
REAL ANALYSIS: A COMPLETE GUIDE

REAL ANALYSIS

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Part I

Single Variable Analysis

Chapter 1

Topology and Construction of the Real Line

1.1.0 Peano Arithmetic

We begin by forming our number system from the ground up, starting with Giuseppe Peano's (1858-1932) axiomatized system for the natural numbers.

Axiom 1.1.1 (Peano's Axioms). *Peano's system for the naturals consists of two central axioms:*

1. Assume that there exists a set \mathbb{N} and an element $0 \notin \mathbb{N}$. Define, notationally, $\tilde{\mathbb{N}} = \mathbb{N} \cup \{0\}$. Then, assume there exists an injective map $s : \tilde{\mathbb{N}} \rightarrow \tilde{\mathbb{N}}$ called the **successor function**
2. **Mathematical Induction:** Whenever a subset $S \subseteq \tilde{\mathbb{N}}$ satisfies $0 \in S$, and if $k \in S$ then $s(k) \in S$, then this implies $S = \tilde{\mathbb{N}}$. Notationally we have

$$(0 \in S \wedge (k \in S \implies s(k) \in S)) \implies S = \tilde{\mathbb{N}}$$

Given these axioms, we can define an addition operation on $\tilde{\mathbb{N}}$:

Definition 1.1.2. We define the binary operation $+$: $\tilde{\mathbb{N}} \times \tilde{\mathbb{N}} \rightarrow \tilde{\mathbb{N}}$ inductively for $x, y \in \tilde{\mathbb{N}}$ by stating

1. $x + 0 = x$
2. $x + s(y) = s(x + y)$

The definition is performed inductively, or recursively. Fix $x \in \tilde{\mathbb{N}}$ and let $S = \{y \in \tilde{\mathbb{N}} : x + y \text{ is defined}\}$. By definition $0 \in S$. Further, if $y \in S$, $x + y$ is defined in $\tilde{\mathbb{N}}$, so $x + s(y) := s(x + y)$. Since $x + y \in \tilde{\mathbb{N}}$, by axiom 1 of Peano's arithmetic $s(x + y) \in \mathbb{N} \subset \tilde{\mathbb{N}}$. Thus, $s(x + y)$ is defined

so $s(y) \in S$. Hence by mathematical induction $S = \tilde{\mathbb{N}}$ so $+$ is a well defined binary operation for all $x, y \in \tilde{\mathbb{N}}$.

We can similarly define multiplication:

Definition 1.1.3. We define the binary operation $\cdot : \tilde{\mathbb{N}} \times \tilde{\mathbb{N}} \rightarrow \tilde{\mathbb{N}}$ inductively for $x, y \in \tilde{\mathbb{N}}$ by stating

1. $x \cdot 0 = 0$
2. $x \cdot s(y) = x \cdot y + x$

This defines $x \cdot y$ inductively as in the case of $+$. Now, we define our unit:

Definition 1.1.4. We define $1 \in \tilde{\mathbb{N}}$ by $1 := s(0)$.

Now we can derive many of the standard properties of the naturals.

Proposition 1.1.1. For all $x \in \tilde{\mathbb{N}}$, $x + 1 = s(x)$.

Proof. Let $x \in \tilde{\mathbb{N}}$. Then $x + 1 = x + s(0)$, but then by our inductive definition for $+$, $x + s(0) = s(x + 0)$, and $x + 0 = x$ by definition, so

$$x + 1 = s(x)$$

■

Proposition 1.1.2. For all $x \in \tilde{\mathbb{N}}$, $0 + x = x$.

Proof. We proceed by induction on $x \in \tilde{\mathbb{N}}$. If $x = 0$, then $0 + 0 = 0 = x$, by definition. Suppose inductively that we have $x \in \tilde{\mathbb{N}}$ such that $0 + x = x$. Then $0 + s(x) = s(0 + x)$. But, $0 + x = x$ by the induction hypothesis, so $0 + s(x) = s(x)$ and our result holds for $s(x)$. Thus, by mathematical induction we conclude that $0 + x = x$ for all $x \in \tilde{\mathbb{N}}$. ■

Proposition 1.1.3. For all $x, y \in \tilde{\mathbb{N}}$, $s(y) + x = s(y + x)$.

Proof. Let $y \in \tilde{\mathbb{N}}$, and we proceed by induction on $x \in \tilde{\mathbb{N}}$. If $x = 0$ then $s(y) + 0 = s(y)$, and $s(y + 0) = s(y)$, so the base case holds. Now, suppose the proposition holds for some $x \in \tilde{\mathbb{N}}$. Then $s(y) + s(x) = s(s(y) + x)$ by definition, and by the induction hypothesis $s(y) + x = s(y + x) = y + s(x)$ by definition. Thus, $s(y) + s(x) = s(y + s(x))$, as desired. Thus, by mathematical induction we conclude that $s(y) + x = s(y + x)$ for all $x, y \in \tilde{\mathbb{N}}$. ■

Proposition 1.1.4. For all $x, y \in \tilde{\mathbb{N}}$, $x + y = y + x$ (Commutative Law).

Proof. Fix $x \in \tilde{\mathbb{N}}$, and we proceed by induction on $y \in \tilde{\mathbb{N}}$. If $y = 0$ then $x + 0 = x$ by definition, and $0 + x = x$ by Proposition 1.1.2, so the base case holds. Now, suppose the proposition holds

for some $y \in \tilde{\mathbb{N}}$. Then $x + s(y) = s(x + y)$ by definition, and by Proposition 1.1.3 we have $s(y) + x = s(y + x)$. By the induction hypothesis $x + y = y + x$, so $s(x + y) = s(y + x)$, and it follows that $s(y) + x = x + s(y)$. Hence, as x was arbitrary, we have by mathematical induction that $x + y = y + x$ for all $x, y \in \tilde{\mathbb{N}}$. ■

Proposition 1.1.5. For all $x, y, z \in \tilde{\mathbb{N}}$, $x + (y + z) = (x + y) + z$ (Associative Law).

Proof. Fix $x, y \in \tilde{\mathbb{N}}$, and proceed by mathematical induction on $z \in \tilde{\mathbb{N}}$. If $z = 0$, $x + (y + 0) = x + y = (x + y) + 0$, so the base case holds. Suppose the proposition holds for some $z \in \tilde{\mathbb{N}}$. Then it follows that

$$\begin{aligned} x + (y + s(z)) &= x + s(y + z) = s(x + (y + z)) \\ &= s((x + y) + z) && \text{(by Induction Hypothesis)} \\ &= (x + y) + s(z) \end{aligned}$$

as desired. Thus by the axiom of mathematical induction we have our result. ■

Proposition 1.1.6. For all $x \in \tilde{\mathbb{N}}$, $x \cdot 1 = x$.

Proof. Fix $x \in \tilde{\mathbb{N}}$. Then $x \cdot 1 = x \cdot s(0) := x \cdot 0 + x = 0 + x = x$, by Proposition 1.1.4. ■

Proposition 1.1.7. For all $x \in \tilde{\mathbb{N}}$, $0 \cdot x = 0$.

Proof. We proceed by induction on $x \in \tilde{\mathbb{N}}$. If $x = 0$, $0 \cdot 0 = 0$ by definition. If $0 \cdot x = 0$ for some $x \in \tilde{\mathbb{N}}$, then $0 \cdot s(x) = 0 \cdot x + 0 = 0$, so by mathematical induction we have our result. ■

Proposition 1.1.8. For all $x, y \in \tilde{\mathbb{N}}$, $s(x) \cdot y = x \cdot y + y$.

Proof. Fix $x \in \tilde{\mathbb{N}}$, and proceed by induction on $y \in \tilde{\mathbb{N}}$. If $y = 0$, $s(x) \cdot 0 = 0 = x \cdot 0 + 0$. Suppose the result holds for some $y \in \tilde{\mathbb{N}}$. Then $s(x) \cdot s(y) = s(x) \cdot y + s(x)$ by definition, and $s(x) \cdot y = x \cdot y + y$ by the induction hypothesis. By Proposition 1.1.5, $(x \cdot y + y) + s(x) = x \cdot y + (y + s(x)) = x \cdot y + s(y + x)$. By Proposition 1.1.4, $x \cdot y + s(y + x) = x \cdot y + s(x + y) = x \cdot y + (x + s(y))$. Finally, by Proposition 1.1.5 again we have $x \cdot y + (x + s(y)) = (x \cdot y + x) + s(y) = x \cdot s(y) + s(y)$, as desired. The result follows by the principle of mathematical induction. ■

Proposition 1.1.9. For all $x, y \in \tilde{\mathbb{N}}$, $x \cdot y = y \cdot x$.

Proof. Fix $x \in \tilde{\mathbb{N}}$, and proceed by mathematical induction on $y \in \tilde{\mathbb{N}}$. If $y = 0$, $x \cdot 0 = 0 = 0 \cdot x$ by Proposition 1.1.7, so the base case holds. Suppose it holds for some $y \in \tilde{\mathbb{N}}$. Then $x \cdot s(y) = x \cdot y + x = y \cdot x + x$ by the induction hypothesis, and by Proposition 1.1.8, $y \cdot x + x = s(y) \cdot x$. Thus by mathematical induction we have commutivity of multiplication. ■

Proposition 1.1.10. For all $x, y, z \in \tilde{\mathbb{N}}$, $(x + y) \cdot z = x \cdot z + y \cdot z$ (Distributivity).

Proof. Fix $x, z \in \tilde{\mathbb{N}}$ and proceed by induction on $y \in \tilde{\mathbb{N}}$. If $y = 0$, $(x + 0) \cdot z = x \cdot z = x \cdot z + 0 \cdot z$ by Proposition 1.1.7. Suppose it holds for some $y \in \tilde{\mathbb{N}}$. Then $(x + s(y)) \cdot z = s(x + y) \cdot z = (x + y) \cdot z + z$

by Proposition 1.1.8. By the induction hypothesis, associativity, and the same proposition again we have

$$(x + y) \cdot z + z = (x \cdot z + y \cdot z) + z = x \cdot z + (y \cdot z + z) = x \cdot z + s(y) \cdot z$$

as desired. Thus we have distributivity of multiplication by mathematical induction. ■

Proposition 1.1.11. *For all $x, y, z \in \tilde{\mathbb{N}}$, if $x + z = y + z$, then $x = y$.*

Proof. Let $x, y \in \tilde{\mathbb{N}}$, and we proceed by induction on $z \in \tilde{\mathbb{N}}$. If $z = 0$, $x + 0 = y + 0$ implies $x = y$, so the base case holds. If it holds for some $z \in \tilde{\mathbb{N}}$, then $x + s(z) = y + s(z)$ implies $s(x + z) = s(y + z)$. But s is an inductive function, so $x + z = y + z$ which implies $x = y$ by the induction hypothesis, and by mathematical induction we have our result. ■

Proposition 1.1.12. *If $x \cdot z = y \cdot z$ and $z \neq 0$, then $x = y$.*

Proof. Suppose $x, y, z \in \tilde{\mathbb{N}}$ such that $x \cdot z = y \cdot z$. We argue by contrapositive and suppose $x \neq y$. Then by Trichotomy (to be shown) $x < y$ or $y < x$. Without loss of generality suppose $x < y$. Then $y = x + u$ for some $u \in \mathbb{N}$. Then $y \cdot z = x \cdot z + u \cdot z$, and so $u \cdot z = 0$ by the cancellation property. If $z \neq 0$, $z = s(w)$, $w \in \tilde{\mathbb{N}}$, so $0 = u \cdot z = u \cdot w + u$. As $u \in \mathbb{N}$ this implies $u \cdot w < 0$, but $0 \leq k$ for all $k \in \tilde{\mathbb{N}}$ which contradicts trichotomy. ■

As noted in the previous proof we used properties of the standard order relation on the naturals which we shall now define and prove.

Definition 1.1.5. *If $x, y \in \tilde{\mathbb{N}}$ we say*

1. $x < y$ if $y = x + u$ for some $u \in \mathbb{N}$
2. $x \leq y$ if $y = x + v$ for some $v \in \tilde{\mathbb{N}}$

We could also say $x \leq y$ if and only if $y \in Rx = \{x + v : v \in \tilde{\mathbb{N}}\}$. We define $y > x \iff x < y$ and $y \geq x \iff x \leq y$ for all $x, y \in \tilde{\mathbb{N}}$.

Proposition 1.1.13. *For $x, y \in \tilde{\mathbb{N}}$, if $x \leq y$ and $y \leq x$, then $x = y$.*

Proof. As $y = x + v$, $v \in \tilde{\mathbb{N}}$, and $x = y + u$ for $u \in \tilde{\mathbb{N}}$ by definition, $x = x + v + u$, so by the cancellation property $v + u = 0$. Towards a contradiction suppose v or u is not 0. Without loss of generality suppose $v \neq 0$, so $v \in \mathbb{N}$ and there exists $m \in \tilde{\mathbb{N}}$ such that $v = s(m)$. Then $0 = u + s(m) = s(u + m) \in \mathbb{N}$, which contradicts our axiom that $0 \notin \mathbb{N}$. Thus, $v = u = 0$, so $x = y$. ■

Proposition 1.1.14 (Trichotomy). *If $x, y \in \tilde{\mathbb{N}}$, then one and only one of the following hold:*

$$x < y \text{ or } x = y \text{ or } x > y$$

Proof. Let $x, y \in \tilde{\mathbb{N}}$. If $x < y$ then $y = x + u$ for some $u \in \mathbb{N}$. If $x = y$ then $u = 0$, but $u \in \mathbb{N}$ so $u \neq 0$, and $x \neq y$. If $x > y$ then $x = y + v$, $v \in \mathbb{N}$, but by the proof of Proposition 1.1.13 this implies $u = v = 0$ contradicting the fact $u, v \in \mathbb{N}$. By similar arguments $x = y \implies x \not< y, x \not> y$, and $x > y$ follows from the first case. Let $y \in \tilde{\mathbb{N}}$ and proceed by induction on $x \in \tilde{\mathbb{N}}$. If $x = 0$, $y = y + 0$ so $y \geq x$. If $y = 0$, $x = y$, and if $y \neq 0$, $y \in \mathbb{N}$ so $y > x$. Suppose the claim holds for some $x \in \tilde{\mathbb{N}}$. If $x < y$, then $s(x) \leq y$. Then either $s(x) = y$ or $s(x) + u = y$ for some $u \neq 0$, so $u \in \mathbb{N}$ and $s(x) < y$. If $x = y$, $s(x) = x + 1 = y + 1$, so $y < s(x)$. A similar argument holds if $y < x$, since $y < s(x)$, completing the induction. ■

We now define the partial function of subtraction on $\tilde{\mathbb{N}}$:

Definition 1.1.6. If $x, y \in \tilde{\mathbb{N}}$ with $x \leq y$, then we define $z := y - x \iff y = x + z$, where $z \in \tilde{\mathbb{N}}$.

Notice $y - x$ is well defined by the cancellation property of addition.

Proposition 1.1.15. If $x, y, u \in \tilde{\mathbb{N}}$, with $x \leq y$, then $(y - x)u = yu - xu$.

Proof. Let $x, y \in \tilde{\mathbb{N}}$ with $x \leq y$ and let $u \in \tilde{\mathbb{N}}$. Then there exists $w \in \tilde{\mathbb{N}}$ such that $y = x + w$, so $yu = xu + wu$ by distributivity. Then by definition $yu - xu = wu = (y - x)u$. ■

Next we move on to a central property of the natural numbers which is equivalent to the axiom of mathematical induction:

Theorem 1 (Well-Ordering Property of $\tilde{\mathbb{N}}$).

If $T \subseteq \tilde{\mathbb{N}}$ is non-empty, then T has a smallest element.

Proof. We proceed by contrapositive. Suppose $T \subseteq \tilde{\mathbb{N}}$ and T has no smallest element. Then $0 \notin T$, since for all $x \in \tilde{\mathbb{N}}$, $0 \leq x$, as either $x = 0$ or $x \in \mathbb{N}$ so $x = x + 0$ and $x > 0$. Let $S = \{x \in \tilde{\mathbb{N}} : x < y, \forall y \in T\}$, so $0 \in S$. Inductively suppose $x \in S$. If $s(x) \in S$, we're done, so suppose $s(x) \geq y$ for some $y \in T$. But $x < y$, so $y = x + s(w)$, for some $w \in \tilde{\mathbb{N}}$, and $y = s(x) + w$. Thus $s(x) \leq y$, so by Proposition 1.1.13, $s(x) = y \in T$. But $s(x) \leq t$ for all $t \in T$, so $s(x)$ is a minimal element of T , contradicting the hypothesis. Thus $s(x) \in S$, so by mathematical induction $S = \tilde{\mathbb{N}}$. Then as $T \subseteq \tilde{\mathbb{N}} \setminus S$, $T = \emptyset$ as desired. ■

In the next section we perform an arithmetic closure of the naturals to obtain the rational field, \mathbb{Q} .

1.2.0 Construction of The Rational Field

First we need the notion of an equivalence relation for our constructions:

Definition 1.2.1 (Equivalence Relation). An equivalence relation on a set S is a subset $E \subseteq S \times S$ such that

1. For all $x \in S$, xEx (reflexivity)
2. For all $x, y \in S$, if xEy then yEx (symmetry)
3. For all $x, y, z \in S$, if xEy and yEz , then xEz (transitivity)

An important property of equivalence relations is their relation to partitions of a set: in particular, we have a bijection between partitions of a set and equivalence relations.

Definition 1.2.2. For an equivalence relation \sim on a set S , and $x \in S$, the equivalence class for x is defined by

$$[x]_{\sim} := \{y \in S : x \sim y\}$$

Note that $[y]_{\sim} = [x]_{\sim}$ if and only if $x \sim y$. Further, the equivalence classes for \sim form a partition on S . That is $S = \cup_{x \in S} [x]_{\sim}$, and if $[y]_{\sim} \neq [x]_{\sim}$, $[y]_{\sim} \cap [x]_{\sim} = \emptyset$.

Definition 1.2.3. Define \sim on $\tilde{\mathbb{N}} \times \tilde{\mathbb{N}}$ by $(a, b) \sim (x, y)$ if and only if $a + y = x + b$.

We consider (a, b) to be $a - b$. We note that this defines an equivalence relation, the proof left to the reader.

Definition 1.2.4. We define the Integers, \mathbb{Z} , to be the set

$$\mathbb{Z} := \{[(x, a)]_{\sim} \in \mathcal{P}(\tilde{\mathbb{N}} \times \tilde{\mathbb{N}}) : x, a \in \tilde{\mathbb{N}}\} = \tilde{\mathbb{N}} \times \tilde{\mathbb{N}} / \sim$$

and we have the natural injection

$$\begin{aligned} \iota : \tilde{\mathbb{N}} &\rightarrow \mathbb{Z} \\ x &\mapsto [(x, 0)] \end{aligned}$$

We can define operations of addition and multiplication on \mathbb{Z} inherited from $\tilde{\mathbb{N}}$.

Definition 1.2.5. For $[(x, a)], [(y, b)] \in \mathbb{Z}$, we define

$$\begin{aligned} [(x, a)] + [(y, b)] &= [(x + y, a + b)] \\ [(x, a)] \cdot [(y, b)] &= [(xy + ab, xb + ay)] \end{aligned}$$

To show these definitions are well defined we must show that the operation is independent of the choice of representative of each equivalence class. This is a routine check left to the reader.

Definition 1.2.6. We define $0 = [(0, 0)]$ and $-1 = [(0, 1)]$ in \mathbb{Z} , and if $m = [(x, a)]$, we define $-m := [(a, x)]$.

Proposition 1.2.1. *For all $m \in \mathbb{Z}$, $m \cdot (-1) = -m$.*

The proof is a quick calculation:

$$m \cdot (-1) = [(x, a)][(0, 1)] = [(x \cdot 0 + a, x + a \cdot 0)] = [(a, x)] = -m$$

Similarly, we have all the properties we derived for $\tilde{\mathbb{N}}$ for the operations on \mathbb{Z} , such as $m \cdot 0 = 0$, $m(n + k) = mn + mk$, $m + n = m + k \implies n = k$, and $m \cdot n = k \cdot n \implies m = k$ if $n \neq 0$. Now we have closed the $\tilde{\mathbb{N}}$ under ring operations, obtaining the integral domain \mathbb{Z} .

Next we perform a similar construction to obtain our field - this process is known as constructing a fraction field for an integral domain.

Definition 1.2.7. *Define an equivalence relation \sim on $\mathbb{Z} \times \mathbb{Z} \setminus \{0\}$ by $(x/a) \sim (y/b)$ if and only if $xb = ya$, for $(x/a), (y/b) \in \mathbb{Z} \times \mathbb{Z} \setminus \{0\}$.*

It is routine to show that this is indeed an equivalence relation on the set. Next, we can define addition and multiplication operations:

Definition 1.2.8. *We define the rationals to be*

$$\mathbb{Q} = \mathbb{Z} \times \mathbb{Z} \setminus \{0\} / \sim$$

For $[m/n], [a/b] \in \mathbb{Q}$, we define

$$[m/n] + [a/b] = [(mb + an)/(nb)]$$

and

$$[m/n] \cdot [a/b] = [(ma)/(nb)]$$

It is a routine verification that these operations are well-defined and independent of the representative. If $x = [(a/b)] \in \mathbb{Q}$, and $x \neq 0$ so $a \neq 0$, then we can define

$$x^{-1} = \frac{1}{x} := [(b/a)] \in \mathbb{Q}$$

We also define $0 := [0/1]$, $1 := [1/1]$, and $-1 := [-1/1]$. So far we have the chain

$$\tilde{\mathbb{N}} \hookrightarrow \mathbb{Z} := \tilde{\mathbb{N}} \times \tilde{\mathbb{N}} / \sim \hookrightarrow \mathbb{Z} \times (\mathbb{Z} \setminus \{0\}) / \sim$$

1.3.0 Divisibility

We now go over some fundamental theorems of number theory involving divisibility.

Definition 1.3.1. *We say $x \in \mathbb{N}$ is **composite** if $a, b \in \mathbb{N}$ such that $x = ab$ and $a, b \neq 1$. If x is not composite, and $x > 1$, then x is said to be **prime**. That is, x is prime if and only if $x = ab$ implies $a = 1$ or $b = 1$.*

Definition 1.3.2. If $x = ab$, $x, a, b \in \mathbb{N}$, then we say a divides x , or a is a divisor of x , and we write $a \mid x$.

Definition 1.3.3. Given $x \in \mathbb{N}$, define the collection of non-trivial divisors as

$$D_x := \{a \in \mathbb{N} \setminus \{1\} : a \mid x\} \subseteq \mathbb{N}$$

Note that if $a \mid x$, then $a \leq x$. As $D_x \subseteq \mathbb{N}$, and $x \in D_x$ so it is non-empty, D_x has a smallest element $p_1 \in D_x$. Then $x = p_1 x_1$ for some $x_1 \in \mathbb{N}$. Then p_1 is prime since if not it can be written as $p_1 = ab$ for $1 < a < p_1$, and then $a \mid x$ with $a < p_1$, contradicting its minimality. If $x_1 > 1$, then we can obtain $x_1 = p_2 x_2$, for p_2 prime and $p_2 \geq p_1$. Repeating in this fashion, since x is finite there must exist $N \in \mathbb{N}$ such that $x_N = 1$ and $x_{N-1} = p_N \cdot 1$. Then $x = p_1 \cdot \dots \cdot p_N$. This is the existence portion of the following result.

Theorem 2 (Fundamental Theorem of Arithmetic).

Every natural number $x > 1$ has a unique factorization, up to reordering, into a product of prime numbers.

Proof. If $x = p_1 \dots p_N = q_1 \dots q_M$, then for each $1 \leq i \leq N$, $p_i \mid q_j$ for some $1 \leq j \leq M$. But, p_i and q_j are prime, so $p_i = q_j$, and after reordering $p_1 \dots p_N = p_1 \dots p_N q_{N+1} \dots q_M$. By cancellation $q_{N+1} \dots q_M = 1$. Thus, $N = M$ and the terms are equal up to reordering. ■

Definition 1.3.4. We say $x, y \in \mathbb{N}$ are coprime if x and y have no common prime factors.

Proposition 1.3.1. If $x, y \in \mathbb{N}$ are coprime, then there exists $m, n \in \mathbb{Z}$ such that

$$xm + ny = 1$$

1.4.0 Reals in terms of Cauchy Sequences

To construct the reals we use the standard notion of a completion of metric spaces using equivalence classes of Cauchy sequences. But first we must define what a sequence is, and what it means for one to be Cauchy.

Definition 1.4.1. We define the absolute value function by

$$|x| = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases}$$

It is a standard proof by cases, that the absolute value function defines a norm on \mathbb{Q} .

Definition 1.4.2. A sequence is a function $a : \mathbb{N} \rightarrow \mathbb{Q}$, denoted $a(j) = a_j$ and $(a_j)_{j=1}^\infty$.

Definition 1.4.3. We say a sequence (a_j) converges to a number $a \in \mathbb{Q}$, and write $a_j \rightarrow a$, if for every $n \in \mathbb{N}$, there exists an index $K(n) \in \mathbb{N}$ such that if $j \geq K(n)$, then $|a_j - a| < \frac{1}{n}$.

Definition 1.4.4. A sequence (a_j) is said to be **Cauchy** if for all $n \in \mathbb{N}$, there exists $K(n) \in \mathbb{N}$ such that if $j, k \geq K(n)$, then

$$|a_j - a_k| < \frac{1}{n}$$

Proposition 1.4.1. If $a_j \rightarrow a$, then (a_j) is Cauchy.

Proof. Since $a_j \rightarrow a$, for $n \in \mathbb{N}$ there exists $K(2n) \in \mathbb{N}$ such that if $j \geq K(2n)$, $|a_j - a| < \frac{1}{2n}$. Thus, if $k, j \geq K(2n)$, then

$$|a_j - a_k| \leq |a_j - a| + |a - a_k| < \varepsilon$$

as desired. ■

Proposition 1.4.2. If (a_j) is Cauchy then (a_j) is bounded.

Proof. Suppose (a_j) is Cauchy. Then there exists $K(1) \in \mathbb{N}$ such that for $k, j \geq K(1)$, $|a_k - a_j| < 1$. Then for all $j \geq K(1)$, $|a_j| < 1 + |a_{K(1)}|$. Letting $M = \max\{|a_1|, \dots, |a_{K(1)-1}|, 1 + |a_{K(1)}|\}$, we have that $a_n \leq M$ or all $n \in \mathbb{N}$, so the sequence is bounded. ■

We now have some standard results about convergence of sequences:

Proposition 1.4.3. If $a_j \rightarrow a$ and $b_j \rightarrow b$, then

$$a_j + b_j \rightarrow a + b, \text{ and } a_j b_j \rightarrow ab$$

If $b \neq 0$, and $b_j \neq 0$ for all j , then

$$a_j/b_j \rightarrow a/b$$

More generally we have

Definition 1.4.5. If $(a_j), (b_j)$ are Cauchy sequences, then $(a_j + b_j)$ is Cauchy, $(a_j b_j)$ is Cauchy, and if there exists $n \in \mathbb{N}$ such that $|b_j| > \frac{1}{n}$ for all j , then (a_j/b_j) is Cauchy.

Although for general metric spaces we have the inclusion

$$\left\{ \begin{array}{c} \text{Convergent} \\ \text{Sequences} \end{array} \right\} \subseteq \left\{ \begin{array}{c} \text{Cauchy} \\ \text{Sequences} \end{array} \right\}$$

the other inclusion is not in general true.

Example 1.4.1. Let $a_j = \sum_{l=0}^j \frac{1}{l!}$, in (\mathbb{Q}, d) , $d(x, y) = |x - y|$. a_j is a Cauchy sequence, as $|a_j - a_k| = \left| \sum_{l=k+1}^j \frac{1}{l!} \right| = \sum_{l=k+1}^j \frac{1}{l!} \rightarrow 0$. For $l \geq 2$ we have $\frac{1/(l+1)!}{1/l!} = \frac{1}{l} \leq \frac{1}{2}$. Then $\frac{1}{(2+j)!} \leq \frac{1}{2^j} \frac{1}{2}$. Then for $j > k \geq 2$,

$$\sum_{l=k+1}^j \frac{1}{l!} = \sum_{l=k-2}^{j-2} \frac{1}{(l+2)!} \leq \sum_{l=k-2}^{l-2} \frac{1}{2^l} \frac{1}{2} < \frac{1}{2} \frac{1}{1 - 1/2} = 1$$

Thus, a_j is a bounded increasing sequence and hence Cauchy. Now observe

$$\begin{aligned} a_{n+j} - a_n &= \frac{1}{(n+1)!} + \dots + \frac{1}{(n+j)!} \\ &\leq \frac{1}{n!} \left(\frac{1}{n+1} + \frac{1}{(n+1)^2} + \dots + \frac{1}{(n+1)^j} \right) \\ &< \frac{1}{n!} \sum_{k=0}^{j-1} \frac{1}{(n+1)^{k+1}} \\ &= \frac{1}{(n+1)!} \frac{1 - \frac{1}{(n+1)^j}}{1 - \frac{1}{n+1}} < \frac{1}{n!n} \end{aligned}$$

So if we fix $N \in \mathbb{N}$, $N+j > N+k \geq N$, then $a_{N+j} - a_{N+k} < \frac{1}{N!N} < \frac{1}{N}$. Hence a_j is Cauchy. Since it is Cauchy, in the complete metric space \mathbb{R} it is convergent, so let $a = \lim a_j$, so we observe $a = \sum_{l=0}^{\infty} \frac{1}{l!} = e$. But $e \notin \mathbb{Q}$, so this limit cannot be in the rationals and hence the rationals is not complete.

The following is a very important series known as the geometric series:

Proposition 1.4.4. *If $a \in \mathbb{Q}$, with $|a| < 1$, then $\sum_{j=0}^{\infty} a^j = \frac{1}{1-a}$.*

Proposition 1.4.5. *If $|a| < 1$, then $|a|^n \rightarrow 0$.*

Proof. If $a = 0$, then $|a|^n = 0$ for all n , so the result holds. Hence, suppose $a \neq 0$. Then $|a|^{j+1} < |a|^j$, so $|a|^n$ is a bounded decreasing sequence, and hence converges in \mathbb{R} . Hence $\lim_{n \rightarrow \infty} |a|^n = k$ for some $k \in \mathbb{R}$. Then $k = \lim_{n \rightarrow \infty} |a|^n = \lim_{n \rightarrow \infty} |a|^{n+1} = |a|k$. But $|a| \neq 1$, so $k = 0$. Thus, $|a|^n \rightarrow 0$, as desired. ■

Proposition 1.4.6 (Bolzano-Weierstrass (Cauchy)). *If (a_j) is a bounded sequence, then there exists a Cauchy subsequence.*

Proof. Since (a_j) is bounded, there exists $M > 0$ such that $|a_j| \leq M$ for all j . In particular, $a_j \in I_0 = [-M, M]$ for all j . Then either $[-M, 0]$ or $[0, M]$ contains an infinite number of a_j . Let I_1 be the one with such. Inductively, suppose there exists $k \in \mathbb{N}$ such that an infinite number of a_j are in I_k , for all $0 \leq l \leq k-1$ $I_{l+1} \subseteq I_l$, and $\ell(I_l) = \frac{2M}{2^l}$. Then, we have a sequence I_j of closed intervals containing infinitely many terms of a_j . Let $b_1 = a_1$, and let $b_k = a_{j(k)}$, where $j(k) = \min \{m \in \mathbb{N} : a_m \in I_k, m > j(k-1)\}$, which exists and is well defined by the construction of I_k and the well-ordering of \mathbb{N} . Then $b_k = a_{j(k)}$ is a subsequence of j , as $j(k) < j(k+1)$ for all k . Now, fix $n \in \mathbb{N}$. As $2^{-j} \rightarrow 0$, there exists $K(2Mn) \in \mathbb{N}$ such that for $j \geq K(2Mn)$, $\frac{1}{2^j} < \frac{1}{2Mn}$. Then, for $k, l \geq K(2Mn)$, $b_k, b_l \in I_{K(2Mn)}$, so

$$|b_k - b_l| \leq \ell(I_{K(2Mn)}) = \frac{2M}{2^{K(2Mn)}} < \frac{2M}{2Mn} = \frac{1}{n}$$

Thus b_j is Cauchy. ■

Corollary 1.4.7. *Each bounded Monotone sequence is Cauchy.*

Proof. Let (a_j) be a bounded monotone sequence. Then we have a Cauchy subsequence (a_{j_n}) . Fix $n \in \mathbb{N}$. Then there exists $K(n) \in \mathbb{N}$ such that if $k, l \geq K(n)$, $|a_{j_k} - a_{j_l}| < \frac{1}{n}$. Let $K'(n) = j_{K(n)}$. Then for $k, l \geq K'(n)$, let $m \in \mathbb{N}$ such that $j_m \geq k, l$ and $m \geq K(n)$. Then as a_j is an increasing (decreasing) sequence, so

$$a_{j_{K(n)}} \leq a_k \leq a_l \leq a_{j_m} \text{ (respectively } a_{j_{K(n)}} \geq a_k \geq a_l \geq a_{j_m} \text{)}$$

Then $0 \leq a_l - a_k \leq a_{j_m} - a_{j_{K(n)}}$, so $|a_l - a_k| < \frac{1}{n}$, and similarly for a decreasing sequence. Hence a_j is Cauchy. ■

We now begin defining the reals using equivalence relations on our Cauchy sequences:

Definition 1.4.6. Let $S = \{(a_j) \subseteq \mathbb{Q} : (a_j) \text{ is Cauchy}\}$. Define an equivalence relation \sim on S by

$$(a_j) \sim (b_j) \iff a_j - b_j \rightarrow 0$$

It is a routine check that \sim is an equivalence relation on S .

Definition 1.4.7. We define $\mathbb{R} := S / \sim$, so $x \in \mathbb{R}$ if and only if $x = [(a_j)]$ for some Cauchy sequence (a_j) in \mathbb{Q} .

Definition 1.4.8. If $x = [(a_j)], y = [(b_j)] \in \mathbb{R}$, we define

$$x + y := [(a_j + b_j)] \quad xy := [(a_j b_j)]$$

and $-x := [(-a_j)]$.

As with the notion of an equivalence relation, it is a routine check using the boundedness of Cauchy sequences to prove that these operations are well defined. We can then define a natural injection $\mathbb{Q} \hookrightarrow \mathbb{R}$ by $a \mapsto [(a, a, a, \dots)]$. In particular, $0 := [(0, 0, 0, \dots)]$ in \mathbb{R} .

Now, note that if $x = [(a_j)], y = [(b_j)] \in \mathbb{R}$, then $x \neq y$ if and only if $a_j - b_j$ does not converge to 0, so there exists $n \in \mathbb{N}$ such that for all $j \in \mathbb{N}$, there exists $k \geq j$ such that

$$|a_k - b_k| \geq \frac{1}{n}$$

Specializing to the case of $y = 0 = [(0, 0, 0, \dots)]$, as (a_j) is Cauchy, there exists $K(2n) \in \mathbb{N}$ such that $k, l \geq K(2n)$, $|a_k - a_l| < \frac{1}{2n}$, so in particular $|a_j| \geq |a_k| - |a_j - a_k| > \frac{1}{2n}$ for all $j \geq K(2n)$. It follows that either $a_j > \frac{1}{2n} > 0$ for all $j \geq K(2n)$, or $a_j < \frac{-1}{2n} < 0$ for all $j \geq K(2n)$.

Thus, if $x \neq 0$, then $x = [(a_j)] = [(\alpha_j)]$ such that there exists $n \in \mathbb{N}$ such that either $\alpha_j \geq \frac{1}{2n}$ for all j , or $\alpha_j \leq \frac{-1}{2n}$ for all j . Then we can define $x^{-1} = \frac{1}{x} := [(\alpha_j^{-1})]$.

Definition 1.4.9. We define the following subsets of \mathbb{R} :

$$\begin{aligned} \mathbb{R}^+ &= \{x = [(a_j)] : \exists n, K \in \mathbb{N}; a_j \geq \frac{1}{2n}, \forall j \geq K\} \\ \mathbb{R}^- &= \{x = [(a_j)] : \exists n, K \in \mathbb{N}; a_j \leq \frac{-1}{2n}, \forall j \geq K\} \end{aligned}$$

We have shown that if $x \neq 0$ then either $x \in \mathbb{R}^+$ or $x \in \mathbb{R}^-$. Thus

$$\mathbb{R} = \mathbb{R}^+ \sqcup \{0\} \sqcup \mathbb{R}^-$$

Proposition 1.4.8. For $x \in \mathbb{R}$, $x \in \mathbb{R}^+$ if and only if $-x \in \mathbb{R}^-$, and $x \in \mathbb{R}^-$ if and only if $-x \in \mathbb{R}^+$.

Definition 1.4.10. We define a total order $<$ on \mathbb{R} by

$$x < y \iff y - x \in \mathbb{R}^+ \iff x = [(a_j)], y = [(b_j)], \exists n, K \in \mathbb{N}; b_j - a_j \geq \frac{1}{2n} \forall j \geq K$$

We have a few standard results about the order relation on \mathbb{R} :

Proposition 1.4.9. Let $x_1, x_2, y_1, y_2 \in \mathbb{R}$. Then

- $x_1 < y_1, x_2 < y_2 \implies x_1 + x_2 < y_1 + y_2$
- $x_1 < y_1 \implies -y_1 < -x_1$
- $0 < x_1 < y_1, c > 0$, then $0 < cx < cy$
- $0 < x < y \iff 0 < \frac{1}{y} < \frac{1}{x}$

Note that in \mathbb{N} we have well-ordering, but under the standard orders on \mathbb{Q} and \mathbb{R} this property does not hold.

Definition 1.4.11. For $S \subseteq \mathbb{R}$, we say x is an upper bound of S if $s \in S$ implies $s \leq x$. Dually, we say y is a lower bound for S if $s \in S$ implies $s \geq y$.

Definition 1.4.12. For $S \subseteq \mathbb{R}$, the least upper bound, denoted $\sup S$, is an upper bound for S such that if y is any other upper bound for S then $\sup S \leq y$. Dually, the greatest lower bound, denoted $\inf S$, is a lower bound for S such that if y is any other lower bound for S , then $y \leq \inf S$.

Theorem 1.4.10 (Completeness of \mathbb{R}). If (x_j) is a Cauchy sequence of real numbers, then there exists $x = [(a_j)] \in \mathbb{R}$ such that $x_j \rightarrow x$, of $x_j \sim a_j$, extending the equivalence relation to \mathbb{R} .

Proposition 1.4.11. If S is a non-empty subset of \mathbb{R} that has an upper bound, then there exists $x \in \mathbb{R}$ such that $x = \sup S$.

Proof. By hypothesis, there exists $x_0 \in \mathbb{R}$ such that for all $s \in S$, $s \leq x_0$. As S is non-empty, there exists $s_0 \in S$. Define an interval $I_0 = [s_0, x_0]$, and divide it into 2 subintervals, I_0^l, I_0^r . If $I_0^l \cap S \neq \emptyset$ let $I_1^* = I_0^r$, and otherwise let $I_1^* = I_0^l$. In either case $I_1 = [s_1, x_1]$ is such that x_1 is an upper bound of S , and where we choose $s_1 \in I_1^*$ such that $s_1 \in S$. Further, $s_0 \leq s_1 \leq x_1 \leq x_0$, and letting $x_0 - s_0 = L$, $\ell(I_1) \leq \frac{L}{2}$. Proceeding inductively we find sequences $s_0 \leq s_1 \leq s_2 \leq \dots$ in S and $x_0 \geq x_1 \geq x_2 \geq \dots$, with $I_j = [s_j, x_j]$, $\ell(I_j) \leq \frac{L}{2^j}$, with $x_j \geq s$ for all $s \in S$, and all

$j \in \tilde{\mathbb{N}}$. Note x_j is a decreasing bounded sequence, so it converges to some $x \in \mathbb{R}$, as \mathbb{R} is complete. As $x_j \geq s$ for all $s \in S$, $x \geq s$ so x is an upper bound. Further, if $\varepsilon > 0$, there exists $K \in \mathbb{N}$ such that for all $j \geq K$, $\frac{1}{2j} < \frac{\varepsilon}{L}$, so $0 \leq x_j - s_j < \frac{L}{2j} < \varepsilon$ for all $j \geq K$. Then $x - \varepsilon < s_j$ for all $j \geq K$. Thus, $x - \varepsilon$ is not an upper bound of S , and hence x must be the least upper bound. ■

1.5.0 Axiomatized Reals

Definition 1.5.1 (The Reals). The real number system \mathbb{R} is an ordered field which contains \mathbb{Q} as a subfield, which satisfies the axiom of choice. In particular, the real numbers is a set \mathbb{R} with two binary operations $+$ and \cdot , two distinct elements 0 and 1 , and a subset \mathbb{P} of positive numbers satisfying the following 13 postulates:

1. Addition is associative: $\forall a, b, c \in \mathbb{R}, a + (b + c) = (a + b) + c$
2. The number 0 is an additive identity: $\forall a \in \mathbb{R}, a + 0 = 0 + a = a$
3. Additive inverses exist: $\forall a \in \mathbb{R}; \exists (-a) \in \mathbb{R} \text{ s.t. } a + (-a) = (-a) + a = 0$
4. Addition is commutative: $\forall a, b \in \mathbb{R}, a + b = b + a$
5. Multiplication is associative: $\forall a, b, c \in \mathbb{R}, a \cdot (b \cdot c) = (a \cdot b) \cdot c$
6. The number 1 is a multiplicative identity: $\forall a \in \mathbb{R} a \cdot 1 = 1 \cdot a = a$
7. Multiplicative inverses exist: $\forall a \neq 0; \exists a^{-1} \in \mathbb{R} \text{ s.t. } a \cdot a^{-1} = a^{-1} \cdot a = 1$
8. Multiplication is commutative: $\forall a, b \in \mathbb{R}, a \cdot b = b \cdot a$
9. The distributive law: $\forall a, b, c \in \mathbb{R}, a \cdot (b + c) = a \cdot b + a \cdot c$
10. The trichotomy of \mathbb{P} : for every $a \in \mathbb{R}$, exactly one of the following holds: $a = 0, a \in \mathbb{P}, (-a) \in \mathbb{P}$
11. Closure under addition: if $a \in \mathbb{P}$ and $b \in \mathbb{P}$, then $a + b \in \mathbb{P}$
12. Closure under multiplication: if $a \in \mathbb{P}$ and $b \in \mathbb{P}$, then $a \cdot b \in \mathbb{P}$
13. (to be added)

From positive postulates we can define the order relations $>, <, \geq, \leq$ on \mathbb{R} for $a, b \in \mathbb{R}$ by

1. $a > b$ if $a - b \in \mathbb{P}$
2. $a < b$ if $b > a$
3. $a \geq b$ if $a > b$ or $a = b$
4. $a \leq b$ if $a < b$ or $a = b$

Note in particular $a > 0$ if and only if $a \in \mathbb{P}$.

Remark 1.5.1. A few points which follow from the postulates are:

1. Finite sums such as $a_1 + a_2 + \dots + a_n$ are well defined
2. The additive identity is unique (also multiplicative)
3. Additive inverses are unique (also multiplicative)
4. Subtraction can be defined
5. $a \cdot b = b \cdot c \iff a = 0 \vee b = c$
6. $a \cdot b = \iff a = 0 \vee b = 0$
7. $a - b = b - a \iff a = b$
8. A “well behaved” order relation can be defined.
9. The “absolute value” function $a \mapsto |a|$ can be defined by

$$|a| = \begin{cases} a, & a \geq 0 \\ -a, & a \leq 0 \end{cases}$$

and for all $a, b \in \mathbb{R}$, the triangle inequality

$$|a + b| \leq |a| + |b|$$

holds

Axiom 1.5.2 (Axiom of Completeness). Every non-empty subset of the real numbers that is bounded above has a least upper bound.

Upper and Lower Bounds

Definition 1.5.3 (Bounds). A set $A \subseteq \mathbb{R}$ is **bounded above** if there exists a number $b \in \mathbb{R}$ such that $a \leq b$ for all $a \in A$. The number b is called an upper bound for A .

Similarly, the set A is **bounded below** if there exists a lower bound $l \in \mathbb{R}$ satisfying $l \leq a$ for every $a \in A$.

Definition 1.5.4 (Least Upper Bound). A real number s is the least upper bound for a set $A \subseteq \mathbb{R}$ if it meets the following two criteria:

1. s is an upper bound for A ;
2. if b is any upper bound for A , then $s \leq b$.

The least upper bound of a set A is also called the supremum of A , and denoted by $\sup A$.

Definition 1.5.5 (Greatest Lower Bound). A real number i is the Greatest Lower bound for a set $A \subseteq \mathbb{R}$ if it meets the following two criteria:

1. i is a lower bound for A ;
2. if b is any lower bound for A , then $b \leq i$.

The greatest lower bound of a set A is also called the infimum of A , and denoted by $\inf A$.

Remark 1.5.2. From the definitions we assert that the least upper bound and greatest lower bound of a set, if they exist, are unique.

Example 1.5.1. Consider the set

$$A = \left\{ \frac{1}{n} : n \in \mathbb{N} \right\} = \left\{ 1, \frac{1}{2}, \frac{1}{3}, \dots \right\}$$

The set A is bounded above and below. Moreover, the least upper bound of A is $\sup A = 1$, which is in A , while $\inf A = 0$, which is not in A .

Definition 1.5.6 (Max and Min). A real number a_0 is a maximum of a set A if a_0 is an element of A and $a_0 \geq a$ for all $a \in A$. Similarly, a number a_1 is a minimum of A if $a_1 \in A$ and $a_1 \leq a$ for all $a \in A$.

Example 1.5.2. Consider the open interval $(0, 2)$, and the closed interval $[0, 2]$. Note both sets are bounded above and below, and both have the same infimum and supremum, namely $\inf = 0$ and $\sup = 2$. However, $[0, 2]$ has both a maximum and a minimum, namely its infimum and supremum, while $(0, 2)$ has neither.

Example 1.5.3. Let $A \subseteq \mathbb{R}$ be a non-empty and bounded above set, and let $c \in \mathbb{R}$. Define the set $c + A$ by

$$c + A := \{c + a : a \in A\}$$

Then I claim that $\sup(c + A) = c + \sup A$.

Proof. Let $\alpha = c + \sup A$. First let us show that α is an upper bound of $c + A$. Indeed, for $x \in c + A$ we can write $x = c + a$ for some $a \in A$ by definition. Then, by definition we have that $a \leq \sup A$. Thus, adding c to both sides we obtain

$$x = c + a \leq c + \sup A = \alpha$$

Therefore, as x was arbitrary α is indeed an upper bound of $c + A$. Now, suppose b is an upper bound of $c + A$. Then, $c + a \leq b$ for all $c + a \in c + A$, so in particular $a \leq b - c$ for all $a \in A$. Then, $b - c$ is an upper bound for A , so as $\sup A$ is the least upper bound of A we have that $\sup A \leq b - c$. Hence, we conclude that $\alpha = c + \sup A \leq b$. Thus α satisfies the axioms of a least upper bound for $c + A$, and we conclude that $\sup(c + A) = c + \sup A$. ■

Lemma 1.5.1. Assume $s \in \mathbb{R}$ is an upper bound for a set $A \subseteq \mathbb{R}$. Then $s = \sup A$ if and only if, for every choice $\epsilon > 0$, there exists an element $a \in A$ satisfying $s - \epsilon < a$.

Proof. Let $s \in \mathbb{R}$ be an upper bound for a set $A \subseteq \mathbb{R}$.

(\implies) First, suppose that $s = \sup A$, and choose $\epsilon \in \mathbb{R}$ with $\epsilon > 0$. Then $s - \epsilon$ is not an upper bound of A . Indeed, if $s - \epsilon$ was an upper bound then $s \leq s - \epsilon$ which implies that $\epsilon \leq 0$, but by assumption $\epsilon > 0$. Thus, there must exist $a \in A$ such that $s - \epsilon < a$, satisfying the implication.

(\impliedby) Conversely, suppose that for all $\epsilon > 0$ there exists $a \in A$ such that $s - \epsilon < a$. Now, suppose that b is an upper bound of A , and towards a contradiction suppose $s > b$. Then $s - b > 0$, so there exists $a \in A$ such that $s - (s - b) < a$. In particular, $b < a$. However, $a \in A$ and b is an upper bound of A by assumption, so $b < a$ is a contradiction. Therefore we conclude that $s \leq b$, so s is the supremum of A by definition. ■

Theorem 1.5.2 (Archimedean Property for the Reals). *For all $x, y > 0$ in \mathbb{R} , there exists $n \in \mathbb{N}$ such that $nx > y$.*

Proof. Towards a contradiction suppose $nx \leq y$ for all $n \in \mathbb{N}$. Then the set $\{nx : n \in \mathbb{N}\}$ is bounded above by y . Thus, by the least upper bound property of \mathbb{R} we have a supremum $\alpha \in \mathbb{R}$. Then for all $n \in \mathbb{N}$ $\alpha \geq nx$. In particular, $\alpha \geq (n+1)x$ for all $n \in \mathbb{N}$, so $\alpha - x \geq nx$ for all $n \in \mathbb{N}$. But this implies that $\alpha - x$ is also an upper bound of the set, which contradicts the fact that α is the least upper bound. Thus, we must have that $nx > y$ for some $n \in \mathbb{N}$, as claimed. ■

Corollary 1.5.3. \mathbb{N} is not bounded above.

Corollary 1.5.4. *For any $\epsilon > 0$ there is a natural number n with $1/n < \epsilon$.*

Proof. Consider $0 < 1/\epsilon \in \mathbb{R}$ and $1 \in \mathbb{R}$. Then by the Archimedean Property of \mathbb{R} there exists $n \in \mathbb{N}$ such that $1 \cdot n > 1/\epsilon$. In particular, we have that $n > 0$, so $\epsilon > 1/n$, completing the proof. ■

1.6.0 Metric Properties of the Reals

First we extend our definition of sequences to the reals:

Definition 1.6.1. *A sequence (p_j) in \mathbb{R} converges to a point $p \in \mathbb{R}$ if and only if for every $\epsilon > 0$ there exists $N \in \mathbb{N}$ such that if $j \geq N$, then $|p_j - p| < \epsilon$.*

Using sequences we can define notions of our topology, such as closed and open sets, and limit points:

Definition 1.6.2. $S \subseteq \mathbb{R}$ is said to be **closed** if and only if whenever $(p_j) \subseteq S$ is a sequence in S which converges to a point $p \in \mathbb{R}$, then $p \in S$.

Definition 1.6.3. A point $p \in \mathbb{R}$ is said to be a **limit point** of S if there exists $(p_j) \subseteq S$ such that p_j converges to p , and $p_j \neq p$ for all $j \in \mathbb{N}$.

Note that S is closed if and only if S contains all of its limit points.

Definition 1.6.4. $U \subseteq \mathbb{R}$ is said to be open if and only if $U^c = \mathbb{R} \setminus U$ is closed.

Definition 1.6.5. For $S \subseteq \mathbb{R}$, the closure of S , \bar{S} , is defined as

$$\bar{S} := S \cup S'$$

where

$$S' = \{p \in \mathbb{R} : p \text{ is a limit point of } S\}$$

Proposition 1.6.1. For all $S \subseteq \mathbb{R}$, $\overline{\bar{S}} = \bar{S}$

Proof. Let $(p_j) \subseteq \bar{S}$ which converges to some point $p \in \mathbb{R}$. Then for each j we have (b_{jk}) in S which converges to p_j . For each $j \in \mathbb{N}$, there exists $K(j) \in \mathbb{N}$ such that for $k \geq K(j)$, $|b_{jk} - p_j| < \frac{1}{j}$. Define (c_j) by $c_j = b_{jK(j)}$. Fix $\varepsilon > 0$. Then there exists $N \in \mathbb{N}$ such that $j \geq N$ implies $|p_j - p| < \frac{\varepsilon}{2}$. By the Archimedian property there exists $n \in \mathbb{N}$ such that $\frac{1}{n} < \frac{\varepsilon}{2}$. Then for a $j \geq \max\{n, N\}$,

$$|c_j - p| \leq |c_j - p_j| + |p_j - p| < \frac{1}{n} + \frac{\varepsilon}{2} < \varepsilon$$

Thus $(c_j) \subseteq S$ and $c_j \rightarrow p$, so $p \in \bar{S}$. Hence, $\bar{S} \supseteq \overline{\bar{S}}$, and by definition $\bar{S} \subseteq \overline{\bar{S}}$, so $\bar{S} = \overline{\bar{S}}$. ■

Theorem 1.6.2. Every Cauchy sequence in \mathbb{R} has a limit point in \mathbb{R} .

Note if $(x_j) = ([a_{jk}])$ is Cauchy in \mathbb{R} , then (a_{jj}) is Cauchy in \mathbb{Q} with $a_{jj} - x_j \rightarrow 0$, so then x_j converges to $[a_{jj}]$.

Proposition 1.6.3 (Density of the Rationals). For all $x \in \mathbb{R}$ and $\varepsilon > 0$, there exists $y \in \mathbb{Q}$ such that $|y - x| < \varepsilon$.

In particular, for all $a < b$ in \mathbb{R} , there exists $c \in \mathbb{Q}$ such that $a < c < b$. Indeed, for $x = [a_j]$, $a_j \rightarrow x$ so there exists $N \in \mathbb{N}$ such that $|a_N - x| < \varepsilon$ for any $\varepsilon > 0$.

Definition 1.6.6. A subset $K \subseteq \mathbb{R}$ is sequentially compact if and only if for every infinite sequence $(p_j) \subseteq K$, there exists a subsequence which converges to a point in K .

Theorem 3 (Bolzano-Weierstrass Property).

Every bounded sequence of real numbers has a convergent subsequence.

Theorem 1.6.4. If $K \neq \emptyset$, $K \subseteq \mathbb{R}$, and K is closed and bounded, then K is sequentially compact.

Proof. If $K \subseteq \mathbb{R}$, $K \neq \emptyset$, is bounded and $(p_j) \subseteq K$, (p_j) has a convergent subsequence (p_{j_k}) by Bolzano-Weierstrass, so $p_{j_k} \rightarrow p$ for some $p \in \mathbb{R}$. But K is closed so $(p_{j_k}) \subseteq K$, so $p \in K$. ■

Note that if $K \subseteq \mathbb{R}$ is compact, then K is closed since all subsequences of a convergent sequence converge to the same point. Additionally, K is bounded as otherwise we can construct $p_1 \in K$, $p_2 \in K$ such that $|p_2| > |p_1| + 1$, and for $p_k \in K$, choose $p_{k+1} \in K$ such that $|p_{k+1}| > |p_k| + 1$. Thus, for all $j, k \in \mathbb{N}$, $|p_j - p_k| > 1$, so (p_j) has no convergent subsequence.

Theorem 4 (Heine-Borel).

If $K \neq \emptyset$, $K \subseteq \mathbb{R}$, the following are equivalent:

- K is sequentially compact
- K is closed and bounded

If K is compact, $K \neq \emptyset$, in \mathbb{R} , then there exists $a, b \in K$ such that

$$a = \min K := \inf K \quad \text{and} \quad b = \max K := \sup K$$

which is to say K contains its infimum and supremum.

Definition 1.6.7. A function $f : S \rightarrow \mathbb{R}$, $\emptyset \neq S \subseteq \mathbb{R}$, is said to be continuous at a point $p \in S$ if whenever $(p_j) \subseteq S$ such that $p_j \rightarrow p$, then $f(p_j) \rightarrow f(p)$

Definition 1.6.8. A point $p \in S$ is said to be an isolated point of S if there exists some $\varepsilon > 0$ such that $(p - \varepsilon, p + \varepsilon) \cap S = \{p\}$

Every function is continuous at isolated points of its domain.

Definition 1.6.9. If $f : S \rightarrow \mathbb{R}$ is continuous at every point $p \in S$, we say f is continuous on S .

Proposition 1.6.5. If $K \subseteq \mathbb{R}$, $K \neq \emptyset$, is a compact subset of \mathbb{R} , and $f : K \rightarrow \mathbb{R}$ is continuous, then $f(K)$ is compact.

Proof. Let $(q_k) \subseteq f(K)$. Then we have $(p_k) \subseteq K$ such that $f(p_k) = q_k$ for all k . Then as K is sequentially compact there exists $p \in K$ and a subsequence $(p_{k_j}) \subseteq K$ such that $p_{k_j} \rightarrow p$. As f is continuous we have $q_{k_j} = f(p_{k_j}) \rightarrow f(p)$, where $f(p) \in f(K)$. Thus $f(K)$ is sequentially compact as claimed. ■

Proposition 1.6.6. If $\emptyset \neq K \subseteq \mathbb{R}$ is sequentially compact and $f : K \rightarrow \mathbb{R}$ is continuous on K , then there exist $q, p \in K$ such that

$$f(p) = \max_K f, \quad f(q) = \min_K f$$

Theorem 5 (Intermediate Value Theorem).

If $f : [a, b] \rightarrow \mathbb{R}$ is continuous on $[a, b]$ and $f(a) < c < f(b)$ (or $f(a) > c > f(b)$), then there exists $x \in (a, b)$ such that $f(x) = c$.

Proof. Let $S = \{y \in [a, b] : f(y) \leq c\}$. Without loss of generality suppose $f(a) < c < f(b)$ (if the other inequality holds, replace f with $-f$). Then $a \in S$ and $b \notin S$. Further, if $(y_j) \in S$, $y_j \rightarrow y$, then by continuity $f(y_j) \rightarrow f(y)$ and as $f(y_j) \leq c$ for all j , $f(y) \leq c$. Thus $y \in S$, so S is closed. As $S \subseteq [a, b]$, S is bounded, so by Heine-Borel S is compact. Let $x = \max S \in S$. Then $f(x) \leq c$. If $f(x) < c$, then for some $\varepsilon > 0$, $f(y) < c$ for all $y \in (x - \varepsilon, x + \varepsilon)$. Let $\varepsilon = c - f(x) > 0$. As f is continuous, there exists $\delta > 0$ such that if $|x - y| < \delta$, $|f(x) - f(y)| < \frac{\varepsilon}{2}$. Then $c - f(y) = c - f(x) - (f(y) - f(x)) \geq |c - f(x)| - |f(y) - f(x)|$, which is greater than or equal to $\varepsilon/2$, so $f(y) < c$. Taking $y = x + \frac{\delta}{2}$, $f(y) \leq c$, so $y \in S$, but $y > x = \max S$ which is a contradiction. Thus, $f(x) \leq c$, so $f(x) = c$. ■

Proposition 1.6.7. Suppose K is sequentially compact and $X_1 \supseteq X_2 \supseteq X_3 \supseteq \dots$ is a sequence of closed subsets of K so all X_i are compact by Heine-Borel. If $X_m \neq \emptyset$, for all m , then $\bigcap_{m \geq 1} X_m \neq \emptyset$.

Proof. Let $x_m \in X_m$. As K is compact and $x_m \in K$, there exists a convergent subsequence $x_{m_j} \rightarrow x \in K$. Since $X_1 \supseteq X_2 \supseteq \dots$,

$$\{x_{m_l} : l \geq j\} \subseteq X_{m_j}$$

But X_{m_j} is closed, so $x \in X_{m_j}$, for all j . Then for all $m \in \mathbb{N}$, $x \in X_m$ as for all $n \in \mathbb{N}$ there exists $m_j \geq n$ so $x \in X_{m_j} \subseteq X_n$. Thus $x \in \bigcap_{m \geq 1} X_m$, as claimed. ■

Corollary 1.6.8. If K is sequentially compact and $U_1 \subseteq U_2 \subseteq \dots$ is a sequence of open sets such that $K \subseteq \bigcup_{j \geq 1} U_j$, then there exists $M \in \mathbb{N}$ such that $K \subseteq U_M$.

Use Proposition 1.6.7 with $X_j = K \setminus U_j$.

We now discuss some general results on open and closed sets:

Proposition 1.6.9. If $\{A_\alpha\}_{\alpha \in J}$ is a family of closed sets in \mathbb{R} , then $\bigcap_{\alpha \in J} A_\alpha$ is closed. If A and B are closed, then $A \cup B$ is closed.

Proof. Suppose $A_\alpha, \alpha \in J$ are as in the hypothesis. If $\emptyset = \bigcap_{\alpha \in J} A_\alpha$ then the claim vacuously holds. Otherwise, let $(p_j) \subseteq \bigcap_{\alpha \in J} A_\alpha$ such that $p_j \rightarrow p \in \mathbb{R}$. As A_α is closed for all $\alpha \in J$, it follows that $p \in A_\alpha$, so $p \in \bigcap_{\alpha \in J} A_\alpha$.

Next, let A and B be closed, and take $(p_j) \subseteq A \cup B$ such that $p_j \rightarrow p \in \mathbb{R}$. Either infinitely many points of the sequence are in A or infinitely many are in B . Without loss of generality suppose infinitely many are in A . Then there exists a subsequence $(p_{j_k}) \subseteq (p_j)$ contained in A , which will converge to p so as A is closed $p \in A$. Thus $p \in A \cup B$, so the union is closed. ■

Corollary 1.6.10. If $\{U_\alpha\}_{\alpha \in J}$ is a family of open sets in \mathbb{R} , then $\bigcup_{\alpha \in J} U_\alpha$ is open. If A and B are open, then $A \cap B$ is open.

Conversely, we have $I_n = [-1 + \frac{1}{n}, 1 - \frac{1}{n}]$, a collection of closed intervals, whose union is $\bigcup_{n \geq 1} I_n = (-1, 1)$ is not closed. Further, if $U_n = (-\frac{1}{n}, 1 + \frac{1}{n})$, then $\bigcap_{n \geq 1} U_n = [0, 1]$ is not open.

Definition 1.6.10. The ball of radius $r > 0$ centered at $x \in \mathbb{R}$ is defined by

$$B_r(x) := \{y \in \mathbb{R} : |x - y| < r\}$$

Proposition 1.6.11. $U \subseteq \mathbb{R}$ is open if and only if for all $x \in U$, there exists $r_x > 0$ such that $B_{r_x}(x) \subseteq U$.

Proof. First we prove the reverse implication:

\Leftarrow If for all $x \in U$ there exists $r_x > 0$ such that $B_{r_x}(x) \subseteq U$, then $U = \bigcup_{x \in U} B_{r_x}(x)$. Each $B_{r_x}(x) = (x - r_x, x + r_x)$ is open as $(-\infty, x - r_x] \cup [x + r_x, \infty)$ is a finite union of closed sets. Thus U is open, being the union of open sets.

\Rightarrow Towards a contradiction there exists $x \in U$ such that for all $r > 0$, $B_r(x) \cap U^c \neq \emptyset$. Then by the axiom of choice there exists $f : X \rightarrow \bigcup X$ with $X = \{B_{1/n}(x) \cap U^c : n \in \mathbb{N}\}$, and we can define a sequence $a(n) = f(B_{1/n}(x) \cap U^c)$ which converges to x , and $(a_n) \subseteq U^c$ which is closed. But $x \in U$ implies $x \notin U^c$ contradicting the closedness of U^c , so U must satisfy the hypothesis. ■

Definition 1.6.11. A topological space (X, τ) is called separable if it has a countable dense subset.

\mathbb{R} is an example of a separable space, with countable dense subset \mathbb{Q} .

Definition 1.6.12. A topological space (X, τ) is called Lindelöf if and only if every open cover of X has a countable subcover.

Definition 1.6.13. A topological space (X, τ) is called second countable if τ has a countable base.

All metrizable spaces are second countable if and only if they are separable, as we can take the rational balls around points of the countably dense subset. Thus, $\tau_{\mathbb{R}} = \bigcup \mathcal{B}$, where $\mathcal{B} = \{B_p(q) : p, q \in \mathbb{Q}, p > 0\}$ is a countable base.

Definition 1.6.14. A covering of a set F is any family of sets $\{X_\alpha\}_{\alpha \in \mathcal{A}}$, such that $F \subseteq \bigcup_{\alpha \in \mathcal{A}} X_\alpha$.

Definition 1.6.15. An open covering of a topological space is a covering by open sets.

Proposition 1.6.12. If $K \subseteq \mathbb{R}$ is sequentially compact, then every open covering of K has a finite subcovering.

Proof. Suppose $\emptyset \neq K \subseteq \mathbb{R}$ is sequentially compact. Let $K \subseteq \bigcup_{\alpha \in J} U_\alpha$ be an open covering.

Note $U_\alpha = \bigcup_{x \in U_\alpha} B_{p_{\alpha,x}}(q_{\alpha,x})$ such that $x \in B_{p_{\alpha,x}}(q_{\alpha,x})$, as U_α is open. Hence

$$K \subseteq \bigcup_{\alpha \in J} U_\alpha = \bigcup_{\alpha \in J} \bigcup_{x \in U_\alpha} B_{p_{\alpha,x}}(q_{\alpha,x})$$

but the right side consists of countably many distinct open sets. Now consider $K \subseteq \bigcup_{j \geq 1} V_j$ is countable. Let $J_n = \bigcup_{j=1}^n V_j$. Then $K \subseteq \bigcup_{j \geq 1} J_j$, and $J_1 \subseteq J_2 \subseteq \dots$ so by Proposition ?? there exists $M \in \mathbb{N}$ such that $K \subseteq J_M = \bigcup_{j=1}^M V_j$. Thus, in particular there exist $B_{p_{\alpha,x_1}}(q_{\alpha,x_1}), \dots, B_{p_{\alpha,x_M}}(q_{\alpha,x_M})$ such that $K \subseteq \bigcup_{j=1}^M B_{p_{\alpha,x_j}}(q_{\alpha,x_j})$. Thus $K \subseteq \bigcup_{j=1}^M U_{\alpha_j}$, so we have a finite subcovering of K as desired. ■

Proposition 1.6.13. *If $K \subseteq \mathbb{R}$ is topologically compact, then K is sequentially compact.*

Proof. We prove the equivalent notion of limit point compactness (which is equivalent for metric spaces). Then we argue by contrapostive, supposing S has no accumulation points. Then S and $S_x = S \setminus \{x\}$ is closed for all $x \in S$. Setting $U_x = \mathbb{R} \setminus S_x$, we have that $K = (\bigcup_{x \in S} U_x) \cup \mathbb{R} \setminus S$ is an open cover, and as K is topologically compact we have a finite subcover $U_{x_1}, \dots, U_{x_N}, \mathbb{R} \setminus S$. Then U_{x_1}, \dots, U_{x_N} covers S , so $S = \bigcup_{i=1}^N U_{x_i} \cap S = \bigcup_{i=1}^N \{x_i\} = \{x_1, \dots, x_N\}$, so S is finite. Thus, K is limit point compact as desired. ■

Thus, we have the equivalence between sequentially compact, topologically compact, and limit point compact, for subsets of \mathbb{R} .

1.7.0 Limits

Remark 1.7.1 (Motivating Definition). The function f approaches the limit $l \in \mathbb{R}$ near $a \in \mathbb{R}$, if we can make $f(x)$ as “close as we like” to l by requiring that x be “sufficiently close to,” but unequal to, a .

Definition 1.7.1 (Limit). *A real valued function $f : \mathbb{R} \rightarrow \mathbb{R}$ approaches the limit l near a if for every $\epsilon > 0$ there is some $\delta > 0$ such that, for all $x \in \mathbb{R}$, if $0 < |x - a| < \delta$, then $|f(x) - l| < \epsilon$.*

Notation 1.7.2. We denote the number l which a function f approaches near $a \in \mathbb{R}$ by $\lim_{x \rightarrow a} f(x)$, read the limit of $f(x)$ as x approaches a .

Lemma 1.7.1.

1. If

$$|x - x_0| < \frac{\epsilon}{2} \text{ and } |y - y_0| < \frac{\epsilon}{2}$$

then

$$|(x + y) - (x_0 + y_0)| < \epsilon$$

2. If

$$|x - x_0| < \min \left(1, \frac{\epsilon}{2(|y_0| + 1)} \right) \text{ and } |y - y_0| < \frac{\epsilon}{2(|x_0| + 1)}$$

then

$$|xy - x_0y_0| < \epsilon$$

3. If $y_0 \neq 0$ and

$$|y - y_0| < \min \left(\frac{|y_0|}{2}, \frac{\epsilon|y_0|^2}{2} \right)$$

then $y \neq 0$ and

$$\left| \frac{1}{y} - \frac{1}{y_0} \right|$$

Proof. (1) Suppose $|x - x_0| < \frac{\epsilon}{2}$ and $|y - y_0| < \frac{\epsilon}{2}$. Then it follows that

$$\begin{aligned} |(x + y) - (x_0 + y_0)| &= |(x - x_0) + (y - y_0)| \\ &\leq |x - x_0| + |y - y_0| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

as desired.

(2) Next, suppose $|x - x_0| < \min \left(1, \frac{\epsilon}{2(|y_0| + 1)} \right)$ and $|y - y_0| < \frac{\epsilon}{2(|x_0| + 1)}$. Note that as $|x - x_0| < 1$ we have that $|x| - |x_0| < 1$ so $|x| < 1 + |x_0|$. It follows that

$$\begin{aligned} |xy - x_0y_0| &= |xy - xy_0 + xy_0 - x_0y_0| \\ &\leq |x||y - y_0| + |y_0||x - x_0| \\ &< (|x_0| + 1) \frac{\epsilon}{2(|x_0| + 1)} + (|y_0| + 1) \frac{\epsilon}{2(|y_0| + 1)} \\ &= \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

(3) Suppose $y_0 \neq 0$ and $|y - y_0| < \min \left(\frac{|y_0|}{2}, \frac{\epsilon|y_0|^2}{2} \right)$. Then note that as $|y - y_0| < \frac{|y_0|}{2}$ $-\frac{|y_0|}{2} < y - y_0 < \frac{|y_0|}{2}$. If $y_0 > 0$ we have that $y_0 = |y_0|$ so $\frac{|y_0|}{2} < y < \frac{3|y_0|}{2}$. On the other hand if $y_0 < 0$ then $y_0 = -|y_0|$ so $-\frac{3|y_0|}{2} < y < -\frac{|y_0|}{2}$. In either case we have that $|y| > \frac{|y_0|}{2} > 0$, so $y \neq 0$. Then it follows that

$$\begin{aligned} \left| \frac{1}{y} - \frac{1}{y_0} \right| &= \left| \frac{y - y_0}{yy_0} \right| \\ &< \frac{\epsilon|y_0|^2}{2} \cdot \frac{1}{|y_0|} \cdot \frac{2}{|y_0|} \\ &= \epsilon \end{aligned}$$

as claimed. ■

Theorem 1.7.2 (Limit Laws). *If $\lim_{x \rightarrow a} f(x) = l$ and $\lim_{x \rightarrow a} g(x) = m$, then*

1. $\lim_{x \rightarrow a} (f + g)(x) = l + m$;
2. $\lim_{x \rightarrow a} (f \cdot g)(x) = l \cdot m$;
3. Moreover, if $m \neq 0$, then $\lim_{x \rightarrow a} \left(\frac{1}{g} \right)(x) = \frac{1}{m}$

Proof. Suppose that $\lim_{x \rightarrow a} f(x) = l$ and $\lim_{x \rightarrow a} g(x) = m$. Let $\epsilon > 0$.

(1) Then since $\lim_{x \rightarrow a} f(x) = l$ and $\lim_{x \rightarrow a} g(x) = m$ there exist $\delta_1, \delta_2 > 0$ such that $|f(x) - l| < \frac{\epsilon}{2}$ if $0 < |x - a| < \delta_1$ and $|g(x) - m| < \frac{\epsilon}{2}$ if $0 < |x - a| < \delta_2$. Choose $\delta = \min(\delta_1, \delta_2)$. Then it follows that for $0 < |x - a| < \delta$:

$$\begin{aligned} |(f + g)(x) - (l + m)| &= |(f(x) - l) + (g(x) - m)| \\ &\leq |f(x) - l| + |g(x) - m| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

Thus, we have that by definition $\lim_{x \rightarrow a} (f + g)(x) = l + m$.

(2) Now, fix $\epsilon_1 = \min\left(1, \frac{\epsilon}{2(|m|+1)}\right)$ and $\epsilon_2 = \frac{\epsilon}{2(|l|+1)}$. Then since $\lim_{x \rightarrow a} f(x) = l$ and $\lim_{x \rightarrow a} g(x) = m$ there exist $\delta_1, \delta_2 > 0$ such that if $0 < |x - a| < \delta_1$ then $|f(x) - l| < \epsilon_1$ and if $0 < |x - a| < \delta_2$ then $|g(x) - m| < \epsilon_2$. Choose $\delta = \min(\delta_1, \delta_2)$. It follows that for $0 < |x - a| < \delta$, we have $|f(x)g(x) - lm| < \epsilon$, so by definition $\lim_{x \rightarrow a} (f \cdot g)(x) = l \cdot m$.

(3) Now, suppose $m \neq 0$. Fix $\epsilon_1 = \min\left(\frac{|m|}{2}, \frac{\epsilon|m|^2}{2}\right)$. Then as $\lim_{x \rightarrow a} g(x) = m$, there exists $\delta > 0$ such that if $|x - a| < \delta$, $|g(x) - m| < \epsilon_1$. By the previous Lemma we have that if $|x - a| < \delta$, $g(x) \neq 0$ and $\left|\frac{1}{g(x)} - \frac{1}{m}\right| < \epsilon$. Hence, by definition $\lim_{x \rightarrow a} \left(\frac{1}{g}\right)(x) = \frac{1}{m}$, as desired. ■

Definition 1.7.2 (Limits from Above and Below). The limit from above for a function f as x goes to a is denoted by $\lim_{x \rightarrow a^+} f(x) = l$, which means for every $\epsilon > 0$ there is a $\delta > 0$ such that for all x ,

$$\text{if } 0 < x - a < \delta, \text{ then } |f(x) - l| < \epsilon$$

where $0 < x - a < \delta$ is equivalent to $0 < |x - a| < \delta$ and $x > a$.

The limit from below for f as x goes to a is denoted by $\lim_{x \rightarrow a^-} f(x) = l$, and means that for every $\epsilon > 0$ there is a $\delta > 0$ such that, for all x ,

$$\text{if } 0 < a - x < \delta, \text{ then } |f(x) - l| < \epsilon$$

Remark 1.7.3. For a function $f : \mathbb{R} \rightarrow \mathbb{R}$, $\lim_{x \rightarrow a} f(x)$ exists if and only if $\lim_{x \rightarrow a^+} f(x)$ and $\lim_{x \rightarrow a^-} f(x)$ both exist and are equal.

Definition 1.7.3 (Limits at Infinity). A limit at infinity is denoted by $\lim_{x \rightarrow \infty} f(x) = l$, and means that for every $\epsilon > 0$ there is $M \in \mathbb{R}$ such that for all x ,

$$\text{if } x > M, \text{ then } |f(x) - l| < \epsilon$$

A limit at negative infinity is defined analogously, replacing $x > M$ with $x < M$.

Definition 1.7.4. We define $\lim_{x \rightarrow a} f(x) = \infty$ to mean that for all $N \in \mathbb{R}$, there exists $\delta > 0$ such that, for all $x \in \mathbb{R}$, if $0 < |x - a| < \delta$, then $f(x) > N$. (the case for $-\infty$ is defined similarly)

1.8.0 Continuous Functions

Definition 1.8.1 (Continuity). Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a real function. Then f is said to be continuous at a point a if

$$\lim_{x \rightarrow a} f(x) = f(a) \tag{1.8.1}$$

Theorem 1.8.1. If f and g are continuous at a point a , then

1. $f + g$ is continuous at a
2. $f \cdot g$ is continuous at a
3. Moreover, if $g(a) \neq 0$, then $1/g$ is continuous at a .

Proof. Suppose f and g are continuous at a point a . Then by the 1.7.2 theorem, we have that as $\lim_{x \rightarrow a} f(x) = f(a)$ and $\lim_{x \rightarrow a} g(x) = g(a)$,

$$\lim_{x \rightarrow a} (f + g)(x) = f(a) + g(a) = (f + g)(a)$$

Hence, $f + g$ is continuous at a . Similarly, again by the 1.7.2 theorem, we have that

$$\lim_{x \rightarrow a} (f \cdot g)(x) = f(a) \cdot g(a) = (f \cdot g)(a)$$

Thus, $f \cdot g$ is continuous at a . Finally, if $g(a) \neq 0$, the

$$\lim_{x \rightarrow a} (1/g)(x) = 1/g(a) = (1/g)(a)$$

so $1/g$ is continuous at a . ■

Theorem 1.8.2. If g is continuous at a , and f is continuous at $g(a)$, then $f \circ g$ is continuous at a .

Proof. Let $\epsilon > 0$. Then by continuity of f there exists $\delta_1 > 0$ such that if $|g(x) - g(a)| < \delta_1$, then

$$|f(g(x)) - f(g(a))| < \epsilon$$

Then, by the continuity of g , there exists $\delta > 0$ such that if $|x - a| < \delta$, then $|g(x) - g(a)| < \delta_1$. Thus, if $|x - a| < \delta$ we have that

$$|(f \circ g)(x) - (f \circ g)(a)| = |f(g(x)) - f(g(a))| < \epsilon$$

proving continuity of $f \circ g$ at a . ■

Definition 1.8.2. A function f is called continuous on an open interval (a, b) , if f is continuous at x for all $x \in (a, b)$.

A function f is called continuous on a closed interval $[a, b]$ if

1. f is continuous at x for all $x \in (a, b)$
2. $\lim_{x \rightarrow a^+} f(x) = f(a)$ and $\lim_{x \rightarrow b^-} f(x) = f(b)$

In general, a function f is continuous if it is continuous at x for all x in its domain.

Theorem 1.8.3. Suppose f is continuous at a , and $f(a) > 0$. Then $f(x) > 0$ for all x in some interval containing a ; more precisely, there is a number $\delta > 0$ such that $f(x) > 0$ for all x satisfying $|x - a| < \delta$. Similarly, if $f(a) < 0$, then there is a number $\delta > 0$ such that $f(x) < 0$ for all x satisfying $|x - a| < \delta$.

Proof. Suppose f is continuous at a . Let $\epsilon = \frac{f(a)}{2} > 0$. Then by continuity there exists $\delta > 0$ such that if $|x - a| < \delta$, $|f(x) - f(a)| < \epsilon$. Then we have that $-\epsilon < f(x) - f(a) < \epsilon$, so $f(x) > \epsilon > 0$, satisfying the claim. The case for $f(a) < 0$ is proved analogously. ■

Important Theorems and Results on Continuity

Theorem 1.8.4. If f is continuous on a closed interval $[a, b]$ (a compact set) and $f(a) < 0 < f(b)$, then there is some $x \in [a, b]$ such that $f(x) = 0$.

Proof. Consider an interval $[a, b]$ such that $f(a) < 0 < f(b)$. Define the set

$$A := \{x \in \mathbb{R} : a \leq x \leq b, \text{ and } f \text{ is negative on } [a, x]\}$$

Clearly $A \neq \emptyset$ as $a \in A$. In fact, there exists some $\delta > 0$ such that A contains all points $x \in \mathbb{R}$ satisfying $a \leq x < a + \delta$, since f is continuous on $[a, b]$ and $f(a) < 0$. Similarly, b is an upper bound for A and, in fact, there is a $\delta > 0$ such that all points satisfying $b - \delta < x \leq b$ are upper bounds for A .

Thus, applying the Least Upper Bound property of \mathbb{R} , A has a least upper bound α and $a < \alpha < b$. We wish to show that $f(\alpha) = 0$. First, if $f(\alpha) < 0$, then by a previous result there is a $\delta > 0$ such that $f(x) < 0$ for $\alpha - \delta < x < \alpha + \delta$. In particular, there is some number $x_0 \in A$ satisfying $\alpha - \delta < x_0 < \alpha$ since α is the supremum of A . Thus f is negative on the whole interval $[a, x_0]$. But, if $x_1 \in (\alpha, \alpha + \delta)$, then f is also negative on the whole interval $[x_0, x_1]$.

Therefore f is negative on the interval $[a, x_1]$ so $x_1 \in A$. But, this contradicts the fact that α is an upper bound for A , so $f(\alpha) < 0$ must be false.

Suppose, on the other hand, that $f(\alpha) > 0$. Then there is a number $\delta > 0$ such that $f(x) > 0$ for all $\alpha - \delta < x < \alpha + \delta$. Now there is some number $x_0 \in A$ such that $\alpha - \delta < x_0 < \alpha$ as α is presumed to be the supremum of A . This means that f is negative on the whole interval $[a, x_0]$, which is impossible since $f(x_0) > 0$. Thus, the assumption $f(\alpha) > 0$ leads to a contradiction, leaving $f(\alpha) = 0$ as the only possible alternative. ■

Lemma 1.8.5. *If f is continuous at a , then there is a number $\delta > 0$ such that f is bounded on the interval $(a - \delta, a + \delta)$.*

Proof. Since f is continuous at a we have that $\lim_{x \rightarrow a} f(x) = f(a)$. Then, fix $\epsilon = 1$. By continuity it follows that there exists $\delta > 0$ such that for all $x \in (a - \delta, a + \delta)$, $|f(x) - f(a)| < 1$. In particular, we have that $f(x) < f(a) + 1$, so f is bounded above by $f(a) + 1$ on $(a - \delta, a + \delta)$. Moreover, $f(x) > f(a) - 1$, so f is bounded below by $f(a) - 1$ on $(a - \delta, a + \delta)$. Thus f is bounded on the interval $(a - \delta, a + \delta)$ as claimed. ■

Corollary 1.8.6. *If $\lim_{x \rightarrow a^+} f(x) = f(a)$ then there exists $\delta > 0$ such that f is bounded on the interval $[a, a + \delta)$. Moreover, if $\lim_{x \rightarrow b^-} f(x) = f(b)$ then there exists $\delta > 0$ such that f is bounded on the interval $(b - \delta, b]$.*

Theorem 1.8.7. *If f is continuous on a closed interval $[a, b]$ (a compact set), then f is bounded above on $[a, b]$, that is, there is some number $M \in \mathbb{R}$ such that $f(x) \leq M$ for all $x \in [a, b]$ (consequence of the continuous image of a compact set being compact and the Heine-Borel Theorem).*

Proof. Define the set

$$A := \{x \in [a, b] : f \text{ is bounded above on } [a, x]\}$$

Clearly $A \neq \emptyset$ as $a \in A$, and A is bounded above by b , so A has a least upper bound $\alpha \in \mathbb{R}$. We wish to show that $\alpha = b$. Suppose towards a contradiction that $\alpha < b$. Then there exists $\delta > 0$ such that f is bounded on $(\alpha - \delta, \alpha + \delta)$ since f is continuous on $[a, b]$, so in particular f is continuous at α . Since α is the least upper bound of A there is some $x_0 \in A$ satisfying $\alpha - \delta < x_0 < \alpha$. This implies that f is bounded on $[a, x_0]$. But, if x_1 is any number with $\alpha < x_1 < \alpha + \delta$, then f is also bounded on $[x_0, x_1]$. Therefore f is bounded on $[a, x_1]$ so $x_1 \in A$, contradicting the fact that α is an upper bound for A . This contradiction shows that $\alpha = b$. Now, there is a $\delta > 0$ such that f is bounded on $(b - \delta, b]$. There is $x_0 \in A$ such that $b - \delta < x_0 < b$, since $\alpha = b$. Thus f is bounded on $[a, x_0]$, and also on $[x_0, b]$, so f is bounded on $[a, b]$, completing the proof. ■

Theorem 1.8.8. *If f is continuous on a closed interval $[a, b]$, then there is some number $y \in [a, b]$ such that $f(y) \geq f(x)$ for all $x \in [a, b]$.*

Proof. From the previous theorem we know that f is bounded on $[a, b]$, so the set $\{f(x) : x \in [a, b]\}$ is bounded. This set is obviously non-empty, so it has a least upper bound $\alpha \in \mathbb{R}$. Since

$\alpha \geq f(x)$ for all $x \in [a, b]$, it suffices to show that $\alpha = f(y)$ for some $y \in [a, b]$. Suppose instead that $\alpha \neq f(y)$ for all $y \in [a, b]$. Then the function g defined by

$$g(x) = \frac{1}{\alpha - f(x)}, x \in [a, b]$$

is continuous on $[a, b]$ since the denominator is never zero and is the sum of continuous functions. On the other hand, α is the least upper bound of $\{f(x) : x \in [a, b]\}$ so for every $\epsilon > 0$ there exists $x \in [a, b]$ such that $\alpha - \epsilon < f(x)$, so $\alpha - f(x) < \epsilon$. This in turn implies that for every $\epsilon > 0$ there exists $x \in [a, b]$ with $g(x) > 1/\epsilon$. But, this implies that g is not bounded on $[a, b]$, contradicting the previous theorem as g is assumed to be continuous. Hence, g is not continuous, and in particular $\alpha - f(y) = 0$ for some $y \in [a, b]$. ■

Theorem 6 (Intermediate Value Theorem).

If f is continuous on $[a, b]$ and $f(a) < c < f(b)$, then there is some $x \in [a, b]$ such that $f(x) = c$ (continuous image of a connected set is connected).

Moreover, if $f(a) > c > f(b)$, then there is some $x \in [a, b]$ such that $f(x) = c$.

Theorem 1.8.9. If f is continuous on $[a, b]$, then f is bounded below on $[a, b]$, that is, there is some number $M \in \mathbb{R}$ such that $f(x) \geq M$ for all $x \in [a, b]$.

Theorem 1.8.10. If f is continuous on $[a, b]$, then there is some $y \in [a, b]$ such that $f(y) \leq f(x)$ for all $x \in [a, b]$.

Corollary 1.8.11. For all $\alpha \in \mathbb{P}$, so $\alpha > 0$, there exists $x \in \mathbb{R}$ such that $x^2 = \alpha$.

Proof. Consider the function $f(x) = x^2$, which is certainly continuous over \mathbb{R} . Consider $\alpha \in \mathbb{P}$. Then there exists $b > 0$ such that $f(b) > \alpha$. Indeed, if $\alpha > 1$ we can take $b = \alpha$, and if $\alpha < 1$ we can take $b = 1$. Then, f is defined on the closed interval $[0, b]$ and $f(0) = 0 < \alpha < f(b)$. Therefore, by the 6 there exists $c \in [0, b]$ such that $f(c) = \alpha$. In particular, $c^2 = \alpha$. ■

Corollary 1.8.12. If n is odd, then any equation

$$x^n + a_{n-1}x^{n-1} + \dots + a_0 = 0 \tag{1.8.2}$$

has a solution, or root.

Proof. Consider the function $f(x) = x^n + a_{n-1}x^{n-1} + \dots + a_0$. Write

$$f(x) = x^n + a_{n-1}x^{n-1} + \dots + a_0 = x^n \left(1 + \frac{a_{n-1}}{x} + \dots + \frac{a_0}{x^n} \right)$$

Then note that

$$\left| \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n} \right| \leq \frac{|a_{n-1}|}{|x|} + \dots + \frac{|a_0|}{|x^n|}$$

Choose x such that

$$|x| > 1, 2n|a_{n-1}|, \dots, 2n|a_0|$$

so $|x^k| > |x|$ for all $k > 1$, and

$$\frac{|a_{n-k}|}{|x^k|} < \frac{|a_{n-k}|}{|x|} < \frac{|a_{n-k}|}{2n|a_{n-k}|} < \frac{1}{2n}$$

Thus, we have that

$$\left| \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n} \right| \leq \frac{|a_{n-1}|}{|x|} + \dots + \frac{|a_0|}{|x^n|} < \underbrace{\frac{1}{2n} + \dots + \frac{1}{2n}}_{n \text{ times}} = \frac{1}{2}$$

In other words,

$$-\frac{1}{2} < \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n} < \frac{1}{2}$$

which implies that

$$\frac{1}{2} < 1 + \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n}$$

Choosing $x_1 > 0$ which satisfies our condition, we have

$$\frac{x_1^n}{2} \leq x_1^n \left(1 + \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n} \right) = f(x_1)$$

so that $f(x_1) > 0$. On the other hand, choosing $x_2 < 0$ satisfying our condition, $x_2^n < 0$ as n is odd and

$$\frac{x_2^n}{2} \geq x_2^n \left(1 + \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n} \right) = f(x_2)$$

so that $f(x_2) < 0$. Applying the 6 to the interval $[x_2, x_1]$ we conclude that there exists $c \in [x_2, x_1]$ such that $f(c) = 0$. ■

Theorem 1.8.13. *If n is even and $f(x) = x^n + a_{n-1}x^{n-1} + \dots + a_0$, then there is a number y such that $f(y) \leq f(x)$ for all $x \in \mathbb{R}$.*

Proof. Choose M such that

$$M = \max(1, 2n|a_{n-1}|, \dots, 2n|a_0|)$$

Then for all x with $|x| \geq M$ we have

$$\frac{1}{2} \leq 1 + \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n}$$

Since n is even, $x^n \geq 0$ for all x , so

$$\frac{x^n}{2} \leq x^n \left(1 + \frac{a_{n-1}}{x} + \frac{a_{n-2}}{x^2} + \dots + \frac{a_0}{x^n} \right) = f(x)$$

provided that $|x| \geq M$. Now consider the number $f(0)$. Let $b > 0$ be a number such that $b^n \geq 2f(0)$ and also $b > M$. Then if $x \geq b$, we have

$$f(x) \geq \frac{x^n}{2} \geq \frac{b^n}{2} \geq f(0)$$

The same holds for $x \leq -b$. In particular, if $x \geq b$ or $x \leq -b$, then $f(x) \geq f(0)$. Applying the extreme value theorem to f on the interval $[-b, b]$, we conclude that there is a number $y \in [-b, b]$ such that if $-b \leq x \leq b$, then $f(y) \leq f(x)$. In particular, $f(y) \leq f(0)$. Thus, if $x \leq -b$ or $x \geq b$, then $f(x) \geq f(0) \geq f(y)$. Combining these results we find that $f(y) \leq f(x)$ for all $x \in \mathbb{R}$. ■

Corollary 1.8.14. Consider the equation

$$x^n + a_{n-1}x^{n-1} + \dots + a_0 = c \quad (1.8.3)$$

for n even. Then there is a number m such that the equation has a solution for $c \geq m$ and has no solution for $c < m$.

Proof. Let $f(x) = x^n + a_{n-1}x^{n-1} + \dots + a_0$. According to our previous theorem there exists $y \in \mathbb{R}$ such that $f(y) \leq f(x)$ for all $x \in \mathbb{R}$. Let $m = f(y)$. If $c < m$ then the equation above has no solution, since the left hand side has a value $\geq m$ always. If $c = m$, then y is a solution of the equation. Finally, for $c > m$, let $b > y$ such that $f(b) > c$. Then the 6 applied to the interval $[y, b]$ states that there exists $x \in [y, b]$ such that $f(x) = c$, so x is a solution of the equation. ■

Uniform Continuity

Definition 1.8.3. A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is **uniformly continuous on an interval I** if for every $\epsilon > 0$ there is some $\delta > 0$ such that, for all $x, y \in I$, if $|x - y| < \delta$ then $|f(x) - f(y)| < \epsilon$.

Lemma 1.8.15. Let $a < b < c$ and let f be continuous on the interval $[a, c]$. Let $\epsilon > 0$ and suppose that

1. if $x, y \in [a, b]$ and $|x - y| < \delta_1$, then $|f(x) - f(y)| < \epsilon$
2. if $x, y \in [b, c]$ and $|x - y| < \delta_2$, then $|f(x) - f(y)| < \epsilon$

Then there is a $\delta > 0$ such that if $x, y \in [a, c]$ and $|x - y| < \delta$, then $|f(x) - f(y)| < \epsilon$.

Proof. Fix $\epsilon > 0$. Since f is continuous at b there exists $\delta_3 > 0$ such that if $|x - b| < \delta_3$, then $|f(x) - f(b)| < \frac{\epsilon}{2}$. It follows that if $|x - b| < \delta_3$ and $|y - b| < \delta_3$ then $|f(x) - f(y)| < \epsilon$. Choose $\delta = \min(\delta_1, \delta_2, \delta_3)$. Let $x, y \in [a, c]$ with $|x - y| < \delta$. If x and y are both in $[a, b]$, then $|f(x) - f(y)| < \epsilon$ by assumption. Similarly, if $x, y \in [b, c]$, then again $|f(x) - f(y)| < \epsilon$ by assumption. Finally, without loss of generality suppose $x < b < y$. Since $|x - y| < \delta$ we have that $|x - b| = |b - x| = b - x < y - x = |y - x| < \delta$ and similarly $|y - b| < \delta$. Thus, we have that $|f(x) - f(y)| < \epsilon$, completing the proof. ■

Theorem 1.8.16 (Uniform Continuity Theorem). If f is continuous on $[a, b]$, then f is uniformly continuous on $[a, b]$.

Proof. Consider $\epsilon > 0$. Define the set

$$A(\epsilon) := \{x \in [a, b] : \exists \delta > 0; \forall y, z \in [a, x]; |y - z| < \delta \implies |f(y) - f(z)| < \epsilon\}$$

Then $A(\epsilon) \neq \emptyset$ since $a \in A(\epsilon)$, and $A(\epsilon)$ is bounded above by b , so $A(\epsilon)$ has a least upper bound $\alpha_\epsilon \in \mathbb{R}$. Suppose towards a contradiction that $\alpha < b$. Since f is continuous at α , there is some δ_0 such that if $|y - \alpha| < \delta_0$, then $|f(y) - f(\alpha)| < \epsilon/2$. Consequently, if $|y - \alpha| < \delta_0$ and $|z - \alpha| < \delta_0$, then $|f(y) - f(z)| < \epsilon$. So, f surely satisfies the condition for containment

in $A(\epsilon)$ on the interval $[\alpha - \delta_0, \alpha + \delta_0]$. On the other hand, since α is the least upper bound of A it is also clear that the condition is satisfied on $[a, \alpha - \delta_0]$, namely $\alpha - \delta_0 \in A$. Then, the Lemma implies that f satisfies the condition on $[a, \alpha + \delta_0]$ since it satisfies it on $[a, \alpha - \delta_0]$ and $[\alpha - \delta_0, \alpha + \delta_0]$. Hence, $\alpha + \delta_0 \in A$, contradicting the fact that α is an upper bound.

To complete the proof we must show that $\alpha = b$ is in A . Since f is continuous at b , there is some $\delta_0 > 0$ such that if $y \in (b - \delta_0, b)$, then $|f(y) - f(b)| < \epsilon/2$. So, for any $x, y \in [b - \delta_0, b]$, $|f(y) - f(x)| < \epsilon$. But, f satisfies the condition for $A(\epsilon)$ on $[a, b - \delta_0]$ since b is the least upper bound of $A(\epsilon)$, so the Lemma implies that f satisfies the condition on $[a, b]$. Therefore, as $\epsilon > 0$ was arbitrary, we conclude that f is uniformly continuous on $[a, b]$, completing the proof. ■

1.9.0 Metric Properties of the Reals Summarized

First we need to define a sequence

1.A.0 Cardinality

In this appendix we investigate the notion of the size of a set. First, we define the set

$$I_n := \{j \in \mathbb{N} : j \leq n\}$$

the prototypical set of size n .

Lemma 1.A.1. $I_1 = \{1\}$, and $I_{n+1} = I_n \cup \{n + 1\}$.

Proof. If $n = 1$, $I_1 = \{j \in \mathbb{N} : j \leq 1\} = \{1\}$, so the base case holds. Further, $I_2 = \{j \in \mathbb{N} : j \leq 2\} = \{1, 2\} = I_1 \cup \{2\}$. Now, suppose for some $j \in \mathbb{N}$, $I_{j+1} = I_j \cup \{j + 1\}$. Then

$$I_{j+2} = \{k \in \mathbb{N} : k \leq j + 2\} = \{k \in \mathbb{N} : k \leq j + 1 \vee k = j + 2\} = I_{j+1} \cup \{j + 2\}$$

■

Definition 1.A.1. A non-empty set S has n elements if and only if there exists a bijective map $\varphi : S \rightarrow I_n$.

Proposition 1.A.2. For $m, n \in \mathbb{N}$, if there exists an injection $\varphi : I_m \rightarrow I_n$, then $m \leq n$.

Proof. If $n = 1$, then $I_n = I_1 = \{1\}$. Now, suppose $\varphi : I_m \rightarrow I_1$ is an injection. If $x, y \in I_m$, then $\varphi(x) = 1 = \varphi(y)$, so by injectivity $x = y$. Thus, I_m has only one element, and since $1 \in I_m$, we must have $I_m = \{1\} = I_1$. Hence, $m = 1 \leq 1 = n$. Assume the result is true for some $1 \leq n < N$. Then let $\varphi : I_m \rightarrow I_N$ be an injection. If $m = 1$ the result is immediately satisfied, so suppose $m \geq 2$.

- (1) Suppose there exist $j \in I_m$ such that $\varphi(j) = N$. Then define $\psi : I_{m-1} \rightarrow I_{N-1}$ by $\psi(l) = \varphi(l)$ for $l < j$, and $\psi(l) = \varphi(l+1)$ for $j \leq l \leq m-1$. Then ψ is injective because φ is injective, so the induction hypothesis $m-1 \leq N-1$, so $m \leq N$.
- (2) If there does not exist $j \in I_m$ such that $\varphi(j) = N$, then we can restrict the codomain of φ to obtain $\varphi : I_m \rightarrow I_{N-1}$. By the induction hypothesis $m \leq N-1 < N$, as desired.

■

Corollary 1.A.3. *If there exists $\varphi : I_m \rightarrow I_n$ bijective, then $m = n$.*

Corollary 1.A.4. *Suppose S is a set, $n, m \in \mathbb{N}$, and there exist bijections $\varphi : S \rightarrow I_n$ and $\psi : S \rightarrow I_m$, then $n = m$.*

The result follows from considering $\varphi \circ \psi^{-1} : I_m \rightarrow I_n$.

Definition 1.A.2. *If either $S = \emptyset$ or S has n elements for some $n \in \mathbb{N}$, then we say S is finite. Otherwise, S is said to be infinite.*

Proposition 1.A.5. *If $n \in \mathbb{N}$ and $S \subseteq I_n$, then there exists $m \leq n$ and $\varphi : S \rightarrow I_m$ bijective.*

Proof. If $n = 1$, then $I_1 = \{1\}$ and the only non-empty subset is $S = \{1\} = I_1$ itself. Then $\varphi : S \rightarrow I_1$ given by $\varphi(1) = 1$ is a bijection so the base case holds. Suppose for $k \geq 1$, if $S \subseteq I_k$, then there exists $m \leq k$ such that $\varphi_k : S \rightarrow I_m$ bijective. Suppose $S \subseteq I_{k+1}$. If $S = I_{k+1}$, then $\text{id} : I_{k+1} \rightarrow I_{k+1}$ is the desired bijection. Otherwise, there exists $j \in I_{k+1}$ such that $j \notin S$. If $j = k+1$, define $\varphi : S \rightarrow I_k$ by $\varphi(s) = s$ for all $s \in S$. Then φ is an injection and $\varphi(S) \subseteq I_k$ so by the induction hypothesis there exists $m \leq k$ and a bijection $\psi : \varphi(S) \rightarrow I_m$. Then $\psi \circ \varphi : S \rightarrow I_m$ is bijective. If $j \neq k+1$, then define $\varphi(S) \rightarrow I_k$ by $\varphi(l) = l$ for $l \leq k$, and $\varphi(k+1) = j$. Then φ is injective, and by the induction hypothesis there exists $m \leq k$ and a bijection $\psi : \varphi(S) \rightarrow I_m$, so $\psi \circ \varphi : S \rightarrow I_m$ is the desired bijection. ■

Proposition 1.A.6. \mathbb{N} is not finite.

Proof. If \mathbb{N} was finite then there would exist $n \in \mathbb{N}$ and a bijection $\varphi : I_n \rightarrow \mathbb{N}$. As $I_{n+1} \subseteq \mathbb{N}$, if we restrict φ to $\varphi^{-1}(I_{n+1}) = S$, we have $\psi : S \rightarrow I_{n+1}$, which is bijective. But $S \subseteq I_n$, so by Proposition 1.A.5 S has m elements with $m \leq n$, and as $n+1 = m \leq n$, a contradiction. Thus, \mathbb{N} must be infinite. ■

Proposition 1.A.7. *If S is not finite, then there exists an injection $\varphi : \mathbb{N} \rightarrow S$.*

Proof. As S is non-empty, there exists $s_1 \in S$, so define $\varphi_1(1) = s_1$. Suppose there exists $k \in \mathbb{N}$ such that for $\varphi_k(l) = s_l \in S \setminus \{s_1, \dots, s_{l-1}\}$ for all $1 \leq l \leq k$. Then as S is infinite, there exists $s_{k+1} \in S$ with $s_{k+1} \notin \{s_1, \dots, s_k\}$, so we define $\varphi_{k+1}(k+1) = s_{k+1}$ and $\varphi_{k+1}(l) = \varphi_k(l)$ for all $1 \leq l \leq k$. Thus, for all $n \in \mathbb{N}$ we have $\varphi_n : I_n \rightarrow S$ injective, and for all $m \leq n$, $\varphi_n|_{I_m} = \varphi_m : I_m \rightarrow S$. Define $\Phi(m) = \varphi_n(m)$ for all $n \geq m$. Then $\Phi : \mathbb{N} \rightarrow S$ is well defined and injective. ■

Definition 1.A.3. We say that a set S is countably infinite if there exists a bijection $\varphi : S \rightarrow \mathbb{N}$.

Definition 1.A.4. Two sets S and T have the same cardinality if there exists a bijection between them, and we write $\text{Card}(S) = \text{Card}(T)$.

Definition 1.A.5. If S is finite:

- $\text{Card}(S) = 0$ if $S = \emptyset$
- $\text{Card}(T) = n$ if S has n elements.

We now move on to a fundamental theorem on cardinalities of sets:

Theorem 7 (Schröder-Bernstein Theorem).

If S and T are two non-empty sets such that there exist injective maps

$$\varphi : S \hookrightarrow T \text{ and } \psi : T \hookrightarrow S$$

then there exists a bijection $\Phi : S \rightarrow T$.

Proof. Let $\varphi : S \rightarrow T$ and $\psi : T \rightarrow S$ be the injections in the hypothesis. If $s \in S$ such that $\varphi(s) = t$, we say s is a parent of t . Similarly, if $t' \in T$ such that $\psi(t') = s' \in S$, then we say t' is a parent of s' . For elements in S and T there are three disjoint cases:

- a) The set of elements who have an infinite number of ancestors
- b) The set of elements whose last ancestor is an element of S
- c) The set of elements whose last ancestor is an element of T

Define $S_a, T_a, S_b, T_b, S_c, T_c$ be the corresponding sets, so $S = S_a \sqcup S_b \sqcup S_c, T = T_a \sqcup T_b \sqcup T_c$. I claim that $\varphi|_{S_a} : S_a \rightarrow T_a$ is bijective. Indeed, φ is injective. If $s \in S_a, \varphi(s) \in T_a$ as all ancestors of s are ancestors of $\varphi(s)$. If $t \in T_a$, then t has infinitely many ancestors, so in particular there exists $s \in S$ such that $\varphi(s) = t$. But, all ancestors of t , except s , are ancestors of s so $s \in S_a$. Hence $\varphi|_{S_a}$ is indeed well defined and bijective.

Next we claim that $\varphi|_{S_b} : S_b \rightarrow T_b$ is bijective. If $s \in S_b$, then s 's ancestors terminate in S , so $\varphi(s) \in T_b$. If $t \in T_b$, then t has at least one ancestor $s \in S$, and as $\varphi(s) \in T_b, s \in S_b$. Thus $\varphi|_{S_b}$ is well defined and bijective. Dually, we have that $\psi|_{T_c} : T_c \rightarrow S_c$ is bijective. Then define $\Phi : S \rightarrow T$ by $\Phi(s) = \varphi(s)$ for $s \in S_a \cup S_b$, and $\Phi(s) = \psi|_{T_c}^{-1}(s)$ for $s \in S_c$, which is by construction bijective. ■

A classical application of this result is in the following example:

Example 1.A.1. $\text{Card}(\mathbb{N}) = \text{Card}(\mathbb{N} \times \mathbb{N})$. Define $\varphi : \mathbb{N} \rightarrow \mathbb{N} \times \mathbb{N}$ by $\varphi = \Delta$ is the diagonal, so φ is injective. Conversely, define $\psi : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{N}$ by $\psi(n, m) = 2^n 3^m$, so by the fundamental theorem of arithmetic ψ is injective. Then by Schröder-Bernstein there exists a bijection $\Phi : \mathbb{N} \rightarrow \mathbb{N} \times \mathbb{N}$, as desired.

The following are the axioms founding the Zermelo-Frankel axioms of set theory with Choice:

Axiom 1.A.6 (ZFC Axioms). *The following constitute the axioms of ZFC:*

1. (Emptyset) *There is a set, denoted by \emptyset , which has no members:*

$$\exists x \forall t \neg t \in x$$

2. (Pairset) *For any two sets x and y there is a set p with the property that $t \in p$ if and only if $t = x$ or $t = y$. This set p is usually denoted $\{x, y\}$:*

$$\forall x \forall y \exists p (t \in p \iff (t = x \vee t = y))$$

3. (Extensionality) *For any two sets x and y , $x = y$ if and only if x and y have exactly the same members:*

$$\forall x \forall y (x = y \iff \forall t (t \in x \iff t \in y))$$

4. (Union Set) *For any set x there exists a set denote by $\bigcup x$ whose members are exactly the members of the members of x :*

$$\forall x \exists y \forall t (t \in y \iff \exists y (y \in x \wedge t \in y))$$

5. (Infinity) *There exists a set I which contains $0 = \emptyset$ as well as the successor of each of its members; that is, if $x \in I$, then $S(x) := x \cup \{x\} \in I$:*

$$\exists x (\emptyset \in I \wedge \forall x (x \in I \implies \bigcup \{x, \{x\}\}))$$

6. (Powerset) *For each set A there exists a set $\mathcal{P}(A)$ whose members are the subsets of A :*

$$\forall x \exists y \forall t (t \in y \iff \forall z (z \in t \implies z \in x))$$

7. (Separation) *Suppose P is a definite condition. For each set A there exists a set B whose members are exactly the members of A that satisfy P :*

$$\forall x \exists y \forall t (t \in B \iff (t \in x \wedge P(t)))$$

8. (Replacement) *Suppose P is a definite binary condition such that for each set x there is a unique set y for which $P(x, y)$ holds. Given a set A there exists a set B with the property that $y \in B$ if and only if there exists $x \in A$ such that $P(x, y)$:*

$$\forall x \exists y \forall t (t \in y \iff \exists z (z \in x \wedge P(z, t)))$$

9. (Regularity) *Every non-empty set A contains an element that is disjoint from A :*

$$\forall x (\neg x = \emptyset \implies \exists t (t \in x \wedge \forall y (y \in t \implies \neg y \in x)))$$

10. (Choice) *Every non-empty set X whose members are all non-empty sets, there exists a function $f : X \rightarrow \bigcup X$ such that $f(A) \in A$ for all $A \in X$.*

Lemma 1.A.8. *If $\varphi : S \rightarrow T$ is onto, then there exists $\psi : T \rightarrow S$ which is injective.*

Proof. Let $\varphi : S \rightarrow T$ be onto. Then let $X = \{\varphi^{-1}(t) : t \in T\}$, so $S = \bigcup X$, and all members of X are non-empty sets since φ is onto. By the axiom of choice there exists a function $f : X \rightarrow \bigcup X$ such that $f(\varphi^{-1}(t)) \in \varphi^{-1}(t)$ for all $t \in T$. Since φ is a well defined function f is injective. Let $g : T \rightarrow X$ by $g(t) = \varphi^{-1}(t)$. Then g is also injective as φ is well-defined, so their composite $f \circ g : T \rightarrow \bigcup X = S$ is an injection. ■

As an application of our results, I claim that $\text{Card}(\mathbb{R}) \neq \text{Card}(\mathbb{N})$:

Proof. First, $\iota : (0, 1) \rightarrow \mathbb{R}$, being the natural inclusion, is an injection, and $\varphi : \mathbb{R} \rightarrow (0, 1)$ given by $\varphi(x) = \frac{e^x}{e^x + 1}$ is an injection, so by Schröder Bernstein there exists a bijection $\Phi : (0, 1) \rightarrow \mathbb{R}$. Towards a contradiction suppose $\text{Card}(\mathbb{N}) = \text{Card}(\mathbb{R}) = \text{Card}((0, 1))$, so we have a bijection $f : \mathbb{N} \rightarrow (0, 1)$. Expand the terms in their decimal expansion, so $f(j) = \sum_{n=1}^{\infty} a_{jn} 10^{-n}$, $a_{jn} \in \{0, 1, 2, \dots, 9\}$. Define x by $x = \sum_{n=1}^{\infty} b_n 10^{-n}$ where $b_n = 2$ if $a_{nn} \neq 2$ and $b_n = 3$ if $a_{nn} = 2$. Thus $x \neq f(j)$ for all $j \in \mathbb{N}$, but by assumption f is bijective, and hence onto, which is a contradiction since $x \in (0, 1)$. Thus, no such bijection can exist. ■

Definition 1.A.7. *For sets S and T we define \leq on the cardinals by $\text{Card}(S) \leq \text{Card}(T)$ if and only if there exists an injection $\varphi : S \rightarrow T$, and $\text{Card}(S) < \text{Card}(T)$ if and only if $\text{Card}(S) \leq \text{Card}(T)$ and $\text{Card}(S) \neq \text{Card}(T)$.*

Then it follows that $\text{Card}(\mathbb{N}) < \text{Card}(\mathbb{R})$.

Continuum Hypothesis. *There exists no set with cardinality strictly between $\aleph_0 = \text{Card}(\mathbb{N})$ and $\aleph_1 = \text{Card}(\mathbb{R})$.*

This hypothesis cannot be proven and taking it to be true or false in your system for set theory leads to no contradictions.

Proposition 1.A.9. *For any set S , $\mathcal{P}(S) \cong 2^S$.*

Proof. Let $\varphi : \mathcal{P}(S) \rightarrow 2^S$ by $\varphi(A)(s) = 1$ if and only if $s \in A$, and 0 otherwise, for all $A \in \mathcal{P}(S)$. This is an injection, and a surjection as we can take $X_f = \{s \in S : f(s) = 1\}$ for all $f \in 2^S$, so $\varphi(X_f) = f$. ■

Proposition 1.A.10 (Cantor's Theorem). *For any set S , $\text{Card}(S) < \text{Card}(\mathcal{P}(S))$*

Proof. The inclusion $\iota : S \rightarrow \mathcal{P}(S)$ by $\iota(s) = \{s\}$ for all $s \in S$, is an injection so $\text{Card}(S) \leq \text{Card}(\mathcal{P}(S))$. Towards a contradiction we have $f : S \rightarrow \mathcal{P}(S)$. Let $B = \{s \in S : s \notin f(s)\}$. Then $f(s) = B$ for some $s \in S$. But then

$$s \notin B \iff s \notin f(s) \iff s \notin B$$

which is a contradiction, so no such f can exist. ■

Due to Cantor's theorem we obtain an infinite chain of infinite cardinals

$$\text{Card}(\mathbb{N}) < \text{Card}(\mathcal{P}(\mathbb{N})) < \text{Card}(\mathcal{P}(\mathcal{P}(\mathbb{N}))) < \dots$$

An important, but non-trivial result, is $\text{Card}(\mathbb{R} \times \mathbb{R}) = \text{Card}(\mathbb{R})$.

Chapter 2

Differentiation

2.1.0 Introduction to Derivatives

Definition 2.1.1 (Differentiability). A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is said to be differentiable at a if

$$\lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h} \quad (2.1.1)$$

exists. In this case the limit is denoted by $f'(a)$ and is called the derivative of f at a . We also say that f is differentiable if f is differentiable at a for all a in its domain.

Definition 2.1.2. We define the tangent line to the graph of f at $(a, f(a))$ to be the line through $(a, f(a))$ with slope $f'(a)$. That is, the tangent line at $(a, f(a))$ is well defined if and only if f is differentiable at a .

Remark 2.1.1. Given a function f , we denote by f' the function whose domain is the set of all numbers $a \in \mathbb{R}$ such that f is differentiable at a , and whose value at such a number a is

$$\lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h} \quad (2.1.2)$$

The function f' is called the derivative of f .

Notation 2.1.2. For a given function $f : \mathbb{R} \rightarrow \mathbb{R}$, the derivative f' is often denoted by

$$\frac{df(x)}{dx} \quad (2.1.3)$$

and the number $f'(a)$ is denoted by

$$\left. \frac{df(x)}{dx} \right|_{x=a} \quad (2.1.4)$$

Theorem 2.1.1. If f is differentiable at a , then f is continuous at a .

Proof. Suppose f is differentiable at a point a . Then we have that the limit

$$\lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h}$$

exists. It follows by 1.7.2 that

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

Thus, by 1.7.2 the result that $\lim_{h \rightarrow 0} f(a+h) - f(a) = 0$ is equivalent to $\lim_{h \rightarrow 0} f(a+h) = \lim_{h \rightarrow 0} f(a) = f(a)$. Thus, f is continuous at a , replacing $a+h$ with x and $h \rightarrow 0$ with $x \rightarrow a$. ■

Definition 2.1.3 (Higher Order Derivatives). Since the derivative of a function f is also a function, we can take its derivative to obtain the function $(f')' = f''$. In general, we denote the $k+1$ -th derivative of f inductively by

$$\begin{aligned}f^{(1)} &= f' \\ f^{(k+1)} &= (f^{(k)})'\end{aligned}$$

These are called higher order derivatives of f . We also define $f^{(0)} = f$. In Leibnizian notation we write

$$\frac{d^k f(x)}{dx} = f^{(k)} \quad (2.1.5)$$

2.2.0 Differentiation Results

Theorem 2.2.1. If f is a constant function, $f(x) = c$, then $f'(a) = 0$ for all $a \in \mathbb{R}$.

Proof. Observe that for $a \in \mathbb{R}$,

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

as desired. ■

Theorem 2.2.2. If f is the identity function, $f(x) = x$, then $f'(a) = 1$ for all $a \in \mathbb{R}$.

Proof. Observe that for $a \in \mathbb{R}$,

$$f'(a) = \lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h} = \lim_{h \rightarrow 0} \frac{a+h - a}{h} = \lim_{h \rightarrow 0} 1 = 1$$

as desired. ■

Theorem 2.2.3 (Linearity). If f and g are differentiable at a , then $f + cg$ is differentiable for all $c \in \mathbb{R}$

Proof. Observe that

$$\begin{aligned}
 (f + cg)'(a) &= \lim_{h \rightarrow 0} \frac{(f + cg)(a + h) - (f + cg)(a)}{h} \\
 &= \lim_{h \rightarrow 0} \frac{f(a + h) + cg(a + h) - [f(a) + cg(a)]}{h} \\
 &= \lim_{h \rightarrow 0} \frac{[f(a + h) - f(a)] + c[g(a + h) - g(a)]}{h} \\
 &= \lim_{h \rightarrow 0} \left(\frac{f(a + h) - f(a)}{h} + c \frac{g(a + h) - g(a)}{h} \right) \\
 &= \lim_{h \rightarrow 0} \frac{f(a + h) - f(a)}{h} + \lim_{h \rightarrow 0} c \frac{g(a + h) - g(a)}{h} \\
 &= f'(a) + c \lim_{h \rightarrow 0} \frac{g(a + h) - g(a)}{h} \\
 &= f'(a) + cg'(a)
 \end{aligned}$$

as desired. ■

Theorem 2.2.4 (Product Rule). *If f and g are differentiable at a , then $f \cdot g$ is also differentiable at a and*

$$(f \cdot g)'(a) = f'(a) \cdot g(a) + f(a) \cdot g'(a)$$

Proof. Observe that

$$\begin{aligned}
 (f \cdot g)'(a) &= \lim_{h \rightarrow 0} \frac{(f \cdot g)(a + h) - (f \cdot g)(a)}{h} \\
 &= \lim_{h \rightarrow 0} \frac{f(a + h)g(a + h) - f(a + h)g(a) + f(a + h)g(a) - f(a)g(a)}{h} \\
 &= \lim_{h \rightarrow 0} \frac{f(a + h)[g(a + h) - g(a)]}{h} + \lim_{h \rightarrow 0} \frac{g(a)[f(a + h) - f(a)]}{h} \\
 &= \lim_{h \rightarrow 0} f(a + h) \cdot \lim_{h \rightarrow 0} \frac{g(a + h) - g(a)}{h} + \lim_{h \rightarrow 0} \frac{f(a + h) - f(a)}{h} \cdot \lim_{h \rightarrow 0} g(a) \\
 &= f(a) \cdot g'(a) + f'(a) \cdot g(a)
 \end{aligned}$$

as claimed, where $\lim_{h \rightarrow 0} f(a + h) = f(a)$ since f is differentiable at a , which implies it is also continuous at a . ■

Theorem 2.2.5 (Power Rule). *IF $f(x) = x^n$ for some natural number n , then*

$$f'(a) = na^{n-1}$$

for all a .

Proof. For the proof we will proceed by induction on n . For $n = 1$ we have shown that $f'(a) = 1 = 1 \cdot a^0$, satisfying the base case. Assume that there exists $k \in \mathbb{N}$ such that if $n = k$, $f'(a) = ka^{k-1}$. Then, for the case of $n = k + 1$ we may write $g(x) = x \cdot x^k = I(x) \cdot f(x)$. Hence, by the product rule we have that for all a

$$g'(a) = (I \cdot f)'(a)$$

$$\begin{aligned}
 &= I'(a) \cdot f(a) + I(a) \cdot f'(a) \\
 &= 1 \cdot a^k + a \cdot k a^{k-1} \\
 &= (k+1)a^k
 \end{aligned}$$

as claimed. Hence, by mathematical induction we conclude that if $f(x) = x^n$ for $n \in \mathbb{N}$, then $f'(a) = n a^{n-1}$ for all $a \in \mathbb{R}$. ■

Theorem 2.2.6 (Derivative of a Quotient). *If g is differentiable at a , and $g(a) \neq 0$, then $1/g$ is differentiable at a and*

$$\left(\frac{1}{g}\right)'(a) = \frac{-g'(a)}{|g(a)|^2}$$

Proof. Note that since g is differentiable at a it is continuous at a . Moreover, since $g(a) \neq 0$, there exists $\delta > 0$ such that $g(a+h) \neq 0$ for $|h| < \delta$. Therefore, $(1/g)(a+h)$ is well defined for small enough h , and we can write

$$\begin{aligned}
 \lim_{h \rightarrow 0} \frac{(1/g)(a+h) - (1/g)(a)}{h} &= \lim_{h \rightarrow 0} \frac{1/g(a+h) - 1/g(a)}{h} \\
 &= \lim_{h \rightarrow 0} \frac{g(a) - g(a+h)}{h[g(a) \cdot g(a+h)]} \\
 &= \lim_{h \rightarrow 0} \frac{-[g(a+h) - g(a)]}{h} \cdot \lim_{h \rightarrow 0} \frac{1}{g(a) \cdot g(a+h)} \\
 &= -g'(a) \cdot \frac{1}{|g(a)|^2}
 \end{aligned}$$

where $\lim_{h \rightarrow 0} 1/g(a+h) = 1/g(a)$ by continuity of g . ■

Theorem 2.2.7 (Quotient Rule). *If f and g are differentiable at a and $g(a) \neq 0$, then f/g is differentiable at a and*

$$(f/g)'(a) = \frac{g(a) \cdot f'(a) - f(a) \cdot g'(a)}{|g(a)|^2}$$

Proof. Note that $f/g = f \cdot (1/g)$, so we have

$$\begin{aligned}
 (f/g)'(a) &= (f \cdot 1/g)'(a) \\
 &= f'(a) \cdot (1/g)(a) + f(a) \cdot (1/g)'(a) && \text{(Product Rule)} \\
 &= \frac{f'(a)}{g(a)} - \frac{f(a)g'(a)}{|g(a)|^2} && \text{(Quotient Derivative)} \\
 &= \frac{f'(a)g(a) - f(a)g'(a)}{|g(a)|^2}
 \end{aligned}$$

as claimed. ■

Theorem 2.2.8 (General Product Rule). *If f_1, f_2, \dots, f_n are differentiable at a for some $n \in \mathbb{N}$, then $f_1 \cdot f_2 \cdot \dots \cdot f_n$ is differentiable at a and*

$$(f_1 \cdot \dots \cdot f_n)'(a) = \sum_{i=1}^n f_1(a) \cdot \dots \cdot f_{i-1}(a) \cdot f'_i(a) \cdot f_{i+1}(a) \cdot \dots \cdot f_n(a)$$

Proof. We proceed by induction on n . If $n = 1$ then $f'_1(a) = f'_1(a)$, so the base case holds. Now, suppose the claim is true for some $k \in \mathbb{N}$. Then it follows that if $n = k + 1$

$$\begin{aligned} (f_1 \cdot \dots \cdot f_k \cdot f_{k+1})'(a) &= (f_1 \cdot \dots \cdot f_k)'(a) f_{k+1}(a) + (f_1 \cdot \dots \cdot f_k)(a) f'_{k+1}(a) && \text{(Product Rule)} \\ &= \left[\sum_{i=1}^k f_1(a) \cdot \dots \cdot f_{i-1}(a) \cdot f'_i(a) \cdot f_{i+1}(a) \cdot \dots \cdot f_k(a) \right] f_{k+1}(a) \\ &\quad + f_1(a) \cdot \dots \cdot f_k(a) \cdot f'_{k+1}(a) && \text{(by Induction Hypothesis)} \\ &= \sum_{i=1}^{k+1} f_1(a) \cdot \dots \cdot f_{i-1}(a) \cdot f'_i(a) \cdot f_{i+1}(a) \cdot \dots \cdot f_{k+1}(a) \end{aligned}$$

as desired. Thus by mathematical induction we conclude that the formula holds for all $n \in \mathbb{N}$. ■

Theorem 2.2.9 (Chain Rule). *If g is differentiable at a and f is differentiable at $g(a)$, then $f \circ g$ is differentiable at a and*

$$(f \circ g)'(a) = f'(g(a)) \cdot g'(a)$$

Proof. Define a function ϕ as follows:

$$\phi(h) = \begin{cases} \frac{f(g(a+h)) - f(g(a))}{g(a+h) - g(a)}, & \text{if } g(a+h) - g(a) \neq 0 \\ f'(g(a)), & \text{if } g(a+h) - g(a) = 0 \end{cases} \quad (2.2.1)$$

Note that by differentiability of g at a , g is continuous at a as well so as $h \rightarrow 0$, $g(a+h) - g(a) \rightarrow 0$, so if $g(a+h) - g(a)$ is not zero, then $\phi(h)$ will approach $f'(g(a))$ as h goes to zero. If it is zero then $\phi(h)$ is exactly $f'(g(a))$. Note that as f is differentiable at $g(a)$ we have

$$\lim_{k \rightarrow 0} \frac{f(g(a) + k) - f(g(a))}{k} = f'(g(a))$$

Thus, if $\epsilon > 0$ there is some number $\delta' > 0$ such that, for all k ,

$$(1) \text{ if } 0 < |k| < \delta', \text{ then } \left| \frac{f(g(a) + k) - f(g(a))}{k} - f'(g(a)) \right| < \epsilon$$

Now, g is differentiable at a , hence continuous at a , so there is $\delta > 0$ such that for all h ,

$$(2) \text{ if } |h| < \delta, \text{ then } |g(a+h) - g(a)| < \delta'$$

Consider now any h with $|h| < \delta$. If $k = g(a+h) - g(a) \neq 0$, then

$$\phi(h) = \frac{f(g(a+h)) - f(g(a))}{g(a+h) - g(a)} = \frac{f(g(a) + k) - f(g(a))}{k}$$

it follows from (2) that $|k| < \delta'$, and hence from (1) that

$$|\phi(h) - f'(g(a))| < \epsilon$$

On the other hand, if $g(a+h) - g(a) = 0$, then $\phi(h) = f'(g(a))$, so it is surely true that

$$|\phi(h) - f'(g(a))| < \epsilon$$

We therefore have proved that

$$\lim_{h \rightarrow 0} \phi(h) = f'(g(a))$$

so ϕ is continuous at 0. If $h \neq 0$, then we have

$$\frac{f(g(a+h)) - f(g(a))}{h} = \phi(h) \cdot \frac{g(a+h) - g(a)}{h}$$

even if $g(a+h) - g(a) = 0$. Therefore, we have that

$$\begin{aligned} (f \circ g)'(a) &= \lim_{h \rightarrow 0} \frac{f(g(a+h)) - f(g(a))}{h} \\ &= \lim_{h \rightarrow 0} \phi(h) \cdot \lim_{h \rightarrow 0} \frac{g(a+h) - g(a)}{h} \\ &= f'(g(a)) \cdot g'(a) \end{aligned}$$

by continuity of $\phi(h)$ at 0. ■

2.3.0 Applications of Derivatives

Definition 2.3.1 (Extrema). Let f be a function and A a set of numbers contained in the domain of f . A point $x \in A$ is **maximum point** for f on A if

$$f(x) \geq f(y) \forall y \in A \quad (2.3.1)$$

The number $f(x)$ is itself called the **maximum value** of f on A .

A point $x \in A$ is a **minimum point** for f on A if

$$f(x) \leq f(y) \forall y \in A \quad (2.3.2)$$

The number $f(x)$ is itself called the **minimum value** of f on A .

Theorem 2.3.1. Let f be any function defined on (a, b) . If x is an extremum point for f on (a, b) , and f is differentiable at x , then $f'(x) = 0$.

Proof. Consider the case where f has a maximum at x . If h is any number such that $x + h \in (a, b)$, then

$$f(x) \geq f(x+h)$$

since f has a maximum on (a, b) at x . This implies that

$$f(x+h) - f(x) \leq 0$$

Thus, if $h > 0$ we have that

$$\frac{f(x+h) - f(x)}{h} \leq 0$$

and consequently

$$\lim_{h \rightarrow 0^+} \frac{f(x+h) - f(x)}{h} \leq 0$$

as otherwise $\frac{f(x+h)-f(x)}{h} > 0$ for some h , contradicting our initial assumptions. Similarly, if $h < 0$ we have

$$\frac{f(x+h)-f(x)}{h} \geq 0$$

so

$$\lim_{h \rightarrow 0^-} \frac{f(x+h)-f(x)}{h} \geq 0$$

By hypothesis f is differentiable at x , so these two limits must be equal, so in fact $f'(x) \leq 0$ and $f'(x) \geq 0$. Thus, $f'(x) = 0$.

On the other hand, suppose f has a minimum at x . Then $-f$ has a maximum at x . Indeed, for all $y \in (a, b)$ we have $f(y) \geq f(x)$, so $-f(y) \leq -f(x)$. Then, from our above argument and the differentiability of f at x , we have $-f'(x) = 0$, which implies that $f'(x) = 0$. ■

Definition 2.3.2 (Local Extrema). Let f be a function, and A a set of numbers contained in the domain of f . A point x in A is a **local maximum [minimum] point** for f on A if there is some $\delta > 0$ such that x is a maximum [minimum] point for f on $A \cap (x - \delta, x + \delta)$.

Definition 2.3.3. A **critical point** of a function f is a number x such that

$$f'(x) = 0 \tag{2.3.3}$$

The number $f(x)$ itself is called a **critical value** of f .

Remark 2.3.1. Give a function continuous f , if x is an extrumum of f on $[a, b]$, then one of the following must be satisfied:

1. x is a critical point of f in $[a, b]$
2. $x = a$ or $x = b$ so x is an endpoint of $[a, b]$
3. x is a point in $[a, b]$ such that f is not differentiable at x

Theorem 8 (Rolle's Theorem).

If f is continuous on $[a, b]$ and differentiable on (a, b) , and $f(a) = f(b)$, then there is a number $x \in (a, b)$ such that $f'(x) = 0$.

Proof. It follows from continuity of f on $[a, b]$ that f has a maximum or minimum value on $[a, b]$ (by the Extreme Value Theorem).

Suppose first that the maximum value occurs at a point $x \in (a, b)$. Then $f'(x) = 0$ by Theorem 2.3.1. On the other hand suppose that the minimum value of f occurs at some point x in (a, b) . Then, again, $f'(x) = 0$ by Theorem 2.3.1.

Finally, suppose the maximum and minimum values both occur at the end points. Since $f(a) = f(b)$, the maximum and minimum values of f are equal, so f is a constant function, and for a constant function we can choose any $x \in (a, b)$ and have $f'(x) = 0$, completing the proof. ■

Theorem 9 (The Mean Value Theorem).

If f is continuous on $[a, b]$ and differentiable on (a, b) , then there is a number $x \in (a, b)$ such that

$$f'(x) = \frac{f(b) - f(a)}{b - a} \quad (2.3.4)$$

Proof. Let

$$h(x) = f(x) - \left[\frac{f(b) - f(a)}{b - a} \right] (x - a)$$

Evidently, h is continuous on $[a, b]$ and differentiable on (a, b) as it is the sum of correspondingly continuous and differentiable functions. Moreover,

$$\begin{aligned} h(a) &= f(a) \\ h(b) &= f(b) - \left[\frac{f(b) - f(a)}{b - a} \right] (b - a) \\ &= f(a) \end{aligned}$$

Consequently, we may apply 8 to h and conclude that there exists $x \in (a, b)$ such that

$$0 = h'(x) = f'(x) - \frac{f(b) - f(a)}{b - a}$$

so that

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

as desired. ■

Corollary 2.3.2. If f is defined on an interval and $f'(x) = 0$ for all x in the interval, then f is constant on the interval.

Proof. Let a and b be any two points in the interval with $a \neq b$. Then there is some $x \in (a, b)$ such that

$$0 = f'(x) = \frac{f(b) - f(a)}{b - a}$$

so $f(b) - f(a) = 0$ and consequently $f(a) = f(b)$. Thus the value of f at any two points in the interval is the same, so f is constant on the interval. ■

Corollary 2.3.3. If f and g are defined on the same interval, and $f'(x) = g'(x)$ for all x in the interval, then there is some number c such that $f = g + c$.

Proof. For all x in the interval we have $(f - g)'(x) = f'(x) - g'(x) = 0$, so by the previous corollary there is some number c such that $f - g = c$. ■

Definition 2.3.4. A function is **increasing** on an interval I if $f(a) < f(b)$ whenever $a, b \in I$ with $a < b$. The function f is **decreasing** on an interval I if $f(a) > f(b)$ for all $a, b \in I$ with $a < b$.

Corollary 2.3.4. If $f'(x) > 0$ for all x in an interval, then f is increasing on the interval; if $f'(x) < 0$ for all x in the interval, then f is decreasing on the interval.

Proof. Consider the case where $f'(x) > 0$. Let $a, b \in I$ with $a < b$. Then by 9 there exists $x \in (a, b)$ such that

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

But, $f'(x) > 0$ for all $x \in (a, b)$, so

$$\frac{f(b) - f(a)}{b - a} > 0$$

Since $b - a > 0$ we conclude that $f(b) > f(a)$ so f is increasing.

Next, consider the case for $f'(x) < 0$. Then $-f'(x) > 0$ for all $x \in I$, so by the first case we have that for all $a, b \in I$ with $a < b$, $-f(a) < -f(b)$. Multiplying both sides by -1 we have that $f(a) > f(b)$ for all $a, b \in I$ such that $a < b$, so f is decreasing, as desired. ■

Theorem 2.3.5 (Second Derivative Test). Suppose $f'(a) = 0$. If $f''(a) > 0$, then f has a local minimum at a ; if $f''(a) < 0$ then f has a local maximum at a .

Proof. By definition

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

Since $f'(a) = 0$ by assumption, we can write

$$f''(a) = \lim_{h \rightarrow 0} \frac{f'(a+h)}{h}$$

Suppose now that $f''(a) > 0$. Then there exists $\delta > 0$ such that if $|h| < \delta$ $f'(a+h)/h > 0$. Thus, for $|h| < \delta$, if $h < 0$ we must have $f'(a+h) < 0$ and if $h > 0$ we must have $f'(a+h) > 0$. This means by our previous corollary that f is increasing in the interval $(a, a + \delta)$, and decreasing in $(a - \delta, a)$. Thus, as $f'(a) = 0$, $f(a)$ must be a local minimum.

If $f''(a) < 0$, then $-f''(a) > 0$ so $-f(a)$ is must be a local minimum. That is, there exists $\delta > 0$ such that if $x \in (a - \delta, a + \delta)$, then $-f(x) \geq -f(a)$. Hence, it follows that $f(x) \leq f(a)$ for all $x \in (a - \delta, a + \delta)$, so $f(a)$ is a local maximum of f . ■

Theorem 2.3.6. Suppose $f''(a)$ exists. If f has a local minimum at a , then $f''(a) \geq 0$; if f has a local maximum at a , then $f''(a) \leq 0$.

Proof. Suppose f has a local minimum at a . If $f''(a) < 0$ then by our previous result f would have a local maximum at a . But, this implies that f would be constant in some interval containing a , so that $f''(a) = 0$, which is a contradiction. Thus, we must have that $f''(a) \geq 0$.

The case for a local maximum is analogous. ■

Theorem 2.3.7. Suppose that f is continuous at a , and that $f'(x)$ exists for all x in some interval containing a , except perhaps for $x = a$. Suppose, moreover, that $\lim_{x \rightarrow a} f'(x)$ exists. Then $f'(a)$ also exists and

$$f'(a) = \lim_{x \rightarrow a} f'(x) \quad (2.3.5)$$

Proof. By definition

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

For sufficiently small $h > 0$ the function f will be continuous on $[a, a+h]$, and differentiable on $(a, a+h)$, by assumption (similarly for sufficiently small $h < 0$). By 9 there is a number $\alpha_h \in (a, a+h)$ such that

$$\frac{f(a+h) - f(a)}{h} = f'(\alpha_h)$$

Now, α_h approaches a as h approaches 0, because α_h is in $(a, a+h)$. Since $\lim_{x \rightarrow a} f'(x)$ exists, it follows that

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

For this last equality write $\lim_{x \rightarrow a} f'(x) = L \in \mathbb{R}$. Fix $\epsilon > 0$. Then there exists $\delta > 0$ such that for all $x \in (a - \delta, a + \delta)$, $|f'(x) - L| < \epsilon$. It follows that for $|h| < \delta$, if $h > 0$ and $\alpha_h \in (a, a+h) \subset (a - \delta, a + \delta)$ we have $|f'(\alpha_h) - L| < \epsilon$ and if $h < 0$ and $\alpha_h \in (a+h, a) \subset (a - \delta, a + \delta)$, then $|f'(\alpha_h) - L| < \epsilon$. Thus, by definition we have that $\lim_{h \rightarrow 0^+} f'(\alpha_h) = \lim_{h \rightarrow 0^-} f'(\alpha_h) = L$, so in particular $\lim_{h \rightarrow 0} f'(\alpha_h) = L = \lim_{x \rightarrow a} f'(x)$, completing the proof. ■

Theorem 10 (The Cauchy Mean Value Theorem).

If f and g are continuous on $[a, b]$ and differentiable on (a, b) , then there is a number $x \in (a, b)$ such that

$$[f(b) - f(a)]g'(x) = [g(b) - g(a)]f'(x) \quad (2.3.6)$$

Proof. Let

$$h(x) = f(x)[g(b) - g(a)] - g(x)[f(b) - f(a)]$$

Then h is continuous on $[a, b]$, differentiable on (a, b) , and

$$h(a) = f(a)g(b) - g(a)f(b) = h(b)$$

It follows by 8 that $h'(x) = 0$ for some $x \in (a, b)$, which implies that

$$0 = h'(x) = f'(x)[g(b) - g(a)] - g'(x)[f(b) - f(a)]$$

completing the proof. ■

Theorem 11 (L'Hôpital's Rule).

Suppose that

$$\lim_{x \rightarrow a} f(x) = 0 \text{ and } \lim_{x \rightarrow a} g(x) = 0 \quad (2.3.7)$$

and suppose also that $\lim_{x \rightarrow a} f'(x)/g'(x)$ exists. Then $\lim_{x \rightarrow a} f(x)/g(x)$ exists, and

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)} \quad (2.3.8)$$

Proof. The hypothesis that $\lim_{x \rightarrow a} f'(x)/g'(x)$ exists contains two implicit assumptions:

1. there is an interval $(a - \delta, a + \delta)$ such that $f'(x)$ and $g'(x)$ exist for all $x \in (a - \delta, a + \delta)$, except, perhaps, $x = a$,
2. in this interval $g'(x) \neq 0$, with the possible exception of $x = a$

If we define $f(a) = g(a) = 0$, then f and g are continuous at a . If $x \in (a, a + \delta)$, then 9 and 10 apply to f and g on $[a, x]$ (a similar statement holds for $x \in (a - \delta, a)$). First, applying the 9 to g , we see that $g(x) \neq 0$, for if $g(x) = 0$ there would exist $x_1 \in (a, x)$ with $g'(x_1) = 0$, contradicting 2.. Now, applying 10 to f and g , we see that there is a number $\alpha_x \in (a, x)$ such that

$$[f(x) - 0]g'(\alpha_x) = [g(x) - 0]f'(\alpha_x)$$

or

$$\frac{f(x)}{g(x)} = \frac{f'(\alpha_x)}{g'(\alpha_x)}$$

Now, let $\lim_{y \rightarrow a} f'(y)/g'(y) = L \in \mathbb{R}$. Fix $\epsilon > 0$. Then there exists $\delta' > 0$ such that if $y \in (a - \delta', a + \delta')$ then $|f'(y)/g'(y) - L| < \epsilon$. Then, for $x \in (a, a + \delta)$ (or $x \in (a - \delta, a)$) we have $(a, x) \subset (a - \delta, a + \delta)$ (or $(x, a) \subset (a - \delta, a + \delta)$). Thus, for $|x - a| < \delta$ we have $\alpha_x \in (a, x) \subset (a - \delta, a + \delta)$ (or $\alpha_x \in (x, a) \subset (a - \delta, a + \delta)$), so $|f'(\alpha_x)/g'(\alpha_x) - L| < \epsilon$. Therefore, we conclude that

$$\lim_{x \rightarrow a^+} \frac{f'(\alpha_x)}{g'(\alpha_x)} = L = \lim_{x \rightarrow a^-} \frac{f'(\alpha_x)}{g'(\alpha_x)}$$

so in particular

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(\alpha_x)}{g'(\alpha_x)} = \lim_{y \rightarrow a} \frac{f'(y)}{g'(y)}$$

completing the proof. ■

Convexity

Definition 2.3.5. A function f is **convex** on an interval I , if for all $a, b \in I$, the line segment joining $(a, f(a))$ and $(b, f(b))$ lies above the graph of f .

This is equivalent to stating that for all $x \in (a, b)$,

$$\frac{f(x) - f(a)}{x - a} < \frac{f(b) - f(a)}{b - a} \quad (2.3.9)$$

Definition 2.3.6. A function f is **concave** on an interval I , if for all $a, b \in I$, the line segment joining $(a, f(a))$ and $(b, f(b))$ lies below the graph of f .

This is equivalent to stating that for all $x \in (a, b)$,

$$\frac{f(x) - f(a)}{x - a} > \frac{f(b) - f(a)}{b - a} \quad (2.3.10)$$

Theorem 2.3.8. *Let f be convex. If f is differentiable at a , then the graph of f lies above the tangent line through $(a, f(a))$, except at $(a, f(a))$ itself. If $a < b$ and f is differentiable at a and b , then $f'(a) < f'(b)$.*

Proof. If $0 < h_1 < h_2$, then $a < a + h_1 < a + h_2$, and applying f 's convexity we have that

$$\frac{f(a + h_1) - f(a)}{h_1} < \frac{f(a + h_2) - f(a)}{h_2}$$

This implies that the values of $[f(a + h) - f(a)]/h$ decrease as $h \rightarrow 0^+$. Consequently,

$$f'(a) < \frac{f(a + h) - f(a)}{h}, h > 0$$

In fact, $f'(a)$ is the infimum of these numbers. Similarly, for h negative, if $h_2 < h_1 < 0$, then

$$\frac{f(a + h_1) - f(a)}{h_1} > \frac{f(a + h_2) - f(a)}{h_2}$$

This shows that the slope of the tangent line is greater than $[f(a + h) - f(a)]/h$ for $h < 0$. In fact, $f'(a)$ is the supremum of all these numbers, so $f(a + h)$ lies above the tangent line if $h < 0$. This satisfies the first part of the theorem. Now, suppose $a < b$. Then we have that

$$f'(a) < \frac{f(a + (b - a)) - f(a)}{b - a} = \frac{f(b) - f(a)}{b - a}$$

since $b - a > 0$ and

$$f'(b) > \frac{f(b + (a - b)) - f(b)}{a - b} = \frac{f(a) - f(b)}{a - b} = \frac{f(b) - f(a)}{b - a}$$

since $a - b < 0$. Combining these inequalities we obtain $f'(a) < f'(b)$, as desired. ■

Lemma 2.3.9. *Suppose f is differentiable and f' is increasing. If $a < b$ and $f(a) = f(b)$, then $f(x) < f(a) = f(b)$ for $a < x < b$.*

Proof. Suppose towards a contradiction that $f(x) \geq f(a) = f(b)$ for some $x \in (a, b)$. Then the maximum of f on $[a, b]$ occurs at some point $x_0 \in (a, b)$ with $f(x_0) \geq f(a)$ and, of course, $f'(x_0) = 0$. On the other hand, applying 9 to the interval $[a, x_0]$, we find that there is x_1 with $a < x_1 < x_0$ and

$$f'(x_1) = \frac{f(x_0) - f(a)}{x_0 - a} \geq 0$$

contradicting the fact that f' is increasing (since $f'(x_0) = 0$ and $x_1 < x_0$). ■

Theorem 2.3.10. *If f is differentiable and f' is increasing, then f is convex.*

Proof. Let $a < b$. Define g by

$$g(x) = f(x) - \frac{f(b) - f(a)}{b - a}(x - a)$$

It is easy to see that g' is also increasing; moreover, $g(a) = g(b) = f(a)$. Applying the lemma to g we conclude that

$$a < x < b \implies g(x) < f(a)$$

In other words, if $a < x < b$, then

$$f(x) - \frac{f(b) - f(a)}{b - a}(x - a) < f(a)$$

or

$$\frac{f(x) - f(a)}{x - a} < \frac{f(b) - f(a)}{b - a}$$

Hence, f is convex. ■

Theorem 2.3.11. *If f is differentiable and the graph of f lies above each tangent line except at the point of contact, then f is convex.*

Proof. Let $a < b$. Since the tangent line at $(a, f(a))$ is the graph of the function

$$g(x) = f'(a)(x - a) + f(a)$$

and since $(b, f(b))$ lies above the tangent line, we have

$$(1) \quad f(b) > f'(a)(b - a) + f(a)$$

Similarly, since the tangent line at $(b, f(b))$ is the graph of $h(x) = f'(b)(x - b) + f(b)$, and $(a, f(a))$ lies above the tangent line at $(b, f(b))$, we have

$$(2) \quad f(a) > f'(b)(a - b) + f(b)$$

It follows from (1) and (2) that $f'(a) < f'(b)$. Then, from our previous theorem we have that f is convex. ■

2.4.0 Inverse Functions

Definition 2.4.1. *For any function f , the inverse image of f , denoted by f^{-1} , is the set of all pairs (a, b) such that $(b, a) \in f$.*

Remark 2.4.1. f^{-1} is a function if and only if f is one-to-one.

Theorem 2.4.1. *If f is increasing (decreasing) on an interval I , then f is injective on I so f^{-1} is a function and in fact f^{-1} is increasing (decreasing).*

Proof. Consider the case that f is increasing. Then suppose $a, b \in I$ with $a \neq b$. Without loss of generality suppose $a < b$. Then since f is increasing $f(a) < f(b)$ so in particular $f(a) \neq f(b)$. Therefore, f is injective as claimed, so f^{-1} is a well-defined function on I . Now, consider $a' < b'$ in $f(I) = I'$. Then there exist $x, y \in I$ such that $f(x) = a'$ and $f(y) = b'$, so in particular $f^{-1}(a') = x$ and $f^{-1}(b') = y$. Since f is increasing and $f(x) = a' < b' = f(y)$ we must have that $x < y$. Thus, $f^{-1}(a') = x < y = f^{-1}(b')$, so f^{-1} is increasing as claimed.

Consider the case that f is decreasing. Then $-f$ is increasing so it is injective and $-f^{-1}$ is increasing by the first case. Hence, we have that f^{-1} is decreasing as desired. ■

Theorem 2.4.2. *If f is continuous and one-to-one on an interval I , then f is either increasing or decreasing on I .*

Proof. We proceed in three steps:

(1) If $a < b < c$ are three points in I , then I claim either $f(a) < f(b) < f(c)$ or $f(a) > f(b) > f(c)$. Indeed, suppose that $f(a) < f(c)$. If we have $f(b) < f(a)$, then the 6 applied to $[b, c]$ gives an $x \in (b, c)$ such that $f(x) = f(a)$, contradicting the fact that f is injective on $[a, c]$. Similarly, if $f(b) > f(c)$ we would find a contradiction, so $f(a) < f(b) < f(c)$. Similar argumentation leads to the result that $f(a) > f(b) > f(c)$ in the second case.

(2) If $a < b < c < d$ are four points in I , then I claim that either $f(a) < f(b) < f(c) < f(d)$ or $f(a) > f(b) > f(c) > f(d)$. Indeed we can apply (1) to $a < b < c$ and then to $b < c < d$.

(3) Take any $a < b$ in I , and suppose $f(a) < f(b)$. Then f is increasing, for if $c, d \in I$ are any two points, we can apply (2) to the collection $\{a, b, c, d\}$ after arranging them in increasing order. ■

Theorem 2.4.3. *If f is continuous and one-to-one on an interval, then f^{-1} is also continuous.*

Proof. Since f is continuous and injective on the interval, it is either increasing or decreasing. Consider the case that f is increasing. We must show that

$$\lim_{x \rightarrow b} f^{-1}(x) = f^{-1}(b)$$

for each b in the domain of f^{-1} . Such a number b is of the form $f(a)$ for some a in the domain of f . For any $\epsilon > 0$, we want to find a $\delta > 0$ such that for all x , if $x \in (f(a) - \delta, f(a) + \delta)$, then $|f^{-1}(x) - a| < \epsilon$, as $a = f^{-1}(b) = f^{-1}(f(a))$. Now, since $a - \epsilon < a < a + \epsilon$ we have that $f(a - \epsilon) < f(a) < f(a + \epsilon)$ since f is presumed increasing. Let $\delta = \min(f(a + \epsilon) - f(a), f(a) - f(a - \epsilon))$. Our choice of δ ensures that

$$f(a - \epsilon) \leq f(a) - \delta \text{ and } f(a) + \delta \leq f(a + \epsilon)$$

Consequently, if

$$f(a) - \delta < x < f(a) + \delta$$

then

$$f(a - \epsilon) < x < f(a + \epsilon)$$

Since f is increasing, f^{-1} is also increasing, and we obtain

$$f^{-1}(f(a - \epsilon)) < f^{-1}(x) < f^{-1}(f(a + \epsilon))$$

so $a - \epsilon < f^{-1}(x) < a + \epsilon$, which is precisely $|f^{-1}(x) - a| < \epsilon$, as desired. ■

Theorem 2.4.4. *If f is a continuous one-to-one function defined on an interval I , and $f'(f^{-1}(a)) = 0$, then f^{-1} is not differentiable at a .*

Proof. We have $f(f^{-1}(x)) = x$. If f^{-1} were differentiable at a , then the chain rule would imply that

$$f'(f^{-1}(a)) \cdot (f^{-1})'(a) = 1$$

hence

$$0 \cdot (f^{-1})'(a) = 1$$

which is impossible. ■

Theorem 2.4.5. *Let f be a continuous one-to-one function defined on an interval I , and suppose that f is differentiable at $f^{-1}(b)$, with derivative $f'(f^{-1}(b)) \neq 0$. Then f^{-1} is differentiable at b , and*

$$(f^{-1})'(b) = \frac{1}{f'(f^{-1}(b))} \quad (2.4.1)$$

Proof. Let $b = f(a)$. Then

$$\lim_{h \rightarrow 0} \frac{f^{-1}(b+h) - f^{-1}(b)}{h} = \lim_{h \rightarrow 0} \frac{f^{-1}(b+h) - a}{h}$$

Now, every number $b+h$ in the domain of f^{-1} can be written in the form $b+h = f(a+k)$ for a unique $k(h)$. Then

$$\begin{aligned} \lim_{h \rightarrow 0} \frac{f^{-1}(b+h) - a}{h} &= \lim_{h \rightarrow 0} \frac{f^{-1}(f(a+k(h))) - a}{f(a+k(h)) - b} \\ &= \lim_{h \rightarrow 0} \frac{k(h)}{f(a+k(h)) - f(a)} \end{aligned}$$

Since $b+h = f(a+k(h))$ we have $f^{-1}(b+h) = a+k(h)$, or $k(h) = f^{-1}(b+h) - f^{-1}(b)$. Now, since f is continuous on I , f^{-1} is also continuous on its domain, and in particular it is continuous at b . This means that $\lim_{h \rightarrow 0} k(h) = 0$, so $k(h)$ goes to zero as h goes to 0. Hence, as

$$\lim_{k \rightarrow 0} \frac{f(a+k) - f(a)}{k} = f'(a) = f'(f^{-1}(b)) \neq 0$$

this implies that f^{-1} is differentiable at b and

$$(f^{-1})'(b) = \frac{1}{f'(f^{-1}(b))}$$
■

2.A.0 Alternative Differentiation Formulation

Definition 2.A.1. A function $f : (a, b) \subseteq \mathbb{R} \rightarrow \mathbb{R}$ (or \mathbb{C}) is said to be differentiable at $x \in (a, b)$ with derivative $f'(x)$ if the limit

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

exists.

If f is differentiable at $x \in (a, b)$, it is immediate that f is continuous at x . Indeed, let $\varepsilon > 0$. Then there exists $\delta > 0$ such that if $0 < |h| < \delta$, $\left| \frac{f(x+h)-f(x)}{h} - f'(x) \right| < \varepsilon$. Then let $\delta' = \min \{ \delta, |f'(x)| + \varepsilon \}$. Then for $x+h \in B_{\delta'}(x)$, $h \neq 0$, we have

$$|f(x+h) - f(x)| = |h| \left| \frac{f(x+h) - f(x)}{h} \right| < \delta' (|f'(x)| + \varepsilon) \leq \varepsilon$$

Now a useful equivalent condition to differentiability at $x \in (a, b)$ is the existence of a function $r(x, h)$ for h close to 0 such that $f(x+h) = f(x) + Dh + r(x, h)$ such that $\frac{r(x, h)}{h} \rightarrow 0$ as $h \rightarrow 0$, and then $D = f'(x)$. Indeed if f is differentiable set $r(x, h) = f(x+h) - (f(x) + f'(x)h)$. On the other hand, if such an $r(x, h)$ exists, then

$$\frac{f(x+h) - f(x)}{h} = \frac{r(x, h)}{h} + D \rightarrow D$$

so the limit exists and is D .

Definition 2.A.2. We say that f is differentiable on (a, b) if it is differentiable at all $x \in (a, b)$.

Proposition 2.A.1. Let f and g be differentiable at x . Then

- $f \pm g$ is differentiable at x with $(f \pm g)'(x) = f'(x) \pm g'(x)$ (additivity)
- fg is differentiable at x with $(fg)'(x) = f'(x)g(x) + f(x)g'(x)$ (Leibnitz's rule)
- If $g(y) \neq 0$ in a neighborhood of x , then $(1/g)$ is differentiable at x with $(1/g)'(x) = -\frac{g'(x)}{g(x)^2}$
- For all $c \in \mathbb{R}$ cf is differentiable at x with $(cf)'(x) = cf'(x)$

Proof. The first bullet is by linearity of limits. The second bullet follows from the computation

$$\frac{(fg)(x+h) - (fg)(x)}{h} = \frac{(f(x+h) - f(x))g(x+h)}{h} + \frac{f(x)(g(x+h) - g(x))}{h}$$

and the fact that g is continuous at x and the product of limits is the limit of the product, if the limits involved all exist. The quotient also follows by a similar computation

$$\frac{\frac{1}{g(x+h)} - \frac{1}{g(x)}}{h} = \frac{-(g(x+h) - g(x))}{hg(x+h)g(x)}$$

and the same properties of limits and g at x . Finally, bullet follows simply by the calculation

$$\frac{cf(x+h) - cf(x)}{h} = c \frac{f(x+h) - f(x)}{h}$$

■

Some basic derivatives from the definition are $f'(x) = 0$ if $f(x) = c \in \mathbb{R}$ is a constant, and later we shall show the converse also holds. Additionally, $id'(x) = 1$, for $id(x) = x$. Then by induction $\frac{d}{dx}x^n = nx^{n-1}$ for all $n = 0, 1, 2, 3, \dots$

Proposition 2.A.2. If $f : (a, b) \rightarrow (\alpha, \beta)$ is differentiable at $x \in (a, b)$ and $g : (\alpha, \beta) \rightarrow \mathbb{R}$ is differentiable at $f(x) \in (\alpha, \beta)$, then $g \circ f$ is differentiable at x with

$$(g \circ f)'(x) = g'(f(x))f'(x)$$

Proof. We use the remainder definition of differentiability to prove the claim. As f is differentiable at x we have $r_f(x, h)$ such that $f(x+h) = f(x) + f'(x)h + r_f(x, h)$, and as g is differentiable at $f(x)$ we have $r_g(x, h)$ such that $g(f(x) + h) = g(f(x)) + g'(f(x))h + r_g(f(x), h)$. Then

$$\begin{aligned} g \circ f(x+h) &= g(f(x) + f'(x)h + r_f(x, h)) \\ &= g(f(x)) + g'(f(x))(f'(x)h + r_f(x, h)) + r_g(f(x), \tilde{h}) \quad (\tilde{h} := f'(x)h + r_f(x, h)) \end{aligned}$$

Let $r_{g \circ f}(x, h) = g'(f(x))r_f(x, h) + r_g(f(x), \tilde{h})$. Then we have $\lim_{h \rightarrow 0} g'(f(x)) \frac{r_f(x, h)}{h} = 0$ and $\lim_{h \rightarrow 0} \tilde{h} = 0$, so

$$\lim_{h \rightarrow 0} \frac{r_{g \circ f}(x, h)}{h} = \lim_{h \rightarrow 0} \frac{r_g(f(x), \tilde{h})}{\tilde{h}} \frac{\tilde{h}}{h} = 0 \cdot f'(x) = 0$$

Thus, we have that $g \circ f$ is differentiable at x with $(g \circ f)'(x) = g'(f(x))f'(x)$, as desired. ■

Proposition 2.A.3. If $f : (a, b) \rightarrow \mathbb{R}$ and $x \in (a, b)$ such that

$$f(x) \geq f(y) \text{ (or } f(x) \leq f(y)) \forall y \in (a, b)$$

then if f is differentiable at x it follows that

$$f'(x) = 0$$

Proof. First, note that

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

But for h such that $x+h \in (a, b)$, and $h > 0$, we have

$$\frac{f(x+h) - f(x)}{h} \leq 0 \text{ (respectively } \geq 0)$$

while if $h < 0$,

$$\frac{f(x+h) - f(x)}{h} \geq 0 \text{ (respectively } \leq 0)$$

Thus, by order properties of limits $f'(x) \leq 0$ and $f'(x) \geq 0$, so $f'(x) = 0$. ■

Next we explore a fundamental result for differentiable functions on an interval, which we will use to prove the fundamental theorem of calculus.

Theorem 12 (Mean Value Theorem).

Suppose f is continuous on $[a, b]$ and is differentiable on (a, b) . Then there exists $\xi \in (a, b)$ such that

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

Proof. Consider $f(x) = f(x) - (x - a)\frac{f(b)-f(a)}{b-a}$. Then g is continuous on $[a, b]$, differentiable on (a, b) , and $g(a) = f(a)$ while $g(b) = f(a)$ as well, so $\frac{g(b)-g(a)}{b-a} = 0$. Since g is continuous on the compact set $[a, b]$, g attains a maximum on $[a, b]$. If it occurs at $\xi \in (a, b)$, then $g'(\xi) = 0$. On the other hand, if the maximum occurs at a or b , then since $g(a) = g(b) = \max_{[a,b]} g$, g must attain its minimum in (a, b) . Thus, there exists $\zeta \in (a, b)$ such that $g(\zeta)$ is a minimum and $g'(\zeta) = 0$. Thus in either case we have a $\xi \in (a, b)$ such that $f'(\xi) - \frac{f(b)-f(a)}{b-a} = 0$, so $f'(\xi) = \frac{f(b)-f(a)}{b-a}$ as desired. ■

Theorem 13 (Inverse Function Theorem).

Suppose f is continuous on $[a, b]$ and differentiable on (a, b) , and there exists $\gamma_0, \gamma_1 \in \mathbb{R}$ such that $0 < \gamma_0 \leq f'(x) \leq \gamma_1 < \infty$ (or $-\infty < \gamma_0 \leq f'(x) \leq \gamma_1 < 0$) for all $x \in (a, b)$. Let $\alpha = f(a)$ and $\beta = f(b)$. Then there exists an inverse function $g : [\alpha, \beta] \rightarrow [a, b]$ (or $g : [\beta, \alpha] \rightarrow [a, b]$) which is continuous on $[\alpha, \beta]$ and differentiable on (α, β) , with derivative

$$(f^{-1})'(y) = g'(y) = \frac{1}{f'(g(y))} = \frac{1}{f'(f^{-1}(y))}$$

for all $y \in (\alpha, \beta)$.

Proof. Let $x_1, x_2 \in [a, b]$, with $a \leq x_1 < x_2 \leq b$. By the mean value theorem there exists $\xi \in (x_1, x_2)$ such that

$$f'(\xi) = \frac{f(x_2) - f(x_1)}{x_2 - x_1}$$

This implies

$$0 < \gamma_0 \leq \frac{f(x_2) - f(x_1)}{x_2 - x_1} \leq \gamma_1 < \infty$$

so

$$0 < \gamma_0(x_2 - x_1) \leq f(x_2) - f(x_1) \leq \gamma_1(x_2 - x_1)$$

for all $a \leq x_1 < x_2 \leq b$. This implies that f is strictly increasing, and so injective. Further, $f(x) \in [\alpha, \beta]$ for all $x \in [a, b]$ since $\alpha = f(a)$ and $\beta = f(b)$. By the intermediate value theorem it follows that f is surjective onto $[\alpha, \beta]$. Since $f : [a, b] \rightarrow [\alpha, \beta]$ is a continuous bijection on a compact set, f is a homeomorphism and $f^{-1} : [\alpha, \beta] \rightarrow [a, b]$ is also a homeomorphism. As f is differentiable on (a, b) , there exists $r_f(x, h)$ satisfying certain properties discussed previously. Then for $y \in (\alpha, \beta)$, there exists $x \in (a, b)$ such that $f^{-1}(y) = x$, so $f(x) = y$. Then

$$\begin{aligned} f^{-1}(y) + h &= x + h = f^{-1}(f(x + h)) = f^{-1}(f(x) + f'(x)h + r_f(x, h)) \\ &= f^{-1}(y + f'(x)h + r_f(x, h)) \end{aligned}$$

Let $\tilde{h} = f'(x)h + r_f(x, h)$, so $h = \frac{\tilde{h}}{f'(x)} - \frac{r_f(x, h)}{f'(x)}$. Then

$$f^{-1}(y + \tilde{h}) = f^{-1}(y) + \frac{1}{f'(x)}\tilde{h} - \frac{r_f(x, h)}{f'(x)}$$

Recall $r_f(x, h) = f(x + h) - f(x) - f'(x)h$. Then let $r_g(x, \tilde{h}) = -\frac{[f(x+h)-f(x)-f'(x)h]}{f'(x)}$. Note $\gamma_0 h + r_f(x, h) \leq \tilde{h} \leq \gamma_1 h + r_f(x, h)$, so

$$\gamma_0 + \frac{r_f(x, h)}{h} \leq \frac{\tilde{h}}{h} \leq \gamma_1 + \frac{r_f(x, h)}{h}$$

which implies $\frac{\tilde{h}}{h}$ and $\frac{h}{\tilde{h}}$ are bounded. Thus

$$\frac{r_g(x, \tilde{h})}{\tilde{h}} = -\frac{1}{f'(x)} \frac{h}{\tilde{h}} \frac{r_f(x, h)}{h}$$

which goes to 0 as \tilde{h} goes to 0, since $\tilde{h} \rightarrow 0$ implies $h \rightarrow 0$. Thus, $g = f^{-1}$ is differentiable at $y = f(x)$, and

$$(f^{-1})'(y) = \frac{1}{f'(f^{-1}(y))}$$

■

The result for a negative derivative follows by replacing f with $-f$.

Note that if f is differentiable in (a, b) then $f'(x)$ is a function on (a, b) . If $f'(x)$ is differentiable at x_0 we may write

$$f''(x_0) = \lim_{h \rightarrow 0} \frac{f'(x_0 + h) - f'(x_0)}{h}$$

and in general $f^{(k+1)}(x) = \frac{d}{dx} f^{(k)}(x)$, for all $k \in \mathbb{N} \cup \{0\}$.

Proposition 2.A.4. *If f is differentiable on (a, b) and $x_0 \in (a, b)$, $f'(x_0) = 0$ but $f''(x_0) > 0$, then there exists $\delta > 0$:*

$$f(x_0) < f(x), \quad \forall x \in (x_0 - \delta, x_0 + \delta) \setminus \{x_0\}$$

We say that f has a local minimum at x_0 .

Proof. Note

$$f''(x_0) = \lim_{h \rightarrow 0} \frac{f'(x_0 + h) - f'(x_0)}{h} > 0$$

Then there exists $\delta > 0$ such that $\frac{f'(x_0 + h) - f'(x_0)}{h} > 0$ for all $h \in [-\delta, \delta]$. In particular, as $f'(x_0) = 0$, $f'(x_0 + h) > 0$ for $h \in (0, \delta]$ and $f'(x_0 + h) < 0$ for $h \in [-\delta, 0)$. Consider $h \in (0, \delta]$. By the mean value theorem there exists $c \in (x_0, x_0 + h)$ such that

$$f(x_0 + h) - f(x_0) = hf'(c) > 0$$

so $f(x_0) < f(x_0 + h)$. If $h \in [-\delta, 0)$, by the mean value theorem there exists $c \in (x_0 + h, x_0)$ such that

$$f(x_0 + h) - f(x_0) = hf'(c) < 0$$

so $f(x_0) < f(x_0 + h)$ again. Thus, for all $x \in (x_0 - \delta, x_0 + \delta) \setminus \{x_0\}$, we have $f(x_0) < f(x)$. ■

The result for a local maximum is then given by replacing f by $-f$ in the previous result.

Proposition 2.A.5. *Suppose f is twice differentiable on (a, b) and $f''(x) > 0$ on (a, b) . Then for all $a < x_0 < x_1 < b$ and $\lambda \in (0, 1)$,*

$$f(\lambda x_0 + (1 - \lambda)x_1) < \lambda f(x_0) + (1 - \lambda)f(x_1)$$

Proof. Let $g(s) = sf(x_0) + (1-s)f(x_1) - f(sx_0 + (1-s)x_1)$. Then $g(0) = f(x_1) - f(x_1) = 0$ and $g(1) = f(x_0) - f(x_0) = 0$. Note g is also twice differentiable. Towards a contradiction suppose there exists $c \in (0, 1)$ such that $g(c) < 0$. Since g is continuous it attains its minimum, so there exists $s_0 \in (0, 1)$ such that $g(s_0) \leq g(c) < 0$. Further, $g'(s_0) = 0$, where $g'(s) = f(x_0) - f(x_1) - f'(sx_0 + (1-s)x_1)(x_0 - x_1)$. Then

$$f'(s_0x_0 + (1-s_0)x_1) = \frac{f(x_1) - f(x_0)}{x_1 - x_0}$$

and $g''(s) = -f''(sx_0 + (1-s)x_1)(x_0 - x_1)^2 < 0$. In particular, $g''(s_0) < 0$, contradicting the fact that $g(s_0)$ is a minimum and Proposition 2.A.4 ■

Chapter 3

Integration

3.1.0 Introduction to Definite Integrals

Definition 3.1.1. Let $a < b$. A **partition** of the interval $I = [a, b]$ is a finite collection of points in $[a, b]$, one of which is a , and one of which is b . Equivalently, a partition of I into N subintervals consists of endpoints $x_0 = a < x_1 < \dots < x_N = b$ with subinterval k being $J_k = [x_k, x_{k+1}]$ for $0 \leq k \leq N - 1$.

The points in a partition can be numbered t_0, \dots, t_n so that

$$a = t_0 < t_1 < \dots < t_{n-1} < t_n = b \quad (3.1.1)$$

we shall always assume that such a numbering has been assigned.

Definition 3.1.2. Suppose $f : I \rightarrow \mathbb{R}$ is bounded on $I = [a, b]$ so there exists $M \in \mathbb{R}^+$ such that $\|f\|_I \leq M$. Let $P = \{t_0, \dots, t_N\} \in \prod([a, b])$ be a partition of $[a, b]$. The **lower Riemann sum** of f for P , denoted $L(f, P)$, is defined as

$$L(f, P) := \sum_{k=0}^{N-1} \inf_{J_k} (f) \ell(J_k) \quad (3.1.2)$$

The **upper Riemann sum** of f for P , denoted $U(f, P)$, is defined as

$$U(f, P) = \sum_{i=0}^{N-1} \sup_{J_k} (f) \ell(J_k) \quad (3.1.3)$$

where $\ell(J_k) = t_{k+1} - t_k > 0$. Note

$$-M \leq \sup_{J_k} (f) \leq M$$

and

$$-M \leq \inf_{J_k} (f) \leq M$$

Remark 3.1.1. If P is any partition, then

$$L(f, P) \leq U(f, P) \quad (3.1.4)$$

because

$$L(f, P) = \sum_{k=0}^{N-1} \inf_{J_k} (f) \ell(J_k)$$

$$U(f, P) = \sum_{i=0}^{N-1} \sup_{J_k} (f) \ell(J_k)$$

and for each i we have $\inf_{J_k} (f) \ell(J_k) \leq \sup_{J_k} (f) \ell(J_k)$.

Definition 3.1.3. Given two partitions P and Q of I , we say P is a refinement of Q if every endpoint in Q belongs to P , and we write

$$P > Q$$

Lemma 3.1.1. If P is a partition of $[a, b]$ which contains Q , that is $P > Q$, then

$$L(f, Q) \leq L(f, P) \text{ and } U(f, Q) \geq U(f, P)$$

Proof. Consider first the special case in which Q contains just one more point than P ;

$$P = \{t_0, \dots, t_n\}$$

$$Q = \{t_0, \dots, t_{k-1}, u, t_k, \dots, t_n\}$$

where

$$a = t_0 < t_1 < \dots < t_{k-1} < u < t_k < \dots < t_n = b$$

Let

$$m' = \inf\{f(x) : t_{k-1} \leq x \leq u\}$$

$$m'' = \inf\{f(x) : u \leq x \leq t_k\}$$

Then

$$L(f, P) = \sum_{i=1}^n m_i(t_i - t_{i-1})$$

$$L(f, Q) = \sum_{i=1}^{k-1} m_i(t_i - t_{i-1}) + m'(u - t_{k-1}) + m''(t_k - u) + \sum_{i=k+1}^n m_i(t_i - t_{i-1})$$

To prove that $L(f, P) \leq L(f, Q)$ it therefore suffices to show that

$$m_k(t_k - t_{k-1}) \leq m'(u - t_{k-1}) + m''(t_k - u)$$

Now, the set $\{f(x) : t_{k-1} \leq x \leq t_k\}$ contains all the numbers in $\{f(x) : t_{k-1} \leq x \leq u\}$ and possibly some smaller ones, so the greatest lower bound of the first set is less than or equal to the greatest lower bound of the second; thus

$$m_k \leq m'$$

Similarly,

$$m_k \leq m''$$

Therefore,

$$m_k(t_k - t_{k-1}) = m_k(t_k - u) + m_k(u - t_{k-1}) \leq m''(t_k - u) + m'(u - t_{k-1})$$

This proves, in this special case that $L(f, P) \leq L(f, Q)$. Now, let

$$\begin{aligned} M' &= \sup\{f(x) : t_{k-1} \leq x \leq u\} \\ M'' &= \sup\{f(x) : u \leq x \leq t_k\} \end{aligned}$$

Then

$$\begin{aligned} U(f, P) &= \sum_{i=1}^n M_i(t_i - t_{i-1}) \\ U(f, Q) &= \sum_{i=1}^{k-1} M_i(t_i - t_{i-1}) + M'(u - t_{k-1}) + M''(t_k - u) + \sum_{i=k+1}^n M_i(t_i - t_{i-1}) \end{aligned}$$

Hence, to prove that $U(f, Q) \leq U(f, P)$ it suffices to show that

$$M'(u - t_{k-1}) + M''(t_k - u) \leq M_k(t_k - t_{k-1})$$

As before, the set $\{f(x) : t_{k-1} \leq x \leq t_k\}$ contains all the numbers in $\{f(x) : t_{k-1} \leq x \leq u\}$ and possibly some larger ones, so the smallest upper bound of the first set is greater than or equal to the smallest upper bound of the second; thus

$$M_k \geq M'$$

Similarly,

$$M_k \geq M''$$

Therefore,

$$M_k(t_k - t_{k-1}) = M_k(t_k - u) + M_k(u - t_{k-1}) \geq M''(t_k - u) + M'(u - t_{k-1})$$

This proves, in this special case that $U(f, P) \geq U(f, Q)$.

The general case can now be deduced quite easily. The partition Q can be obtained from P by adding one point at a time; in otherwords, there is a sequence of partition

$$P = P_1 \subsetneq P_2 \subsetneq P_3 \subsetneq \dots \subsetneq P_\alpha = Q$$

such that $P_{j+1} = P_j \cup \{u_{j+1}\}$ for some $u_{j+1} \in [a, b] - P_j$. Then

$$L(f, P) = L(f, P_1) \leq L(f, P_2) \leq \dots \leq L(f, P_\alpha) = L(f, Q)$$

and

$$U(f, P) = U(f, P_1) \geq U(f, P_2) \geq \dots \geq U(f, P_\alpha) = U(f, Q)$$

completing the proof. ■

Theorem 3.1.2. Let P_1 and P_2 be partitions of $[a, b]$, and let f be a function which is bounded on $[a, b]$. Then

$$L(f, P_1) \leq U(f, P_2) \quad (3.1.5)$$

Proof. There is a partition P which contains both P_1 and P_2 (let $P = P_1 \cup P_2$). According to the lemma

$$L(f, P_1) \leq L(f, P) \leq U(f, P) \leq U(f, P_2)$$

■

Definition 3.1.4. Let $\mathcal{I}(I)$ denote the set of all partitions of I . We define the upper and lower Riemann integrals by

$$U_I(f) = \inf_{P \in \mathcal{I}(I)} U(f, P) \geq L_I(f) = \sup_{P \in \mathcal{I}(I)} L(f, P)$$

Definition 3.1.5 (Definite Integral). A function f which is bounded on $[a, b]$ is said to be Riemann integrable on $[a, b]$ if and only if

$$L_I(f) = U_I(f)$$

In this case, this common number is called the integral of f on $[a, b]$ and is denoted by

$$\int_I f = \int_a^b f(x) dx = L_I(f) = U_I(f) \quad (3.1.6)$$

The integral $\int_I f$ is also called the area of $R(f, a, b)$ when $f(x) \geq 0$ for all $x \in [a, b]$.

Theorem 3.1.3. If f is bounded on $[a, b]$, then f is integrable on $[a, b]$ if and only if for every $\epsilon > 0$ there is a partition P of $[a, b]$ such that

$$U(f, P) - L(f, P) < \epsilon$$

Proof. Suppose first that for every $\epsilon > 0$ there is such a partition P . Since

$$\begin{aligned} U_I(f) &\leq U(f, P) \\ L_I(f) &\geq L(f, P) \end{aligned}$$

it follows that

$$U_I(f) - L_I(f) \leq U(f, P) - L(f, P) < \epsilon$$

Since this is true for all $\epsilon > 0$, it follows that

$$U_I(f) = L_I(f)$$

so by definition, then, f is integrable. Conversely, if f is integrable then

$$U_I(f) = L_I(f)$$

Let M denote the value of this. Then for each $\epsilon > 0$ there exist partitions P' and P'' such that $|U(f, P') - M| < \epsilon/2$ and $|L(f, P'') - M| < \epsilon/2$. Then as $U(f, P') \geq L(f, P'')$ from the previous theorem, we have that

$$U(f, P') - L(f, P'') = |U(f, P') - L(f, P'')| \leq |U(f, P') - M| + |M - L(f, P'')| < \epsilon$$

Let $P = P' \cup P''$ be a common refinement. Then, according to the lemma $U(f, P) \leq U(f, P')$ and $L(f, P) \geq L(f, P'')$ so

$$U(f, P) - L(f, P) \leq U(f, P') - L(f, P'') < \epsilon$$

■

Example 3.1.1. Define $f(x) = \begin{cases} 1 & x \in \mathbb{Q} \cap [0, 1] \\ 0 & x \notin \mathbb{Q} \cap [0, 1] \end{cases}$ Since both $S = \mathbb{Q} \cap [0, 1]$ and $[0, 1] \setminus S$ are dense in $[0, 1]$, for any subinterval J_k we have $\sup_{J_k}(f) = 1$ and $\inf_{J_k}(f) = 0$ so $L_I(f) = 0 < 1 = U_I(f)$. Thus f is not Riemann integrable, but it is Lebesgue integrable since \mathbb{Q} is a set of measure 0.

Theorem 3.1.4. If $f \in C(I)$ is continuous on $I = [a, b]$, then $f \in \mathcal{R}(I)$ is integrable on $I = [a, b]$.

Proof. Notice, first, that f is bounded on $[a, b]$, because it is continuous on $[a, b]$. To prove that f is integrable on $[a, b]$, we want to use our previous theorem, and show that for every $\epsilon > 0$ there is a partition P of $[a, b]$ such that

$$U(f, P) - L(f, P) < \epsilon$$

Now we know, by our result on uniform continuity, that f is uniformly continuous on $[a, b]$. So there is some $\delta > 0$ such that for all $x, y \in [a, b]$, if $|x - y| < \delta$, then $|f(x) - f(y)| < \epsilon/[2(b-a)]$. We choose a partition $P = \{t_0, \dots, t_N\}$ such that each $|t_{k+1} - t_k| < \delta$. Then for each subinterval J_k we have

$$|f(x) - f(y)| < \frac{\epsilon}{2(b-a)}$$

for all $x, y \in J_k$. Then, $f(x) < \frac{\epsilon}{2(b-a)} + f(y)$ for all $x \in J_k$, so $\sup_{J_k}(f) \leq \frac{\epsilon}{2(b-a)} + f(y)$. Further, $f(y) \geq \sup_{J_k}(f) - \frac{\epsilon}{2(b-a)}$ for all $y \in J_k$, so $\inf_{J_k}(f) \geq \sup_{J_k}(f) - \frac{\epsilon}{2(b-a)}$, so $\sup_{J_k}(f) - \inf_{J_k}(f) \leq \frac{\epsilon}{2(b-a)}$. Since this is true for all k , we have that

$$\begin{aligned} U(f, P) - L(f, P) &= \sum_{k=0}^{N-1} (\sup_{J_k}(f) - \inf_{J_k}(f)) \ell(J_k) \\ &< \frac{\epsilon}{b-a} \sum_{k=0}^{N-1} \ell(J_k) \\ &= \frac{\epsilon}{b-a} \ell(I) \\ &= \epsilon \end{aligned}$$

Thus, by our previous theorem f is integrable. ■

Proposition 3.1.5. $\mathcal{R}(I)$ is a \mathbb{R} -vector space. If $f, g \in \mathcal{R}(I)$, $a \in \mathbb{R}$, then $af + g \in \mathcal{R}(I)$, and

$$\int_I (af + g) = a \int_I f + \int_I g$$

Proof. First we do additivity. Let $J_k \subseteq I$. Then $\sup_{J_k}(f + g) \leq \sup_{J_k}(f) + \sup_{J_k}(g)$ and $\inf_{J_k}(f + g) \geq \inf_{J_k}(f) + \inf_{J_k}(g)$. So it follows that $U(f + g, P) \leq U(f, P) + U(g, P)$ for any $P \in \mathcal{P}(I)$ and $L(f + g, P) \geq L(f, P) + L(g, P)$. Then we have

$$L_I(f) + L_I(g) \leq L_I(f + g) \leq U_I(f + g) \leq U_I(f) + U_I(g)$$

where by assumption $L_I(f) = U_I(f)$ and $L_I(g) = U_I(g)$, so $U_I(f + g) = L_I(f + g)$, and $f + g \in \mathcal{R}(I)$. Further, $\int_I(f + g) = U_I(f + g) = U_I(f) + U_I(g) = \int_I f + \int_I g$.

Next, let $a \in \mathbb{R}$. If $a = 0$, then $af = 0$ so $U(af, P) = 0 = L(af, P)$ for all partitions P of $[a, b]$, and so $U_I(af) = 0 = L_I(af)$. Thus, $af \in \mathcal{R}(I)$, and $\int_I af = 0 = a \int_I f$. Next, if $a > 0$, then $U(af, P) = aU(f, P)$ and $L(af, P) = aL(f, P)$. Then $U_I(af) = aU_I(f) = aL_I(f) = L_I(af)$, and we have our desired result. On the other hand, if $a < 0$, $U(af, P) = aL(f, P)$, and $L(af, P) = aU(f, P)$. Further, $U_I(af) = aL_I(f) = aU_I(f) = L_I(af)$, so we again obtain our desired result. ■

Theorem 3.1.6. *Let $a < c < b$. If f is integrable on $[a, b]$, then f is integrable on $[a, c]$ and on $[c, b]$. Conversely, if f is integrable on $[a, c]$ and on $[c, b]$, then f is integrable on $[a, b]$. Finally, if f is integrable on $[a, b]$, then*

$$\int_a^b f = \int_a^c f + \int_c^b f \quad (3.1.7)$$

Proof. (1) Suppose f is integrable on $[a, b]$. Then f is bounded on $[a, b]$, so it is bounded on $[a, c]$ and $[c, b]$. Indeed, f being bounded implies that there exists $M \in \mathbb{R}$ such that for all $x \in [a, b]$ $|f(x)| \leq M$. Thus, as this applies for all $x \in [a, b]$ and $[a, c], [c, b] \subset [a, b]$, we have that it holds for all $x \in [a, c]$ and all $x \in [c, b]$. Now fix $\epsilon > 0$. Then there exists a partition P of $[a, b]$ such that

$$U(f, P) - L(f, P) < \epsilon$$

Without loss of generality suppose $c = t_j$ for some $t_j \in P = \{t_0, t_1, \dots, t_n\}$. Then we have partitions $P' = \{t_0, \dots, t_j\}$ and $P'' = \{t_j, \dots, t_n\}$ for $[a, c]$ and $[c, b]$ respectively. Moreover,

$$\begin{aligned} U(f, P) &= U(f, P') + U(f, P'') \\ L(f, P) &= L(f, P') + L(f, P'') \end{aligned}$$

Hence, we have that

$$[U(f, P') - L(f, P')] + [U(f, P'') - L(f, P'')] = U(f, P) - L(f, P) < \epsilon$$

But $U(f, P') \geq L(f, P')$ and $U(f, P'') \geq L(f, P'')$, so

$$\begin{aligned} U(f, P') - L(f, P') &\leq U(f, P) - L(f, P) < \epsilon \\ U(f, P'') - L(f, P'') &\leq U(f, P) - L(f, P) < \epsilon \end{aligned}$$

Therefore, f is integrable on $[a, c]$ and $[c, b]$

(2) Suppose f is integrable on $[a, c]$ and $[c, b]$. Thus, there exists $M_1, M_2 \in \mathbb{R}$ such that for all $x \in [a, c]$ $|f(x)| \leq M_1$ and for all $x \in [c, b]$ $|f(x)| \leq M_2$. Let $M = \max(M_1, M_2)$. Then

for all $x \in [a, b]$ we have $|f(x)| \leq M$, so f is bounded on $[a, b]$. Let $\epsilon > 0$. Then there exist partitions P_1, P_2 of $[a, c]$ and $[c, b]$ respectively such that

$$U(f, P_1) - L(f, P_1) < \epsilon/2$$

$$U(f, P_2) - L(f, P_2) < \epsilon/2$$

Let $P = P_1 \cup P_2$, where $P_1 \cap P_2 = \{c\}$. Then we have that

$$U(f, P) - L(f, P) = [U(f, P_1) - L(f, P_1)] + [U(f, P_2) - L(f, P_2)] < \epsilon/2 + \epsilon/2 = \epsilon$$

Therefore, by definition f is integrable on $[a, b]$.

(3) Suppose f is integrable on $[a, b]$, so by the previous results f is integrable on $[a, c]$ and $[c, b]$. Let $\int_a^b f = R$, $\int_a^c f = R_1$, and $\int_c^b f = R_2$. Let P be a partition of $[a, b]$, and without loss of generality suppose $c \in P = \{t_0, \dots, t_j = c, \dots, t_n\}$. Then let $P_1 = \{t_0, \dots, t_j\}$ and $P_2 = \{t_j, \dots, t_n\}$ be partitions of $[a, c]$ and $[c, b]$. It then follows that

$$L(f, P_1) \leq R_1 \leq U(f, P_1)$$

$$L(f, P_2) \leq R_2 \leq U(f, P_2)$$

Hence, we have that

$$L(f, P) = L(f, P_1) + L(f, P_2) \leq R_1 + R_2$$

$$U(f, P) = U(f, P_1) + U(f, P_2) \geq R_1 + R_2$$

Thus $L(f, P) \leq R_1 + R_2 \leq U(f, P)$. Note that this holds for all partitions P , as if P' is a partition, then considering the partition $P'_c = P' \cup \{c\}$ we have that

$$L(f, P') \leq L(f, P'_c) \leq R_1 + R_2 \leq U(f, P'_c) \leq U(f, P')$$

Therefore, this holds for all partitions of $[a, b]$, but R is the unique number which does this so we must have that $R = R_1 + R_2$. Thus

$$\int_a^b f = \int_a^c f + \int_c^b f$$

■

Definition 3.1.6. Using the previous theorem, we define

$$\int_a^a f := 0 \quad \text{and} \quad \int_a^b f := - \int_b^a f, \quad \text{for } a > b \quad (3.1.8)$$

Theorem 3.1.7. Suppose f is integrable on $[a, b]$ and that

$$m \leq f(x) \leq M \quad \forall x \in [a, b] \quad (3.1.9)$$

Then

$$m(b-a) \leq \int_a^b f \leq M(b-a) \quad (3.1.10)$$

Proof. It is clear that $M \geq \sup\{f(x) : x \in [a, b]\}$ and $m \leq \inf\{f(x) : x \in [a, b]\}$, so

$$m(b-a) \leq L(f, P) \text{ and } M(b-a) \geq U(f, P)$$

for every partition P . Since $\int_a^b f = \sup\{L(f, P)\} = \inf\{U(f, P)\}$ we have that

$$m(b-a) \leq \sup\{L(f, P)\} = \int_a^b f = \inf\{U(f, P)\} \leq M(b-a)$$

■

Remark 3.1.2. If f is integrable on $[a, b]$, we can define a new function F on $[a, b]$ by

$$F(x) = \int_a^x f = \int_a^x f(t)dt \quad (3.1.11)$$

Theorem 3.1.8. If f is integrable on $[a, b]$ and F is defined on $[a, b]$ by

$$F(x) = \int_a^x f$$

then F is continuous on $[a, b]$.

Proof. Suppose $c \in [a, b]$. Since f is integrable on $[a, b]$ it is, by definition, bounded on $[a, b]$; let M be a number such that

$$|f(x)| \leq M, \forall x \in [a, b]$$

If $h > 0$ for $c+h \in [a, b]$, then

$$F(c+h) - F(c) = \int_a^{c+h} f - \int_a^c f = \int_c^{c+h} f$$

Since $-M \leq f(x) \leq M$ for all $x \in [a, b]$ it follows from the Theorem 3.1.7 that

$$-M \cdot h \leq \int_c^{c+h} f \leq M \cdot h$$

In other words

$$-M \cdot h \leq F(c+h) - F(c) \leq M \cdot h$$

If $h < 0$, with $c+h \in [a, b]$ we find the inequality

$$-M \cdot h \geq F(c+h) - F(c) \geq M \cdot h$$

In either case we have that

$$|F(c+h) - F(c)| \leq M \cdot |h|$$

Therefore, if $\epsilon > 0$, we have

$$|F(c+h) - F(c)| < \epsilon$$

provided that $|h| < \epsilon/M$. This proves that

$$\lim_{h \rightarrow 0} F(c+h) = F(c)$$

so F is continuous at c .

■

3.2.0 Reimann Sums

Definition 3.2.1. Suppose $P = \{t_0, \dots, t_N\}$ is a partition of $[a, b]$, and for each k choose $\xi_k \in J_k$. Then we clearly have that

$$L(f, P) \leq \sum_{k=0}^{N-1} f(\xi_k) \ell(J_k) \leq U(f, P) \quad (3.2.1)$$

Any sum of the form

$$\sum_{k=0}^{N-1} f(\xi_k) \ell(J_k) \quad (3.2.2)$$

is called a **Reimann sum** of f for P .

Before proving an important result related to Riemann sums and definite integrals, we handle the following proposition:

Proposition 3.2.1. Suppose $f : [a, b] \rightarrow \mathbb{R}$ is bounded by $M \in \mathbb{R}^+$. If P and Q are partitions of $[a, b]$ such that for some $k > 1$

$$\text{maxsize}(P) \leq \frac{\text{minsize}(Q)}{k}$$

then

$$U(f, P) \leq U(f, Q) + \frac{2M\ell([a, b])}{k}$$

and

$$L(f, P) \geq L(f, Q) - \frac{2M\ell([a, b])}{k}$$

Proof. Let $P_1 = P \cup Q$ be the common refinement of P and Q . The intervals in P , denoted \tilde{J}_i , can be separated into two classes,

- (i) $\tilde{J}_i \subseteq J_k$ for some k , where J_k are the intervals in Q
- (ii) $\tilde{J}_i \not\subseteq J_k$ for all k

Note that in the case of (i), \tilde{J}_i also belongs to P_1 . In the second case, \tilde{J}_i is split into two intervals in P_1 . Then

$$|U(f, P) - U(f, P_1)| \leq \sum_{\text{intervals in (ii)}} \left| \sup_{\tilde{J}_i} (f) \ell(\tilde{J}_i) - (\sup_{\tilde{J}_i^+} (f) \ell(\tilde{J}_i^+) + \sup_{\tilde{J}_i^-} (f) \ell(\tilde{J}_i^-)) \right|$$

where the intervals in class (i) cancel since they belong to both partitions. If \tilde{J}_i is in class (ii), then $\tilde{J}_i = \tilde{J}_i^+ \cup \tilde{J}_i^-$ in P_1 . Then proceeding with the inequality

$$|U(f, P) - U(f, P_1)| \leq M \sum_{\in (ii)} \ell(\tilde{J}_i) + \ell(\tilde{J}_i^+) + \ell(\tilde{J}_i^-)$$

$$= 2M \sum_{i \in (ii)} \ell(\tilde{J}_i)$$

If \tilde{J}_i is in class (ii), then there exists a unique endpoint x_l in Q such that $x_l \in \tilde{J}_i^\circ$ (the interior of the interval) so

$$\ell(\tilde{J}_i) \leq \frac{\ell(J_l)}{k}$$

Now

$$|U(f, P) - U(f, P_1)| \leq 2M \sum_{i \in (ii)} \ell(\tilde{J}_i) \leq 2M \sum_{i \in (ii)} \frac{\ell(J_l)}{k} \leq \frac{2M\ell(I)}{k}$$

As P_1 refines Q , $U(f, P_1) \leq U(f, Q)$, so

$$U(f, P_1) \leq U(f, P) \leq U(f, P_1) + \frac{2M\ell(I)}{k} \leq U(f, Q) + \frac{2M\ell(I)}{k}$$

Similarly, $L(f, P_1)$ refines Q so $L(f, P_1) \geq L(f, Q)$, and by the same chain as above $|L(f, P) - L(f, P_1)| \leq \frac{2M\ell(I)}{k}$, so

$$L(f, P_1) \geq L(f, P) \geq L(f, P_1) - \frac{2M\ell(I)}{k} \geq L(f, Q) - \frac{2M\ell(I)}{k}$$

as desired. ■

Now we move on to our fundamental result:

Theorem 14 (Darboux's Theorem).

Let $f : [a, b] \rightarrow \mathbb{R}$ be bounded. Let $P_\nu \in \prod([a, b])$ be a sequence of partitions of $I = [a, b]$ such that

$$\lim_{\nu \rightarrow \infty} \maxsize(P_\nu) = 0$$

Then

$$U_I(f) = \lim_{\nu \rightarrow \infty} U(f, P_\nu)$$

and

$$L_I(f) = \lim_{\nu \rightarrow \infty} L(f, P_\nu)$$

In particular, $f \in \mathbb{R}([a, b])$ if and only if

$$\int_I f = \lim_{\nu \rightarrow \infty} \sum_{k=0}^{N_\nu-1} f(\xi_{\nu,k}) \ell(J_{\nu,k})$$

where $P_\nu = (a = x_{\nu,0} < \dots < x_{\nu,N_\nu} = b)$, $J_{\nu,k} = [x_{\nu,k}, x_{\nu,k+1}]$, and where $\xi_{\nu,k}$ is an arbitrary point of $J_{\nu,k}$.

Proof. Let $P_\nu \in \prod([a, b])$ be a sequence of partition such that $\lim_{\nu \rightarrow \infty} \maxsize P_\nu = 0$. Note $U_I(f) = \inf_{P \in \prod([a, b])} U(f, P)$, which exists and is well defined if f is bounded, and similarly for $L_I(f) = \sup_{P \in \prod([a, b])} L(f, P)$. Given $\varepsilon > 0$, there exists $Q \in \prod(I)$ such that $U_I(f) + \varepsilon \geq$

$U(f, Q) \geq U_I(f)$ and taking a refinement if needed, $L_I(f) - \varepsilon \leq L(f, Q) \leq L_I(f)$. Let $\nu, \mu \geq N$ such that

$$\text{maxsize} P_\nu \leq \varepsilon \text{minsize} Q, \quad \forall \nu \geq N$$

In particular, we can choose $\varepsilon = \frac{1}{k}$, $k \in \mathbb{N}$, $k > 1$. By the previous proposition

$$\begin{aligned} U(f, P_\nu) &\leq U(f, Q) + \varepsilon 2M\ell(I) \\ L(f, P_\nu) &\geq L(f, Q) - \varepsilon 2M\ell(I) \end{aligned}$$

Then $U(f, P_\nu) \leq U_I(f) + \varepsilon(2M\ell(I) + 1)$ and $L(f, P_\nu) \geq L_I(f) - \varepsilon(2M\ell(I) + 1)$. Then

$$|U(f, P_\nu) - U_I(f)| \leq \varepsilon(2M\ell(I) + 1)$$

and

$$|L_I(f) - L(f, P_\nu)| \leq \varepsilon(2M\ell(I) + 1)$$

for all $\nu \geq N$. As we can make ε as small as we wish,

$$\lim_{\nu \rightarrow \infty} U(f, P_\nu) = U_I(f) \quad \text{and} \quad \lim_{\nu \rightarrow \infty} L(f, P_\nu) = L_I(f)$$

Then $f \in \mathcal{R}(I)$ if and only if $U_I(f) = L_I(f)$, which occurs if and only if $\lim_{\nu \rightarrow \infty} U(f, P_\nu) = \lim_{\nu \rightarrow \infty} L(f, P_\nu)$. We observe that these last limits are equal if and only if $\lim_{\nu \rightarrow \infty} \sum_{k=0}^{N_\nu-1} f(\xi_{\nu,k})\ell(J_{\nu,k})$ exists whenever $\text{maxsize} P_\nu \rightarrow 0$ for any choices of $\xi_{\nu,k} \in J_{\nu,k}$, as

$$L(f, P_\nu) \leq \sum_{k=0}^{N_\nu-1} f(\xi_{\nu,k})\ell(J_{\nu,k}) \leq U(f, P_\nu)$$

■

3.3.0 The Fundamental Theorem of Calculus

Theorem 15 (The Fundamental Theorem of Calculus Part 1).

Let $f \in \mathcal{R}([a, b])$ be integrable on $[a, b]$, and define F on $[a, b]$ by

$$F(x) = \int_a^x f = \int_a^x f(t)dt \quad (3.3.1)$$

If f is continuous at c in $[a, b]$, then F is differentiable at c , and

$$F'(c) = f(c) \quad (3.3.2)$$

(if $c = a$ or b , then $F'(c)$ is understood to mean the right or left hand derivative of F).

Proof. First, consider $c \in (a, b)$. By definition,

$$F'(c) = \lim_{h \rightarrow 0} \frac{F(c+h) - F(c)}{h}$$

Suppose first that $h > 0$. Then

$$F(c+h) - F(c) = \int_c^{c+h} f$$

Define m_h and M_h as follows:

$$\begin{aligned} m_h &= \inf\{f(x) : c \leq x \leq c+h\} \\ M_h &= \sup\{f(x) : c \leq x \leq c+h\} \end{aligned}$$

It follows from Theorem 3.1.7 that

$$m_h \cdot h \leq \int_c^{c+h} f \leq M_h \cdot h$$

Therefore,

$$m_h \leq \frac{F(c+h) - F(c)}{h} \leq M_h$$

If $h < 0$, let

$$\begin{aligned} m_h &= \inf\{f(x) : c+h \leq x \leq c\} \\ M_h &= \sup\{f(x) : c+h \leq x \leq c\} \end{aligned}$$

It follows from Theorem 3.1.7 that

$$m_h \cdot (-h) \leq \int_{c+h}^c f \leq M_h \cdot (-h)$$

Since

$$F(c+h) - F(c) = \int_c^{c+h} f = - \int_{c+h}^c f$$

this yields

$$m_h \cdot h \geq F(c+h) - F(c) \geq M_h \cdot h$$

Since $h < 0$, we have that

$$m_h \leq \frac{F(c+h) - F(c)}{h} \leq M_h$$

This inequality is true for any integrable function, continuous or not. Since f is continuous at c , however,

$$\lim_{h \rightarrow 0} m_h = \lim_{h \rightarrow 0} M_h = f(c)$$

and this proves that

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

Now, if $c = a$ we need only look at when $h > 0$, and in this case we still have

$$m_h \leq \frac{F(a+h) - F(a)}{h} \leq M_h$$

and from our previous limits,

$$\lim_{h \rightarrow 0^+} m_h = \lim_{h \rightarrow 0^+} m_h = f(a)$$

thus we have that

$$F'(a) = \lim_{h \rightarrow 0^+} \frac{F(a+h) - F(a)}{h} = f(a)$$

Similarly, if $c = b$ we need only look at $h < 0$, so we have that

$$\lim_{h \rightarrow 0^-} m_h = \lim_{h \rightarrow 0^-} m_h = f(b)$$

and

$$F'(b) = \lim_{h \rightarrow 0^-} \frac{F(b+h) - F(b)}{h} = f(b)$$

completing the proof. ■

We may consider

$$F(x) = \int_a^x f \quad (3.3.3)$$

when $x < a$. In this case we have that

$$F(x) = - \int_x^a f = - \left(\int_b^a f - \int_b^x f \right) \quad (3.3.4)$$

so for $c \in [a, b]$,

$$F'(c) = -(-f(c)) = f(c) \quad (3.3.5)$$

as before.

Theorem 16 (Fundamental Theorem of Calculus Part 2).

Suppose G is continuous in $[a, b]$ and differentiable in (a, b) , with $G' \in \mathcal{R}([a, b])$. Then

$$\int_a^b G'(t) dt = G(b) - G(a)$$

Proof. Let G be as described. Let P_n be a partition with endpoints $a + \frac{b-a}{n}k$ for $0 \leq k \leq n$. By Darboux's theorem, for arbitrary $\xi_{n,k} \in J_{n,k} = [a + \frac{b-a}{n}k, a + \frac{b-a}{n}(k+1)]$,

$$\int_a^b G'(t) dt = \lim_{n \rightarrow \infty} \sum_{k=0}^{n-1} G'(\xi_{n,k}) \ell(J_{n,k}) = \lim_{n \rightarrow \infty} \sum_{k=0}^{n-1} G'(\xi_{n,k}) \frac{b-a}{n}$$

Now observe we have the telescopic sum

$$G(b) - G(a) = G(x_n) - G(x_0) = \sum_{k=0}^{n-1} G(x_{k+1}) - G(x_k)$$

As G is continuous on $[a, b]$ and differentiable on (a, b) , we have by the mean value theorem that there exists $\xi_{n,k}^* \in (x_k, x_{k+1})$ such that

$$G(x_{k+1}) - G(x_k) = G'(\xi_{n,k}^*)(x_{k+1} - x_k)$$

Then let the arbitrary $\xi_{n,k}$ be the $\xi_{n,k}^*$, so

$$\begin{aligned} \int_a^b G'(t)dt &= \lim_{n \rightarrow \infty} \sum_{k=0}^{n-1} G'(\xi_{n,k}^*) \frac{b-a}{n} \\ &= \lim_{n \rightarrow \infty} \sum_{k=0}^{n-1} (G(x_{k+1}) - G(x_k)) \\ &= \lim_{n \rightarrow \infty} (G(b) - G(a)) = G(b) - G(a) \end{aligned}$$

as desired. ■

It is important to note that this is merely a useful result for certain functions f , not a definition.

If f is any bounded function on $I = [a, b]$, then

$$L_I(f) \text{ and } U_I(f) \quad (3.3.6)$$

will both exist. These numbers are called the lower integral of f on $[a, b]$ and the upper integral of f on $[a, b]$, respectively, and will sometimes be denoted by

$$\mathbf{L} \int_a^b f \text{ and } \mathbf{U} \int_a^b f \quad (3.3.7)$$

If $a < c < b$, then

$$\mathbf{L} \int_a^b f = \mathbf{L} \int_a^c f + \mathbf{L} \int_c^b f \text{ and } \mathbf{U} \int_a^b f = \mathbf{U} \int_a^c f + \mathbf{U} \int_c^b f \quad (3.3.8)$$

and if $m \leq f(x) \leq M$ for all $x \in [a, b]$, then

$$m(b-a) \leq \mathbf{L} \int_a^b f \leq \mathbf{U} \int_a^b f \leq M(b-a) \quad (3.3.9)$$

f is integrable precisely when

$$\mathbf{L} \int_a^b f = \mathbf{U} \int_a^b f \quad (3.3.10)$$

We shall now demonstrate an alternate proof for the following theorem stated previously.

Theorem 3.3.1. *If f is continuous on $[a, b]$, then f is integrable on $[a, b]$.*

Proof. Define function L and U on $[a, b]$ by

$$L(x) = \mathbf{L} \int_a^x f \text{ and } U(x) = \mathbf{U} \int_a^x f$$

Let $x \in (a, b)$. If $h > 0$ and

$$m_h = \inf\{f(t) : x \leq t \leq x + h\}$$

$$M_h = \sup\{f(t) : x \leq t \leq x + h\}$$

then

$$m_h \cdot h \leq \mathbf{L} \int_x^{x+h} f \leq \mathbf{U} \int_x^{x+h} f \leq M_h \cdot h$$

so

$$m_h \cdot h \leq L(x+h) - L(x) \leq U(x+h) - U(x) \leq M_h \cdot h$$

or

$$m_h \leq \frac{L(x+h) - L(x)}{h} \leq \frac{U(x+h) - U(x)}{h} \leq M_h$$

If $h < 0$ and

$$m_h = \inf\{f(t) : x+h \leq t \leq x\}$$

$$M_h = \sup\{f(t) : x+h \leq t \leq x\}$$

one obtains the same inequality, precisely as in the proof of 15.

Since f is continuous at x , we have

$$\lim_{h \rightarrow 0} m_h = \lim_{h \rightarrow 0} M_h = f(x)$$

and this proves that

$$L'(x) = U'(x) = f(x), \forall x \in (a, b)$$

This means that there is a number c such that

$$U(x) = L(x) + c, \forall x \in [a, b]$$

Since $U(a) = L(a) = 0$, the number c must be equal to 0, so

$$U(x) = L(x) \forall x \in [a, b]$$

In particular,

$$\mathbf{U} \int_a^b f = U(b) = L(b) = \mathbf{L} \int_a^b f$$

so f is integrable on $[a, b]$. ■

3.4.0 Content of Sets

Using properties of sets, we can investigate the collection of Riemann integrable functions more carefully.

Definition 3.4.1. Given $S \subseteq I$ we define the characteristic function for S by

$$\chi_S(x) = \begin{cases} 1 & x \in S \\ 0 & x \notin S \end{cases}$$

and the upper content of S and the lower content of S by

$$\text{cont}^+(S) := U_I(\chi_S) \text{ and } \text{cont}^-(S) = L_I(\chi_S)$$

If $\text{cont}^+(S) = \text{cont}^-(S)$ we say that S has **content**

$$m(S) = \text{cont}^+(S) = \text{cont}^-(S)$$

and say S is **contented**.

We observe by Darboux's theorem $\text{cont}^+(S) = U_I(\chi_S) = \lim_{v \rightarrow \infty} U(\chi_S, P_v)$ if $\text{maxsize } P_v \rightarrow 0$. Since $\sup_J \chi_S = 1$ if $S \cap J \neq \emptyset$, $\sup_J \chi_S = 0$ if $S \cap J = \emptyset$, $\inf_J (\chi_S) = 1$ if $S \supseteq J$, and $\inf_J (\chi_S) = 0$ if $S \not\supseteq J$, we can formulate the upper and lower contents by

$$\text{cont}^+(S) = \inf \left\{ \sum_{k=1}^N \ell(J_k) : S \subseteq \bigcup_{k=1}^N J_k \right\}$$

and

$$\text{cont}^-(S) = \sup \left\{ \sum_{k=1}^N \ell(J_k) : S \supseteq \sqcup_{k=1}^N J_k \right\}$$

(Note we need disjoint sets for the lower content)

We now define the Lebesgue measure, which extends the upper content to what is known as an outer measure.

Definition 3.4.2. We define the **Lebesgue measure** by

$$m^*(S) = \inf \left\{ \sum_{k \geq 1} \ell(J_k) : S \subseteq \bigcup_{k \geq 1} J_k \right\}$$

which is an **outer measure**, and we can define the associated **inner measure** by

$$m_*(S) = \sup \left\{ \sum_{k \geq 1} \ell(J_k) : S \supseteq \sqcup_{k \geq 1} J_k \right\}$$

Example 3.4.1. We observe that $\text{cont}^+(\mathbb{Q} \cap [0, 1]) = 1$ and $\text{cont}^-(\mathbb{Q} \cap [0, 1]) = 0$, but $m^*(\mathbb{Q} \cap [0, 1]) = 0$. Indeed, as $\mathbb{Q} \cap [0, 1] = \{q_1, q_2, \dots\}$ is countable, if $\varepsilon > 0$ we can choose $J_k = [q_k - \frac{\varepsilon}{2^{k+2}}, q_k + \frac{\varepsilon}{2^{k+2}}] \cap [0, 1]$. Then $\mathbb{Q} \cap [0, 1] \subseteq \bigcup_{k \geq 1} J_k$ and

$$\sum_{k \geq 1} \ell(J_k) \leq \sum_{k \geq 1} \frac{\varepsilon}{2^{k+1}} \leq \frac{\varepsilon}{2} < \varepsilon$$

In general, if S is countable then $m^*(S) = 0$. We can now investigate a necessary and sufficient condition for Riemann integrability:

Proposition 3.4.1. If $f : I = [a, b] \rightarrow \mathbb{R}$ is bounded, and S is the set of points of discontinuity of f in $[a, b]$, then $m^*(S) = 0$ implies $f \in \mathcal{R}(I)$, where

$$m^*(S) = \inf \left\{ \sum_{k \geq 1} \ell(J_k) : S \subseteq \bigcup_{k \geq 1} J_k \right\}$$

Proof. As f is bounded, there exists $M > 0$ such that $\|f\|_\infty \leq M$. Let $\varepsilon > 0$. As $m^*(S) = 0$, there exists $J_k, k \geq 1$, such that

$$S \subseteq \bigcup_{k \geq 1} J_k \text{ and } \sum_{k=1}^{\infty} \ell(J_k) < \varepsilon$$

If $x \in I \setminus S$, then there exists an open interval K_x containing x such that

$$0 \leq \sup_{K_x}(f) - \inf_{K_x}(f) < \varepsilon$$

as f is continuous at x . Then $I \subseteq \left(\bigcup_{k \geq 1} J_k\right) \cup \left(\bigcup_{x \in I \setminus S} K_x\right)$. But I is compact so there exists a finite covering

$$I \subseteq \left(\bigcup_{k=1}^N J_k\right) \cup \left(\bigcup_{i=1}^M K_i\right)$$

Let $P \in \mathcal{P}(I)$ be the partition conformed by all the endpoints of intervals $J_l, 1 \leq l \leq N$, and $K_i, 1 \leq i \leq M$. Write $P = \{L_1, \dots, L_\mu\}$. We have two cases:

1. $L_j \subseteq K_i$ for some i or
2. $L_j \subseteq J_l$ for some l

Let $A = \{1 \leq j \leq \mu : \exists i; L_j \subseteq K_i\}$ and $B = \{1 \leq j \leq \mu : \exists l; L_j \subseteq J_l\}$. Note $\sum_{j \in B} \ell(L_j) \leq \sum_{k=1}^N \ell(J_k) < \varepsilon$ and

$$\begin{aligned} 0 \leq U(f, P) - L(f, P) &= \sum_{j \in A} \left(\sup_{L_j}(f) - \inf_{L_j}(f) \right) \ell(L_j) + \sum_{j \in B} \left(\sup_{L_j}(f) - \inf_{L_j}(f) \right) \ell(L_j) \\ &< \varepsilon \sum_{j \in A} \ell(L_j) + 2M \sum_{j \in B} \ell(L_j) \\ &\leq \varepsilon \ell(I) + 2M\varepsilon \\ &= \varepsilon(\ell(I) + 2M) \end{aligned}$$

which goes to 0 as we can make ε arbitrarily small. Thus $f \in \mathcal{R}([a, b])$ as desired. \blacksquare

3.A.0 Trigonometric Functions

Definition 3.A.1. We define the mathematical constant π as the area of the unit circle, or in this case, twice the area of a semi-circle:

$$\pi := 2 \cdot \int_{-1}^1 \sqrt{1-x^2} dx \quad (3.A.1)$$

Definition 3.A.2. If $-1 \leq x \leq 1$, then the area of the sector bounded between the upper unit circle from $[x, 1]$ and the x -axis and radial arm is

$$A(x) := \frac{x\sqrt{1-x^2}}{2} + \int_x^1 \sqrt{1-t^2} dt \quad (3.A.2)$$

Remark 3.A.1. For $-1 < x < 1$, A is differentiable at x and

$$\begin{aligned} A'(x) &= \frac{1}{2} \left[\sqrt{1-x^2} + x \cdot \frac{-2x}{2\sqrt{1-x^2}} \right] - \sqrt{1-x^2} \\ &= \frac{1}{2} \frac{1-x^2-x^2}{\sqrt{1-x^2}} - \frac{1-x^2}{\sqrt{1-x^2}} \\ &= \frac{1}{2} \frac{-1}{\sqrt{1-x^2}} \\ &= \frac{-1}{2\sqrt{1-x^2}} \end{aligned}$$

Note that on $[-1, 1]$, the function A decreases from $A(-1) = \frac{\pi}{2}$ to $A(1) = 0$.

Definition 3.A.3. If $0 \leq x \leq \pi$, then $\cos x$ is the unique number in $[-1, 1]$ such that

$$A(\cos x) = \frac{x}{2} \quad (3.A.3)$$

and

$$\sin x := \sqrt{1 - (\cos x)^2} \quad (3.A.4)$$

Note that such a $\cos x$ exists as A is continuous on $[-1, 1]$, and $A(-1) = \frac{\pi}{2}$ while $A(1) = 0$. Hence, by 6 there exists $y \in [-1, 1]$ such that $A(y) = \frac{x}{2}$ for all $x \in [0, \pi]$.

Theorem 3.A.1. If $0 < x < \pi$, then

$$\begin{aligned} \cos'(x) &= -\sin x \\ \sin'(x) &= \cos x \end{aligned}$$

Proof. If $B = 2A$, then the definition $A(\cos x) = x/2$ can be written

$$B(\cos x) = x$$

in other words, \cos is just the inverse of B . We have already computed that

$$A'(x) = -\frac{1}{2\sqrt{1-x^2}}$$

from which we conclude

$$B'(x) = -\frac{1}{\sqrt{1-x^2}}$$

Consequently we have that

$$\begin{aligned} \cos'(x) &= (B^{-1})'(x) \\ &= \frac{1}{B'(B^{-1}(x))} \\ &= \frac{1}{-\frac{1}{\sqrt{1-[B^{-1}(x)]^2}}} \\ &= -\sqrt{1 - (\cos x)^2} \end{aligned}$$

$$= -\sin x$$

Then, since $\sin x = \sqrt{1 - (\cos x)^2}$ we also obtain

$$\begin{aligned}\sin'(x) &= \frac{1}{2} \cdot \frac{-2 \cos x \cdot \cos'(x)}{\sqrt{1 - (\cos x)^2}} \\ &= \frac{-\cos x \cdot (-\sin x)}{\sin x} \\ &= \cos x\end{aligned}$$

■

Definition 3.A.4. Now, to define \sin and \cos on \mathbb{R} , we proceed as follows

1. If $\pi \leq x \leq 2\pi$, the

$$\begin{aligned}\sin x &= -\sin(2\pi - x) \\ \cos x &= \cos(2\pi - x)\end{aligned}$$

2. If $x = 2\pi k + x'$ for some integer k and some $x' \in [0, 2\pi]$, then

$$\begin{aligned}\sin x &= \sin x' \\ \cos x &= \cos x'\end{aligned}$$

Lemma 3.A.2. Suppose f has a second derivative everywhere and that

$$\begin{aligned}f'' + f &= 0 \\ f(0) &= 0 \\ f'(0) &= 0\end{aligned}$$

Then $f = 0$

Proof. Multiplying both sides of the first equation by f' yields

$$f'f'' + ff' = 0$$

Thus

$$[(f')^2 + f^2]' = 2(f'f'' + ff') = 0$$

so $(f')^2 + f^2$ is a constant function. From $f(0) = 0$ and $f'(0) = 0$ it follows that the constant is 0; thus

$$[f'(x)]^2 + [f(x)]^2 = 0 \forall x$$

This implies that

$$f(x) = 0 \forall x$$

■

Theorem 3.A.3. *If f has a second derivative everywhere and*

$$f'' + f = 0$$

$$f(0) = a$$

$$f'(0) = b$$

then

$$f = b \cdot \sin + a \cdot \cos$$

Proof. Let

$$g(x) = f(x) - b \sin x - a \cos x$$

Then

$$g'(x) = f'(x) - b \cos x + a \sin x$$

$$g''(x) = f''(x) + b \sin x + a \cos x$$

Consequently,

$$g'' + g = 0$$

$$g(0) = 0$$

$$g'(0) = 0$$

which shows by the previous lemma that

$$0 = g(x) = f(x) - b \sin x - a \cos x, \forall x$$

■

Theorem 3.A.4. *If x and y are any two numbers, then*

$$\sin(x + y) = \sin x \cos y + \cos x \sin y$$

$$\cos(x + y) = \cos x \cos y - \sin x \sin y$$

Proof. For any particular $y \in \mathbb{R}$, we can define a function f by

$$f(x) = \sin(x + y)$$

Then $f'(x) = \cos(x + y)$ and $f''(x) = -\sin(x + y)$. Consequently,

$$f'' + f = 0$$

$$f(0) = \sin y$$

$$f'(0) = \cos y$$

It follows from the previous theorem that

$$f = (\cos y) \cdot \sin + (\sin y) \cdot \cos$$

that is

$$\sin(x + y) = \cos y \sin x + \sin y \cos x, \forall x$$

Since any number y could have been chosen to begin with, this proves the first formula for x and y .

Similarly, for any $y \in \mathbb{R}$ define $f(x) = \cos(x + y)$, so $f'(x) = -\sin(x + y)$ and $f''(x) = -\cos(x + y)$. Then $f'' + f = 0$, $f(0) = \cos y$ and $f'(0) = -\sin y$. Then we have that

$$\cos(x + y) = \cos y \cos x - \sin y \sin x$$

proving the second formula. ■

Remark 3.A.2. Since

$$\arcsin'(x) = \frac{1}{\sqrt{1-x^2}}, \quad -1 < x < 1$$

it follows from 16 that

$$\arcsin x = \arcsin x - \arcsin 0 = \int_0^x \frac{1}{\sqrt{1-t^2}} dt$$

Using this definition of arcsin we could define \sin as \arcsin^{-1} , and the formula for the derivative of an inverse function would show that

$$\sin'(x) = \sqrt{1 - \sin^2 x}$$

which could be defined as $\cos x$.

3.B.0 The Logarithm and Exponential Functions

Definition 3.B.1. If $x > 0$, then define

$$\log x := \int_1^x \frac{1}{t} dt \tag{3.B.1}$$

Theorem 3.B.1. If $x, y > 0$, then

$$\log(xy) = \log x + \log y \tag{3.B.2}$$

Proof. Notice first that $\log'(x) = 1/x$, by 15. Now, choose a number $y > 0$ and let

$$f(x) = \log(xy)$$

Then

$$f'(x) = \log'(xy) \cdot y = \frac{1}{xy} \cdot y = \frac{1}{x}$$

Thus, $f' = \log'$. This means that there is a number c such that $f(x) = \log(x) + c$ for all $x > 0$, that is,

$$\log(xy) = \log x + c, \quad \forall x > 0$$

The number c can be evaluated by noting that $\log(1) = 0$, so $\log(1 \cdot y) = c$. Thus

$$\log(xy) = \log x + \log y$$

for all x . Since this is true for all $y > 0$, the theorem is proved. ■

Corollary 3.B.2. *If n is a natural number and $x > 0$, then*

$$\log(x^n) = n \log x \quad (3.B.3)$$

Proof. We proceed by induction on $n \in \mathbb{N}$. If $n = 1$ we simply have $\log(x^1) = 1 \cdot \log x$, so the base case holds. Now suppose inductively that there exists $k \geq 1$ such that if $n = k$,

$$\log(x^k) = k \log x$$

Then, observe that by the previous theorem

$$\begin{aligned} \log(x^{k+1}) &= \log(x^k x) \\ &= \log(x^k) + \log x \\ &= k \log x + \log x && \text{(by the Induction Hypothesis)} \\ &= (k+1) \log x \end{aligned}$$

as desired. Thus by mathematical induction we conclude that for all $n \geq 1$, $\log(x^n) = n \log x$. ■

Corollary 3.B.3. *If $x, y > 0$, then*

$$\log\left(\frac{x}{y}\right) = \log x - \log y$$

Proof. This result follows from the equation

$$\log x = \log\left(\frac{x}{y} \cdot y\right) = \log\left(\frac{x}{y}\right) + \log y$$

■

Definition 3.B.2. The exponential function, \exp , is defined as \log^{-1} .

Theorem 3.B.4. *For all numbers x ,*

$$\exp'(x) = \exp(x)$$

Proof. Observe that

$$\begin{aligned} \exp'(x) &= (\log^{-1})'(x) \\ &= \frac{1}{\log'(\log^{-1}(x))} \\ &= \frac{1}{\frac{1}{\log^{-1}(x)}} \\ &= \log^{-1}(x) = \exp(x) \end{aligned}$$

■

Theorem 3.B.5. *If x and y are any two numbers, then*

$$\exp(x + y) = \exp(x) \cdot \exp(y)$$

Proof. Let $x' = \exp(x)$ and $y' = \exp(y)$, so that $x = \log x'$ and $y = \log y'$. Then

$$x + y = \log x' + \log y' = \log(x'y')$$

This means that

$$\exp(x + y) = x'y' = \exp(x) \cdot \exp(y)$$

■

Definition 3.B.3. *We define*

$$e := \exp(1) \tag{3.B.4}$$

and this is equivalent to the equation

$$1 = \log e = \int_1^e \frac{1}{t} dt \tag{3.B.5}$$

Then, we note that $\exp(x) = [\exp(1)]^x = e^x$ for rational x , so we define for any $x \in \mathbb{R}$,

$$e^x = \exp(x) \tag{3.B.6}$$

Definition 3.B.4. *If $a > 0$, then, for any real number x ,*

$$a^x := e^{x \log a} \tag{3.B.7}$$

If $a = e$ this definition agrees with our previous one.

Theorem 3.B.6. *If $a > 0$, then*

$$(1) \quad (a^b)^c = a^{bc}, \quad \forall a, b \in \mathbb{R}$$

and

$$(2) \quad a^1 = a \text{ and } a^{x+y} = a^x \cdot a^y, \quad \forall x, y \in \mathbb{R}$$

Proof. First, observe that

$$\begin{aligned} (a^b)^c &= e^{c \log a^b} \\ &= e^{c \log e^{b \log a}} \\ &= e^{cb \log a} \\ &= a^{bc} \end{aligned}$$

Next, observe that

$$a^1 = e^{1 \log a} = e^{\log a} = a$$

and

$$\begin{aligned} a^{x+y} &= e^{(x+y) \log a} \\ &= e^{x \log a + y \log a} \\ &= e^{x \log a} \cdot e^{y \log a} \\ &= a^x \cdot a^y \end{aligned}$$

■

Theorem 3.B.7. *If f is differentiable and*

$$f'(x) = f(x), \quad \forall x \in \mathbb{R}$$

then there is a number c such that

$$f(x) = ce^x, \quad \forall x \in \mathbb{R}$$

Proof. Let $g(x) = f(x)/e^x$, which is possible as $e^x \neq 0$ for all x . Then

$$g'(x) = \frac{e^x f'(x) - f(x)e^x}{(e^x)^2} = 0$$

Therefore, there is a number c such that

$$g(x) = \frac{f(x)}{e^x} = c, \quad \forall x$$

■

Theorem 3.B.8. *For any natural number n ,*

$$\lim_{x \rightarrow \infty} \frac{e^x}{x^n} = \infty \quad (3.B.8)$$

Proof. Step 1. We claim that $e^x > x$ for all x , and consequently $\lim_{x \rightarrow \infty} e^x = \infty$.

For $x \leq 0$ this is immediate. Now, it suffices to show $x > \log x$ for all $x > 0$. If $x < 1$ this clearly holds since $\log x < 0$. If $x > 1$, then $x - 1$ is an upper sum for $f(t) = \frac{1}{t}$ on $[1, x]$, so $\log x < x - 1 < x$.

Step 2. We claim $\lim_{x \rightarrow \infty} \frac{e^x}{x} = \infty$. First, note that

$$\frac{e^x}{x} = \frac{e^{x/2} \cdot e^{x/2}}{\frac{x}{2} \cdot 2} = \frac{1}{2} \left(\frac{e^{x/2}}{\frac{x}{2}} \right) \cdot e^{x/2}$$

By Step 1. the expression in parentheses is greater than 1, and $\lim_{x \rightarrow \infty} e^{x/2} = \infty$; this shows that $\lim_{x \rightarrow \infty} e^x/x = \infty$.

Step 3. To prove the main claim note that

$$\frac{e^x}{x^n} = \frac{(e^{x/n})^n}{\left(\frac{x}{n}\right)^n \cdot n^n} = \frac{1}{n^n} \cdot \left(\frac{e^{x/n}}{\frac{x}{n}} \right)^n$$

The expression in parentheses becomes arbitrarily large, by Step 2., so the n th power certainly becomes arbitrarily large. ■

Chapter 4

Sequences and Series

4.1.0 Approximation by Polynomial Functions

Definition 4.1.1. Given a function f that is n times differentiable in a neighborhood of a point a , let

$$a_k = \frac{f^{(k)}(a)}{k!}, \quad 0 \leq k \leq n,$$

and define

$$P_{n,a}(x) = a_0 + a_1(x-a) + \dots + a_n(x-a)^n$$

The polynomial $P_{n,a}$ is called the **Taylor polynomial of degree n for f at a .**

Remark 4.1.1. The Taylor polynomial has been defined so that

$$P_{n,a}^{(k)}(a) = f^{(k)}(a) \quad \text{for } 0 \leq k \leq n$$

in fact, it is evidently the only polynomial of degree $\leq n$ with this property.

Example 4.1.1. Consider the sin function. We have

$$\begin{aligned}\sin(0) &= 0 \\ \sin'(0) &= \cos 0 = 1 \\ \sin''(0) &= -\sin 0 = 0 \\ \sin'''(0) &= -\cos 0 = -1 \\ \sin^{(4)}(0) &= \sin 0 = 0\end{aligned}$$

From this point on, the derivatives repeat modulo 4. The coefficients become

$$a_k = \frac{\sin^{(k)}(0)}{k!} = \begin{cases} 0 & \text{if } \exists l \in \mathbb{N}; k = 2l \\ \frac{(-1)^l}{(2l+1)!} & \text{if } \exists l \in \mathbb{N}; k = 2l + 1 \end{cases}$$

Therefore, the Taylor polynomial $P_{2n+1,0}$ of degree $2n + 1$ for sin at 0 is

$$P_{2n+1,0}(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots + (-1)^n \frac{x^{2n+1}}{(2n+1)!}$$

Via a similar derivation we find that the Taylor polynomial $P_{2n,0}$ of degree $2n$ for \cos at 0 is

$$P_{2n,0} = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots + (-1)^n \frac{x^{2n}}{(2n)!}$$

Example 4.1.2. Note that for all $k \geq 0$, $\exp^{(k)}(0) = \exp(0) = 1$, so the Taylor polynomial of degree n for \exp at 0 is

$$P_{n,0}(x) = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots + \frac{x^n}{n!}$$

For \log , observe that

$$\begin{aligned} \log'(x) &= \frac{1}{x}, & \log'(1) &= 1 \\ \log''(x) &= -\frac{1}{x^2}, & \log''(1) &= -1 \\ \log'''(x) &= \frac{2}{x^3}, & \log'''(1) &= 2 \end{aligned}$$

in general

$$\log^{(k)}(x) = \frac{(-1)^{k-1}(k-1)!}{x^k}, \quad \log^{(k)}(1) = (-1)^{k-1}(k-1)!$$

for $k \geq 1$, and $\log(1) = 0$. Therefore, the Taylor polynomial of degree n for \log at 1 is

$$P_{n,1}(x) = (x-1) - \frac{(x-1)^2}{2} + \frac{(x-1)^3}{3} - \dots + \frac{(-1)^{n-1}(x-1)^n}{n}$$

If we consider the function $f(x) = \log(1+x)$, then the Taylor polynomial of degree n of f at 0 is

$$P_{n,0}(x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots + \frac{(-1)^{n-1}x^n}{n}$$

Theorem 4.1.1. Suppose that f is a function and $a \in \mathbb{R}$ such that

$$f'(a), \dots, f^{(n)}(a)$$

all exist. Let

$$a_k = \frac{f^{(k)}(a)}{k!}, \quad 0 \leq k \leq n$$

and define

$$P_{n,a}(x) = a_0 + a_1(x-a) + \dots + a_n(x-a)^n$$

Then

$$\lim_{x \rightarrow a} \frac{f(x) - P_{n,a}(x)}{(x-a)^n} = 0$$

Proof. Weiting out $P_{n,a}(x)$ explicitly we obtain

$$\frac{f(x) - P_{n,a}(x)}{(x-a)^n} = \frac{f(x) - \sum_{i=0}^{n-1} \frac{f^{(i)}(a)}{i!}(x-a)^i}{(x-a)^n} - \frac{f^{(n)}(a)}{n!}$$

Let us introduce the new functions

$$Q(x) = \sum_{i=0}^{n-1} \frac{f^{(i)}(a)}{i!} (x-a)^i \quad \text{and} \quad g(x) = (x-a)^n;$$

now we must prove that

$$\lim_{x \rightarrow a} \frac{f(x) - Q(x)}{g(x)} = \frac{f^{(n)}(a)}{n!}$$

Note that $Q^{(k)}(a) = f^{(k)}(a)$ for $k \leq n-1$, and $g^{(k)}(x) = n! \frac{(x-a)^{n-k}}{(n-k)!}$. By the continuity of $f^{(k)}$ and $Q^{(k)}$ for $k \leq n-1$, we have that

$$\lim_{x \rightarrow a} [f^{(k)}(x) - Q^{(k)}(x)] = f^{(k)}(a) - Q^{(k)}(a) = 0$$

and

$$\lim_{x \rightarrow a} g^{(k)}(x) = 0$$

Then applying l'Hopital's Rule $n-1$ times, we obtain

$$\lim_{x \rightarrow a} \frac{f(x) - Q(x)}{(x-a)^n} = \lim_{x \rightarrow a} \frac{f^{(n-1)}(x) - Q^{(n-1)}(x)}{n!(x-a)}$$

But the $n-1$ st derivative of Q is constant, and in fact $Q^{(n-1)}(x) = f^{(n-1)}(a)$, so

$$\lim_{x \rightarrow a} \frac{f(x) - Q(x)}{(x-a)^n} = \lim_{x \rightarrow a} \frac{f^{(n-1)}(x) - f^{(n-1)}(a)}{n!(x-a)} = \frac{f^{(n)}(a)}{n!}$$

by definition of $f^{(n)}(a)$, as desired. ■

Theorem 4.1.2. Suppose that

$$f'(a) = \dots = f^{(n-1)}(a) = 0, \quad \text{and} \quad f^{(n)}(a) \neq 0$$

1. If n is even and $f^{(n)}(a) > 0$, then f has a local minimum at a .
2. If n is even and $f^{(n)}(a) < 0$, then f has a local maximum at a .
3. If n is odd, then f has neither a local maximum nor a local minimum at a .

Proof. Let f be as in the hypothesis, and without loss of generality let $f(a) = 0$, as otherwise one can replace f with $f - f(a)$ without affecting the hypothesis. Then, since the first $n-1$ derivatives of f at a are 0, the Taylor polynomial $P_{n,a}$ of f is

$$\begin{aligned} P_{n,a}(x) &= \sum_{i=0}^n \frac{f^{(i)}(a)}{i!} (x-a)^i \\ &= \frac{f^{(n)}(a)}{n!} (x-a)^n \end{aligned}$$

Thus, Theorem 4.1.1 states that

$$0 = \lim_{x \rightarrow a} \frac{f(x) - P_{n,a}(x)}{(x-a)^n} = \lim_{x \rightarrow a} \left[\frac{f(x)}{(x-a)^n} - \frac{f^{(n)}(a)}{n!} \right]$$

Consequently, if x is sufficiently close to a , then $f(x)/(x-a)^n$ has the same sign as $f^{(n)}(a)/n!$. Suppose now that n is even. In this case $(x-a)^n > 0$ for all $x \neq a$. Since $f(x)/(x-a)^n$ has the same sign as $f^{(n)}(a)/n!$ for x sufficiently close to a , it follows that $f(x)$ itself has the same sign as $f^{(n)}(a)/n!$ for x sufficiently close to a . If $f^{(n)}(a) > 0$, this means that

$$f(x) > 0 = f(a)$$

for x close to a . Consequently, f has a local minimum at a . If $f^{(n)}(a) < 0$, this means that

$$f(x) < 0 = f(a)$$

for x close to a , so f has a local minimum at a .

Conversely, suppose that n is odd. Then if x is sufficiently close to a $f(x)/(x-a)^n$ always has the same sign, since it has the same sign as $f^{(n)}(a)/n!$ which is constant. But $(x-a)^n > 0$ for $x > a$ and $(x-a)^n < 0$ for $x < a$. Therefore $f(x)$ has different signs for $x > a$ and $x < a$. Hence, f has neither a local maximum nor a local minimum at a . ■

Definition 4.1.2. Two functions f and g are equal up to order n at a if

$$\lim_{x \rightarrow a} \frac{f(x) - g(x)}{(x-a)^n} = 0$$

Theorem 4.1.3. Let P and Q be two polynomials in $(x-a)$, of degree $\leq n$, and suppose that P and Q are equal up to order n at a . Then $P = Q$.

Proof. Let $R = P - Q$. Since R is a polynomial of degree $\leq n$, it is only necessary to prove that if $R(x) = b_0 + \dots + b_n(x-a)^n$ satisfies

$$\lim_{x \rightarrow a} \frac{R(x)}{(x-a)^n} = 0$$

then $R = 0$. Now the hypothesis on R surely implies that

$$\lim_{x \rightarrow a} \frac{R(x)}{(x-a)^i} = 0 \quad \text{for } 0 \leq i \leq n$$

For $i = 0$ this condition reads that $\lim_{x \rightarrow a} R(x) = 0$. On the other hand $\lim_{x \rightarrow a} R(x) = b_0$. Thus $b_0 = 0$. Similarly, we find that

$$\frac{R(x)}{x-a} = b_1 + b_2(x-a) + \dots + b_n(x-a)^{n-1}$$

and

$$\lim_{x \rightarrow a} \frac{R(x)}{x-a} = b_1$$

so $b_1 = 0$. Continuing in this way, by induction we find that

$$b_0 = b_1 = \dots = b_n = 0$$

so $R(x) = 0$ and $P = Q$. ■

Corollary 4.1.4. Let f be n -times differentiable at a , and suppose that P is a polynomial in $(x - a)$ of degree $\leq n$, which equals f up to order n at a . Then $P = P_{n,a,f}$ (The Taylor polynomial of f of degree n at a).

Proof. Since P and $P_{n,a,f}$ both equal f up to order n at a , using the triangle inequality and an epsilon-delta proof it can be shown that P equals $P_{n,a,f}$ up to order n at a . Consequently, $P = P_{n,a,f}$ by the preceding Theorem. ■

Definition 4.1.3. If f is a function for which $P_{n,a}(x)$ exists, we define the remainder term $R_{n,a}(x)$ by

$$R_{n,a}(x) = f(x) - P_{n,a}(x)$$

If $f^{(n+1)}$ is continuous on $[a, x]$, then

$$R_{n,a}(x) = \int_a^x \frac{f^{(n+1)}(t)}{n!} (x-t)^n dt$$

Remark 4.1.2. If m and M are the minimum and maximum of $f^{(n+1)}n!$ on $[a, x]$, then $R_{n,a}(x)$ satisfies

$$m \int_a^x (x-t)^n dt \leq R_{n,a}(x) \leq M \int_a^x (x-t)^n dt$$

so we can write

$$R_{n,a}(x) = \alpha \cdot \frac{(x-a)^{n+1}}{n+1}$$

for some number α between m and M . Since we have assumed that $f^{(n+1)}$ is continuous, for some $t \in (a, x)$ we can also write

$$R_{n,a}(x) = \frac{f^{(n+1)}(t)}{n!} \frac{(x-a)^{n+1}}{n+1} = \frac{f^{(n+1)}(t)}{(n+1)!} (x-a)^{n+1}$$

This is known as the Lagrange form of the remainder.

Lemma 4.1.5. Suppose that the function R is $(n+1)$ -times differentiable on $[a, b]$, and

$$R^{(k)}(a) = 0 \quad \text{for } k = 0, 1, 2, \dots, n$$

Then for any $x \in (a, b]$ we have

$$\frac{R(x)}{(x-a)^{n+1}} = \frac{R^{(n+1)}(t)}{(n+1)!} \quad \text{for some } t \text{ in } (a, x)$$

Proof. For $n = 0$, this is simply 9, and we will proceed for the remaining n by induction on n . To do this we use 10 to write

$$\frac{R(x)}{(x-a)^{n+2}} = \frac{R'(z)}{(n+2)(z-a)^{n+1}} = \frac{1}{n+2} \frac{R'(z)}{(z-a)^{n+1}} \quad \text{for some } z \text{ in } (a, x),$$

and then apply the induction hypothesis to R' on the interval $[a, z]$ to get

$$\frac{R(x)}{(x-a)^{n+2}} = \frac{1}{n+2} \frac{(R')^{(n+1)}(t)}{(n+1)!} \quad \text{for some } z \text{ in } (a, x),$$

$$= \frac{R^{(n+2)}(t)}{(n+2)!}$$

as desired. ■

Theorem 17 (Taylor's Theorem).

Suppose $f', \dots, f^{(n+1)}$ are defined on $[a, x]$, and that $R_{n,a}(x)$ is defined by

$$R_{n,a}(x) = f(x) - P_{n,a}(x)$$

Then

$$R_{n,a}(x) = \frac{f^{(n+1)}(t)}{(n+1)!} (x-a)^{n+1} \quad \text{for some } t \text{ in } (a, x)$$

Proof. The function $R_{n,a}$ satisfies the conditions of the preceding Lemma by the definition of the Taylor polynomial, so

$$\frac{R_{n,a}(x)}{(x-a)^{n+1}} = \frac{R_{n,a}^{(n+1)}(t)}{(n+1)!}$$

for some t in (a, x) . But,

$$R_{n,a}^{(n+1)} = f^{(n+1)}$$

since $R_{n,a} - f$ is a polynomial of degree n . Substituting gives the Lagrange form for the remainder, as desired. ■

Example 4.1.3. Applying 17 to the functions \sin , \cos , and \exp , with $a = 0$, we obtain the following formulas:

$$\begin{aligned} \sin x &= \sum_{i=0}^n \frac{(-1)^i x^{2i+1}}{(2i+1)!} + \frac{\sin^{(2n+2)}(t)}{(2n+2)!} x^{2n+2} \\ \cos x &= \sum_{i=0}^n \frac{(-1)^i x^{2i}}{(2i)!} + \frac{\cos^{(2n+1)}(t)}{(2n+1)!} x^{2n+1} \\ \exp x &= \sum_{i=0}^n \frac{x^i}{i!} + \frac{\exp t}{(n+1)!} x^{n+1} \end{aligned}$$

(of course, we could go one power higher in the remainder terms for \sin and \cos)

4.2.0 Infinite Sequences

Definition 4.2.1. An infinite sequence of real numbers is a real valued function whose domain is \mathbb{N} .

Definition 4.2.2. A sequence $\{a_n\}$ converges to $\ell \in \mathbb{R}$, denoted by $\lim_{n \rightarrow \infty} a_n = \ell$, if for every $\epsilon > 0$ there exists $N \in \mathbb{N}$ such that for all $n \in \mathbb{N}$, if $n \geq N$ then

$$|a_n - \ell| < \epsilon$$

A sequence $\{a_n\}$ is said to converge if such an ℓ exists, and to diverge otherwise.

Theorem 4.2.1 (Limit Laws). *If $\lim_{n \rightarrow \infty} a_n$ and $\lim_{n \rightarrow \infty} b_n$ both exist, then*

$$\begin{aligned}\lim_{n \rightarrow \infty} (a_n + b_n) &= \lim_{n \rightarrow \infty} a_n + \lim_{n \rightarrow \infty} b_n \\ \lim_{n \rightarrow \infty} a_n \cdot b_n &= \lim_{n \rightarrow \infty} a_n \cdot \lim_{n \rightarrow \infty} b_n\end{aligned}$$

moreover, if $\lim_{n \rightarrow \infty} b_n \neq 0$, then $b_n \neq 0$ for all n greater than some N , and

$$\lim_{n \rightarrow \infty} a_n/b_n = \lim_{n \rightarrow \infty} a_n / \lim_{n \rightarrow \infty} b_n$$

Proof. (To be completed) ■

Theorem 4.2.2. *Let f be a function defined in an open interval containing c , except perhaps at c itself, with*

$$\lim_{x \rightarrow c} f(x) = l$$

Suppose that $\{a_n\}$ is a sequence such that

1. each a_n is in the domain of f ,
2. each $a_n \neq c$,
3. $\lim_{n \rightarrow \infty} a_n = c$

Then the sequence $\{f(a_n)\}$ satisfies

$$\lim_{n \rightarrow \infty} f(a_n) = l$$

Conversely, if this is true for every sequence $\{a_n\}$ satisfying the above conditions, then $\lim_{x \rightarrow c} f(x) = l$.

Proof. Suppose first that $\lim_{x \rightarrow c} f(x) = l$. Then for every $\varepsilon > 0$ there is a $\delta > 0$ such that, for all x ,

$$\text{if } 0 < |x - c| < \delta, \text{ then } |f(x) - l| < \varepsilon$$

If the sequence $\{a_n\}$ satisfies $\lim_{n \rightarrow \infty} a_n = c$, then there is a natural number N such that for all $n \in \mathbb{N}$,

$$\text{if } n \geq N, \text{ then } 0 < |a_n - c| < \delta$$

By our choice of δ this implies that

$$|f(a_n) - l| < \varepsilon$$

showing that $\lim_{n \rightarrow \infty} f(a_n) = l$.

Suppose, conversely, that $\lim_{n \rightarrow \infty} f(a_n) = l$ for every sequence $\{a_n\}$ satisfying our three conditions. If $\lim_{x \rightarrow c} f(x) = l$ were not true, there would be some $\varepsilon > 0$ such that for all $\delta > 0$ there exists x such that $0 < |x - c| < \delta$ but $|f(x) - l| \geq \varepsilon$. In particular, for each n there would

exist x_n such that $0 < |x_n - c| < 1/n$, but $|f(x_n) - l| \geq \varepsilon$. Define a sequence $\{x_n\}$ using these x_n . Then x_n is in the domain of f for each n , and as $0 < |x_n - c|$ for each n , $x_n \neq c$ for all n . Moreover, for all $\varepsilon' > 0$ there exists $N \in \mathbb{N}$ such that $\varepsilon' > 1/N > 0$ (by the Archimedean Property of \mathbb{R}), so for all $n \geq N$, $0 < |x_n - c| < 1/n < \varepsilon'$. Consequently, $\lim_{n \rightarrow \infty} x_n = c$, so the sequence satisfies all of our initial conditions. However, then by assumption $\lim_{n \rightarrow \infty} f(x_n) = l$. But, by construction, for ε we have that for all $n \in \mathbb{N}$, $0 < |x_n - c| < 1/n$ but $|f(x_n) - l| \geq \varepsilon$, so $f(x_n)$ does not converge to l , contradicting our hypothesis. Thus $\lim_{x \rightarrow c} f(x) = l$ must be true. ■

Definition 4.2.3. A sequence $\{a_n\}$ is **increasing** if $a_{n+1} > a_n$ for all n , **nondecreasing** if $a_{n+1} \geq a_n$ for all n , and **bounded above** if there is a number M such that $a_n \leq M$ for all n . Similarly, a sequence $\{a_n\}$ is **decreasing** if $a_{n+1} < a_n$ for all n , **nonincreasing** if $a_{n+1} \leq a_n$ for all n , and **bounded below** if there is a number m such that $a_n \geq m$ for all n .

Theorem 4.2.3. If $\{a_n\}$ is nondecreasing and bounded above, then $\{a_n\}$ converges.

Proof. The set $A := \{a_n : n \in \mathbb{N}\}$ is, by assumption, bounded above, so A has a least upper bound $\alpha \in \mathbb{R}$. We claim that $\lim_{n \rightarrow \infty} a_n = \alpha$. If $\varepsilon > 0$, then $\alpha - \varepsilon$ is not an upper bound for A so there exists a_N in A such that $a_N > \alpha - \varepsilon$, so $\alpha - a_N < \varepsilon$. Then for all $n \geq N$, $a_n \geq a_N$ since $\{a_n\}$ is nondecreasing so

$$|\alpha - a_n| = \alpha - a_n \leq \alpha - a_N < \varepsilon$$

Consequently, we conclude that $\lim_{n \rightarrow \infty} a_n = \alpha$. ■

Definition 4.2.4. A **subsequence** of a sequence $\{a_n\}$ is a sequence

$$a_{n_1}, a_{n_2}, a_{n_3}, \dots$$

where the n_j are natural numbers with $n_1 < n_2 < n_3 < \dots$.

Lemma 4.2.4. Any sequence $\{a_n\}$ contains a subsequence which is either nondecreasing or nonincreasing.

Proof. Call a natural number n a “peak point” of a sequence $\{a_n\}$ if $a_m < a_n$ for all $m > n$.

Case 1. The sequence has infinitely many peak points. In this case, if $n_1 < n_2 < n_3 < \dots$ are the peak points, then $a_{n_1} > a_{n_2} > a_{n_3} > \dots$, so $\{a_{n_j}\}$ is a nonincreasing subsequence of $\{a_n\}$.

Case 2. The sequence has only finitely many peak points. In this case, let n_1 be greater than all peak points. Since n_1 is not a peak point, there is some $n_2 > n_1$ such that $a_{n_2} \geq a_{n_1}$. Since n_2 is not a peak point, there is some $n_3 > n_2$ such that $a_{n_3} \geq a_{n_2}$. Suppose there exists $k \geq 3$ such that for all $1 \leq m < k$, $a_{n_m} \leq a_{n_{m+1}}$ and $n_m < n_{m+1}$. Then since n_k is not a peak point, there is some n_{k+1} such that $n_{k+1} > n_k$ and $a_{n_{k+1}} \geq a_{n_k}$. Thus, by recursive definition we have constructed a nondecreasing subsequence $\{a_{n_k}\}$ of $\{a_n\}$. ■

Corollary 4.2.5 (The Bolzano-Weierstrass Theorem). *Every bounded sequence has a convergent subsequence.*

Definition 4.2.5. A sequence $\{a_n\}$ is a **Cauchy sequence** if for every $\varepsilon > 0$ there is a natural number N such that, for all $m, n \in \mathbb{N}$, if $m, n \geq N$, then

$$|a_n - a_m| < \varepsilon$$

(This can be written as $\lim_{m, n \rightarrow \infty} |a_m - a_n| = 0$)

Theorem 4.2.6. A sequence $\{a_n\}$ converges if and only if it is a Cauchy sequence.

Proof. First assume that $\lim_{n \rightarrow \infty} a_n = l$ for some $l \in \mathbb{R}$. Then given $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that if $n \geq N$, then $|a_n - l| < \varepsilon/2$. Hence, if $m, n \geq N$, then

$$|a_n - a_m| \leq |a_n - l| + |a_m - l| < \varepsilon/2 + \varepsilon/2 = \varepsilon$$

Thus, $\{a_n\}$ is Cauchy.

Conversely, suppose that $\{a_n\}$ is a Cauchy sequence. I claim that this implies $\{a_n\}$ is bounded. First, for $\varepsilon = 1 > 0$, there exists $N \in \mathbb{N}$ such that if $m, n \geq N$, then $|a_m - a_n| < \varepsilon = 1$. In particular, for all $n \geq N$, $|a_N - a_n| < 1$. Take $M = \max(a_N + 1, a_{N-1}, \dots, a_1)$, and $m = \min(a_N - 1, a_{N-1}, \dots, a_1)$. Then for all $k \leq N$ we have that $m \leq a_k \leq M$. On the other hand, for $k \geq N$, we have that $a_N - 1 < a_k < a_N + 1$, so $m < a_k < M$. Thus $\{a_n : n \in \mathbb{N}\}$ is bounded.

Then, by ?? $\{a_n\}$ has a convergent subsequence $\{a_{n_k}\}$. Let $\lim_{k \rightarrow \infty} a_{n_k} = l$, for some $l \in \mathbb{R}$. Then, fix $\varepsilon > 0$. It follows that there exist $K, K' \in \mathbb{N}$ such that for $m, n \geq K$ and $j \geq K'$, $|a_m - a_n| < \varepsilon/2$, while $|a_{n_j} - l| < \varepsilon/2$. Note that $n_j \geq j$, since the sequence $\{n_k\}$ is increasing. Then, for all $i \geq \max(K, K')$ we have that

$$|a_i - l| \leq |a_i - a_{n_i}| + |a_{n_i} - l| < \varepsilon/2 + \varepsilon/2 = \varepsilon$$

Therefore, by definition $\{a_n\}$ converges to l as well. ■

4.3.0 Infinite Series

Definition 4.3.1. The sequence $\{a_n\}$ is **summable** if the sequence $\{s_n\}$ converges, where

$$s_n = \sum_{i=1}^n a_i$$

is the n -th **partial sum**. In this case, $\lim_{n \rightarrow \infty} s_n$ is denoted by

$$\sum_{n=1}^{\infty} a_n$$

and is called the **sum** of the sequence $\{a_n\}$.

Remark 4.3.1. If $\{a_n\}$ and $\{b_n\}$ are summable, then

$$\begin{aligned}\sum_{n=1}^{\infty} (a_n + b_n) &= \sum_{i=1}^{\infty} a_n + \sum_{i=1}^{\infty} b_n \\ \sum_{n=1}^{\infty} c \cdot a_n &= c \cdot \sum_{i=1}^{\infty} a_n\end{aligned}$$

for all $c \in \mathbb{R}$.

Theorem 18 (The Cauchy Criterion).

The sequence $\{a_n\}$ is summable if and only if for all $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that for all $m \geq n \in \mathbb{N}$, if $m, n \geq N$, then

$$\left| \sum_{i=1}^m a_i - \sum_{i=1}^n a_i \right| = \left| \sum_{i=n+1}^m a_i \right| < \varepsilon$$

Remark 4.3.2. This result is a direct consequence of the fact that a sequence in \mathbb{R} is Cauchy if and only if it converges applied to the sequence of partial sums for $\{a_n\}$.

Theorem 19 (The Vanishing Condition).

If $\{a_n\}$ is summable, then

$$\lim_{n \rightarrow \infty} a_n = 0$$

Proof. If $\lim_{n \rightarrow \infty} s_n = l$, then

$$\begin{aligned}\lim_{n \rightarrow \infty} a_n &= \lim_{n \rightarrow \infty} (s_n - s_{n-1}) = \lim_{n \rightarrow \infty} s_n - \lim_{n \rightarrow \infty} s_{n-1} \\ &= l - l = 0\end{aligned}$$

■

Example 4.3.1. The geometric series are of the form

$$\sum_{n=0}^{\infty} r^n = 1 + r + r^2 + r^3 + \dots$$

For $|r| \geq 1$, $\lim_{n \rightarrow \infty} r^n \neq 0$, so $\{r^n\}$ is not summable. On the other hand, if $|r| < 1$ the sequence is summable. First write

$$s_n = 1 + r + r^2 + \dots + r^n, \text{ and } rs_n = r + r^2 + r^3 + \dots + r^{n+1}$$

It follows that

$$s_n(1 - r) = 1 - r^{n+1}$$

so

$$s_n = \frac{1 - r^{n+1}}{1 - r}$$

since $r \neq 1$. Finally, it follows that

$$\sum_{n=0}^{\infty} r^n = \lim_{n \rightarrow \infty} s_n = \lim_{n \rightarrow \infty} \frac{1 - r^{n+1}}{1 - r} = \frac{1}{1 - r}$$

as $|r| < 1$.

Definition 4.3.2. A sequence $\{a_n\}$ such that $a_n \geq 0$ for all $n \in \mathbb{N}$ is said to be nonnegative.

Theorem 20 (The Boundedness Criterion).

A nonnegative sequence $\{a_n\}$ is summable if and only if the set of partial sums s_n is bounded.

Proof. Since $\{a_n\}$ is nonnegative, $\{s_n\}$ is nondecreasing. Hence from our previous results on monotone sequences, $\{s_n\}$ converges if and only if $\{s_n\}$ is bounded. ■

Theorem 21 (The Comparison Test).

Suppose that $\{a_n\}$ and $\{b_n\}$ are sequences such that $0 \leq a_n \leq b_n$ for all $n \in \mathbb{N}$. Then if $\sum_{n=1}^{\infty} b_n$ converges, so does $\sum_{n=1}^{\infty} a_n$.

Proof. Let s_n denote the n -th partial sum of $\{a_n\}$, and let t_n denote the n -th partial sum of $\{b_n\}$. Then $0 \leq s_n \leq t_n$ for all $n \in \mathbb{N}$. Now $\{t_n\}$ converges by assumption, so it is bounded. Hence, there exists $M \in \mathbb{R}$ such that $0 \leq s_n \leq t_n \leq M$ for all $n \in \mathbb{N}$, so $\{s_n\}$ is also bounded. Thus by 20 $\{a_n\}$ is summable, so by definition $\sum_{n=1}^{\infty} a_n$ converges. ■

Theorem 22 (The Limit Comparison Test).

If $a_n, b_n > 0$ for convergent sequences $\{a_n\}$ and $\{b_n\}$, and $\lim_{n \rightarrow \infty} a_n/b_n = c \neq 0$, then $\sum_{n=1}^{\infty} a_n$ converges if and only if $\sum_{n=1}^{\infty} b_n$ converges.

Proof. Suppose $\sum_{n=1}^{\infty} b_n$ converges. Since $\lim_{n \rightarrow \infty} a_n/b_n = c$, there is some N such that

$$a_n/b_n - c \leq c \implies a_n \leq 2cb_n, \quad \text{for } n \geq N$$

But the sequence $2c \sum_{n=N}^{\infty} b_n$ certainly converges. Then by 21 we have that $\sum_{n=N}^{\infty} a_n$ converges, and this implies convergence of the whole series $\sum_{n=1}^{\infty} a_n$, which only has finitely many additional terms.

Note that

$$\lim_{n \rightarrow \infty} b_n/a_n = \frac{1}{\lim_{n \rightarrow \infty} a_n/b_n} = 1/c \neq 0$$

so the converse follows immediately. ■

Theorem 23 (The Ratio Test).

Let $\{a_n\}$ be a positive sequence, and suppose that

$$\lim_{n \rightarrow \infty} \frac{a_{n+1}}{a_n} = r$$

for some $r \geq 0$. Then $\sum_{n=1}^{\infty} a_n$ converges if $r < 1$. On the other hand, if $r > 1$, then the terms a_n are unbounded, so $\sum_{n=1}^{\infty} a_n$ diverges.

Proof. Suppose first that $r < 1$. Choose any number s with $r < s < 1$. The hypothesis $\lim_{n \rightarrow \infty} a_{n+1}/a_n = r < 1$ implies that there is some $N \in \mathbb{N}$ such that if $n \geq N$,

$$a_{n+1}/a_n - r < s - r \implies a_{n+1}/a_n < s$$

This can be written as $a_{n+1} < sa_n$. Thus,

$$\begin{aligned} a_{N+1} &< sa_N \\ a_{N+2} &< sa_{N+1} < s^2 a_N \\ &\vdots \\ a_{N+k} &< s^k a_N \end{aligned}$$

Since $\sum_{k=0}^{\infty} a_N s^k = a_N \sum_{k=0}^{\infty} s^k$ converges, since $|s| < 1$, 21 shows that

$$\sum_{n=N}^{\infty} a_n = \sum_{k=0}^{\infty} a_{N+k}$$

converges as $a_{N+k} < a_N s^k$ for all $k \geq 0$. This implies that $\sum_{n=0}^{\infty} a_n$ as a whole converges.

If $r > 1$, choose some $s \in \mathbb{R}$ such that $1 < s < r$. Then there is a number $N \in \mathbb{N}$ such that

$$r - a_{n+1}/a_n < r - s \implies s < a_{n+1}/a_n$$

for all $n \geq N$. This implies that

$$a_{N+k} > a_N s^k,$$

for all $k \in \mathbb{N}$, so the terms are unbounded. ■

Theorem 24 (The Integral Test).

Suppose that f is positive and decreasing on $[1, \infty)$, and that $f(n) = a_n$ for all $n \in \mathbb{N}$. Then $\sum_{n=1}^{\infty} a_n$ converges if and only if the limit

$$\int_1^{\infty} f = \lim_{A \rightarrow \infty} \int_1^A f$$

exists.

Proof. The existence of $\lim_{A \rightarrow \infty} \int_1^A f$ is equivalent to the convergence of the series

$$\int_1^2 f + \int_2^3 f + \int_3^4 f + \dots$$

Since f is decreasing, we have

$$f(n+1) < \int_n^{n+1} f < f(n)$$

The first half of this double inequality shows that the series $\sum_{n=1}^{\infty} a_{n+1}$ may be compared to the series $\sum_{n=1}^{\infty} \int_n^{n+1} f$, proving that $\sum_{n=1}^{\infty} a_{n+1}$ (and hence $\sum_{n=1}^{\infty} a_n$) converges if $\lim_{A \rightarrow \infty} \int_1^A f$ exists.

The second half of the inequality shows that the series $\sum_{n=1}^{\infty} \int_n^{n+1} f$ may be compared to the series $\sum_{n=1}^{\infty} a_n$, proving that $\lim_{A \rightarrow \infty} \int_1^A f$ must exist if $\sum_{n=1}^{\infty} a_n$ converges. ■

Corollary 4.3.1. The series $\sum_{n=1}^{\infty} 1/n^p$ converges if and only if $p > 1$.

Proof. If $p < 0$ then $\lim_{n \rightarrow \infty} 1/n^p \neq 0$. If $p > 0$, the convergence of $\sum_{n=1}^{\infty} 1/n^p$ is equivalent, by 24, to the existence of

$$\lim_{A \rightarrow \infty} \int_1^A \frac{1}{x^p} dx$$

Now, observe that

$$\int_1^A \frac{1}{x^p} dx = \begin{cases} -\frac{1}{p-1} \cdot \frac{1}{A^{p-1}} + \frac{1}{p-1}, & p \neq 1 \\ \log A, & p = 1 \end{cases}$$

This shows that $\lim_{A \rightarrow \infty} \int_1^A 1/x^p dx$ exists if $p > 1$, but not if $p \leq 1$. Thus, $\sum_{n=1}^{\infty} 1/n^p$ converges precisely for $p > 1$. ■

Definition 4.3.3. The series $\sum_{n=1}^{\infty} a_n$ is **absolutely convergent** if the series $\sum_{n=1}^{\infty} |a_n|$ is convergent. (In formal language, the sequence $\{a_n\}$ is said to be **absolutely summable** if the sequence $\{|a_n|\}$ is summable.)

Theorem 4.3.2. Every absolutely convergent series is convergent. Moreover, a series is absolutely convergent if and only if the series formed from its positive terms and the series formed from its negative terms both converge.

Proof. If $\sum_{n=1}^{\infty} |a_n|$ converges, then, by 18,

$$\lim_{m, n \rightarrow \infty} \sum_{i=n+1}^m |a_i| = 0$$

Since

$$\left| \sum_{i=n+1}^m a_i \right| \leq \sum_{i=n+1}^m |a_i|$$

it follows that

$$\lim_{m,n \rightarrow \infty} \sum_{i=n+1}^m a_i = 0$$

which shows that $\sum_{n=1}^{\infty} a_n$ converges.

To prove the second portion of the theorem, let $\{a_n^+\}$ and $\{a_n^-\}$ be sequences defined by

$$a_n^+ = \begin{cases} a_n, & \text{if } a_n \geq 0 \\ 0, & \text{if } a_n \leq 0 \end{cases}$$

$$a_n^- = \begin{cases} a_n, & \text{if } a_n \leq 0 \\ 0, & \text{if } a_n \geq 0 \end{cases}$$

It follows that

$$\sum_{n=1}^{\infty} |a_n| = \sum_{n=1}^{\infty} [a_n^+ - a_n^-] = \sum_{n=1}^{\infty} a_n^+ - \sum_{n=1}^{\infty} a_n^-$$

so if $\sum_{n=1}^{\infty} a_n^+$ and $\sum_{n=1}^{\infty} a_n^-$ are convergent, so is $\sum_{n=1}^{\infty} |a_n|$.

Conversely, suppose $\sum_{n=1}^{\infty} |a_n|$ converges. Then by our initial argument $\sum_{n=1}^{\infty} a_n$ converges also.

Therefore,

$$\sum_{n=1}^{\infty} a_n^+ = \sum_{n=1}^{\infty} \frac{1}{2} [a_n + |a_n|] = \frac{1}{2} \left(\sum_{n=1}^{\infty} a_n + \sum_{n=1}^{\infty} |a_n| \right)$$

and

$$\sum_{n=1}^{\infty} a_n^- = \sum_{n=1}^{\infty} \frac{1}{2} [a_n - |a_n|] = \frac{1}{2} \left(\sum_{n=1}^{\infty} a_n - \sum_{n=1}^{\infty} |a_n| \right)$$

both converge. ■

Remark 4.3.3. A consequent of this result is that every convergent series with positive terms can be used to obtain infinitely many other convergent series simply by putting minus signs at random.

Definition 4.3.4. A convergent series which is not absolutely convergent is said to be conditionally convergent.

Theorem 25 (Leibniz's Theorem).

Suppose that $\{a_n\}$ is a non-decreasing non-negative sequence such that

$$\lim_{n \rightarrow \infty} a_n = 0$$

Then the series

$$\sum_{n=1}^{\infty} (-1)^{n+1} a_n = a_1 - a_2 + a_3 - a_4 + \dots$$

converges.

Proof. First, observe that

1. $s_2 \leq s_4 \leq s_6 \leq \dots$
2. $s_1 \geq s_3 \geq s_5 \geq \dots$
3. $s_k \leq s_l$ if k is even and l is odd.

Indeed, note that for all n , $a_{2n+1} \geq a_{2n+2}$, so $a_{2n+1} - a_{2n+2} \geq 0$, so

$$s_{2n+2} = s_{2n} + a_{2n+1} - a_{2n+2} \geq s_{2n}$$

and similarly as $a_{2n+2} \geq a_{2n+3}$, we have

$$s_{2n+3} = s_{2n+1} - a_{2n+2} + a_{2n+3} \leq s_{2n+1}$$

To prove the third inequality, first notice that

$$s_{2n} = s_{2n-1} - a_{2n} \leq s_{2n-1}$$

since $a_{2n} \geq 0$. Now, if k is even and l is odd, choose n such that $k \leq 2n$ and $l \leq 2n - 1$. Then

$$s_k \leq s_{2n} \leq s_{2n-1} \leq s_l$$

which proves the third inequality.

Now, the sequence $\{s_{2n}\}$ converges, because it is nondecreasing and is bounded above (by s_l for any odd l). Let $\alpha = \sup\{s_{2n}\} = \lim_{n \rightarrow \infty} s_{2n}$. Similarly, let $\beta = \inf\{s_{2n+1}\} = \lim_{n \rightarrow \infty} s_{2n+1}$. It follows from our third inequality that $\alpha \leq \beta$; since

$$s_{2n+1} - s_{2n} = a_{2n+1} \quad \text{and} \quad \lim_{n \rightarrow \infty} a_n = 0$$

it is actually the case that $\alpha = \beta$. This proves that $\alpha = \beta = \lim_{n \rightarrow \infty} s_n$. ■

Definition 4.3.5. A sequence $\{a_n\}$ is a **rearrangement** of a sequence $\{a_n\}$ if each $b_n = a_{f(n)}$ where f is a certain permutation on the natural numbers.

Theorem 4.3.3. If $\sum_{n=1}^{\infty} a_n$ converges, but does not converge absolutely; then for any number α there is a rearrangement $\{b_n\}$ of $\{a_n\}$ such that $\sum_{n=1}^{\infty} b_n = \alpha$.

Proof. Let $\sum_{n=1}^{\infty} p_n$ denote the series formed from the positive terms of $\{a_n\}$ and let $\sum_{n=1}^{\infty} q_n$ denote the series of negative terms. It follows from Theorem 4.3.2 that at least one of these series does not converge. As a matter of fact, both must fail to converge, for if one had bounded partial sums, and the other had unbounded partial sums, then the original series $\sum_{n=1}^{\infty} a_n$ would also have unbounded partial sums, contradicting the assumption that it converges.

Let α be any number. Assume, for simplicity, that $\alpha > 0$. Since the series $\sum_{n=1}^{\infty} p_n$ there is a number N such that

$$\sum_{n=1}^N p_n > \alpha$$

We will choose N_1 to be the smallest N with this property. This means that

$$\sum_{n=1}^{N_1-1} p_n \leq \alpha \quad \text{and} \quad \sum_{n=1}^{N_1} p_n > \alpha$$

Then if $S_1 = \sum_{n=1}^{N_1} p_n$, we have $S_1 - \alpha \leq p_{N_1}$. Next, choose the smallest integer M_1 for which

$$T_1 = S_1 + \sum_{n=1}^{M_1} q_n < \alpha$$

As before, we have $\alpha - T_1 \leq -q_{M_1}$. We continue this process indefinitely. The sequence

$$p_1, \dots, p_{N_1}, q_1, \dots, q_{M_1}, q_{N_1+1}, \dots, p_{N_2}, \dots$$

is a rearrangement of $\{a_n\}$. The partial sums of this rearrangement increase to S_1 , then decrease to T_1 , then increase to S_2 , etc. To complete the proof we note that $|S_k - \alpha|$ and $|T_k - \alpha|$ are less than or equal to p_{N_k} or $-q_{M_k}$, respectively, and that these terms, being numbers of the original sequence $\{a_n\}$, must decrease to 0, since $\sum_{n=1}^{\infty} a_n$ converges. ■

Theorem 4.3.4. If $\sum_{n=1}^{\infty} a_n$ converges absolutely, and $\{b_n\}$ is any rearrangement of $\{a_n\}$, then

$\sum_{n=1}^{\infty} b_n$ also converges (absolutely), and in particular

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} b_n$$

Proof. Denote the partial sums of $\{a_n\}$ by s_n , and the partial sums of $\{b_n\}$ by t_n . Suppose that $\varepsilon > 0$. Since $\sum_{n=1}^{\infty} a_n$ converges, there is some N such that

$$\left| \sum_{n=1}^{\infty} a_n - s_N \right| < \varepsilon$$

Moreover, since $\sum_{n=1}^{\infty} |a_n|$ converges, we can also choose N' so that

$$\sum_{n=1}^{\infty} |a_n| - (|a_1| + \dots + |a_{N'}|) < \varepsilon$$

so that

$$\sum_{n=N+1}^{\infty} |a_n| < \varepsilon$$

Choose M such that each a_1, \dots, a_N appear among b_1, \dots, b_M . Then whenever $m > M$, the difference $t_m - s_N$ is the sum of certain a_i , where $i > N$. Consequently,

$$|t_m - s_N| \leq \sum_{n=N+1}^{\infty} |a_n| < \varepsilon$$

Thus, if $m > M$, then

$$\begin{aligned} \left| \sum_{n=1}^{\infty} a_n - t_m \right| &= \left| \sum_{n=1}^{\infty} a_n - s_N - (t_m - s_N) \right| \\ &\leq \left| \sum_{n=1}^{\infty} a_n - s_N \right| + |t_m - s_N| \\ &< \varepsilon + \varepsilon \end{aligned}$$

Since this is true for every $\varepsilon > 0$, the series $\sum_{n=1}^{\infty} b_n$ converges to $\sum_{n=1}^{\infty} a_n$.

To show that $\sum_{n=1}^{\infty} b_n$ converges absolutely, note that $\{|b_n|\}$ is a rearrangement of $\{|a_n|\}$; since $\sum_{n=1}^{\infty} |a_n|$ converges absolutely, $\sum_{n=1}^{\infty} |b_n|$ converges by the first part of the theorem. ■

Theorem 4.3.5. If $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$ converge absolutely, and $\{c_n\}$ is any sequence containing the products $a_i b_j$ for each pair $(i, j) \in \mathbb{N} \times \mathbb{N}$, then

$$\sum_{n=1}^{\infty} c_n = \sum_{n=1}^{\infty} a_n \cdot \sum_{n=1}^{\infty} b_n$$

Proof. Notice first that the sequence

$$p_L = \sum_{i=1}^L |a_i| \cdot \sum_{j=1}^L |b_j|$$

converges since $\{a_n\}$ and $\{b_n\}$ are absolutely convergent, and since the limit of a product is the product of the limits. So $\{p_L\}$ is a Cauchy sequence, which means that for any $\varepsilon > 0$, if there exists N such that for all $L, L' \geq N$,

$$\left| \sum_{i=1}^{L'} |a_i| \cdot \sum_{j=1}^{L'} |b_j| - \sum_{i=1}^L |a_i| \cdot \sum_{j=1}^L |b_j| \right| < \varepsilon/2$$

It follows that

$$\sum_{i \text{ or } j > L} |a_i| \cdot |b_j| \leq \varepsilon/2 < \varepsilon \quad (1)$$

Now suppose that N is such that the terms c_n for $n \leq N$ include all $a_i b_j$ for $i, j \leq L$. Then the difference

$$\sum_{n=1}^N c_n - \sum_{i=1}^L a_i \cdot \sum_{j=1}^L b_j$$

consists of terms $a_i b_j$ with $i > L$ or $j > L$, so

$$\left| \sum_{n=1}^N c_n - \sum_{i=1}^L a_i \cdot \sum_{j=1}^L b_j \right| \leq \sum_{i \text{ or } j > L} |a_i| \cdot |b_j| < \varepsilon \quad (2)$$

But since the limit of a product is the product of the limits we also have

$$\left| \sum_{i=1}^{\infty} a_i \cdot \sum_{j=1}^{\infty} b_j - \sum_{i=1}^L a_i \cdot \sum_{j=1}^L b_j \right| < \varepsilon \quad (3)$$

for sufficiently large L . Consequently, if we choose L and then N large enough, we will have

$$\begin{aligned} \left| \sum_{i=1}^{\infty} a_i \cdot \sum_{j=1}^{\infty} b_j - \sum_{i=1}^N c_i \right| &\leq \left| \sum_{i=1}^{\infty} a_i \cdot \sum_{j=1}^{\infty} b_j - \sum_{i=1}^L a_i \cdot \sum_{j=1}^L b_j \right| \\ &\quad + \left| \sum_{n=1}^N c_n - \sum_{i=1}^L a_i \cdot \sum_{j=1}^L b_j \right| \\ &< 2\varepsilon \end{aligned}$$

which proves the theorem. ■

4.4.0 Uniform Convergence and Power Series

Remark 4.4.1. We are now interested in the study of series of functions, or in other words functions of the form

$$f(x) = f_1(x) + f_2(x) + f_3(x) + \dots$$

In such a situation $\{f_n\}$ will be some sequence of functions; for each x we obtain a sequence of numbers $\{f_n(x)\}$, and $f(x)$ is the sum of this sequence. Recall that each sum $f_1(x) + f_2(x) + f_3(x) + \dots$ is, by definition, the limit of the sequence $f_1(x), f_1(x) + f_2(x), f_1(x) + f_2(x) + f_3(x), \dots$. If we define a new sequence of functions $\{s_n\}$ by

$$s_n = f_1 + \dots + f_n$$

then we can express this fact more succinctly by writing

$$f(x) = \lim_{n \rightarrow \infty} s_n(x)$$

for some $x \in \mathbb{R}$.

Remark 4.4.2. First let us consider functions of the form

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

All this form may seem simple, it is very important to note that *nothing one would hope to be true actually is*. Instead we have a flurry of lovely counter-examples.

Example 4.4.1 (Counter-Example 1). Even if each f_n is continuous, the function f may not be! Indeed, consider the sequence of functions

$$f_n(x) = \begin{cases} x^n, & 0 \leq x \leq 1 \\ 1, & x \geq 1 \end{cases}$$

These functions are all continuous, but the function $f(x) = \lim_{n \rightarrow \infty} f_n(x)$ is not continuous; in fact,

$$\lim_{n \rightarrow \infty} f_n(x) = \begin{cases} 0, & 0 \leq x < 1 \\ 1, & x \geq 1 \end{cases}$$

Another example of this phenomenon is illustrated by the family of functions

$$f_n(x) = \begin{cases} -1, & x \leq -\frac{1}{n} \\ nx, & -\frac{1}{n} \leq x \leq \frac{1}{n} \\ 1, & \frac{1}{n} \leq x \end{cases}$$

In this case, if $x < 0$ $f_n(x)$ is eventually -1 , and if $x > 0$, then $f_n(x)$ is eventually 1 , while $f_n(0) = 0$ for all n . Thus,

$$\lim_{n \rightarrow \infty} f_n(x) = \begin{cases} -1, & x < 0 \\ 0, & x = 0 \\ 1, & x > 0 \end{cases}$$

so once again $f(x) = \lim_{n \rightarrow \infty} f_n(x)$ is not continuous.

Example 4.4.2 (Counter-Example 2). It is even possible to produce a sequence of differentiable functions $\{f_n\}$ for which the function $f(x) = \lim_{n \rightarrow \infty} f_n(x)$ is not continuous. One such sequence is

$$f_n(x) = \begin{cases} -1, & x \leq -\frac{1}{n} \\ \sin\left(\frac{n\pi x}{2}\right), & -\frac{1}{n} \leq x \leq \frac{1}{n} \\ 1, & \frac{1}{n} \leq x \end{cases}$$

These functions are differentiable, but we still have

$$\lim_{n \rightarrow \infty} f_n(x) = \begin{cases} -1, & x < 0 \\ 0, & x = 0 \\ 1, & x > 0 \end{cases}$$

Definition 4.4.1. If f is a function defined on some set A , and a sequence of functions $\{f_n\}$, all defined on the same set A , are such that only

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

for all $x \in A$. Precisely, $\{f_n\}$ is said to **converge pointwise to f on A** if for all $\varepsilon > 0$, and for all $x \in A$, there is some N such that if $n \geq N$, then $|f(x) - f_n(x)| < \varepsilon$.

Definition 4.4.2 (Pointwise Convergence (alt.)). Suppose $S \subseteq \mathbb{R}$ and $f_n : S \rightarrow \mathbb{R}$ is a real-valued function for each $n \in \mathbb{N}$. We say that the sequence of functions $\{f_n\}$ **converges pointwise on S to $f : S \rightarrow \mathbb{R}$** if for every $x \in S$ and every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that if $n \geq N$, $|f_n(x) - f(x)| < \varepsilon$.

Example 4.4.3. Take $f_n(x) = x^n$ on $S = [0, 1]$. If $0 \leq x < 1$ notice that $\lim_{n \rightarrow \infty} x^n = 0$ (geometric sequence). If $x = 1$, then $f_n(1) = 1^n = 1$, which converges to 1 as n goes to infinity. Thus, f_n converges pointwise to

$$f(x) = \begin{cases} 0 & 0 \leq x < 1 \\ 1 & x = 1 \end{cases}$$

Notice each f_n is continuous on $[0, 1]$, but f is not.

This example answers the following question in the negative:

Question 4.4.3. Suppose f_n converges pointwise to f on $S \subseteq \mathbb{R}$. If $a \in S'$ (an accumulation/limit point for S), $\lim_{x \rightarrow a} f(x)$ exists and $\lim_{x \rightarrow a} f_n(x)$ exists for all n , is it true that

$$\lim_{x \rightarrow a} \lim_{n \rightarrow \infty} f_n(x) = \lim_{n \rightarrow \infty} \lim_{x \rightarrow a} f_n(x)?$$

In particular, in our example we take $a = 1$, then $\lim_{x \rightarrow a} f_n(x) = \lim_{x \rightarrow 1} x^n = 1$, so $\lim_{n \rightarrow \infty} 1 = 1$, but $\lim_{x \rightarrow 1} f(x) = 0$.

Example 4.4.4. Consider the sequence $g_n(x) = \frac{1}{1+x^n}$ on $S = (-\infty, -1) \cup (-1, \infty)$. As n goes to infinity we have that the sequence converges pointwise to 1 for $|x| < 1$, $1/2$ for $x = 1$, and 0 for $|x| > 1$.

Example 4.4.5. Let $S = [0, \infty)$ and define

$$f_n(x) = \begin{cases} n^2 x & 0 \leq x \leq \frac{1}{n} \\ -n^2 \left(x - \frac{2}{n}\right) & \frac{1}{n} < x \leq \frac{2}{n} \\ 0 & x > \frac{2}{n} \end{cases}$$

We claim that $\lim_{n \rightarrow \infty} f_n(x) = 0$ for all $x \geq 0$. When $x = 0$, $f_n(0) = 0$ which converges to 0. If $0 < x$: By the Archimedean property there exists $N \in \mathbb{N}$ such that $\frac{2}{N} < x$. Then $f_N(x) = 0$ and $f_n(x) = 0$ for all $n \geq N$. Thus, $\lim_{n \rightarrow \infty} f_n(x) = 0$, as claimed. This argument can be intuitively realized by noting that for n large enough, the tent is always to the left of any $0 < x$.

We note that this gives an example of an unbounded sequence $\{f_n\}$ converging pointwise to a bounded function.

Example 4.4.6. Take $S = \mathbb{R}$ and define $f_n(x) = \frac{\sin(nx)}{\sqrt{n}}$, waves of declining amplitude but increasing frequency. Note that $0 \leq |f_n(x)| = \left| \frac{\sin(nx)}{\sqrt{n}} \right| \leq \frac{1}{\sqrt{n}}$ which goes to 0 as n goes to infinity, so the sequence converges pointwise to 0. Notice $f'_n(x) = \frac{n}{\sqrt{n}} \cos(nx) = \sqrt{n} \cos(nx)$, which has no limit for any $x \in \mathbb{R}$.

This is an example of pointwise convergence where the derivatives do not converge pointwise. Moreover, as we will see, the original sequence actually converges uniformly (the bound on the terms does not depend on x), which suggests we need a stronger requirement for convergence of derivatives.

Definition 4.4.3. Let $\{f_n\}$ be a sequence of functions defined on A , and let f be a function which is also defined on A . Then f is called the uniform limit of $\{f_n\}$ on A if for every $\varepsilon > 0$ there is some N such that for all $x \in A$,

$$\text{if } n > N, \text{ then } |f(x) - f_n(x)| < \varepsilon$$

We also say that $\{f_n\}$ converges uniformly to f on A , or that f_n approaches f uniformly on A .

Definition 4.4.4 (Uniform Convergence (alt.)). Suppose $S \subseteq \mathbb{R}$ and $f_n : S \rightarrow \mathbb{R}$ are real-valued functions for each $n \in \mathbb{N}$. We say that f_n converges uniformly on S to $f : S \rightarrow \mathbb{R}$ if for all $\varepsilon > 0$, there is an $N \in \mathbb{N}$ (depends only on ε) such that $n \geq N$ implies

$$|f_n(x) - f(x)| < \varepsilon$$

for all $x \in S$.

We will use the notation $f_n \rightarrow_u f$ sometimes to denote uniform convergence. Intuitively uniform convergence can be understood by saying that given any band or tube containing f on S , there is a point past which the tail functions of the sequence reside entirely in this band.

Remark 4.4.4. Note that uniform convergence implies pointwise convergence, but the converse is not true.

Definition 4.4.5 (Uniform Norm). Suppose $S \subseteq \mathbb{R}$ and f is a function on S . The uniform norm of f on S is given by

$$\|f\|_S := \sup_{x \in S} |f(x)|$$

We note that this may not be finite. When the context is clear we will write $\|f\|_\infty$.

Remark 4.4.5. Suppose $f : S \rightarrow \mathbb{R}$ is a function:

- (i) f is bounded on S if and only if $\|f\|_S < \infty$
- (ii) If f is continuous on S and S is compact, then $\|f\|_S = \max_{s \in S} |f(s)|$ (e.g. $\|x^n\|_{[0,1]} = 1$)

Proposition 4.4.1. A sequence of functions f_n converges uniformly to f on S if and only if $\|f_n - f\|_S \rightarrow 0$.

Proof. Let f_n be a sequence of functions, each defined on S , and let f be another function on S .

First, let us suppose that the f_n converge uniformly to f on S . Fix $\varepsilon > 0$. Then there exists $N \in \mathbb{N}$ such that for $n \geq N$, $|f_n(x) - f(x)| < \varepsilon/2$ for all $x \in S$. This implies that $\varepsilon/2$ is an upper bound of all $|f_n(x) - f(x)|$, so by definition $\|f_n - f\|_S \leq \varepsilon/2 < \varepsilon$ for all $n \geq N$. Hence, as $\|f_n - f\|_S = |||f_n - f||_S - 0|$, we have that the sequence $\|f_n - f\|_S$ converges to 0 in \mathbb{R} .

Conversely, suppose that $\|f_n - f\|_S$ converges to 0, and let $\varepsilon > 0$. Then, there exists $N \in \mathbb{N}$ such that for all $n \geq N$, $\|f_n - f\|_S < \varepsilon$. It follows that for all $x \in S$, $|f_n(x) - f(x)| \leq \|f_n - f\|_S < \varepsilon$ for $n \geq N$, so we find that f_n converges uniformly to f on S by definition. ■

Example 4.4.7. Let $S = [0, 1]$ and $f_n(x) = x^n$. f_n does not converge uniformly to any function. Indeed if f_n converges uniformly to anything on $[0, 1]$, it must be the pointwise limit $f(x) = 0, 0 \leq x < 1$ and $f(x) = 1, x = 1$, since uniform implies pointwise convergence (and limits are unique in Hausdorff spaces). This implies $\sup_{x \in [0, 1]} |f_n(x) - f(x)|$ goes to zero as n goes to infinity.

But if $x = 1 - \frac{1}{n}$, then $|f_n(1 - 1/n) - f(1 - 1/n)| = (1 - 1/n)^n$, which converges to $e^{-1} = \frac{1}{e}$, and not zero. Further, this must be less than what the limit of the supremums converges to, so the supremums cannot converge to 0, as that would result in a contradiction. Hence, the sequence does not converge uniformly.

The tent function is another example of pointwise but not uniform convergence, since $\|f_n - 0\|_\infty = n$, which does not converge to 0.

Theorem 4.4.2 (Cauchy Criterion for Uniform Convergence). Suppose $f_n : S \rightarrow \mathbb{R}$. Then f_n converges uniformly on S if and only if for all $\varepsilon > 0$ there is an $N \in \mathbb{N}$ such that $m, n \geq N$ implies

$$\|f_n - f_m\|_\infty < \varepsilon$$

Proof. Let $f_n : S \rightarrow \mathbb{R}$ be a sequence of functions.

First, suppose f_n converges uniformly on S to some $f : S \rightarrow \mathbb{R}$. Fix $\varepsilon > 0$. Then there exists $N \in \mathbb{N}$ such that for $n \geq N$, $|f_n(x) - f(x)| < \varepsilon/3$, for all $x \in S$. It follows by the triangle inequality that for $k, m \geq N$, $|f_k(x) - f_m(x)| < 2\varepsilon/3$ for all $x \in S$. Thus, $\|f_k - f_m\|_\infty \leq 2\varepsilon/3 < \varepsilon$, so f_n is uniformly Cauchy (i.e. it is Cauchy with respect to the uniform norm $\|\cdot\|_\infty$).

Conversely, suppose f_n is uniformly Cauchy on S . Let $\varepsilon > 0$. Then there exists $N \in \mathbb{N}$ such that for $k, m \geq N$, $\|f_k - f_m\|_\infty < \varepsilon/2$. Then for all $x \in S$, $|f_k(x) - f_m(x)| < \varepsilon/2$ for $k, m \geq N$. As $(\mathbb{R}, |\cdot|)$ is a complete metric space, for each $x \in S$ there exists $f(x) \in \mathbb{R}$ such that $f_k(x)$ converges to $f(x)$. Then, taking the limit as m goes to infinity in $|f_k(x) - f_m(x)| < \varepsilon/2$, and using the order properties of limits in \mathbb{R} , we have that $|f_k(x) - f(x)| \leq \varepsilon/2$ for all $x \in S$ and $k \geq N$. Thus, for $k \geq N$ we have that $\|f_k - f\|_\infty < \varepsilon$, so f_k converges to f uniformly on S , as desired. ■

Example 4.4.8. Let $S = [0, 1]$ and $f_n(x) = nx(1 - x^2)^n$. We claim that f_n converges pointwise to 0, but not uniformly. If $x = 0, 1$, then $f_n(x) = 0 \rightarrow 0$. If $0 < x < 1$, then $0 < 1 - x^2 < 1$. Then $1/(1 - x^2) > 1$, so there exists $y > 0$ such that $1/(1 - x^2) = 1 + y$. Then, for $n \geq 2$ we have by the binomial theorem that $(1 + y)^n \leq 1 + ny + n(n + 1)/2y^2 \leq 1 + ny + n^2y^2/2$. It follows that

$$\begin{aligned} 0 \leq \lim_{n \rightarrow \infty} nx(1 - x^2)^n &\leq \lim_{n \rightarrow \infty} \frac{nx}{1 + ny + n^2y^2/2} && \text{(for some } y > 0) \\ &= x \lim_{n \rightarrow \infty} \frac{1}{1/n + y + ny^2/2} \\ &= x \cdot 0 = 0 \end{aligned}$$

as claimed. But, the convergence is not uniform since if $\|f_n\|_\infty \rightarrow 0$, then $|f_n(x_n)| \rightarrow 0$ for any sequence x_n in $[0, 1]$. Let $x_n = \frac{1}{\sqrt{n}}$. Then $f_n(x_n) = n \frac{1}{\sqrt{n}} (1 - 1/n)^n = \sqrt{n} (1 - 1/n)^n$, which converges to ∞ as $\sqrt{n} \rightarrow \infty$ and $(1 - 1/n)^n \rightarrow e^{-1}$.

Example 4.4.9. Let $S = [0, b]$ for some $b > 0$. Then $f_n(x) = n \sin(x/n)$ converges uniformly on S but not on $[0, \infty)$. Note if we fix x and take n large enough, then $\sin(x/n) \approx x/n$. Then

$$\lim_{n \rightarrow \infty} f_n(x) = \lim_{n \rightarrow \infty} \frac{\sin(x/n)}{x/n} x = x$$

so $f_n(x) \rightarrow x$ for all x . We first show $f_n \not\rightarrow_u x$ on $[0, \infty)$. Suppose it did. Then $|f_n(x_n) - x_n| \rightarrow 0$ for any sequence x_n in $[0, \infty)$. Try $x_n = n^2$. Then $|f_n(n^2) - n^2| = |n \sin(n) - n^2| = n |\sin(n) - n| \rightarrow \infty$, which is a contradiction, so the claim holds. To show uniform convergence on $[0, b]$, note that $\sin(x/n) \leq x/n$ for all $x \geq 0$, so $n \sin(x/n) \leq x$. Let $g(x) = x - n \sin(x/n) \geq 0$. Then $g'(x) = 1 - \cos(x/n) \geq 0$. Thus, g is a monotone increasing function on $[0, b]$. Thus, $\|g\|_\infty = g(b) = b - n \sin(b/n)$. Then $\|f_n - x\|_{[0, b]} = \|g\|_{[0, b]} = b - n \sin(b/n)$, which converges to $b - b = 0$ as $n \rightarrow \infty$.

Note that $[0, \infty) = \bigcup_{b>0} [0, b]$, so this gives an example of uniform convergence on many sets, but not on the union of those sets.

Theorem 4.4.3. Suppose $S \subseteq \mathbb{R}$, and $f_n : S \rightarrow \mathbb{R}$ are continuous functions. If f_n converges uniformly to f on S , then f is also continuous on S .

Proof. First, fix $\varepsilon > 0$. Then there exists $N \in \mathbb{N}$ such that for $k \geq N$, $\|f_k - f\|_S < \varepsilon/3$. Let $x \in S$. As f_N is continuous at x , there exists $\delta > 0$ such that for $y \in B_\delta^*(x)$, $|f_N(y) - f_N(x)| < \varepsilon/3$. Then, for $|x - y| < \delta$ we have that

$$|f(x) - f(y)| \leq |f(x) - f_N(x)| + |f_N(x) - f_N(y)| + |f_N(y) - f(y)| < 3\varepsilon/3 = \varepsilon$$

so f is indeed continuous at x , and hence on S . ■

Proposition 4.4.4. If f_n converges uniformly to f on S and each f_n is uniformly continuous on S , then f is uniformly continuous on S .

Proof. First, fix $\varepsilon > 0$. As $f_n \rightarrow_u f$, there exists $N \in \mathbb{N}$ such that for $k \geq N$, $\|f_k - f\|_S < \varepsilon/3$. Then, as f_N is uniformly continuous there exists $\delta > 0$ such that if $|x - y| < \delta$, $|f_N(x) - f_N(y)| < \varepsilon/3$ for all $x, y \in S$. Thus, if $|x - y| < \delta$ and $x, y \in S$, it follows that

$$\begin{aligned} |f(x) - f(y)| &\leq |f(x) - f_N(x)| + |f_N(x) - f_N(y)| + |f_N(y) - f(y)| \\ &< 3\varepsilon/3 = \varepsilon \end{aligned}$$

so f is uniformly continuous on S , as desired. ■

Example 4.4.10. Let $S = [0, 1]$ and $f_n(x) = \frac{1}{1+x^n}$. We have seen that $f_n(x) \rightarrow 1$ for $x \in [0, 1)$, and $f_n(1) \rightarrow 1/2$, pointwise. Evidently, the convergence is not uniform since each f_n is continuous on $[0, 1]$, but the limit function is not.

Lemma 4.4.5. Suppose f_n converges uniformly to f on S . If each f_n are bounded on S , then f is bounded on S as well. Moreover, the sequence is uniformly bounded:

$$\sup_{n \in \mathbb{N}} \|f_n\|_S < \infty$$

Proof. First, there exists $N \in \mathbb{N}$ such that if $k \geq N$, $\|f_k - f\|_S < 1$, by uniform convergence. Then, for all $x \in S$, $|f(x)| \leq |f(x) - f_N(x)| + |f_N(x)| < \|f_N\|_S + 1$. But f_N is assumed bounded on S , so $\|f_N\|_S < \infty$, and hence $\|f\|_S \leq \|f_N\|_S + 1 < \infty$, so f is also bounded on S . Now, for all $k \geq N$ we have that $\|f_k\|_S \leq \|f\|_S + 1$. Let $M = \max\{\|f_1\|_S, \dots, \|f_{N-1}\|_S, \|f_N\|_S + 1\}$. Then it follows that $\|f_n\|_S \leq M$ for all $n \in \mathbb{N}$, and $M < \infty$ is finite, so $\sup_{n \in \mathbb{N}} \|f_n\|_S \leq M < \infty$, as desired. ■

Theorem 4.4.6. Suppose that f_n are bounded and integrable functions on $[a, b]$, $f_n \in \mathcal{R}([a, b])$, converging uniformly to f on $[a, b]$. Then f is integrable on $[a, b]$ and

$$\lim_{n \rightarrow \infty} \int_a^b f_n(x) dx = \int_a^b f(x) dx$$

Proof. By the previous lemma we have that f is bounded on $[a, b]$. First, if f is integrable on $[a, b]$, then

$$\begin{aligned} \left| \int_a^b f_n(x) dx - \int_a^b f(x) dx \right| &\leq \int_a^b |f_n(x) - f(x)| dx \\ &\leq \int_a^b \|f_n - f\|_\infty dx \\ &= (b - a) \|f_n - f\|_\infty \end{aligned}$$

which goes to 0 as $n \rightarrow \infty$ by uniform convergence. Thus, all we need to show is f is integrable. Fix $\varepsilon > 0$. Then there exists $N \in \mathbb{N}$ such that $\|f_n - f\| < \frac{\varepsilon}{3(b-a)}$. Since each f_n is integrable, there exists a partition $P_n \in \mathcal{P}([a, b])$ with

$$U(f_n, P_n) - L(f_n, P_n) < \frac{\varepsilon}{3}$$

Write $P_n = \{a = x_{0,n}, x_{1,n}, \dots, x_{M_n,n} = b\}$. Let $J_{k,n} = [x_{k,n}, x_{k+1,n}]$ for $0 \leq k \leq M_n$. Then $\|f - f_n\|_{J_k} < \frac{\varepsilon}{3(b-a)}$ for $n \geq N$. Then

$$\|f\|_{J_k} \leq \frac{\varepsilon}{3(b-a)} + \|f_n\|_{J_k}$$

and

$$\|f_n\|_{J_k} \leq \frac{\varepsilon}{3(b-a)}$$

, so

$$|\sup_{J_k}(f) - \sup_{J_k}(f_n)| \leq \frac{\varepsilon}{3(b-a)}$$

for all $n \geq N$. It follows that

$$|U(f, P_n) - U(f_n, P_n)| = \left| \sum_{k=0}^{M_n-1} (\sup_{J_k}(f) - \sup_{J_k}(f_n)) \ell(J_k) \right|$$

$$\begin{aligned}
 &\leq \sum_{k=0}^{M_n-1} |\sup_{J_k}(f) - \sup_{J_k}(f_n)| \ell(J_k) \\
 &< \sum_{k=0}^{M_n-1} \frac{\varepsilon}{3(b-a)} \ell(J_k) \\
 &= \frac{\varepsilon}{3(b-a)} \ell([a, b]) = \frac{\varepsilon}{3}
 \end{aligned}$$

Similarly, $|L(f, P_n) - L(f_n, P_n)| < \varepsilon/3$. Finally,

$$\begin{aligned}
 U(f, P_n) - L(f, P_n) &= U(f, P_n) - U(f_n, P_n) + U(f_n, P_n) - L(f_n, P_n) + L(f_n, P_n) - L(f, P_n) \\
 &\leq |U(f, P_n) - U(f_n, P_n)| + |U(f_n, P_n) - L(f_n, P_n)| + |L(f_n, P_n) - L(f, P_n)| \\
 &< 3 \cdot \frac{\varepsilon}{3} = \varepsilon
 \end{aligned}$$

Thus, f is Riemann integrable on $[a, b]$. ■

Remark 4.4.6. Although these last two theorems are great successes, differentiability sadly fails. Even if each f_n is differentiable and $\{f_n\}$ converges uniformly to f , it need not be the case that f is differentiable. Moreover, even if f is itself differentiable, it need not be the case that

$$f'(x) = \lim_{n \rightarrow \infty} f'_n(x)$$

Example 4.4.11 (Counter Example 3). Consider the family of functions

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

then $\{f_n\}$ converges uniformly to the function $f(x) = 0$, but

$$f'_n(x) = n \cos(n^2 x)$$

and $\lim_{n \rightarrow \infty} n \cos(n^2 x)$ does not even always exist (for example if $x = 0$).

Theorem 4.4.7. Suppose that $\{f_n\}$ is a sequence of functions which are differentiable on $[a, b]$, with integrable derivatives f'_n , and that $\{f_n\}$ converges (pointwise) to f . Suppose, moreover, that $\{f'_n\}$ converges uniformly on $[a, b]$ to some continuous function g . Then f is differentiable and

$$f'(x) = \lim_{n \rightarrow \infty} f'_n(x)$$

Proof. Applying Theorem 1 to the interval $[a, x]$, we see that for each x we have

$$\begin{aligned}
 \int_a^x g &= \lim_{n \rightarrow \infty} \int_a^x f'_n \\
 &= \lim_{n \rightarrow \infty} [f_n(x) - f_n(a)] && \text{(by ??)} \\
 &= f(x) - f(a)
 \end{aligned}$$

Since g is continuous, it follows that $f'(x) = g(x) = \lim_{n \rightarrow \infty} f'_n(x)$ for all x in the interval $[a, b]$, by ??. ■

Example 4.4.12. Consider $\int_0^\pi \frac{n+\sin x}{3n+\sin^2(nx)} dx$. Observe that

$$\begin{aligned} \left| \frac{n+\sin x}{3n+\sin^2(nx)} - \frac{1}{3} \right| &= \left| \frac{3n+3\sin x-3n-\sin^2(nx)}{3(3n+\sin^2(nx))} \right| \\ &\leq \frac{|3\sin x - \sin^2(nx)|}{9n} \leq \frac{3+1}{9n} = \frac{4}{9n} \end{aligned}$$

for all $x \in [0, \pi]$. Thus, $\|f_n - \frac{1}{3}\|_{[0,\pi]} \leq \frac{4}{9n} \rightarrow 0$, so it converges uniformly. It follows that

$$\begin{aligned} \lim_{n \rightarrow \infty} \int_0^\pi \frac{n+\sin x}{3n+\sin^2(nx)} dx &= \int_0^\pi \lim_{n \rightarrow \infty} \frac{n+\sin x}{3n+\sin^2(nx)} dx \\ &= \int_0^\pi \frac{1}{3} dx \\ &= \frac{\pi}{3} \end{aligned}$$

Definition 4.4.6. The series $\sum_{n=1}^\infty f_n$ **converges uniformly** (more formally, the sequence $\{f_n\}$ is **uniformly summable**) **to f on A** , if the sequence

$$f_1, f_1 + f_2, f_1 + f_2 + f_3, \dots$$

converges uniformly to f on A .

Definition 4.4.7 (Series of Functions (alt.)). Suppose S is a subset of \mathbb{R} and $f_n : S \rightarrow \mathbb{R}$. We say that the series $\sum_{n=1}^\infty f_n(x)$ **converges pointwise** if the sequence of partial sums $s_k(x) = \sum_{n=1}^k f_n(x)$ converges pointwise to a function $f : S \rightarrow \mathbb{R}$. In this case, write $f(x) = \sum_{n=1}^\infty f_n(x)$. We say that the series $\sum_{n=1}^\infty f_n(x)$ **converges uniformly** if s_k converges uniformly to f on S .

Corollary 4.4.8. Let $\sum_{n=1}^\infty f_n$ converge uniformly to f on $[a, b]$.

1. If each f_n is continuous on $[a, b]$, then f is continuous on $[a, b]$.
2. If f and each f_n is integrable on $[a, b]$, then

$$\int_a^b f = \int_a^b \sum_{n=1}^\infty f_n = \sum_{n=1}^\infty \int_a^b f_n$$

Moreover, if $\sum_{n=1}^\infty f_n$ converges (pointwise) to f on $[a, b]$, each f_n has an integrable derivative f'_n and $\sum_{n=1}^\infty f'_n$ converges uniformly on $[a, b]$ to some continuous function, then

3. $f'(x) = \sum_{n=1}^\infty f'_n(x)$ for all $x \in [a, b]$

Proof. Let $\{s_n\}$ be the sequence of partial sums of the $\{f_n\}$. Then since each f_n is continuous, so is each s_n . Then as $\{s_n\}$ converges uniformly to f we have by a previous theorem that f is also continuous on $[a, b]$. Next, since each f_n is integrable on $[a, b]$, so is each s_n . Then as $\{s_n\}$ converges uniformly to f we have that

$$\begin{aligned}\int_a^b f &= \lim_{n \rightarrow \infty} \int_a^b s_n \\ &= \lim_{n \rightarrow \infty} t_n \\ &= \sum_{n=1}^{\infty} \int_a^b f_n\end{aligned}$$

where $\{t_n\}$ is the sequence such that

$$t_n = \sum_{i=1}^n \int_a^b f_i = \int_a^b s_n$$

Finally, suppose s_n converges (pointwise) to f on $[a, b]$, and each f_n has an integrable derivative f'_n . Then each s_n has an integrable derivative s'_n on $[a, b]$ by the linearity of the derivative and integral operators. Moreover, suppose s'_n converges uniformly on $[a, b]$ to some continuous function g . Then it follows that for all $x \in [a, b]$

$$f'(x) = \lim_{n \rightarrow \infty} s'_n(x) = \sum_{n=1}^{\infty} f'_n(x)$$

■

Example 4.4.13. Let $S = [-r, r]$ with $0 < r < 1$. Let $f(t) = \sum_{n=0}^{\infty} (-r)^n$. Then as $t \in [-r, r] \subset (-1, 1)$ we have $f(t) = \frac{1}{1-t}$. Convergence is uniform on $[-r, r]$ since $|t| \leq r$, so $|(-t)^n| \leq r^n$, and $\sum_{n=0}^{\infty} r^n$ converges. By the last corollary, we have that for $x \in [-r, r]$,

$$\begin{aligned}\log(1+x) &= \int_0^x \frac{1}{1+t} dt && \text{(by the FTC)} \\ &= \int_0^x \sum_{n=0}^{\infty} (-t)^n dt \\ &= \sum_{n=0}^{\infty} \int_0^x (-1)^n t^n dt \\ &= \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+1}}{n+1} && \text{(by the FTC)}\end{aligned}$$

Thus, $\log(1+x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+1}}{n+1}$ for all $x \in (-1, 1)$

Theorem 26 (The Weierstrass M-Test).

Let $\{f_n\}$ be a sequence of functions defined on A , and suppose that $\{M_n\}$ is a sequence of numbers such that

$$|f_n(x)| \leq M_n, \forall x \in A$$

Suppose moreover that $\sum_{n=1}^{\infty} M_n$ converges. Then for each x in A the series $\sum_{n=1}^{\infty} f_n(x)$ converges absolutely, and $\sum_{n=1}^{\infty} f_n$ converges uniformly on A to the function

$$f(x) = \sum_{n=1}^{\infty} f_n(x)$$

Proof. For each $x \in A$, the series $\sum_{n=1}^{\infty} |f_n(x)|$ converges by 21; consequently $\sum_{n=1}^{\infty} f_n(x)$ converges absolutely. Moreover, for all $x \in A$ we have

$$\begin{aligned} \left| f(x) - \sum_{i=1}^N f_i(x) \right| &= \left| \sum_{n=N+1}^{\infty} f_n(x) \right| \\ &\leq \sum_{n=N+1}^{\infty} |f_n(x)| \\ &\leq \sum_{n=N+1}^{\infty} M_n \end{aligned}$$

Since $\sum_{n=1}^{\infty} M_n$ converges, the number $\sum_{n=N+1}^{\infty} M_n$ can be made as small as desired (by 18), by choosing N sufficiently large. ■

Example 4.4.14. The series $\sum_{n=0}^{\infty} \frac{x^n}{n!}$ converges uniformly on $[-R, R]$ for any $R > 0$, but not on \mathbb{R} . If $-R \leq x \leq R$, then $\left| \frac{x^n}{n!} \right| \leq \frac{R^n}{n!} =: M_n$. Note that $\sum_{n=0}^{\infty} M_n$ converges by the ratio test. This implies by the Weierstrass M-test that $\sum_{n=0}^{\infty} \frac{x^n}{n!}$ converges uniformly on $[-R, R]$. Note if $\sum_n f_n$ converges uniformly on S to some function s , then $f_n \rightarrow_u 0$. In particular, $\|f_n\|_{\infty} \rightarrow 0$. But, $\|x^n/n!\|_{\mathbb{R}} = \infty$, so the series cannot be uniformly convergent on all of \mathbb{R} .

The converse to the uniform limit of the terms needing to go to zero for the series to converge is false. For example, if $f_n(x) = 1/n$, $x \in \mathbb{R}$, then $\|f_n\|_{\mathbb{R}} = 1/n \rightarrow 0$, but $\sum_{n=1}^{\infty} \frac{1}{n}$ diverges (the harmonic series).

Example 4.4.15. Recall we saw that $\sum_{n=0}^{\infty} \frac{x^n}{n!}$ converges uniformly on $[-R, R]$ for any $R > 0$ by Weierstrass M-test. Since $\sum_{n=0}^N \frac{x^n}{n!}$ are continuous, $\sum_{n=0}^{\infty} \frac{x^n}{n!}$ is continuous on $[-R, R]$ for all R so it is continuous on \mathbb{R} .

Theorem 4.4.9 (Riemann 1861; Weierstrass 1872; du Bois-Reymond 1875). *There is a continuous function on \mathbb{R} that is nowhere differentiable.*

Proof. Let $g(x) = |x|$ on $[-1, 1]$, and continuously and periodically extend to \mathbb{R} so $g(x+2) = g(x)$ for all x . Let $r, s \in \mathbb{R}$. If $|r-s| > 1$, then $|r-s| > 1 \geq |g(r) - g(s)|$, as $-1 = 0 - 1 \geq g(r) - g(s) \leq 1 - 0 = 1$. Otherwise, suppose $|r-s| \leq 1$. Without loss of generality suppose $r \geq s$. If there does not exist $s \leq n \leq r$ for some $n \in \mathbb{Z}$, then there exists $n \in \mathbb{Z}$ such that $n \leq s \leq r \leq n+1$. It follows that either $g(r) - g(s) = r - n - (s - n) = r - s$,

or $g(r) - g(s) = -(r - n - 1) + (s - n - 1) = s - r$. In either case $|g(r) - g(s)| = |r - s|$. Otherwise, there exists $n \in \mathbb{Z}$ such that $n - 1 \leq s \leq n \leq r \leq n + 1$. Then

$$g(r) - g(s) = (r - n) - |s - n| = r - n - n + s = r + s - 2n \leq r + s - 2s = r - s = |r - s|$$

or

$$g(r) - g(s) = |r - (n + 1)| - (s - (n - 1)) = n + 1 - r - s + n - 1 = 2n - r - s \leq 2r - r - s = r - s = |r - s|$$

Thus, in any case we have $|g(r) - g(s)| \leq |r - s|$ for all $r, s \in \mathbb{R}$. This says that g is Lipschitz continuous, and in particular is uniformly continuous on \mathbb{R} . Now, for all $n \in \mathbb{N}$, let $g_n(x) = \frac{3^n}{4^n} g(4^n x)$. Notice that $|g_n(x)| \leq \left(\frac{3}{4}\right)^n$, so the sum $\sum_n g_n$ converges uniformly on \mathbb{R} by the Weierstrass M-test. Let $f(x) = \sum_{n=0}^{\infty} g_n(x)$, where $g_0(x) = g(x)$. Then f is continuous on \mathbb{R} as the g_n are continuous and they converge uniformly (in particular, f is uniformly continuous on \mathbb{R}). Fix $x \in \mathbb{R}$ and $m \in \mathbb{N}$. Define $\delta_m = \pm \frac{1}{2} \cdot \frac{1}{4^m}$, where $+$ or $-$ is selected so that there is no integer between $4^m x$ and $4^m(x + \delta_m)$, which has distance $\frac{1}{2}$. We have $|4^m x - 4^m(x + \delta_m)| = \frac{1}{2}$. We will show $\left| \frac{f(x + \delta_m) - f(x)}{\delta_m} \right| \rightarrow \infty$ as $m \rightarrow \infty$, so $\delta_m \rightarrow 0$. We compute

$$\begin{aligned} f(x + \delta_m) - f(x) &= \sum_{n=0}^{\infty} g_n(x + \delta_m) - g_n(x) \\ &= \sum_{n=0}^{\infty} \frac{3^n}{4^n} [g(4^n x + 4^n \delta_m) - g(4^n x)] \end{aligned}$$

We have three cases on each term:

- (i) $n > m$: Then $4^n \delta_m = \frac{\pm 4^{n-m}}{2}$ is an even integer. Since $g(t + 2) = g(t)$ for all t , $g(4^n x + 4^n \delta_m) = g(4^n x)$. So

$$f(x + \delta_m) - f(x) = \sum_{n=0}^m \frac{3^n}{4^n} [g(4^n x + 4^n \delta_m) - g(4^n x)]$$

- (ii) $n < m$: We have $|g(r) - g(s)| \leq |r - s|$ for all $r, s \in \mathbb{R}$. Thus

$$|g(4^n x + 4^n \delta_m) - g(4^n x)| \leq 4^n |\delta_m|$$

- (iii) $n = m$: There is no integer between $4^n x + 4^n \delta_n$ and $4^n x$ which means g maps these two points to the same line segment. Then $|g(4^n x + 4^n \delta_n) - g(4^n x)| = |4^n \delta_n| = \frac{1}{2}$

Now we compute

$$\begin{aligned} \left| \frac{f(x + \delta_m) - f(x)}{\delta_m} \right| &= \left| \sum_{n=0}^m 3^n 4^n \frac{g(4^n x + 4^n \delta_m) - g(4^n x)}{\delta_m} \right| \\ &\geq \left| \frac{3^m}{4^m} \frac{1/2}{\delta_m} \right| - \sum_{n=0}^{m-1} \left| \frac{3^n (g(4^n x + 4^n \delta_m) - g(4^n x))}{4^n \delta_m} \right| \\ &\geq 3^m - \sum_{n=0}^{m-1} \frac{4^n |\delta_m|}{|\delta_m|} \frac{3^n}{4^n} \end{aligned}$$

$$\begin{aligned}
 &= 3^m - \sum_{n=0}^{m-1} 3^n \\
 &= 3^m - \frac{1 - 3^m}{1 - 3} \\
 &= \frac{2 \cdot 3^m + 1 - 3^m}{2} \\
 &= \frac{1}{2}(3^m + 1) \rightarrow \infty
 \end{aligned}$$

as $m \rightarrow \infty$, as desired. Thus, as if f was differentiable this limit would be its derivative, so f is not differentiable at any $x \in \mathbb{R}$. ■

Example 4.4.16. Let $S = (0, 1)$ and $f(x) = \sum_{n=0}^{\infty} \frac{1}{n^2 x + 1}$. Determine where f is continuous and where the convergence of the series is uniform. Note that $f_n(1/n^2) = \frac{1}{1+1} = \frac{1}{2} \not\rightarrow 0$, so f_n does not converge uniformly to 0 on S , and hence the sum does not converge uniformly. Let $0 < a < 1$, and consider f on $[a, 1)$. Then $|f_n(x)| = \frac{1}{n^2 x + 1} \leq \frac{1}{n^2 a + 1}$ for $x \in [a, 1)$. But $\sum_{n=0}^{\infty} \frac{1}{n^2 a + 1} < \infty$, so by the Weierstrass M-test, $\sum_{n=0}^{\infty} f_n$ converges uniformly on $[a, 1)$. Since each f_n is continuous on $[a, 1)$, this implies f is continuous on $[a, 1)$. Finally, $0 < a < 1$ is arbitrary, so $f(x) = \sum_{n=0}^{\infty} f_n(x)$ is continuous on $S = (0, 1)$.

Power Series

Definition 4.4.8. An infinite sum of functions of the form

$$f(x) = \sum_{n=0}^{\infty} a_n(x - a)^n$$

is called a **power series centered at a** . One especially important family of power series are those of the form

$$\sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (x - a)^n$$

where f is some infinitely differentiable function at a ; this series is called the **Taylor series for f at a** .

A power series is a formal notion. It may not converge for many values of x . It always converges at $x = 0$ (a , its center).

Remark 4.4.7. Given a function f infinitely differentiable at a , we have for $x \in \mathbb{R}$ that

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (x - a)^n$$

if and only if the remainder terms satisfy $\lim_{n \rightarrow \infty} R_{n,a}(x) = 0$.

Theorem 4.4.10. Suppose that the series

$$f(x_0) = \sum_{n=0}^{\infty} a_n x_0^n$$

converges, and let a be any number with $0 < a < |x_0|$. Then on $[-a, a]$ the series

$$f(x) = \sum_{n=0}^{\infty} a_n x^n$$

converges uniformly (and absolutely). Moreover, the same is true for the series

$$g(x) = \sum_{n=1}^{\infty} n a_n x^{n-1}$$

Finally, f is differentiable and

$$f'(x) = \sum_{n=1}^{\infty} n a_n x^{n-1}$$

for all x with $|x| < |x_0|$.

Proof. First, since $\sum_{n=0}^{\infty} a_n x_0^n$ converges, $\lim_{n \rightarrow \infty} a_n x_0^n = 0$. Hence, the sequence $\{a_n x_0^n\}$ is surely bounded: there is some number M such that

$$|a_n x_0^n| = |a_n| \cdot |x_0|^n \leq M$$

for all n . Now if x is in $[-a, a]$, then $|x| \leq |a|$, so

$$\begin{aligned} |a_n x^n| &= |a_n| \cdot |x|^n \\ &\leq |a_n| \cdot |a|^n \\ &= |a_n| \cdot |x_0|^n \cdot \left| \frac{a}{x_0} \right|^n \\ &\leq M \left| \frac{a}{x_0} \right|^n \end{aligned}$$

But $|a/x_0| < 1$, so the (geometric) series

$$\sum_{n=0}^{\infty} M \left| \frac{a}{x_0} \right|^n = M \sum_{n=0}^{\infty} \left| \frac{a}{x_0} \right|^n$$

converges. Choosing $M \cdot |a/x_0|^n$ as the number M_n in 26, it follows that $\sum_{n=0}^{\infty} a_n x^n$ converges uniformly on $[-a, a]$.

To prove the same assertion for $g(x) = \sum_{n=1}^{\infty} n a_n x^{n-1}$ notice that

$$\begin{aligned} |n a_n x^{n-1}| &= n |a_n| \cdot |x|^{n-1} \\ &\leq n |a_n| \cdot |a|^{n-1} \\ &= \frac{|a_n|}{|a|} \cdot |x_0|^{n-1} n \left| \frac{a}{x_0} \right|^{n-1} \\ &\leq \frac{M}{|a|} n \left| \frac{a}{x_0} \right|^{n-1} \end{aligned}$$

Since $|a/x_0| < 1$, the series

$$\sum_{n=1}^{\infty} \frac{M}{|a|} n \left| \frac{a}{x_0} \right|^n = \frac{M}{|a|} \sum_{n=1}^{\infty} n \left| \frac{a}{x_0} \right|^n$$

converges (by an application of the Ratio Test). Another appeal to 26 proves that $\sum_{n=1}^{\infty} n a_n x^{n-1}$ converges uniformly on $[-a, a]$.

Finally, our corollary proves, first that g is continuous, and then that

$$f'(x) = g(x) = \sum_{n=1}^{\infty} n a_n x^{n-1}$$

for all $x \in [-a, a]$. Since we could have chosen any a with $0 < a < |x_0|$, this result holds for all x with $|x| < |x_0|$. ■

Theorem 4.4.11 (Ratio and Root Test). *If $\sum_{n=0}^{\infty} a_n$ for $a_n \in \mathbb{C}$ non-zero, then we have*

- *If $\limsup \frac{|a_{n+1}|}{|a_n|} < 1$, then $\sum_n a_n$ converges absolutely*
- *If $\limsup \frac{|a_{n+1}|}{|a_n|} > 1$, then $\sum_n a_n$ diverges*
- *If $\limsup |a_n|^{\frac{1}{n}} < 1$, then $\sum_n a_n$ converges absolutely*
- *If $\limsup |a_n|^{\frac{1}{n}} > 1$, then $\sum_n a_n$ diverges*

Example 4.4.17. If $a_n = 1$ for all n , we get the geometric series $\sum_{n=0}^{\infty} x^n = \frac{1}{1-x}$ provided $|x| < 1$.

The natural domain of a power series $f(x) = \sum_{n=0}^{\infty} a_n x^n$ is all x for which the sum converges.

Proposition 4.4.12 (Radius of Convergence). *Let $\sum_n a_n x^n$ be a power series and define $\alpha := \limsup |a_n|^{1/n}$. Define*

$$R = \begin{cases} \frac{1}{\alpha} & 0 < \alpha < \infty \\ \infty & \alpha = 0 \\ 0 & \alpha = \infty \end{cases}$$

*which we call the **radius of convergence** of the power series. Then $\sum_n a_n x^n$ converges absolutely for $|x| < R$. If $R = 0$, it converges only when $x = 0$. If $R = \infty$, it converges absolutely on all of \mathbb{R} . The series may or may not converge when $|x| = R$.*

Proof. Let $b_n = a_n x^n$, and

$$\beta = \limsup |b_n|^{1/n} = \limsup |a_n|^{1/n} |x|^{1/n} = |x| \alpha$$

Apply the root test to $\sum_{n=0}^{\infty} b_n$:

- (i) If $\alpha = 0$ then $\beta = 0 < 1$, so the series converges absolutely for all $x \in \mathbb{R}$
- (ii) If $\alpha = \infty$, $\beta = 0$ if $x = 0$ and ∞ otherwise, so the series converges absolutely only at $x = 0$
- (iii) If $0 < \alpha < \infty$, $\beta = |x|\alpha < 1$ if and only if $|x| < \frac{1}{\alpha} = R$, so the series converges absolutely for $|x| < R$ and diverges for $|x| > R$.

■

Corollary 4.4.13. If $\lim_{n \rightarrow \infty} \frac{|a_n|}{|a_{n+1}|}$ exists, it equals R above.

Example 4.4.18. Consider $\sum_{n=0}^{\infty} \frac{n!x^n}{n^n}$, so $a_n = \frac{n!}{n^n}$. Observe that

$$\lim_{n \rightarrow \infty} \frac{a_n}{a_{n+1}} = \lim_{n \rightarrow \infty} \frac{(n+1)^n}{n^n} = \lim_{n \rightarrow \infty} \left(1 + \frac{1}{n}\right)^n = e = R$$

For $x = \pm e$ we must use stirling's approximation $n! \approx \sqrt{2\pi n} \frac{n^n}{e^n}$, which becomes exact in the limit.

Proposition 4.4.14. Suppose $\sum_n a_n x^n$ has radius of convergence $R > 0$. Then $\sum_n a_n x^n$ converges uniformly on any set of the form $[-K, K]$ for $0 \leq K < R$.

Proof. Suppose $x \in [-K, K]$. Then $|a_n x^n| \leq |a_n| K^n$. But $\sum_{n=0}^{\infty} |a_n| K^n$ converges since $K \in (-R, R)$. Thus, by the Weierstrass M test $\sum_{n=0}^{\infty} a_n x^n$ converges uniformly on $[-K, K]$. ■

In particular, this tells us that $\sum_{n=0}^{\infty} a_n x^n$ is continuous on $[-K, K]$ for any $0 < K < R$, so it is continuous on $(-R, R)$.

Proposition 4.4.15. Suppose $f(x) = \sum_n a_n x^n$ has radius of convergence $R > 0$. Then f is differentiable on $(-R, R)$ and $f'(x) = \sum_n n a_n x^{n-1}$. Moreover, f' also has radius of convergence R .

Proof. We have shown previously that if $f_n \rightarrow f$ pointwise, f'_n are continuous, and $f'_n \rightarrow_u g$ for some g , then f is differentiable and $f' = g$. Let $s_m(x) = \sum_{n=0}^m a_n x^n$, which converges uniformly to $\sum_{n=0}^{\infty} a_n x^n = f(x)$ on $[-K, K]$ for any $0 \leq K < R$. Note s_m is differentiable with $s'_m(x) = \sum_{n=1}^m n a_n x^{n-1}$, which converges uniformly to $\sum_{n=1}^{\infty} n a_n x^{n-1} =: g(x)$ on $[-K, K]$ for all $0 \leq K < R$ as $\frac{1}{R'} = \limsup \frac{|(n+1)a_{n+1}|}{|n a_n|} = \limsup \frac{|a_{n+1}|}{|a_n|} = \frac{1}{R}$, so g 's radius of convergence is also R . This implies that f is differentiable on $(-K, K)$ and $f'(x) = g(x)$ for all $x \in (-K, K)$. As this holds for all $0 \leq K < R$, this implies $f'(x) = g(x)$ on $(-R, R)$. ■

Corollary 4.4.16. The power series $f(x) = \sum_n a_n x^n$ with radius of convergence $R > 0$ has derivatives of all orders on $(-R, R)$ and $f^{(k)}(x) = \sum_{n \geq k} \frac{n!}{(n-k)!} a_n x^{n-k}$ on $(-R, R)$.

Proof. From the previous proposition we have $f'(x) = \sum_{n=1}^{\infty} n a_n x^{n-1}$ with radius of convergence R . Applying this result repeatedly we have $f^{(k)}(x) = \sum_{n=k}^{\infty} \frac{n!}{(n-k)!} a_n x^{n-k}$ has radius of convergence R . ■

Note that in the formula above, it follows that $f^{(k)}(0) = k!a_k$, so $a_k = \frac{f^{(k)}(0)}{k!}$.

Corollary 4.4.17. If $\sum_n a_n x^n = \sum_n b_n x^n$ for all $x \in (-R, R)$, where R is the radius of convergence of both series, then $a_n = b_n$ for all n .

Using the remark above, letting $f(x) = \sum_n a_n x^n = \sum_n b_n x^n$, we have $a_n = \frac{f^{(n)}(0)}{n!} = b_n$ for all n .

Definition 4.4.9 (Power Series Representation). A function $f : S \rightarrow \mathbb{R}$ has a power series representation on S if there exists a sequence (a_n) such that

$$f(x) = \sum_{n=0}^{\infty} a_n x^n$$

for all $x \in S$. In particular, the series on the right hand side above converges for all $x \in S$.

We recall Taylor's Theorem:

Theorem 4.4.18 (Taylor's Theorem). Suppose f is $(n + 1)$ times differentiable on (a, b) containing 0, then

$$f(x) = \underbrace{\sum_{k=0}^n \frac{f^{(k)}(0)}{k!} x^k}_{\text{Taylor Polynomial } P_n(x)} + \underbrace{\frac{f^{(n+1)}(c)}{(n+1)!} x^{n+1}}_{\text{Taylor remainder } R_n(x)}$$

for some $c \in (0, x)$ (or $(x, 0)$). We get $|f(x) - P_n(x)| = |R_n(x)|$. If $R_n(x) \rightarrow 0$ as $n \rightarrow \infty$, then $f(x) = \lim_{n \rightarrow \infty} P_n(x) = \sum_{k=0}^{\infty} \frac{f^{(k)}(0)}{k!} x^k$.

This result gives a sufficient condition for a function admitting a power series representation. Note that if f admits a power series representation, it automatically has derivatives of all orders on the radius of convergence.

Example 4.4.19. Consider

$$f(x) = \begin{cases} e^{-1/x^2} & x \neq 0 \\ 0 & x = 0 \end{cases}$$

f has derivatives of all orders at $x = 0$:

$$f'(0) = \lim_{h \rightarrow 0} \frac{e^{-1/h^2}}{h} = \lim_{h \rightarrow 0} \frac{2h}{e^{1/h^2}} = 0$$

Similarly, $f^{(k)}(0) = 0$ for all k . So, $\sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!} x^n = 0$, which converges for all x but only agrees with $f(x)$ at $x = 0$. So f has only a power series representation at $x = 0$.

Theorem 4.4.19 (Abel). Suppose the power series $\sum_n a_n x^n$ has radius of convergence $R \in (0, \infty)$. If $\sum_n a_n x^n$ converges at $x = R$, then $\sum_n a_n x^n$ converges uniformly on $[0, R]$. Similarly, if $\sum_n a_n x^n$ converges at $x = -R$, then $\sum_n a_n x^n$ converges uniformly on $[-R, 0]$.

Proof. By rescaling if necessary, we can assume $R = 1$ (i.e. replace $f(x)$ with $f_R(x) = f(x/R)$). We use the Cauchy criterion for uniform convergence. Fix $\varepsilon > 0$. We have convergence at $x = 1$, so there exists $N \in \mathbb{N}$ such that $m \geq N$ implies $\left| \sum_{n=m}^{m+k} a_n \right| < \varepsilon$ for all $k \in \mathbb{N}$. For $m \geq N$ and for each $j \in \mathbb{N} \cup \{0\}$, define $s_j = \sum_{n=m}^{m+j} a_n$, so $|s_j| < \varepsilon$ for all j . Then write

$$\begin{aligned} \sum_{n=m}^{m+k} a_n x^n &= s_0 x^m + \sum_{n=1}^k (s_n - s_{n-1}) x^{m+n} \\ &= \sum_{n=0}^{k-1} s_n (x^{m+n} - x^{m+n+1}) + s_k x^{m+k} \\ &= x^m \left[\sum_{n=0}^{k-1} s_n (x^n - x^{n+1}) + s_k x^k \right] \\ &= x^m \left[\sum_{n=0}^{k-1} s_n x^n (1 - x) + s_k x^k \right] \\ &= x^m (1 - x) \sum_{n=0}^{k-1} s_n x^n + s_k x^{m+k} \end{aligned}$$

For $x \in [0, 1]$

$$\begin{aligned} \left| \sum_{n=m}^{m+k} a_n x^n \right| &\leq |x|^m |1 - x| \sum_{n=0}^{k-1} |s_n| |x|^n + |s_k| |x|^{m+k} \\ &< x^m (1 - x) [\varepsilon + \varepsilon x + \dots + \varepsilon x^{k-1}] + \varepsilon x^{m+k} \\ &= \varepsilon x^m (1 - x^k) + \varepsilon x^{m+k} \\ &= \varepsilon x^m < \varepsilon \end{aligned}$$

as desired. The proof for $[-1, 0]$ is similar. ■

We now investigate power series in the complex numbers. First, recall that if $r \in \mathbb{C}$, $|r| < 1$, then we have the geometric series

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

Definition 4.4.10. A power series (in \mathbb{C}) is a series of functions of the form

$$f(z) = \sum_{k=0}^{\infty} a_k z^k, \quad a_k \in \mathbb{C}, z \in \mathbb{C}$$

Note by definition $f(z) = \lim_{n \rightarrow \infty} \sum_{k=0}^n a_k z^k$.

Proposition 4.4.20. If $f(z) = \sum_{k=0}^{\infty} a_k z^k$ is defined for some $z_0 \in \mathbb{C}$, $z_0 \neq 0$, then $f(z)$ converges absolutely and uniformly for all $|z| < |z_0|$.

Proof. Note that if $|z| < |z_0|$, $|a_k z^k| < |a_k| |z_0|^k$ for all $k \geq 0$. Further, as $\sum_{k=0}^n a_k z_0^k$ is convergent, it is Cauchy so $|a_k z_0^k| \rightarrow 0$, and in particular $|a_k z_0^k| \leq C$ for all $k \geq 0$ for some $C \in \mathbb{R}$. Then $0 \leq \frac{|z|}{|z_0|} = r < 1$. So

$$\left| \sum_{k=0}^n a_k z^k \right| \leq \sum_{k=0}^n |a_k z_0^k| r^k \leq C \sum_{k=0}^n r^k \leq \frac{C}{1-r}$$

Thus $\sum_{k=0}^n |a_k z^k|$ is a bounded increasing sequence, and so converges. In particular, letting $M_k = C r^k = C \frac{|z_1|^k}{|z_0|^k}$, we have that for all $|z| < |z_1| < |z_0|$, $|a_k z^k| \leq M_k$ and $\sum_{k=0}^{\infty} M_k < \infty$, so $\sum_{k=0}^n a_k z^k$ is uniformly convergent to $f(z)$ on $|z| < |z_1|$ for all $|z_1| < |z_0|$, so in particular it is uniformly convergent on $|z| < |z_0|$. ■

From this theorem we have a few cases for $f(z)$:

- $f(z)$ converges for all $z \in \mathbb{C}$
- There exists $R > 0$ such that the series converges absolutely for $|z| < R$, but diverges for $|z| > R$.
- The series does not converge for any $z \neq 0$ ($R = 0$)

Proposition 4.4.21. *If $f(z) = \sum_{k=0}^{\infty} a_k z^k$ converges in $D_R = \{z \in \mathbb{C} : |z| < R\}$, then it converges uniformly in any disk D_S with $0 < S < R$. In particular, this yields $f(z)$ is continuous on D_R .*

Proof. Let $0 < S < R$ and pick T such that $0 < S < T < R$. Then the series converges for any $|z| = T$. In particular, there exists $C > 0$ such that $|a_k T^k| < C$ for all $k \geq 0$. If $z \in D_S$, then $|a_k z^k| \leq |a_k T^k| \frac{|z|^k}{|T|^k} \leq C r^k$, where $0 \leq r = \frac{|z|}{|T|} < 1$. As $|r| < 1$, $C \sum_{k=0}^n r^k$ converges, and so is Cauchy. Thus, for $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that if $m > n \geq N$,

$$\sum_{k=n}^m \|a_k z^k\|_{D_S} \leq \sum_{k=n}^m C r^k < \varepsilon$$

so $\sum_{k=0}^n a_k z^k$ is uniformly Cauchy on D_S . So it converges uniformly to $f(z)$ in D_S for all $S < R$. So $f(z)$ is continuous in D_S for all $S < R$, and in particular f is continuous on D_R . ■

Definition 4.4.11. For $f(z) = \sum_{k=0}^{\infty} (z - z_0)^k$, let the radius of convergence R be defined by

$$\frac{1}{R} = \limsup_{n \rightarrow \infty} |a_n|^{1/n}$$

If the right hand side is 0, $R = \infty$, and if the right hand side is ∞ , $R = 0$.

Proposition 4.4.22. *The series $f(z) = \sum_{k=0}^{\infty} a_k (z - z_0)^k$ converges absolutely for $|z - z_0| < R$, and diverges when $|z - z_0| > R$. Then when $R > 0$, f is a continuous function $f : D_R(z_0) \rightarrow \mathbb{C}$.*

Proof. If $R' < R$, and $R' \neq 0$, $\frac{1}{R'} < \frac{1}{R}$. Note $\frac{1}{R} = \limsup_{n \rightarrow \infty} |a_n|^{1/n}$, and let $\varepsilon = (\frac{1}{R'} - \frac{1}{R})$. Then there exists $N \in \mathbb{N}$ such that for $n \geq N$, $\sup_{k \geq n} |a_k|^{1/k} < \frac{1}{R} + \varepsilon$, so $\sup_{k \geq n} |a_k|^{1/k} < \frac{1}{R'}$,

so $|a_n|^{1/n}R' < 1$ and $|a_n|R'' < 1$ for all $n \geq N$. If $|z - z_0| < R'$, then $\frac{|z - z_0|}{R'} = r < 1$, so $|a_n(z - z_0)^n| = |a_n|R''^n r^n < r^n$ for all $n \geq N$. Then $\sum_{n=m}^{\infty} |a_n(z - z_0)|_{D_{R'}} \leq \sum_{n=m}^{\infty} r^n \rightarrow 0$ for all $m \geq N$. So we have absolute uniform convergence in $D_{R'}(z_0)$, for all $0 < R' < R$.

Divergence: Let $R'' > R$, so $\frac{1}{R''} < \frac{1}{R} = \limsup_{n \rightarrow \infty} |a_n|^{1/n}$. Then for all n , $\sup_{k \geq n} |a_k|^{1/k} > \frac{1}{R''}$, and in particular there are infinitely many $k \geq n$, for all n , such that $|a_k|^{1/k} > \frac{1}{R''}$, so $|a_k|R''^k > 1$. If $|z - z_0| \geq R''$, then $|a_n(z - z_0)^n| \geq |a_n|R''^n > 1$ for infinitely many $n \geq 0$. Thus, $|a_n(z - z_0)^n|$ does not converge to 0, so the series diverges. ■

Definition 4.4.12. A function defined by $\sum_{k=0}^{\infty} a_k z^k$ with radius of convergence $R > 0$ is said to be analytic on D_R .

Definition 4.4.13. In \mathbb{R}^n with $x = (x_1, \dots, x_n)$, for any multi-index $\alpha = (\alpha_1, \dots, \alpha_n)$ with $\alpha_j \in \mathbb{N}_0$, we define

$$x^\alpha = x_1^{\alpha_1} \cdots x_n^{\alpha_n}$$

and we define a power series in \mathbb{R}^n by

$$f(x) = \sum_{|\alpha| \geq 0} a_\alpha x^\alpha$$

Products of Series

We investigate when we can distribute multiplication of two series:

Proposition 4.4.23. If $A = \sum_{k=0}^{\infty} a_k$ and $B = \sum_{k=0}^{\infty} b_k$ are absolutely convergent, then

$$AB = \sum_{k=0}^{\infty} c_k, \quad c_k = \sum_{j=0}^k a_{k-j} b_j$$

Proof. Let $A_k = \sum_{n=0}^k a_n$ and $B_k = \sum_{n=0}^k b_n$. Then

$$\begin{aligned} A_k B_k &= \sum_{n=0}^k \sum_{m=0}^k a_n b_m \\ &= \sum_{l=0}^k \sum_{j=0}^l a_j b_{l-j} + R_l = \sum_{l=0}^k c_l + R_k \end{aligned}$$

where $R_k = \sum_{(n,m) \in \sigma(k)} a_n b_m$ where $\sigma(k) := \{(n, m) \in \mathbb{N}_0 \times \mathbb{N}_0 : n, m \leq k, n + m > k\}$. Then

$$\begin{aligned} |R_k| &\leq \sum_{(n,m) \in \sigma(k)} |a_n b_m| \\ &\leq \sum_{k \geq n \geq k/2} \sum_{m \leq k} |a_n| |b_m| + \sum_{n \leq k} \sum_{k/2 \leq m \leq k} |a_n| |b_m| \\ &\leq \sum_{k/2 \leq n \leq k} \sum_{m=0}^{\infty} |a_n| |b_m| + \sum_{k/2 \leq m \leq k} \sum_{n=0}^{\infty} |b_m| |a_n| \end{aligned}$$

$$\leq A \sum_{k/2 \leq m} |b_m| + B \sum_{k/2 \leq n} |a_n|$$

where both sums on the right go to zero as k goes to infinity. So for all $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $k \geq N$ implies $|R_k| < \varepsilon$. Then

$$A_k B_k = \sum_{l=0}^k c_l + R_k$$

so

$$\lim_{k \rightarrow \infty} \sum_{l=0}^k c_l = \lim_{k \rightarrow \infty} (A_k B_k - R_k) = AB + 0 + AB$$

and we conclude

$$AB = \sum_{l=0}^{\infty} c_l$$

as claimed. ■

Corollary 4.4.24. *If the series*

$$f(z) = \sum_{n=0}^{\infty} a_n (z - z_0)^n, \quad g(z) = \sum_{n=0}^{\infty} b_n (z - z_0)^n$$

converge for some $|z - z_0| < R$, then

$$f(z)g(z) = \sum_{n=0}^{\infty} c_n (z - z_0)^n$$

converges for $|z - z_0| < R$ with

$$c_n = \sum_{j=0}^n a_j b_{n-j}$$

It follows that the set of analytic functions on some disk is an algebra over \mathbb{C} .

Proposition 4.4.25. *If $a_{jk} \in \mathbb{C}$ and $\sum_{j,k=0}^{\infty} |a_{j,k}| < \infty$, then for each k , $\alpha_k = \sum_{j=0}^{\infty} a_{j,k}$ and for each j $\beta_j = \sum_{k=0}^{\infty} a_{j,k}$ are absolutely convergent, where*

$$\lim_{n \rightarrow \infty} \sum_{j=0}^n \sum_{k=0}^n |a_{j,k}| =: \sum_{j,k=0}^{\infty} |a_{j,k}|$$

Then

$$\sum_{j=0}^{\infty} \beta_j = \sum_{k=0}^{\infty} \alpha_k = \sum_{j,k=0}^{\infty} a_{j,k}$$

or equivalently

$$\sum_{j=0}^{\infty} \left(\sum_{k=0}^{\infty} a_{j,k} \right) = \sum_{k=0}^{\infty} \left(\sum_{j=0}^{\infty} a_{j,k} \right) = \sum_{j,k=0}^{\infty} a_{j,k}$$

Proof. For all $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that

$$\sum_{j,k \geq n} |a_{j,k}| < \varepsilon$$

Thus for all $j \in \mathbb{N}$ and all $k \in \mathbb{N}$,

$$\sum_{k=0}^{\infty} |a_{j,k}| < \sum_{j,k} |a_{j,k}| < \infty$$

and

$$\sum_{j=0}^{\infty} |a_{j,k}| < \sum_{j,k} |a_{j,k}| < \infty$$

Then for all $M, K \geq N$,

$$\left| \sum_{k=0}^M \sum_{j=0}^K a_{j,k} - \sum_{j,k} a_{j,k} \right| < \sum_{j,k \geq N} |a_{j,k}| < \varepsilon$$

In particular, taking the limit as K goes to infinity,

$$\left| \sum_{k=0}^M \sum_{j=0}^{\infty} a_{j,k} - \sum_{j,k} a_{j,k} \right| \leq \sum_{j,k \geq N} |a_{j,k}| < \varepsilon$$

and

$$\left| \sum_{k=0}^{\infty} \sum_{j=0}^{\infty} a_{j,k} - \sum_{j,k} a_{j,k} \right| \leq \sum_{j,k \geq N} |a_{j,k}| < \varepsilon$$

Reversing the sums before taking the limits, we obtain the other direction, so

$$\sum_{j=0}^{\infty} \left(\sum_{k=0}^{\infty} a_{j,k} \right) = \sum_{j,k=0}^{\infty} a_{j,k} = \sum_{k=0}^{\infty} \left(\sum_{j=0}^{\infty} a_{j,k} \right)$$

as desired. ■

Part II

Higher-Dimensional Analysis

Chapter 5

Metric Spaces

5.1.0 Euclidean Spaces

We begin our study with one of the most well studied metric spaces, Euclidean n -space.

Definition 5.1.1. Euclidean n -space is defined as the product

$$\mathbb{R}^n := \mathbb{R} \times \cdots \times \mathbb{R} = \{(x_1, \dots, x_n) : x_1, \dots, x_n \in \mathbb{R}\}$$

We define $+$: $\mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^n$ component-wise, and we define a module action \cdot : $\mathbb{R} \times \mathbb{R}^n \rightarrow \mathbb{R}^n$ also component-wise, turning \mathbb{R}^n into an \mathbb{R} -linear space.

Euclidean space is a special type of vector space which satisfies certain additional structures:

Definition 5.1.2. A real-inner product on a real vector space V is a map $\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{R}$ such that

1. $\langle v, v \rangle \geq 0$ for all $v \in V$, and $\langle v, v \rangle = 0$ if and only if $v = 0_V$
2. $\langle v, w \rangle = \langle w, v \rangle$ for all $v, w \in V$
3. $\langle av + bu, w \rangle = a\langle v, w \rangle + b\langle u, w \rangle$ for all $v, u, w \in V$ and all $a, b \in \mathbb{R}$.

Definition 5.1.3. A norm on a real vector space V is a map $\|\cdot\| : V \rightarrow \mathbb{R}$ such that

1. $\|v\| \geq 0$ for all $v \in V$, and $\|v\| = 0$ if and only if $v = 0_V$
2. $\|av\| = |a| \cdot \|v\|$ for all $v \in V$ and all $a \in \mathbb{R}$
3. $\|v + w\| \leq \|v\| + \|w\|$ for all $v, w \in V$ (triangle inequality)

Then $(V, \|\cdot\|)$ is called a normed linear space.

Definition 5.1.4. A metric on a set X is a map $d : X \times X \rightarrow \mathbb{R}$ such that

1. $d(x, y) \geq 0$ for all $x, y \in X$, and $d(x, y) = 0$ if and only if $x = y$
2. $d(x, y) = d(y, x)$ for all $x, y \in X$
3. $d(x, z) \leq d(x, y) + d(y, z)$ for all $x, y, z \in X$ (triangle inequality)

In this case we call (X, d) a metric space.

Proposition 5.1.1. If $\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{R}$ is an inner product, $\| \cdot \| : V \rightarrow \mathbb{R}$ defined by $\| \cdot \| = \sqrt{\langle \cdot, \cdot \rangle}$ is a norm, and $d : V \times V \rightarrow \mathbb{R}$ defined by $d(a, b) = \|a - b\|$ is a metric.

We now define the inner product on Euclidean n -space:

Definition 5.1.5. The Euclidean inner product on \mathbb{R}^n is given by

$$\langle x, y \rangle = x \cdot y = \sum_{i=1}^n x_i y_i$$

for all $x = (x_1, \dots, x_n), y = (y_1, \dots, y_n) \in \mathbb{R}^n$.

Proposition 5.1.2 (Cauchy-Schwarz Inequality). For any inner product $\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{R}$

$$|\langle v, w \rangle| \leq |\langle v, v \rangle| |\langle w, w \rangle|$$

Proof. Let $t > 0$, and consider $0 \leq \langle tx - t^{-1}y, tx - t^{-1}y \rangle$, so $0 \leq t^2 \|x\|^2 - 2\langle x, y \rangle + t^{-2} \|y\|^2$. Without loss of generality suppose $x, y \neq 0$. Then let $t^2 = \frac{\|y\|}{\|x\|}$, so we have $2\langle x, y \rangle \leq 2\|y\| \cdot \|x\|$, so we have our desired result. Replacing x with $-x$ we obtain $-\langle x, y \rangle \leq \|y\| \cdot \|x\|$, so $|\langle x, y \rangle| \leq \|x\| \cdot \|y\|$. ■

The triangle inequality follows from this Cauchy-Schwarz inequality. Thus, \mathbb{R}^n is a metric space, and in particular it is a normed linear space.

Sequences and Convergence

We can now use the metric on \mathbb{R}^n to define notions of convergence for sequences.

Definition 5.1.6. If $(\vec{x}_j)_{j=1}^\infty \subset \mathbb{R}^n$, then $\vec{x}_j \rightarrow \vec{x} \in \mathbb{R}^n$ if and only if $\|\vec{x}_j - \vec{x}\|$ converges to 0 in \mathbb{R} . Further, we say such a sequence is Cauchy if and only if for all $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for $j, k \geq N$, $\|\vec{x}_j - \vec{x}_k\| < \varepsilon$.

We note that we can consider $\mathbb{C} \cong \mathbb{R}^2$ as normed linear spaces over \mathbb{R} .

Proposition 5.1.3. \mathbb{R}^n is a complete metric space.

Proof. By completeness of \mathbb{R} , and the fact that $(x_j)_{j=1}^\infty = (\langle x_{j,1}, \dots, x_{j,n} \rangle)_{j=1}^\infty$ is Cauchy if and only if the $(x_{j,i})_{j=1}^\infty$ are Cauchy for all i . ■

Topological Properties of Euclidean Space

First we define the notions of open and closed sets in \mathbb{R}^n :

Definition 5.1.7. We say that $S \subseteq \mathbb{R}^n$ is closed if and only if for all sequences $(x_j)_{j=1}^\infty \subseteq S$ such that x_j converges to $x \in \mathbb{R}^n$, $x \in S$.

Definition 5.1.8. We say that a set $U \subseteq \mathbb{R}^n$ is open if and only if $\mathbb{R}^n \setminus U = U^c$ is closed. This holds if and only if for all $x \in U$, there exists $\varepsilon > 0$ such that $B_\varepsilon(x) \subseteq U$, where

$$B_\varepsilon(x) := \{y \in \mathbb{R}^n : d(x, y) < \varepsilon\}$$

is the ε -ball centered at $x \in \mathbb{R}^n$.

Definition 5.1.9. A set $K \subseteq \mathbb{R}^n$ is sequentially compact if and only if for all $(p_j)_{j=1}^\infty \subseteq K$, there exists a subsequence $(p_{j_k})_{k=1}^\infty \subseteq K$ and a $p \in K$ such that p_{j_k} converges to p .

That is every sequence in a sequentially compact set has a convergent subsequence.

Definition 5.1.10. A set $S \subseteq T \subseteq \mathbb{R}^n$ is said to be dense in T if $\overline{S} \supseteq T$, where \overline{S} is the closure of S :

$$\overline{S} := \bigcap \{C \subseteq \mathbb{R}^n : S \subseteq C \text{ and } C \text{ is closed}\}$$

Note that the closure of a set S is the smallest closed set containing S .

Definition 5.1.11. A topological space (X, τ) is said to be separable if it has a countable dense subset.

We note that \mathbb{R}^n is separable with countable dense subset \mathbb{Q}^n . Indeed, for all $U \subseteq \mathbb{R}^n$, U is open if and only if for all $p \in U$, there exists $q \in \mathbb{Q}^n$ and $r \in \mathbb{Q}^+$ such that $p \in B_r(q) \subseteq U$. Hence,

$$\mathcal{B} := \{B_r(q) : r \in \mathbb{Q}^+, q \in \mathbb{Q}^n\}$$

is a countable base for the topology on \mathbb{R}^n , so \mathbb{R}^n is a second countable space. We have the following useful results about compactness in Euclidean spaces:

Corollary 5.1.4. If $K \subseteq \mathbb{R}^n$ is sequentially compact then it is topologically compact.

To prove this corollary we first prove some intermediate results.

Proposition 5.1.5. *If $K \subseteq \mathbb{R}^n$ is sequentially compact, and $X_1 \supseteq X_2 \supseteq X_3 \supseteq \dots$ is a chain of nonempty closed subsets of K , then $\bigcap_{j \geq 1} X_j \neq \emptyset$.*

Proof. Let $x_j \in X_j \subseteq K$ for each j . Then $(x_j)_{j=1}^\infty \subseteq K$, so as K is compact we have a subsequence $(x_{j_k})_{k=1}^\infty \subseteq K$ such that $x_{j_k} \rightarrow x \in K$. But, for each $m \in \mathbb{N}$, $\{x_{j_k} : k \geq m\} \subseteq X_m$, so as X_m is closed it follows that $x \in X_m$. Thus, $x \in \bigcap_{j \geq 1} X_j$, so $\bigcap_{j \geq 1} X_j \neq \emptyset$. ■

Proposition 5.1.6. *If $K \subseteq \mathbb{R}^n$ is compact and $U_1 \subseteq U_2 \subseteq \dots$ is a chain of open sets which cover K , $K \subseteq \bigcup_{j \geq 1} U_j$, then there exists $M \in \mathbb{N}$ such that $K \subseteq U_M$.*

Proof. Consider $X_m = K \setminus U_m$, which gives a chain of closed sets. We have that $\bigcap_{j \geq 1} X_j = \emptyset$, so by the contrapositive of the previous proposition there exists $M \in \mathbb{N}$ such that $X_M = \emptyset$. Then $K \subseteq U_M$, as desired. ■

Now we proceed to the proof of the corollary:

Proof. Let $\{U_\alpha\}_{\alpha \in J}$ be an open cover of K , which is sequentially compact in \mathbb{R}^n . For each α we have $U_\alpha = \bigcup_{j \geq 1} B_{r_{\alpha_j}}(q_{\alpha_j})$ is the union of a countable number of open sets in our countable base. Then, $K \subseteq \bigcup_{\alpha \in J} \bigcup_{j \geq 1} B_{r_{\alpha_j}}(q_{\alpha_j})$, which is a union over a countable collection of open sets since \mathcal{B} is countable. We claim any countable cover has a finite subcover for K . Indeed, consider $U_m = \bigcup_{j=1}^m B_j$ for a countable cover $\bigcup_{j \geq 1} B_j$. Then by the previous proposition there exists $M \in \mathbb{N}$ such that $K \subseteq \bigcup_{j=1}^M B_j$. Thus, there exist $\alpha_1, \dots, \alpha_N \in J$, and M_j such that $K \subseteq \bigcup_{j=1}^N \bigcup_{k=1}^{M_j} B_{r_{\alpha_{j,k}}}(q_{\alpha_{j,k}}) \subseteq \bigcup_{j=1}^N U_{\alpha_j}$, so K is topologically compact. ■

5.2.0 Metric Space Properties

Definition 5.2.1 (Metric Space). *A set X together with a function $d : X \times X \rightarrow [0, \infty)$ is called a metric space if the function d , called a metric satisfies the following properties for all $x, y, z \in X$:*

- (1) $d(x, y) = 0$ if and only if $x = y$ (Positive definiteness)
- (2) $d(x, y) = d(y, x)$ (Symmetry)
- (3) $d(x, y) \leq d(x, z) + d(z, y)$ (Triangle inequality)

Example 5.2.1. \mathbb{R} and \mathbb{C} with the usual modulus are metric spaces. In this case $d(x, y) = |x - y|$. Additionally, as seen in the last section \mathbb{R}^n and \mathbb{C}^n are metric spaces, with the Euclidean metric

$$d(\vec{x}, \vec{y}) = \sqrt{\sum_{i=1}^n |x_i - y_i|^2}$$

where the triangle inequality follows by the Cauchy-Schwartz inequality.

Proposition 5.2.1. *Let V be a real inner product space. Then for all $u, v \in V$,*

$$|\langle u, v \rangle|^2 \leq \langle u, u \rangle \cdot \langle v, v \rangle$$

Proof. Let $t \in \mathbb{R} \setminus \{0\}$, and consider

$$0 \leq \langle tx - t^{-1}y, tx - t^{-1}y \rangle = t^2|x|^2 - 2\langle x, y \rangle + t^{-2}|y|^2$$

Now, if x or y is the zero vector, then the result holds trivially. Thus, suppose $x, y \neq 0$, and let $t^2 = \frac{|y|}{|x|}$. It follows that

$$2\langle x, y \rangle \leq |y||x| + |x||y| = 2|x||y|$$

so $\langle x, y \rangle \leq |x||y|$. Exchanging x with $-x$ we obtain $-\langle x, y \rangle \leq |x||y|$, so $|\langle x, y \rangle| \leq |x||y|$. Squaring both sides we obtain the desired inequality. ■

Example 5.2.2 (Discrete Metric). Let X be any set. Then we can define the discrete metric on X by

$$d(x, y) = \begin{cases} 1 & x \neq y \\ 0 & x = y \end{cases}$$

which gives X the discrete topology, in which $\tau_X = \mathcal{P}(X)$.

Example 5.2.3 (Subsets of Metric Spaces). If $Y \subseteq X$ and (X, d) is a metric space, then $(Y, d|_Y)$ is also a metric space, with topology corresponding to the subspace topology.

Normed Linear Spaces

Definition 5.2.2 (Normed Linear Space). Let V be a vector space over \mathbb{R} or \mathbb{C} . We say that V is a **normed linear space** if there is a function $\|\cdot\| : V \rightarrow [0, \infty)$ called a norm satisfying the following properties for all $v, w \in V$ and constants c :

- (1) $\|v\| = 0$ if and only if $v = 0$ (Positive definiteness)
- (2) $\|cv\| = |c|\|v\|$, (Absolute homogeneity)
- (3) $\|v + w\| \leq \|v\| + \|w\|$ (triangle inequality)

Proposition 5.2.2. A normed linear space $(V, \|\cdot\|)$ is also a metric space with metric $d(v, w) = \|v - w\|$.

Proof. First, observe that $d(v, v) = \|v - v\| = \|0\| = 0$, and if $d(v, w) = \|v - w\| = 0$ then $v - w = 0_V$, so $v = w$. Next,

$$d(v, w) = \|v - w\| = \|-(w - v)\| = |-1|\|w - v\| = d(w, v)$$

so we have symmetry. Finally, for all $u, v, w \in V$,

$$d(v, w) = \|v - w\| = \|v - u + u - w\| \leq \|v - u\| + \|u - w\| = d(v, u) + d(u, w)$$

so the triangle inequality is satisfied. ■

This leads to the question:

Question 5.2.1. Does every metric on a vector space arise from a norm?

The answer is negative. Let V be a vector space and assume $\dim V \geq 1$ (so it isn't the zero vector space). Equip V with the discrete metric. For the sake of contradiction assume there is a norm $\|\cdot\|$ on V with $d(v, w) = \|v - w\|$. If $v \neq 0$, then

$$1 = d(v, 0) = \|v - 0\| = \|v\|$$

But, using absolute homogeneity,

$$1 = d(2v, 0) = \|2v\| = 2\|v\|$$

which is a contradiction.

Example 5.2.4. We define the Euclidean norm on \mathbb{R}^n and \mathbb{C}^n by

$$\|\vec{x}\|_2 := \sqrt{\sum_{j=1}^n |x_j|^2}$$

This norm induces the Euclidean metric.

Example 5.2.5 (Spaces of Continuous Functions). Let $S \subseteq \mathbb{R}$. Define the following:

(i) Continuous functions on S :

$$C(S) = \{f : S \rightarrow \mathbb{R} \mid f \text{ is continuous}\}$$

This is an \mathbb{R} -vector space since $f + g$ and cf are continuous on S whenever f, g are and $c \in \mathbb{R}$

(ii) Continuous bounded functions on S :

$$C_b(S) = \{f : S \rightarrow \mathbb{R} \mid f \text{ is continuous and } \|f\|_S < \infty\}$$

This is a subspace of $C(S)$ and is also a normed linear space with norm $\|f\|_S = \sup_{x \in S} |f(x)|$. Indeed, $\|f\|_S = 0$ if and only if $|f(x)| = 0$ for all $x \in S$, if and only if $f \equiv 0$. Further, $|cf(x)| = |c||f(x)|$, and taking the supremum of both sides $\|cf\|_S = |c|\|f\|_S$. Finally, if $f, g \in C_b(S)$, then

$$|f(x) + g(x)| \leq |f(x)| + |g(x)| \leq \|f\|_S + \|g\|_S$$

for all $x \in S$, so $\|f + g\|_S \leq \|f\|_S + \|g\|_S$.

(iii) Continuous functions vanishing at ∞ :

$$C_0(S) = \{f : S \rightarrow \mathbb{R} \mid f \text{ is continuous and } \forall \varepsilon > 0, \exists K \subseteq S \text{ compact; } \sup_{x \in S \setminus K} |f(x)| < \varepsilon\}$$

That is to say f is “small” outside of a compact set. $C_0(S)$ is a subspace of $C_b(S)$ with norm $\|\cdot\|_\infty$. Note that

$$C_0(\mathbb{R}) = \{f : \mathbb{R} \rightarrow \mathbb{R} \mid \lim_{x \rightarrow \infty} f(x) = 0 = \lim_{x \rightarrow -\infty} f(x)\}$$

(iv) Continuous functions with compact support on S :

$$C_c(S) = \{f : S \rightarrow \mathbb{R} \mid \exists K \subseteq S \text{ with } \overline{K} \text{ compact and } f(x) = 0 \forall x \in S \setminus K\}$$

K is called the support of f . $C_c(S)$ is a subspace of $C_0(S)$.

Remark 5.2.2. We note that

- (i) If S is compact, $C(S) = C_b(S) = C_0(S) = C_c(S)$
- (ii) All of these may be defined for \mathbb{C} valued functions as well
- (iii) If $S = [a, b]$, then there are many familiar norms on $C([a, b])$, one such being

$$\|f\|_p := \left[\int_a^b |f(x)|^p dx \right]^{1/p}$$

for any $p \geq 1$.

Proposition 5.2.3. Suppose $n \in \mathbb{N}$. The quantity

$$\|x\|_\infty = \max\{|x_k| : 1 \leq k \leq n\}$$

defines a norm called the ∞ -norm on \mathbb{R}^n and \mathbb{C}^n .

Proof. First, observe that $\|x\|_\infty = 0$ if $x = \vec{0}$. Further, if $\|x\|_\infty = 0$, then $0 \leq |x_k| \leq 0$ for all $1 \leq k \leq n$, so $x_k = 0$ for all k and hence $x = (0, 0, \dots, 0)$. Then, if $c \in \mathbb{C}$, it follows that

$$\begin{aligned} \|cx\|_\infty &= \max\{|cx_k| : 1 \leq k \leq n\} \\ &= \max\{|c||x_k| : 1 \leq k \leq n\} \\ &= |c| \max\{|x_k| : 1 \leq k \leq n\} = |c| \|x\|_\infty \end{aligned}$$

Finally, if $x, y \in \mathbb{C}^n$, then

$$|x_k + y_k| \leq |x_k| + |y_k| \leq \max\{|x_k| : 1 \leq k \leq n\} + \max\{|y_k| : 1 \leq k \leq n\} = \|x\|_\infty + \|y\|_\infty$$

for all k , since $|\cdot|$ is a norm on \mathbb{C} , so

$$\|x + y\|_\infty = \max\{|x_k + y_k| : 1 \leq k \leq n\} \leq \|x\|_\infty + \|y\|_\infty$$

■

Proposition 5.2.4. Suppose $n \in \mathbb{N}$. The quantity

$$\|x\|_1 = \sum_{k=1}^n |x_k|$$

defines a norm called the 1-norm on \mathbb{R}^n and \mathbb{C}^n .

Proof. First, $\|x\|_1 = 0$ if and only if $\sum_{k=1}^n |x_k| = 0$ if and only if $|x_k| = 0$ for all k if and only if $x_k = 0$ for all k , if and only if $x = \vec{0}$. Next,

$$\|cx\|_1 = \sum_{k=1}^n |cx_k| = |c| \sum_{k=1}^n |x_k| = |c| \|x\|_1$$

and

$$\|x + y\|_1 = \sum_{k=1}^n |x_k + y_k| \leq \sum_{k=1}^n |x_k| + |y_k| = \|x\|_1 + \|y\|_1$$

■

Definition 5.2.3 (ℓ^p norm). Suppose $p \geq 1$ and $n \in \mathbb{N}$. For any vector $x = (x_1, \dots, x_n) \in \mathbb{R}^n$ or \mathbb{C}^n , the quantity

$$\|x\|_p = \left(\sum_{k=1}^n |x_k|^p \right)^{1/p}$$

is called the p -norm. When $p = \infty$ we use

$$\|x\|_\infty = \max\{|x_k| : 1 \leq k \leq n\}$$

We now aim to verify this is a norm for the case of p not equal to 1 or ∞ .

Lemma 5.2.5 (Young's Inequality). Suppose $p > 1$ and $q > 1$ satisfy $\frac{1}{p} + \frac{1}{q} = 1$. If $a > 0$ and $b > 0$ then

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}$$

Equality holds if and only if $a^p = b^q$.

Proof. If $p = q = 2$, then $(a - b)^2 \geq 0$ so $a^2 - 2ab + b^2 \geq 0$, so $\frac{a^2 + b^2}{2} \geq ab$. Further, note $\frac{p-1}{p} = 1 - \frac{1}{p} = \frac{1}{q}$, and so $q = \frac{p}{p-1}$ for $p \neq 1$.

Now, define $y = x^{p-1}$ for $x > 0$. Then y is invertible as a function of x and $x = y^{q-1}$ since $\frac{1}{p-1} = \frac{q}{p} = q - 1$. Then

$$\int_0^a x^{p-1} dx + \int_0^b y^{q-1} dy = \frac{x^p}{p} \Big|_{x=0}^a + \frac{y^q}{q} \Big|_{y=0}^b = \frac{a^p}{p} + \frac{b^q}{q}$$

The area of the box corresponding to sidelengths a and b is $ab \leq \frac{a^p}{p} + \frac{b^q}{q}$, and equality holds if and only if (a, b) is on the graph of $y = x^{p-1}$, or in other words $b = a^{p-1}$, which happens if and only if $b^q = a^{(p-1)q} = a^p$. ■

Lemma 5.2.6 (Hölder's Inequality). Suppose $p > 1$ and $q > 1$ satisfy $\frac{1}{p} + \frac{1}{q} = 1$. For any vectors $x = (x_1, \dots, x_n)$ and $y = (y_1, \dots, y_n)$ in \mathbb{R}^n or \mathbb{C}^n we have

$$\sum_{k=1}^n |x_k y_k| \leq \|x\|_p \|y\|_q$$

Note that the case of $p = q = 2$ is the Cauchy-Schwartz Inequality.

Proof. If $\vec{x} = 0$ or $\vec{y} = 0$, we get 0 on both sides so we may assume $\|\vec{x}\|_p > 0$ and $\|\vec{y}\|_q > 0$. Define $a_j = \frac{|x_j|}{\|\vec{x}\|_p}$ and $b_j = \frac{|y_j|}{\|\vec{y}\|_q}$. Then

$$\begin{aligned} \sum_{j=1}^n \frac{|x_j y_j|}{\|\vec{x}\|_p \|\vec{y}\|_q} &= \sum_{j=1}^n a_j b_j \\ &\leq \sum_{j=1}^n \frac{a_j^p}{p} + \frac{b_j^q}{q} && \text{(by Young's Inequality)} \\ &= \sum_{j=1}^n \frac{|x_j|^p}{p \|\vec{x}\|_p^p} + \sum_{j=1}^n \frac{|y_j|^q}{q \|\vec{y}\|_q^q} \\ &= \frac{1}{p \|\vec{x}\|_p^p} \|\vec{x}\|_p^p + \frac{1}{q \|\vec{y}\|_q^q} \|\vec{y}\|_q^q \\ &= \frac{1}{p} + \frac{1}{q} = 1 \end{aligned}$$

Multiplying both sides by $\|\vec{x}\|_p \|\vec{y}\|_q$ we obtain the desired inequality

$$\sum_{j=1}^n |x_j y_j| \leq \|\vec{x}\|_p \|\vec{y}\|_q$$

■

Theorem 5.2.7. For any $p \geq 1$, including $p = \infty$, and $n \in \mathbb{N}$, the vector space \mathbb{R}^n or \mathbb{C}^n together with the norm $\|\cdot\|_p$ is a normed linear space.

Proof. Without loss of generality we may assume $1 < p < \infty$. Then $\|\vec{x}\|_p = \left(\sum_{j=1}^n |x_j|^p \right)^{1/p} = 0$ if and only if $|x_j|^p = 0$ for all j , which occurs if and only if $x_j = 0$ for all j , or $\vec{x} = \vec{0}$. Secondly, for all $c \in \mathbb{C}$,

$$\|c\vec{x}\|_p = \left(\sum_{j=1}^n |cx_j|^p \right)^{1/p} = \left(|c|^p \sum_{j=1}^n |x_j|^p \right)^{1/p} = |c| \left(\sum_{j=1}^n |x_j|^p \right)^{1/p} = |c| \|\vec{x}\|_p$$

Finally, write $\vec{x} = (x_1, \dots, x_n)^T$ and $\vec{y} = (y_1, \dots, y_n)^T$. Then

$$\begin{aligned} \|\vec{x} + \vec{y}\|_p^p &= \sum_{j=1}^n |x_j + y_j|^p = \sum_{j=1}^n |x_j + y_j| |x_j + y_j|^{p-1} && (p-1 > 0) \\ &\leq \sum_{j=1}^n |x_j| |x_j + y_j|^{p-1} + \sum_{j=1}^n |y_j| |x_j + y_j|^{p-1} \\ &\leq \left(\sum_{j=1}^n |x_j|^p \right)^{1/p} \left(\sum_{j=1}^n |x_j + y_j|^{(p-1)q} \right)^{1/q} + \left(\sum_{j=1}^n |y_j|^p \right)^{1/p} \left(\sum_{j=1}^n |x_j + y_j|^{(p-1)q} \right)^{1/q} \\ &&& \text{(by Hölder's inequality)} \end{aligned}$$

$$\begin{aligned}
 &= (||\vec{x}||_p + ||\vec{y}||_p) \left(\sum_{j=1}^n |x_j + y_j|^p \right)^{(p-1)/p} \\
 &\quad \text{(as } \frac{1}{p} + \frac{1}{q} = 1, \text{ so } p = q(p-1)) \\
 &= (||\vec{x}||_p + ||\vec{y}||_p) ||\vec{x} + \vec{y}||_p^{p-1}
 \end{aligned}$$

Note that if $\vec{x} + \vec{y} = 0$, the triangle inequality follows by definition of the p -norm. Assuming $||\vec{x} + \vec{y}||_p \neq 0$ and dividing the above inequality by $||\vec{x} + \vec{y}||_p^{p-1} > 0$ we obtain

$$||\vec{x} + \vec{y}||_p \leq ||\vec{x}||_p + ||\vec{y}||_p$$

known as **Minkowski's Inequality** ■

Definition 5.2.4. We denote \mathbb{R}^n or \mathbb{C}^n together with the p -norm as ℓ_n^p .

Example 5.2.6. Let (X, d) be a metric space. Then X is also a metric space with the metric $\tilde{d} = \frac{d}{1+d}$. The first two axioms are immediate from the fact that d is a metric. Now, if $0 \leq a \leq b$, then $\frac{a}{1+a} \leq \frac{b}{1+b}$ since this is true if and only if $a + ab \leq b + ab$, which holds if and only if $a \leq b$. Then

$$\begin{aligned}
 \tilde{d}(x, y) &= \frac{d(x, y)}{1 + d(x, y)} \leq \frac{d(x, z) + d(z, y)}{1 + d(x, z) + d(z, y)} \\
 &= \frac{d(x, z)}{1 + d(x, z) + d(z, y)} + \frac{d(z, y)}{1 + d(x, z) + d(z, y)} \\
 &\leq \frac{d(x, z)}{1 + d(x, z)} + \frac{d(z, y)}{1 + d(z, y)} \\
 &= \tilde{d}(x, z) + \tilde{d}(z, y)
 \end{aligned}$$

Even if V is a normed linear space, and d is induced by a norm, the metric \tilde{d} is never induced by a norm, unless V is zero dimensional. Indeed, suppose $d(v, w) = ||v - w||$ and $\dim V > 0$, then $\tilde{d}(v, w) = \frac{||v-w||}{1+||v-w||}$. Assume for the sake of contradiction that $\tilde{d}(v, w) = |||v - w|||$ for some norm $||| \cdot |||$. If $v \neq 0$, $\tilde{d}(v, 0) = |||v||| = \frac{||v||}{1+||v||}$. But

$$|||2v||| = \frac{||2v||}{1+||2v||} = \frac{2||v||}{1+2||v||} \neq \frac{2||v||}{1+||v||} = 2|||v|||$$

Sequences and Limits

Throughout this section let (X, d) be a metric space. Then we can define convergence of sequences as follows:

Definition 5.2.5. A sequence, that is a denumerable list of elements, (x_n) in a metric space (X, d) is said to converge if there is an $x \in X$ such that for all $\varepsilon > 0$ there is an $N \in \mathbb{N}$ such that $n \geq N$ implies $d(x_n, x) < \varepsilon$. Equivalently, if $\lim_{n \rightarrow \infty} d(x_n, x) = 0$.

Example 5.2.7. Vectors \vec{x}_n in ℓ_n^p converge to \vec{x} if and only if $||\vec{x}_n - \vec{x}||_p \rightarrow 0$.

This is identical for all normed linear spaces

Example 5.2.8. f_n in $C_b(S)$ for $S \subseteq \mathbb{R}$ converge to $f \in C_b(S)$ if and only if $\|f_n - f\|_\infty \rightarrow 0$. That is, convergence in this space is uniform convergence.

Definition 5.2.6. A sequence $(x_j)_{j=1}^\infty$ in a metric space X is said to be **Cauchy** (with respect to d) if and only if $d(x_j, x_k)$ converges to 0 in \mathbb{R} as k and j go to infinity. Equivalently, if and only if for all $\varepsilon > 0$ there is an $N \in \mathbb{N}$ such that $m, n \geq N$ implies

$$d(x_n, x_m) < \varepsilon$$

Proposition 5.2.8. In any metric space (X, d) , convergent sequences are Cauchy.

Proof. Suppose $x_n \rightarrow x$ in X . Then for $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that for $n \geq N$, $d(x_n, x) < \varepsilon/2$. It follows that for $m, n \geq N$,

$$d(x_n, x_m) \leq d(x_n, x) + d(x, x_m) < \varepsilon/2 + \varepsilon/2 = \varepsilon$$

so the sequence is Cauchy. ■

Definition 5.2.7. X is said to be a **complete metric space**, or a **Fréchet space**, if and only if for all Cauchy sequences $(x_j)_{j=1}^\infty \subseteq X$, there exists $x \in X$ such that x_j converges to x .

Example 5.2.9. With respect to the usual absolute value metric, \mathbb{R} is complete. With this same metric, \mathbb{Q} is not complete. For \mathbb{Q} , let x_n = the n th decimal truncation of $\sqrt{2}$. In \mathbb{R} $x_n \rightarrow \sqrt{2}$, and limits are unique. Since \mathbb{Q} is a metric subspace of \mathbb{R} under the same metric, it must have the same limit. But $\sqrt{2} \notin \mathbb{Q}$.

Example 5.2.10. Every discrete space is complete. Indeed, if (X, d) is a discrete space, then x_n converges to $x \in X$ if and only if there exists $N \in \mathbb{N}$ such that $x_n = x$ for all $n \geq N$, and equivalently, x_n is Cauchy if and only if there exists $N \in \mathbb{N}$ such that $x_n = x_m$ for all $n, m \geq N$.

Example 5.2.11. The space $C_b(S)$ for $S \subseteq \mathbb{R}$ is complete. The norm here is the supremum norm, $\|\cdot\|_\infty$. Recall the Cauchy criterion for uniform convergence: $f_n \rightarrow_u f$ if and only if f_n is Cauchy with respect to $\|\cdot\|_\infty$. Additionally, as the uniform limit of a sequence of bounded functions is bounded, the limit function will also be in $C_b(S)$. But, $C_c(S)$ is not generally complete. Consider $f_n \in C_c(\mathbb{R})$, with

$$f_n(x) = \begin{cases} \frac{1}{1+x^2} & x \in [-n, n] \\ \text{"continuous linear piecewise"} & x \in [-n-1, -n] \cup [n, n+1] \\ 0 & x < -(n+1) \text{ or } x > n+1 \end{cases}$$

$f_n \in C_c(\mathbb{R})$ since $(-n-1, n+1) = \{x | f_n(x) \neq 0\}$ has compact closure $[-n-1, n+1]$. First, for $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $\frac{1}{1+N^2} < \varepsilon$. Then for $n \geq N$ we have that $\|f_n - f\|_\infty \leq \frac{1}{1+N^2} < \varepsilon$, so $f_n \rightarrow_u f$. But, $f(x) = \frac{1}{1+x^2} \notin C_c(\mathbb{R})$. So $C_c(\mathbb{R})$ is not complete.

Example 5.2.12. The continuous function on $[0, 1]$ with norm $\|f\|_1 = \int_0^1 |f(x)| dx$ is not complete. Let f_n be the piecewise continuous function

$$f_n(x) = \begin{cases} 1 & 0 \leq x \leq 1/2 \\ -\frac{2}{n} \left(x - \frac{n+2}{2n}\right) & \frac{1}{2} \leq x \leq \frac{1}{2} + \frac{1}{n} \\ 0 & \frac{1}{2} + \frac{1}{n} \leq x \leq 1 \end{cases}$$

Let $n \geq m \in \mathbb{N}$. Then for $0 \leq x \leq 1/2$, $|f_n(x) - f_m(x)| = 0 \leq \frac{1}{n} + \frac{1}{m}$. If $1/2 \leq x \leq 1/2 + 1/n$, then

$$\begin{aligned} \|f_n - f_m\|_1 &= \int_0^1 |f_n(x) - f_m(x)| dx \\ &= \int_{1/2}^{1/2+1/n} |f_n(x) - f_m(x)| dx + \int_{1/2+1/n}^{1/2+1/m} |f_n(x) - f_m(x)| dx \\ &\leq \frac{1}{n} + \frac{1}{m} - \frac{1}{n} \\ &\leq \frac{1}{n} + \frac{1}{m} \end{aligned}$$

Now, fix $\varepsilon > 0$. Find $N \in \mathbb{N}$ such that $\frac{2}{N} < \varepsilon$. Then if $m, n \geq N$, it follows that

$$\|f_n - f_m\|_1 \leq \frac{1}{n} + \frac{1}{m} \leq \frac{1}{N} + \frac{1}{N} < \varepsilon$$

So (f_n) is uniformly Cauchy. Then under the $\|\cdot\|_1$ norm, the limit is $f(x) = 1$, for $0 \leq x \leq 1/2$, and 0 for $1/2 < x \leq 1$. Note that f is integrable and

$$\begin{aligned} \|f - f_n\|_1 &= \int_0^1 |f_n - f| dx \\ &= \int_{1/2}^{1/2+1/n} | -n(x - (n+2)/2n) | dx \\ &= \frac{n+2}{2} x - \frac{n}{2} x^2 \Big|_{1/2}^{1/2+1/n} \\ &= \frac{n+2}{2n} - \frac{n}{2} \left(\frac{1}{n^2} + \frac{1}{n} \right) \\ &= \frac{1}{2} + \frac{1}{n} - \frac{1}{2n} - \frac{1}{2} \\ &= \frac{1}{2n} \rightarrow 0 \end{aligned}$$

But f is not continuous, and so not in $C([0, 1])$. The limit f does however reside in the larger space $L^1([0, 1])$, where it is the limit of f_n . In the subspace $C([0, 1])$, there is no limit.

Proposition 5.2.9. *Limits of convergent sequences are unique in any metric space.*

Proof. Suppose $x_n \rightarrow x$ and $x_n \rightarrow y$. Then $d(x, y) \leq d(x, x_n) + d(x_n, y) \rightarrow 0 + 0 = 0$, so $d(x, y) = 0$ which holds if and only if $x = y$ by properties of metrics. ■

Theorem 5.2.10. *Let $\{\vec{x}_m\}$ be a sequence of vectors in \mathbb{R}^n . Write $\vec{x}_m = (x_{m,1}, \dots, x_{m,n})$ so that each $\{x_{m,i}\}$ is a sequence of real numbers. Then \vec{x}_m converges in any p -norm if and only if each $x_{m,i}$ converges.*

Proof. First, if $p = \infty$, then $\|\vec{x}_k - \vec{x}\|_\infty \rightarrow 0$ if and only if $\max_{1 \leq k \leq n} |x_{k,i} - x_i| \rightarrow 0$, which occurs if and only if $|x_{k,i} - x_i| \rightarrow 0$ for all $1 \leq i \leq n$, as desired.

Next, suppose $1 \leq p < \infty$. Then

$$\begin{aligned} |x_{k,i} - x_i| &= (|x_{k,i} - x_i|^p)^{1/p} \\ &\leq \left(\sum_{i=1}^n |x_{k,i} - x_i|^p \right)^{1/p} \\ &= \|\vec{x}_k - \vec{x}\|_p \end{aligned}$$

so if $\|\vec{x}_k - \vec{x}\|_p \rightarrow 0$, then $|x_{k,i} - x_i| \rightarrow 0$ for all $1 \leq i \leq n$. Conversely, if each $x_{k,i} \rightarrow x_i$ for all $1 \leq i \leq n$, then

$$\|\vec{x}_k - \vec{x}\|_p^p = \sum_{i=1}^n |x_{k,i} - x_i|^p \rightarrow 0 + \dots + 0$$

so $\|\vec{x}_k - \vec{x}\|_p \rightarrow 0$ ■

Corollary 5.2.11. *The space ℓ_n^p is complete for any $p \geq 1$, including $p = \infty$, and any $n \geq 1$.*

Proof. Using the same notation and argument in the previous proposition, we can show (\vec{x}_k) in ℓ_n^p is Cauchy if and only if $\{x_{k,i}\}$ is Cauchy in \mathbb{R} for all $1 \leq i \leq n$. But $\{x_{k,i}\}$ is Cauchy in \mathbb{R} if and only if it converges since \mathbb{R} is a complete metric space. Thus, by the proposition (\vec{x}_k) converges in ℓ_n^p ■

Example 5.2.13 (Doubly recursive sequence in \mathbb{R}^2). In ℓ_2^2 let $\vec{v}_0 = [0 \ 0]^T$ and $\vec{v}_n = [x_n \ y_n]^T$ where

$$x_{n+1} = \frac{x_n + y_n + 1}{2}$$

and

$$y_{n+1} = \frac{x_n - y_n + 1}{2}$$

So for instance $\vec{v}_1 = [1/2 \ 1/2]^T$, $\vec{v}_2 = [1 \ 1/2]^T$, $\vec{v}_3 = [5/4 \ 3/4]^T$, and $\vec{v}_4 = [3/2 \ 3/4]^T$. I claim that $\vec{v}_n \rightarrow [2 \ 1]^T$. For now, assume it converges to $[x \ y]^T$. Then

$$[x \ y]^T = \lim_{n \rightarrow \infty} \frac{1}{2} [x_n + y_n + 1 \ x_n - y_n + 1]^T = \frac{1}{2} [x + y + 1 \ x - y + 1]^T$$

using our previous result. Then $x = y + 1$ and $3y = x + 1$, so $3y - 1 = y + 1$, and $2y = 2$. It follows that $y = 1$ and $x = 2$. So now we show $[2 \ 1]$ is the limit. Compute

$$\begin{aligned} \|\vec{v}_{n+1} - [2 \ 1]^T\|_2^2 &= \|[x_{n+1} \ y_{n+1}]^T - [2 \ 1]^T\|_2^2 \\ &= \|[x_n + y_n + 1 \ x_n - y_n + 1]^T / 2 - [2 \ 1]^T\|_2^2 \\ &= \left(\frac{x_n + y_n + 1}{2} - 2 \right)^2 + \left(\frac{x_n - y_n + 1}{2} - 1 \right)^2 \\ &= \frac{(x_n + y_n - 3)^2}{4} + \frac{(x_n - y_n - 1)^2}{4} \\ &= \frac{x_n^2 + y_n^2 + 2x_n y_n - 6x_n - 6y_n + 9 + x_n^2 + y_n^2 - 2x_n y_n - 2x_n + 2y_n + 1}{4} \\ &= \frac{2x_n^2 - 8x_n + 2y_n^2 - 4y_n + 10}{4} \end{aligned}$$

$$\begin{aligned}
 &= \frac{2(x_n - 2)^2 + 2(y_n - 1)^2}{4} \\
 &= \frac{(x_n - 2)^2}{2} + \frac{(y_n - 1)^2}{2} \\
 &= \frac{1}{2} \|[x_n - 2 \ y_n - 1]^T\|_2^2 \\
 &= \frac{1}{2} \|\vec{v}_n - [2 \ 1]^T\|_2^2 && \text{(iterate this argument)} \\
 &= \frac{1}{2^{n+1}} \|\vec{v}_0 - [2 \ 1]^T\|_2^2 \\
 &= \frac{5}{2^{n+1}} \rightarrow 0
 \end{aligned}$$

as claimed.

5.3.0 Topology of Metric Spaces

We now define the natural topology on metric spaces defined by their metrics:

Definition 5.3.1. Let (X, d) be a metric space. For $x_0 \in X$ and $r > 0$, define the open ball centred at x_0 of radius r by

$$B_r(x_0) = \{x \in X \mid d(x, x_0) < r\}$$

The closed ball centred at x_0 of radius r is

$$\overline{B}_r(x_0) = \{x \in X \mid d(x, x_0) \leq r\}$$

If V is a normed linear space, the unit ball is the set $B_1(0)$ and the closed unit ball is the set $\overline{B}_1(0)$.

Example 5.3.1. We draw the unit balls for $\ell_2^1, \ell_2^2, \ell_2^4$, and ℓ_2^∞ . Note for $p = 1$

$$B_1(\vec{0}) = \{[x \ y]^T \mid |x| + |y| < 1\}$$

for $p = 2$,

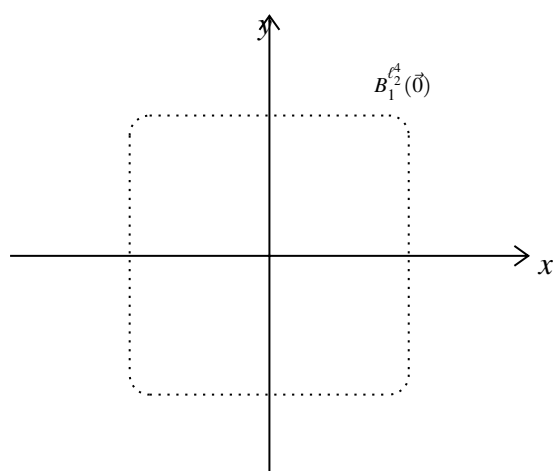
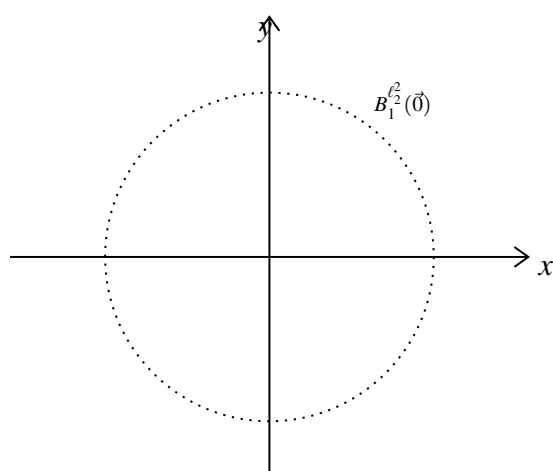
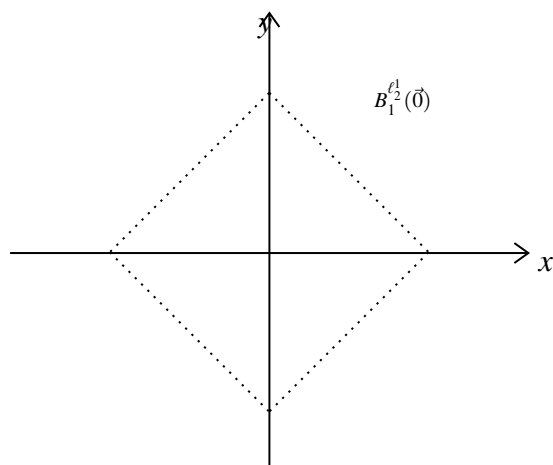
$$B_1(\vec{0}) = \{[x \ y]^T \mid x^2 + y^2 < 1\}$$

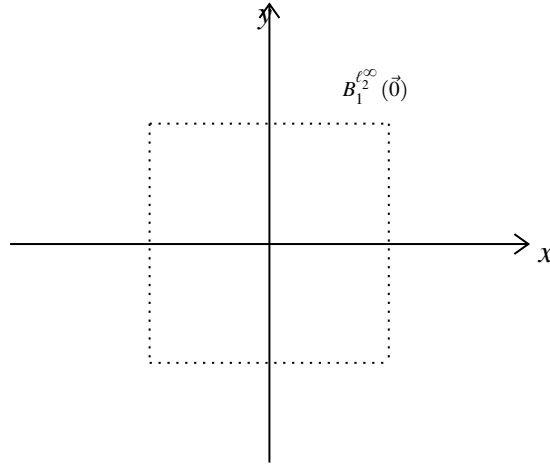
for $p = 4$

$$B_1(\vec{0}) = \{[x \ y]^T \mid x^4 + y^4 < 1\}$$

and for $p = \infty$

$$B_1(\vec{0}) = \{[x \ y]^T \mid \max\{|x|, |y|\} < 1\}$$





Example 5.3.2. The closed unit ball for $C([0, 1])$ is given by

$$\overline{B}_1(0) = \{f \mid \|f\|_\infty \leq 1\}$$

which is any function $f \in C([0, 1])$ contained in the unit rectangle.

Definition 5.3.2 (Interior). Suppose (X, d) is a metric space and $x_0 \in S \subseteq X$. We say that x_0 is an **interior point for S** if there is an $r > 0$ such that $B_r(x_0) \subseteq S$. The **interior of S** , denoted $\text{Int}S$ or S° is the set of all interior points for S . We say that S is **open in X** if $S = S^\circ$.

Example 5.3.3. In any metric space X , both X and \emptyset are always open. \emptyset is open since it contains only interior points, vacuously. If $x_0 \in X$, then $B_r(x_0) \subseteq X$ for any $r > 0$ by definition.

Example 5.3.4. Any open ball is open. Fix $x_0 \in X$ and $r > 0$. Let $y \in B_r(x_0)$. Let $\delta = r - d(y, x_0) > 0$. Then for all $z \in B_\delta(y)$, $d(z, x_0) \leq d(z, y) + d(y, x_0) < \delta + d(y, x_0) = r$, so $z \in B_r(x_0)$. Thus $B_\delta(y) \subseteq B_r(x_0)$, so the ball is indeed open.

Example 5.3.5. Suppose X is any set and d the discrete metric. Then every subset of X is open. Indeed, for any x_0 , $B_{1/2}(x_0) = \{x_0\}$. Thus, if $S \subseteq X$, for all $x \in S$, $B_{1/2}(x) \subseteq S$ so S is open.

Example 5.3.6. The set $S = \{(x, y) \mid y > x^2\}$ is open in ℓ_2^p for any $p \geq 1$. Let $f(x, y) = y - x^2$, so $S = f^{-1}((0, \infty)) = \{(x, y) \mid f(x, y) > 0\}$. Then f is continuous and as we will show later, this implies the inverse image of an open set is open in X .

Proposition 5.3.1. Let I be an arbitrary index set and $\{V_i\}_{i \in I}$ a collection of open sets in a metric space X . Then $\bigcup_{i \in I} V_i$ is open in X . If U_1, \dots, U_n are open sets in X , then $\bigcap_{i=1}^n U_i$ is open in X .

Proof. Let $V = \bigcup_{i \in I} U_i$, and let $x \in V$. Then there exists $i \in I$ such that $x \in U_i$. As U_i is open there exists $r > 0$ such that $B_r(x) \subseteq U_i \subseteq V$, so V is also open. Let $U = \bigcap_{i=1}^n U_i$ and let $x \in U$. Then for each i , $x \in U_i$ so as U_i is open there exists $r_i > 0$ such that $B_{r_i}(x) \subseteq U_i$. Let $r = \min\{r_1, \dots, r_n\} > 0$. Then $B_r(x) \subseteq B_{r_i}(x) \subseteq U_i$ for all i , so $B_r(x) \subseteq U$. Thus, U is indeed open as claimed. ■

Example 5.3.7. The intersection of infinitely many open sets may not be open. Using the usual metric on \mathbb{R} , $\bigcap_{n=1}^\infty (-1/n, 1/n) = \{0\}$, which is not open in \mathbb{R} .

Definition 5.3.3. Let X be a metric space. We say that $S \subseteq X$ is closed in X if $X \setminus S$ is open in X .

Example 5.3.8. In any metric space X , the subsets X and \emptyset are always closed.

Example 5.3.9. Closed balls are closed:

$$\overline{B}_r(x_0) = \{y \in X \mid d(x_0, y) \leq r\}$$

So $X \setminus \overline{B}_r(x_0) = \{y \in X \mid d(x_0, y) > r\}$ This is open by the same argument used for $B_r(x_0)$.

Example 5.3.10. In any discrete space, all subsets are closed. Every $X \setminus Y$ is open, so $Y = X \setminus (X \setminus Y)$ is closed.

Proposition 5.3.2. Let I be an arbitrary index set and $\{S_i\}_{i \in I}$ a collection of closed sets in a metric space X . Then $\bigcap_{i \in I} S_i$ is closed in X . If T_1, \dots, T_n are closed sets in X , then $\bigcup_{i=1}^n T_i$ is closed in X .

The proof of these statements follow by the corresponding statements for open sets and deMorgan's laws.

Example 5.3.11. In \mathbb{R} the intervals (a, b) , $(-\infty, b)$, (a, ∞) , and \mathbb{R} are open, the intervals $[a, b]$, $[a, \infty)$, $(-\infty, b]$ and \mathbb{R} are closed, and $(a, b]$ and $[a, b)$ are neither.

With all of this discussion of open and closed, we note that this relies heavily on what our parent space is. For example, if $Z \subseteq Y \subseteq X$ are all metric spaces with the same metric, questions like: is Z open in Y ? Open in X ? Do these coincide? are answered depending on the exact sets X and Y , with the answer to the third being in general no. Consider $Y = [0, 1)$ as a metric space under $d(x, y) = |x - y|$. Y is both open and closed in itself, but neither in \mathbb{R} . A ball in Y is given by $B_r(y_0) = \{y \in Y \mid d(y_0, y) < r\}$. For instance, $[1/2, 1)$ is closed in Y since $Y \setminus [1/2, 1) = [0, 1/2)$ which is open. Why? Well $(0, 1/2)$ are all interior points evidently, but $\{0\}$ is also an interior point since $B_{1/4}(0) = \{y \in [0, 1) \mid |y| < 1/4\} = [0, 1/4) \subseteq [0, 1/2)$.

Proposition 5.3.3. Suppose X is a metric space, and $Y \subseteq X$ is the induced metric space taken by restricting d . Then $V \subseteq Y$ is open in Y if and only if $V = Y \cap U$ for some U which is open in X .

Proof. Suppose $V \subseteq Y$ is open in Y . Then, for all $x \in V$, there exists $r_x > 0$ such that $B_{r_x}^Y(x) = \{y \in Y \mid d(x, y) < r_x\} \subseteq V$. But,

$$B_{r_x}^Y(x) = \{y \in X \mid d(x, y) < r_x\} \cap Y = B_{r_x}(x) \cap Y$$

Then, observe that

$$V = \bigcup_{x \in V} B_{r_x}^Y(x) = \bigcup_{x \in V} B_{r_x}(x) \cap Y = Y \cap \bigcup_{x \in V} B_{r_x}(x)$$

But, $B_{r_x}(x)$ is open in X for all x , so the union is also open in X , and $V = Y \cap U$ for $U = \bigcup_{x \in V} B_{r_x}(x)$ open in X .

Conversely, suppose U is open in X and let $V = U \cap Y$. Let $x \in V$. Then there exists $r > 0$ such that $B_r(x) \subseteq U$ since U is open. Then

$$B_r^Y(x) = B_r(x) \cap Y \subseteq U \cap Y = V$$

so V is open in Y , as claimed. ■

Example 5.3.12 (Products of open sets). Suppose U_1 and U_2 are open in $(\mathbb{R}, |\cdot|)$. Show that $U_1 \times U_2 = \{(x, y) | x \in U_1, y \in U_2\}$ is open in ℓ_2^2 . Let $(x_0, y_0) \in U_1 \times U_2$. Then there exists $r_i > 0$ such that $B_{r_1}(x_0) \subseteq U_1$ and $B_{r_2}(y_0) \subseteq U_2$. Let $r = \min\{r_1, r_2\}/2$. We claim $B_r((x_0, y_0)) \subseteq U_1 \times U_2$. If $(x, y) \in B_r((x_0, y_0))$, then

$$|x - x_0| \leq \sqrt{(x - x_0)^2 + (y - y_0)^2} < r \leq r_1/2 < r_1$$

and identically for $|y - y_0|$, so $x \in U_1$ and $y \in U_2$, so $(x, y) \in U_1 \times U_2$. Thus $B_r((x_0, y_0)) \subseteq U_1 \times U_2$ so $U_1 \times U_2$ is open.

If X_1, \dots, X_n are metric spaces with metrics d_1, \dots, d_n , then for any $p \geq 1$ the set $X_1 \times \dots \times X_n$ is a metric space under the metric

$$d((x_1, \dots, x_n), (y_1, \dots, y_n)) := \left[\sum_{i=1}^n d_i(x_i, y_i)^p \right]^{1/p}$$

Boundary and Limit Points

Definition 5.3.4. Suppose X is a metric space and $S \subseteq X$. We say that $x_0 \in X$ is a **boundary point for S** if for all $r > 0$, the intersections $B_r(x_0) \cap S$ and $B_r(x_0) \cap (X \setminus S)$ are non-empty. The **boundary of S** , denoted $\text{Bd}S$ or ∂S , is the set of all boundary points for S .

x_0 is said to be an **accumulation point for S** (or limit point, or cluster point) if for all $r > 0$, the intersection $(B_r(x_0) \setminus \{x_0\}) \cap S$ is non-empty. The set of accumulation points for S is denoted S' , and called the **derived set**.

$x_0 \in S$ is said to be an **isolated point for S** if x_0 is not in S' . Equivalently, there exists $r > 0$ such that $(B_r(x_0) \setminus \{x_0\}) \cap S = \emptyset$.

The interior and isolated points for S belong to S , by definition. But boundary points and accumulation points for S may or may not belong to S .

Example 5.3.13 (Subsets of \mathbb{R}). Let $S = (-\infty, -3) \cup [1, 2) \cup \{3\} \cup \{\pi\}$. Then $S^\circ = (-\infty, -3) \cup (1, 2)$, $\partial S = \{-3, 1, 2, 3, \pi\}$, $S' = (-\infty, -3] \cup [1, 2]$, and the isolated points are $S \setminus S' = \{3, \pi\}$. Note that $S \cup S' = S \cup \partial S$ (this isn't a coincidence).

Example 5.3.14. Consider $S = \{(x, y) \in \ell_2^2 | y^2 - x^2 > 1\}$. S is open, so $S^\circ = S$. $\partial S = \{(x, y) | y^2 - x^2 = 1\}$, and in this case $S^\circ \subseteq S'$, so $S' = S \cup \partial S = \{(x, y) | y^2 - x^2 \geq 1\}$. There are no isolated points for this set.

Example 5.3.15. Consider $\mathbb{Q}^n \subseteq \ell_n^p$. Then $\partial\mathbb{Q}^n = \mathbb{R}^n$, $(\mathbb{Q}^n)' = \mathbb{R}^n$ (\mathbb{Q}^n is dense in \mathbb{R}^n), $\mathbb{Q}^{n\circ} = \emptyset$, and there are no isolated points. This follows from $\mathbb{Q}' = \partial\mathbb{Q} = \mathbb{R}$ and $\mathbb{Q}^\circ = \emptyset$ in \mathbb{R} under the usual metric.

Example 5.3.16. Let V be a normed linear space, $r > 0$, and $v_0 \in V$. Then $B_r(v_0)$ is open so $B_r^\circ(v_0) = B_r(v_0)$. Further, $\partial(B_r(v_0)) = \{v \in V \mid \|v - v_0\| = r\}$ (the sphere of radius r).

Example 5.3.17. If X is any set under the discrete metric, we've already seen that any $S \subseteq X$ is both open and closed. Every point in S is isolated since $B_{1/2}(x_0) = \{x_0\} \subseteq S$. But, $\partial S = \emptyset$ since $B_{1/2}(x_0) = \{x_0\}$, so either $B_r(x_0) \cap S$ or $B_r(x_0) \cap (X \setminus S)$ is empty.

Proposition 5.3.4. A subset S of a metric space X is closed in X if and only if $S' \subseteq S$.

Proof. Suppose S is closed in X and $x_0 \in S'$. For the sake of contradiction suppose $x_0 \in X \setminus S = U$, which is open. Then there exists $r > 0$ such that $B_r(x_0) \subseteq U$. But then $B_r(x_0) \cap S = \emptyset$, which implies $(B_r(x_0) \setminus \{x_0\}) \cap S = \emptyset$, contradicting the fact that $x_0 \in S'$. Thus, $S' \subseteq S$.

Conversely, suppose $S' \subseteq S$, and towards a contradiction suppose S is not closed, so $U = X \setminus S$ is not open. Then there exists $x \in U$ such that for all $r > 0$, $B_r(x) \not\subseteq U$, and in particular $(B_r(x) \cap \{x\}) \cap S \neq \emptyset$ for all $r > 0$. Thus, by definition $x \in S'$. But then $x \in S$ as $S' \subseteq S$, and $x \in X \setminus S$ which implies $x \notin S$, which is a contradiction. Consequently we conclude that S must be closed. ■

Proposition 5.3.5. Suppose X is a metric space with $x_0 \in X$ and $S \subseteq X$. Then $x_0 \in S'$ if and only if there is a sequence $\{x_n\}$ in $S \setminus \{x_0\}$ with x_n converging to x_0 .

Proof. If $x_0 \in S'$, then for all $n \in \mathbb{N}$, $B_{1/n}^*(x_0) \cap S \neq \emptyset$, where $B_{1/n}^*(x_0) = (B_{1/n}(x_0) \setminus \{x_0\})$. Then by the axiom of choice, for each $n \in \mathbb{N}$ we can choose $x_n \in (B_{1/n}(x_0) \setminus \{x_0\}) \cap S$. Then $0 < d(x_0, x_n) < 1/n$ for each n . Thus $\lim_{n \rightarrow \infty} d(x_0, x_n) = 0$, so $\lim_{n \rightarrow \infty} x_n = x_0$.

Conversely, suppose there exists $\{x_n\} \subseteq S \setminus \{x_0\}$ with $d(x_n, x_0) \rightarrow 0$. If $r > 0$, find $N \in \mathbb{N}$ such that if $n \geq N$, $d(x_n, x_0) < r$. Then $x_N \in B_r^*(x_0) \cap S$, so as r was arbitrary $x_0 \in S'$. ■

Example 5.3.18. The general linear group over the reals of order 2 is given by

$$\mathbf{GL}_2(\mathbb{R}) := \{A \in M_2(\mathbb{R}) \mid \det A \neq 0\}$$

Think of $\mathbf{GL}_2(\mathbb{R})$ as a subset of ℓ_4^2 (as a metric space). That is,

$$d\left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}, \begin{bmatrix} x & y \\ z & t \end{bmatrix}\right) := \sqrt{(a-x)^2 + (b-y)^2 + (c-z)^2 + (d-t)^2}$$

Then $\mathbf{GL}_2(\mathbb{R})$ is open in $M_2(\mathbb{R})$. We will show $M_2(\mathbb{R}) \setminus \mathbf{GL}_2(\mathbb{R})$ is closed. Combining the above two results, it suffices to show that if $A_n = \begin{bmatrix} a_n & b_n \\ c_n & d_n \end{bmatrix} \in M_2(\mathbb{R}) \setminus \mathbf{GL}_2(\mathbb{R})$ and $A_n \rightarrow A = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in M_2(\mathbb{R})$, then $A \in M_2(\mathbb{R}) \setminus \mathbf{GL}_2(\mathbb{R})$. We know in ℓ_4^2 that $\begin{bmatrix} a_n & b_n \\ c_n & d_n \end{bmatrix} \rightarrow \begin{bmatrix} a & b \\ c & d \end{bmatrix}$ if and only if $a_n \rightarrow a, b_n \rightarrow b, c_n \rightarrow c$, and $d_n \rightarrow d$. Then $0 = a_n d_n - b_n c_n \rightarrow ad - bc = \det(A)$, so $\det(A) = 0$ and $A \in M_2(\mathbb{R}) \setminus \mathbf{GL}_2(\mathbb{R})$ as desired.

Definition 5.3.5 (Closures). Suppose X is a metric space and $S \subseteq X$. The closure of S in X is the set

$$\overline{S} = \bigcap \{B \subseteq X \mid S \subseteq B \text{ and } B \text{ is closed}\}$$

Note that \overline{S} is an intersection of closed sets, and hence closed. Additionally, $S \subseteq \overline{S}$ by construction. Finally, \overline{S} is the smallest closed set containing S . If $S \subseteq C$ and C is closed, then C is a part of the collection being intersected so $C \supseteq \overline{S}$.

Proposition 5.3.6. Suppose X is a metric space and $S \subseteq X$. Then S is closed in X if and only if $\overline{S} = S$.

Proof. If $S = \overline{S}$, then S is closed from the discussion above. If S is closed then it is in the collection being intersected so $\overline{S} \subseteq S$. But $S \subseteq \overline{S}$, by construction, so $S = \overline{S}$. ■

Proposition 5.3.7. Suppose X is a metric space and $S \subseteq X$. Then S is closed in X if and only if whenever x_n is a convergent sequence in S then its limit also belongs to S .

Proof. If S is closed, we know $S' \subseteq S$. Suppose $(x_n) \subseteq S$, with $x_n \rightarrow x \in X$. If $x \in S'$, then $x \in S$ and we are done. Otherwise $x \notin S'$. So there exists $r > 0$ such that $B_r^*(x) \cap S = \emptyset$. But, there exists $N \in \mathbb{N}$ such that $x_n \in B_r(x)$ for $n \geq N$, while $x_n \notin B_r^*(x)$, so $x_n \in \{x\}$ for all $n \geq N$. Thus, $x = x_N \in S$.

Conversely, suppose S has the property that whenever $(x_n) \subseteq S$ with $x_n \rightarrow x \in X$, then $x \in S$. We know if $x_0 \in S'$, there exists $(x_n) \subseteq S$ with $x_n \rightarrow x_0$, so $x_0 \in S$ by assumption. Hence $S' \subseteq S$ and S is closed. ■

Example 5.3.19. Suppose $A \subseteq B \subseteq X$. We claim $A^\circ \subseteq B^\circ$. Indeed, if $x_0 \in A^\circ$, then there exists $r > 0$ such that $B_r(x_0) \subseteq A \subseteq B$, and hence $x_0 \in B^\circ$. However, both statements $\partial A \subseteq \partial B$ and $\partial B \subseteq \partial A$ are false in general. Take $A = [0, 1]$, $B = [-1, 2]$. Then $\partial A = \{0, 1\}$ and $\partial B = \{-1, 2\}$.

Example 5.3.20. Consider the balls $B_r(x_0) = \{x \in X \mid d(x, x_0) < r\}$ and $\overline{B}_r(x_0) = \{x \in X \mid d(x, x_0) \leq r\}$. What is $\overline{B_r(x_0)}$? First, we have $B_r(x_0) \subseteq \overline{B}_r(x_0)$, which is closed, so $\overline{B_r(x_0)} \subseteq \overline{B}_r(x_0)$. This inclusion can be in some cases strict:

Let X be any set with at least two elements equipped with the discrete metric. Then $\overline{B}_1(x_0) = X$, but $B_1(x_0) = \{x_0\}$ is closed so $\overline{B_1(x_0)} = \{x_0\} \neq X$.

In a normed linear space, we always have $\overline{B_r(v_0)} = \overline{B}_r(v_0)$. First look at $v_0 = 0$. Then $B_r(0) = \{v \mid \|v\| < r\}$ and if $\|v\| = r$ then let $v_n = (1 - 1/n)v$; Then $\|v_n\| = (1 - 1/n)r < r$, so $v_n \in B_r(0)$ for all n and $\|v_n - v\| \rightarrow 0$. This implies $v \in B_r(0)'$, so $v \in \overline{B_r(0)}$ and $\overline{B_r(0)} = \overline{B}_r(0)$. If $v_0 \neq 0$, we use the identities

$$B_r(v_0) = \{v \mid \|v - v_0\| < r\} = \{v + v_0 \mid \|v\| < r\}$$

and $\overline{B}_r(v_0) = \{v + v_0 \mid \|v\| \leq r\}$. Then, take $v_n = v_0 + (1 - 1/n)v$ for $\|v\| = r$, and the same result holds.

Proposition 5.3.8. Suppose X is a metric space and $S \subseteq X$. Then

$$(1) S^\circ = \bigcup \{U \subseteq S \mid U \text{ is open in } X\}$$

(2) S is open if and only if $S^\circ = S$.

Proof. (1): Suppose $x_0 \in S^\circ$. Then there exists $r > 0$ such that $B_r(x_0) \subseteq S$. But $B_r(x_0)$ is open, so $x_0 \in \text{union}$. If $x_0 \in \text{union}$, then $x_0 \in U$ for some open set $U \subseteq S$. U being open implies there exists $r > 0$ such that $B_r(x_0) \subseteq U \subseteq S$, so $x_0 \in S^\circ$ and we have set equality.

(2): S° is open, so evidently if $S^\circ = S$ then S is open. Conversely, if S is open then $x_0 \in S^\circ$ for all $x_0 \in S$, so $S^\circ \subseteq S \subseteq S^\circ$. Hence $S = S^\circ$. ■

Example 5.3.21. Note that $B_r(x_0) = B_r(x_0)^\circ$ as they are open. As $B_r(x_0) \subseteq \overline{B_r(x_0)}$, we also have $B_r(x_0) = B_r(x_0)^\circ \subseteq [\overline{B_r(x_0)}]^\circ$. In a normed linear space we have equality, but in a discrete space, equality may fail.

Question 5.3.1. If S is closed, is it true that $\overline{S^\circ} = S$? If S is open, is it true that $\overline{S^\circ} = S$?

The answer is no to both! In \mathbb{R} , let $S = \mathbb{Z}$. Then $S^\circ = \emptyset$, and $\overline{\emptyset} = \emptyset \neq \mathbb{Z}$. For the second, $\overline{S} = \mathbb{Z}$ since the space has no accumulation points, and $S^\circ = \emptyset \neq \mathbb{Z}$.

Definition 5.3.6 (Bounded Set). A subset S of a metric space X is said to be bounded if there is an $x_0 \in X$ and $r > 0$ such that $S \subseteq B_r(x_0)$.

Example 5.3.22. The usual intervals (a, b) , $[a, b)$, $(a, b]$, $[a, b]$ are all bounded. All of which are contained in $B_{2 \max\{|a|, |b|\}}(0)$.

Example 5.3.23. Bounded subsets of a normed linear space are of the form $S \subseteq B_r(v)$, which implies $\|v - v_0\| < r$ for all $v \in S$, or $\|v\| < r + \|v_0\| = M$ for all $v \in S$, which implies $S \subseteq B_M(0)$. Thus, S is bounded if and only if $\|v\| \leq M$ for all $v \in S$ and for some $M > 0$.

Theorem 27 (Bolzano-Weierstrass).

Suppose $p \in [1, \infty]$ and $n \in \mathbb{N}$. Any bounded sequence in ℓ_n^p has a convergent subsequence.

Proof. Let $(\vec{x}_k) = ((x_{k,1}, \dots, x_{k,n}))$ be a bounded sequence in ℓ_n^p , so there exists $M > 0$ such that

$$\|\vec{x}_k\|_p \leq M$$

for all $k \in \mathbb{N}$. If $p < \infty$, we have $|x_{k,j}| = (|x_{k,j}|^p)^{1/p} \leq M$, and for $p = \infty$ we have directly $|x_{k,j}| \leq M$, for all k and all $1 \leq j \leq n$. So by the Bolzano-Weierstrass theorem for \mathbb{R} , there exists a convergent subsequence $x_{s_1(k),1}$ converging to $x \in \mathbb{R}$. Then $x_{s_1(k),2}$ also has a convergent subsequence $x_{s_2(k),2}$ converging to some $x_2 \in \mathbb{R}$. Continuing in this manner we have that for all $1 \leq j \leq n-1$ there exists a subsequence $x_{s_{j+1}(k),j+1}$ of $x_{s_j(k),j+1}$ converging to some $x_{j+1} \in \mathbb{R}$. Then $(\vec{x}_{s_n(k)})$ is a subsequence in which for all $1 \leq j \leq n$, $x_{s_n(k),j}$ converges to $x_j \in \mathbb{R}$, so $\vec{x}_{s_n(k)} \rightarrow \vec{x} = (x_1, \dots, x_n) \in \ell_n^p$. ■

Corollary 5.3.9. Any bounded and infinite subset S of ℓ_n^p has an accumulation point.

Proof. Choose a sequence of distinct points (\vec{x}_k) in S , which is possible as S is infinite. This sequence is bounded and hence has a convergent subsequence. Let $\vec{x} \in X$ be the limit. If x occurs in the sequence at $N \in \mathbb{N}$, then $\vec{x} \notin (\vec{x}_{k_j})_{j>N}$ as the points are distinct, for our convergent subsequence. Thus, $(\vec{x}_{k_j})_{j>N} \subseteq S \setminus \{\vec{x}\}$, so by definition $\vec{x} \in S'$. ■

5.4.0 Completion of a Metric Space

As in the case of \mathbb{Q} to \mathbb{R} , we can form the completion of a general metric space.

Definition 5.4.1. If (X, d) is not complete, we can define its completion (\hat{X}, \hat{d}) by taking $\hat{X} = \{[(x_j)_{j=1}^\infty] : (x_j)_{j=1}^\infty \subseteq X \text{ is Cauchy}\}$, where $[(x_j)]$ is the equivalence class defined by $(x_j) \sim (x'_j)$ if and only if $d(x_j, x'_j) \rightarrow 0$ in \mathbb{R} . For $\xi = [(x_j)]$ and $\eta = [(y_j)]$, we define

$$\hat{d}(\xi, \eta) := \lim_{j \rightarrow \infty} d(x_j, y_j)$$

It remains to show that \hat{d} is a well defined metric. Note by the triangle inequality $d(x, y) \leq d(x, z) + d(z, y)$, so $d(x, y) - d(x, z) \leq d(y, z)$ and using $d(x, z) \leq d(x, y) + d(y, z)$, $d(x, z) - d(x, y) \leq d(y, z)$. Thus

$$|d(x, z) - d(x, y)| \leq d(y, z)$$

Then suppose $(x_j) \sim (x'_j)$ and $(y_j) \sim (y'_j)$. It follows that

$$\begin{aligned} |d(x_j, y_j) - d(x'_j, y'_j)| &= |d(x_j, y_j) - d(x_j, y'_j) + d(x_j, y'_j) - d(x'_j, y'_j)| \\ &\leq |d(x_j, y_j) - d(x_j, y'_j)| + |d(x_j, y'_j) - d(x'_j, y'_j)| \\ &\leq d(y_j, y'_j) + d(x_j, x'_j) \end{aligned}$$

which goes to 0 as $(x_j) \sim (x'_j)$ and $(y_j) \sim (y'_j)$. This proves that if the limit exists, then it is independent of representative. Now, as \mathbb{R} is complete, to show $\hat{d}(\xi, \eta) = \lim_{j \rightarrow \infty} d(x_j, y_j)$ exists it is sufficient to show $d(x_j, y_j)$ is Cauchy. Then

$$\begin{aligned} |d(x_j, y_j) - d(x_k, y_k)| &= |d(x_j, y_j) - d(x_j, y_k) + d(x_j, y_k) - d(x_k, y_k)| \\ &\leq |d(x_j, y_j) - d(x_j, y_k)| + |d(x_j, y_k) - d(x_k, y_k)| \\ &\leq d(y_j, y_k) + d(x_j, x_k) \end{aligned}$$

which goes to 0 as j and k go to ∞ as (y_j) and (x_j) are Cauchy, so $d(x_j, y_j)$ is Cauchy. Thus \hat{d} is well defined. Further, $\hat{d}(\xi, \eta) = \lim_{j \rightarrow \infty} d(x_j, y_j) \geq 0$, $\hat{d}(\xi, \eta) = 0$ if and only if $d(x_j, y_j) \rightarrow 0$, which holds if and only if $\xi = \eta$ by definition of \sim ,

$$\hat{d}(\xi, \eta) = \lim_{j \rightarrow \infty} d(x_j, y_j) = \lim_{j \rightarrow \infty} d(y_j, x_j) = \hat{d}(\eta, \xi)$$

and

$$\hat{d}(\xi, \eta) = \lim_{j \rightarrow \infty} d(x_j, y_j) \leq \lim_{j \rightarrow \infty} (d(x_j, z_j) + d(z_j, y_j)) = \hat{d}(\xi, \mu) + \hat{d}(\mu, \eta)$$

for any $\mu = [(z_j)] \in \hat{X}$. Thus (\hat{X}, \hat{d}) is indeed a metric space.

Example 5.4.1. Consider $\mathbb{Q}[x]$, the set of polynomials over \mathbb{Q} , and define $d(p, q) = \max_{x \in [0, 1]} |p(x) - q(x)|$. The max exists as $[0, 1]$ is a compact set in \mathbb{R} and all polynomials are continuous. Then $d(p, q) = 0$ if and only if $p = q$, as polynomials of degree > 0 have only a finite number of roots, $d(p, q) = d(q, p)$, and $d(p, q) \leq d(p, r) + d(r, q)$ using the triangle inequality for $|\cdot|$ on \mathbb{R} . Note this is a countable metric space. But, this is not complete as \mathbb{Q} is not complete. Then $(\hat{X}, \hat{d}) = \{[p_j] : (p_j) \text{ is Cauchy in } (\mathbb{Q}[x], d)\}$. We will see that $\hat{X} = C([0, 1])$, all continuous functions in $[0, 1]$. This says if f is continuous in $[0, 1]$, for all $\varepsilon > 0$ there exists $p \in \mathbb{Q}[x]$ such that $\hat{d}(p, f) < \varepsilon$. Suppose now we define $X = \mathbb{Q}[x]$ with the distance

$$d_1(p, q) = \max_{x \in [0, 1]} |p(x) - q(x)| + \max_{x \in [0, 1]} |p'(x) - q'(x)|$$

Note $X \subseteq \mathbb{C}^\infty([0, 1])$. Upon completion we obtain $(\hat{X}, \hat{d}_1) = C^1([0, 1])$, the space of all continuous functions with continuous first derivative.

We claim that \hat{X} is indeed a complete metric space:

Lemma 5.4.1. X is dense in \hat{X} .

and

Proposition 5.4.2. (\hat{X}, \hat{d}) is complete.

which follow similarly to the case of \mathbb{R} .

We now proceed with a full derivation:

Theorem 5.4.3 (Completion of a Metric Space). Suppose (X, d) is a metric space. There exists a complete metric space (\hat{X}, \hat{d}) and an isometry $\varphi : X \rightarrow \hat{X}$ so that $\varphi(X)$ is dense in \hat{X} (i.e. that $\overline{\varphi(X)} = \hat{X}$) Moreover, \hat{X} is uniquely determined by this property up to homeomorphism.

Definition 5.4.2. The space \hat{X} above is called the completion of X .

What do we mean when we say unique? Suppose (Y, d_Y) is a metric space with an isometry $\varphi : X \rightarrow Y$ such that $\overline{\varphi(X)} = Y$, with Y complete. Then there is a bijective isometry $\Gamma : Y \rightarrow \hat{X}$ such that

$$\begin{array}{ccc} X & \xrightarrow{\psi} & Y \\ \varphi \downarrow & \swarrow \exists! \Gamma & \\ \hat{X} & & \end{array}$$

the diagram commutes. Defin $\gamma : \psi(X) \rightarrow \hat{X}$ by $\gamma(\psi(x)) := \varphi(x)$ for all $x \in X$. Then γ is an isometry:

$$\hat{d}(\gamma(\psi(x)), \gamma(\psi(y))) := \hat{d}(\varphi(x), \varphi(y)) = d(x, y)$$

since φ is an isometry. Let's extend γ to a map $\Gamma : Y \rightarrow \hat{X}$ by

$$\Gamma(y) = \lim_{n \rightarrow \infty} \gamma(\psi(x_n)) = \lim_{n \rightarrow \infty} \varphi(x_n)$$

where $\psi(x_n) \rightarrow y$, where (x_n) exists since $\overline{\psi(X)} = Y$. Then the following hold:

- Γ is well-defined and isometric
- Γ is onto

Note that if $S \subseteq X$ and X is complete, then $\hat{S} \cong \bar{S}$. In this case, Γ is just the identity $\text{Id} : S \rightarrow \bar{S}$, and note \bar{S} is complete since X is complete.

Example 5.4.2 (The Hardy space of the disk). Let $P = \{a_0 + a_1z + \dots + z_n z^n \mid n \in \mathbb{N} \cup \{0\}, a_i \in \mathbb{C}\}$ denote the polynomials with complex variable z . Define a norm $\|\cdot\|_2$ on P as follows

$$\|a_0 + a_1z + \dots + a_n z^n\|_2 = \sqrt{\sum_{i=0}^n |a_i|^2}$$

P is infinite dimensional with basis $\{1, z, z^2, z^3, \dots\}$, but P is not complete. Let $p_n(z) = \sum_{k=0}^n \frac{z^k}{k!}$. Then $\{p_n\}$ is Cauchy, but cannot converge to any $g(z) = b_0 + b_1z + \dots + b_m z^m$ with respect to $\|\cdot\|_2$, since for $n \gg m$,

$$\|p_n - g\|_2^2 = \sum_{k=0}^m \left| \frac{1}{k!} - b_k \right|^2 + \sum_{k=m+1}^n \frac{1}{(k!)^2} \geq \frac{1}{[(m+1)!]^2} > 0$$

So as $n \rightarrow \infty$, there is no way the right hand side goes to 0. The completion of P is called $H^2(\mathbb{D})$, the **Hardy space of the unit disk**. We define

$$H^2(\mathbb{D}) := \{f : \mathbb{D} \rightarrow \mathbb{C} \mid f \text{ is analytic and } f(z) = \sum_{n=0}^{\infty} a_n z^n \text{ with } \sum_{n=0}^{\infty} |a_n|^2 < \infty\}$$

where $\mathbb{D} = \{z \in \mathbb{C} \mid |z| < 1\}$ with norm $\|f\|_2 = \sqrt{\sum_{n=0}^{\infty} |a_n|^2}$.

We now prove the completion theorem:

Proof. Let (X, d) be a metric space. Let X' denote the set of Cauchy sequences in X . Define a relation on X' as follows: $(x_n) \sim (y_n)$ if and only if $d(x_n, y_n) \rightarrow 0$. \sim is an equivalence relation. Indeed, $d(x_n, x_n) = 0 \rightarrow 0$, $d(y_n, x_n) = d(x_n, y_n) \rightarrow 0$, and if $(x_n) \sim (y_n) \sim (z_n)$, then

$$d(x_n, z_n) \leq d(x_n, y_n) + d(y_n, z_n) \rightarrow 0$$

Let \hat{X} denote the set of equivalence classes arising from \sim . Given $[(x_n)]$ and $[(y_n)]$ in \hat{X} , define $a_n := d(x_n, y_n)$. (a_n) is Cauchy in \mathbb{R} since

$$|a_n - a_m| = |d(x_n, y_n) - d(x_m, y_m)| \leq d(x_n, x_m) + d(y_n, y_m) \rightarrow 0$$

since (x_n) and (y_n) are Cauchy in X . \mathbb{R} is complete with respect to $|\cdot|$, so a_n has a limit, say a . Define \hat{d} on $\hat{X} \times \hat{X}$ by

$$\hat{d}([(x_n)], [(y_n)]) := \lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} d(x_n, y_n)$$

We must show \hat{d} is well defined, so suppose $(x_n) \sim (x'_n)$ and $(y_n) \sim (y'_n)$. Then

$$|d(x_n, y_n) - d(x'_n, y'_n)| \leq d(x_n, x'_n) + d(y_n, y'_n) \rightarrow 0$$

so $\lim_{n \rightarrow \infty} d(x_n, y_n) = \lim_{n \rightarrow \infty} d(x'_n, y'_n)$.

Since d is a metric, \hat{d} is a metric as it is the limit of this metric and limits are additive and satisfy order preservation properties. Define $\varphi : X \rightarrow \hat{X}$ by $\varphi(x) = [(x, x, x, \dots)]$, which is the equivalence class of all Cauchy sequences (y_n) with $d(y_n, x) \rightarrow 0$, i.e. all sequences converging to x . φ is an isometry since

$$\hat{d}(\varphi(x), \varphi(y)) = \lim_{n \rightarrow \infty} d(x, y) = d(x, y)$$

Next, to show $\overline{\varphi(X)} = \hat{X}$, let $\hat{x} = [(x_n)] \in \hat{X}$ and fix $\varepsilon > 0$. (x_n) is Cauchy in X by construction. So there exists $N \in \mathbb{N}$ such that for $m \geq N$, $d(x_N, x_m) < \varepsilon$. Then it follows that

$$\hat{d}(\hat{x}, \varphi(x_N)) = \lim_{n \rightarrow \infty} d(x_n, x_N) \leq \varepsilon$$

Finally, we show \hat{X} is complete. Suppose (\hat{x}_k) is a Cauchy sequence in \hat{X} . For $k \in \mathbb{N}$, choose \hat{z}_k in $\varphi(X)$ such that

$$\hat{d}(\hat{x}_k, \hat{z}_k) < \frac{1}{k}$$

Then

$$\hat{d}(\hat{z}_k, \hat{z}_m) \leq \hat{d}(\hat{z}_k, \hat{x}_k) + \hat{d}(\hat{x}_k, \hat{x}_m) + \hat{d}(\hat{x}_m, \hat{z}_m) \leq \frac{1}{k} + \hat{d}(\hat{x}_k, \hat{x}_m) + \frac{1}{m}$$

which goes to zero as m and k go to infinity. So (\hat{z}_k) is Cauchy in $\varphi(X)$. Noting that $\varphi : X \rightarrow \varphi(X)$ is invertible since φ is Cauchy, let $y_k = \varphi^{-1}(\hat{z}_k) \in X$. Then (y_k) is Cauchy in X since (\hat{z}_k) is Cauchy in $\varphi(X)$, and φ^{-1} is an isometry. Let \hat{y} be the equivalence class in \hat{X} which includes (y_k) . Then

$$\hat{d}(\hat{x}_k, \hat{y}) \leq \hat{d}(\hat{x}_k, \hat{z}_k) + \hat{d}(\hat{z}_k, \hat{y}) < \frac{1}{k} + \lim_{n \rightarrow \infty} d(y_k, y_n)$$

which goes to zero as (y_k) is Cauchy, so \hat{y} is the limit of \hat{x}_k in \hat{X} , and \hat{X} is complete! ■

5.5.0 Contractive Maps and Fixed Points

Definition 5.5.1 (Contractive Map). Suppose X is a metric space. A function $f : X \rightarrow X$ is a **contractive map** (distance shrinking) if there is a constant $r \in (0, 1)$ with $d(f(x), f(y)) \leq rd(x, y)$ for all $x, y \in X$.

Contractive maps are uniformly continuous, as they are Lipschitz.

Example 5.5.1. A bounded operator $T : V \rightarrow V$ is contractive if $\|T\| \leq r < 1$ for some r , so

$$\|Tv - Tw\| \leq \|T\| \|v - w\| \leq r \|v - w\|$$

Theorem 28 (Banach Fixed Point Theorem (or the Contraction Mapping Principle)).

Suppose X is a **complete metric space** and $f : X \rightarrow X$ is a contractive map. Then f has a **unique** fixed point. That is there is a unique $x_0 \in X$ such that $f(x_0) = x_0$.

Proof. For uniqueness suppose x_1 and x_2 are both fixed points, $f(x_1) = x_1$ and $f(x_2) = x_2$. Then

$$d(x_1, x_2) = d(f(x_1), f(x_2)) \leq rd(x_1, x_2)$$

for some $0 < r < 1$. This holds if and only if $d(x_1, x_2) = 0$, which is to say $x_1 = x_2$.

For existence suppose $x_1 \in X$. Define $x_2 = f(x_1)$, $x_3 = f(x_2)$, and in general $x_n = f^{n-1}(x_1)$. For $n \in \mathbb{N}$ and $k \in \mathbb{N}$,

$$\begin{aligned} d(x_{n+k}, x_n) &= d(f^{n+k-1}(x_1), f^{n-1}(x_1)) \\ &\leq r^{n-1} d(f^k(x_1), x_1) = r^{n-1} d(x_{k+1}, x_1) \\ &\leq r^{n-1} [d(x_{k+1}, x_k) + d(x_k, x_{k-1}) + \dots + d(x_2, x_1)] \\ &= r^{n-1} \sum_{j=0}^{k-1} r^j d(x_2, x_1) \\ &\leq r^{n-1} \frac{1}{1-r} d(x_2, x_1) \end{aligned}$$

This implies (x_n) is Cauchy in X , and so there exists x_0 with $x_n \rightarrow x_0$ by completeness. Then

$$f(x_0) = f(\lim_{n \rightarrow \infty} x_n) = \underbrace{\lim_{n \rightarrow \infty} f(x_n)}_{\text{continuity}} = \lim_{n \rightarrow \infty} x_{n+1} = x_0$$

so $f(x_0) = x_0$. ■

Theorem 5.5.1 (Picard's Theorem for First Order Differential Equations). Suppose $(x_0, y_0) \in \ell_2^2$, $r > 0$, and let $B = B_r(x_0, y_0)$. If $f : B \rightarrow \mathbb{R}$ is continuous and bounded and there is a $C > 0$ such that

$$|f(x, y_1) - f(x, y_2)| \leq C|y_1 - y_2|$$

for all pairs (x, y_1) and (x, y_2) in B , then there exists a unique solution y to the initial value problem

$$\frac{dy}{dx} = f(x, y); y(x_0) = y_0$$

on the interval $(x_0 - \delta, x_0 + \delta)$ for some $\delta > 0$.

Proof. Let $M = \sup_{(x,y) \in B} |f(x, y)|$. Find $\delta > 0$ such that

$$(i) \quad \delta < \frac{1}{M}$$

$$(ii) \{(x, y) \mid |x - x_0| < \delta, |y - y_0| < M\delta\} \subseteq B$$

$$(iii) \delta < \frac{1}{C}$$

Let $X = \{\varphi \in C([x_0 - \delta, x_0 + \delta]) \mid |\varphi(x) - y_0| \leq M\delta\}$. X consists of continuous functions whose graph is in the open rectangle described in (ii). Note $C([x_0 - \delta, x_0 + \delta])$ is a complete space, with uniform metric. X is a closed subset of $C([x_0 - \delta, x_0 + \delta])$. Indeed, if $f_n \in X$ and $f_n \rightarrow_u f$, then $\lim_{n \rightarrow \infty} |f_n(x) - y_0| \leq M\delta$, so $|f(x) - y_0| \leq M\delta$. Thus, X is complete itself. Define a map $T : X \rightarrow X$ by

$$T\varphi(x) = y_0 + \int_{x_0}^x f(t, \varphi(t)) dt$$

and this process is called the **Picard iteration**. Note $T\varphi$ is continuous on $[x_0 - \delta, x_0 + \delta]$. Further,

$$|T\varphi(x) - y_0| \leq \left| \int_{x_0}^x |f(t, \varphi(t))| dt \right| \leq \delta M$$

so $T\varphi \in X$, and T is well-defined. Further, T is contractive since

$$\begin{aligned} |T\varphi_1(x) - T\varphi_2(x)| &\leq \int_{x_0}^x |f(t, \varphi_1(t)) - f(t, \varphi_2(t))| dt \\ &\leq \int_{x_0}^x C |\varphi_1(t) - \varphi_2(t)| dt \leq \int_{x_0}^x C \sup_{x_0 - \delta < t < x_0 + \delta} |\varphi_1(t) - \varphi_2(t)| dt \\ &= |x - x_0| C \sup |\varphi_1(t) - \varphi_2(t)| \\ &< \delta C \|\varphi_1 - \varphi_2\|_{[x_0 - \delta, x_0 + \delta]} \end{aligned}$$

Taking the supremum

$$\|T\varphi_1 - T\varphi_2\|_\infty \leq \delta C \|\varphi_1 - \varphi_2\|_\infty < \|\varphi_1 - \varphi_2\|_\infty$$

since we assumed $\delta < \frac{1}{C}$. So T is contractive and hence has a fixed point. In particular, there exists $\varphi_0 \in X$ with $\varphi_0(x) = T\varphi_0(x) = y_0 + \int_{x_0}^x f(t, \varphi_0(t)) dt$. Then $\varphi_0(x_0) = y_0 + 0 = y_0$. Finally, by the FTIC1,

$$\frac{d}{dx} \varphi_0(x) = f(x, \varphi_0(x))$$

which is to say $y = \varphi_0(x)$ solves the DE $\frac{dy}{dx} = f(x, y)$ with initial condition $y(x_0) = y_0$. ■

5.6.0 Compactness for Metric Spaces

Recall that $\emptyset \neq S \subseteq \mathbb{R}$ is **compact** if every sequence in S has a convergent subsequence with limit in S . Further, the Heine-Borel theorem told us that $\emptyset \neq S$ is compact if and only if it is closed and bounded. This is not the case for a general metric space, as we shall now show:

Example 5.6.1. Let $S = \overline{B}_1(0) \subseteq C([0, 1])$ with the supremum norm. S is closed and bounded, but the sequence $f_n(x) = x^n$ has no uniformly convergent subsequences (it converges pointwise to a discontinuous function).

We now introduce a more topologically useful definition.

Definition 5.6.1 (Open Covers). Let X be a metric space and A a subset of X . A collection $\{U_i\}_{i \in I}$ of open subsets of X is said to be an open cover for A if

$$A \subseteq \bigcup_{i \in I} U_i$$

Given such a cover for A , a finite subcover for A is a finite subcollection U_{i_1}, \dots, U_{i_n} of $\{U_i\}_{i \in I}$ such that

$$A \subseteq \bigcup_{j=1}^n U_{i_j}$$

Definition 5.6.2 (Compactness). A non-empty subset A of a metric space X is compact in X if every open cover of A in X has a finite subcover. A non-empty subset A is sequentially compact in X if every sequence in A has a convergent subsequence whose limit is in A .

In other words:

Definition 5.6.3. X is sequentially compact if every sequence $(x_j) \subseteq X$ has a convergent subsequence.

And we also have:

Definition 5.6.4. X is limit point compact if every infinite subset of X has an accumulation point in X .

These are equivalent for metric spaces by the axiom of choice.

Example 5.6.2. \mathbb{R} is not compact. Indeed, we have the open cover $\mathbb{R} = \bigcup_{n=1}^{\infty} (-n, n)$ which has no finite subcover, as $\mathbb{R} \not\subseteq \bigcup_{k=1}^N (-n_k, n_k) = (-K, K)$ for some $K > 0$. Similarly, $(0, 1)$ is not compact since

$$(0, 1) = \bigcup_{n=1}^{\infty} (0, 1 - 1/n)$$

has no finite subcover.

Example 5.6.3. Let X be any set with the discrete metric. Then $A \subseteq X$ is compact if and only if A is finite. If A is finite and $A \subseteq \bigcup_{i \in I} U_i$, then write $A = \{a_1, \dots, a_n\}$, and for each $k \in \{1, \dots, n\}$ there exists U_{i_k} such that $a_k \in U_{i_k}$. Then $A \subseteq \bigcup_{k=1}^n U_{i_k}$, which gives a finite subcover. If A is infinite, then $A = \bigcup_{a \in A} \{a\}$ is an open cover with no finite subcover since singletons are open in the discrete metric.

Example 5.6.4. I claim that open balls in normed linear spaces are not compact. Indeed,

$$B_r(0) = \{v \in V \mid \|v\| < r\} = \bigcup_{0 < s < r} B_s(0)$$

has no finite subcover since

$$\bigcup_{j=1}^n B_{s_j}(0) = B_s(0) \subsetneq B_r(0)$$

as $s = \max_{1 \leq j \leq n} s_j < r$.

Although not all closed and bounded sets are compact in metric spaces in general, we do have the converse:

Proposition 5.6.1. *Compact subsets of a metric space are closed and bounded.*

Proof. Let $a \in \mathcal{A}$ with \mathcal{A} compact in X . Then $\{B_n(a) | n \in \mathbb{N}\}$ is an open cover for \mathcal{A} . By compactness there exist n_1, \dots, n_k such that

$$\mathcal{A} \subseteq \bigcup_{j=1}^k B_{n_j}(a) = B_{\max_{1 \leq j \leq k} n_j}(a)$$

so \mathcal{A} is bounded.

To show \mathcal{A} is closed, suppose $x_0 \in \mathcal{A}'$. Assume $x_0 \notin \mathcal{A}$. Define $r_a := \frac{d(a, x_0)}{2}$ for each $a \in \mathcal{A}$, and note $r_a > 0$ as $x_0 \notin \mathcal{A}$. Then $\mathcal{A} \subseteq \bigcup_{a \in \mathcal{A}} B_{r_a}(a)$, so $\{B_{r_a}(a) | a \in \mathcal{A}\}$ is an open cover for \mathcal{A} . By compactness, there exist $a_1, \dots, a_n \in \mathcal{A}$ with $\mathcal{A} \subseteq \bigcup_{i=1}^n B_{r_{a_i}}(a_i)$. Let $r = \min\{r_{a_1}, \dots, r_{a_n}\} > 0$. Then $B_r(x_0) \cap B_{r_{a_i}}(a_i) = \emptyset$ for all $1 \leq i \leq n$. In particular, $B_r(x_0) \cap \mathcal{A} = \emptyset$. But $x_0 \in \mathcal{A}'$, a contradiction. ■

We will now show compactness implies sequential compactness - this result will later be repeated with a similar proof.

Proposition 5.6.2. *Every infinite subset of a compact subset A of a metric space X has an accumulation point in A . In particular, if A contains a sequence of distinct points, then that sequence must contain a convergent subsequence. Consequently, compactness implies sequential compactness.*

Proof. Suppose $C \subseteq A$ with C infinite; if A is finite every sequence has a convergent subsequence since every sequence must repeat some point an infinite number of times (pigeon hole principle). We want to show $C' \cap A \neq \emptyset$. Suppose $C' \cap A = \emptyset$. Then for all $a \in A$, there exists $r_a > 0$ with

$$(B_{r_a}(a) \setminus \{a\}) \cap C = \emptyset$$

The collection $\{B_{r_a}(a) : a \in A\}$ is an open cover for A . By compactness there exist a_1, \dots, a_n with $C \subseteq A \subseteq \bigcup_{i=1}^n B_{r_{a_i}}(a_i)$. But then C intersects only the a_i , at most, so $C \subseteq \{a_1, \dots, a_n\}$, contradicting the assumption that C is infinite. ■

Proposition 5.6.3. *Suppose A is a compact subset in a metric space X and C is a closed subset of A (or X). Then C is compact in A (in X).*

Proof. Let $\{U_i\}$ be an open cover for C . C is closed in A so $A \setminus C$ is open in A . But then

$$A \subseteq \left(\bigcup_{i \in I} U_i \right) \cup (A \setminus C)$$

so $\{U_i\} \cup \{A \setminus C\}$ is an open cover of A . But A is compact, so there exist i_1, \dots, i_n such that

$$A \subseteq U_{i_1} \cup \dots \cup U_{i_n} \cup (A \setminus C)$$

and $C \subseteq U_{i_1} \cup \dots \cup U_{i_n}$, so C has a finite subcover and hence is compact. ■

Example 5.6.5. As we show in our function section, if $f : X \rightarrow Y$ is continuous and if X is compact, then $f(X)$ is compact in Y . Indeed, suppose $\{U_i\}_{i \in I}$ is an open cover for $f(X)$, so $f(X) \subseteq \bigcup_{i \in I} U_i$. Then

$$X \subseteq f^{-1} \left(\bigcup_{i \in I} U_i \right) = \bigcup_{i \in I} f^{-1}(U_i)$$

which is an open cover as f is continuous. So $X \subseteq f^{-1}(U_{i_1}) \cup \dots \cup f^{-1}(U_{i_n})$ for some finite subcover, which implies

$$f(X) \subseteq U_{i_1} \cup \dots \cup U_{i_n}$$

Example 5.6.6. As we shall show later, continuous invertible maps on compact spaces are homeomorphisms. Suppose $f : X \rightarrow Y$ is continuous and invertible with X compact. Then f^{-1} is continuous and hence f is a homeomorphism. To see this we will show $f(C) = (f^{-1})^{-1}(C)$ is closed whenever C is closed in X . But X is compact, so C is compact as it is closed. Then $f(C)$ is compact in Y by the previous result, so $f(C)$ is closed in Y , completing the claim.

Note that, as stated above, the property that every infinite subset of A has an accumulation point, often coined **limit point compactness**, is equivalent to sequential compactness for A in metric spaces.

Definition 5.6.5. A subset A of a metric space X is **totally bounded** if for every $\varepsilon > 0$ there exists a finite set $\{x_1, \dots, x_N\} \subseteq X$ such that

$$A \subseteq \bigcup_{j=1}^N B_\varepsilon(x_j)$$

Example 5.6.7. Balls may not be totally bounded. Indeed, $\overline{B}_1(0)$ in $C([0, 1])$ is not totally bounded. For example, take $f_n(x) = 0$ for $0 \leq x \leq 1/2^n$, $f_n(x) = 2^{n+1}(x - 1/2^n)$ for $1/2^n \leq x \leq 1/2^n + 1/2^{n+1}$, $f_n(x) = -2^{n+1}(x - 1/2^{n-1})$ for $1/2^n + 1/2^{n+1} \leq x \leq 1/2^{n-1}$, and $f_n(x) = 0$ for $1/2^{n-1} \leq x \leq 1$ (disjoint triangles of height 1)

Proposition 5.6.4. If X is a sequentially compact metric space, then X is totally bounded.

Proof. Let $\varepsilon > 0$. If X is empty, there is nothing to prove, so suppose $X \neq \emptyset$. Let $x_1 \in X$. If $X = B_\varepsilon(x_1)$ we're done. Otherwise, choose $x_2 \in X \setminus B_\varepsilon(x_1)$. If $X = B_\varepsilon(x_1) \cup B_\varepsilon(x_2)$, we're done. Then either this process terminates at a finite step, in which case we're done, or we obtain a sequence x_1, x_2, \dots such that $d(x_j, x_i) \geq \varepsilon$ for all $i \neq j$. But then (x_j) has no convergent subsequence, contradicting the assumption that X is compact. Thus, this process must terminate at a finite step, so there exists $N \in \mathbb{N}$ such that

$$X = \bigcup_{j=1}^N B_\varepsilon(x_j)$$

■

Corollary 5.6.5. *If X is a sequentially compact metric space, then X has a countable dense subset, which is to say X is separable.*

Proof. By Proposition 5.6.4 X is totally bounded. Let $S_n = \{x_{n1}, \dots, x_{nm_n}\}$ such that

$$X = \bigcup_{j=1}^{m_n} B_{2^{-n}}(x_{nj}), \quad C := \bigcup_{n=1}^{\infty} S_n$$

Then C is countable being the countable union of finite sets. Let $x \in X$ and $\varepsilon > 0$. Let $n \in \mathbb{N}$ such that $2^{-n} < \varepsilon$. Then $X = \bigcup_{j=1}^{m_n} B_{2^{-n}}(x_{nj})$ so $x \in B_{2^{-n}}(x_{nj})$ for some $1 \leq j \leq m_n$. Thus $d(x, x_{nj}) < 2^{-n} < \varepsilon$, so $x_{nj} \in B_\varepsilon(x)$ and $B_\varepsilon(x) \cap C \neq \emptyset$. Thus C is dense in X . ■

This implies a relation between sequentially compact metric spaces and its size. In particular, metric plus compact implies separable.

Proposition 5.6.6. *If X is a sequentially compact metric space and $K_1 \supseteq K_2 \supseteq \dots$ is a chain of non-empty closed subsets, then $\bigcap_{j=1}^{\infty} K_j \neq \emptyset$.*

The proof of this result is identical to that of the case for Euclidean Spaces, and the same holds for its corollary:

Corollary 5.6.7. *If X is a sequentially compact metric space and $U_1 \subseteq U_2 \subseteq \dots$ is a chain of open sets such that $X = \bigcup_{j=1}^{\infty} U_j$, then there exists $M \in \mathbb{N}$ such that $X = U_M$.*

Proposition 5.6.8. *If X is a sequentially compact metric space, then X is topologically compact.*

Proof. Let $\{U_\alpha\}_{\alpha \in J}$ be an open cover of X . By Proposition ?? X is separable, so we have a countable dense subset C . Let $\mathcal{R} = \{B_q(x) : x \in C, q \in \mathbb{Q}^+\}$. Then \mathcal{R} is countable. Further, if $U \subseteq X$ is open, for all $p \in U$ there exists $\varepsilon > 0$ such that $B_\varepsilon(p) \subseteq U$. Then as C is dense, $C \cap B_{\varepsilon/3}(p) \neq \emptyset$, so there exists $c \in C$ such that $c \in B_{\varepsilon/3}(p)$. Then as \mathbb{Q} is dense in \mathbb{R} there exists $q \in \mathbb{Q}$ such that $\varepsilon/3 < q < 2\varepsilon/3$. It follows that $p \in B_q(c) \subseteq B_\varepsilon(p) \subseteq U$. Thus $U = \bigcup \{B \in \mathcal{R} : B \subseteq U\}$, so every open set can be written as a countable union of open sets in \mathcal{R} . Then $X = \bigcup_{\alpha \in J} U_\alpha = \bigcup_{\alpha \in J} \bigcup_{j \geq 1} B_{q_{\alpha,j}}(c_{\alpha,j})$. Suppose $\{B_1, B_2, \dots\}$ is a countable cover of X . Define $U_m = B_1 \cup \dots \cup B_m$. Then by Corollary 5.6.7 there exists $M \in \mathbb{N}$ such that $X = \bigcup_{j=1}^M B_j$. Thus as $\bigcup_{\alpha \in J} \bigcup_{j \geq 1} B_{q_{\alpha,j}}(c_{\alpha,j})$ is countable, there exists $M \in \mathbb{N}$ such that $X = B_{q_{\alpha_1, i_1}}(c_{\alpha_1, i_1}) \cup \dots \cup B_{q_{\alpha_M, i_M}}(c_{\alpha_M, i_M})$, so $X = U_{\alpha_1} \cup \dots \cup U_{\alpha_M}$ is a finite subcover. ■

Theorem 29 (Heine-Borel Property).

If X is a metric space, then X is sequentially compact if and only if it is compact in terms of open covers.

Proof. Proposition 5.6.8 is the forward implication, so suppose X is topologically compact. We show the equivalence with limit point compactness. We argue by contrapositive and suppose $S \subseteq X$ has no accumulation points. Then in particular S is closed, as $\overline{S} = S \cup S' = S$, since

$S' = \emptyset$. Then $S_x = S \setminus \{x\}$ for all $x \in S$ is also closed, also having no accumulation points. Then $U_x \in X \setminus S_x$ is a cover for S , with $U_x \cap S = \{x\}$. But then $\{U_x\}_{x \in S} \cup \{X \setminus S\}$ is an open cover for X . As X is open cover compact, we have x_1, \dots, x_n such that $U_{x_1}, \dots, U_{x_n}, X \setminus S$ covers X . But then U_{x_1}, \dots, U_{x_n} covers S , so $S = \bigcup_{i=1}^n S \cap U_{x_i} = \{x_1, \dots, x_n\}$ so S is finite. Thus, X is limit point compact, completing the proof. ■

Note that a metric space which is compact is totally bounded and complete. Now we have the converse:

Proposition 5.6.9. *If X is a complete metric space which is totally bounded, then X is compact.*

Proof. Let $S \subseteq X$ be infinite. Because X is totally bounded, there exist $x_1, \dots, x_N \in X$ such that $X \subseteq \bigcup_{j=1}^N B_{1/2}(x_j)$. Since $S \subseteq X$ is infinite, by the pigeon hole principle there exists $x_j =: x^1$ such that $B_{1/2}(x^1) \cap S$ is infinite. Then there exists $\{x_{2,1}, \dots, x_{2,N_2}\} \subseteq X$ such that $X \subseteq \bigcup_{j=1}^{N_2} B_{1/2^2}(x_{2,j})$ and again there exists $x_{2j} =: x^2$ such that $B_{1/2^2}(x^2) \cap (B_{1/2}(x^1) \cap S)$ is infinite. Continuing in this way there exists $x^j \in X$ such that

$$B_{1/2^j}(x^j) \cap \dots \cap B_{1/2}(x^1) \cap S$$

is infinite. Let X_j be the closure of this j th set, so we have a decreasing chain $X_1 \supseteq X_2 \supseteq \dots$ of non-empty closed sets, such that $X_j \cap S$ is infinite for all j . Pick $z_1 \in X_1 \cap S$, and $z_{j+1} \in X_{j+1} \cap S \setminus \{z_1, \dots, z_j\}$, which is possible using the axiom of choice as each set is infinite. Then $(z_j) \subseteq X_1 \cap S$ is a Cauchy sequence. By completeness there exists $z \in X$ such that z_j converges to z . But $(z_j) \subseteq S$, and the z_j are distinct, so $z \in X$ is an accumulation point of S . ■

We prove this result again, with its converse, as follows

Theorem 5.6.10. *A non-empty subset A of a metric space X is compact in X if and only if A is complete and totally bounded.*

Proof. Suppose A is compact and $r > 0$. Then $\{B_r(x) | x \in A\}$ is an open cover for A . So there exist $x_1, \dots, x_n \in X$ with $A \subseteq B_r(x_1) \cup \dots \cup B_r(x_n)$. So A is totally bounded. If $\{x_n\} \subseteq A$ is Cauchy, then there exists a subsequence $x_{n_k} \rightarrow x \in A$ by sequential compactness. Then as the sequence is Cauchy and a subsequence converges, $x_n \rightarrow x$. So A is complete.

Conversely, suppose A is complete and totally bounded. If A is finite it is compact and we're done. So assume A is infinite. Let $\{x_n\}$ be any sequence of distinct points in A . Cover A by finitely many balls of radius 1 by total boundedness. At least one of these, say $B_1(y_1)$, contains infinitely many x_i . $A \cap B_1(y_1)$ is also totally bounded, and hence can be covered with finitely many balls of radius $1/2$. At least one of these, say $B_{1/2}(y_2)$, contains infinitely many of the x_i . Thus, for each k , there exists $x_{n_k} \in B_{1/2^k}(y_k)$. These can be chosen such that $\{x_{n_k}\}_{k \geq l} \subseteq B_{1/2^l}(y_l)$. This implies $d(x_{n_k}, x_{n_m}) < 1/2^{l-1}$ for $k, m \geq l$. Thus $\{x_{n_k}\}$ is Cauchy. By completeness, there exists $x \in A$ with $x_{n_k} \rightarrow x$. Thus A is sequentially compact, and the result follows. ■

Proposition 5.6.11. *If X is a compact metric space, then $\text{diam}(X) < \infty$, where*

$$\text{diam}(X) = \sup\{d(x, y) : x, y \in X\}$$

Proof. As X is compact there exist $x_1, \dots, x_N \in X$ such that $X \subseteq \bigcup_{j=1}^N B_1(x_j)$. Then, let $M = \max\{d(x_i, x_j) : 1 \leq i, j \leq N\}$. Now, let $x, y \in X$. Then there exist i, j such that $x \in B_1(x_i)$ and $y \in B_1(x_j)$. It follows that

$$d(x, y) \leq d(x, x_i) + d(x_i, x_j) + d(x_j, y) < 1 + M + 1 = M + 2$$

Thus, we have that $\text{diam}(X) \leq M + 2 < \infty$, as desired. ■

We now prove this result ones more using a slightly different technique, and slightly different results.

Definition 5.6.6. Let X be a metric space and let $\{U_n\}_{n \in \mathbb{N}}$ be a countable collection of open sets in X . If for any open set V of X , and any $x \in V$, there exists i such that $x \in U_i \subseteq V$, then $\{U_n\}_{n \in \mathbb{N}}$ is a countable bases for the topology on X , and is called a countable base for A .

Lemma 5.6.12. Suppose A is a non-empty subset of a metric space X with the property that every infinite subset of A has an accumulation point (i.e. that \bar{A} is sequentially compact). Then there are open sets $\{U_n\}_{n \in \mathbb{N}}$ of X with the property that if V is any open set in X and $x \in A \cap V$, then there is a U_i with $x \in U_i \subseteq V$.

That is A has a countable base.

Proof. We claim for each $n \in \mathbb{N}$ there is a finite set $\{x_1, \dots, x_{N(n)}\} \subseteq X$ such that

$$A \subseteq \bigcup_{j=1}^{N(n)} B_{1/n}(x_j)$$

We show this by contradiction, assuming the inclusion does not hold. Thus, there is no finite collection of balls of radius $1/n$ covering A , for some n . Let $y_1 \in A$ with $A \not\subseteq B_{1/n}(y_1)$, $y_2 \in A \setminus B_{1/n}(y_1)$ with $d(y_2, y_1) \geq 1/n$, and inductively take $y_{k+1} \in A \setminus \bigcup_{j=1}^k B_{1/n}(y_j)$ with $d(y_j, y_{k+1}) \geq 1/n$ for all $1 \leq j \leq k$. By construction $\{y_k\}$ consists of infinitely many points. But it has no accumulation points since $d(y_i, y_j) \geq 1/n$ for all i and j . This contradicts the assumption that any infinite set in \bar{A} has an accumulation point. So we take the countable collection

$$\{B_{1/n}(x_i) | n \in \mathbb{N}, 1 \leq i \leq N(n)\}$$

This collection satisfies the conclusion of the theorem. ■

Theorem 5.6.13. A non-empty subset A of a metric space X is compact in X if and only if it is sequentially compact in X .

Proof. We already have compactness implies sequential compactness. Suppose A is sequentially compact. Suppose $A \subseteq \bigcup_{i \in I} U_i$ is an open cover. We first prove A has a countable subcover. Let $x \in A$ so $x \in U_i$ for some i . $\bar{A} = A$ satisfies the hypotheses of the result above. Let $\{V_n\}_{n \in \mathbb{N}}$ be the collection in the conclusion. There exists V_j with $x \in V_j \subseteq U_i$. Thus,

$$A \subseteq \bigcup_{j=1}^{\infty} V_j \subseteq \bigcup_{\text{countable}} U_i$$

taking the countable subcover of U_i 's associated to the V_j 's. We can write $A \subseteq \bigcup_{j=1}^{\infty} U_{i_j}$, and we want a finite subcover. Towards a contradiction suppose there is no finite subcollection covering A . Then there exists $x_1 \in A \setminus U_{i_1}$, $x_2 \in A \setminus U_{i_1} \cup U_{i_2}$, and in general $x_k \in A \setminus \bigcup_{j=1}^k U_{i_j}$. By assumption there exists a subsequence $x_{n_k} \rightarrow x \in A$. The U_{i_j} cover A . So there exists $N \in \mathbb{N}$ such that $x \in U_{i_N}$. But U_{i_N} is open. So there exists M such that for $n_k \geq M$, $x_{n_k} \in U_{i_N}$. So U_{i_N} contains all but finitely many of the x_{n_k} . But by construction each U_{i_j} can only contain finitely many x_k , which is a contradiction. Thus, a finite subcover must exist. ■

Theorem 5.6.14 (Heine-Borel). *A non-empty subset A of ℓ_n^p is compact if and only if A is closed and bounded.*

Proof. We know compact implies closed and bounded. Suppose $A \subseteq \ell_n^p$ is closed and bounded. We show A is sequentially compact. Let $\vec{x}_k \in A$. By Bolzano-Weierstrass, since A is bounded, $\vec{x}_{n_k} \rightarrow \vec{x} \in \ell_n^p$ for some subsequence. Since A is closed, $\vec{x} \in A$. ■

A reminder that Heine-Borel fails in other metric spaces, such as the example $f_n(x) = x^n$ in $C([0, 1]) \cap \overline{B}_1(0)$, which has no (uniformly) convergent subsequence as discussed previously.

5.7.0 Product Spaces

We now define finite and countable products of metric spaces, and their associated properties.

Definition 5.7.1. *If $(X_1, d_1), \dots, (X_N, d_N)$ are metric spaces, we define the product metric space*

$$X := X_1 \times \cdots \times X_N = \prod_{j=1}^N X_j$$

and define a metric d in X for $x = (x_1, \dots, x_N), y = (y_1, \dots, y_N)$ by

$$d(x, y) = \sum_{j=1}^N d_j(x_j, y_j)$$

Equivalently, we could define

$$\delta(x, y) = \sqrt{\sum_{j=1}^N d_j(x_j, y_j)^2}$$

where the equivalence is in the sense that they define the same topology on the product. In particular, we characterize two metrics being equivalent as follows:

Definition 5.7.2. *If X is a set with metrics d_1 and d_2 , then d_1 and d_2 are said to be equivalent if there exists $0 < C_0 \leq C_1 < \infty$ such that*

$$C_0 d_1(x, y) \leq d_2(x, y) \leq C_1 d_1(x, y)$$

for all $x, y \in X$.

Definition 5.7.3. For $p \in \mathbb{N}$, the ℓ_p norm on \mathbb{R}^n is

$$\|\vec{x}\|_p = \left(\sum_{i=1}^n |x_i|^p \right)^{1/p}$$

which gives the metric

$$d_p(\vec{x}, \vec{y}) = \|\vec{x} - \vec{y}\|_p$$

For $p = \infty$, define

$$\|\vec{x}\|_\infty = \max_{1 \leq j \leq n} |x_j|$$

and

$$d_\infty(\vec{x}, \vec{y}) = \max_{1 \leq j \leq n} |x_j - y_j|$$

It is an important, but non-trivial result, that d_p and d_q are equivalent for all $0 < p, q \leq \infty$. Now we define countable products:

Definition 5.7.4. Let $(X_1, d_1), (X_2, d_2), \dots$ be a countable collection of metric spaces. Define

$$X = \prod_{j=1}^{\infty} X_j$$

where $x \in X$ is a sequence $x = (x_j)$, $x_j \in X_j$. We define the metric by

$$d(x, y) = \sum_{j=1}^{\infty} 2^{-j} \frac{d_j(x_j, y_j)}{1 + d_j(x_j, y_j)}$$

We have that compactness of product spaces occurs if and only if we have compactness of the individual component spaces.

Proposition 5.7.1. The product $X = \prod_{j=1}^N X_j$ is compact if and only if X_j is compact for all j .

Proof. First, suppose the product is compact and let $(x_{n,j})_{n=1}^{\infty} \subseteq X_j$. Let $x_i \in X_i$ for $i \neq j$. Then $(x_1, \dots, x_{n,j}, \dots, x_N) \subseteq X$ has a convergent subsequence $(x_1, \dots, x_{n_k,j}, \dots, x_N)$ converging to $(x_1, \dots, x_j, \dots, x_N)$ in X since X is compact. Then for all $\varepsilon > 0$, there exists $M \in \mathbb{N}$ such that for $k \geq M$, $d_j(x_{n_k,j}, x_j) = d((x_1, \dots, x_{n_k,j}, \dots, x_N), (x_1, \dots, x_j, \dots, x_N)) < \varepsilon$, so $(x_{n_k,j})$ is a convergent subsequence of (x_j) . Thus X_j is compact for all j , as desired. Now suppose that X_j is compact for each j , and $((x_{n,1}, \dots, x_{n,N})) \subseteq X$. As X_1 is compact there exists a subsequence $(x_{s_1(n),1})$ which converges to some $x_1 \in X_1$. Then $(x_{s_1(n),2}) \subseteq X_2$ has a convergent subsequence $(x_{s_2(n),2})$ since X_2 is compact, which converges to $x_2 \in X$. Proceeding in this way we arrive at $((x_{s_N(n),1}, \dots, x_{s_N(n),N})) \subseteq ((x_{n,1}, \dots, x_{n,N}))$, where $(x_{s_N(n),j}) \subseteq (x_{s_j(n),j})$ which converges to $x_j \in X_j$, and hence $(x_{s_N(n),1}, \dots, x_{s_N(n),N})$ converges to (x_1, \dots, x_N) . Thus X is compact, as desired. ■

Proposition 5.7.2. The product $X = \prod_{j=1}^{\infty} X_j$ is compact if and only if X_j is compact for all j .

Proof. The forward implication follows analogously to the proof of the previous proposition. Now, suppose each X_j is compact, and let $((x_{v,1}, x_{v,2}, \dots)) \subseteq X$ be an arbitrary sequence. Then, as X_1 is compact, we have a subsequence $x_{s_1(v),1}$ which converges to some $x_1 \in X_1$. Then, we can take a subsequence $x_{s_2(v),2}$ of $x_{s_1(v),2}$ which converges to some $x_2 \in X_2$ since X_2 is compact. Let $(x_v^j) = ((x_{s_j(v),1}, x_{s_j(v),2}, \dots))$. Then we have a decreasing sequence of subsequences $(x_v) \supseteq (x_v^1) \supseteq (x_v^2) \supseteq \dots$, such that $x_{s_j(v),i}$ converges to $x_i \in X_i$ for all $1 \leq j \leq i$. Then, let (ξ_v) be the subsequence defined by $\xi_v = x_v^v$, the diagonal. Then for all $j \in \mathbb{N}$, $(\xi_v)_{v=j}^\infty \subseteq (x_v^j)_{v=1}^\infty$, so for each j $x_{s_v(v),j}$ converges to $x_j \in X_j$. Thus, ξ_v converges to $(x_1, x_2, \dots) \in X$, and hence X is compact. ■

5.8.0 Baire Category Theorem

We now construct a result on the size of complete metric spaces, known as the Baire's Category Theorem. First we define the notion of a category for a topological space:

Definition 5.8.1. For a topological space (X, τ) , a subset A is said to be of the **first category** in X if and only if A can be written as a countable union of nowhere dense subsets of X .

Definition 5.8.2. A subset $S \subseteq X$ is **nowhere dense** if and only if \overline{S} does not contain any non-empty open subsets, which occurs in a metric space if and only if \overline{S} does not contain any open ball $B_r(x)$ for $r > 0$ and $x \in X$. Equivalently, S is nowhere dense if and only if $X \setminus \overline{A} = \overline{A}^c$ is dense in X .

Definition 5.8.3. For a topological space X , a subset A is said to be of the **second category** in X if and only if A is not of the first category.

Theorem 30 (Baire's Category Theorem).

If X is a complete metric space, then X is of second category.

Proof. Let $S_k \subseteq X$ be a sequence of nowhere dense sets. We claim $X \setminus \bigcup_{k \geq 1} S_k \neq \emptyset$. Let $T_k = \bigcup_{j=1}^k S_j = \bigcup_{j=1}^k \overline{S_j}$, so T_k is closed and nowhere dense. Further, $T_1 \subseteq T_2 \subseteq \dots$. Let $U_k = X \setminus T_k$, so U_k is open and dense. Indeed, if $x \in X$, and $N_x \subseteq N(x)$, an open neighborhood, $N_x \not\subseteq T_k$, so $N_x \cap U_k \neq \emptyset$. Thus $\overline{U_k} = X$, so U_k is dense. Then we have $U_1 \supseteq U_2 \supseteq \dots$. We claim that the intersection is non-empty. Let $p_1 \in U_1$, so there exists $\varepsilon_1 > 0$ such that $\overline{B_{\varepsilon_1}(p_1)} \subseteq U_1$. By density of U_2 , there exists $p_2 \in B_{\varepsilon_1/2} \cap U_2$. But U_2 is open so there exists $\varepsilon_2 < \varepsilon_1/2$ such that $\overline{B_{\varepsilon_2}(p_2)} \subseteq B_{\varepsilon_1}(p_1) \cap U_2$. Inductively, take $p_{k+1} \in B_{\varepsilon_k}(p_k) \cap U_{k+1}$, and $\varepsilon_{k+1} < \varepsilon_k/2$ such that $\overline{B_{\varepsilon_{k+1}}(p_{k+1})} \subseteq B_{\varepsilon_k}(p_k) \cap U_{k+1}$. Then $\varepsilon_k < \varepsilon/2^{k-1}$. Note (p_k) is a Cauchy sequence, because $p_l \in \overline{B_{\varepsilon_l}(p_l)} \subseteq B_{\varepsilon_k}(p_k)$ for all $l > k$, where $\varepsilon_k < \varepsilon/2^{k-1}$. By completeness of X , there exists $p \in X$ such that $p_l \rightarrow p$. Then $p \in \overline{B_{\varepsilon_k}(p_k)}$ for all k as they are closed, so in particular $p \in U_k$ for all k . Therefore, $p \in \bigcap_{i=1}^\infty U_i$, so $\bigcap_{i=1}^\infty U_i \neq \emptyset$, as claimed. ■

We re-visit this investigation through a slightly different light:

Lemma 5.8.1. A is nowhere dense in X if and only if $\overline{A}^\circ = \emptyset$.

Proof. First, if $B \subseteq X$, $X \setminus \overline{B} = (X \setminus B)^\circ$ and $X \setminus B^\circ = \overline{X \setminus B}$. Indeed, $X \setminus \overline{B} \subseteq X \setminus B$ and is open so $X \setminus \overline{B} \subseteq (X \setminus B)^{\text{circ}}$. Conversely, $(X \setminus B)^\circ \subseteq X \setminus B$, so $X \setminus (X \setminus B)^\circ \supseteq B$ is a closed set containing B , implying $X \setminus (X \setminus B)^\circ \supseteq \overline{B}$. It follows that $(X \setminus B)^\circ \subseteq X \setminus \overline{B}$ and we have equality, $X \setminus \overline{B} = (X \setminus B)^\circ$. For the other equality, $X \setminus B^\circ \supseteq X \setminus B$ is a closed cover, so $X \setminus B^\circ \supseteq \overline{X \setminus B}$. Conversely, $X \setminus (\overline{X \setminus B}) \subseteq B$ is open, so $X \setminus (\overline{X \setminus B}) \subseteq B^\circ$, so $\overline{X \setminus B} \supseteq X \setminus B^{\text{circ}}$, and we have equality $X \setminus B^\circ = \overline{X \setminus B}$.

Then $\overline{A}^\circ = \emptyset$ if and only if $X \setminus \overline{A}^\circ = X$, if and only if $\overline{X \setminus A} = X$, if and only if $X \setminus \overline{A}$ is dense in X , if and only if A is nowhere dense. ■

Example 5.8.1. If $\{x_0\}$ in X is not isolated, then $\{x_0\}$ is nowhere dense, since $\overline{\{x_0\}} = \{x_0\}$ and it has no interior points. If X has no isolated points, then countable sets are of the first category.

Example 5.8.2. \mathbb{Q} is of the first category, being the countable union of singletons and having no isolated points. $\mathbb{R} \setminus \mathbb{Q}$ is of the second category, which follows from Baire's theorem.

Example 5.8.3. The middle thirds Cantor set C is nowhere dense. It is compact, and hence closed, and contains no intervals, and hence no interior.

Example 5.8.4. Collection of lines in \mathbb{R}^2 : in ℓ_2^2 , the line $\{(x, mx + b) | m, b \in \mathbb{R}\}$ is nowhere dense, since it is already closed and each point is a boundary point.

Theorem 5.8.2 (Baire). Suppose X is a complete metric space and $\{U_n\}$ is a denumerable collection of open and dense subsets of X . Then

$$\bigcap_{n \in \mathbb{N}} U_n$$

is dense in X .

Proof. Note that $\overline{A} = X$ if and only if, for all $x \in X$, either $x \in A$ or $x \in A'$. If $x \in A$, then for every open neighborhood $U \subseteq X$ of x , $A \cap U \neq \emptyset$. If $x \in A'$, then for every $U \subseteq X$ open neighborhood of x , $A \cap (U \setminus \{x\}) \neq \emptyset$, so in particular $A \cap U \neq \emptyset$.

We must show that if $V \subseteq X$ is open and non-empty, then $\bigcap_{n=1}^{\infty} U_n \cap V \neq \emptyset$. Let $x_1 \in V \cap U_1$, which is possible since U_1 is dense. Then there exists $r_1 > 0$ with $\overline{B}_{r_1}(x_1) \subseteq V \cap U_1$, since $V \cap U_1$ is open. As U_2 is dense and $B_{r_1}(x_1)$ is open there exists $x_2 \in U_2 \cap B_{r_1}(x_1) \subseteq U_2 \cap U_1 \cap V$. Repeating this process, we can find $r_2 < r_1/2$ with

$$\overline{B}_{r_2}(x_2) \subseteq B_{r_1}(x_1) \cap U_2 \subseteq U_2 \cap U_1 \cap V$$

Inductively, find $x_n \in X$ and $r_n < r_{n-1}/2$ with

$$\overline{B}_{r_n}(x_n) \subseteq B_{r_{n-1}}(x_{n-1}) \cap U_n \subseteq \bigcap_{j=1}^n U_j \cap V$$

By construction, $(x_k)_{k \geq n} \subseteq \overline{B}_{r_n}(x_n)$. Since $r_n \rightarrow 0$, (x_k) is Cauchy and therefore has a limit x_0 since X is complete. Moreover, $\overline{B}_{r_n}(x_n)$ contains x_0 since it is closed. So by construction

$$x_0 \in \bigcap_{j=1}^{\infty} B_{r_j}(x_j) \subseteq \left(\bigcap_{j=1}^{\infty} U_j \right) \cap V$$

■

Corollary 5.8.3 (The Baire Category Theorem). *Complete metric spaces are of the second category.*

Proof. Suppose the proposition does not hold. Let $X = \bigcup_{n=1}^{\infty} A_n$ with A_n nowhere dense (i.e. $X \setminus \overline{A_n}$ is dense in X , and open). By Baire's theorem $\bigcap_{n=1}^{\infty} X \setminus \overline{A_n}$ is dense in X , which holds if and only if $X \setminus \bigcup_{n=1}^{\infty} \overline{A_n}$ is dense in X . But, $\bigcup_{n=1}^{\infty} \overline{A_n} = X$, so this holds if and only if \emptyset is dense in X . ■

Example 5.8.5. The irrationals: \mathbb{Q} is of the first category, so $\mathbb{R} \setminus \mathbb{Q}$ must be of the second, as otherwise $\mathbb{R} = \mathbb{Q} \cup (\mathbb{R} \setminus \mathbb{Q})$ would be of the first, which it is not being a complete metric space.

Example 5.8.6. Any basis of an infinite dimensional complete normed linear space is necessarily uncountable. However, there are infinite dimensional incomplete space having a countable basis: for example, the normed linear space of polynomials with norm $\|a_0 + a_1x + \dots + a_nx^n\| = \sum_{i=1}^n |a_i|$ has countable basis $\{1, x, x^2, x^3, \dots\}$ since each polynomial can be written as a unique finite linear combination of these elements.

Now, suppose to the contrary that $\{v_1, v_2, \dots\}$ is a vector space basis for such a NLS V . For each n , let $V_n = \text{span}\{v_1, \dots, v_n\}$. Each V_n is nowhere dense. Indeed, each V_n is closed, as to be shown below, and if U is an open ball in V_n , by subtracting the center of this ball we are still in V_n . So we may assume $B_r(0) \subseteq V_n$. So if $v \in V \setminus \{0\}$, we have $\frac{v}{2\|v\|}r \in V_n$. But V_n is a subspace, so $v \in V_n$. This implies $V = V_n$, contradicting the fact that V is finite dimensional. Thus V_n is nowhere dense.

Notice by assumption $V = \bigcup_{n=1}^{\infty} V_n$. By Baire's theorem, this contradicts the completeness of V .

Theorem 31 (Uniform Boundedness Principal).

Let X be a complete metric space and $S \subseteq C(X)$. Suppose that for each $x \in X$ there exists a positive constant $M_x > 0$ such that $|f(x)| \leq M_x$ for all $f \in S$ (pointwise bound). Then there is a non-empty open subset U of X and $M > 0$ such that $|f(x)| \leq M$ for all f in S and all x in U (uniform bound).

If $\sup_x M_x < \infty$, we can just use this as M and $U = X$

Proof. Fix $n \in \mathbb{N}$ and $f \in S$. Define

$$S_{n,f} = \{x \in X \mid |f(x)| \leq n\} = f^{-1}([-n, n])$$

$S_{n,f}$ is closed being the pre-image of a closed set under a continuous map. Define $S_n := \bigcap_{f \in S} S_{n,f}$, which is again closed. Note $S_n \subseteq S_{n+1}$. Note $x \in S_n$ if and only if $|f(x)| \leq n$ for all $f \in S$. By assumption, $X = \bigcup_{n=1}^{\infty} S_n$, which is a countable union of closed sets. By Baire's theorem, at least one of the S_N must contain an open set $U \subseteq S_N \subseteq X$. This means for all $x \in U$, we have $|f(x)| \leq N$ for all $f \in S$, as desired. ■

Example 5.8.7. Let $X = [0, \infty)$ with the usual metric, and let $S = \{f_n(x) = \sqrt[n]{x}\} \subseteq C(X)$. For fixed $x \geq 0$, $|f_n(x)| = \sqrt[n]{x} \leq \max\{1, x\} =: M_x$. Note $\sup_x M_x = \infty$. Observe that

$U = [0, a)$ is open in $[0, \infty)$ for any $a > 0$. In this case, $|f_n(x)| \leq \max\{1, a\}$, for all $x \in U$ and all n .

Using this result we can explore certain examples of Banach spaces.

Definition 5.8.4 (Banach Space). A complete normed linear space is called a **Banach space**.

Example 5.8.8. Note we have already shown that ℓ_n^p is a Banach space for $p \in [1, \infty]$ and $n \in \mathbb{N}$.

Example 5.8.9. We have also shown that $C_b(S)$ is a Banach space for $S \subseteq \mathbb{R}$.

Example 5.8.10. The classical Banach sequence spaces, ℓ^p , for $1 \leq p < \infty$: If $1 \leq p < \infty$,

$$\ell^p = \left\{ x = (x_k) \text{ sequence of real or complexes} \mid \|x\|_p := \left(\sum_{k=1}^{\infty} |x_k|^p \right)^{1/p} < \infty \right\}$$

and for $p = \infty$:

$$\ell^\infty = \{x = (x_k) \mid \|x\|_\infty = \sup_k |x_k| < \infty\}$$

We claim that $\|\cdot\|_p$ are all norms for $1 \leq p \leq \infty$. The first two axioms, positive definiteness and absolute homogeneity, are similar to the finite case. For the triangle inequality for $\|\cdot\|_\infty$, $|x_i + y_i| \leq |x_i| + |y_i| \leq \|x\|_\infty + \|y\|_\infty$ for all i , so $\|x + y\|_\infty \leq \|x\|_\infty + \|y\|_\infty$. For $p = 1$,

$$\sum_{i=1}^n |x_i + y_i| \leq \sum_{i=1}^n |x_i| + \sum_{i=1}^n |y_i| \leq \|x\|_1 + \|y\|_1$$

for all n , so $\|x + y\|_1 \leq \|x\|_1 + \|y\|_1$.

For $1 < p < \infty$, we have by Hölder's inequality that

$$\sum_{k=1}^n |x_k| |y_k| \leq \|x\|_p \|y\|_q$$

for $x = [x_1 \dots x_n], y = [y_1 \dots y_n]$ and $\frac{1}{p} + \frac{1}{q} = 1$. Now, let $x \in \ell^p$ and $y \in \ell^q$ such that $\frac{1}{p} + \frac{1}{q} = 1$. Then

$$\begin{aligned} \sum_{k=1}^n |x_k| |y_k| &\leq \left(\sum_{k=1}^n |x_k|^p \right)^{1/p} \left(\sum_{k=1}^n |y_k|^q \right)^{1/q} \\ &\leq \left(\sum_{k=1}^{\infty} |x_k|^p \right)^{1/p} \left(\sum_{k=1}^{\infty} |y_k|^q \right)^{1/q} = \|x\|_p \|y\|_q \end{aligned}$$

This holds for all n , so the sum on the left converges as $n \rightarrow \infty$ and

$$\sum_{k=1}^{\infty} |x_k| |y_k| \leq \|x\|_p \|y\|_q$$

The triangle inequality now follows from Hölder's inequality, using the same argument as the finite dimensional case.

We claim ℓ^p is complete. For $1 \leq p < \infty$, let (x_m) be a Cauchy sequence in ℓ^p . Write $x_m = (x_{m,1}, x_{m,2}, \dots)$. For each i ,

$$|x_{m,i} - x_{l,i}|^p \leq \sum_{j=1}^{\infty} |x_{m,j} - x_{l,j}|^p = \|x_m - x_l\|_p^p$$

which implies $(x_{m,i})_{m=1}^{\infty}$ is Cauchy for each i , and hence has a limit, say \hat{x}_i since \mathbb{R} is complete. Let $x = (\hat{x}_1, \hat{x}_2, \dots)$. Fix $\varepsilon > 0$ and any $n \in \mathbb{N}$. Find $m, l \geq N$ such that

$$\sum_{j=1}^m |x_{m,j} - x_{l,j}|^p \leq \|x_m - x_l\|_p^p < \varepsilon^p$$

The left hand side is a finite sum so we can let $l \rightarrow \infty$, giving

$$\sum_{j=1}^n |x_{m,j} - \hat{x}_j|^p \leq \varepsilon^p$$

But this is true for all n . So taking the limit on n , $\|x_m - x\|_p^p < \varepsilon^p$, so $x_m \rightarrow x$ in ℓ^p . Now, $x \in \ell^p$ since

$$\sum_{j=1}^n |\hat{x}_j|^p \leq \|x - x_m\|_p^p + \|x_m\|_p^p$$

for all n , and taking the sup over all n we have our result.

Recall that if V is a finite dimensional vector space over \mathbb{R} with basis $\{v_1, \dots, v_n\}$, there is a vector space isomorphism, the coordinate isomorphism for the basis, sending $e_i \in \mathbb{R}^n$ to v_i in V . Any norm on \mathbb{R}^n imparts a norm onto V with $\|r_1 v_1 + \dots + r_n v_n\| := \|[r_1 \dots r_n]\|$.

Theorem 5.8.4. *Any two norms on \mathbb{R}^n are equivalent.*

Proof. Let $\{e_1, \dots, e_n\}$ be the standard orthonormal basis for \mathbb{R}^n . Each $v \in \mathbb{R}^n$ can be written uniquely as $v = r_1 e_1 + \dots + r_n e_n$. Let $\|\cdot\|$ be any norm on \mathbb{R}^n . Then

$$\|v\| \leq \sum_{i=1}^n |r_i| \|e_i\| \leq C \sum_{i=1}^n |r_i| = C \|v\|_1$$

where $C = \max_{1 \leq i \leq n} \{\|e_i\|\}$. Let $S = \{v \in \mathbb{R}^n \mid \|v\|_1 = 1\}$. S is compact by Heine-Borel. Define $\alpha : S \rightarrow [0, \infty)$ by $\alpha(v) = \|v\|$. α is continuous since $|\|v\| - \|w\|| \leq \|v - w\|$. This implies $\alpha(S)$ is compact in $[0, \infty)$. Thus, α achieves its minimum at some $v_0 \in S$. That is, $\alpha(v_0) \leq \alpha(v)$ for all $v \in S$. Let $d = \alpha(v_0)$. If $v \neq 0$, we have $\frac{v}{\|v\|_1} \in S$, so

$$\left\| \frac{v}{\|v\|_1} \right\| = \alpha \frac{v}{\|v\|_1} \geq d$$

so $\|v\| \geq d \|v\|_1$. Thus $\|\cdot\|$ and $\|\cdot\|_1$ are equivalent. ■

Corollary 5.8.5. *Finite dimensional vector spaces over \mathbb{R} (or \mathbb{C}) are Banach spaces.*

Proof. From the theorem above, \mathbb{R}^n is complete with any norm. Any finite dimensional vector space V will then be complete by the induced norm on it. ■

5.9.0 Continuous Functions on Metric Spaces

We now explore the homomorphisms of the category of metric spaces: continuous functions.

Definition 5.9.1. Suppose (X, d_X) and (Y, d_Y) are metric spaces and $f : X \rightarrow Y$ is a function. Given $x_0 \in X' \cap X$ we say that the limit of f as x tends to x_0 is L in Y and write

$$\lim_{x \rightarrow x_0} f(x) = L$$

if for every $\varepsilon > 0$, there is a $\delta > 0$ such that $d_Y(f(x), L) < \varepsilon$ whenever $0 < d_X(x, x_0) < \delta$.

Definition 5.9.2. A function $f : X \rightarrow Y$ for metric spaces $(X, d_X), (Y, d_Y)$, is continuous at $x \in X$ if whenever $x_j \rightarrow x$ in X , then $f(x_j) \rightarrow f(x)$ in Y . We say f is continuous on X if and only if f is continuous at $x \in X$ for all x .

Equivalently, f is continuous at $x_0 \in X$ if for every $\varepsilon > 0$, there is a $\delta > 0$ such that $d_Y(f(x), f(x_0)) < \varepsilon$ whenever $d_X(x, x_0) < \delta$. Note we do not require x_0 to be an accumulation point for continuity. We say that f is continuous on X if f is continuous at each $x_0 \in X$.

If x_0 is an accumulation point, continuity at x_0 is equivalent to $\lim_{x \rightarrow x_0} f(x) = f(x_0)$. If x_0 is an isolated point, continuity is automatic.

Example 5.9.1. If X is discrete and $f : X \rightarrow Y$ then f is continuous. Indeed, every singleton in X is open so every point is isolated. If $\varepsilon > 0$, choosing $\delta = 1$ we have $d_X(x, x_0) < 1$ implies $x = x_0$ and so $d_Y(f(x), f(x_0)) = 0 < \varepsilon$.

Proposition 5.9.1. Suppose (X, d_X) and (Y, d_Y) are metric spaces and $f : X \rightarrow Y$. Then $\lim_{x \rightarrow x_0} f(x) = L$ if and only if whenever x_n is a sequence in $X \setminus \{x_0\}$ converging to x_0 , then $f(x_n)$ converges to L in Y .

Proof. First assume $\lim_{x \rightarrow x_0} f(x) = L$. Fix $\varepsilon > 0$ and find $\delta > 0$ such that $0 < d_X(x, x_0) < \delta$ implies $d_Y(f(x), L) < \varepsilon$. If $(x_n) \subseteq X \setminus \{x_0\}$ with $x_n \rightarrow x_0$, find $N \in \mathbb{N}$ such that $n \geq N$ implies $0 < d_X(x_n, x_0) < \delta$. Then for $n \geq N$ we have $d_Y(f(x_n), L) < \varepsilon$ so $f(x_n) \rightarrow L$.

Conversely, suppose $\lim_{x \rightarrow x_0} f(x)$ is not L . Then there exists $\varepsilon > 0$ such that for all $\delta > 0$, there exists $x_\delta \in X \setminus \{x_0\}$ with $0 < d_X(x_\delta, x_0) < \delta$ but $d_Y(f(x_\delta), L) \geq \varepsilon$. For $\delta = 1/n$, $n \in \mathbb{N}$, write $x_n = x_{1/n}$. Then $0 < d_X(x_n, x_0) < 1/n$ so $x_n \rightarrow x_0$. But $d_Y(f(x_n), L) \geq \varepsilon$ for all n . This implies $f(x_n)$ does not converge to L , as desired. ■

We now show that our two characterizations of continuity are equivalent:

Proposition 5.9.2. Suppose (X, d_X) and (Y, d_Y) are metric spaces and $f : X \rightarrow Y$. Then f is continuous at x_0 if and only if $f(x_n)$ converges to $f(x_0)$ in Y whenever x_n converges to x_0 in X .

Proof. If $x_0 \in X'$, use $L = f(x_0)$ in the proposition above. If x_0 is isolated, then f is automatically continuous at x_0 , and any sequence which converges to x_0 must be eventually constant

and hence the images sequence becomes $f(x_0)$, which trivially converges to $f(x_0)$. ■

Proposition 5.9.3. *A function $f : X \rightarrow Y$ is continuous if and only if $U \subseteq Y$ open implies $f^{-1}(U) \subseteq X$ is open, where $f^{-1}(U) = \{x \in X : f(x) \in U\}$.*

Proof. Suppose $f : X \rightarrow Y$ is continuous and $U \subseteq Y$ is open. Let $x_0 \in f^{-1}(U)$, which is to say $f(x_0) \in U$. As U is open in Y there exists $\varepsilon > 0$ such that $B_\varepsilon(f(x_0)) \subseteq U$. By continuity, there exists $\delta > 0$ such that $x \in B_\delta(x_0)$ then $f(x) \in B_\varepsilon(f(x_0))$. This implies

$$f(B_\delta(x_0)) \subseteq B_\varepsilon(f(x_0)) \implies B_\delta(x_0) \subseteq f^{-1}(B_\varepsilon(f(x_0))) \subseteq f^{-1}(U)$$

so $f^{-1}(U)$ is open. The converse is the same argument reversed. ■

Corollary 5.9.4. *Suppose X and Y are metric spaces and $f : X \rightarrow Y$ a function. f is continuous on X if and only if $f^{-1}(C)$ is closed in X whenever C is closed in Y .*

Follows from the previous result and $X \setminus f^{-1}(C) = f^{-1}(Y \setminus C)$.

Example 5.9.2. The function $f : \ell_2^2 \rightarrow \mathbb{R}$ given by

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

is discontinuous at $(0, 0)$. Consider the sequence $(x_n, y_n) = (1/\sqrt{n}, 1/n) \rightarrow (0, 0)$. Then

$$f(1/\sqrt{n}, 1/n) = \frac{1/n^2}{1/n^2 + 1/n^2} = \frac{1}{2} \not\rightarrow 0 = f(0, 0)$$

so the function is not continuous at $(0, 0)$.

Example 5.9.3. The function $f : \ell_2^2 \rightarrow \mathbb{R}$ given by

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

is continuous at $(0, 0)$. Indeed,

$$\begin{aligned} |f(x, y) - f(0, 0)| &= \frac{x^2 |y|}{\sqrt{x^2 + y^2}} \\ &\leq \frac{(x^2 + y^2) |y|}{\sqrt{x^2 + y^2}} \\ &= \sqrt{x^2 + y^2} |y| \\ &\leq \sqrt{x^2 + y^2} \sqrt{x^2 + y^2} \\ &\leq \|(x, y)\|_2^2 \end{aligned}$$

Fix $\varepsilon > 0$ and choose $\delta = \sqrt{\varepsilon}$. If $\|(x, y)\|_2 < \delta$, then $|f(x, y) - f(0, 0)| < \delta^2 = \varepsilon$, as desired.

Example 5.9.4. The evaluation and integration maps on $C([0, 1])$ are continuous. For any $x \in [0, 1]$, define $E_x : C([0, 1]) \rightarrow \mathbb{R}$ by $E_x(f) = f(x)$. Then E_x is continuous. Suppose $(f_n) \subseteq C([0, 1])$ and $f_n \rightarrow_u f$, noting that $\|\cdot\|_\infty$ is the standard norm on $C([0, 1])$. Then $E_x(f_n) = f_n(x)$, which converges to $f(x) = E_x(f)$ since uniform convergence implies pointwise convergence. So E_x is continuous at f for any $f \in C([0, 1])$. Define the integral map $I : C([0, 1]) \rightarrow \mathbb{R}$ by $I(f) = \int_0^1 f(x)dx$. Suppose $f_n \rightarrow_u f$ in $C([0, 1])$. Then, since the convergence is uniform we have that

$$\lim_{n \rightarrow \infty} I(f_n) = \lim_{n \rightarrow \infty} \int_0^1 f_n(x)dx = \int_0^1 f(x)dx = I(f)$$

Operators and NLS

Definition 5.9.3 (Bounded Operators). Suppose V and W are normed linear spaces and $T : V \rightarrow W$ is a linear transformation. We say that T is a **bounded operator** (or bounded linear operator, or bounded linear transformation) if T is continuous on V .

Question 5.9.1. Why the word *bounded*?

We will see later that the bounded linear maps are precisely the ones that map bounded sets to bounded sets. They are not “bounded” in the usual sense of the word. For example, $\text{Id} : \mathbb{R} \rightarrow \mathbb{R}, \text{Id}(x) = x$, is continuous, linear, but “unbounded” in the sense that $\sup_{\mathbb{R}} |f| = \infty$.

Proposition 5.9.5. Suppose V and W are normed linear spaces and $T : V \rightarrow W$ is linear. Then T is bounded if and only if T is continuous at 0.

Proof. Fix $\varepsilon > 0$. Suppose T is continuous at 0. Then there exists $\delta > 0$ such that $\|v\|_V < \delta$ implies $\|Tv\|_W < \varepsilon$. If $u \in V$ and $\|u - u_0\|_V < \delta$, then we get

$$\|T(u - u_0)\|_W < \varepsilon$$

by continuity at 0. But, by linearity $T(u - u_0) = Tu - Tu_0$, so $\|Tu - Tu_0\|_W < \varepsilon$, so T is continuous at u_0 .

The implication follows by definition of a bounded operator. ■

Example 5.9.5. The identity map between the same space with different norms may not be bounded. Let $V = \{C([0, 1]), \|\cdot\|_\infty\}$, and $W = \{C([0, 1]), \|\cdot\|_1 = \int_0^1 |\cdot| dx\}$, and consider $T : V \rightarrow W$ with $Tf = f$. T is bounded. Indeed, assume $f_n \rightarrow_u 0$. Then $Tf_n = f_n$, and we need to show $\|f_n\|_1 \rightarrow 0$. But, by uniform convergence of the f_n to 0,

$$\int_0^1 |f_n(x)|dx \rightarrow \int_0^1 0dx = 0$$

so indeed T is continuous at 0, and by the last result is consequently bounded.

However, $T^{-1} : W \rightarrow V$ is not bounded. We will find a sequence $f_n \rightarrow 0$ in W , but $T^{-1}f_n = f_n \not\rightarrow 0$ in V . Define $f_n(x)$ as $f_n(x) = -n(x - 1/n)$ for $0 \leq x \leq 1/n$ and $f_n(x) = 0$ for $1/n \leq x \leq 1$. Then $\|f_n\|_1 = \frac{1}{2n} \rightarrow 0$, but $\|f_n\|_\infty = 1 \not\rightarrow 0$.

Example 5.9.6. The anti-differentiation map: Define $A : C([0, 1]) \rightarrow C([0, 1])$, both with uniform norm, by

$$Af(x) = \int_0^x f(t)dt$$

By the FTC we have that $Af(x) \in C([0, 1])$, and $(Af)' = f$. A is linear because the Riemann integral is linear. To show boundedness, suppose $f_n \rightarrow_u 0$. Then

$$|Af_n(x)| = \left| \int_0^x f_n(t)dt \right| \leq \int_0^x |f_n(t)|dt \leq x \|f_n\|_\infty \leq \|f_n\|_\infty$$

Hence, it follows that $\|Af_n\|_\infty \leq \|f_n\|_\infty \rightarrow 0$, so $Af_n \rightarrow_u 0$, and A is bounded.

Example 5.9.7. The differentiation map on smooth functions: Let $C^1([0, 1])$, which is a normed linear space with norm $\|f\| := \|f\|_\infty + \|f'\|_\infty$. Define $D : C^1([0, 1]) \rightarrow C([0, 1])$, both with the uniform norm, where $Df = f'$. Although D is linear, it is not continuous at 0. Consider

$$f_n(x) = \frac{\sin(nx)}{\sqrt{n}}, \quad \|f_n\|_\infty \leq \frac{1}{\sqrt{n}} \rightarrow 0$$

But $f'_n(x) = \sqrt{n} \cos(nx)$ does not even converge pointwise. However, $D : (C^1([0, 1]), \|\cdot\|) \rightarrow (C([0, 1]), \|\cdot\|_\infty)$ is bounded. Indeed,

$$\|Df\|_\infty = \|f'\|_\infty \leq \|f\|$$

Then if $\|f_n\| \rightarrow 0$, then $\|Df_n\|_\infty \leq \|f_n\| \rightarrow 0$ and we have continuity at 0.

Example 5.9.8. Maps on spaces of polynomials: Let $\mathcal{P} = \{a_0 + a_1x + \dots + a_nx^n | n \in \mathbb{N} \cup \{0\}, a_0, \dots, a_n \in \mathbb{R}\}$. Then \mathcal{P} is an infinite dimensional space with basis $\{1, x, x^2, x^3, \dots\}$. \mathcal{P} has many norms. Let's use the 1-norm: for $p(x) = \sum_{k=0}^n a_k x^k$,

$$\|p\|_1 := \sum_{j=0}^n |a_j|$$

Define $A : \mathcal{P} \rightarrow \mathcal{P}$ by $Ap(x) := \int_0^x p(t)dt$, so

$$Ap(x) = \sum_{k=0}^n \frac{a_k}{k+1} x^{k+1}$$

Notice that

$$\|Ap\|_1 = \sum_{j=0}^n \left| \frac{a_j}{j+1} \right| \leq \sum_{j=0}^n |a_j| = \|p\|_1$$

so if $\|p_n\|_1 \rightarrow 0$, then $\|Ap_n\|_1 \leq \|p_n\|_1 \rightarrow 0$.

On the other hand, the derivative map $D : \mathcal{P} \rightarrow \mathcal{P}$, $Dp = p'$, is not bounded! Let $p_n(x) = \frac{x^n}{n}$. Then $\|p_n\|_1 = \frac{1}{n} \rightarrow 0$. But $\|Dp_n\|_1 = \|x^{n-1}\|_1 = 1 \not\rightarrow 0$.

Example 5.9.9. Linear transformations on finite dimensional spaces are always continuous. Suppose $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$ with any p -norm. Then L is bounded. The coordinate functions $p_i : \mathbb{R}^n \rightarrow \mathbb{R}$, $p_i(x_1, \dots, x_n) = x_i$, for each $1 \leq i \leq m$ are all continuous as $|x_i| \leq \|x\|_p$.

Next, we have that if S and T are bounded, so are $S + T$ and λS for all $\lambda \in \mathbb{R}$. Indeed,

$$\|(S + T)(x_n)\|_p \leq \|S(x_n)\|_p + \|T(x_n)\|_p \rightarrow 0$$

if $x_n \rightarrow 0$, and

$$\|\lambda S(x_n)\|_p = |\lambda| \|S(x_n)\|_p \rightarrow 0$$

So linear combinations of the f_i are continuous. That is function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ of the form

$$f(x_1, \dots, x_n) = \sum_{i=1}^n a_i f_i(x_1, \dots, x_n)$$

If $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is linear, we can write $L\vec{x} = A\vec{x}$ for some $m \times n$ matrix A . Write $A = [a_{ij}]$ then

$$A\vec{x} = \begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n \end{bmatrix}$$

If $\|\vec{x}_k\|_p \rightarrow 0$, then by continuity of linear combinations of coordinate functions, each entry in $A\vec{x}$ must converge to 0. Consequently, $\|A\vec{x}_k\|_p \rightarrow 0$, so A is bounded.

Definition 5.9.4 (Homeomorphisms and Homeomorphic). Let X and Y be metric spaces and suppose that $\varphi : X \rightarrow Y$ is continuous. If φ is invertible and φ^{-1} is also continuous, we call φ a homeomorphism. In this case, we say X and Y are homeomorphic and write $X \cong Y$.

Example 5.9.10. Continuous invertible maps need not be homeomorphisms. Indeed, from above we saw that $T : (C([0, 1]), \|\cdot\|_\infty) \rightarrow (C([0, 1]), \|\cdot\|_1)$, $Tf = f$, is continuous and invertible but has a discontinuous inverse.

Proposition 5.9.6. The relation “ \cong ” is an equivalence relation on metric spaces.

Indeed $X \cong X$ using the identity, as it is a homeomorphism, symmetric since $X \cong Y$ implies there exists $\varphi : X \rightarrow Y$ a homeomorphism, which has $\varphi^{-1} : Y \rightarrow X$ also as a homeomorphism so $Y \cong X$. Finally, if $\varphi : X \rightarrow Y$ and $\psi : Y \rightarrow Z$ are homeomorphism, so is $\psi \circ \varphi : X \rightarrow Z$, so $X \cong Z$.

Example 5.9.11. With respect to the usual metric on \mathbb{R} , the sets $(0, 1)$ and $(0, \infty)$ are homeomorphic. consider $f(t) = \frac{1}{1-t}$ on $(0, 1)$. Then $f : (0, 1) \rightarrow (1, \infty)$ is a homeomorphism with inverse $f^{-1}(t) = 1 - \frac{1}{t}$. Then $(0, \infty) \cong (1, \infty)$ via the map $t \mapsto t + 1$.

Further, we have $(-\pi/2, \pi/2) \cong \mathbb{R}$ via $f(t) = \tan(t)$. But, $(a, b) \cup (c, d)$ for $a < b < c < d$ is not \cong to \mathbb{R} . No homeomorphism is possible as $(a, b) \cup (c, d)$ can be expressed as the disjoint union of open balls, while \mathbb{R} cannot be expressed as such.

Example 5.9.12. The unit circle and the unit cross are not homeomorphic, as we will see later by results on connected sets.

We remark that $f : X \rightarrow Y$ is a homeomorphism if and only if f is invertible and $f(x_n) \rightarrow f(x)$ in Y whenever $x_n \rightarrow x$ in X and $f^{-1}(y_n) \rightarrow f^{-1}(y)$ in X whenever $y_n \rightarrow y$ in Y . But f is bijective, so this is equivalent to $f(x_n) \rightarrow f(x)$ in Y if and only if $x_n \rightarrow x$ in X .

Definition 5.9.5 (Equivalent Norms). Suppose V is a normed linear space equipped with two norms $\|\cdot\|_a$ and $\|\cdot\|_b$. We say that these norms are equivalent if there exist positive constants c and C so that

$$c\|x\|_b \leq \|x\|_a \leq C\|x\|_b$$

for all $x \in V$.

Proposition 5.9.7. The relation of equivalence between norms on a normed linear space is an equivalence relation.

Proof. Indeed, $\|\cdot\|_a \sim \|\cdot\|_a$ using $c = C = 1$, and if $\|\cdot\|_a \sim \|\cdot\|_b$, so $c\|\cdot\|_b \leq \|\cdot\|_a \leq C\|\cdot\|_b$, then $\|\cdot\|_b \sim \|\cdot\|_a$ with $\frac{1}{C}\|\cdot\|_a \leq \|\cdot\|_b \leq \frac{1}{c}\|\cdot\|_a$. Finally, if $\|\cdot\|_a \sim \|\cdot\|_b \sim \|\cdot\|_c$ with c, C and d, D , it follows that

$$dc\|\cdot\|_c \leq \|\cdot\|_a \leq DC\|\cdot\|_c$$

so $\|\cdot\|_a \sim \|\cdot\|_c$. ■

Proposition 5.9.8. Suppose V is a normed linear space with two norms $\|\cdot\|_a$ and $\|\cdot\|_b$. The identity map $\text{Id}_V : (V, \|\cdot\|_a) \rightarrow (V, \|\cdot\|_b)$ is a homeomorphism if and only if $\|\cdot\|_a$ and $\|\cdot\|_b$ are equivalent.

Proof. First, suppose there exist $c < C$ positive with $c\|\cdot\|_b \leq \|\cdot\|_a \leq C\|\cdot\|_b$ and note that Id_V is invertible. Then, if $v_n \rightarrow v$ in V with respect to $\|\cdot\|_a$, $\|v_n - v\|_b \leq \frac{1}{c}\|v_n - v\|_a \rightarrow 0$, so $\text{Id}_V(v_n) \rightarrow \text{Id}_V(v)$ with respect to $\|\cdot\|_b$. On the other hand, $\|v_n - v\|_a \leq C\|v_n - v\|_b$, so if $v_n \rightarrow v$ with respect to $\|\cdot\|_b$, then $v_n \rightarrow v$ with respect to $\|\cdot\|_a$.

Conversely, suppose Id_V is a homeomorphism. Let $B_r^a(0) = \{v \in V \mid \|v\|_a < r\}$ and $B_s^b(0) = \{v \in V \mid \|v\|_b < s\}$. Then $B_1^a(0)$ is open in $(V, \|\cdot\|_a)$. Id_V is a homeomorphism, so Id_V^{-1} is continuous. So

$$(\text{Id}_V^{-1})^{-1}(B_1^a(0)) = B_1^a(0)$$

is open in $(V, \|\cdot\|_b)$. By definition of open, there exists $r > 0$ such that $B_r^b(0) \subseteq B_1^a(0)$. Hence, if $\|v\|_b < r$ then $\|v\|_a < 1$. If $v \neq 0$, then

$$\frac{vr}{2\|v\|_b} \in B_r^b(0)$$

so

$$\left\| \frac{vr}{2\|v\|_b} \right\|_a < 1$$

It follows that $\|v\|_a < \frac{2}{r}\|v\|_b$. On the other hand, Id_V is continuous so

$$\text{Id}_V^{-1}(B_1^b(0)) = B_1^b(0)$$

is open in $(V, \|\cdot\|_a)$. By definition of open there exists $t > 0$ such that $B_t^a(0) \subseteq B_1^b(0)$. Hence if $\|v\|_a < t$, then $\|v\|_b < 1$. If $v \neq 0$, then

$$\frac{vt}{2\|v\|_a} \in B_t^a(0)$$

so

$$\left\| \frac{vt}{2\|v\|_a} \right\|_b < 1$$

Thus, $\frac{t}{2}\|v\|_b < \|v\|_a < \frac{2}{r}\|v\|_b$, as desired. ■

Proposition 5.9.9. *All of the p -norms on \mathbb{R}^n are equivalent.*

Proof. We will show $\|\cdot\|_\infty$ and $\|\cdot\|_p$ are equivalent for any $1 \leq p < \infty$. Fix $\vec{x} = (x_1, \dots, x_n) \in \mathbb{R}^n$. Then $\|\vec{x}\|_\infty = \max_{1 \leq i \leq n} |x_i| = |x_j|$ for some $1 \leq j \leq n$. Then

$$\|\vec{x}\|_\infty = |x_j| = [|x_j|^p]^{1/p} \leq \left[\sum_{i=1}^n |x_i|^p \right]^{1/p} = \|\vec{x}\|_p$$

and

$$\|\vec{x}\|_p \leq \left[\sum_{i=1}^n |x_i|^p \right]^{1/p} = n^{1/p} |x_j| = n^{1/p} \|\vec{x}\|_\infty$$

So $\|\vec{x}\|_\infty \leq \|\vec{x}\|_p \leq n^{1/p} \|\vec{x}\|_\infty$, and the norms are equivalent. \blacksquare

Definition 5.9.6 (Operator Norm). . Suppose V and W are normed linear spaces and $T : V \rightarrow W$ is a linear transformation. The **operator norm** for T is

$$\|T\| = \inf\{C > 0 \mid \|Tv\|_W \leq C\|v\|_V, \forall v \in V\}$$

We will adopt the convention that if the set on the right is empty, then $\|T\| = \infty$.

Note that by definition $\|Tv\|_W \leq \|T\| \|v\|_V$ for all $v \in V$.

Proposition 5.9.10. Suppose V and W are normed linear spaces and $T : V \rightarrow W$ is a linear transformation. The following are equivalent:

- (1) T is bounded (i.e. continuous on V)
- (2) T is continuous at 0
- (3) $\|T\| < \infty$

Proof. We have already shown the equivalence between (1) and (2). We will show (2) \iff (3).

First, suppose (2) holds. Fix $\varepsilon = 1$. Then there exists $\delta > 0$ such that $\|v\|_V < \delta$ then $\|Tv\|_W < 1$. If $v \neq 0$, then $\left\| \frac{\delta v}{2\|v\|_V} \right\|_V = \frac{\delta}{2}$, so

$$\left\| T \frac{\delta v}{2\|v\|_V} \right\|_W < 1$$

As T is linear it follows that

$$\|Tv\|_W < \frac{2}{\delta} \|v\|_V$$

Thus, T is bounded and $\|T\| \leq \frac{2}{\delta}$.

Conversely, suppose (3) holds. We have $\|Tv\|_W \leq \|T\| \|v\|_V$ for all $v \in V$, where $\|T\| < \infty$. So if $v_n \rightarrow 0$ in V , then

$$\|Tv_n\|_W \leq \|T\| \cdot \|v_n\|_V \rightarrow 0$$

so $Tv_n \rightarrow 0$ in W and T is continuous at 0. \blacksquare

In light of the above result, we can now say that an operator is bounded if and only if its operator norm is finite.

Definition 5.9.7. The set of all bounded operators from V to W is denoted $B(V, W)$. We use the notation $B(V)$ for $B(V, V)$.

Proposition 5.9.11. Suppose $T \in B(V, W)$. Then

$$\|T\| = \sup_{\|v\|=1} \|Tv\|_W = \sup_{\|v\| \leq 1} \|Tv\|_W = \sup_{v \neq 0} \frac{\|Tv\|_W}{\|v\|_V}$$

Proof. We shall show the second equals the third, and that $(1) \leq (2) \leq (3) \leq (1)$. For $(2) = (4)$, if $v \neq 0$ then $\frac{v}{\|v\|_V}$ is a unit vector and

$$T(v/\|v\|_V) = \frac{1}{\|v\|_V} Tv$$

applying supremums to both sides we obtain the desired inequality.

Next, for $(1) \leq (2)$, if $v \neq 0$ then

$$\left\| T \left(\frac{v}{\|v\|_V} \right) \right\|_W \leq (2)$$

by definition, so $\|Tv\|_W \leq \|v\|_V(2)$ and so by definition of $\|T\|$, $\|T\| \leq (2)$. $(2) \leq (3)$ is immediate as (3) is a supremum over a larger set. Finally, for $(3) \leq (1)$ suppose $C \geq 0$ satisfying $\|Tv\|_W \leq C\|v\|_V$ for all $v \in V$. We must show $(3) \leq C$ and $((3) \leq \|T\|$ by definition). If $\|v\| \leq 1$, then $\|Tv\|_W \leq C$, so

$$(3) = \sup_{\|v\| \leq 1} \|Tv\|_W \leq C$$

and the result follows. ■

Proposition 5.9.12. Let V and W be normed linear spaces.

- (1) $B(V, W)$ is a normed linear space using the operator norm
- (2) $B(V, W)$ is complete when W is complete
- (3) if Z is a normed vector space, $T \in B(V, W)$ and $S \in B(W, Z)$, then $S \circ T \in B(V, Z)$ and

$$\|S \circ T\| \leq \|S\| \cdot \|T\|$$

which is to say the operator norm is submultiplicative

Proof. (1): First, let $\lambda \in \mathbb{R}$. Note that $\|(\lambda T)v\|_W = |\lambda| \|Tv\|_W \leq |\lambda| \|T\| \|v\|_V$ for all $v \in V$, so $\|\lambda T\| \leq |\lambda| \|T\|$. Further, if $\lambda = 0$ the result is immediate, so suppose $\lambda \neq 0$, and it follows that

$$\|Tv\|_W = \frac{1}{|\lambda|} \|(\lambda T)v\|_W \leq \frac{\|\lambda T\|}{|\lambda|} \|v\|_V$$

for all $v \in V$, so $\|T\| \cdot |\lambda| \leq \|\lambda T\|$, and we have equality $\|\lambda T\| = |\lambda| \cdot \|T\|$. If $T = 0$, then $\|Tv\| = 0$ for all $v \in V$, so $\|T\| = 0$. Conversely, if $\|T\| = 0$, then $\|Tv\|_W = 0$ for all $\|v\|_V \leq 1$. Then for all $w \neq 0$, we have

$$\|T \frac{w}{\|w\|_V}\|_W = 0$$

so $\|Tw\|_W = 0$, and as $\|\cdot\|_W$ is a norm, $Tw = 0$ for all $w \in V$. Thus, $T \equiv 0$. Finally, suppose $T, S \in B(V, W)$. Then if $\|v\|_V = 1$,

$$\|(T + S)v\|_W = \|Tv + Sv\|_W \leq \|Tv\|_W + \|Sv\|_W \leq \|T\| + \|S\| < \infty$$

so using our previous equality chain result, $\|T + S\| \leq \|T\| + \|S\|$.

(2) Suppose $(T_n) \subseteq B(V, W)$ is a Cauchy sequence. Then for all $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that for $m, n \geq N$, $\|T_n - T_m\| < \varepsilon$. Note for any $v \neq 0$ in V , we have

$$T_n(v/\|v\|_V) - T_m(v/\|v\|_V)\|_W < \varepsilon$$

so

$$\|T_nv - T_mv\|_W < \varepsilon\|v\|_V$$

This implies (T_nv) is a Cauchy sequence in W . W being complete, we can define $T : V \rightarrow W$ by

$$Tv := \lim_{n \rightarrow \infty} T_nv$$

This defines a linear map $T : V \rightarrow W$ since

$$T(v + w) = \lim_{n \rightarrow \infty} T_n(v + w) = \lim_{n \rightarrow \infty} T_nv + \lim_{n \rightarrow \infty} T_nw = Tv + Tw$$

and

$$T(\lambda v) = \lim_{n \rightarrow \infty} T_n(\lambda v) = \lim_{n \rightarrow \infty} \lambda T_nv = \lambda Tv$$

First we show that $\|T - T_n\| \rightarrow 0$. If $v \in V$ with $\|v\|_V = 1$, then

$$\|Tv - T_nv\|_W \leq \|Tv - T_mv\|_W + \|T_mv - T_nv\|_W < \|Tv - T_mv\|_W + \varepsilon \rightarrow 0$$

since $\|Tv - T_mv\|_W \rightarrow 0$ as $m \rightarrow \infty$. Then $\|Tv - T_nv\|_W \leq \varepsilon$. Taking the supremum over all $\|v\|_V = 1$,

$$\|T - T_n\| \leq \varepsilon$$

Finally, $T \in B(V, W)$ since $\|T\| \leq \|T - T_n\| + \|T_n\| < \infty$.

(3) If $T \in B(V, W)$, $S \in B(W, Z)$, then $S \circ T : V \rightarrow Z$ is linear. If $\|v\|_V = 1$, then

$$\|STv\|_Z \leq \|S\| \|Tv\|_W \leq \|S\| \|T\| \|v\|_V = \|S\| \|T\|$$

Now taking the supremum over all $\|v\|_V = 1$ we get $\|ST\| \leq \|S\| \|T\|$. ■

Recall 5.9.2. Recall that we can represent linear transformations on finite dimensional vector spaces by matrices. If $T : \ell_n^2 \rightarrow \ell_m^2$ is linear, then its standard matrix representation is

$$A = [Te_1 \ Te_2 \ \dots \ Te_n]$$

for $\{e_1, \dots, e_n\}$ the standard orthonormal basis for \mathbb{R}^n . In this way, $T(\vec{x}) = A\vec{x}$.

Example 5.9.13. We consider the *operator spectral norm* for a diagonal matrix. The *spectral norm* means the operator norm on $A \in M_{m \times n}$. Consider $T_A : \ell_n^2 \rightarrow \ell_n^2$ with $A =$

$$\begin{bmatrix} a_1 & & & 0 \\ & a_2 & & \\ & & \ddots & \\ 0 & & & a_n \end{bmatrix}, \text{ so } T\vec{x} = [a_1x_1 \dots a_nx_n]^T. \text{ Let } a = \max\{|a_1|, \dots, |a_n|\}. \text{ Then}$$

$$\|T\vec{x}\|_2^2 = \sum_{i=1}^n a_i^2 x_i^2 \leq \sum_{i=1}^n a^2 x_i^2 = a^2 \|\vec{x}\|_2^2$$

so $\|T\| \leq a$. There is some i with $a = |a_i|$, so $\|Te_i\|_2 = |a_i| = a\|e_i\|_2$, as $\|e_i\|_2 = 1$, so $\|T\| \geq a$, since $\|T\| = \sup_{\|v\|=1} \|Tv\|$. Thus, $\|T\| = a$.

Example 5.9.14. For any $T : \ell_n^2 \rightarrow \ell_n^2$, we have seen T is bounded. Let $A = [T]$ be the standard matrix for T . The $n \times n$ matrix $A^T A$ is positive semidefinite. That is $A^T A$ is symmetric, and has all eigenvalues ≥ 0 . Indeed, observe that for all $v \in \ell_n^2$, $v^T A^T A v = (Av) \cdot (Av) = \|Av\|_2^2 \geq 0$. Then, if $\lambda \in \mathbb{R}$ is an eigenvalue with eigenvector $v \in \ell_n^2$, then

$$0 \leq \|Av\|_2^2 = v^T A^T A v = v^T (\lambda v) = \lambda \|v\|_2^2$$

As $v \neq 0$, $\|v\|_2^2 \neq 0$, so $\lambda \geq 0$, as claimed.

Now, there is an orthogonal matrix U , $U^T = U^{-1}$, such that $U^T (A^T A) U = D$ is diagonal. The diagonal entries of D , $\lambda_1, \dots, \lambda_n$, are called the singular values for A with $\lambda_i \geq 0$. Define \sqrt{D} as the diagonal matrix with $\sqrt{\lambda_i}$ on the diagonal, and note that $\sqrt{D}^2 = D$. We have $UU^T = U^T U = I_n$, so for any $\vec{x} \in \ell_n^2$,

$$\|\vec{x}\|_2^2 = \vec{x} \cdot \vec{x} = U^T U \vec{x} \cdot \vec{x} = U \vec{x} \cdot U \vec{x} = \|U \vec{x}\|_2^2$$

and $\|U^T \vec{x}\|_2 = \|\vec{x}\|_2$. Let \vec{x} be a unit vector. Then

$$\begin{aligned} \|A\vec{x}\|_2^2 &= A\vec{x} \cdot A\vec{x} = A^T A \vec{x} \cdot \vec{x} \\ &= U D U^T \vec{x} \cdot \vec{x} \\ &= D U^T \vec{x} \cdot U^T \vec{x} \\ &= \sqrt{D} U^T \vec{x} \cdot \sqrt{D} U^T \vec{x} \\ &= \|\sqrt{D} U^T \vec{x}\|_2^2 \\ &\leq \|\sqrt{D}\|^2 \|U^T \vec{x}\|_2^2 = \|\sqrt{D}\|^2 \end{aligned}$$

So $\|A\| \leq \|\sqrt{D}\|$. Similarly, $\|\sqrt{D}\vec{x}\|_2^2 = \|AU\vec{x}\|_2^2 \leq \|A\|^2$, so $\|\sqrt{D}\| \leq \|A\|$. Together these inequalities imply $\|A\| = \|\sqrt{D}\| = \max_{1 \leq i \leq n} \sqrt{\lambda_i}$.

Example 5.9.15. Consider $A = \begin{bmatrix} 2 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} : \ell_3^2 \rightarrow \ell_2^2$. Then

$$A^T A = \begin{bmatrix} 5 & 2 & 0 \\ 2 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

has characteristic polynomial $t[(t-5)(t-1)-4] = t(t^2-6t+1)$, so its eigenvalues are $\lambda = 0, 3 \pm 2\sqrt{2}$. Thus,

$$\|A\| = \sqrt{3+2\sqrt{2}}$$

Even if A is $n \times n$ and diagonalizable, it may not be the case that $\|A\|$ is equal to the largest eigenvalue of A (in modulus). It turns out that $\|A\|$ is always at least this number, though.

By convention, we will also insist that if $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is linear, we are using the 2-norm for both spaces.

Definition 5.9.8. Suppose (X, d_X) and (Y, d_Y) are metric spaces and $\varphi : X \rightarrow Y$. We say that φ is an isometry if $d_Y(\varphi(x), \varphi(y)) = d_X(x, y)$ for all $x, y \in X$.

That is to say, isometries preserve distances.

Proposition 5.9.13. *Isometries are continuous.*

Proof. Fix $\varepsilon > 0$ and $\delta = \varepsilon$. Then if $d_X(x, y) < \delta$, $d_Y(\varphi(x), \varphi(y)) = d_X(x, y) < \delta = \varepsilon$. ■

Example 5.9.16. We saw above if $U : \ell_n^2 \rightarrow \ell_n^2$ is orthogonal, then $\|U\vec{x}\|_2^2 = \|\vec{x}\|_2^2$. So U is an isometry since

$$\|U\vec{x} - U\vec{y}\|_2^2 = \|U(\vec{x} - \vec{y})\|_2^2 = \|\vec{x} - \vec{y}\|_2^2$$

Definition 5.9.9. An affine function $\varphi : \ell_n^2 \rightarrow \ell_n^2$ is given by

$$\varphi(\vec{x}) = U\vec{x} + \vec{b}$$

for some orthogonal matrix U and some vector $\vec{b} \in \ell_n^2$.

From the previous example, affine functions are common examples of isometries. In fact there are no other isometries.

Example 5.9.17. Suppose $\varphi : \mathbb{R} \rightarrow \mathbb{R}$ is an isometry. First assume $\varphi(0) = 0$. Then $|\varphi(x) - \varphi(0)| = |x - 0| = |x|$, so $\varphi(x) = \pm x$. We want $\varphi(x) = x$ for all $x \in \mathbb{R}$, or $\varphi(x) = -x$ for all x . Suppose this was not the case. Then there exist $x \neq y \in \mathbb{R} \setminus \{0\}$ with $\varphi(x) = x$ and $\varphi(y) = -y$. But then $0 \neq |x - y| = |\varphi(x) - \varphi(y)| = |x + y|$, which implies $(x - y)^2 = (x + y)^2$, which occurs if and only if $-2xy = 2xy$, or either $x = 0$ or $y = 0$, which is a contradiction. Thus, $\varphi(x) = x$ or $\varphi(x) = -x$. If $p : \mathbb{R} \rightarrow \mathbb{R}$ is any isometry, then $\varphi : \mathbb{R} \rightarrow \mathbb{R}$ defined by $\varphi(x) = p(x) - p(0)$ is an isometry with the same property as above, so $\varphi(x) = x$ or $-x$. Thus, $p(x) = x + b$ or $p(x) = -x + b$ for some $b \in \mathbb{R}$.

Example 5.9.18. The space of smooth functions is complete: the space $(C^1([0, 1]), \|\cdot\|)$. Let $(f_n) \subseteq C^1([0, 1])$ be Cauchy with respect to $\|\cdot\|$. Then the f_n are Cauchy with respect to $\|\cdot\|_\infty$, so as $(C([0, 1]), \|\cdot\|_\infty)$ is complete, there exists $f \in C([0, 1])$ such that $f_n \rightarrow_u f$. Similarly, f'_n are Cauchy with respect to $\|\cdot\|_\infty$, so there exists $g \in C([0, 1])$ such that $f'_n \rightarrow_u g$. Then, for $x \in [0, 1]$,

$$\begin{aligned} \int_0^x g(t) dt &= \lim_{n \rightarrow \infty} \int_0^x f'_n(t) dt && \text{(by uniform convergence)} \\ &= \lim_{n \rightarrow \infty} (f_n(x) - f_n(0)) && \text{(by FTC2)} \\ &= f(x) - f(0) && \text{(by pointwise convergence)} \end{aligned}$$

Then, by the FTOC1, $f(x) - f(0)$ is differentiable at $x \in [0, 1]$ as $g(x)$ is continuous on $[0, 1]$, and $(f(x) - f(0))' = f'(x) = g(x)$. Thus, $f' \in C([0, 1])$. Hence, $f \in C^1([0, 1])$, and

$$|||f - f_n||| = ||f - f_n||_\infty + ||f' - f'_n||_\infty = ||f - f_n||_\infty + ||g - f'_n||_\infty \rightarrow 0$$

so $(C^1([0, 1]), ||| \cdot |||)$ is complete.

Maps on Compact Spaces

Proposition 5.9.14. *If $f : X \rightarrow Y$ is continuous and $K \subseteq X$ is compact in X , then $f(K)$ is compact in Y .*

Proof. Let $(y_j) \subseteq f(K)$. Then there exists $(x_j) \subseteq K$ such that $f(x_j) = y_j$ for all j . But, K is compact so there exists a convergent subsequence (x_{j_v}) which converges to some $x \in K$. As f is continuous, $f(x_{j_v}) \rightarrow f(x)$. But then $y_{j_v} = f(x_{j_v}) \rightarrow f(x) \in f(K)$, so (y_j) has a convergent subsequence and $f(K)$ is compact. ■

Proposition 5.9.15. *If X is a compact metric space and $f : X \rightarrow \mathbb{R}$ is continuous, then f assumes a max and min value in X .*

This follows from the characterization of compact sets in \mathbb{R} , which are precisely the closed and bounded sets.

Definition 5.9.10. *For $f : X \rightarrow \mathbb{R}$, we define*

$$\sup_X f = \begin{cases} \sup_{x \in X} f(x) & \text{if } f(X) \text{ is bounded from above} \\ \infty & \text{if not bounded above} \end{cases}$$

and

$$\inf_X f = \begin{cases} \inf_{x \in X} f(x) & \text{if } f(X) \text{ is bounded from below} \\ -\infty & \text{if not bounded below} \end{cases}$$

Using this convention, we define a notion of a limit which always exists in the extended reals, even if the actual limit does not exist.

Definition 5.9.11. *For any sequence $(x_n) \subseteq \mathbb{R}$, we define*

$$\limsup_{n \rightarrow \infty} x_n := \lim_{n \rightarrow \infty} \left(\sup_{k \geq n} x_k \right)$$

and

$$\liminf_{n \rightarrow \infty} x_n := \lim_{n \rightarrow \infty} \left(\inf_{k \geq n} x_k \right)$$

Note $\sup_{k \geq n} x_k$ is a decreasing sequence and $\inf_{k \geq n} x_k$ is an increasing sequence.

So \limsup is the limit of a monotone decreasing sequence and \liminf is the limit of a monotone increasing sequence. Further we have that $(x_n) \subseteq \mathbb{R}$ is convergent if and only if $\limsup x_n = \liminf x_n$.

Uniform Continuity

We now define a more powerful notion of continuity of functions on metric spaces.

Definition 5.9.12. Let (X, d_X) and (Y, d_Y) be metric spaces. A function $f : X \rightarrow Y$ is said to be uniformly continuous on X if for all $\varepsilon > 0$ there exists $\delta > 0$ such that

$$d_X(x, y) < \delta \implies d_Y(f(x), f(y)) < \varepsilon$$

for all $x, y \in X$.

This is the same definition as for uniformly continuous functions on the real line.

Example 5.9.19. An example of a continuous function which is not uniformly continuous is the topologists sine curve, $\sin(1/x)$ (Image here)

Example 5.9.20. $f(x) = x^2$ is continuous. For any $\varepsilon > 0$, observe $|x^2 - y^2| < \varepsilon \implies |x - y||x + y| < \varepsilon$. If $|x - y| < \delta$, $|x - y||x + y| \leq (2|x| + 1)\delta$ if $\delta = \min \left\{ \frac{\varepsilon}{2|x|+1}, 1 \right\}$. But this depends on x . This does work for x' such that $|x'| \leq |x|$, but for bigger x' we would need a smaller δ , so f is not uniformly continuous.

Proposition 5.9.16. Suppose $\varphi : X \rightarrow Y$ is uniformly continuous. If (x_n) is Cauchy in X , then $(\varphi(x_n))$ is Cauchy in Y .

Proof. Fix $\varepsilon > 0$ such that $d_X(x, y) < \delta$ implies $d_Y(\varphi(x), \varphi(y)) < \varepsilon$. If (x_n) is Cauchy there exists $N \in \mathbb{N}$ such that for $m, n \geq N$, $d_X(x_n, x_m) < \delta$. Then, for all $m, n \geq N$ we have

$$d_Y(\varphi(x_n), \varphi(x_m)) < \varepsilon$$

so $(\varphi(x_n))$ is Cauchy in Y . ■

Example 5.9.21. Consider $f(x) = 1/x$ and $g(x) = \sin(1/x)$, which are not uniformly continuous on $(0, \infty)$. For example, $x_n = 1/n$ is Cauchy in $(0, \infty)$ but $f(1/n) = n$ is not, and $g(1/n) = \sin(n)$ is also not.

Example 5.9.22. Consider $f : \mathbb{R}^2 \rightarrow \mathbb{R}$, $f(x, y) = x^2 + y^2$. Fix $\varepsilon = 1$ and $\delta > 0$. Let $x = 1/\delta, y = 1/\delta$. Then

$$|f(x + \delta/2, y + \delta/2) - f(x, y)| = 2(1/\delta + \delta/2)^2 - 2/\delta^2 = 2|1 + \delta^2/4| > 2 > \varepsilon$$

Then $\|(x + \delta/2, y + \delta/2) - (x, y)\|_2 = \|(\delta/2, \delta/2)\|_2 = \sqrt{2}\delta/2 < \delta$. Thus, f cannot be uniformly continuous

Example 5.9.23. Consider $f : \mathbb{R}^2 \setminus \{0\} \rightarrow \mathbb{R}$ defined by $f(x, y) = \frac{1}{x^2 + y^2}$. Then $f(1/n, 0) = n^2$ is not Cauchy in \mathbb{R} , but $(1/n, 0)$ is Cauchy in \mathbb{R}^2 .

Proposition 5.9.17. Bounded operators are uniformly continuous.

Proof. Let $T \in B(V, W)$ and let $\varepsilon > 0$. Then

$$\|Tv - Tw\| \leq \|T\| \|v - w\|$$

for $\|T\| < \infty$. Let $\delta = \frac{\varepsilon}{\|T\|+1}$. Then if $\|v - w\| < \delta$, $\|Tv - Tw\| < \varepsilon$. ■

Further, we also have that all isometries are uniformly continuous as they are in fact Lipschitz continuous.

Proposition 5.9.18. *If X is compact and $f : X \rightarrow Y$ is continuous, then f is uniformly continuous.*

Proof. Let $\varepsilon > 0$. Let $f(X) = \bigcup_{x \in X} B_{\varepsilon/2}(f(x))$ cover the image. For each x there exist $\delta_x > 0$ such that $f(B_{\delta_x}(x)) \subseteq B_{\varepsilon/2}(f(x))$. Then $X \subseteq \bigcup_{x \in X} B_{\delta_x/2}(x)$ is an open cover, so there exists $x_1, \dots, x_N \in X$ such that $X \subseteq \bigcup_{i=1}^N B_{\delta_{x_i}/2}(x_i)$ since X is compact. Let $\delta = \min_{1 \leq i \leq N} (\delta_{x_i}/2)$. Then let $x, y \in X$ such that $d_X(x, y) < \delta$. Since the $B_{\delta_{x_i}/2}(x_i)$ cover X , there exists $1 \leq i \leq N$ such that $x \in B_{\delta_{x_i}/2}(x_i)$. Then

$$d_X(x_i, y) \leq d_X(x_i, x) + d_X(x, y) < \delta_{x_i}/2 + \delta \leq \delta_{x_i}$$

so $x, y \in B_{\delta_{x_i}}(x_i)$. It follows that $f(x), f(y) \in B_{\varepsilon/2}(f(x_i))$ so

$$d_Y(f(x), f(y)) \leq d_Y(f(x), f(x_i)) + d_Y(f(x_i), f(y)) < \varepsilon/2 + \varepsilon/2 = \varepsilon$$

completing the proof. ■

Now we come to the notion of an isomorphism in the category of metric spaces:

Definition 5.9.13. *A function $f : X \rightarrow Y$ is said to be a homeomorphism if it is continuous, bijective, and f^{-1} is continuous.*

Proposition 5.9.19. *If X is a compact metric space, then $f : X \rightarrow Y$ being continuous and bijective implies f^{-1} is continuous.*

Proof. Let $g = f^{-1} : Y \rightarrow X$. Note g is continuous in Y if and only if $g^{-1}(V) = f(V)$ is closed in Y for all V closed in X . Note V is compact in X if it is closed, so $f(V)$ is compact. Then as Y is a metric space V being compact implies it is closed. Thus g is continuous, as desired. ■

Sequences and Series of Functions

Next we consider convergence of sequences of functions:

Definition 5.9.14. *Let $f_j : X \rightarrow Y$, $j \in \mathbb{N}$, be a sequence of functions. If $f : X \rightarrow Y$, and $f_j(x) \rightarrow f(x)$ for all $x \in X$, we say that $f_j \rightarrow f$ pointwise on X .*

Definition 5.9.15. A sequence $f_j : X \rightarrow Y$ converges uniformly to $f : X \rightarrow Y$ if and only if for all $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that if $j \geq N$,

$$d_Y(f_j(x), f(x)) < \varepsilon, \forall x \in X$$

or equivalently

$$\sup_{x \in X} d_Y(f_j(x), f(x)) \leq \varepsilon$$

Proposition 5.9.20. If $f_j : X \rightarrow Y$ are continuous and converge uniformly to $f : X \rightarrow Y$, then f is continuous.

Proof. Let $\varepsilon > 0$ and $x \in X$. Then there exists $N \in \mathbb{N}$ such that for $j \geq N$, $d_Y(f_j(y), f(y)) < \varepsilon/3$ for all $y \in X$. As f_N is continuous, there exists $\delta > 0$ such that $f_N(B_\delta(x)) \subseteq B_{\varepsilon/3}(f_N(x))$. Then for $d_X(x, y) < \delta$,

$$d_Y(f(x), f(y)) \leq d_Y(f(x), f_N(x)) + d_Y(f_N(x), f_N(y)) + d_Y(f_N(y), f(y)) < \varepsilon$$

so f is continuous. ■

Example 5.9.24. If $f_j : [0, 1] \rightarrow [0, 1]$ is defined by $f_j(x) = x^j$, all of which are continuous, then $f_j(x)$ converge pointwise to $f(x) = \begin{cases} 0 & x < 1 \\ 1 & x = 1 \end{cases}$, which is discontinuous, and hence the convergence can't be uniform.

Definition 5.9.16. A sequence of functions $f_j : X \rightarrow Y$ is said to be uniformly Cauchy if for all $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for $j, k \geq N$,

$$\sup_{x \in X} d_Y(f_j(x), f_k(x)) \leq \varepsilon$$

or equivalently $\lim_{j, k \rightarrow \infty} \sup_{x \in X} d_Y(f_j(x), f_k(x)) = 0$.

Proposition 5.9.21. If Y is a complete metric space and $f_j : X \rightarrow Y$ is uniformly Cauchy, then there exists $f : X \rightarrow Y$ such that f_j converge uniformly to f .

Proof. As f_j is uniformly Cauchy, for each $x \in X$, $(f_j(x)) \subseteq Y$ is Cauchy. As Y is complete there exists $y_x \in Y$ such that $f_j(x) \rightarrow y_x$. Then define $f : X \rightarrow Y$ by $f(x) = \lim_{j \rightarrow \infty} f_j(x)$. Fix $\varepsilon > 0$. As f_j is uniformly Cauchy there exists $N \in \mathbb{N}$ such that $j \geq N$ and $k \geq 0$ implies $d_Y(f_j(x), f_{j+k}(x)) < \varepsilon$. Taking the limit as k goes to infinity we have $d_Y(f_j(x), f(x)) \leq \varepsilon$ for all $x \in X$. Thus, f_j converges uniformly to f . ■

Now we consider basic properties of series:

Definition 5.9.17. We say a sequence $f_j : X \rightarrow \mathbb{R}^n$ is pointwise summable if and only if the sequence

$$s_n(x) = \sum_{j=0}^n f_j(x)$$

is pointwise convergent.

Definition 5.9.18. $f_j : X \rightarrow \mathbb{R}^n$ is uniformly summable if and only if $s_n(x) = \sum_{j=0}^n f_j(x)$ is uniformly convergent.

Theorem 32 (Weierstrass M-Test (General)).

Let $f_j : X \rightarrow \mathbb{R}^n$ be a sequence of functions. Assume there exist $M_k \in \mathbb{R}$ such that $\sup_{x \in X} \|f_k(x)\| \leq M_k$ and

$$\sum_{k=0}^{\infty} M_k < \infty$$

Then the series $\sum_{k=0}^n f_k(x)$ converges uniformly on X to a limit $s(x)$.

Proof. Suppose the hypotheses of the theorem. As $\sum_{k=0}^n M_k$ is Cauchy, for $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that for $j, k \geq N$,

$$\left| \sum_{n=j+1}^k f_n(x) \right| \leq \sum_{n=j+1}^k |f_n(x)| \leq \sum_{n=j+1}^k M_n < \varepsilon$$

for all $x \in X$, so $\sum_{n=0}^k f_n(x)$ is uniformly Cauchy, and hence uniformly convergent since \mathbb{R}^n is complete. ■

5.10.0 Connected Sets

We now define a notion for what it means for a space to be connected, or not disconnected.

Definition 5.10.1. A topological space (X, τ) is not connected or disconnected if there exists $U, V \in \tau$ such that $U, V \neq \emptyset$, $U \cap V = \emptyset$, and

$$X = U \sqcup V$$

If no such U and V exist, then X is said to be connected.

Equivalently a space X is connected if and only if the only clopen sets are X and \emptyset . For metric spaces we say:

Definition 5.10.2. A subset S of a metric space X is disconnected if there are open subsets U and V of X such that

- The intersection $U \cap S$ and $V \cap S$ are non-empty
- $(U \cap S) \cap (V \cap S) = \emptyset$
- $S = (U \cap S) \cup (V \cap S)$

The pair (U, V) is called a separation of S . If S has no separations, then we say that S is connected.

If $S = X$, this just means $X = U \cup V$ with $U \cap V = \emptyset$.

Example 5.10.1. A disconnected set in ℓ_2^2 is $B_1((-1, 0)) \cup B_1((1, 0))$.

Example 5.10.2. Connected subsets of a discrete space: $Y \subseteq X$ is connected if and only if $Y = \{y\}$. $\{y\}$ is connected. If $|Y| \geq 2$, let $y_0 \in Y$, $U = \{y_0\}$, and $V = Y \setminus \{y_0\}$, which is a separation.

Proposition 5.10.1. All intervals in \mathbb{R} are connected.

Proof. Suppose I is an interval in \mathbb{R} . That is for all $a, b \in I$, with $a < b$, $[a, b] \subseteq I$. Suppose we have a separation $A, B \subseteq \mathbb{R}$ open such that $I = (I \cap A) \cup (I \cap B)$, with $I \cap A, I \cap B \neq \emptyset$, and $(I \cap A) \cap (I \cap B) = \emptyset$. Let $A' = I \cap A$ and $B' = I \cap B$. Let $a \in A' \subseteq I$ and $b \in B' \subseteq I$ so $a \neq b$. Without loss of generality suppose $a < b$. Then $[a, b] \subseteq I$ and covered by A', B' . Then let $s = \sup A' \cap [a, b]$. Then $s \leq b$. We proceed by cases:

- Suppose $s \in A'$. Then as A is open, there exists $\varepsilon > 0$ such that $(s - \varepsilon, s + \varepsilon) \subseteq A$. Let $\varepsilon' = \min\{\varepsilon, |s - b|\} > 0$. Then $[s, s + \varepsilon'] \subseteq A' \cap [a, b]$. In particular $s + \varepsilon'/2 \in A' \cap [a, b]$, contradicting the fact that $s = \sup A' \cap [a, b]$.
- Suppose $s \in B' \cap [a, b]$. As B is open, there exists $\varepsilon > 0$ such that $B_\varepsilon(s) \subseteq B$. Then let $\varepsilon' = \min\{\varepsilon, |s - a|\} > 0$, so $(s - \varepsilon', s) \subseteq B' \cap [a, b]$ and $s - \varepsilon'/2 \in B' \cap [a, b]$, so $t \leq s - \varepsilon'/2$ for all $t \in A' \cap [a, b]$, contradicting the fact $s = \sup A' \cap [a, b]$.

■

Definition 5.10.3. If (X, τ) is a topological space and $A \subseteq X$, the subspace topology on A is defined by

$$\tau_A := \{U \cap A \subseteq A : U \in \tau\}$$

Note if $\iota : A \hookrightarrow X$ is the inclusion, τ_A is the coarsest topology/weakest topology making ι continuous

$$U \subseteq A \text{ open} \iff \exists V \in \tau; \iota^{-1}(V) = U \cap A = U$$

Definition 5.10.4. A topological space (X, τ) is path connected if and only if for all $p, q \in X$, there exists a continuous map

$$\gamma : [0, 1] \rightarrow X, \gamma(0) = p, \gamma(1) = q$$

Proposition 5.10.2. Path connected implies connected.

Proof. Suppose X is path connected. Towards a contradiction suppose X has a separation A, B . Let $a \in A, b \in B$, and $\gamma : [0, 1] \rightarrow X$ with $\gamma(0) = a, \gamma(1) = b$. Then $\gamma^{-1}(A) \subseteq [0, 1], \gamma^{-1}(B) \subseteq [0, 1]$ are open, disjoint, and cover $[0, 1]$, contradicting the fact that $[0, 1]$ is connected. Thus X must be connected. ■

Example 5.10.3. The metric space

$$X = \{(0, y) \in \mathbb{R}^2 : y \in [-1, 1]\} \cup \{(x, \sin 1/x) \in \mathbb{R}^2 : x \in (0, 1]\}$$

with metric $d_X = d_{\mathbb{R}^2}$ is compact and connected, but not path connected.

Theorem 33 (Intermediate Value Theorem).

Suppose (X, τ) is a connected space and $f : X \rightarrow \mathbb{R}$ is continuous. Suppose $p, q \in X$ such that $f(p) = a < b = f(q)$. Then for all $c \in (a, b)$ there exists $z \in X$ such that $f(z) = c$.

Proof. Let $A = f^{-1}((-\infty, c))$ and $B = f^{-1}((c, \infty))$, so A and B are open, non-empty, and disjoint. Thus, as X is connected, $X \neq A \cup B$ so there must exist $t \in f^{-1}(\{c\})$, so in particular $f(t) = c$. ■

Proposition 5.10.3. Suppose X and Y are metric spaces and $f : X \rightarrow Y$ is continuous. If S is connected in X , then $f(S)$ is connected in Y .

Proof. If U, V is a separation of $f(S)$, so $f(S) \subseteq U \cup V$, then

$$S \subseteq f^{-1}(U \cup V) = f^{-1}(U) \cup f^{-1}(V)$$

Since f is continuous, these are both open, and are in fact a separation of S , which is a contradiction. ■

Chapter 6

Approximations and Continuous Functions

6.1.0 Algebras

Definition 6.1.1 (Algebras and Subalgebras). Suppose \mathcal{A} is a (real or complex) vector space. We say that \mathcal{A} is an **algebra** if there is a multiplication $\mathcal{A} \times \mathcal{A} \rightarrow \mathcal{A}$ satisfying the following properties for all $A, B, C \in \mathcal{A}$ and constants r :

- (1) $(AB)C = A(BC)$ (associative)
- (2) $r(AB) = (rA)B = A(rB)$ (scalar multiplication)
- (3) $A(B + C) = AB + AC$ and $(A + B)C = AC + BC$ (distributive)

If in addition there is an element $1 \in \mathcal{A}$ satisfying $1A = A1 = A$ for all A , then we say that \mathcal{A} is **unital**. A subspace \mathcal{B} of \mathcal{A} is called a **subalgebra** if \mathcal{B} is itself an algebra with the multiplication inherited from \mathcal{A} .

Definition 6.1.2. If \mathcal{A} is an algebra equipped with a vector space norm that also satisfies $\|AB\| \leq \|A\| \|B\|$ for all $A, B \in \mathcal{A}$, it is called a **normed algebra**. If \mathcal{A} is complete with respect to this norm, it is called a **Banach algebra**.

Example 6.1.1. Algebras of matrices: $M_n(\mathbb{R})$ or $M_n(\mathbb{C})$ is a unital Banach algebra under the spectral norm and matrix multiplication. Recall the spectral norm is an operator norm for maps from $\ell_n^2 \rightarrow \ell_n^2$. Such norms always satisfy $\|AB\| \leq \|A\| \|B\|$, as shown in a separate section. The upper triangular matrices $T_n(\mathbb{R}) = \{[a_{ij}] | a_{i,j} = 0 \text{ if } i > j\}$ is a unital subalgebra of $M_n(\mathbb{R})$. The strictly upper triangular $J_n(\mathbb{R}) = \{[a_{ij}] | a_{i,j} = 0 \text{ if } i \geq j\}$ are a non-unital subalgebra of $T_n(\mathbb{R})$ and $M_n(\mathbb{R})$.

Definition 6.1.3. Let X be a compact metric space. Define the space of continuous functions on X by

$$C(X) = \{f : X \rightarrow \mathbb{R} | f \text{ is continuous}\}$$

Note, we can replace \mathbb{R} with \mathbb{C} above, but for the remainder of this section we will restrict to the real case.

Proposition 6.1.1. $C(X)$ is a Banach algebra with the uniform norm and pointwise product.

Proof. As X is compact and $f \in C(X)$ is continuous, $\|f\|_\infty := \sup_{x \in X} |f(x)| < \infty$. The product is pointwise, so $fg(x) = f(x)g(x)$. It is evident that $C(X)$ is a NLS under $\|\cdot\|_\infty$. It is also a normed algebra since for $f, g \in C(X)$,

$$|f(x)g(x)| = |f(x)||g(x)| \leq \|f\|_{\infty} \|g\|_\infty$$

Taking the supremum, $\|fg\|_\infty \leq \|f\|_\infty \|g\|_\infty$. For completeness, suppose (f_n) is Cauchy. Then

$$|f_n(x) - f_m(x)| \leq \|f_n - f_m\|_\infty$$

which implies $(f_n(x))$ is Cauchy in \mathbb{R} for each $x \in X$, and hence there is a pointwise limit $\lim_{n \rightarrow \infty} f_n(x) =: f(x)$. For every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for $n \geq N$ and $k \in \mathbb{N}$, $\|f_n - f_{n+k}\|_\infty < \varepsilon$. Taking the limit as $k \rightarrow \infty$, $\|f_n - f\|_\infty \leq \varepsilon$. Thus, $\|f_n - f\|_\infty \rightarrow 0$. Further, for all $x, y \in X$,

$$|f(x) - f(y)| \leq |f(x) - f_n(x)| + |f_n(x) - f_n(y)| + |f_n(y) - f(y)| \rightarrow 0$$

as $d_X(x, y) \rightarrow 0$, so $f \in C(X)$. ■

Definition 6.1.4. Let X be a compact metric space. A subset $S \subseteq C(X)$ is said to separate X if for all $x \neq y$ in X , there is an $f \in S$ such that $f(x) \neq f(y)$.

Example 6.1.2. The algebra of even polynomials on $[-1, 1]$: Let $\mathcal{A} = \text{span}\{1, x^2, x^4, \dots\} \subseteq C([-1, 1])$. \mathcal{A} is a unital subalgebra of $C([-1, 1])$. \mathcal{A} does not separate $[-1, 1]$. If f is any function in \mathcal{A} we have $f(-x) = f(x)$ for all $x \in [-1, 1]$. \mathcal{A} does separate $[0, 1]$. For example, if $0 \leq x < y \leq 1$, then $f(x) = x^2 \neq y^2 = f(y)$.

Example 6.1.3. Let $S = \text{span}\{1, x(x-1)f(x) | f \in C([0, 1])\} \subseteq C([0, 1])$. A generic element in S is of the form $g(x) = c + x(x-1)f(x)$ where $f \in C([0, 1])$. S is a subspace since it is a span. S is also a subalgebra since

$$[c_1 + x(x-1)f_1(x)][c_2 + x(x-1)f_2(x)] = c_1c_2 + x(x-1)[c_2 + c_2 + x(x-1)f_1(x)f_2(x)] \in S$$

S does not separate $[0, 1]$ since $g(0) = g(1)$ for all $g \in S$.

Example 6.1.4. The algebra of polynomials: Let $K \subseteq \mathbb{R}$ be compact. The algebra of polynomials $\mathcal{P} \subseteq C(K)$ separates K . If $x_1 \neq y_1$ are in K and $a, b \in \mathbb{R}$, then define

$$p_1(x) = \frac{a}{x_1 - y_1}(x - y_1) \quad \text{and} \quad p_2(x) = \frac{b}{y_1 - x_1}(x - x_1)$$

and notice $p_1(x_1) = a$, $p_1(y_1) = 0$, and $p_2(x_1) = 0$, $p_2(y_1) = b$.

6.2.0 Stone-Weierstrass

Theorem 6.2.1 (Weierstrass 1885). Suppose $K \subseteq \mathbb{R}^n$ is compact. Then for each f in $C(K)$, there is a sequence of polynomials p_n so that p_n converges uniformly to f .

We will not prove this result exactly, but instead a more general formulation of it due to Stone.

Example 6.2.1. If $S = [0, 1]$, the polynomials in Weierstrass' theorem can be explicitly written down. Define

$$b_{1,n}(t) = \binom{n}{i} t^i (1-t)^{n-1}, \quad p_n(t) = \sum_{k=0}^n f(k/n) b_{k,n}(t)$$

Then $\|p_n - f\|_\infty \rightarrow 0$.

One of our main results is Stone's theorem:

Theorem 34 (Stone 1941).

Suppose X is a compact metric space and \mathcal{A} is a unital subalgebra of $C(X)$. Then $\overline{\mathcal{A}} = C(X)$ if and only if \mathcal{A} separates X .

We first must prove several preliminary results:

Theorem 35 (Dini's Theorem).

Suppose X is a compact metric space and f_n is a sequence in $C(X)$ converging pointwise to $f \in C(X)$. Suppose further that $f_n(x)$ is a monotonically increasing sequence for each $x \in X$, so $f_{n+1}(x) \geq f_n(x)$ for all $n \in \mathbb{N}$. Then f_n converges uniformly to f on X .

Proof. Let $g_n(x) = f(x) - f_n(x) \geq 0$ for all $x \in X$. $g_n(x)$ is decreasing in n to 0. Fix $\varepsilon > 0$ and let $E_n = \{x \in X \mid g_n(x) < \varepsilon\} = g_n^{-1}((-\infty, \varepsilon))$, so E_n is continuous as g_n is continuous and $(-\infty, \varepsilon)$ is open. Note $E_n \subseteq E_{n+1}$ since $g_{n+1}(x) \leq g_n(x)$. Since $g_n(x) \rightarrow 0$, this implies that $X = \bigcup_{n=1}^{\infty} E_n$.

By compactness there exists a finite subcover $X = E_{n_1} \cup \dots \cup E_{n_k} = E_N$ where $N = \max\{n_1, \dots, n_k\}$. Then $X = E_N$ implies $g_N(x) < \varepsilon$ for all $x \in X$. But then for $n \geq N$, $0 \leq g_n(x) \leq g_N(x) < \varepsilon$. So $g_n \rightarrow_u 0$, so

$$\|f - f_n\|_\infty = \|g_n\|_\infty \rightarrow 0$$

and $f_n \rightarrow_u f$ as desired. ■

Lemma 6.2.2. Suppose X is compact and \mathcal{A} is a subalgebra of $C(X)$. If $f \in \mathcal{A}$ and $0 \leq f(x) \leq 1$ for all $x \in X$, then $\sqrt{f} \in \overline{\mathcal{A}}$.

Proof. Let $f_1 = 0 \in \mathcal{A}$ and $f_{n+1} = f_n + \frac{f-f_n^2}{2}$. By induction, $f_n \in \mathcal{A}$. We claim $0 \leq f_n(x) \leq$

$\sqrt{f(x)}$ for all $x \in X$. If $n = 1$, the result is immediate. Suppose inductively that the result holds for some n . Then $f(x) - f_n(x)^2 \geq 0$ for all x , so

$$f_{n+1}(x) = f_n(x) + \frac{f(x) - f_n(x)^2}{2} \geq 0$$

We also have

$$\begin{aligned} f_{n+1}(x) &= f_n(x) + \frac{1}{2}(\sqrt{f(x)} - f_n(x))(\sqrt{f(x)} + f_n(x)) \\ &\leq f_n(x) + \frac{1}{2}(\sqrt{f(x)} - f_n(x))(\sqrt{f(x)} + \sqrt{f(x)}) \\ &\leq f_n(x) + \frac{1}{2}2(\sqrt{f(x)} - f_n(x)) = \sqrt{f(x)} \end{aligned}$$

We also get $f_{n+1}(x) \geq f_n(x)$ for all $x \in X$ since $f_{n+1}(x) - f_n(x) = \frac{f(x) - f_n(x)^2}{2} \geq 0$. By Dini's Theorem, $f_n \rightarrow_u g \in C(X)$ and $g(x) \leq \sqrt{f(x)}$. But then

$$f_{n+1} = f_n + \frac{f - f_n^2}{2} \implies g = g + \frac{f - g^2}{2} \implies g = \sqrt{f}$$

so $f_n \rightarrow_u \sqrt{f}$ and $\sqrt{f} \in \overline{\mathcal{A}}$. ■

Definition 6.2.1 (Lattice). Suppose X is a compact metric space. A subspace L of $C(X)$ is called a **lattice** if $|f| \in L$ whenever $f \in L$.

Example 6.2.2. The lemma above shows that if \mathcal{A} is a subalgebra of $C(X)$, then $\overline{\mathcal{A}}$ is a lattice. Let $f \neq 0$ in \mathcal{A} , and $g = \frac{f^2}{\|f\|_\infty^2}$ so that $0 \leq g \leq 1$. By the above result, $\sqrt{g} \in \overline{\mathcal{A}}$, but $\sqrt{g} = \frac{|f|}{\|f\|_\infty}$, so $|f|$ is in $\overline{\mathcal{A}}$.

If $f, g \in L$, a lattice, then

$$\max\{f(x), g(x)\} = \frac{f(x) + g(x) + |f(x) - g(x)|}{2} \in L$$

and

$$\min\{f(x), g(x)\} = \frac{f(x) + g(x) - |f(x) - g(x)|}{2} \in L$$

Lemma 6.2.3 (Key part of Stone's). Suppose X is compact and $L \subseteq C(X)$ is a lattice. Suppose further that for each $x, y \in X$ and $a, b \in \mathbb{R}$, there is a function $f_{xy} \in L$ with $f_{xy}(x) = a$ and $f_{xy}(y) = b$. Then $\overline{L} = C(X)$.

Proof. Let $f \in C(X)$ and fix $\varepsilon > 0$. Let $x, y \in X$ and write $a := f(x)$ and $b := f(y)$. Find $f_{xy} \in L$ by assumption with $f_{xy}(x) = a$, $f_{xy}(y) = b$. Let

$$U_{xy} = \{z \in X \mid f_{xy}(z) < f(z) + \varepsilon\}$$

which is non-empty since $x, y \in U_{xy}$, and

$$V_{xy} = \{z \in X \mid f(z) - \varepsilon < f_{xy}(z)\}$$

which is also non-empty. Both are pre-images of open sets for continuous functions and are therefore open.

Fix $y \in X$, then $X = \bigcup_{x \in X} U_{xy}$ since $x \in U_{xy}$. By compactness, there exist $x_1, \dots, x_n \in X$ with $X = \bigcup_{i=1}^n U_{x_i y}$. Let $h_y = \min\{f_{x_1 y}, f_{x_2 y}, \dots, f_{x_n y}\} \in L$ as each $f_{xy} \in L$ by assumption and L is a lattice. Then, by definition, $h_y(z) < f(z) + \varepsilon$ for all $z \in X$. Also note that $f(z) - \varepsilon < h_y(z)$ for all $z \in \bigcap_{i=1}^n V_{x_i y}$, which is open. Let $V_y = \bigcap_{i=1}^n V_{x_i y}$, and note $y \in V_y$. Then $X = \bigcup_{y \in X} V_y$, so by compactness there exist $y_1, \dots, y_m \in X$ with $X = \bigcup_{j=1}^m V_{y_j}$. Let $h = \max\{h_{y_1}, h_{y_2}, \dots, h_{y_m}\}$. We already know $h(z) < f(z) + \varepsilon$ for all $z \in X$. Further, $h(z) > f(z) - \varepsilon$ for all $z \in X$, so

$$|h(z) - f(z)| < \varepsilon$$

for all z so $\|h - f\|_\infty \leq \varepsilon$. As $h \in L$ and $f \in C(X)$, and this holds for all $\varepsilon > 0$, $f \in \overline{L}$, and $\overline{L} = C(X)$. ■

Stone's Theorem Proof. Let \mathcal{A} be a unital subalgebra of $C(X)$ that separates points in X . We already know $\overline{\mathcal{A}}$ is a lattice. By the lemma above, we need to show for all $x \neq y \in X$ and $a, b \in \mathbb{R}$, there exists $f_{xy} \in \overline{\mathcal{A}}$ with $f_{xy}(x) = a$ and $f_{xy}(y) = b$. This will prove by the lemma that $\overline{\mathcal{A}} = \overline{\overline{\mathcal{A}}} = C(X)$. Assume $x \neq y$ and find $g \in \mathcal{A}$ with $g(x) \neq g(y)$. Let

$$f_{xy}(t) = a \left(\frac{g(t) - g(y)}{g(x) - g(y)} \right) + b \left(\frac{g(t) - g(x)}{g(y) - g(x)} \right) \in \mathcal{A}$$

Then $f_{xy}(x) = a + 0 = a$ and $f_{xy}(y) = 0 + b = b$, as desired.

The converse is also true. If \mathcal{A} is unital and $\overline{\mathcal{A}} = C(X)$, then \mathcal{A} separates X . Suppose \mathcal{A} does not separate X . Then there exists $x \neq y$ in X with $f(x) = f(y)$ for all $f \in \mathcal{A}$. But then $g(x) = g(y)$ for all $g \in C(X)$ since uniform convergence implies pointwise convergence, and \mathcal{A} is dense in $C(X)$. This is a contradiction, as all $C(X)$ separates X . ■

Example 6.2.3. The polynomials \mathcal{P} are a separating unital subalgebra for $C(K)$, $K \subseteq \mathbb{R}$ compact. So $\overline{\mathcal{P}} = C(K)$, i.e. Stone's theorem implies Weierstrass' polynomial approximation theorem.

Further, Stone's theorem implies Weierstrass' theorem in the general case since the polynomials are an algebra separating any subset of points in \mathbb{R}^n .

Example 6.2.4. Take $\mathcal{A} = \text{span}\{f(x)g(y) | f, g \in C([0, 1])\}$ is dense in $C([0, 1] \times [0, 1])$. Note something like $x^2y + 1 + \frac{x}{y^2+1}$ is in \mathcal{A} , but $\sin^{-1}(x+y)$ is not, so it is a proper subspace. Note \mathcal{A} is unital since we can just let $f(x) = 1 = g(y)$. \mathcal{A} is a subalgebra as

$$\left(\sum_{i=1}^n f_i(x)g_i(y) \right) \left(\sum_{j=1}^m h_j(x)k_j(y) \right) = \sum_{i,j} f_i(x)h_j(x)g_i(y)k_j(y)$$

To confirm $\overline{\mathcal{A}} = C([0, 1] \times [0, 1])$, we show \mathcal{A} separates points and then use Stone's theorem. Suppose $(x_0, y_0) \neq (x_1, y_1) \in [0, 1]^2$. If $x_0 \neq x_1$, then $f(x, y) = x \in \mathcal{A}$ and $f(x_0, y_0) = x_0 \neq x_1 = f(x_1, y_1)$. If $y_0 \neq y_1$, we just use $f(x, y) = y$ instead.

Example 6.2.5 (Real Trig Polynomials). Let $\mathcal{A} = \text{span}_{m,n \in \mathbb{N} \cup \{0\}} \{\cos(nx), \sin(mx)\} \subseteq C([0, 1])$. Note $1 \in \mathcal{A}$ setting $m = n = 0$. \mathcal{A} is a span, and hence a subspace. \mathcal{A} is an algebra using angle reduction formulas, such as $\cos^2(x) = \frac{1+\cos(2x)}{2}$. \mathcal{A} separates $[0, \pi]$ since, for example, $f(x) = \cos(x)$ is injective on $[0, \pi]$. Thus, $\overline{\mathcal{A}} = C([0, \pi])$.

Stone's theorem also works for complex-valued functions, but we need the following additional assumption on \mathcal{A} ; for every $f \in \mathcal{A}$ we also have $\overline{f} \in \mathcal{A}$.

Example 6.2.6 (Complex trig polynomials on the torus). Let $\mathbb{T} = \{z \in \mathbb{C} \mid |z| = 1\}$ (the unit circle). Let $\mathcal{A} = \text{span}_{n \in \mathbb{Z}} \{e^{in\theta} \mid \theta \in [0, 2\pi]\} \subseteq C(\mathbb{T}, \mathbb{C})$. \mathcal{A} is unital since $e^{i0\theta} = e^0 = 1 \in \mathcal{A}$. If $f \in \mathcal{A}$ then $\overline{f} \in \mathcal{A}$ since $\overline{e^{in\theta}} = e^{-in\theta} \in \mathcal{A}$. Just as in the previous example, \mathcal{A} separates \mathbb{T} , so $\overline{\mathcal{A}} = C(\mathbb{T}, \mathbb{C})$.

Example 6.2.7 (Density of nowhere differentiable functions). Recall there exist $W \in C([0, 1])$ that is nowhere differentiable. We know if $f \in C([0, 1])$, there exist polynomials $p_n \rightarrow_u f$ by Stone-Weierstrass. Let $f_n := p_n + \frac{1}{n}W$, which are nowhere differentiable. Then

$$\|f - f_n\|_\infty \leq \|f - p_n\|_\infty + \frac{1}{n}\|W\|_\infty \rightarrow 0$$

6.3.0 Equicontinuity and Arzela-Ascoli

Definition 6.3.1 (Equicontinuity). Suppose X is a compact metric space and $\mathcal{F} \subseteq C(X)$. We say that \mathcal{F} is **equicontinuous on X** if for every $\varepsilon > 0$ there is a $\delta > 0$ such that for any $x, y \in X$ satisfying $d_X(x, y) < \delta$, we have

$$|f(x) - f(y)| < \varepsilon$$

for every $f \in \mathcal{F}$.

Note δ only depends on ε . This can be thought of as simultaneous uniform continuity.

Remark 6.3.1. Think of:

- Separating X corresponds to “many function”
- Equicontinuous corresponds to “few functions”

Definition 6.3.2. In general, for metric spaces X and Y , $\mathcal{F} \subseteq C(X, Y)$ is equicontinuous if for every $\varepsilon > 0$ there exists $\delta > 0$ such that if $f \in \mathcal{F}$ then $d_Y(f(x), f(z)) < \varepsilon$ for all $x, z \in X$ such that $d_X(x, z) < \delta$.

Proposition 6.3.1. Let X and Y be metric spaces with X compact, and equip $C(X, Y)$ with the L_∞ -norm. That is, the distance d in $C(X, Y)$ is

$$d(f, g) = \sup_{x \in X} d_Y(f(x), g(x))$$

Then if $\mathcal{F} \subseteq C(X, Y)$ is compact, it is equicontinuous.

Proof. Suppose $\mathcal{F} \subseteq C(X, Y)$ is compact. Fix $\varepsilon > 0$. As X is compact, each $f \in C(X, Y)$ is uniformly continuous, so there exists $\delta_f > 0$ such that $d_Y(f(x), f(y)) < \varepsilon/3$ for all $x, y \in X$ such that $d_X(x, y) < \delta_f$. Then $\mathcal{F} \subseteq \bigcup_{f \in \mathcal{F}} B_{\varepsilon/3}(f)$ is an open cover, so as \mathcal{F} is compact there exist f_1, \dots, f_N such that $\mathcal{F} \subseteq \bigcup_{j=1}^N B_{\varepsilon/3}(f_j)$. Then, let $\delta = \min_{1 \leq j \leq N} \{\delta_{f_j}\}$. Now let $f \in \mathcal{F}$ and let $x, y \in X$ with $d_X(x, y) < \delta$. Then there exists j such that $f \in B_{\varepsilon/3}(f_j)$. It follows that

$$d_Y(f(x), f(y)) \leq d_Y(f(x), f_j(x)) + d_Y(f_j(x), f_j(y)) + d_Y(f_j(y), f(y)) < \varepsilon/3 + \varepsilon/3 + \varepsilon/3 = \varepsilon$$

so indeed \mathcal{F} is equicontinuous. \blacksquare

Example 6.3.1 (Uniformly converging sequences are equicontinuous). If $\mathcal{F} = \{f\}$ is a singleton, then $\{f\}$ is equicontinuous since f is uniformly continuous. If $\mathcal{F} = \{f_1, \dots, f_n\} \subseteq C(X)$ then it is equicontinuous. Fix $\varepsilon > 0$. For each f_i , there exists $\delta_i > 0$ from uniform continuity of f_i . Then $\delta = \min\{\delta_1, \dots, \delta_n\}$ works for the definition of uniform continuity. Equivalently, we could recognize that every finite subset of a topological space is compact, and use the previous result.

Suppose $f_n \rightarrow_u f$ in $C(X)$. Then $\mathcal{F} = \{f_n\}_{n \in \mathbb{N}}$ is equicontinuous:

$$|f_n(x) - f_n(y)| \leq |f_n(x) - f(x)| + |f(x) - f(y)| + |f(y) - f_n(y)|$$

f is uniformly continuous so there exists $\delta > 0$ such that $d_X(x, y) < \delta$ implies $|f(x) - f(y)| < \varepsilon/3$. By uniform convergence there exist $N \in \mathbb{N}$ such that $n \geq N$ implies $|f(x) - f_n(x)| < \varepsilon/3$ for all $x \in X$. For $d_X(x, y) < \delta$, we obtain $|f_n(x) - f_n(y)| < \varepsilon$ (then $k < N$ is a finite set and we can use the previous part for that).

Example 6.3.2. Totally bounded subsets of $C(X)$ are equicontinuous. Recall that compact is equivalent to complete and totally bounded in metric spaces. Suppose $\mathcal{F} \subseteq C(X)$ is totally bounded. Then if $\varepsilon > 0$, there exist f_1, \dots, f_n such that $\mathcal{F} \subseteq \bigcup_{i=1}^n B_{\varepsilon/3}(f_i)$. If $f \in \mathcal{F}$, find i such that $\|f - f_i\|_\infty < \varepsilon/3$. Then

$$|f(x) - f(y)| < 2\varepsilon/3 + |f_i(x) - f_i(y)|$$

As $\{f_1, \dots, f_n\}$ is equicontinuous, there exists $\delta > 0$ such that $d_X(x, y) < \delta$ implies $|f_i(x) - f_i(y)| < \varepsilon/3$, and the result follows.

Note this result holds in general for totally bounded subsets of $C(X, Y)$ for X compact.

Example 6.3.3. Let α and K be fixed positive constants. The set

$$\mathcal{F} = \{f \in C([0, 1]) \mid |f(x) - f(y)| \leq L(x - y)^\alpha \text{ for all } x, y \in [0, 1]\}$$

is equicontinuous.

Fix $\varepsilon > 0$. Let $\delta = (\varepsilon/K)^{1/\alpha}$. If $|x - y| < \delta$,

$$|f(x) - f(y)| < K((\varepsilon/K)^{1/\alpha})^\alpha = \varepsilon$$

for all $f \in \mathcal{F}$.

Let $G = \{f \in C([0, 1]) \mid f' \text{ is continuous on } [0, 1] \text{ and } \|f'\|_\infty \leq 1\}$. G is equicontinuous since if $x < y$ there exists $c \in (x, y)$ with

$$|f'(c)| = \frac{|f(y) - f(x)|}{|y - x|}$$

implies

$$|f(y) - f(x)| = |f'(c)| |y - x| \leq |y - x|$$

So $G \subseteq \mathcal{F}$ with $\alpha = K = 1$.

Example 6.3.4. Let

$$\mathcal{F} = \left\{ F(x) = \int_0^x f(t)dt \mid f \in C([0, 1]) \text{ and } \|f\|_\infty \leq 1 \right\} \subseteq C([0, 1])$$

is equicontinuous and not closed. $F(0) = 0$ for all $F \in \mathcal{F}$. If $F = \int_0^x f$, then $F'(x) = f(x)$ by the FTOC1. Then

$$|F(x) - F(y)| = \left| \int_y^x f(t)dt \right| \leq \left| \int_y^x |f(t)|dt \right| \leq \left| \int_y^x 1dt \right| = |y - x|$$

So \mathcal{F} is a subset of the \mathcal{F} in the previous example with $\alpha = K = 1$.

\mathcal{F} is not closed in $C([0, 1])$, as

$$f_n(x) = \sqrt{(x - 1/2)^2 + 1/n} - \sqrt{1/4 + 1/n}$$

has $f_n(0) = 0$, and $|f'_n(x)| = \frac{|x-1/2|}{\sqrt{(x-1/2)^2 + 1/n}} \leq 1$ and $f'_n \in C([0, 1])$, so

$$f_n(x) = \int_0^x f'_n(t)dt \in \mathcal{F}$$

by FTOC2. But $f_n \rightarrow |x - 1/2| - 1/2$ which is not differentiable, and hence not in \mathcal{F} .

Theorem 36 (Arzela 1884; Ascoli 1895).

Let X be a compact metric space. A set $\mathcal{F} \subseteq C(X)$ is compact in $C(X)$ if and only if \mathcal{F} is closed, bounded, and equicontinuous.

Proof. We saw \mathcal{F} compact implies \mathcal{F} equicontinuous. We also already know compact implies closed and bounded in metric spaces. Conversely, let $(f_n) \subseteq \mathcal{F}$ with \mathcal{F} equicontinuous. We will show (f_n) admits a uniformly convergent subsequence.

Note since X is compact, it is totally bounded. Then for each $n \in \mathbb{N}$, there exists $x_{n(1)}, \dots, x_{n(k)}$ with $X \subseteq \bigcup_{j=1}^k B_{1/n}(x_{n(j)})$. Then the countable set $\bigcup_{n \in \mathbb{N}} \{x_{n(j)}\}$ is dense in X .

Let $\{x_1, x_2, \dots\}$ be a countable dense subset in X . The sequence $\{f_n(x_1)\}_{n=1}^\infty$ is bounded in \mathbb{R} since \mathcal{F} is assumed bounded, so there exists $C > 0$ such that $\|f\|_\infty \leq C$ for all $f \in \mathcal{F}$. By Bolzano-Weierstrass, $\{f_n(x_1)\}$ has a convergent subsequence $\{f_{s_1(n)}(x_1)\}$. Then $\{f_{s_2(n)}(x_2)\}$ is a bounded sequence in \mathbb{R} , and also has a convergent subsequence $\{f_{s_2(n)}(x_2)\}$. Inductively define $\{f_{s_k(n)}\} \subseteq \{f_{s_{k-1}(n)}\} \subseteq \dots \subseteq \{f_n\} \subseteq \mathcal{F}$, with $\{f_{s_k(n)}(x_k)\}$ convergent. Define the subsequence $\xi_v = f_{s_v(v)}$. By construction, $\xi_v(x_i)$ converges for all x_i . Fix $\varepsilon > 0$ and find $\delta > 0$ by equicontinuity such that $d_X(x, y) < \delta$ implies $|\xi_n(x) - \xi_n(y)| < \varepsilon$ for all $n \in \mathbb{N}$. We want to establish the Cauchy criterion for ξ_v . Then

$$|\xi_n(x) - \xi_m(x)| \leq |\xi_n(x) - \xi_n(x_i)| + |\xi_n(x_i) - \xi_m(x_i)| + |\xi_m(x_i) - \xi_m(x)|$$

We can find x_i such that $x \in B_\delta(x_i)$ by density, so using equicontinuity and the fact ξ_n is Cauchy on the countable dense subset, we obtain an $\varepsilon/3$ argument yielding our desired result. ■

We can extend this result, without any difficulty, to subsets of $C(X, \mathbb{R}^n)$ for $n \in \mathbb{N}$.

Corollary 6.3.2. $\mathcal{F} \subseteq C(X)$ is totally bounded if and only if \mathcal{F} is bounded and equicontinuous.

Proof. \mathcal{F} is totally bounded if and only if $\overline{\mathcal{F}}$ is totally bounded. The if direction is immediate, and for the only if direction, fix $\varepsilon > 0$. Then there exist f_1, \dots, f_n such that $\mathcal{F} \subseteq \bigcup_{i=1}^n B_\varepsilon(f_i)$, then

$$\overline{\mathcal{F}} \subseteq \overline{\bigcup_{i=1}^n B_\varepsilon(f_i)} \subseteq \bigcup_{i=1}^n \overline{B_\varepsilon(f_i)} \subseteq \bigcup_{i=1}^n B_{2\varepsilon}(f_i)$$

Then, $\overline{\mathcal{F}}$ is totally bounded if and only if it $\overline{\mathcal{F}}$ is complete and totally bounded since $C(X)$ is complete and $\overline{\mathcal{F}}$ is closed, which occurs if and only if \mathcal{F} is complete, if and only if $\overline{\mathcal{F}}$ is closed, bounded, and equicontinuous by Arzéla-Ascoli, which holds if and only if \mathcal{F} is bounded and equicontinuous. ■

Example 6.3.5. Closed balls in $C([0, 1])$ are not equicontinuous. Consider $\overline{B}_r(f_0)$, which contains the sequence $f_0 + \frac{1}{2^r}x^n$, which we know has no uniformly convergent subsequence, and is not compact and hence is not equicontinuous by Arzéla-Ascoli.

Chapter 7

Higher-Dimensional Differentiation

7.1.0 Basic Notions of Higher-Dimensional Derivatives

In this section, we will always use the 2-norm on \mathbb{R}^n and denote it $\|\cdot\|$. For a linear operator or matrix, $\|\cdot\|$ will also denote the operator or spectral norm. U will denote an open subset of \mathbb{R}^n .

Definition 7.1.1 (The Derivative). Let $f : U \rightarrow \mathbb{R}^m$. We say that f is differentiable at $a \in U$ if there exists a linear transformation $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ such that

$$\lim_{h \rightarrow 0} \frac{\|f(a+h) - f(a) - Th\|_{\mathbb{R}^m}}{\|h\|_{\mathbb{R}^n}} = 0$$

for $a+h \in U$, where as U is open $a+h \in U$ for h small enough. This can be interpreted to mean $f(a+h) \approx f(a) + Th$ for h small enough. We call T the derivative of f at a and write it as $T = Df(a)$. We say that f is differentiable on U if f is differentiable at each $a \in U$.

Remark 7.1.1. The linear transformation T in the above definition is unique. Suppose S and T both satisfy the definition of the derivative at a . Then

$$\frac{\|Th - Sh\|}{\|h\|} \leq \frac{\|f(a+h) - f(a) - Th\|}{\|h\|} + \frac{\|f(a+h) - f(a) - Sh\|}{\|h\|} \rightarrow 0$$

Indeed, for any $\alpha > 0$ constant, and $1 \leq j \leq n$,

$$0 = \lim_{\alpha \rightarrow 0} \frac{\|T\alpha e_j - S\alpha e_j\|}{\|\alpha e_j\|} = \lim_{\alpha \rightarrow 0} \|Te_j - Se_j\|$$

so $Te_j = Se_j$, and hence $T = S$.

If the case of $m = n = 1$, if $f : U \rightarrow \mathbb{R}$ is a function with $U \subseteq \mathbb{R}$ open, the linear transformation T is just the constant $f'(a)$, where as $f'(a) = \lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h}$,

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

and in this case $f(a+h) \approx f(a) + f'(a)h$.

Notation 7.1.2. Given a function $f : U \rightarrow \mathbb{R}^m$, we will write f as $f(x) = (f_1(x), \dots, f_m(x))^T$, where each $f_i : U \rightarrow \mathbb{R}$ and $f_i = p_i \circ f$, for $p_i : \mathbb{R}^m \rightarrow \mathbb{R}$ the i -th projection function.

Proposition 7.1.1. *If $f : U \rightarrow \mathbb{R}^m$ is differentiable at $a \in U$, then f is continuous at a .*

Proof. We must show that $\lim_{h \rightarrow 0} f(a + h) = f(a)$. Find $\delta > 0$ such that $\|h\| < \delta$ implies

$$\frac{\|f(a + h) - f(a) - Df(a)h\|}{\|h\|} < 1$$

Then $\|f(a + h) - f(a) - Df(a)h\| \leq \|h\|$, so by the triangle inequality, and using the spectral norm,

$$\|f(a + h) - f(a)\| \leq \|Df(a)h\| + \|h\| \leq \|Df(a)\| \|h\| + \|h\| \rightarrow 0$$

as $h \rightarrow 0$, so f is continuous at a . ■

Definition 7.1.2 (Directional Derivative). *Let $f : U \rightarrow \mathbb{R}^m$ and let $v \in \mathbb{R}^n$ be a unit vector. The directional derivative for f at $a \in U$ in the direction of v is given by*

$$D_v f(a) := \lim_{t \rightarrow 0} \frac{f(a + tv) - f(a)}{t} \in \mathbb{R}^m$$

for all $a \in U$ and t small enough such that $a + tv \in U$, provided the limit above exists. If $v = e_i$, the canonical orthonormal basis element for \mathbb{R}^n , we call $D_{e_i} f(a)$ the partial derivative of f with respect to x_i at a and denote it $D_i f(a)$ or $\frac{\partial f}{\partial x_i}(a)$.

Note that the limit for $D_v f(a)$ can be written as

$$D_v f(a) = \lim_{t \rightarrow 0} \begin{pmatrix} \frac{f_1(a+tv) - f_1(a)}{t} \\ \vdots \\ \frac{f_m(a+tv) - f_m(a)}{t} \end{pmatrix} = \begin{pmatrix} D_v f_1(a) \\ \vdots \\ D_v f_m(a) \end{pmatrix}$$

if the $D_v f_i(a)$ exist as we know that sequences in \mathbb{R}^m converge if and only if each component sequence converges. Thus, $D_v f(a)$ exists if and only if $D_v f_i(a)$ exists for each $i = 1, \dots, m$.

Example 7.1.1 (Affine maps are differentiable). Let $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be defined by $f(x) = Ax + b$ for A $m \times n$ and $b \in \mathbb{R}^m$. Then $Df(x) = A$ for all $x \in \mathbb{R}^n$, since for any $h \in \mathbb{R}^n$

$$\|f(a + h) - f(a) - Ah\| = \|Aa + Ah - Aa - Ah\| = 0$$

Example 7.1.2. The function $f : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ given by $f(x, y) = (x^2, y^2)^T$ is differentiable. We claim $Df(x, y) = \begin{bmatrix} 2x & 0 \\ 0 & 2y \end{bmatrix}$. To see this, let $h = [h_1 \ h_2]^T$. Since all norms on \mathbb{R}^n and \mathbb{R}^m are equivalent, we can use whichever norm makes the easiest computation:

$$\begin{aligned} \lim_{h \rightarrow 0} \frac{\|\langle (x + h_1)^2 - x^2, (y + h_2)^2 - y^2 \rangle - \langle 2xh_1, 2yh_2 \rangle\|_1}{\|h\|_1} &= \lim_{h \rightarrow 0} \frac{|(x + h_1)^2 - x^2 - 2xh_1| + |(y + h_2)^2 - y^2 - 2yh_2|}{|h_1| + |h_2|} \\ &= \lim_{h \rightarrow 0} \frac{h_1^2 + h_2^2}{|h_1| + |h_2|} \\ &\leq \lim_{h \rightarrow 0} \frac{h_1^2}{|h_1|} + \frac{h_2^2}{|h_2|} = 0 \end{aligned}$$

Proposition 7.1.2. If $f : U \rightarrow \mathbb{R}^m$ and $g : U \rightarrow \mathbb{R}$ are differentiable at $a \in U$, then so is fg and

$$D(fg)(a) = f(a)Dg(a) + g(a)Df(a)$$

Proof. First, note that $fg : U \rightarrow \mathbb{R}^m$. Then observe that for all $\|h\| > 0$, with $a + h \in U$,

$$\begin{aligned} \frac{\|fg(a+h) - fg(a) - f(a)Dg(a)h - g(a)Df(a)h\|}{\|h\|} &= \frac{\|f(a+h)g(a+h) - f(a)g(a+h) + f(a)g(a+h) - f(a)g(a) - f(a)Dg(a)h - g(a)Df(a)h\|}{\|h\|} \\ &\leq \frac{\|f(a+h)g(a+h) - f(a)g(a+h) - g(a)Df(a)h\|}{\|h\|} + \frac{\|f(a)g(a+h) - f(a)g(a) - f(a)Dg(a)h\|}{\|h\|} \\ &= \frac{\|f(a+h)g(a+h) - f(a)g(a+h) - g(a+h)Df(a)h\|}{\|h\|} + \frac{\|f(a)g(a+h) - f(a)g(a) - f(a)Dg(a)h\|}{\|h\|} \\ &\leq \frac{\|g(a+h)\| \|f(a+h) - f(a) - Df(a)h\|}{\|h\|} + \frac{\|Df(a)h\|}{\|h\|} \\ &\leq \frac{\|g(a+h)\| \|f(a+h) - f(a) - Df(a)h\|}{\|h\|} + \|Df(a)\| \\ &= \frac{\|g(a+h)\| \|f(a+h) - f(a) - Df(a)h\|}{\|h\|} + \|Df(a)\| \end{aligned}$$

Then, note that each term in the above expansion goes to zero since g being differentiable implies it is continuous. ■

Proposition 7.1.3. Suppose $f : U \rightarrow \mathbb{R}^m$ is differentiable at $a \in U$. Then $D_v f(a)$ exists for all unit vectors v . Moreover,

$$D_v f(a) = Df(a)v$$

(note $D_v f(a) \in \mathbb{R}^m$, $Df(a) \in \mathbb{R}^{m \times n}$, and $v \in \mathbb{R}^n$)

Proof. We need to show $\lim_{t \rightarrow 0} \frac{f(a+tv) - f(a)}{t}$ exists. In the definition of $Df(a)$, let $h = tv$. Then $\|h\| = |t|$, so $h \rightarrow 0$ if and only if $t \rightarrow 0$, since v is assumed to be a unit vector. Then

$$\begin{aligned} 0 &= \lim_{t \rightarrow 0} \frac{\|f(a+tv) - f(a) - Df(a)tv\|}{|t|} \\ &= \lim_{t \rightarrow 0} \left\| \frac{f(a+tv) - f(a)}{t} - \frac{Df(a)tv}{t} \right\| \\ &= \lim_{t \rightarrow 0} \left\| \frac{f(a+tv) - f(a)}{t} - Df(a)v \right\| \end{aligned}$$

Thus, the limit exists and $\lim_{t \rightarrow 0} \frac{f(a+tv) - f(a)}{t} = Df(a)v$. ■

Example 7.1.3. If $U \subseteq \mathbb{R}^n$ and $f : U \rightarrow \mathbb{R}$, then Df is a $1 \times n$ row (called the gradient), so $Df(a)v = Df(a) \cdot v$ for $v \in \mathbb{R}^n$.

If $\{e_1, \dots, e_n\}$ is the canonical orthonormal basis for \mathbb{R}^n , then Ae_i is the i th column of A . The i th partial derivative for f at a is $Df(a)e_i = D_i f(a) =$ the i th column of $Df(a)$, so

$Df(a) = [D_1f(a) \ D_2f(a) \ \dots \ D_nf(a)]$. Now, if $f = (f_1, \dots, f_m)^T$, then by the chain rule, which we shall prove shortly, $Df(a)$ exists if and only if $Df_i(a)$ exists for all $i = 1, \dots, m$ and

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

Together we get $Df(a) = [D_if_j(a)]$ for $i = 1, \dots, n$, $j = 1, \dots, m$, provided $Df(a)$ exists.

Example 7.1.4. Consider

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

which is not continuous, and hence not differentiable, at $(0, 0)$. Indeed,

$$f(1/n, 1/n) = \frac{1/n^2}{2/n^2} = \frac{1}{2} \not\rightarrow 0 = f(0, 0)$$

Then, let $v = (v_1, v_2)^T$ be a unit vector, so $v_1^2 + v_2^2 = 1$. Then

$$\begin{aligned} D_v f(0, 0) &= \lim_{t \rightarrow 0} \frac{f(tv_1, tv_2) - f(0, 0)}{t} \\ &= \lim_{t \rightarrow 0} \frac{tv_1 v_2}{t^2 v_1^2 + t^2 v_2^2} \\ &= \lim_{t \rightarrow 0} \frac{v_1 v_2}{t} \end{aligned}$$

which does not exist for any unit vector v unless $v_1 = \pm 1$ and $v_2 = 0$, or $v_1 = 0$ and $v_2 = \pm 1$. So $D_1 f(0, 0) = D_2 f(0, 0) = 0$, but no other directionals exist!

Example 7.1.5. Consider

$$f(x, y) = \begin{cases} 0 & (x, y) = (0, 0) \\ \frac{x^3}{x^2+y^2} & (x, y) \neq (0, 0) \end{cases}$$

which is continuous at $(0, 0)$, all directional derivatives exist at $(0, 0)$, but f is not differentiable at $(0, 0)$. For continuity

$$\left| \frac{x^3}{x^2+y^2} \right| = \frac{|x|x^2}{x^2+y^2} \leq \frac{\sqrt{x^2+y^2}}{x^2+y^2} x^2 \leq \frac{\sqrt{x^2+y^2}}{x^2+y^2} (x^2+y^2) = \sqrt{x^2+y^2} \rightarrow 0$$

as $(x, y) \rightarrow 0$. For directionals, let $v = (v_1, v_2)$ be a unit vector. Then $\lim_{t \rightarrow 0} \frac{t^2 v_1^3}{t^2 v_1^2 + t^2 v_2^2} = \lim_{t \rightarrow 0} v_1^3 = v_1^3$. So $D_v f(0, 0)$ exists for all v . In particular, $D_1 f(0, 0) = 1^3 = 1$ and $D_2 f(0, 0) = 0$. We know that if $Df(0, 0)$ exists, it must be $[1 \ 0]$. Then

$$\begin{aligned} \lim_{h \rightarrow 0} \frac{|f(h_1, h_2) - f(0, 0) - [1 \ 0](h_1, h_2)^T|}{\|h\|} &= \lim_{h \rightarrow 0} \frac{\left| \frac{h_1^3}{h_1^2+h_2^2} - h_1 \right|}{\sqrt{h_1^2+h_2^2}} \\ &= \lim_{h \rightarrow 0} \frac{|h_1 h_2^2|}{(h_1^2+h_2^2)^{3/2}} \end{aligned}$$

which does not tend to 0 since the sequence $(1/n, 1/n)^T$ yields

$$\lim_{n \rightarrow \infty} \frac{1/n^3}{(2/n^2)^{3/2}} = \frac{1}{2^{3/2}} \neq 0$$

Example 7.1.6 (Projection maps are Differentiable). Define $\pi_i : \mathbb{R}^n \rightarrow \mathbb{R}$ by $\pi_i(x_1, \dots, x_n) = x_i$. π_i is linear, given by the matrix $\pi_i(x) = [0 \dots 0 \ 1 \ 0 \dots 0]x$, for 1 in the i th position. Thus, as it is linear it is its own derivative at any point $a \in \mathbb{R}^n$.

Proposition 7.1.4 (Chain Rule). Suppose $U \subseteq \mathbb{R}^n$ is open, that $f : U \rightarrow \mathbb{R}^m$ is differentiable on U , and that $g : V \rightarrow \mathbb{R}^p$ is differentiable on an open set $V \subseteq \mathbb{R}^m$ containing $f(U)$. Then $g \circ f$ is differentiable on U , and

$$D(g \circ f)(a) = Dg(f(a))Df(a)$$

where $Dg(f(a))$ is a $p \times m$ matrix and $Df(a)$ is an $m \times n$ matrix, and $D(g \circ f)(a)$ is $p \times n$.

Proof. Let $b = f(a)$, $L = Df(a)$, $M = Dg(b)$, and define

$$\begin{aligned} \varphi(x) &= f(x) - f(a) - L(x - a), \quad \varphi : U \rightarrow \mathbb{R}^m \\ \psi(y) &= g(y) - g(b) - M(y - b), \quad \psi : V \rightarrow \mathbb{R}^p \\ p(x) &= g(f(x)) - g(f(a)) - ML(x - a), \quad p : U \rightarrow \mathbb{R}^p \end{aligned}$$

By differentiability of f and g ,

$$\lim_{x \rightarrow a} \frac{\|\varphi(x)\|}{\|x - a\|} = 0, \quad \text{and} \quad \lim_{y \rightarrow b} \frac{\|\psi(y)\|}{\|y - b\|} = 0$$

We have $p(x) = \psi(f(x)) + M\varphi(x)$ and we want to show

$$\lim_{x \rightarrow a} \frac{\|p(x)\|}{\|x - a\|} = 0$$

Compute

$$\frac{\|p(x)\|}{\|x - a\|} \leq \frac{\|\psi(f(x))\|}{\|x - a\|} + \frac{\|M\varphi(x)\|}{\|x - a\|} \leq \frac{\|\psi(f(x))\|}{\|x - a\|} + \frac{\|M\| \|\varphi(x)\|}{\|x - a\|}$$

where the second term goes to zero since $\|\varphi(x)\|/\|x - a\| \rightarrow 0$. Fix $\varepsilon > 0$ and find $\delta > 0$ such that $\|x - a\| < \delta$ implies $\|\psi(f(x))\| < \varepsilon\|f(x) - b\|$. Rearrange φ to get $f(x) - b = \varphi(x) + L(x - a)$, so $\|f(x) - b\| \leq \|\varphi(x)\| + \|L\| \|x - a\|$. Then for $\|x - a\| < \delta$,

$$\|\psi(f(x))\| < \varepsilon(\|\varphi(x)\| + \|L\| \|x - a\|)$$

so

$$\frac{\|\psi(f(x))\|}{\|x - a\|} \leq \varepsilon \left(\frac{\|\varphi(x)\|}{\|x - a\|} + \|L\| \right)$$

Since $\frac{\|\varphi(x)\|}{\|x - a\|} \rightarrow 0$, and $\|L\| < \infty$ is a number, we can make the right hand side as small as we wish, so $\frac{\|\psi(f(x))\|}{\|x - a\|} \rightarrow 0$. Thus, $\lim_{x \rightarrow a} \frac{\|p(x)\|}{\|x - a\|} = 0$ as desired, giving $D(g \circ f)(a) = Dg(f(a))Df(a)$. ■

Example 7.1.7. Let $g : \mathbb{R} \rightarrow \mathbb{R}^n$ be differentiable with $g(t) = \begin{pmatrix} g_1(t) \\ \vdots \\ g_n(t) \end{pmatrix}$, a parametric curve, and

$f : \mathbb{R}^n \rightarrow \mathbb{R}$ also differentiable. Then $Dg(t) = \begin{pmatrix} g'_1(t) \\ \vdots \\ g'_n(t) \end{pmatrix}$, an $n \times 1$ column, and $Df(x_1, \dots, x_n) = [D_1f(x_1, \dots, x_n) \cdots D_nf(x_1, \dots, x_n)]$, a $1 \times n$ row. Then $f \circ g : \mathbb{R} \rightarrow \mathbb{R}$, with $f(g_1(t), \dots, g_n(t))$, and

$$D(f \circ g)(t) = Df(g(t))Dg(t) = [D_1f(g(t)) \cdots D_nf(g(t))] \begin{bmatrix} g'_1(t) \\ \vdots \\ g'_n(t) \end{bmatrix} = \sum_{i=1}^n D_if(g(t))g'_i(t)$$

Proposition 7.1.5. $f = (f_1, \dots, f_m)^T : U \rightarrow \mathbb{R}^m$ is differentiable at $a \in U$ if and only if each f_i is differentiable at a .

Proof. Recall $\pi_i : \mathbb{R}^m \rightarrow \mathbb{R}$ with $\pi_i(x_1, \dots, x_m) = x_i$, which is a linear transformation, and so differentiable. If f is differentiable then so is $\pi_i \circ f = f_i$ by the chain rule, and

$$Df_i(x) = D\pi_i(f(x))Df(x) = \pi_i Df(x)$$

which is the i th row of $Df(x)$. That is,

$$Df(x) = \begin{bmatrix} Df_1(x) \\ \vdots \\ Df_m(x) \end{bmatrix}$$

Conversely, if each f_i is differentiable, write T to be the linear transformation just found, but at a . Then

$$\begin{aligned} \lim_{h \rightarrow 0} \frac{\|f(a+h) - f(a) - Th\|_1}{\|h\|_1} &= \lim_{h \rightarrow 0} \frac{\|f(a+h) - f(a) - [Df_1(a)h \cdots Df_m(a)h]^T\|_1}{\|h\|_1} \\ &= \lim_{h \rightarrow 0} \frac{\sum_{i=1}^m |f_i(a+h) - f_i(a) - Df_i(a)h|}{\|h\|_1} \\ &= \lim_{h \rightarrow 0} \sum_{i=1}^m \frac{|f_i(a+h) - f_i(a) - Df_i(a)h|}{\|h\|_1} \end{aligned}$$

which goes to zero by the differentiability of the f_i . ■

Example 7.1.8. Consider

$$f(x, y) = \begin{cases} 0 & (x, y) = (0, 0) \\ (x^2 + y^2) \sin\left(\frac{1}{\sqrt{x^2 + y^2}}\right) & (x, y) \neq (0, 0) \end{cases}$$

which is differentiable at $(0, 0)$, but both partials are not continuous at $(0, 0)$. For differentiability at $(0, 0)$, we claim $Df(0, 0) = [0 \ 0]$ since

$$\lim_{h \rightarrow 0} \frac{|f(h_1, h_2) - f(0, 0) - [0 \ 0](h_1, h_2)^T|}{\|h\|} = \lim_{h \rightarrow 0} \frac{(h_1^2 + h_2^2) \sin\left(\frac{1}{\sqrt{h_1^2 + h_2^2}}\right)}{\sqrt{h_1^2 + h_2^2}}$$

$$= \lim_{h \rightarrow 0} \sqrt{h_1^2 + h_2^2} \sin \left(\frac{1}{\sqrt{h_1^2 + h_2^2}} \right) = 0$$

since \sin is bounded. Then $\frac{\partial f}{\partial x}(0, 0) = 0$ and $\frac{\partial f}{\partial y}(0, 0) = 0$. But

$$\frac{\partial f}{\partial x}(x, y) = \begin{cases} (x^2 + y^2) \cos \left(\frac{1}{\sqrt{x^2 + y^2}} \right) (x^2 + y^2)^{-3/2} \cdot \left(\frac{-1}{2} \right) \cdot 2x + 2x \sin \left(\frac{1}{\sqrt{x^2 + y^2}} \right) & (x, y) \neq (0, 0) \\ 0 & (x, y) = (0, 0) \end{cases}$$

which has an infinite discontinuity at $(0, 0)$, and similarly for $\frac{\partial f}{\partial x}(x, y)$.

Example 7.1.9. Consider

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

which is not continuous at $(0, 0)$, but every directional derivative exists at $(0, 0)$. For continuity

$$f(1/n, 1/n^2) = \frac{1/n^4}{1/n^4 + 1/n^4} = \frac{1}{2} \not\rightarrow 0 = f(0, 0)$$

so f is not continuous at $(0, 0)$. Let $u = [u_1 \ u_2]^T$ be a unit vector. Then

$$\begin{aligned} D_u f(0, 0) &= \lim_{t \rightarrow 0} \frac{f(tu_1, tu_2) - f(0, 0)}{t} \\ &= \lim_{t \rightarrow 0} \frac{t^2 u_1^2 u_2}{t^4 u_1^4 + t^2 u_2^2} \\ &= \lim_{t \rightarrow 0} \frac{u_1^2 u_2^2}{t^2 u_1^4 + u_2^2} = \frac{u_1^2 u_2}{u_2^2} = \frac{u_1^2}{u_2} \end{aligned}$$

provided $u_2 \neq 0$. But it is 0 if $u_2 = 0$, $u_1 = \pm 1$.

Example 7.1.10. Consider

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

which is continuous at $(0, 0)$, all directional derivatives exist at $(0, 0)$, but $Df(0, 0)$ does not exist. For continuity

$$\frac{|x^2 y| \sqrt{x^2 + y^2}}{x^4 + y^2} \leq \frac{\frac{1}{2}(x^4 + y^2) \sqrt{x^2 + y^2}}{x^4 + y^2} \rightarrow 0$$

since $(x^2 \pm y)^2 \geq 0$ implies $x^4 \pm 2x^2 y + y^2 \geq 0$, and so $\frac{x^4 + y^2}{2} \geq |x^2 y|$. For the directionals,

$$\begin{aligned} D_u f(0, 0) &= \lim_{t \rightarrow 0} \frac{f(tu_1, tu_2) - f(0, 0)}{t} \\ &= \lim_{t \rightarrow 0} \frac{t^2 u_1^2 u_2 \sqrt{t^2 u_1^2 + t^2 u_2^2}}{t^4 u_1^4 + t^2 u_2^2} \end{aligned}$$

$$= \lim_{t \rightarrow 0} \frac{tu_1^2 u_2^2}{t^2 u_1^4 + u_2^2} = 0$$

so $D_1 f(0, 0) = 0 = D_2 f(0, 0)$. If $Df(0, 0)$ exists, it must be $[0 \ 0]$. But then

$$0 = \lim_{h \rightarrow 0} \frac{|f(h_1, h_2) - f(0, 0) - [0 \ 0](h_1, h_2)^T|}{\sqrt{h_1^2 + h_2^2}} = \lim_{h \rightarrow 0} \frac{h_1^2 h_2}{h_1^4 + h_2^2}$$

which does not hold since for $h_1 = 1/n$, $h_2 = 1/n^2$, the limit is

$$\lim_{h \rightarrow 0} \frac{1/n^4}{1/n^4 + 1/n^4} = \frac{1}{2}$$

Example 7.1.11. Space curves on the unit sphere are orthogonal to their derivative. Consider $f : \mathbb{R} \rightarrow \mathbb{R}^3$ differentiable. Write $f(t) = (f_1(t), f_2(t), f_3(t))^T$, so that $f'(t) = (f'_1(t), f'_2(t), f'_3(t))^T$. Further suppose $\|f(t)\| = 1$ for all t (that is the curve is on the unit sphere). Then $f_1(t)^2 + f_2(t)^2 + f_3(t)^2 = 1$, and so we have

$$2f_1(t)f'_1(t) + 2f_2(t)f'_2(t) + 2f_3(t)f'_3(t) = 0$$

which implies $f(t) \cdot f'(t) = 0$.

Example 7.1.12. Define $f : [0, \infty) \times [0, 2\pi] \times [0, \pi]$ by

$$f(p, \theta, \varphi) = \begin{pmatrix} p \cos \theta \sin \varphi \\ p \sin \theta \sin \varphi \\ p \cos \varphi \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Then

$$Df(p, \theta, \varphi) = \begin{bmatrix} \cos \theta \sin \varphi & -p \sin \theta \sin \varphi & p \cos \theta \cos \varphi \\ \sin \theta \sin \varphi & p \cos \theta \sin \varphi & p \sin \theta \cos \varphi \\ \cos \varphi & 0 & -p \sin \varphi \end{bmatrix}$$

Recall the change of volume element:

$$\det(Df(p, \theta, \varphi)) = p^2 \sin \varphi$$

Proposition 7.1.6. Suppose $f : U \rightarrow \mathbb{R}^m$ and write $f = (f_1, \dots, f_m)^T$. Suppose that all partial derivatives for the f_i exist and that $D_j f_i$ are continuous on U for all i, j . Then f is differentiable on U (and $Df(a) = [D_j f_i(a)]_{ij}$ for all $a \in U$)

Proof. Assume $m = 1$. (If we can prove this case we already have Df exists if and only if Df_i exist). Suppose $x = (x_1, \dots, x_n) \in U$ and $h = (h_1, \dots, h_n) \in \mathbb{R}^n$ such that $x + h \in \mathbb{R}^n$. Observe that

$$\frac{|f(x+h) - f(x) - \sum_{i=1}^n D_i f(x) h_i|}{\|h\|} \leq \sum_{i=1}^n \frac{|f(x_1, \dots, x_i + h_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) - f(x_1, \dots, x_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n)|}{\|h\|}$$

By the Mean Value Theorem, there exist c_i in between x_i and $x_i + h_i$ with

$$f(x_1, \dots, x_i + h_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) - f(x_1, \dots, x_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) = D_i f(x_1, \dots, c_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) h_i$$

Then

$$\begin{aligned}
 \frac{|f(x+h) - f(x) - \sum_{i=1}^n D_i f(x) h_i|}{\|h\|} &\leq \sum_{i=1}^n \frac{|D_i f(x_1, \dots, c_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) h_i - D_i f(x) h_i|}{\|h\|} \\
 &\leq \sum_{i=1}^n \frac{|h_i| |D_i f(x_1, \dots, c_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) - D_i f(x)|}{|h_i|} \\
 &= \sum_{i=1}^n |D_i f(x_1, \dots, c_i, x_{i+1} + h_{i+1}, \dots, x_n + h_n) - D_i f(x)|
 \end{aligned}$$

Since the $D_i f$ are continuous by assumption, and as $h \rightarrow 0$ so $h_i \rightarrow 0$, we have $c_i \rightarrow x_i$, so the above limit tends to 0. ■

Example 7.1.13. Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ satisfies $|f(x)| \leq \|x\|^\alpha$ for all $x \in \mathbb{R}^n$ where $\alpha > 1$. Show that f is differentiable at 0 and show that $Df(0) = [0 \dots 0]$.

Observe that

$$\frac{|f(0+h) - f(0) - [0 \dots 0]h|}{\|h\|} = \frac{|f(h)|}{\|h\|} \leq \|h\|^{\alpha-1} \rightarrow 0$$

as $\alpha - 1 > 0$.

Theorem 37 (Mean value Theorem in Several Variables).

Suppose U is an open and convex subset of \mathbb{R}^n . (Note: Convex means that if $x, y \in U$, then the entire line segment connecting x and y is also in U). If $f : U \rightarrow \mathbb{R}$ is differentiable, then for all $x \neq y \in U$ there is a $c \in (0, 1)$ so that

$$f(y) - f(x) = Df(z)(y - x)$$

where $z = (1 - c)x + cy$.

Proof. Convex means if $x \neq y$ are in U , then $(1 - t)x + ty \in U$ for all $0 \leq t \leq 1$. Define $F : [0, 1] \rightarrow \mathbb{R}$ by $F(t) = f((1 - t)x + ty)$ where $x \neq y$ are fixed in U . By the chain rule,

$$F'(t) = Df((1 - t)x + ty) \frac{d}{dt}((1 - t)x + ty) = Df((1 - t)x + ty)(y - x)$$

By the Mean Value Theorem, there exists $c \in (0, 1)$ such that

$$f(y) - f(x) = F(1) - F(0) = F'(c) = Df((1 - c)x + cy)(y - x)$$

as desired. ■

Corollary 7.1.7. Suppose $f : U \rightarrow \mathbb{R}$ is differentiable where U is an open and convex subset of \mathbb{R}^n . If $Df(a) = 0$ for all $a \in U$, then f is constant in U .

By the generalized mean value theorem $f(y) - f(x) = 0$ for all $x \neq y$, so f must be constant.

Corollary 7.1.8. Suppose $f : U \rightarrow \mathbb{R}^m$ is differentiable with U open and convex in \mathbb{R}^n . If $x \neq y \in U$ and $v \in \mathbb{R}^m$, then there exists a $c \in (0, 1)$ so that

$$v \cdot (f(y) - f(x)) = v \cdot (Df(z)(y - x))$$

for $z = (1 - c)x + cy$.

We apply the theorem to the function $v \cdot f(x) = \sum_{j=1}^m v_j f_j(x)$, so $D(v \cdot f)(z) = \sum_{j=1}^m v_j Df_j(z)$, by linearity of D .

Definition 7.1.3 (Higher Order Derivatives). Given a differentiable function $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, we may regard $Df : U \rightarrow \mathbb{R}^{mn}$ and discuss its differentiability. If Df is differentiable on U , we say that f is twice differentiable. In this case, we may identify $D(Df)(a)$ with an $mn \times n$ matrix.

Proposition 7.1.9. If $f : U \rightarrow \mathbb{R}^m$ is differentiable on U and $Df : U \rightarrow \mathbb{R}^{mn}$ is differentiable at $a \in U$, then $D(Df)(a) = [D_i(D_j f_k)]$ where $1 \leq i, j \leq n$ and $1 \leq k \leq m$.

Proof. First, we note that $Df(a) = [D_1 f_1(a) \dots D_n f_1(a) \dots D_1 f_m(a) \dots D_n f_m(a)]^T \in \mathbb{R}^{mn}$. Then, by the chain rule row $1 \leq (k-1)n + i \leq mn$, with $1 \leq k \leq m$, $1 \leq i \leq n$, is $D(D_i f_k)(a)$. Next, for $1 \leq j \leq n$ column j of $D(D_i f_k)(a)$ is $D(D_i f_k)(a)e_j = D_j(D_i f_k)(a)$. Thus, the entries of $D(Df)(a)$ are $D_j(D_i f_k)$ for $1 \leq i, j \leq n$ and $1 \leq k \leq m$, as desired. ■

Note that $\mathbb{R}^{mn} \cong M_{m \times n}(\mathbb{R})$ as linear spaces. Further, the 2-norm on \mathbb{R}^{mn} is equivalent to the spectral norm on $M_{m \times n}(\mathbb{R})$ since all norms on finite dimensional vector spaces are equivalent. Thus $\mathbb{R}^{mn} \cong M_{m \times n}(\mathbb{R})$ are isomorphic as normed linear spaces, and hence metric spaces.

Example 7.1.14. Consider

$$f(x, y) = \begin{cases} 0 & (x, y) = (0, 0) \\ \frac{x^3 y - xy^3}{x^2 + y^2} & (x, y) \neq (0, 0) \end{cases}$$

is twice differentiable at $(0, 0)$, but $D_{12}f(0, 0) \neq D_{21}f(0, 0)$. Note $D_1 f(0, 0) = f_x(0, 0) = 0 = D_2 f(0, 0)$. For $x, y \neq 0$

$$f_x(x, y) = \frac{4x^2 y^3 + x^4 y - y^5}{(x^2 + y^2)^2}$$

Now

$$f_{xy}(0, 0) = \lim_{k \rightarrow 0} \frac{f_x(0, k) - f_x(0, 0)}{k} = \lim_{k \rightarrow 0} (-1) = -1$$

Similarly we find $f_{yx}(0, 0) \neq -1$.

Proposition 7.1.10. Suppose $f : U \rightarrow \mathbb{R}^m$ is twice differentiable. If $D_i(D_j f)$ and $D_j(D_i f)$ are continuous on U , then they are equal.

Proof. Without loss of generality we may suppose $m = 1$, and glue together rows in the general case using the Chain rule. So $Df = [D_1 f \dots D_n f]$, is $1 \times n$. Since we are considering all others

variables besides i and j to be fixed when taking partial derivatives, they can be regarded as constants and we can regard f as a function of two variables. That is $n = 2$. Let $(a, b) \in U$ and find $h > 0$ such that $B_{2h}(a, b) \subseteq U$. Define

$$A(h) = \frac{1}{h^2} [f(a+h, b+h) - f(a, b+h) + f(a+h, b) - f(a, b)]$$

where all of the inputs to f are in U . By the mean value theorem there exist $c_1, c_2 \in (a, a+h)$ with

$$\begin{aligned} f(a+h, b+h) - f(a, b+h) &= f_x(c_1, b+h)h \\ f(a+h, b) - f(a, b) &= f_x(c_2, b)h \end{aligned}$$

Apply the mean value theorem again to f_x . There exists c_3 between c_1 and c_2 , and d_1 between b and $b+h$ such that

$$f_x(c_1, b+h) - f_x(c_2, b) = hf_{xy}(c_3, d_1)$$

where the left hand side is $hA(h)$. Similarly, there exist c_4, d_2 with $hA(h) = hf_{yx}(c_4, d_2)$, that is, $f_{xy}(c_3, d_1) = f_{yx}(c_4, d_2)$. As $h \rightarrow 0$, $c_3, c_4 \rightarrow a, d_1, d_2 \rightarrow b$. Now, since both f_{xy} and f_{yx} are continuous by assumption, we have

$$f_{xy}(a, b) = f_{yx}(a, b)$$

completing the proof. ■

7.2.0 The Inverse and Implicit Function Theorems

Simple cases of what we are trying to do:

- $f : I \rightarrow \mathbb{R}$, where I is an interval, and $f'(x) \neq 0$ on I . From analysis one we have f is invertible, and $f^{-1} : f(I) \rightarrow I$. f^{-1} is differentiable on $f(I)$, and $(f^{-1})'(f(x)) = \frac{1}{f'(x)}$
- Suppose $f : \mathbb{R}^m \rightarrow \mathbb{R}^n$ is affine, so $f(x) = Ax + b$, where A is $n \times m$ and $b \in \mathbb{R}^n$. Then $Df = A$. If A is invertible, then f is invertible and $f^{-1}(x) = A^{-1}(x - b)$, so $Df^{-1} = A^{-1}$

Definition 7.2.1. If $f : U \rightarrow \mathbb{R}^m$ is differentiable and $Df : U \rightarrow \mathbb{R}^{m \times m}$ is continuous, we say that f is C^1 .

Lemma 7.2.1. $f : U \rightarrow \mathbb{R}^m$ is C^1 if and only if all partials $D_i f_j$ exist and are continuous on U .

Sketch. If $D_i f_j$ are all continuous, we know by a previous result that Df exists. Moreover,

$$Df(a+h) - Df(a) = [D_i f_j(a+h) - D_i f_j(a)] \rightarrow 0$$

since each entry goes to 0 by continuity of $D_i f_j$. On the other hand, if Df is continuous, so is $\pi_i Df \pi_j =$ the ij -th entry of Df , which is $D_j f_i$. ■

Lemma 7.2.2 (Key to Inverse Function Theorem). Suppose $f : U \rightarrow \mathbb{R}^n$ is C^1 and $x_0 \in U$ with $Df(x_0)$ an invertible $n \times n$ matrix. There is an open set $W \subseteq U$ containing x_0 and a $c > 0$ such that

$$\|f(y) - f(x)\| \geq c\|y - x\|$$

for all $x, y \in W$.

Proof. If $A \in M_n$ then $\|Ax - Ay\| \leq \|A\| \|x - y\|$, where $\|A\|$ is the spectral norm. If A is invertible, then

$$\|x - y\| = \|A^{-1}Ax - A^{-1}Ay\| \leq \|A^{-1}\| \|Ax - Ay\|$$

Since $A^{-1} \neq 0$, $\|A^{-1}\| > 0$ and we can divide by it to obtain

$$\frac{1}{\|A^{-1}\|} \|x - y\| \leq \|Ax - Ay\|$$

Now suppose $Df(x_0)$ is invertible and let $c = \frac{1}{2\|Df(x_0)^{-1}\|}$. Let $f = (f_1, \dots, f_n)$. All f_i are C^1 on U , so there exists an open ball W in U containing x_0 such that

$$\|Df_i(y) - Df_i(x_0)\| \leq \frac{c}{n}$$

when $y \in W$, where the left hand side is the spectral or operator norm of a row.

Suppose A is $n \times n$ with rows A_i , $1 \times n$. Suppose $\|A_i\| \leq \frac{c}{n}$, so $\|A_i v\| \leq \frac{c}{n} \|v\|$ for all $v \in \mathbb{R}^n$. Then, we have that

$$\|Av\| = \left\| \begin{pmatrix} A_1 v \\ \vdots \\ A_n v \end{pmatrix} \right\| \leq \sum_{i=1}^n \|A_i v\| \leq c$$

This implies $\|Df(y) - Df(x_0)\| \leq c$ for all $y \in W$. (Note we could have gotten this immediately from continuity of Df) By the mean value theorem in multiple variables, there exists $c_i \in (0, 1)$ and $z_i = (1 - c_i)x + c_i y \in W$ since W is an open ball and open balls are convex, with $f_i(y) - f_i(x) = Df_i(z_i)(y - x)$. We have

$$\begin{aligned} \|f_i(y) - f_i(x) - Df_i(x_0)(y - x)\| &= \|Df_i(z_i)(y - x) - Df_i(x_0)(y - x)\| \\ &\leq \|Df_i(z_i) - Df_i(x_0)\| \|y - x\| \\ &< \frac{c}{n} \|y - x\| \end{aligned}$$

Then we have that

$$\|Df(x_0)(y - x)\| - \|f(y) - f(x)\| \leq \|f(y) - f(x) - Df(x_0)(y - x)\| \leq c\|y - x\|$$

This implies

$$\|Df(x_0)(y - x)\| - c\|y - x\| \leq \|f(y) - f(x)\|$$

By the first part of the proof,

$$\|Df(x_0)(y - x)\| \geq \frac{1}{\|Df(x_0)^{-1}\|} \|y - x\|$$

By our previous inequality this implies

$$\|f(y) - f(x)\| \geq \frac{1}{\|Df(x_0)^{-1}\|} \|y - x\| - c\|y - x\| = c\|y - x\|$$

since $c = \frac{1}{2\|Df(x_0)^{-1}\|}$. ■

Corollary 7.2.3. Suppose $f : U \rightarrow \mathbb{R}^n$ is C^1 and $x_0 \in U$ with $Df(x_0)$ an invertible $n \times n$ matrix. There is an open set $W \subseteq U$ containing x_0 so that $f|_W : W \rightarrow f(W)$ is invertible.

Using W from the proof above, $f(x) = f(y)$ for $x, y \in W$ only if $x = y$ by the inequality $\|f(x) - f(y)\| \geq c\|x - y\|$, so $f|_W$ is injective.

Example 7.2.1. The assumption that f is C^1 in the above results is required. Consider

$$f(x) = \begin{cases} x + 2x^2 \sin(1/x) & x \neq 0 \\ 0 & x = 0 \end{cases}$$

is differentiable on \mathbb{R} but f' is not continuous. $f'(0) = 1$ (so invertible), but f is not monotone in any neighborhood of 0. Hence it cannot be invertible in any neighborhood of 0.

Lemma 7.2.4. Suppose $f : U \rightarrow \mathbb{R}^n$ is C^1 and $x_0 \in U$ with $Df(x_0)$ an invertible $n \times n$ matrix. There is an open ball $V \subseteq U$ containing x_0 so that $f|_V$ is a homeomorphism.

Proof. There exists an open ball W containing x_0 so that

- (i) there exists $c > 0$ with $\|f(y) - f(x)\| \geq c\|y - x\|$ for all $x, y \in W$
- (ii) $\overline{W} \subseteq U$
- (iii) $Df(x)$ is invertible for all $x \in W$.

Note, Df is continuous so $Df(x)$ is invertible if x is close to x_0 . To see (iii) is invertible in M_n , we note that the space of invertible linear transformations is an open set, since $\det : M_n \rightarrow \mathbb{R}$ is continuous and the invertibles are $\det^{-1}(\mathbb{R} \setminus \{0\})$.

This means if $Df(x)$ is close enough to $Df(x_0)$ then it is invertible. But f is C^1 , which means $Df : U \rightarrow M_n$ is continuous. So there exists $V \subseteq W$ containing x_0 such that $x \in V$ implies $Df(x)$ is close enough to $Df(x_0)$ so that $Df(x)$ is invertible. Take this V and consider $f|_V : V \rightarrow f(V)$. All we must show is that $f^{-1}|_{f(V)}$ is continuous since it is already the restriction of a bijective continuous map. We do this by showing $f(O)$ is open whenever O is open in V . It is enough, by considering unions, to assume O is an open ball with $\overline{O} \subseteq V$. Let $S = \partial O$ be the boundary of O , so S is a sphere, which is compact. Note $\overline{O} = S \cup O \subseteq V$. If $x \in V \setminus S$, then

$$d = \text{dist}(f(x), f(S)) := \inf_{s \in S} \|f(x) - f(s)\| > 0$$

since S is compact, f is continuous, and so $f(S)$ is a compact set not containing $f(x)$ as f is injective on V . To show $f(O)$ is open, we will show

$$B_{d/2}(f(x)) \subseteq f(O)$$

Let $z \in B_{d/2}(f(x))$, so $\|z - f(x)\| < d/2$. Then

$$\text{dist}(z, f(\overline{O})) = \inf_{t \in \overline{O}} \|z - f(t)\| \leq \int_{t \in S} \|z - f(t)\|$$

Let $s \in S$. Then

$$\begin{aligned} \|z - f(s)\| &= \|z - f(x) + f(x) - f(s)\| \\ &\geq \|f(x) - f(s)\| - \|z - f(x)\| \\ &> d - d/2 = d/2 \end{aligned}$$

It follows that $\text{dist}(z, f(S)) \geq d/2$. For $x \in \bar{O} = O \cup S$, define

$$g(x) = \|z - f(x)\|^2 = \sum_{i=1}^n |z_i - f_i(x)|^2$$

\bar{O} is compact and g is continuous, hence it attains its minimum on some $x_1 \in \bar{O}$, that is

$$\|z - f(x_1)\| = \text{dist}(z, f(\bar{O}))$$

We claim $x_1 \in O$ and not in S . Otherwise,

$$d/2 \leq \text{dist}(z, f(S)) = \text{dist}(z, f(\bar{O})) < d/2$$

a contradiction. So $x_1 \in O$. So x_1 is interior which implies $Dg(x_1) = 0$. For $1 \leq j \leq n$,

$$0 = D_j g(x_1) = -2 \sum_{i=1}^n (z_i - f_i(x_1)) D_j f_i(x_1)$$

by the chain rule, so

$$Df(x_1)(z - f(x_1)) = 0$$

which implies $z = f(x_1) \in f(O)$ since $Df(x_1)$ is invertible. ■

Theorem 38 (Inverse Function Theorem).

Suppose $f : U \rightarrow \mathbb{R}^n$ is C^1 and $x_0 \in U$ with $Df(x_0)$ an invertible $n \times n$ matrix. There is an open ball $V \subseteq U$ containing x_0 with

(1) $f : V \rightarrow f(V)$ is a homeomorphism

(2) $f^{-1} : f(V) \rightarrow V$ is C^1 and

$$Df^{-1}(f(x)) = Df(x)^{-1}$$

for all $x \in V$ (that is $Df^{-1}(y) = Df(f^{-1}(y))^{-1}$)

Proof. Let V be as in the previous proof. (1) is already established by the previous result. We also know by the proof that $Df(x)$ is invertible for $x \in V$. Let $x \in V$ and $y = f(x)$. Write for $z \in f(V)$,

$$\begin{aligned} \frac{\|f^{-1}(z) - f^{-1}(y) - Df(x)^{-1}(z - y)\|}{\|z - y\|} &= \frac{\|Df(x)^{-1}(Df(x)f^{-1}(z) - Df(x)f^{-1}(y)) - Df(x)^{-1}(z - y)\|}{\|z - y\|} \\ &\leq \|Df(x)^{-1}\| \frac{\|Df(x)f^{-1}(z) - Df(x)f^{-1}(y) - (z - y)\|}{\|z - y\|} \\ &\leq \|Df(x)^{-1}\| \frac{\|Df(x)(f^{-1}(z) - x) - (z - y)\|}{c\|f^{-1} - x\|} \end{aligned}$$

where there exists $c > 0$ with $\|z - y\| \geq c\|f^{-1}(z) - f^{-1}(y)\| = c\|f^{-1}(z) - x\|$ using our key lemma. The last line goes to 0 as $f^{-1}(z) \rightarrow f^{-1}(y) = x$ since f is differentiable at x .

Finally, Df^{-1} is continuous if and only if its entries are continuous. The map $^{-1} : \mathbf{GL}_n \rightarrow \mathbf{GL}_n, A \mapsto A^{-1}$, is continuous. Since the entries of $Df(x)$ are continuous as f is C^1 , this implies the entries of $Df(x)^{-1} = Df^{-1}(f(x))$ are continuous. ■

Example 7.2.2. Consider the function $f(x, y) = (e^x \cos y, e^x \sin y)^T = (u, v)^T$, $f : \mathbb{R}^2 \rightarrow \mathbb{R}^2$. Note if $z = x + iy$, this f is the complex exponential. f is not invertible, since $f(x, y) = f(x, y + 2\pi)$ for all $x, y \in \mathbb{R}^2$. Observe

$$Df(x, y) = \begin{bmatrix} u_x & u_y \\ v_x & v_y \end{bmatrix} = \begin{bmatrix} e^x \cos y & -e^x \sin y \\ e^x \sin y & e^x \cos y \end{bmatrix}$$

and $\det(Df(x, y)) = e^{2x} > 0$, so $Df(x, y)$ is invertible and the inverse function theorem applies. This means there is a neighborhood U of (x, y) such that $f|_U$ is invertible, and

$$\begin{bmatrix} x_u & x_v \\ y_u & y_v \end{bmatrix} = Df^{-1}(u(x, y), v(x, y)) = \begin{bmatrix} u_x & u_y \\ v_x & v_y \end{bmatrix}^{-1}$$

Example 7.2.3. More generally, if $f(x, y) = (u(x, y), v(x, y))^T$ is C^1 with

$$Df(x, y) = \begin{bmatrix} u_x & u_y \\ v_x & v_y \end{bmatrix}$$

invertible, then

$$\begin{bmatrix} x_u & x_v \\ y_u & y_v \end{bmatrix} = Df^{-1}(u, v) = \begin{bmatrix} u_x & u_y \\ v_x & v_y \end{bmatrix}^{-1}$$

by the IFT.

Example 7.2.4. Consider $x^2 + y^2 = 1$, the unit circle. Implicitly, y as a function of x for $x \neq \pm 1$ and $\frac{dy}{dx} = \frac{-x}{y}$. Of course $y = \pm \sqrt{1 - x^2}$ is an explicit representation of this, but depends on the sign of y . We can also view x as a function of y for $x \neq 0$, and $\frac{dx}{dy} = -\frac{y}{x}$. For all (x, y) on the unit circle, one variable can be implicitly written as a C^1 function of the other.

Example 7.2.5 (Systems of linear equations). Let $\vec{x} = (x_1, \dots, x_n)^T \in \mathbb{R}^n$ and $\vec{y} = (y_1, \dots, y_m)^T \in \mathbb{R}^m$, so $(\vec{x}, \vec{y}) \in \mathbb{R}^{n+m}$. Suppose A is an $n \times (n + m)$ matrix. Write

$$A = \left[A_x \middle| A_y \right]$$

where A_x is an $n \times n$ matrix block and A_y is an $n \times m$ matrix block. The linear system $A(\vec{x}, \vec{y}) = 0$ is a system of n equations in $m + n$ variables, has m parameters in its solution if A_x is invertible (i.e. A has rank n). In this case $0 = A(\vec{x}, \vec{y}) = A_x \vec{x} + A_y \vec{y}$ if and only if $\vec{x} = -A_x^{-1}(A_y \vec{y})$ (\vec{x} is our n variables and \vec{y} is our m parameters).

For the next few results, a point $(x_1, \dots, x_n, y_1, \dots, y_m)$ in \mathbb{R}^{n+m} will be abbreviated as (\vec{x}, \vec{y}) with $\vec{x} = (x_1, \dots, x_n) \in \mathbb{R}^n$ and $\vec{y} = (y_1, \dots, y_m) \in \mathbb{R}^m$.

Theorem 39 (Implicit Function Theorem).

Suppose U is an open subset of \mathbb{R}^{m+n} and $f : U \rightarrow \mathbb{R}^n$ is C^1 . Suppose $f(\vec{a}, \vec{b}) = 0$ where $a \in \mathbb{R}^n$ and $b \in \mathbb{R}^m$ and

$$A = Df(\vec{a}, \vec{b}) = \left[A_x \mid A_y \right]$$

where A_x is $n \times n$ and A_y is $n \times m$. Write $f = (f_1, \dots, f_n)^T$, each f_i depends on $m + n$ variables. Note $f(\vec{a}, \vec{b}) = 0$ is n equations in $m + n$ variables.

If A_x is invertible, then there exist open sets $V \subseteq U$ and $W \subseteq \mathbb{R}^m$ with $(a, b) \in V$ and $b \in W$ so that for all $y \in W$ there is a unique x with $(x, y) \in V$ and $f(x, y) = 0$. Write $x = g(y)$ in this case, so that $f(g(y), y) = 0$ on W . Then $g : W \rightarrow \mathbb{R}^n$ is C^1 , $g(b) = a$, and

$$Dg(b) = -A_x^{-1}A_y$$

In other words, we can implicitly solve for the variables x_1, \dots, x_n in terms of the parameters y_1, \dots, y_m with a C^1 function on W .

Proof. Define $F : \mathbb{R}^{n+m} \rightarrow \mathbb{R}^{n+m}$ by $F(\vec{x}, \vec{y}) = (f(\vec{x}, \vec{y}), \vec{y})$. Then

$$DF(\vec{x}, \vec{y}) = \left[\begin{array}{c|c} Df(\vec{x}, \vec{y}) & \\ \hline 0 & I_m \end{array} \right]$$

We know $Df(\vec{a}, \vec{b}) = [A_x \mid A_y]$ so

$$DF(\vec{a}, \vec{b}) = \left[\begin{array}{cc} A_x & A_y \\ 0 & I_m \end{array} \right]$$

So F is C^1 and $DF(\vec{a}, \vec{b})$ is invertible since A_x is invertible, so $\det(DF(\vec{a}, \vec{b})) = \det(A_x) \det(I_m) \neq 0$.

Apply the Inverse Function Theorem to F at (\vec{a}, \vec{b}) . There exists W' open in \mathbb{R}^{m+n} containing (\vec{a}, \vec{b}) such that $F : W' \rightarrow F(W')$ is a homeomorphism. $F(W')$ is open and $F(\vec{a}, \vec{b}) = (f(\vec{a}, \vec{b}), \vec{b}) = (0, \vec{b}) \in F(W')$. Let $W = \{\vec{y} \in \mathbb{R}^m \mid (0, \vec{y}) \in F(W')\}$ so $\vec{b} \in W$. Then $F(W') \cap \{\vec{0}_n\} \times \mathbb{R}^m = \{\vec{0}_n\} \times W$, $\{\vec{0}_n\} \times W$ is open in $\{\vec{0}_n\} \times \mathbb{R}^m \cong \mathbb{R}^m$, so W is open in \mathbb{R}^m . If $\vec{y} \in W$, then $(0, \vec{y}) \in F(W')$, which implies $(0, \vec{y}) = F(\vec{x}, \vec{y}) = (f(\vec{x}, \vec{y}), \vec{y})$ for some $\vec{x} \in \mathbb{R}^n$. This implies $f(\vec{x}, \vec{y}) = 0$. That is there is a neighborhood of (\vec{a}, \vec{b}) consisting of solutions to $f(\vec{x}, \vec{y}) = 0$. Fix \vec{y} and suppose $(\vec{x}, \vec{y}) \in F(W')$ and $(\vec{x}_1, \vec{y}) \in F(W')$ such that

$$F(\vec{x}, \vec{y}) = (0, \vec{y}) = F(\vec{x}_1, \vec{y})$$

F is also injective on W' , so $\vec{x}_1 = \vec{x}$. This shows for all $\vec{y} \in W$, there exists a unique $\vec{x} \in \mathbb{R}^n$ with $f(\vec{x}, \vec{y}) = 0$. Write $\vec{x} = g(\vec{y})$ in this case. So $g : W \rightarrow \mathbb{R}^n$. By construction $f(g(\vec{y}), \vec{y}) = 0$ for all $\vec{y} \in W$. In particular, $g(\vec{b}) = \vec{a}$. Now $(g(\vec{y}), \vec{y}) = F^{-1}(0, \vec{y})$ and we know F^{-1} is C^1 on $F(W')$ by the inverse function theorem. This gives by the chain rule that g is C^1 on W , as $g(\vec{y}) = \pi_{1-m} \circ F^{-1}(0, \vec{y})$. Write $\Phi(\vec{y}) = (g(\vec{y}), \vec{y})$, so

$$D\Phi(\vec{y}) = \left[\begin{array}{c} Dg(\vec{y}) \\ I_m \end{array} \right]$$

which is $(m+n) \times m$. We know $f \circ \Phi = 0 \in \mathbb{R}^n$. Applying the chain rule:

$$0 = Df(\Phi(\vec{y}))D\Phi(\vec{y})$$

Let $\vec{y} = \vec{b}$, so $\Phi(\vec{b}) = (g(\vec{b}), \vec{b}) = (\vec{a}, \vec{b})$. Then

$$0 = Df(\vec{a}, \vec{b}) \begin{bmatrix} Dg(\vec{b}) \\ I_m \end{bmatrix} = [A_x \ A_y] \begin{bmatrix} Dg(\vec{b}) \\ I_m \end{bmatrix} = A_x Dg(\vec{b}) + A_y$$

so it follows that

$$Dg(\vec{b}) = -A_x^{-1}A_y$$

■

Example 7.2.6. Consider the unit sphere $x^2 + y^2 + z^2 = 1$. Here $f(x, y, z) = x^2 + y^2 + z^2 - 1 = 0$. Note

$$Df(x, y, z) = [2x \ 2y \ 2z]$$

If $x \neq 0$, then A_x is invertible, so there exists $g \in C^1$ such that $x = g(y, z)$. In this case

$$Dg(y, z) = -A_x^{-1}A_y = -\frac{1}{2x}[2y \ 2z]$$

Note we could have used any square block in Df as our A_x . For example, taking $A_x = 2y$, $A_y = [2x \ 2z]$, if $y \neq 0$ then there exists C^1 h with $y = h(x, z)$ and $Dh(x, z) = -\frac{1}{2y}[2x \ 2z]$.

Example 7.2.7. Consider

$$f(x_1, x_2, y_1, y_2, y_3) = \begin{bmatrix} 2e^{x_1} + x_2 y_1 - 4y_2 + 3 \\ x_2 \cos(x_1) - 6x_1 + 2y_1 - y_3 \end{bmatrix} : \mathbb{R}^5 \rightarrow \mathbb{R}^2$$

We have the solution $f(0, 1, 3, 2, 7) = [0 \ 0]^T$, which corresponds with 2 equations in 5 unknowns. Applying the implicit function theorem to $\vec{a} = (0, 1)^T$ and $\vec{b} = (3, 2, 7)^T$ (i.e. solve for x_1, x_2 in terms of y_1, y_2, y_3),

$$\begin{aligned} Df(\vec{a}, \vec{b}) &= \begin{bmatrix} 2e^{x_1} & y_1 & x_2 & -4 & 0 \\ (-x_2 \sin(x_1) - 6) & \cos(x_1) & 2 & 0 & -1 \end{bmatrix} \bigg|_{(\vec{a}, \vec{b})} \\ &= \begin{bmatrix} 2 & 3 & 1 & -4 & 0 \\ -6 & 1 & 2 & 0 & -1 \end{bmatrix} \end{aligned}$$

where $A_x = \begin{bmatrix} 2 & 3 \\ -6 & 1 \end{bmatrix}$ and $A_y = \begin{bmatrix} 1 & -4 & 0 \\ 2 & 0 & -1 \end{bmatrix}$. A_x is invertible since $\det(A_x) = 2 + 18 = 20 \neq 0$. Therefore, by the implicit function theorem, there is a $g = (g_1, g_2)^T$ which is C^1 with $x_1 = g_1(y_1, y_2, y_3)$ and $x_2 = g_2(y_1, y_2, y_3)$ and

$$Dg(\vec{b}) = -A_x^{-1}A_y = \begin{bmatrix} 1/4 & 1/5 & -3/20 \\ -1/2 & 6/5 & 1/10 \end{bmatrix}$$

so $-1/2 = \frac{\partial}{\partial y_1} g_2(3, 2, 7)$.

Can we do this with y_2, y_3 as the dependent variables? Yes! In this case $\vec{b} = (0, 1, 3)^T$ and $\vec{a} = (2, 7)^T$, where $A_y = \begin{bmatrix} 2 & 3 & 1 \\ -6 & 1 & 2 \end{bmatrix}$ and $A_x = \begin{bmatrix} -4 & 0 \\ 0 & -1 \end{bmatrix}$. $\det(A_x) = 4 \neq 0$, so A_x is

invertible and $A_x^{-1} = \begin{bmatrix} -1/4 & 0 \\ 0 & -1 \end{bmatrix}$. Then there exists $h = (h_1, h_2)^T, C^1$, with $y_2 = h_1(x_1, x_2, y_1)$ and $y_3 = h_2(x_1, x_2, y_1)$, and

$$\begin{aligned} Dh(0, 1, 3) &= -A_x^{-1}A_y \\ &= \begin{bmatrix} 1/4 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & 3 & 1 \\ -6 & 1 & 2 \end{bmatrix} \\ &= \begin{bmatrix} 1/2 & 3/4 & 1/4 \\ -6 & 1 & 2 \end{bmatrix} \end{aligned}$$

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Appendices

.1.0 Multivariate Calculus - with Applications

Vector Functions and Derivatives

Definition .1.1. A vector function of one variable is a function $\vec{f}: J \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ defined by $t \mapsto \vec{f}(t)$, where $\vec{f}(t) \in \mathbb{R}^n$ is unique.

Definition .1.2. Let $\vec{f}: \mathbb{R} \rightarrow \mathbb{R}^n$ be a vector valued function. Then we define the derivative of \vec{f} at t by

$$\frac{d\vec{f}(t)}{dt} = \lim_{\Delta t \rightarrow 0} \frac{\vec{f}(t + \Delta t) - \vec{f}(t)}{\Delta t} \quad (.1.1)$$

Remark .1.1 (Properties). Let $\vec{f}: J \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ and $\vec{g}: I \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ be vector functions such that

$$\vec{f} = \langle f_1, \dots, f_n \rangle \text{ and } \vec{g} = \langle g_1, \dots, g_n \rangle \quad (.1.2)$$

The for all $t \in J \cap I$ and all $\lambda: D_\lambda \subseteq \mathbb{R} \rightarrow \mathbb{R}$ we have

1. $(\vec{f} + \vec{g})(t) := \vec{f}(t) + \vec{g}(t)$
2. $(\lambda \vec{f})(t) := \lambda(t) \vec{f}(t)$
3. $(\vec{f} \cdot \vec{g})(t) = \vec{f}(t) \cdot \vec{g}(t)$
4. For $n = 3$, $(\vec{f} \times \vec{g})(t) = \vec{f}(t) \times \vec{g}(t)$

Recall .1.2. Given $A \in \mathbb{R}^{n \times n}$, the lagrange expansion is

$$\det(A) = \sum_{i=1}^n (-1)^{i+j} \det(A_{ij}) \text{ (along } j\text{-th column)} \quad (.1.3)$$

$$\det(A) = \sum_{j=1}^n (-1)^{i+j} \det(A_{ij}) \text{ (along } i\text{-th row)} \quad (.1.4)$$

where A_{ij} is the minor matrix of A obtained by deleting the i th row and j th column of A .

Definition .1.3. Suppose $\vec{f}(t) = \langle f_1(t), \dots, f_n(t) \rangle$ and $\vec{L} = \langle L_1, \dots, L_n \rangle$ Then

$$\lim_{t \rightarrow t_0} \vec{f}(t) = \vec{L} \implies \lim_{t \rightarrow t_0} f_i(t) = L_i, \forall 1 \leq i \leq n \quad (.1.5)$$

Remark .1.3. The right hand limit $\lim_{t \rightarrow t_0^+} \vec{f}(t)$ and the left hand limit $\lim_{t \rightarrow t_0^-} \vec{f}(t)$ are defined in the same way.

Remark .1.4 (Limit Rules). If $\lim_{t \rightarrow t_0}$ for $\vec{f}(t)$, $\vec{g}(t)$, and $\lambda(t)$ exist and $k \in \mathbb{R}$, then

1. $\lim_{t \rightarrow t_0} (\vec{f}(t) + \vec{g}(t)) = \lim_{t \rightarrow t_0} \vec{f}(t) + \lim_{t \rightarrow t_0} \vec{g}(t)$

2. $\lim_{t \rightarrow t_0} k\vec{f}(t) = k \lim_{t \rightarrow t_0} \vec{f}(t)$
3. $\lim_{t \rightarrow t_0} \lambda(t)\vec{f}(t) = (\lim_{t \rightarrow t_0} \lambda(t))(\lim_{t \rightarrow t_0} \vec{f}(t))$
4. $\lim_{t \rightarrow t_0} \vec{f}(t) \cdot \vec{g}(t) = (\lim_{t \rightarrow t_0} \vec{f}(t)) \cdot (\lim_{t \rightarrow t_0} \vec{g}(t))$
5. $\lim_{t \rightarrow t_0} \vec{f}(t) \times \vec{g}(t) = (\lim_{t \rightarrow t_0} \vec{f}(t)) \times (\lim_{t \rightarrow t_0} \vec{g}(t)), \text{ for } n = 3.$

Definition .1.4 (Continuity). A vector function $\vec{f}(t) = \langle f_1(t), \dots, f_n(t) \rangle$ is said to be continuous at $t = t_0$ if

$$\lim_{t \rightarrow t_0} \vec{f}(t) = \vec{f}(t_0) \quad (.1.6)$$

In other words, each component function is continuous at $t = t_0$.

Definition .1.5 (Differentiability). A vector function $\vec{f}(t) = \langle f_1(t), \dots, f_n(t) \rangle$ is said to be differentiable at $t = t_0$ if $\vec{f}'(t)$ is defined at and around t and

$$\lim_{t \rightarrow t_0} \frac{\vec{f}(t) - \vec{f}(t_0)}{t - t_0} \quad (.1.7)$$

exists. We call this limit the derivative of $\vec{f}(t)$ at $t = t_0$ and is denoted by $\vec{f}'(t_0)$ if it exists.

Theorem .1.1. We say that the vector function is differentiable at $t = t_0$ if and only if its component functions are differentiable at $t = t_0$, and

$$\vec{f}'(t_0) = \langle f'_1(t_0), \dots, f'_n(t_0) \rangle \quad (.1.8)$$

Remark .1.5 (Differentiation Rules). Let $\vec{f}(t)$, $\vec{g}(t)$ and $\lambda(t)$ be differentiable and $k \in \mathbb{R}$. Then

1. $(\vec{f} + \vec{g})'(t) = \vec{f}'(t) + \vec{g}'(t)$
2. $(k\vec{f})'(t) = k\vec{f}'(t)$
3. $(\lambda\vec{f})'(t) = \lambda'(t)\vec{f}(t) + \lambda(t)\vec{f}'(t)$
4. $(\vec{f} \cdot \vec{g})'(t) = \vec{f}'(t) \cdot \vec{g}(t) + \vec{f}(t) \cdot \vec{g}'(t)$
5. $(\vec{f} \times \vec{g})'(t) = \vec{f}'(t) \times \vec{g}(t) + \vec{f}(t) \times \vec{g}'(t)$ for $n = 3$
6. $(\vec{f}(\lambda(t)))' = \vec{f}'(\lambda(t))\lambda'(t)$

Definition .1.6. Let $\vec{f}(t) = \langle f_1(t), \dots, f_n(t) \rangle$ be a vector function defined on a closed interval $[a, b]$. We say that $\vec{f}(t)$ is **integrable** on $[a, b]$ if each $f_i(t)$ is integrable on $[a, b]$. When that is the case we define

$$\int_a^b \vec{f}(t) dt := \left\langle \int_a^b f_1(t) dt, \dots, \int_a^b f_n(t) dt \right\rangle \quad (.1.9)$$

the definite integral of $\vec{f}(t)$ on $[a, b]$

Remark .1.6 (Properties). Let $\vec{f}(t), \vec{g}(t)$ be integrable on $[a, b]$ and $k \in \mathbb{R}$. Then

1. $\int_a^b k\vec{f}(t)dt = k \int_a^b \vec{f}(t)dt$
2. $\int_a^b (\vec{f}(t) + \vec{g}(t))dt = \int_a^b \vec{f}(t)dt + \int_a^b \vec{g}(t)dt$
3. $\int_a^b \vec{f}(t)dt = \int_a^c \vec{f}(t)dt + \int_c^b \vec{f}(t)dt, a \leq c \leq b.$
4. $\left| \int_a^b \vec{f}(t)dt \right| \leq \int_a^b \left| \vec{f}(t) \right| dt$ (The triangle inequality)

Parametric Curves and Paths

Definition .1.7. Let $\vec{f}: J \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ given by $t \mapsto \langle f_1(t), \dots, f_n(t) \rangle$, and $f_j: J \subseteq \mathbb{R} \rightarrow \mathbb{R}$ be the j th component function of \vec{f} . We define the image

$$\vec{f}(J) = \mathcal{C} \quad (.1.10)$$

and call \mathcal{C} a **curve parametrized** by \vec{f} . If $J = [a, b]$ for $a \leq b \in \mathbb{R}$ and $\vec{f}(a) = \vec{f}(b)$, then \mathcal{C} is a **closed curve**. If there exists a parametrization $\vec{g}: I \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ of \mathcal{C} such that \vec{g} is injective (except maybe at end points), then \mathcal{C} is said to be a **non-self intersecting** curve. If such a curve is closed it is called a **simple closed curve**.

Remark .1.7. The pair $(\vec{f}(t), J)$ is called a **parametrization** of the curve \mathcal{C} . The triple $(\vec{f}(t), J, \mathcal{C})$ is called a **path with curve** \mathcal{C} .

Definition .1.8. If $\vec{f}: J \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ is a one-to-one function, then the image $\vec{f}(J) = \mathcal{C}$ is an **oriented curve** and \vec{f} is a **consistently oriented path** which covers \mathcal{C} .

Remark .1.8 (Ellipse). The parametrization of an ellipse with equation $\frac{(x-x_0)^2}{a^2} + \frac{(y-y_0)^2}{b^2} = 1$, $a, b > 0$ are constants, is $\vec{f}(t) = \langle x_0 + a \cos(t), y_0 + b \sin(t) \rangle$, for $t \in [0, 2\pi)$.

Remark .1.9 (Line). Let A and B be points in \mathbb{R}^n . The parametrization of the line segment connecting A to B is

$$(\vec{f}(t) = \overline{OA} + t(\overline{OB} - \overline{OA}), [0, 1]) \quad (.1.11)$$

Definition .1.9. The tangent vector to a curve \mathcal{C} with parametrization (\vec{f}, I) exists at a point $t = t_0$ if \vec{f} is $\vec{f}'(t)$ exists.

Definition .1.10. Let \mathcal{C} be a parametric curve with parametrization $(\vec{f}(t), [a, b])$. If $\vec{f}(t)$ is differentiable at $t = t_0$, then $\vec{f}'(t_0)$ is called a **tangent vector** to \mathcal{C} at $P_0 = \text{tip}(\vec{f}'(t_0))$, provided $\vec{f}'(t_0) \neq \vec{0}$. If $\vec{f}(t)$ is differentiable at every $t \in (a, b)$ and $\vec{f}'(t) \neq \vec{0}$, we say that the parametric curve \mathcal{C} is a **smooth parametric curve**.

Definition .1.11. Let \mathcal{C} be a parametric curve and let $(\vec{f}(t), I)$ be a parametrization. If $P_0 = \text{tip}(\vec{f}(t_0))$, for $t_0 \in I$, such that $\vec{f}'(t_0) \neq \vec{0}$. Then

$$\vec{T}(t_0) = \frac{1}{|\vec{f}'(t_0)|} \vec{f}'(t_0) \quad (.1.12)$$

is called the **unit tangent vector** associated with the parametrization $(\vec{f}(t), I)$. $\vec{T}(t_0)$ always forces the direction in which $\vec{f}(t)$ traces \mathcal{C} . The vector

$$\vec{N}(t_0) = \frac{1}{|\vec{T}'(t_0)|} \vec{T}'(t_0) \quad (.1.13)$$

is perpendicular to $\vec{T}(t_0)$ and is called the **unit principal normal** to \mathcal{C} at P_0 .

Definition .1.12. A curve \mathcal{C} is called **piecewise smooth** if it consists of a finite number of smooth parametric curves $\mathcal{C}_1, \dots, \mathcal{C}_k$, where the endpoint of \mathcal{C}_i is the starting point of \mathcal{C}_{i+1} for $i = 1, 2, \dots, k-1$.

Definition .1.13. Let \mathcal{C} be a bounded continuous curve specified by a parametrization $\vec{f} : [a, b] \rightarrow \mathbb{R}^n$. We consider partitions of $[a, b]$ into n -subintervals by

$$a = t_0 < t_1 < \dots < t_n = b \quad (.1.14)$$

So the points $\vec{f}(t_i)$ subdivide \mathcal{C} , and using the **chord length** $|\vec{f}(t_i) - \vec{f}(t_{i-1})|$ we define the sequence of lengths approximating \mathcal{C} by

$$s_n = \sum_{i=1}^n |\vec{f}(t_i) - \vec{f}(t_{i-1})| \quad (.1.15)$$

We say \mathcal{C} is **rectifiable** if there exists $K \in \mathbb{R}$ such that $s_n \leq K$ for all $n \in \mathbb{N}$ and all choices of points. From the completeness axiom of \mathbb{R} there exists a least such K . This K we define as the **length** of \mathcal{C} and we denote it by s . Let $\Delta t_i = t_i - t_{i-1}$ and $\Delta \vec{f}_i = \vec{f}(t_i) - \vec{f}(t_{i-1})$ so

$$s_n = \sum_{i=1}^n \left| \frac{\Delta \vec{f}_i}{\Delta t_i} \right| \Delta t_i \quad (.1.16)$$

If $\vec{f}(t)$ has a continuous derivative, then

$$s = \lim_{\substack{n \rightarrow \infty \\ \sup \Delta t_i \rightarrow 0}} s_n = \int_a^b \left| \frac{d\vec{f}}{dt} \right| dt \quad (.1.17)$$

is the **arclength**.

Definition .1.14. Let $\vec{f} : [a, b] \rightarrow \mathbb{R}^n$ be a smooth parametrization of a curve \mathcal{C} . Then the **arclength function** of \vec{f} is a function $s : [a, b] \rightarrow \mathbb{R}$ where

$$s(t) := \int_a^t \left| \frac{d\vec{f}}{dt} \right| dt \quad (.1.18)$$

and the arclength element for \mathcal{C} is given by

$$ds := \left| \frac{d}{dt} \vec{f} \right| dt \quad (.1.19)$$

Definition .1.15. If $\vec{f} : J \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ parametrizes a curve \mathcal{C} with the parameter being the arclength along the curve relative to some initial point, then we call this an arclength or intrinsic parametrization. Such a parametrization traces \mathcal{C} at unit speed

$$\left| \frac{d\vec{f}(s)}{ds} \right| = 1 \quad (.1.20)$$

Curvature and the Frenet Frame

The Frenet Frame forms a right handed orthogonal basis at any point along a smooth curve. The curvature measures the rate at which a curve is turning (away from its tangent line) at any point. The Torsion measures the rate at which the curve is twisting (out of the plane in which it is turning) at any point.

Definition .1.16. Let $\gamma : I \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ denote a smooth parametric curve. Then $d\gamma/dt$ gives a tangent vector to the curve at any point, and it points in the direction of the orientation of the curve. We assume that this derivative is nowhere zero so we can define a unit tangent vector, $\hat{T}(t)$, at $\gamma(t)$ by

$$\hat{T}(t) := \frac{d\gamma(t)/dt}{\|d\gamma(t)/dt\|}$$

Note that when the parameterization is in terms of arclength the denominator is 1. If $\gamma(t)$ has a continuous nonvanishing derivative, then $\hat{T}(t)$ is continuous and the angle it makes with any fixed vector is also continuous.

Having unit length the tangent vector field satisfies $\hat{T}(t) \cdot \hat{T}(t) = 1$, so $2\hat{T}(t) \cdot \frac{d\hat{T}(t)}{dt} = 0$. Thus, the derivative of the tangent is orthogonal to the tangent at any point on the curve.

Definition .1.17. The curvature of a smooth curve $\gamma : I \subseteq \mathbb{R} \rightarrow \mathbb{R}^n$ parameterized in terms of arclength is defined to be

$$\kappa(s) = \left| \frac{d\hat{T}(s)}{ds} \right|$$

The radius of curvature, denoted ρ , is the reciprocal of the curvature:

$$\rho(s) = \frac{1}{\kappa(s)}$$

The curvature of γ measures the rate of turning of the tangent line to the curve at any point.

Definition .1.18. If the curvature of a smooth curve γ is nonzero, we define the **unit principal normal** to γ in terms of an arclength parameterization to be

$$\hat{N}(s) = \frac{d\hat{T}(s)/ds}{\|d\hat{T}(s)/ds\|}$$

Note that the principal normal is perpendicular to the curve at any point, and points in the direction that the unit tangent, and consequently the curve, is turning.

Theorem .1.2. Let $\kappa > 0$ on an interval containing s and let $\delta\theta$ be the angle between $\hat{T}(s + \delta s)$ and $\hat{T}(s)$, the unit tangent vectors at neighboring points on the curve. Then

$$\kappa(s) = \lim_{\delta s \rightarrow 0} \left| \frac{\delta s}{\delta s} \right|$$

The plane passing through $\gamma(s)$ and spanned by $\hat{T}(s)$ and $\hat{N}(s)$ is called the **osculating plane** to the curve at $\gamma(s)$.

Assuming $\kappa(s) \neq 0$, let $\gamma_c(s) = \gamma(s) + \rho(s)\hat{N}(s)$. Then $\gamma_c(s)$ is called the **center of curvature** to γ at $\gamma(s)$, and the circle in the osculating plane with center $\gamma_c(s)$ and radius $\rho(s)$ is the best approximation of the curve near $\gamma(s)$, and is called the **osculating circle**.

Definition .1.19. At any point on $\gamma(s)$ where $\hat{T}(s), \hat{N}(s)$ are both defined, we define the **unit binormal** field to be

$$\hat{B}(s) = \hat{T}(s) \times \hat{N}(s)$$

The three vectors $\{\hat{T}(s), \hat{N}(s), \hat{B}(s)\}$ correspond to a right-handed coordinate system, the **Frenet Frame** for γ at any point $\gamma(s)$. Note that

$$\frac{d\hat{B}}{ds} = \hat{T} \times \frac{d\hat{N}}{ds}$$

and as with any unit normal field, \hat{B} 's derivative is orthogonal to itself, so we have that $\frac{d\hat{B}}{ds}$ lies on the line spanned by \hat{N} .

Definition .1.20. On any interval where $\kappa(s) \neq 0$ there exists a function $\tau(s)$ such that

$$\frac{d\hat{B}}{ds} = -\tau(s)\hat{N}(s)$$

The number $\tau(s)$ is called the **torsion** of γ at $\gamma(s)$.

The torsion measures the degree of twisting that the curve exhibits near a point, that is, the extent to which the curve fails to be planar.

Let $\delta\psi$ be the angle between $\hat{B}(s)$ and $\hat{B}(s + \delta s)$. Then

$$|\tau(s)| = \lim_{\delta s \rightarrow 0} \left| \frac{\delta\psi}{\delta s} \right|$$

Proposition .1.3. The Frenet-Serret Formulas for our Frenet Frame are given by

$$\begin{aligned}\frac{d\hat{T}}{ds} &= \kappa(s)\hat{N}(s) \\ \frac{d\hat{N}}{ds} &= -\kappa(s)\hat{T}(s) + \tau(s)\hat{B}(s) \\ \frac{d\hat{B}}{ds} &= -\tau(s)\hat{N}(s)\end{aligned}$$

These can be summarized by the matrix equation

$$\frac{d}{ds} \begin{bmatrix} \hat{T}(s) \\ \hat{N}(s) \\ \hat{B}(s) \end{bmatrix} = \begin{bmatrix} 0 & \kappa(s) & 0 \\ -\kappa(s) & 0 & \tau(s) \\ 0 & -\tau(s) & 0 \end{bmatrix} \begin{bmatrix} \hat{T}(s) \\ \hat{N}(s) \\ \hat{B}(s) \end{bmatrix}$$

Theorem .1.4. Let γ_1 and γ_2 be two curves, both of which have the same nonvanishing curvature function $\kappa(s)$ and the same torsion function $\tau(s)$. Then the curves are congruent. That is, there exists a rigid motion so as to coincide one curve exactly with the other.

Functions of Several Variables

Definition .1.21. A function $f : \mathcal{D}(f) \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$, where $\mathcal{D}(f)$ is the domain of f , is called a scalar field on $\mathcal{D}(f)$. The image of f is

$$\text{Im}(f) := \{x \in \mathbb{R} : \exists \vec{v} \in \mathcal{D}(f), f(\vec{v}) = x\} \quad (.1.21)$$

The natural domain of f is the largest subset of \mathbb{R}^n such that f is well-defined.

Definition .1.22. The graph of a function $f : A \rightarrow B$ is the set

$$\Gamma(f) := \{(x, f(x)) : x \in A\} \quad (.1.22)$$

For

$$f : \prod_{i=1}^n X_i \rightarrow B \quad (.1.23)$$

we have the graph

$$\Gamma(f) := \{((x_1, \dots, x_n), f(x_1, \dots, x_n)) : (x_1, \dots, x_n) \in \prod_{i=1}^n X_i\} \quad (.1.24)$$

Remark .1.10. The graph of a function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ can be considered as a surface in \mathbb{R}^{n+1} by a natural embedding.

Definition .1.23. Given a function $f : \mathbb{R}^n \rightarrow \mathbb{R}$, a k-level surface of f is a set

$$S_k := \{\vec{x} \in \mathbb{R}^n : f(\vec{x}) = k\} \quad (.1.25)$$

where k is a fixed constant.

Definition .1.24. Let $\vec{x}_0 \in \mathbb{R}^n$ and $r > 0$ a real number. Then the open ball of radius r centered at \vec{x}_0 is defined as

$$B_r(\vec{x}_0) := \{\vec{x} \in \mathbb{R}^n : \|\vec{x} - \vec{x}_0\| < r\} \quad (.1.26)$$

the closed ball is defined by

$$\bar{B}_r(\vec{x}_0) := \{\vec{x} \in \mathbb{R}^n : \|\vec{x} - \vec{x}_0\| \leq r\} \quad (.1.27)$$

Definition .1.25. A neighborhood of a point $\vec{x}_0 \in \mathbb{R}^n$ is any set $U \subseteq \mathbb{R}^n$ such that there exists $r > 0$ so that $B_r(\vec{x}_0) \subseteq U$.

Definition .1.26. Let $E \subseteq \mathbb{R}^n$, where we equip \mathbb{R}^n with \mathcal{T}_{st} . We say E is open if $E \in \mathcal{T}_{st}$. Equivalently, E is open if for all $\vec{x} \in E$, E is a neighborhood of \vec{x} . We say E is closed if its complement $E^C = \mathbb{R}^n \setminus E$ is open.

Definition .1.27. A point $\vec{x}_0 \in \mathbb{R}^n$ is called a boundary point of E if for any $r > 0$, $B_r(\vec{x}_0) \cap E \neq \emptyset$ and $B_r(\vec{x}_0) \cap E^C \neq \emptyset$.

Definition .1.28. The set of all boundary points of a set $E \subseteq \mathbb{R}^n$ is called the boundary of E .

Definition .1.29. Let $E \subseteq \mathbb{R}^n$. We say that E is bounded if there exists $R > 0$ such that $\|\vec{x}\| \leq R$ for all $\vec{x} \in E$. E is unbounded if for all $R > 0$ there exists $\vec{x}_0 \in E$ such that $\|\vec{x}_0\| > R$.

Definition .1.30. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a function. We say $\lim_{\vec{x} \rightarrow \vec{x}_0} f(\vec{x}) = L$, provided that

1. Every punctured neighborhood $B_r^*(\vec{x}_0)$ of \vec{x}_0 intersects $\mathcal{D}(f)$

$$B_r^*(\vec{x}_0) \cap \mathcal{D}(f) \neq \emptyset \quad (.1.28)$$

that is, \vec{x}_0 is a limit point of $\mathcal{D}(f)$.

2. For all $\varepsilon > 0$, there exists $\delta > 0$ such that $f(\vec{x}) \in B_\varepsilon(L)$ whenever $\vec{x} \in B_\delta^*(\vec{x}_0) \cap \mathcal{D}(f)$. That is

$$f(\mathcal{D}(f) \cap B_\delta^*(\vec{x}_0)) \subseteq B_\varepsilon(L) \quad (.1.29)$$

Remark .1.11. As \mathbb{R}^n and \mathbb{R} are metric spaces, they are Hausdorff, so if the limit exists it is unique.

Remark .1.12 (Limit Properties). Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ and $g : \mathbb{R}^n \rightarrow \mathbb{R}$ and $\vec{x}_0 \in \mathbb{R}^n$ such that $\lim_{\vec{x} \rightarrow \vec{x}_0} f(\vec{x}) = L$ and $\lim_{\vec{x} \rightarrow \vec{x}_0} g(\vec{x}) = M$. Then if \vec{x}_0 is not an isolated point of $\mathcal{D}(f) \cap \mathcal{D}(g)$, then

1. $\lim_{\vec{x} \rightarrow \vec{x}_0} (f(\vec{x}) \pm g(\vec{x})) = L \pm M$
2. $\lim_{\vec{x} \rightarrow \vec{x}_0} f(\vec{x})g(\vec{x}) = LM$
3. $\lim_{\vec{x} \rightarrow \vec{x}_0} \frac{f(\vec{x})}{g(\vec{x})} = \frac{L}{M}$ if $M \neq 0$
4. If $F : \mathbb{R} \rightarrow X$ is continuous at L , then $\lim_{\vec{x} \rightarrow \vec{x}_0} F(f(\vec{x})) = F(L)$.

Definition .1.31. We say a function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is continuous at a point $\vec{x}_0 \in \mathbb{R}^n$ if

$$\lim_{\vec{x} \rightarrow \vec{x}_0} f(\vec{x}) = f(\vec{x}_0) \quad (.1.30)$$

Remark .1.13. If setting $x = x_0$ and $y = y_0$ in the expression for $f(x, y)$ does not evaluate to a real number, then we can try using polar coordinates: $x = x_0 + r \cos(\theta)$ and $y = y_0 + r \sin(\theta)$. Recall $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$, $0 \leq \theta < 2\pi$. As a result, $(x, y) \rightarrow (x_0, y_0)$ is equivalent to $r \rightarrow 0$, so

$$\lim_{(x,y) \rightarrow (x_0,y_0)} f(x, y) = \lim_{r \rightarrow 0} f(x_0 + r \cos(\theta), y_0 + r \sin(\theta)) \quad (.1.31)$$

Theorem .1.5 (Squeeze Theorem). Let $f(x, y)$, $g(x, y)$ and $h(x, y)$ be defined in a neighborhood U of (x_0, y_0) , except maybe at (x_0, y_0) , and such that

$$g(x, y) \leq f(x, y) \leq h(x, y), \forall (x, y) \in U \setminus \{(x_0, y_0)\} \quad (.1.32)$$

If

$$\lim_{(x,y) \rightarrow (x_0,y_0)} g(x, y) = L, \quad \lim_{(x,y) \rightarrow (x_0,y_0)} h(x, y) = L \quad (.1.33)$$

Then $\lim_{(x,y) \rightarrow (x_0,y_0)} f(x, y) = L$.

Theorem .1.6. If one can find two continuous parametric curves \mathcal{C}_1 and \mathcal{C}_2 that pass through the point (x_0, y_0) such that

$$\lim_{\substack{(x,y) \rightarrow (x_0,y_0) \\ (x,y) \in \mathcal{C}_1}} f(x, y) = L_1, \quad \lim_{\substack{(x,y) \rightarrow (x_0,y_0) \\ (x,y) \in \mathcal{C}_2}} f(x, y) = L_2, \text{ and } L_1 \neq L_2 \quad (.1.34)$$

then $\lim_{(x,y) \rightarrow (x_0,y_0)} f(x, y)$ does not exist.

Definition .1.32. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a function.

1. We say that f is continuous at $\vec{x}_0 \in \mathbb{R}^n$ if

- (a) There exists a neighborhood U of \vec{x}_0 such that $f(U)$ is defined
- (b) $\lim_{\vec{x} \rightarrow \vec{x}_0} f(\vec{x}) = f(\vec{x}_0)$

2. We say that f is continuous on a region D if it is continuous at every point \vec{x} in the region.

Remark .1.14 (Constructing Continuous Functions). Let $f, g : \mathbb{R}^n \rightarrow \mathbb{R}$ be continuous at $\vec{x}_0 \in \mathbb{R}^n$, and if $\lambda \in \mathbb{R}$, then

- 1. $f \pm g$, $f \cdot g$, and λf are continuous at \vec{x}_0
- 2. f/g is continuous at \vec{x}_0 provided $g(\vec{x}_0) \neq 0$.

Suppose $u(t)$ is continuous at $t_0 = f(\vec{x}_0)$. Then $u(f(\vec{x}))$ is continuous at \vec{x}_0 .

Theorem 40 (Extreme Value Theorem).

If $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is continuous on a closed and bounded region $D \subseteq \mathbb{R}^n$, then there exist $\vec{x}_m, \vec{x}_M \in D$ such that

$$f(\vec{x}_m) \leq f(\vec{x}) \leq f(\vec{x}_M), \forall \vec{x} \in D \quad (.1.35)$$

$m = f(\vec{x}_m)$ is called the absolute minimum of f on D , while $M = f(\vec{x}_M)$ is called the absolute maximum of f on D .

Partial Derivatives

Definition .1.33. The first partial derivatives of a function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ with respect to the variable x_i , $1 \leq i \leq n$, is the function

$$f_i(x_1, \dots, x_n) = \lim_{h \rightarrow 0} \frac{f(x_1, \dots, x_i + h, \dots, x_n) - f(x_1, \dots, x_i, \dots, x_n)}{h} \quad (.1.36)$$

provided the limit exists and f is defined in a neighborhood of (x_1, \dots, x_n) .

Notation .1.15. We often write

$$\frac{\partial}{\partial x_i} f(x_1, \dots, x_n) = f_i(x_1, \dots, x_n) = D_i f(x_1, \dots, x_n) \quad (.1.37)$$

and

$$\left(\frac{\partial}{\partial x_i} f(\vec{x}) \right) \Big|_{\vec{x}_0} = f_i(\vec{x}_0) = D_i f(\vec{x}_0) \quad (.1.38)$$

Remark .1.16. If a function $f : J \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ has first partial derivatives at \vec{x}_0 in a region $D \subseteq \mathbb{R}^n$, then this defines n new functions

$$\frac{\partial f}{\partial x_i} \Big| : \mathbb{R} \rightarrow \mathbb{R} \quad (.1.39)$$

where we differentiate f with respect to x_i .

Definition .1.34. Given a function $f : \mathbb{R}^n \rightarrow \mathbb{R}$, the gradient of f is the vector function

$$\nabla f = \text{grad}(f) : \mathbb{R}^n \rightarrow \mathbb{R}^n \quad (.1.40)$$

such that

$$\nabla f(x_1, \dots, x_n) = \left\langle \frac{\partial}{\partial x_1} f, \dots, \frac{\partial}{\partial x_n} f \right\rangle \quad (.1.41)$$

where ∇ is the del operator

$$\nabla = \left[\frac{\partial}{\partial x_1}, \dots, \frac{\partial}{\partial x_n} \right]^T \quad (.1.42)$$

Definition .1.35. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be defined in a neighborhood of a point \vec{x}_0 such that its first partial derivatives exist at \vec{x}_0 . Then by definition, the linear approximation of f at \vec{x}_0 is the polynomial of degree 1, $L(\vec{x})$, that matches f at \vec{x}_0 and matches its partials at \vec{x}_0 . In particular, we have that

$$L(\vec{x}, \vec{x}_0) = f(\vec{x}_0) + \sum_{i=1}^n \frac{\partial}{\partial x_i} f(\vec{x}_0)(x_i - x_{i,0}) \quad (.1.43)$$

Definition .1.36. Let $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ be a function defined around $\vec{x}_0 \in \mathbb{R}^n$ with first partials also defined. Let $L(\vec{x})$ be its linear approximation at \vec{x}_0 . We say that f is differentiable at \vec{x}_0 if the limit

$$\lim_{\vec{x} \rightarrow \vec{x}_0} \frac{f(\vec{x}) - L(\vec{x})}{\|\vec{x} - \vec{x}_0\|} = 0 \quad (.1.44)$$

Definition .1.37. Let $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a multivariate function defined in a neighborhood of $\vec{x}_0 \in \mathbb{R}^n$ with first partial derivatives also defined. Then the Jacobian matrix of f is defined to be

$$Df(\vec{x}) = \begin{bmatrix} \partial_1 f_1(\vec{x}) & \partial_2 f_1(\vec{x}) & \dots & \partial_n f_1(\vec{x}) \\ \partial_1 f_2(\vec{x}) & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \partial_1 f_m(\vec{x}) & \dots & \dots & \partial_n f_m(\vec{x}) \end{bmatrix} \quad (.1.45)$$

Then we say that f is differentiable at \vec{x}_0 if

$$\lim_{\vec{x} \rightarrow \vec{x}_0} \frac{\|f(\vec{x}) - f(\vec{x}_0) - Df(\vec{x} - \vec{x}_0)\|}{\|\vec{x} - \vec{x}_0\|} = 0 \quad (.1.46)$$

If all the first partial derivatives of f are continuous in a neighborhood of \vec{x}_0 then this holds.

Remark .1.17 (Properties). For $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$:

1. If f is differentiable at \vec{x}_0 , then f is continuous at \vec{x}_0
2. If f and g are differentiable at \vec{x}_0 , then $f \pm g, kf, fg$ ($m = 1$) are differentiable at \vec{x}_0 .
3. If the partials of f are continuous in a neighborhood of \vec{x}_0 , then f is differentiable at \vec{x}_0 . The converse is not true in general.

Definition .1.38. Consider $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$, we have

$$\partial_i f(\vec{x}_0) = \lim_{t \rightarrow 0} \frac{f(\vec{x}_0 + t\hat{e}_i) - f(\vec{x}_0)}{t} \quad (.1.47)$$

so we can generalize this to define the directional derivative in the direction of \hat{u} :

$$\partial_{\hat{u}} f(\vec{x}_0) = \lim_{t \rightarrow 0} \frac{f(\vec{x}_0 + t\hat{u}) - f(\vec{x}_0)}{t} \quad (.1.48)$$

Theorem .1.7. If $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ is differentiable at \vec{x}_0 , then the directional derivative of f at \vec{x}_0 exists in the direction of \hat{u} , and is equal to

$$\partial_{\hat{u}} f(\vec{x}_0) = \nabla f(\vec{x}_0) \cdot \hat{u} \quad (.1.49)$$

Theorem .1.8. Notice if $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ is differentiable at \vec{x}_0 , and \hat{u} is a unit vector, we have that

$$\partial_{\hat{u}} f(\vec{x}_0) = \nabla f(\vec{x}_0) \cdot \hat{u} = |\nabla f(\vec{x}_0)| \cos(\theta) \quad (.1.50)$$

with θ being the angle between $\nabla f(\vec{x}_0)$ and \hat{u} . As a result:

1. The largest value of $\partial_{\hat{u}}f(\vec{x}_0)$ is equal to $|\nabla f(\vec{x}_0)|$, and occurs when \hat{u} is in the same direction as the gradient
2. The smallest value of $\partial_{\hat{u}}f(\vec{x}_0)$ is equal to $-|\nabla f(\vec{x}_0)|$ when \hat{u} is in the same direction as $-\nabla f(\vec{x}_0)$
3. When \hat{u} is perpendicular to $\nabla f(\vec{x}_0)$, the directional derivative is zero.

Theorem .1.9 (Chain Rule V1). Let $f : D_f \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ and $g : D_g \subseteq \mathbb{R} \rightarrow \mathbb{R}$ such that $g(t) = f(\vec{x}(t))$. Then

$$\frac{dg}{dt} = \nabla f(\vec{x}) \cdot \frac{d}{dt}\langle x_1, \dots, x_n \rangle = \sum_{i=1}^n \partial_i f \frac{dx_i}{dt} \quad (.1.51)$$

Theorem .1.10 (Chain Rule V2). Let $f : D_f \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ and $g : D_g \subseteq \mathbb{R}^m \rightarrow \mathbb{R}$ such that $g(\vec{x}) = f(y_1(\vec{x}), \dots, y_n(\vec{x}))$. Then

$$\partial_i g(\vec{x}) = \nabla f(y_1(\vec{x}), \dots, y_n(\vec{x})) \cdot \frac{\partial}{\partial x_i} \vec{y} \quad (.1.52)$$

for $\vec{y} = \langle y_1, \dots, y_n \rangle$.

Theorem .1.11 (Clairout's Theorem). Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ has continous first and second partials on an open ball B_r . Then $f_{ij}(\vec{x}) = f_{ji}(\vec{x})$ for all $\vec{x} \in D$.

Implicit Differentiation

Theorem .1.12 (Implicit Function Theorem (Two variables)). Consider $F(x, y) = 0$. Let $(x_0, y_0) \in \mathbb{R}^2$ such that $F(x_0, y_0) = 0$, and suppose F 's first partials are continuous in a neighborhood of (x_0, y_0) . Then

1. If $F_y(x_0, y_0) \neq 0$, then $F(x, y) = 0$ uniquely defines y as a continuously differentiable function of x in a neighborhood of x_0 , and we have that

$$\frac{dy}{dx} = -\frac{\partial_x F(x, y)}{\partial_y F(x, y)} \quad (.1.53)$$

2. Similarly for $F_x(x_0, y_0) \neq 0$.

Theorem .1.13 (Implicit Function Theorem (n variables)). Consider $F(\vec{x}) = 0(\star)$, $\vec{x} = (x_1, \dots, x_n)$. Let \vec{a} satisfy $F(\vec{a}) = 0$, and suppose $F(\vec{x})$ has continuous first partial derivatives at and in a neighborhood of \vec{a} . Let β be one of the variables $\{x_1, \dots, x_n\}$, and let \vec{a} be the rest. If $\partial_\beta F(\vec{a}) \neq 0$, then the equation (\star) uniquely defines the variable β as a continuously differentiable function of \vec{a} , and for $x_j \neq \beta$, we have

$$\partial_{x_j} \beta(\vec{a}) = -\frac{\partial_{x_j} F(\vec{a})}{\partial_\beta F(\vec{a})} \quad (.1.54)$$

Theorem 41 (Implicit Function Theorem (General)).

Consider a system of n equations in $n + m$ variables

$$\begin{cases} F_{(1)}(x_1, \dots, x_m, y_1, \dots, y_n) = 0 \\ \vdots \\ F_{(n)}(x_1, \dots, x_m, y_1, \dots, y_n) = 0 \end{cases} \quad (.1.55)$$

and a point P_0 which satisfies the system. Suppose each $F_{(i)}$ is differentiable near P_0 , so they have continuous first partial derivatives. Finally, suppose

$$\frac{\partial(F_{(1)}, \dots, F_{(n)})}{\partial(y_1, \dots, y_n)} \Big|_{P_0} \neq 0 \quad (.1.56)$$

Then the system defines y_1, \dots, y_n uniquely as continuously differentiable functions of x_1, \dots, x_m in some neighborhood of P_0 . Moreover,

$$\partial_{x_j} y_i = - \frac{\frac{\partial(F_{(1)}, \dots, F_{(n)})}{\partial(y_1, \dots, x_j, \dots, y_n)}}{\frac{\partial(F_{(1)}, \dots, F_{(n)})}{\partial(y_1, \dots, y_i, \dots, y_n)}} \quad (.1.57)$$

This formula is a consequence of Cramer's Rule applied to the n linear equations in n unknowns which is the system differentiated with respect to x_j .

Differentials

Definition .1.39. Let $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ be a function defined at and around a point \vec{d} . Given $\Delta\vec{x}$, of small magnitude,

$$\Delta f_{\vec{d}}(\Delta\vec{x}) = f(\vec{d} + \Delta\vec{x}) - f(\vec{d}) \quad (.1.58)$$

represents the change in the value of the function associated with the change $\Delta\vec{x}$ in \vec{x} at \vec{d} . Then, we approximate this change with the differential at \vec{d} defined by

$$df_{\vec{d}}(\Delta\vec{x}) = \nabla f(\vec{d}) \cdot \Delta\vec{x} \quad (.1.59)$$

If $\Delta\vec{x}$ is sufficiently small, these changes are approximately equal.

Taylor Polynomials

Theorem 42 (Taylor's Theorem (One Variable)).

Let $f(x)$ be a function with $n + 1$ continuous derivatives in the open interval (a, b) . Let

$$T_n(x) := \sum_{i=0}^n \frac{f^{(i)}(c)(x - c)^i}{i!} \quad (.1.60)$$

be the **degree n Taylor polynomial** of $f(x)$ centered at $x = c \in (a, b)$. Then, for any $x \in (a, b)$, there exists a number θ between c and x such that

$$f(x) = T_n(x) + \frac{f^{(n+1)}(\theta)}{(n+1)!} (x - c)^{n+1} \quad (.1.61)$$

Definition .1.40 (Two Variable Taylor Polynomial). Let $f(x, y)$ be a smooth function (continuous partial derivatives up to whatever degree needed) in a open set $D \subset \mathbb{R}^2$. The **degree n Taylor polynomial** of $f(x, y)$ at a point $(a, b) \in D$, is the polynomial $T_n(x, y)$ of degree n that equals $f(x, y)$ and its first n partial derivatives at (a, b) . It can be written as

$$T_n(x, y) := \sum_{i=0}^n \frac{[(x-a)\partial_x + (y-b)\partial_y]^{(i)} f(a, b)}{i!} \quad (.1.62)$$

where $[(x-a)\partial_x + (y-b)\partial_y]^{(i)}$ is to be expanded as an algebraic expression and the products of ∂_x and ∂_y correspond to composition of operators.

Theorem 43 (Taylor's Theorem (Two variables)).

Let $f(x, y)$ be a function with continuous partial derivatives up to $(n+1)$ in some neighborhood D of $(a, b) \in \mathbb{R}^2$. Let $T_n(x, y)$ be the degree n Taylor polynomial of $f(x, y)$ at (a, b) . Then for any $(x, y) \in D$, there exists $(\alpha, \beta) \in D$ such that

$$f(x, y) = T_n(x, y) + \frac{[(x-a)\partial_x + (y-b)\partial_y]^{(n+1)} f(\alpha, \beta)}{(n+1)!} \quad (.1.63)$$

This is called the **Taylor formula/expansion of order n** of f at (a, b) .

$$R_n(x, y) := \frac{[(x-a)\partial_x + (y-b)\partial_y]^{(n+1)} f(\alpha, \beta)}{(n+1)!} = f(x, y) - T_n(x, y) \quad (.1.64)$$

is called the **remainder** of the expansion.

Remark .1.18. If all partial derivatives of order $(n+1)$ are bounded by some constant $M > 0$, then

$$|f(x, y) - T_n(x, y)| \leq \frac{M}{(n+1)!} \left[\sum_{j=0}^{n+1} \binom{n+1}{j} |x-a|^{n+1-j} |y-b|^j \right] \quad (.1.65)$$

Theorem 44 (Taylor's Theorem (General)).

Let $f : D \subset \mathbb{R}^n \rightarrow \mathbb{R}$ be a function with continuous partial derivatives of order up to $m+1$ in a neighborhood D of $\vec{d} \in \mathbb{R}^n$. Then for all $\vec{x} \in D$ there exists $\vec{\theta} \in D$ such that

$$f(\vec{x}) = T_m(\vec{x}) + R_m(\vec{x}, \vec{\theta}) \quad (.1.66)$$

where

$$T_m(\vec{x}) := \sum_{k=0}^m \frac{[(\vec{x}-\vec{d}) \cdot \nabla]^{(k)} f(\vec{d})}{k!} \quad (.1.67)$$

is the degree m Taylor polynomial of f at \vec{d} , and

$$R_m(\vec{x}, \vec{\theta}) := \frac{[(\vec{x}-\vec{d}) \cdot \nabla]^{(m+1)} f(\vec{\theta})}{(m+1)!} \quad (.1.68)$$

is the remainder. If all partial derivatives of f are continuous and there exists $r \in \mathbb{R}^+$ such that whenever $\|\vec{x} - \vec{d}\| < r$ we have for all $t \in [0, 1]$

$$\lim_{m \rightarrow \infty} R_m(\vec{x}, \vec{d} + t(\vec{x} - \vec{d})) = 0 \quad (.1.69)$$

Then we can represent $f(\vec{x})$ as the **Taylor series**

$$f(\vec{x}) = \sum_{n=0}^{\infty} \frac{[(\vec{x} - \vec{a}) \cdot \nabla]^n f(\vec{a})}{n!} \quad (.1.70)$$

Local Extrema of Multivariate Functions

Definition .1.41. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a function of n variables defined in a neighborhood of $\vec{x}_0 \in \mathbb{R}^n$:

1. We say f has a **local maximum** at \vec{x}_0 if there exists a neighborhood D of \vec{x}_0 for which f is defined and

$$f(\vec{x}) \leq f(\vec{x}_0), \forall \vec{x} \in D \quad (.1.71)$$

2. We say f has a **local minimum** at \vec{x}_0 if there exists a neighborhood D of \vec{x}_0 for which f is defined and

$$f(\vec{x}) \geq f(\vec{x}_0), \forall \vec{x} \in D \quad (.1.72)$$

↳ If f has a local maximum or minimum at \vec{x}_0 , we say f has a **local extremum** at \vec{x}_0 .

Theorem .1.14 (Fermat). If $f : \mathbb{R}^n \rightarrow \mathbb{R}$ has a local extremum at \vec{x}_0 , then one of the following must hold:

1. $\nabla f(\vec{x}_0) = \vec{0}$ when all first partials of f exist at \vec{x}_0
2. At least one of the first partials of f are not defined at \vec{x}_0

Definition .1.42. Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is defined in a neighborhood of \vec{x}_0 . If one of the conditions of Fermat's Theorem is satisfied by \vec{x}_0 , we say \vec{x}_0 is a **critical point** of f .

Remark .1.19. To determine if f has a local max or min at a critical point \vec{x}_0 , study the sign of

$$f(\vec{x}_0 + \vec{h}) - f(\vec{x}_0) \quad (.1.73)$$

for small $|\vec{h}|$. If it is always positive, f has a local minimum, if it is always negative f has a local maximum, and if it changes sign, f does not have a local extremum and in this case we say f has a **saddle point** at \vec{x}_0 .

Theorem 45 (Second Derivative Test).

Suppose $f(x, y)$ has continuous second partial derivatives in a neighborhood of a critical point (x_0, y_0) . Define the **Hessian** matrix of f at (x_0, y_0) to be

$$H_f(x_0, y_0) := \begin{bmatrix} f_{xx}(x_0, y_0) & f_{xy}(x_0, y_0) \\ f_{yx}(x_0, y_0) & f_{yy}(x_0, y_0) \end{bmatrix} \quad (.1.74)$$

Let $\delta_1 = f_{xx}(x_0, y_0)$ and $\delta_2 = \det(H_f(x_0, y_0))$. Then

1. If $\delta_1 > 0$ and $\delta_2 > 0$, then f has a local minimum at (x_0, y_0)
2. If $\delta_1 < 0$ and $\delta_2 > 0$, then f has a local maximum at (x_0, y_0)
3. If $\delta_2 \neq 0$ but neither case 1 nor case 2 hold, then f has a saddle point at (x_0, y_0) .
4. If $\delta_2 = 0$ the test is inconclusive.

Theorem 46 (Second Derivative Test (general)).

Suppose $f : D \subset \mathbb{R}^n \rightarrow \mathbb{R}$ has continuous second partial derivatives in a neighborhood of a critical point $\vec{x}_0 \in D$. Define the Hessian matrix of f at \vec{x}_0 to be

$$H_f(\vec{x}_0) := \begin{bmatrix} f_{11}(\vec{x}_0) & f_{12}(\vec{x}_0) & \dots & f_{1n}(\vec{x}_0) \\ f_{21}(\vec{x}_0) & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ f_{n1}(\vec{x}_0) & \dots & \dots & f_{nn}(\vec{x}_0) \end{bmatrix} \quad (.1.75)$$

Denote the k th principal minor of $H_f(\vec{x}_0)$ by

$$\delta_k := \begin{vmatrix} f_{11}(\vec{x}_0) & f_{12}(\vec{x}_0) & \dots & f_{1k}(\vec{x}_0) \\ f_{21}(\vec{x}_0) & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ f_{k1}(\vec{x}_0) & \dots & \dots & f_{kk}(\vec{x}_0) \end{vmatrix} \quad (.1.76)$$

. Then

1. If for all $i \in \{1, 2, \dots, n\}$, $\delta_i > 0$, then f has a local minimum at \vec{x}_0
2. If for all $i \in \{1, 2, \dots, n\}$, $\delta_{2i-1} < 0$ and $\delta_{2i} > 0$, then f has a local maximum at \vec{x}_0
3. If $\delta_n = \det(H_f(\vec{x}_0)) \neq 0$ but neither case 1 nor case 2 hold, then f has a saddle point at \vec{x}_0 .
4. If $\delta_n = \det(H_f(\vec{x}_0)) = 0$ the test is inconclusive.

Vector Fields

Definition .1.43. A vector field is a vector function $\vec{F} : D \subset \mathbb{R}^n \rightarrow \mathbb{R}^n$. In the case of three variables we write

$$\vec{F}(x, y, z) = \langle P(x, y, z), Q(x, y, z), R(x, y, z) \rangle \quad (.1.77)$$

Remark .1.20. A vector field $\vec{F} : D \subset \mathbb{R}^n \rightarrow \mathbb{R}^n$ is said to be of class C^k for $k \in \mathbb{Z}^+$ in D if the first k partial derivatives of the component functions of \vec{F} are continuous in D .

Definition .1.44 (Conservative Fields). A vector field $\vec{F} : D \subset \mathbb{R}^n \rightarrow \mathbb{R}^n$ is called conservative in a region $E \subseteq D$ if there exists a scalar function $f : D_f \subset \mathbb{R}^n \rightarrow \mathbb{R}$ such that

$$\vec{F}(\vec{x}) = \nabla f(\vec{x}), \forall \vec{x} \in E \quad (.1.78)$$

where f is called a potential function of the vector field \vec{F} .

Definition .1.45. Let $\vec{F} : D \subset \mathbb{R}^n \rightarrow \mathbb{R}^n$ be a differentiable vector field. The **divergence** of \vec{F} is the scalar field

$$\nabla \cdot \vec{F} = \sum_{i=1}^n \partial_i F_i \quad (.1.79)$$

where F_i are the component function of \vec{F} .

Definition .1.46. Let $\vec{F} : D \subset \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be a differentiable vector field. The **curl** of \vec{F} is the vector field

$$\nabla \times \vec{F} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial_x & \partial_y & \partial_z \\ P & Q & R \end{vmatrix} \quad (.1.80)$$

where F_i are the component function of \vec{F} .

Proposition .1.15 (Properties of Divergence). If $\vec{F} : D \subset \mathbb{R}^n \rightarrow \mathbb{R}^n$ and $\vec{G} : D \subset \mathbb{R}^n \rightarrow \mathbb{R}^n$ vector fields and $f : D \subset \mathbb{R}^n \rightarrow \mathbb{R}$ is a scalar field, and $C_1, C_2 \in \mathbb{R}$, then

1. (Linearity) $\nabla \cdot (C_1 \vec{F} + C_2 \vec{G}) = C_1 \nabla \cdot \vec{F} + C_2 \nabla \cdot \vec{G}$
2. (Product rule) $\nabla \cdot (f \vec{F}) = \nabla f \cdot \vec{F} + f \nabla \cdot \vec{F}$
3. (Laplacian) $\Delta f = \nabla \cdot \nabla f = \partial_{xx}^2 f + \partial_{yy}^2 f + \partial_{zz}^2 f$

Proposition .1.16 (Properties of Divergence). If $\vec{F} : D \subset \mathbb{R}^3 \rightarrow \mathbb{R}^3$ and $\vec{G} : D \subset \mathbb{R}^3 \rightarrow \mathbb{R}^3$ vector fields and $f : D \subset \mathbb{R}^3 \rightarrow \mathbb{R}$ is a scalar field, that are all defined and differentiable in D . Let $C_1, C_2 \in \mathbb{R}$, then

1. (Linearity) $\nabla \times (C_1 \vec{F} + C_2 \vec{G}) = C_1 \nabla \times \vec{F} + C_2 \nabla \times \vec{G}$
2. (Product rule) $\nabla \times (f \vec{F}) = \nabla f \times \vec{F} + f(\nabla \times \vec{F})$
3. (Conservative Property) $\nabla \times (\nabla f) = 0$
4. $\nabla \times (\nabla \times \vec{F}) = \nabla(\nabla \cdot \vec{F}) - (\nabla \cdot \nabla) \vec{F}$ (provided \vec{F} has continuous second partial derivatives, and where $(\nabla \cdot \nabla) \vec{F} = (\Delta P, \Delta Q, \Delta R)$)

Definition .1.47. Let $E \subseteq \mathbb{R}^n$

1. We say that E is **path connected** if for any two points A and B in E if there exists a continuous function $f : [0, 1] \rightarrow E$ such that $f(0) = A$ and $f(1) = B$.
2. We say E is **simply connected** if E is path connected and any simple closed curve C that completely lies in E can be continuously deformed into a single point without leaving E .

Theorem .1.17. Let \vec{F} be a class C^1 in an open region $E \subseteq \mathbb{R}^3$. If \vec{F} is conservative in E , then $\nabla \times \vec{F} = \vec{0}$ at every point of E . Moreover, if $\nabla \times \vec{F} = \vec{0}$ at every point of E and E is simply connected, then \vec{F} is conservative in E .

Line Integrals

Definition .1.48. Let C be a bounded continuous parametric curve in \mathbb{R}^n . Recall that C is a smooth curve if it has a parameterization $\vec{r} : I \subset \mathbb{R} \rightarrow \mathbb{R}^n$ such that $\frac{d\vec{r}}{dt}$ is continuous and nonzero in I . We say C is a smooth arc if it is a smooth curve with finite parameter interval $I = [a, b]$.

Definition .1.49. Given a smooth curve C with parameterization $\vec{r} : [a, b] \rightarrow \mathbb{R}^n$ we have

$$l_C = \int_C ds = \int_a^b \left| \frac{d\vec{r}}{dt} \right| dt \quad (.1.81)$$

In general, for a scalar field $f : \mathbb{R}^n \rightarrow \mathbb{R}$, we define the line integral along C to be

$$\int_C f(\vec{x}) ds = \int_a^b f(\vec{r}(t)) \left| \frac{d\vec{r}}{dt} \right| dt \quad (.1.82)$$

This definition is parameterization independent.

Definition .1.50. If \vec{F} is a continuous vector field and C is an oriented smooth curve, then the line integral of the tangential component of \vec{F} along C is

$$\int_C \vec{F} \cdot d\vec{r} = \int_C \vec{F} \cdot \hat{T} ds \quad (.1.83)$$

Definition .1.51. If C is a closed curve we also call this line integral the circulation of \vec{F} around C , and we denote it by

$$\oint_C \vec{F} \cdot d\vec{r} \quad (.1.84)$$

Remark .1.21. A line integral over a piecewise smooth path is the sum of the line integrals over the individual smooth arcs

$$\int_{\bigcup_{i=1}^n C_i} ds = \sum_{i=1}^n \int_{C_i} ds \quad (.1.85)$$

Line Integral Theorems

Theorem 47 (Fundamental Theorem of Line Integrals).

Let C be a piecewise smooth parametric curve with initial point A and terminal point B . If $f : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ is a scalar function with continuous first partial derivatives in an open region containing C , then

$$\int_C \nabla f \cdot d\vec{r} = f(B) - f(A) \quad (.1.86)$$

Corollary .1.18. If C is a piecewise smooth closed curve contained in a region D where the vector field $\vec{F} : D \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^n$ is conservative, then

$$\oint_C \vec{F} \cdot d\vec{r} = 0 \quad (.1.87)$$

Definition .1.52. A vector field \vec{F} is said to be **path-independent** in a region Ω if for every pair of points A and B in Ω and every pair of piecewise smooth curves C_1 and C_2 with initial point A and terminal point B , we have

$$\int_{C_1} \vec{F} \cdot d\vec{r} = \int_{C_2} \vec{F} \cdot d\vec{r} \quad (.1.88)$$

Theorem .1.19. Let D be an open connected domain in \mathbb{R}^n and let \vec{F} be a smooth vector field defined on D . Then the following properties are equivalent:

1. \vec{F} is conservative in D
2. $\oint_C \vec{F} \cdot d\vec{r} = 0$ for every piecewise smooth closed curve $C \subset D$
3. \vec{F} is path independent in D .

Theorem 48 (Green's Theorem).

Let R be a closed region in the xy -plane whose boundary ∂R consists of a finite number of piecewise smooth simple closed curves that are positively oriented with respect to R . If \vec{F} is a smooth vector field on R , then

$$\oint_{\partial R} \vec{F} \cdot d\vec{r} = \iint_R (\nabla \times \vec{F}) \cdot \hat{k} dA \quad (.1.89)$$

In particular \hat{k} is the unit normal field specifying the orientation of R , and ∂R is oriented such that its principal normal field \vec{N} points away from the region and

$$\hat{N} = \hat{T} \times \hat{k} \quad (.1.90)$$

Remark .1.22. You don't need anything past this point yet.

Theorem 49 (Plane Divergence Theorem).

Let R be a closed region in the xy -plane whose boundary ∂R consists of a finite number of piecewise smooth simple closed curves. Let \vec{N} denote the unit outward (from R) normal field on C . If \vec{F} is a smooth vector field on R , then

$$\oint_{\partial R} \vec{F} \cdot \hat{N} ds = \iint_R \nabla \cdot \vec{F} dA \quad (.1.91)$$

Theorem 50 (Stoke's Theorem).

Let S be a piecewise smooth oriented surface in 3-space having a unit normal field \hat{N} and

boundary C consisting of a finite number of piecewise smooth closed curves with orientation inherited from S . If \vec{F} is a smooth vector field defined on an open set containing S , then

$$\oint_C \vec{F} \cdot d\vec{r} = \int \int_S (\nabla \times \vec{F}) \cdot \hat{N} dS \quad (.1.92)$$

Surface Integrals

Definition .1.53. A parametric surface in 3-space is a continuous function $\vec{r} : R \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^3$ for some rectangle R

$$R = \{(u, v) \in \mathbb{R}^2 : a \leq u \leq b, c \leq v \leq d\} \quad (.1.93)$$

in the uv -plane having values in 3-space:

$$\vec{r}(u, v) = \langle x(u, v), y(u, v), z(u, v) \rangle, (u, v) \in R \quad (.1.94)$$

Remark .1.23. If \vec{r} is one-to-one the surface does not intersect itself. In this case \vec{r} maps the boundary of R onto a curve in 3-space called the boundary of the parametric surface. A surface with no boundary is called a closed surface.

Definition .1.54. If a finite number of parametric surfaces are joined pairwise along their boundaries one obtains a composite surface, or just a surface thinking geometrically.

Definition .1.55. A set $S \subseteq \mathbb{R}^3$ is a smooth surface if any point $P \in S$ has a neighborhood N that is the domain of a smooth function $g : N \rightarrow \mathbb{R}$ satisfying

1. $N \cap S = \{Q \in N : g(Q) = 0\}$
2. $\nabla g(Q) \neq \vec{0}$ if $Q \in N \cap S$

Remark .1.24. This means the surface has a unique tangent plane at any non-boundary point P .

Definition .1.56. If $\vec{r} : D \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is a parameterization of a smooth surface S , the normal vector to S at $\vec{r}(u, v)$ is

$$\vec{n} = \frac{\partial \vec{r}}{\partial u} \times \frac{\partial \vec{r}}{\partial v} \quad (.1.95)$$

Definition .1.57. The area element at $\vec{r}(u, v)$ on S is given by

$$dS = \left| \frac{\partial \vec{r}}{\partial u} \times \frac{\partial \vec{r}}{\partial v} \right| du dv \quad (.1.96)$$

Then if $f(\vec{r})$ is continuous on S and the domain of \vec{r} is D in the uv -plane

$$\int \int_S f dS = \int \int_D f(\vec{r}(u, v)) \left| \frac{\partial \vec{r}}{\partial u} \times \frac{\partial \vec{r}}{\partial v} \right| du dv \quad (.1.97)$$

Definition .1.58. A smooth surface S in 3-space is said to be **orientable** if there exists a unit vector field \hat{N} defined on S that varies **continuously** over S , and is everywhere normal to S . Any such vector field \hat{N} induces an orientation on S . The side of S out of which \hat{N} points is the **positive side**, and the other side is the **negative side**. An **oriented surface** is a smooth surface with a particular choice of orienting unit normal vector field \hat{N} .

Remark .1.25. An oriented surface S **induces an orientation** on any of its boundary curves C ; if we stand on the positive side of the surface S and walk around C in the direction of its orientation, then S will be on our left side.

Definition .1.59. Given any continuous vector field \vec{F} , the **flux** of \vec{F} across the orientable surface S is the surface integral of the normal component of \vec{F} over S

$$\iint_S \vec{F} \cdot \hat{N} dS = \iint_S \vec{F} \cdot d\vec{S} \quad (.1.98)$$

and when the surface is closed we write

$$\oiint_S \vec{F} \cdot \hat{N} dS = \oiint_S \vec{F} \cdot d\vec{S} \quad (.1.99)$$

Remark .1.26. If $\vec{r}(u, v)$ parametrizes S with domain D , we have normal

$$\vec{n} = \frac{\partial \vec{r}}{\partial u} \times \frac{\partial \vec{r}}{\partial v} \quad (.1.100)$$

and $dS = |\vec{n}| du dv$. Hence

$$d\vec{S} = \hat{N} dS = \pm \frac{\vec{n}}{|\vec{n}|} |\vec{n}| du dv = \pm \vec{n} du dv \quad (.1.101)$$

where the sign reflects the orientation of the surface and parameterization.

Theorem 51 (Divergence Theorem).

Let D be a three dimensional domain bounded by piecewise smooth closed surfaces. Suppose its boundary S is an oriented closed surface with unit normal field \hat{N} pointing out of D . If \vec{F} is a smooth vector field defined on D , then

$$\oiint_S \vec{F} \cdot \hat{N} dS = \iiint_D \nabla \cdot \vec{F} dV \quad (.1.102)$$