) + ||\mathbf{h}||\varphi(\mathbf{h})\Big|\Big| \cdot \tilde{\psi}(F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a})) \\
&= dG_{F(\mathbf{a})} \circ dF_{\mathbf{a}}(\mathbf{h}) + ||\mathbf{h}|| dG_{F(\mathbf{a})}(\varphi(\mathbf{h})) + ||\mathbf{h}|| \Big|\Big|dF_{\mathbf{a}}(\frac{\mathbf{h}}{||\mathbf{h}||}) + \varphi(\mathbf{h})\Big|\Big| \cdot \tilde{\psi}(F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a}))
\end{aligned}$$

$$\Rightarrow \quad \frac{H(\mathbf{a}+\mathbf{h}) - H(\mathbf{a}) - dG_{F(\mathbf{a})} \circ dF_{\mathbf{a}}(\mathbf{h})}{||\mathbf{h}||} = dG_{F(\mathbf{a})}(\varphi(\mathbf{h})) + \Big|\Big|dF_{\mathbf{a}}(\frac{\mathbf{h}}{||\mathbf{h}||}) + \varphi(\mathbf{h})\Big|\Big| \cdot \tilde{\psi}(F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a}))$$

$dG_{F(\mathbf{a})}$ is linear $\Rightarrow$ continuous, and $\lim_{\mathbf{h}\to\mathbf{0}} \varphi(\mathbf{h}) = \mathbf{0} \quad \Rightarrow \quad \lim_{\mathbf{h}\to\mathbf{0}} dG_{F(\mathbf{a})}(\varphi(\mathbf{h})) = \mathbf{0}$.
Since F is continuous at $\mathbf{a}$ and $\lim_{\mathbf{k}\to\mathbf{0}} \psi(\mathbf{k}) = \mathbf{0} \quad \Rightarrow \quad \lim_{\mathbf{h}\to\mathbf{0}} \tilde{\psi}(F(\mathbf{a}+\mathbf{h}) - F(\mathbf{a})) = \mathbf{0}$.
$dF_{\mathbf{a}}$ is linear $\Rightarrow$ continuous $\Rightarrow$ bounded $\Rightarrow \exists M, ||dF_{\mathbf{a}}(\mathbf{x})|| \leq M||\mathbf{x}||$.
Therefore, the limit of the entire expression above $\to \mathbf{0} \ \Rightarrow \ dH_{\mathbf{a}} = dG_{F(\mathbf{a})} \circ dF_{\mathbf{a}}$. $\square$

Theorem. *Let $U \subseteq \mathbb{R}^n$ be open and connected. $F : U \to \mathbb{R}^m$. $F'(\mathbf{x}) = \mathbf{0}$ for all $\mathbf{x} \in U$ $\Leftrightarrow$ F is constant.*

Proof. Since F is constant $\Leftrightarrow$ each of its component functions is constant,
and the matrix $F'(\mathbf{x}) = \mathbf{0} \Leftrightarrow$ each of its rows is $\mathbf{0}$, we may assume $F = f : U \to \mathbb{R}$.
Suppose $f'(\mathbf{x}) = \nabla f(\mathbf{x}) = \mathbf{0}$, $\forall \mathbf{x} \in U$.
Given $\mathbf{a}$ and $\mathbf{b} \in U$, let $\gamma : \mathbb{R} \to U$ be a differentiable mapping with $\gamma(0) = \mathbf{a}$, $\gamma(1) = \mathbf{b}$.
$\mathbb{R} \to_\gamma \mathbb{R}^n \to_f \mathbb{R}$
If $g = f \circ \gamma : \mathbb{R} \to \mathbb{R}$, then

$$g'(t) = \nabla f(\gamma(t)) \cdot \gamma'(t) = 0$$

$\forall t \in \mathbb{R} \Rightarrow g$ is constant on $[0,1]$, so $f(\mathbf{a}) = f(\gamma(0)) = g(0) = g(1) = f(\gamma(1)) = f(\mathbf{b})$. □

Example 1. $w = w(x,y),\ x = x(r,\theta),\ y = y(r,\theta)$

$$\begin{bmatrix} \frac{\partial w}{\partial r} & \frac{\partial w}{\partial \theta} \end{bmatrix} = \begin{bmatrix} \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} \end{bmatrix} \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} \end{bmatrix} = \begin{bmatrix} \frac{\partial w}{\partial r} & \frac{\partial w}{\partial \theta} \end{bmatrix} \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{bmatrix}^{-1}$$

Example 2. $f(x,y,z) = 0,\ \frac{\partial f}{\partial z} \neq 0 \ \Rightarrow \ z = h(x,y),\ f(x,y,h(x,y)) \equiv 0.$
For example, can solve for $\frac{\partial z}{\partial x}$: $0 = \frac{\partial}{\partial x} f(x,y,h(x,y)) = \frac{\partial f}{\partial x}\frac{\partial x}{\partial x} + \frac{\partial f}{\partial y}\frac{\partial y}{\partial x} + \frac{\partial f}{\partial z}\frac{\partial z}{\partial x} = \frac{\partial f}{\partial x} + \frac{\partial f}{\partial z}\frac{\partial z}{\partial x}$.
$\Rightarrow \ \frac{\partial z}{\partial x} = -\frac{\partial f}{\partial x} / \frac{\partial f}{\partial z}$.
Similarly, can solve for $\frac{\partial y}{\partial z}$ and $\frac{\partial x}{\partial y}$, from $\frac{\partial}{\partial z} f(x, y(x,z), z)$ and $\frac{\partial}{\partial y} f(x(y,z), y, z)$, respectively, and show $\frac{\partial x}{\partial y}\frac{\partial y}{\partial z}\frac{\partial z}{\partial x} = -1$.

12.3.2 Mean Value Theorem

Theorem. *Let $f : U \subseteq \mathbb{R}^n \to \mathbb{R}$ be differentiable, and $\mathbf{a}$ and $\mathbf{b} \in U$, such that $[\mathbf{a}, \mathbf{b}] \subseteq U$. Then $\exists \mathbf{c} \in (\mathbf{a}, \mathbf{b})$, such that*

$$f(\mathbf{b}) - f(\mathbf{a}) = \nabla f(\mathbf{c}) \cdot (\mathbf{b} - \mathbf{a}).$$

Proof. Define $\gamma : [0,1] \to [\mathbf{a}, \mathbf{b}]$ as $\gamma(t) = \mathbf{a} + t(\mathbf{b} - \mathbf{a}) = (1-t)\mathbf{a} + t\mathbf{b}, \quad t \in [0,1]$.
Then $\gamma'(t) = \mathbf{b} - \mathbf{a}$. Let $g = f \circ \gamma$. $\mathbb{R} \to_\gamma \mathbb{R}^n \to_f \mathbb{R}$
Since $g : [0,1] \to \mathbb{R}$, then by single-variable MVT, $\exists \xi \in [0,1]$, such that $g(1) - g(0) = g'(\xi)$. If $\mathbf{c} = \gamma(\xi)$, then

$$f(\mathbf{b}) - f(\mathbf{a}) = f(\gamma(1)) - f(\gamma(0)) = g(1) - g(0) = g'(\xi) =$$

$$=_{Chain\ Rule} = \nabla f(\gamma(\xi)) \cdot \gamma'(\xi) = \nabla f(\mathbf{c}) \cdot (\mathbf{b} - \mathbf{a}).$$ □

12.3.3 $\frac{\partial}{\partial x}(\frac{\partial f}{\partial y}) = \frac{\partial}{\partial y}(\frac{\partial f}{\partial x})$

Theorem. *Let $f : U \subseteq \mathbb{R}^n \to \mathbb{R}$. If $f, \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}$ exist and are* ***continuous*** *on U and $\frac{\partial^2 f}{\partial x \partial y}, \frac{\partial^2 f}{\partial y \partial x}$ exist on U and are* ***continuous*** *at a, then*

$$\frac{\partial}{\partial x}\Big(\frac{\partial f}{\partial y}\Big) = \frac{\partial}{\partial y}\Big(\frac{\partial f}{\partial x}\Big) \qquad \textit{on } U.$$

Proof. Consider $S_h(x,y) = f(x+h, y+h) - f(x+h, y) - f(x, y+h) + f(x,y)$.
Let $g(x,y) = f(x+h,y) - f(x,y)$. Then,

$$\begin{aligned} S_h(x,y) &= f(x+h, y+h) - f(x+h, y) - f(x, y+h) + f(x,y) = g(x,y+h) - g(x,y) = \\ &= {}_{MVT} = h\frac{\partial g}{\partial y}(x, y+\beta h) = h\big[\frac{\partial f}{\partial y}(x+h, y+\beta h) - \frac{\partial f}{\partial y}(x, y+\beta h)\big] = \\ &= {}_{MVT} = h^2 \frac{\partial}{\partial x}(\frac{\partial f}{\partial y})(x+\alpha h, y+\beta h) \end{aligned}$$

where $0 < \alpha, \beta < 1$.
Let $r(x,y) = f(x, y+h) - f(x,y)$. Then,

$$\begin{aligned} S_h(x,y) &= f(x+h, y+h) - f(x+h, y) - f(x, y+h) + f(x,y) = r(x+h,y) - r(x,y) = \\ &= {}_{MVT} = h\frac{\partial r}{\partial x}(x+\alpha' h, y) = h\big[\frac{\partial f}{\partial x}(x+\alpha' h, y+h) - \frac{\partial f}{\partial x}(x+\alpha' h, y)\big] = \\ &= {}_{MVT} = h^2 \frac{\partial}{\partial y}(\frac{\partial f}{\partial x})(x+\alpha' h, y+\beta' h) \end{aligned}$$

where $0 < \alpha', \beta' < 1$.
For each small enough $h > 0$, $\frac{\partial}{\partial x}\big(\frac{\partial f}{\partial y}\big)(x+\alpha h, y+\beta h) = \frac{\partial}{\partial y}\big(\frac{\partial f}{\partial x}\big)(x+\alpha' h, y+\beta' h)$.
Since the mixed partial derivatives are continuous at $\mathbf{a} = (x,y)$, let $h \to 0 \quad \Rightarrow$
$\Rightarrow \quad \frac{\partial}{\partial x}\big(\frac{\partial f}{\partial y}\big)(x,y) = \frac{\partial}{\partial y}\big(\frac{\partial f}{\partial x}\big)(x,y)$. □

12.4 Taylor's Theorem

n-th degree Taylor polynomial of f at a; $(h = x - a)$

$$P_n(h) = f(a) + f'(a)h + \cdots + \frac{f^{(n)}(a)}{n!}h^n$$

Mean Value Theorem ($\mathbb{R} \to \mathbb{R}$, Revisited). *$f : [a,b] \to \mathbb{R}$. Suppose that f' exists on $[a,b]$. $h = b - a$. Then $\exists \xi$ between a and b such that*

$$R_0(h) = f'(\xi)h$$

$$f(a+h) = f(a) + f'(\xi)h = P_0(h) + R_0(h)$$

Proof. Need to show: $R_0(h) = f'(\xi)h$. For $t \in [0,h]$, define
$R_0(t) = f(a+t) - P_0(t) = f(a+t) - f(a)$. So, $R_0'(t) = f'(a+t)$.
Define $\varphi : [0,h] \to \mathbb{R}$ by

$$\varphi(t) = R_0(t) - \frac{R_0(h)}{h}t \qquad \Rightarrow \qquad \varphi(0) = \varphi(h) = 0$$

$\Rightarrow$ By Rolle's theorem, $\exists c \in (0,h)$ such that

$$0 = \varphi'(c) = R_0'(c) - \frac{R_0(h)}{h} = f'(a+c) - \frac{R_0(h)}{h}$$

$\Rightarrow$ For $\xi = a + c$, $R_0(h) = f'(\xi)h$. $\square$

Taylor's Theorem ($\mathbb{R} \to \mathbb{R}$). *$f : [a,b] \to \mathbb{R}$. Suppose that $f^{(n+1)}$ exists on $[a,b]$. $h = b - a$. Then $\exists \xi$ between a and b such that*

$$R_n(h) = \frac{f^{(n+1)}(\xi)}{(n+1)!}h^{n+1}.$$

$$f(a+h) = f(a) + f'(a)h + \cdots + \frac{f^{(n)}(a)}{n!}h^n + \frac{f^{(n+1)}(\xi)}{(n+1)!}h^{n+1} = P_n(h) + R_n(h).$$

Proof. Need to show: $R_n(h) = \frac{f^{(n+1)}(\xi)}{(n+1)!}h^{n+1}$. For $t \in [0,h]$, define $R_n(t) = f(a+t) - P_n(t)$, and note that

$$R_n(0) = R_n'(0) = \cdots = R_n^{(n)}(0) = 0 \tag{12.3}$$

since the first n derivatives of $P_n(t)$ at 0 agree with those of f at a. Also,

$$R_n^{(n+1)}(t) = f^{(n+1)}(a+t) \tag{12.4}$$

since $P_n^{(n+1)}(t) \equiv 0$ because $P_n(t)$ is a polynomial of degree n.
Define $\varphi : [0,h] \to \mathbb{R}$ by

$$\varphi(t) = R_n(t) - \frac{R_n(h)}{h^{n+1}}t^{n+1} \qquad \Rightarrow \qquad \varphi(0) = \varphi(h) = 0$$

$\Rightarrow$ By Rolle's theorem, $\exists c_1 \in (0,h)$ such that $\varphi'(c_1) = 0$.
It follows from (12.3) and (12.4) that

$$\varphi(0) = \varphi'(0) = \cdots = \varphi^{(n)}(0) = 0 \tag{12.5}$$

$$\varphi^{(n+1)}(t) = f^{(n+1)}(a+t) - \frac{R_n(h)}{h^{n+1}}(n+1)! \tag{12.6}$$

Therefore, we can apply Rolle's theorem to φ' on $[0, c_1]$ to obtain $c_2 \in (0, c_1)$ such that $\varphi''(c_2) = 0$.
By (12.5), φ'' satisfies the hypothesis of Rolle's theorem on $[0, c_2]$, so we can continue in this way. After $n+1$ applications of Rolle's theorem, we obtain $c_{n+1} \in (0, h)$ such that $\varphi^{(n+1)}(c_{n+1}) = 0$. From (12.6) we obtain $R_n(h) = \frac{f^{(n+1)}(\xi)}{(n+1)!}h^{n+1}$ where $\xi = a + c_{n+1}$. $\square$

Problem (F'03, #5). *Assume $f : \mathbb{R}^2 \to \mathbb{R}$ is a function such that all partial derivatives of order 3 exist and are continuous. Write down (explicitly in terms of partial derivatives of f) a quadratic polynomial $P(x, y)$ in x and y such that*

$$|f(x,y) - P(x,y)| \leq C(x^2 + y^2)^{\frac{3}{2}}$$

for all (x, y) in some small neighborhood of $(0, 0)$, where C is a number that may depend on f but not on x and y. Then prove the above estimate.

Proof. Taylor expand $f(x, y)$ around $(0, 0)$:

$$\begin{aligned} f(x,y) &= f(0,0) + xf_x(0,0) + yf_y(0,0) + \frac{1}{2!}\big[x^2 f_{xx}(0,0) + 2xyf_{xy}(0,0) + y^2 f_{yy}(0,0)\big] \\ &+ \frac{1}{3!}\big[x^3 f_{xxx}(0,0) + 3x^2 y f_{xxy}(0,0) + 3xy^2 f_{xyy}(0,0) + y^3 f_{yyy}(0,0)\big] + O(x^4) \end{aligned}$$

$$|f(x,y) - P_2(x,y)| = \Big|\frac{1}{3!}\big[x^3 f_{xxx}(\xi,\eta) + 3x^2 y f_{xxy}(\xi,\eta) + 3xy^2 f_{xyy}(\xi,\eta) + y^3 f_{yyy}(\xi,\eta)\big]\Big|$$

Note that $|x^3|, |x^2y|, |xy^2|, |y^3| \leq (x^2+y^2)^{\frac{3}{2}}$. Also, since 3^{rd} order partial derivatives are continuous, $\exists C_1 \in \mathbb{R}$ s.t. $\max\{f_{xxx}, 3f_{xxy}, 3f_{xyy}, f_{yyy}\} < \frac{C_1}{4}$ in some nbd of $(0,0)$.
Thus,
$|f(x,y) - P_2(x,y)| \leq |\frac{1}{3!}(x^2+y^2)^{\frac{3}{2}} C_1| \leq C(x^2+y^2)^{\frac{3}{2}}$. $\square$

Problem (F'02, #5). *Suppose $f : \mathbb{R}^2 \to \mathbb{R}$ has partial derivatives at every point bounded by $A > 0$.*
(a) Show that there is an M such that

$$|f((x,y)) - f((x_0,y_0))| \le M((x-x_0)^2 + (y-y_0)^2)^{\frac{1}{2}} \qquad \circledast$$

(b) What is the smallest value of M (in terms of A) for which this always works?
(c) Give an example where that value of M makes the inequality an equality.

Proof. (a) Since $|\frac{\partial f}{\partial x}| \le A, |\frac{\partial f}{\partial y}| \le A$, by the Mean Value Theorem,

$$\begin{aligned}
|f(x,y) - f(x_0,y)| &\le A|x - x_0| \\
|f(x,y) - f(x,y_0)| &\le A|y - y_0| \\
|f(x,y) - f(x_0,y_0)| &\le |f(x,y) - f(x_0,y)| + |f(x_0,y) - f(x_0,y_0)| \\
&\le A(|x-x_0| + |y-y_0|) \le A\sqrt{2}(|x-x_0|^2 + |y-y_0|^2)^{\frac{1}{2}}
\end{aligned}$$

(b) This always works for $M = A\sqrt{2}$.
(c) If $|x - x_0| = |y - y_0|$, then we have an equality in $\circledast$, since then
$A(|x-x_0| + |y-y_0|) \le A\sqrt{2}(|x-x_0|^2 + |y-y_0|^2)^{\frac{1}{2}}$
$\Rightarrow \quad 2A|x-x_0| \le A\sqrt{2}(2|x-x_0|^2)^{\frac{1}{2}}$
$\Rightarrow \quad 2A|x-x_0| \le 2A|x-x_0|$ □

Problem (F'03, #2). *Let $f : \mathbb{R} \to \mathbb{R}$ be infinitely differentiable function. Assume that $\forall x \in [0,1]$, $\exists m > 0$, such that $f^{(m)}(x) \neq 0$.*
Prove that $\exists M$ such that the following stronger statement holds:
$\forall x \in [0,1]$, $\exists m > 0$, $m \le M$ such that $f^{(m)}(x) \neq 0$.

Proof. There are uncountably many x_α's in $[0,1]$, and for each $x_\alpha \in [0,1]$, $\exists m_\alpha > 0$ such that $f^{(m_\alpha)} \neq 0$ for $[x_\alpha - \epsilon_\alpha, x_\alpha + \epsilon_\alpha]$, for some $\epsilon_\alpha > 0$ (since $f^{(m_\alpha)}$ is continuous). Let $\epsilon = \min_\alpha(\epsilon_\alpha)$. Partition $[0,1]$ into $n = 1/\epsilon$ subintervals (since $\epsilon > 0$, $n < \infty$):

$$0 < \epsilon = x_0 < x_1 < \ldots < x_n = 1 - \epsilon < 1,$$

such that $x_0 = \epsilon$, $x_i = x_0 + i\epsilon$, $i = 1, \ldots, n$. Thus $[0,1]$ is covered by finitely many overlapping intervals $[x_i - \epsilon, x_i + \epsilon]$. For each x_i, $i = 1, \ldots, n$, $\exists m_i > 0$ such that $f^{(m_i)}(x_i) \neq 0$ on $[x_i - \epsilon, x_i + \epsilon]$. Take $M = \max_{0 \le i \le n}(m_i)$. Thus, $\forall x \in [0,1]$, $\exists m > 0$, $m \le M$ such that $f^{(m)}(x) \neq 0$. □

Problem (S'03, #4). *Consider the following equation for a function $F(x,y)$ on $\mathbb{R}^2$:*

$$\frac{\partial^2 F}{\partial x^2} = \frac{\partial^2 F}{\partial y^2} \qquad \circledast$$

(a) Show that if a function F has the form $F(x,y) = f(x+y)+g(x-y)$ where $f:\mathbb{R}\to\mathbb{R}$ and $g:\mathbb{R}\to\mathbb{R}$ are twice differentiable, then F satisfies the equation $\circledast$.
(b) Show that if $F(x,y) = ax^2+bxy+cy^2$, $a,b,c\in\mathbb{R}$, satisfies $\circledast$ then $F(x,y) = f(x+y)+g(x-y)$ for some polynomials f and g in one variable.

Proof. (a) Let $\xi(x,y) = x+y$, $\eta(x,y) = x-y$, so $F(x,y) = f(\xi(x,y))+g(\eta(x,y))$. By Chain Rule,

$$\begin{aligned}
\frac{\partial F}{\partial x} &= \frac{df}{d\xi}\cdot\frac{\partial \xi}{\partial x} + \frac{dg}{d\eta}\cdot\frac{\partial \eta}{\partial x} = \frac{df}{d\xi}\cdot 1 + \frac{dg}{d\eta}\cdot 1 = \frac{df}{d\xi} + \frac{dg}{d\eta}, \\
\frac{\partial^2 F}{\partial x^2} &= \frac{\partial}{\partial x}\left(\frac{df}{d\xi} + \frac{dg}{d\eta}\right) = \frac{d^2 f}{d\xi^2}\cdot\frac{\partial \xi}{\partial x} + \frac{d^2 g}{d\eta^2}\cdot\frac{\partial \eta}{\partial x} = \frac{d^2 f}{d\xi^2} + \frac{d^2 g}{d\eta^2},
\end{aligned}$$

and similarly $\quad \dfrac{\partial F}{\partial y} = \dfrac{df}{d\xi} - \dfrac{dg}{d\eta}$, and $\dfrac{\partial^2 F}{\partial x^2} = \dfrac{d^2 f}{d\xi^2} + \dfrac{d^2 g}{d\eta^2}$, and thus , $\dfrac{\partial^2 F}{\partial x^2} = \dfrac{\partial^2 F}{\partial y^2}$.

(b) Suppose $F(x,y) = ax^2+bxy+cy^2$, $a,b,c\in\mathbb{R}$ satisfies $\circledast$, then

$$\begin{aligned}
\frac{\partial F}{\partial x} &= 2ax+by \quad\Rightarrow\quad \frac{\partial^2 F}{\partial x^2} = 2a, \qquad \frac{\partial F}{\partial y} = 2cy+bx \quad\Rightarrow\quad \frac{\partial^2 F}{\partial y^2} = 2c \qquad\Rightarrow\quad a = c. \\
F(x,y) &= ax^2+bxy+ay^2 = a(x^2+y^2)+bxy = a\frac{(x+y)^2+(x-y)^2}{2} + b\frac{(x+y)^2-(x-y)^2}{4}.
\end{aligned}$$

□

12.5 Lagrange Multipliers

Theorem. *Let f and g be C^1 on $\mathbb{R}^2$. Suppose that f attains its maximum or minimum value on the zero set S of g at the point $\mathbf{p}$ where $\nabla g(\mathbf{p}) \neq \mathbf{0}$. Then*

$$\nabla f(\mathbf{p}) = \lambda \nabla g(\mathbf{p})$$

for some number λ.

Problem (S'03, #5). *Consider the function $F(x,y) = ax^2+2bxy+cy^2$ on the set $A = \{(x,y) : x^2+y^2 = 1\}$.*
(a) Show that F has a maximum and minimum on A.
(b) Use Lagrange multipliers to show that if the maximum of F on A occurs at a point (x_0,y_0), then the vector (x_0,y_0) is an eigenvector of the matrix $\begin{pmatrix} a & b \\ b & c \end{pmatrix}$.

Proof. (a) Since F is continuous and the circle is closed and bounded, F attains both a maximum and minimum values on the unit circle $g(x,y) = x^2+y^2-1 = 0$.
(b) Applying the above theorem, we obtain the three equations (for x,y,λ)

$$2ax+2by = 2\lambda x, \qquad 2bx+2cy = 2\lambda y, \qquad x^2+y^2 = 1.$$

$$\begin{pmatrix} a & b \\ b & c \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \lambda\begin{pmatrix} x \\ y \end{pmatrix}, \qquad \text{and } \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \text{ is an eigenvector of this matrix.}$$

□

13 Successive Approximations and Implicit Functions

13.1 Contraction Mappings

$C \subseteq \mathbb{R}^n$. The mapping $\varphi : C \to C$ is a **contraction mapping** with contraction constant $k < 1$ if

$$|\varphi(\mathbf{x}) - \varphi(\mathbf{y})| \leq k|\mathbf{x} - \mathbf{y}| \qquad \forall \mathbf{x}, \mathbf{y} \in C.$$

Contraction Lemma. *If M is complete and $\varphi : M \to M$ is a contraction mapping with $k < 1$, then φ has a unique fixed point $\mathbf{x}^*$.*

Proof. $|x_{n+1} - x_n| = |\varphi(x_n) - \varphi(x_{n-1})| \leq k|x_n - x_{n-1}| \leq k^n|x_1 - x_0|$.
If $m > n > 0$, then

$$\begin{aligned} |x_m - x_n| &\leq |x_m - x_{m-1}| + \cdots + |x_{n+1} - x_n| \leq (k^{m-1} + \cdots + k^n)|x_1 - x_0| \\ &\leq k^n|x_1 - x_0|(1 + k + k^2 + \cdots) \leq \frac{k^n}{1-k}|x_1 - x_0|. \end{aligned}$$

Thus the sequence $\{x_n\}$ is a Cauchy sequence, and therefore converges to a point x^*. Letting $m \to \infty$, we get

$$|x^* - x_n| \leq \frac{k^n}{1-k}|x_1 - x_0|.$$

Since φ is contraction, it is continuous. Therefore,

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

If x^{**} were another fixed point of φ, we would have $|x^* - x^{**}| = |\varphi(x^*) - \varphi(x^{**})| \leq k|x^* - x^{**}|$. Since $k < 1$, it follows that $x^* = x^{**}$, so x^* is the unique fixed point of φ. □

13.2 Inverse Function Theorem

Lemma. [17] *Suppose $f : \mathbb{R}^n \to \mathbb{R}^n$ is C^1, $\mathbf{0} \in W$, $f(\mathbf{0}) = \mathbf{0}$, $f'(\mathbf{0}) = I$. Suppose $||f'(\mathbf{x}) - I|| \leq \epsilon$, $\forall \mathbf{x} \in B_r$. Then*

$$B_{(1-\epsilon)r} \subset f(B_r) \subset B_{(1+\epsilon)r}. \tag{13.1}$$

If $U = B_r \bigcap f^{-1}(B_{(1-\epsilon)r})$, then $f : U \to B_{(1-\epsilon)r}$ is bijection, and the inverse mapping $g : V \to U$ is differentiable at $\mathbf{0}$.

Proof. $||f'(\mathbf{x}) - I|| \leq \epsilon < 1$, $\forall \mathbf{x} \in B_r$. Apply MVT[18] to $g(\mathbf{x}) = f(\mathbf{x}) - \mathbf{x}$. $\mathbf{a}, \mathbf{b} \in B_r$, then

$$||(f(\mathbf{b}) - \mathbf{b}) - (f(\mathbf{a}) - \mathbf{a})|| = ||g(\mathbf{b}) - g(\mathbf{a})|| \leq ||g'(\xi)||\,||\mathbf{b} - \mathbf{a}|| = ||f'(\xi) - I||\,||\mathbf{b} - \mathbf{a}|| \leq \epsilon||\mathbf{b} - \mathbf{a}|| \tag{13.2}$$

$$(1 - \epsilon)||\mathbf{b} - \mathbf{a}|| \leq ||f(\mathbf{b}) - f(\mathbf{a})|| \leq (1 + \epsilon)||\mathbf{b} - \mathbf{a}|| \tag{13.3}$$

The left-hand inequality shows that f is 1-1 on B_r. The right-hand inequality (with $\mathbf{a} = \mathbf{0}$) shows $f(B_r) \subset B_{(1+\epsilon)r}$.

---

[17] Problem F'01, # 6.
[18] $f : U \subset \mathbb{R}^n \to \mathbb{R}^m$ is $C^1 \quad \Rightarrow \quad ||f(\mathbf{b}) - f(\mathbf{a})|| \leq ||\mathbf{b} - \mathbf{a}|| \max_{\mathbf{x}\in L} ||f'(\mathbf{x})||$.

To show $B_{(1-\epsilon)r} \subset f(B_r)$, we use contraction mapping theorem. Given $\mathbf{y} \in B_{(1-\epsilon)r}$, define $\varphi : \mathbb{R}^n \to \mathbb{R}^n$ by

$$\varphi(\mathbf{x}) = \mathbf{x} - f(\mathbf{x}) + \mathbf{y}.$$

We want to show that φ is a contraction mapping of B_r; its unique fixed point will then be the desired point $\mathbf{x} \in B_r$ such that $f(\mathbf{x}) = \mathbf{y}$.
To see that φ maps B_r into itself:

$$||\varphi(\mathbf{x})|| \le ||f(\mathbf{x}) - \mathbf{x}|| + ||\mathbf{y}|| \le \text{ (by (13.2) with } \mathbf{a} = \mathbf{0}) \le \epsilon||\mathbf{x}|| + (1-\epsilon)r \le \epsilon r + (1-\epsilon)r = r,$$

so if $\mathbf{x} \in B_r$, then $\varphi(\mathbf{x}) \in B_r$. Thus, $\varphi(B_r) \subseteq B_r$.
To see $\varphi : B_r \to B_r$ is a contraction mapping, note that

$$||\varphi(\mathbf{b}) - \varphi(\mathbf{a})|| = ||f(\mathbf{b}) - f(\mathbf{a}) - (\mathbf{b} - \mathbf{a})|| \le \epsilon||\mathbf{b} - \mathbf{a}||$$

Thus, φ has a unique fixed point $\mathbf{x}^*$, $\varphi(\mathbf{x}^*) = \mathbf{x}^*$, such that $f(\mathbf{x}^*) = \mathbf{y}$. From the statement of theorem, $U = B_r \bigcap f^{-1}(B_{(1-\epsilon)r})$. f is a bijection of U onto $B_{(1-\epsilon)r}$.
It remains to show that $g : V \to U$ is differentiable at $\mathbf{0}$, where $g(\mathbf{0}) = \mathbf{0}$. Need to show

$$\lim_{|\mathbf{h}| \to 0} \frac{||g(\mathbf{h}) - g(\mathbf{0}) - \mathbf{h}||}{||\mathbf{h}||} = \lim_{|\mathbf{h}| \to 0} \frac{||g(\mathbf{h}) - \mathbf{h}||}{||\mathbf{h}||} = 0.$$

This will prove that $g'(\mathbf{0}) = I$. Applying (13.2) with $\mathbf{a} = \mathbf{0}$, $\mathbf{b} = g(\mathbf{h})$, $\mathbf{h} = f(\mathbf{b})$, we get

$$||g(\mathbf{h}) - \mathbf{h}|| \le \epsilon||\mathbf{b}|| \le by\ (13.3) \le \frac{\epsilon}{1-\epsilon}||f(\mathbf{b})|| = \frac{\epsilon}{1-\epsilon}||\mathbf{h}||$$

Therefore, $\lim_{|\mathbf{h}| \to 0} \frac{||g(\mathbf{h}) - \mathbf{h}||}{||\mathbf{h}||} = 0$, with $g'(\mathbf{0}) = I$. □

Theorem. [19]*Suppose $f : W \subset \mathbb{R}^n \to \mathbb{R}^n$ is C^1, $\mathbf{a} \in W$, $\mathbf{b} = f(\mathbf{a})$, and the matrix $f'(\mathbf{a})$ is nonsingular.*[20] *Then there exist*[21] *open sets $U \subset W$ of $\mathbf{a}$ and V of $\mathbf{b}$, such that f maps U bijectively onto V. ($\exists$ 1-1 C^1 mapping $g : V \to W$ such that*

$$g(f(\mathbf{x})) = \mathbf{x} \quad for \quad \mathbf{x} \in U,$$
$$f(g(\mathbf{y})) = \mathbf{y} \quad for \quad \mathbf{y} \in V. \quad)$$

Also, for all $\mathbf{y} \in V$ $(\mathbf{y} = f(\mathbf{x}))$, $g = f^{-1}$ satisfies $g'(\mathbf{y}) = g'(f(\mathbf{x})) = f'(\mathbf{x})^{-1}$.

Proof. Fix $\mathbf{a} \in U$ and let $\mathbf{b} = f(\mathbf{a})$. Put $T = f'(\mathbf{a})$, a matrix / linear map. Define

$$\tilde{f}(\mathbf{h}) = T^{-1}(f(\mathbf{a} + \mathbf{h}) - \mathbf{b}) = T^{-1}(f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}))$$

Note $\tilde{f}(\mathbf{0}) = T^{-1} \cdot (\mathbf{0}) = \mathbf{0}$;
$\tilde{f}'(\mathbf{0}) = T^{-1}f'(\mathbf{a}) = T^{-1}T = I$. Thus, by previous Lemma, $\exists U_0$ open, $\mathbf{0} \in U_0$, such that $\tilde{f} : U_0 \to V_0$ is a bijection, $\mathbf{0} \in V_0$.
$\tilde{f}$ maps U_0 bijectively onto V_0 containing $\mathbf{0}$. Lets express f in terms of $\tilde{f}$.
$f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) = T\tilde{f}(\mathbf{h})$. Let $\mathbf{x} = \mathbf{a} + \mathbf{h}$:
$f(\mathbf{x}) - f(\mathbf{a}) = T\tilde{f}(\mathbf{x} - \mathbf{a})$,

[19] f is *locally one-to-one* in $E \equiv$ each point $\mathbf{x} \in E$ has a neighborhood in which f is 1-1.
[20] Jacobian of $f = |\det f'(\mathbf{a})| = |\frac{\partial f_i}{\partial x_j}(\mathbf{a})| \ne 0$.
[21] i.e. A C^1 map $f : W \to V$ is *locally invertible* at $\mathbf{a} \equiv$ there exist open sets $U \subset W$ of $\mathbf{a}$ and V of $\mathbf{b} = f(\mathbf{a})$, and a C^1 map $g : V \to U$ such that f and g are inverse to each other.

$f(\mathbf{x}) = T\tilde{f}(\mathbf{x}-\mathbf{a}) + f(\mathbf{a}),$
$f : \underbrace{U_0 + \mathbf{a}}_{U} \quad \to \quad T\tilde{f}(V_0) + f(\mathbf{a}), \quad$ bijection.
Let's compute f^{-1}:
Let $\mathbf{y} = T\tilde{f}(\mathbf{x}-\mathbf{a}) + f(\mathbf{a})$
$T\tilde{f}(\mathbf{x}-\mathbf{a}) = \mathbf{y} - f(\mathbf{a})$
$\tilde{f}(\mathbf{x}-\mathbf{a}) = T^{-1}(\mathbf{y} - f(\mathbf{a}))$
$\mathbf{x} - \mathbf{a} = \tilde{f}^{-1}(T^{-1}(\mathbf{y} - f(\mathbf{a}))) = \tilde{g}(T^{-1}(\mathbf{y} - f(\mathbf{a})))$
$f^{-1}(\mathbf{y}) = \mathbf{x} = \tilde{g}(T^{-1}(\mathbf{y} - f(\mathbf{a}))) + \mathbf{a}$
$(f^{-1})'(\mathbf{y}) = (\tilde{g})'(T^{-1}(\mathbf{y} - f(\mathbf{a}))) \cdot T^{-1}$
$(f^{-1})'(\mathbf{b}) = (\tilde{g})'(\mathbf{0}) \cdot T^{-1} = T^{-1} = f'(\mathbf{a})^{-1}.$ $\square$

Problem (S'02, #7; W'02, #7; F'03, #6). *Suppose $F : \mathbb{R}^2 \to \mathbb{R}^2$ is C^1 and that the Jacobian matrix of F is everywhere nonsingular. Suppose that $F(\mathbf{0}) = \mathbf{0}$ and that $||F(x, y)|| \geq 1$ for all (x, y) with $||(x, y)|| = 1$. Denote $U = \{(x, y) : ||(x, y)|| < 1\}$. Prove that $F(U) \supset U$.*
Hint: Show that $F(U) \bigcap U$ is both open and closed in U.

Proof. Since U is connected, clopenness of $F(U) \bigcap U$ in U implies that either $F(U) \bigcap U = U$ or $F(U) \bigcap U = \phi$. Since there exists a point, namely $\mathbf{0}$ such that it is inside both U and $F(U)$, $F(U) \bigcap U$ cannot be empty, and thus clopenness of $F(U) \bigcap U$ in U would imply that $F(U) \bigcap U = U$ (which would mean $U \subseteq F(U)$).
1) Show $F(U) \bigcap U$ is ***open*** in U.
$F(U)$ is open in $\mathbb{R}^2$. Say $y_0 \in F(U)$, $y_0 = F(x_0)$, $F'(x_0)$ invertible. By inverse function thm, F maps open set U_0 onto open set V_0; $x_0 \in U_0 \;\Rightarrow\; y_0 = F(x_0) \in V_0$. $y_0 \in V_0 \subseteq F(U) \;\Rightarrow\; F(U) \bigcap U$ is open in U.
2) Show $F(U) \bigcap U$ is ***closed*** in U.
Say $x_n \in F(U) \bigcap U$, $x_n \to x^* \in U$.
$x_n = F(y_n),\; y_n \in U \subset \overline{U}$.
There is a subsequence $y_{n_k} \to y \in \overline{U}$.
Since F is continuous, $F(y_{n_k}) \to F(y) = x^*$.
$||y|| = 1 \;\Rightarrow\; ||F(y)|| \geq 1 \;\Rightarrow\; F(y) = x^* \notin U$. Contradiction. □

13.3 Implicit Function Theorem

$(\mathbf{x}, \mathbf{y}) = (x_1, \ldots, x_m, y_1, \ldots, y_n)$

Theorem. *Suppose $G : \mathbb{R}^{m+n} \to \mathbb{R}^n$ is C^1. $G(\mathbf{a}, \mathbf{b}) = \mathbf{0}$ for some point $(\mathbf{a}, \mathbf{b})$. Partial derivative matrix $\frac{\partial G}{\partial \mathbf{y}}(\mathbf{a}, \mathbf{b})$ is invertible.*
Then there exist open sets U of $\mathbf{a}$ in $\mathbb{R}^m$ and W of $(\mathbf{a}, \mathbf{b})$ in $\mathbb{R}^{m+n}$ and a C^1 mapping $h : U \to \mathbb{R}^n$, such that $\mathbf{y} = h(\mathbf{x})$ solves the equation $G(\mathbf{x}, \mathbf{y}) = \mathbf{0}$ in W.

Example. $f(x, y, z) = 0$, $\frac{\partial f}{\partial z} \neq 0 \;\Rightarrow$ *can solve for* $z = h(x, y)$, $f(x, y, h(x, y)) \equiv 0$.

Example. $m = n = 1$. $G(x, y) = 0$, $y = h(x) \;\Rightarrow\; G(x, h(x)) = 0 \;\Rightarrow\; \frac{d}{dx} G(x, h(x)) = 0$
$\Rightarrow\; \frac{\partial G}{\partial x} + \frac{\partial G}{\partial h} h'(x) = 0 \;\Rightarrow\; h'(x) = -\frac{\partial G}{\partial x} / \frac{\partial G}{\partial h},\; \frac{\partial G}{\partial h} \neq 0$.
Say $G(x, y) = x^2 + y^2 - 1$, $x^2 + y^2 - 1 = 0 \;\Rightarrow\; y = \pm\sqrt{1 - x^2}$, *problem at* $(1, 0)$.
$\frac{\partial G}{\partial h}$ *cannot be equal to* 0.

Problem (S'02, #6). *Suppose $f : \mathbb{R}^3 \to \mathbb{R}$ is C^1 with $\nabla f \neq \mathbf{0}$ at $\mathbf{0}$. Show that there are two other C^1 functions $g, h : \mathbb{R}^3 \to \mathbb{R}$, such that the function*

$$(x, y, z) \to (f(x, y, z), g(x, y, z), h(x, y, z))$$

from $\mathbb{R}^3$ to $\mathbb{R}^3$ is one-to-one on some neighborhood of $\mathbf{0}$.

Proof. $\nabla f \neq \mathbf{0} \;\Rightarrow$ one of $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$ is not 0. $F = (f, g, h)$.

$$\nabla F = \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} & \frac{\partial f}{\partial z} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} & \frac{\partial g}{\partial z} \\ \frac{\partial h}{\partial x} & \frac{\partial h}{\partial y} & \frac{\partial h}{\partial z} \end{bmatrix}$$

Need to produce functions g, h such that the matrix above is invertible.
If $\frac{\partial f}{\partial x}(\mathbf{0}) \neq 0$, let $g(x, y, z) = z$, $h(x, y, z) = y$. Then

$$\begin{bmatrix} \frac{\partial f}{\partial x} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \qquad \text{and} \quad F = F(f(x, y, z), z, y).$$

Similarly, we can find a set of functions g, h by choosing a matrix in each of the other two cases, i.e. when $\frac{\partial f}{\partial y}(\mathbf{0}) \neq 0$ and $\frac{\partial f}{\partial z}(\mathbf{0}) \neq 0$. □

Problem (F'02, #6). *Suppose $F : \mathbb{R}^3 \to \mathbb{R}^2$ is C^1. Suppose for some $v_0 \in \mathbb{R}^3$ and $x_0 \in \mathbb{R}^2$ that $F(v_0) = x_0$ and $F'(v_0) : \mathbb{R}^3 \to \mathbb{R}^2$ is onto. Show that there is a C^1 function $\gamma : (-\epsilon, \epsilon) \to \mathbb{R}^3$ for some $\epsilon > 0$, such that*

$$
\begin{aligned}
&(i) \quad \gamma'(0) \neq \mathbf{0} \in \mathbb{R}^3, \qquad \textit{and} \\
&(ii) \quad F(\gamma(t)) = x_0 \textit{ for all } t \in (-\epsilon, \epsilon).
\end{aligned}
$$

Proof. Since $F'(v_0)$ is onto, the matrix $F'(v_0)$ has rank 2. So, 2 of the 3 columns of $F'(v_0)$ are linearly independent.

$$
F'(v_0) = \left[\begin{array}{ccc} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} \end{array} \right]_{v_0}.
$$

Assume the last two columns are linearly independent.
Consider the function $G(x_1, x_2, x_3) = F(x_1, x_2, x_3) - x_0$. Write $(x_1, x_2, x_3) = (s_1, s_2)$ where $s_1 = x_1$, $s_2 = (x_2, x_3)$. Write $v_0 = (u_1, u_2)$. Then $G(u_1, u_2) = 0$ and $\frac{\partial G}{\partial s_2}(v_0)$ is invertible. By Implicit Function Theorem, $\exists\, \epsilon > 0$ and $h \in C^1$, such that $h : (u_1 - \epsilon, u_1 + \epsilon) \to \mathbb{R}^2$ and $G(s_1, h(s_1)) = 0$, $\forall s_1 \in (u_1 - \epsilon, u_1 + \epsilon)$.
$\Rightarrow \quad F(s_1, h(s_1)) = x_0$, $\forall s_1 \in (u_1 - \epsilon, u_1 + \epsilon)$.
Define $\gamma(t) : (-\epsilon, \epsilon) \to \mathbb{R}^3$ by $\gamma(t) = (u_1 + t, h(u_1 + t))$. Then $\gamma(t)$ is a differentiable curve satisfying

$$
\begin{aligned}
&(i) \quad \gamma'(t) = (1, h'(u_1 + t)) \neq \mathbf{0}, \\
&(ii) \quad F(\gamma(t)) = x_0 \text{ for all } t \in (-\epsilon, \epsilon).
\end{aligned}
$$

□

13.4 Differentiation Under Integral Sign

Problem (W'02, #1). *$f : [a,b] \times [c,d] \to \mathbb{R}$ $((x,y) \to f(x,y))$. Suppose $\frac{\partial f}{\partial y}$ exists on $[a,b] \times (c,d)$ and extends to a continuous function on $[a,b] \times [c,d]$. Let*

$$F(y) = \int_a^b f(x,y)dx.$$

Then F is differentiable in $[a,b]$ and

$$\frac{d}{dy}F(y) = \int_a^b \frac{\partial f}{\partial y}(x,y)dx.$$

$$\Rightarrow \qquad \frac{d}{dy}\int_b^a f(x,y)dx = \int_a^b \frac{\partial f}{\partial y}(x,y)dx.$$

Proof.

$$\begin{aligned}\left|\frac{F(y+h)-F(y)}{h} - \int_a^b \frac{\partial f}{\partial y}(x,y)dx\right| &= \left|\int_a^b \Big[\frac{f(x,y+h)-f(x,y)}{h} - \frac{\partial f}{\partial y}(x,y)\Big]dx\right| \\ &\leq \int_a^b \left|\frac{f(x,y+h)-f(x,y)}{h} - \frac{\partial f}{\partial y}(x,y)\right|dx \leq \quad \Rightarrow \quad \circledast\end{aligned}$$

By MVT, $\exists c$, $0 < c < 1$, such that

$$\frac{f(x,y+h)-f(x,y)}{h} = \frac{\partial f}{\partial y}(x,y+ch).$$

$||(x,y+ch)-(x,y)|| = c|h| \leq h$.
Since $\frac{\partial f}{\partial y}$ is continuous on $[a,b]\times[c,d]$ $\Rightarrow$ $\frac{\partial f}{\partial y}$ is uniformaly continuous on $[a,b]\times[c,d]$.
Choose δ such that $||(x,y)-(x',y')|| \leq \delta \quad \Rightarrow \quad |\frac{\partial f}{\partial y}(x',y') - \frac{\partial f}{\partial y}(x,y)| \leq \frac{\epsilon}{b-a}$

$$\Rightarrow \quad \circledast \quad = \int_a^b \left|\frac{\partial f}{\partial y}(x,y+ch) - \frac{\partial f}{\partial y}(x,y)\right|dx \leq \int_a^b \frac{\epsilon}{b-a}dx = (b-a)\frac{\epsilon}{b-a} = \epsilon.$$

$\square$