

# Topology

Alec Zabel-Mena

June 29, 2022



# Chapter 1

## Topological Spaces and Continuous Functions.

### 1.1 Topological Spaces.

**Definition.** A **topology** on a set  $X$  is a collection  $\mathcal{T}$  of subsets of  $X$  such that:

- (1)  $\emptyset \in \mathcal{T}$  and  $X \in \mathcal{T}$
- (2) For any collection  $\{U_\alpha\}$  of subsets of  $X$ ,  $\bigcup_\alpha U_\alpha \in \mathcal{T}$ .
- (3) For any finite collection  $\{U_i\}_{i=1}^n$  of subsets of  $X$ ,  $\bigcap_{i=1}^n U_i \in \mathcal{T}$ .

We call the pair  $(X, \mathcal{T})$  a **topological space**, and we call the elements of  $\mathcal{T}$  **open sets**.

**Example 1.1.** (1) Let  $X$  be any set, the collection of all subsets of  $X$ ,  $2^X$  is a topology on  $X$ , which we call the **discrete topology**. We call the topology  $\mathcal{T} = \{\emptyset, X\}$  the **indiscrete topology**.

- (2) The set of three points  $\{a, b, c\}$  has the 9 following topologies in figure 1.1.

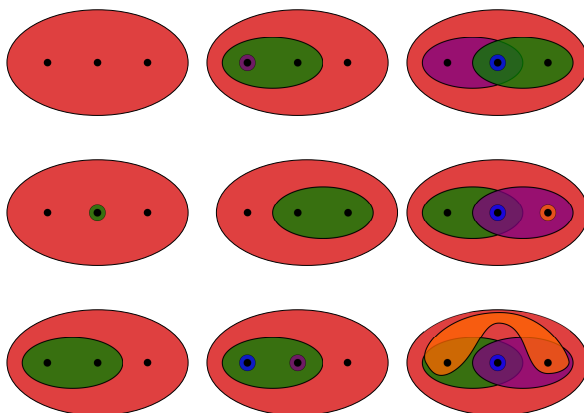


Figure 1.1: The Topologies on  $\{a, b, c\}$ .

- (3) Let  $X$  be any set, and let  $\mathcal{T}_f = \{U \subseteq X : X \setminus U \text{ is finite, or } X \setminus U = X\}$ . Then  $\mathcal{T}_f$  is a topology and called the **finite complement topology**.
- (4) Let  $X$  be any set, and let  $\mathcal{T}_c = \{U \subseteq X : X \setminus U \text{ is countable, or } X \setminus U = X\}$ . Then  $\mathcal{T}_c$  is a topology on  $X$  called the **countable complement topology**.
- (5) Let  $X$  be any set and consider the collection  $\mathcal{T}_\infty = \{U \subseteq X : X \setminus U = \emptyset, X \setminus U = X, \text{ or } X \setminus U \text{ is infinite}\}$ . Certainly, we have that  $\emptyset, X \in \mathcal{T}_\infty$  as  $X \setminus X = \emptyset$  and  $X \setminus \emptyset = X$ . However, if  $X = \mathbb{R}$ , and we have the sets  $(0, 1)$ , and  $(-\infty, 0) \cup (1, \infty)$ , then  $\mathbb{R} \setminus (0, 1) = (-\infty, 0] \cup [1, \infty)$ , and  $\mathbb{R} \setminus ((-\infty, 0) \cup (1, \infty)) = [0, 1]$ , both of which are infinite, but,  $[0, 1] \cap ((-\infty, 0] \cup [1, \infty)) = \{0, 1\}$ , which is finite. So it is not true in general that the collection  $\mathcal{T}_\infty$  is a topology.

**Lemma 1.1.1.** *Let  $X$  be a topological space. If  $A \subseteq X$  is such that for each  $x \in A$ , there exists an open set  $U$  with  $x \in U \subseteq A$ , then  $A$  is also open in  $X$ .*

*Proof.* We have that for each  $x \in A$ , there is an open set  $U_x$  such that  $x \in U_x \subseteq A$ . Now, let  $U = \bigcup_{x \in A} U_x$ , which is open in  $X$  by definition. Then, we have  $U \subseteq A$  by hypothesis; moreover, since  $x \in A$  implies  $x \in U_x$ , then  $x \in U$ . This makes  $A \subseteq U$ , so  $A = U$ . ■

**Definition.** Let  $X$  be a set, and let  $\mathcal{T}$  and  $\mathcal{T}'$  be topologies on  $X$ . We say that  $\mathcal{T}$  is **coarser** than  $\mathcal{T}'$ , and  $\mathcal{T}'$  **finer** than  $\mathcal{T}$  if  $\mathcal{T} \subseteq \mathcal{T}'$ . If two topologies are either coarser, or finer than each other, we call them **comparable**.

**Example 1.2.** The topologies  $\mathcal{T}_f$  and  $\mathcal{T}_c$  are comparable, and we see that  $\mathcal{T}_f \subseteq \mathcal{T}_c$ , so  $\mathcal{T}_f$  is coarser than  $\mathcal{T}_c$ , and  $\mathcal{T}_c$  is finer than  $\mathcal{T}_f$ .

**Lemma 1.1.2.** *If  $\{\mathcal{T}_\alpha\}$  is a collection of topologies on a set  $X$ , then the intersection of all  $\mathcal{T}_\alpha$ ,  $\bigcap \mathcal{T}_\alpha$  is also a topology on  $X$ .*

*Proof.* Let  $\mathcal{T} = \bigcap \mathcal{T}_\alpha$ . We have that  $\emptyset, X \in \mathcal{T}_\alpha$  for each  $\alpha$ , so that  $\emptyset, X \in \mathcal{T}$ .

Now let  $\{U_\alpha\}$  be a collection of open sets such that  $U_\alpha \in \mathcal{T}_\alpha$  for each  $\alpha$ . Then  $U_\alpha \in \mathcal{T}$ , for each  $\alpha$ , so that  $\bigcup U_\alpha \in \mathcal{T}$ . Lastly, take a finite subcollection  $\{U_i\}_{i=1}^n$  of  $\{U_\alpha\}$ , then  $\bigcap_{i=1}^n U_i \in \mathcal{T}$  by similar reasoning. ■

**Example 1.3.** If  $X$  is any set, and  $\{\mathcal{T}_\alpha\}$  is a collection of topologies in  $X$ , it is not in general true that  $\bigcup \mathcal{T}_\alpha$  is also a topology on  $X$ . Consider the 9 topologies on the set  $X = \{a, b, c\}$  in the preceding examples. Let  $\mathcal{T}_1 = \{\emptyset, \{a\}, \{a, b\}, X\}$ ,  $\mathcal{T}_2 = \{\emptyset, \{a, b\}, \{b\}, \{b, c\}, \{c\}, X\}$ , and let  $\mathcal{T}_3 = \mathcal{T}_1 \cup \mathcal{T}_2$ . The sets  $\{a\}$  and  $\{c\}$  have union  $\{a, c\}$ , however,  $\{a, c\} \notin \mathcal{T}_3$ .

## 1.2 The Basis and Subbasis for a Topology.

**Definition.** If  $X$  is a set, the **basis** for a topology on  $X$  is a collection  $\mathcal{B}$  of subsets of  $X$ , called **basis elements**, such that:

- (1) For every  $x \in X$ , there is a  $B \in \mathcal{B}$  such that  $x \in B$ .
- (2) For  $B_1, B_2 \in \mathcal{B}$ , if  $x \in B_1 \cap B_2$ , then there is a  $B_3 \in \mathcal{B}$  such that  $x \in B_3 \subseteq B_1 \cap B_2$

We define the topology  $\mathcal{T}$  **generated** by  $\mathcal{B}$  to be collection of open sets:  $\mathcal{T} = \{U \subseteq X : \text{for all } x \in U, \text{ there exists a } B \in \mathcal{B} \text{ such that } x \in B\}$ .

**Theorem 1.2.1.** *Let  $X$  be a set, and  $\mathcal{B}$  a basis of  $X$ , then the collection of subsets of  $X$ ,  $\mathcal{T} = \{U \subseteq X : \text{for all } x \in U, \text{ there exists a } B \in \mathcal{B} \text{ such that } x \in B\}$  is a topology on  $X$ .*

*Proof.* Let  $\mathcal{B}$  be a basis for a topology in  $X$ , and consider  $\mathcal{T}$  as defined above. Clearly,  $\emptyset \in \mathcal{T}$  and so is  $X$ .

Now let  $\{U_\alpha\}$  be a collection of subsets of  $X$ , and let  $U = \bigcup U_\alpha$ . Then if  $x \in U$  for some  $\alpha$ , there is a  $B_\alpha$  such that  $x \in B_\alpha \subseteq U_\alpha$ , thus  $x \in B_\alpha \subseteq U$ .

Now let  $x \in U_1 \cap U_2$ , and choose  $B_1, B_2 \in \mathcal{B}$  such that  $x \in B_1 \subseteq U_1$  and  $x \in B_2 \subseteq U_2$ . Then by definition, there is a  $B_3$  for which  $x \in B_3 \subseteq B_1 \cap B_2$ . Now suppose for arbitrary  $n$ , that  $U = \bigcap_{i=1}^n U_i \in \mathcal{T}$ , for some finite collection  $\{U_i\}$  of subsets of  $X$ . Then by let  $B_n, B_{n+1} \in \mathcal{B}$  such that  $x \in B_n \subseteq U$  and  $x \in B_{n+1} \subseteq U_{n+1}$ . Then by our hypothesis, there is a  $B$  for which  $x \in B \subseteq B_n \cap B_{n+1}$ , thus  $U \cap U_{n+1} = \bigcap_{i=1}^{n+1} U_i \in \mathcal{T}$ . This make  $\mathcal{T}$  a topology on  $X$ . ■

**Example 1.4.** (1) Let  $\mathcal{B}$  be the set of all circular regions in the plane  $\mathbb{R} \times \mathbb{R}$ , then  $\mathcal{B}$  satisfies the conditions needed for a basis.

(2) The collection  $\mathcal{B}'$  in  $\mathbb{R} \times \mathbb{R}$  of all rectangular region also forms a basis for a topology on  $\mathbb{R} \times \mathbb{R}$ .

(3) For any set  $X$ , the set of all 1-point subsets of  $X$  forms a basis for a topology on  $X$ .

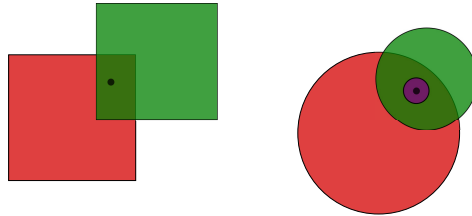


Figure 1.2: The basis for  $\mathcal{B}$  and  $\mathcal{B}'$  in  $\mathbb{R} \times \mathbb{R}$  (see example (2)).

**Lemma 1.2.2.** *Let  $X$  be a set, and  $\mathcal{B}$  be a basis for a topology  $\mathcal{T}$  on  $X$ . Then  $\mathcal{T} = \{\bigcup B : B \in \mathcal{B}\}$ .*

*Proof.* Given a collection  $\{B_i\}_{i=1}^\infty$  of basis elements in  $\mathcal{B}$ , since they are all in  $\mathcal{T}$ , their unions are also in  $\mathcal{T}$ . Conversely, given  $U \in \mathcal{T}$ , then for every point  $x \in U$ , choose a  $B_x \in \mathcal{B}$  such that  $x \in B_x \subseteq U$ , then  $U = \bigcup_{x \in U} B_x$ . ■

**Lemma 1.2.3.** *Let  $(X, \mathcal{T})$  be a topological space, and let  $\mathcal{C} \subseteq \mathcal{T}$  be a collection of open sets of  $X$  such that for every  $x \in U$ , there is a  $C \in \mathcal{C}$  such that  $x \in C \subseteq U$ . Then  $\mathcal{C}$  is the basis for a  $\mathcal{T}$  on  $X$ .*

*Proof.* Take any  $x \in X$ , then there is a  $C \in \mathcal{C}$  such that  $x \in C \subseteq U$ , thus the first condition for a basis is satisfied. Now let  $x \in C_1 \cap C_2$  for  $C_1, C_2 \in \mathcal{C}$ , since  $C_1 \cap C_2$  is open in  $X$ , there is a  $C_3 \in \mathcal{C}$  such that  $x \in C_3 \subseteq C_1 \cap C_2$ . Therefore  $\mathcal{C}$  is a basis for a topology on  $X$ .

Now let  $\mathcal{T}_{\mathcal{C}}$  be the topology generated by  $\mathcal{C}$ , now for  $U \in \mathcal{T}$ , we have by the hypothesis, that  $U \in \mathcal{T}_{\mathcal{C}}$ ; and by lemma 1.2.2,  $W \in \mathcal{T}_{\mathcal{C}}$  is the union of elements of  $\mathcal{C}$ , which is a subcollection of  $\mathcal{T}$ , thus  $W \in \mathcal{T}$ . Therefore  $\mathcal{T}_{\mathcal{C}} = \mathcal{T}$ . ■

**Lemma 1.2.4.** *Let  $\mathcal{B}$  and  $\mathcal{B}'$  be bases for topologies  $\mathcal{T}$  and  $\mathcal{T}'$  on  $X$ . Then the  $\mathcal{T} \subseteq \mathcal{T}'$  if and only if for all  $x \in X$ , and all  $B \in \mathcal{B}$ , there is a  $B' \in \mathcal{B}'$  such that  $x \in B' \subseteq B$ .*

*Proof.* Suppose first that  $\mathcal{T} \subseteq \mathcal{T}'$ , and let  $x \in X$ , and choose  $B \in \mathcal{B}$  such that  $x \in B$ , then  $B$  is open in  $\mathcal{T}$ , thus it is open in  $\mathcal{T}'$ , thus there is a  $B' \in \mathcal{B}'$  such that  $x \in B' \subseteq B$ . Conversely, suppose there is a  $B' \in \mathcal{B}'$  for which  $x \in B' \subseteq B$  for all  $x \in X$ ,  $B \in \mathcal{B}$ . Take  $x \in U \in \mathcal{T}$ , since  $\mathcal{B}$  generates  $\mathcal{T}$ ,  $x \in B \subseteq U$ , since  $B' \subseteq B$ , this implies that  $U \in \mathcal{T}'$  and  $\mathcal{T} \subseteq \mathcal{T}'$ . ■

**Definition.** If  $\mathcal{B}$  is the collection of open intervals  $(a, b)$  in  $\mathbb{R}$ , we call the topology generated by  $\mathcal{B}$  the **standard topology** on  $\mathbb{R}$ , and we denote it simply by  $\mathbb{R}$ .

**Definition.** If  $\mathcal{B}$  is the collection of half open intervals  $[a, b)$  in  $\mathbb{R}$ , we call the topology generated by  $\mathcal{B}$  the **lower limit topology** on  $\mathbb{R}$ , and we denote it simply by  $\mathbb{R}_l$ . If  $\mathcal{B}'$  is the collection of all half open intervals  $(a, b]$  in  $\mathbb{R}$ , then we call the topology generated by  $\mathcal{B}'$  the **upper limit topology** on  $\mathbb{R}$ , and denote it  $\mathbb{R}_L$ .

**Definition.** If  $\mathcal{B}$  is the collection of all open intervals of the form  $(a, b) \setminus \frac{1}{\mathbb{Z}^+}$ , where  $\frac{1}{\mathbb{Z}^+} = \{\frac{1}{n} : n \in \mathbb{Z}^+\}$ , we call the topology generated by  $\mathcal{B}$  the  **$\frac{1}{\mathbb{Z}^+}$ -topology** on  $\mathbb{R}$ , and we denote it  $\mathbb{R}_{\frac{1}{\mathbb{Z}^+}}$ .

**Lemma 1.2.5.** *The topologies  $\mathbb{R}_l$ ,  $\mathbb{R}_L$ , and  $\mathbb{R}_{\frac{1}{\mathbb{Z}^+}}$  are all strictly finer than  $\mathbb{R}$ , but are not comparable with each other.*

*Proof.* Let  $(a, b)$  be a basis element for  $\mathbb{R}$ , and let  $x \in (a, b)$ , the basis element  $[x, b) \in \mathbb{R}_l$  lies in  $(a, b)$  and contains  $x$ , however, there can be no interval  $(a, b)$  in  $[x, b)$  as  $x \leq a$ , thus  $\mathbb{R} \subset \mathbb{R}_l$ ; a similar argument holds for  $\mathbb{R}_L$ .

Similarly, for  $(a, b) \in \mathbb{R}$ , the basis element  $(a, b) \setminus \frac{1}{\mathbb{Z}^+}$  of  $\mathbb{R}_{\frac{1}{\mathbb{Z}^+}}$  lies in  $(a, b)$ , however, choose the basis  $B = (-1, 1) \setminus \frac{1}{\mathbb{Z}^+}$ , and choose  $0 \in B$ , since  $\mathbb{Z}^+$  is dense in  $\mathbb{R}$ , there is no interval  $(a, b)$  containing 0 and lying in  $B$ , thus  $\mathbb{R} \subseteq \mathbb{R}_{\frac{1}{\mathbb{Z}^+}}$ .

Now choose  $[0, 1)$  in  $\mathbb{R}_l$ , and choose  $\frac{1}{k} \in [0, 1)$  such that  $k \in \mathbb{Z}^+$ . Now  $(0, 1) \subseteq [0, 1)$ , so we cannot say that  $[0, 1)$  is a basis for  $\mathbb{R}$ , and moreover,  $[0, 1) \setminus \frac{1}{\mathbb{Z}^+}$  cannot be said to be a basis in  $\mathbb{R}_{\frac{1}{\mathbb{Z}^+}}$ , thus  $\mathbb{R}_l$  and  $\mathbb{R}_{\frac{1}{\mathbb{Z}^+}}$  are incomparable, a similar argument holds for  $\mathbb{R}_L$ .

Lastly, let  $(a, b)$  be in  $\mathbb{R}$  and choose  $x \in (a, b)$ . Then  $(a, x]$  and  $[x, b)$  are both in  $(a, b)$ , however it is clear that  $(a, x]$  and  $[x, b)$  cannot be contained in each other, thus  $\mathbb{R}_l$  and  $\mathbb{R}_L$  are incomparable. ■

**Definition.** A **subbasis**,  $\mathcal{S}$ , for a topology on  $X$  is a collection of subsets of  $X$  whose union equals  $X$ . We call the **topology generated by  $\mathcal{S}$**  to be the collection of all unions of finite intersections of elements of  $\mathcal{S}$ , that is:

$$\mathcal{T} = \left\{ \bigcup_{i=1}^n S_i : S_i \in \mathcal{S} \text{ for } 1 \leq i \leq n \right\}$$

**Theorem 1.2.6.** *Let  $\mathcal{S}$  be a subbasis for a topology on  $X$ . Then the collection  $\mathcal{T} = \{\bigcup \bigcap_{i=1}^n S_i : S_i \in \mathcal{S} \text{ for } 1 \leq i \leq n\}$  is a topology on  $X$ .*

*Proof.* It is sufficient to show that the collection  $\mathcal{B}$  of all finite intersections of elements of  $\mathcal{S}$  is a basis for a topology on  $X$ . By lemma 1.2.1, for  $x \in X$ , it belongs to an element  $S$  of  $\mathcal{S}$ , and therefore, to an element of  $\mathcal{B}$ . Now let  $B_1 = \bigcap_{i=1}^m S_i$  and  $B_2 = \bigcap_{j=1}^n S'_j$  be basis elements of  $\mathcal{B}$ . The intersection  $B_1 \cap B_2$  is a finite intersection of elements of  $\mathcal{S}$ , and hence also belongs in  $\mathcal{B}$ , and hence we can take another basis element  $B_3$  such that  $x \in B_3 \subseteq B_1 \cap B_2$ . ■

## 1.3 The Order Topology.

**Definition.** Let  $X$  be a set with a simple order relation, and suppose that  $|X| > 1$ . Let  $\mathcal{B}$  be the collection of sets of the following forms:

- (1) All open intervals  $(a, b) \in X$ .
- (2) All half open intervals  $[a_0, b)$  where  $a_0$  is the least element (if any) of  $X$ .
- (3) All half open intervals of the form  $(a, b_0]$  where  $b_0$  is the greatest element (if any) of  $X$ .

Then  $\mathcal{B}$  forms the basis for a topology on  $X$  called the **order topology**

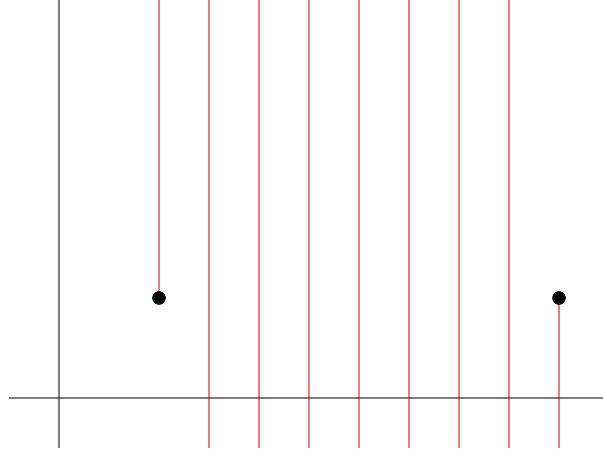
**Theorem 1.3.1.** *The collection  $\mathcal{B}$  forms a basis.*

*Proof.* Consider  $x \in X$ , if  $x$  is the least element of  $X$ , then it lies in all intervals of type (2), if it is the largest, then it lies in all intervals of type (3). If  $x$  is neither the least nor largest element, then  $x \in (a_0, b_0)$  with  $a_0$  and  $b_0$  the least and largest elements (if any) of  $X$ . If no such elements exist, then  $x \in (a, b)$ , for some lowerbound  $a$  and upperbound  $b$ . Thus, in all three cases, there is a basis element containing  $x$ .

Now suppose  $B_1, B_2 \in \mathcal{B}$  such that  $x \in B_1 \cap B_2$ . If  $B_1$  and  $B_2$  are both of type (1), then let  $B_1 = (a, b)$ ,  $B_2 = (c, d)$ , then  $B_1 \cap B_2$  is an open interval of type (1), now fix  $B_1$  to be of type one. If  $B_2$  is of type (2), then letting  $B_2 = [a_0, c)$ , then  $x \in [a_0, d)$  for some  $d \in X$ . Likewise, if  $B_2 = (c, b_0]$ , is of type (3), we get a similar result. Moreover, the results are analogous if we fix  $B_2$  and let  $B_1$  range between intervals of the three types. Thus in all cases, there is a  $B_3 \in \mathcal{B}$  such that  $x \in B_3 \subseteq B_1 \cap B_2$ . ■

**Example 1.5.** (1) The standard topology on  $\mathbb{R}$  is the order topology on  $\mathbb{R}$  induced by the usual order relation. We have that  $\mathbb{R}$  under this topology has no intervals of type (2), nor (3), so all bases elements in the standard topology are open intervals in  $\mathbb{R}$ .

- (2) Consider the dictionary order on  $\mathbb{R} \times \mathbb{R}$ . Since  $\mathbb{R} \times \mathbb{R}$  has no intervals of type (2), nor (3), the bases of  $\mathbb{R} \times \mathbb{R}$  under the dictionary order are the open intervals of the form  $(a \times b, c \times d)$  Where  $a \leq c$ , and  $b < d$ .
- (3) The positive integers  $\mathbb{Z}^+$  with the least element 1 form an ordered set under the usual order. Taking  $n > 1$ , we see the bases of  $\mathbb{Z}^+$  under the order topology are of the form  $(n-1, n+1) = \{n\}$  and  $[1, n) = \{1, \dots, n-1\}$ . Thus the order topology on  $\mathbb{Z}^+$  is the discrete topology.

Figure 1.3: The order topology on  $\mathbb{R} \times \mathbb{R}$ .

- (4) The set  $X = \{1, 2\} \times \mathbb{Z}^+$  over the dictionary order is also an ordered set, with the least element  $1 \times 1$ . Denote  $1 \times n$  as  $a_n$  and  $2 \times n$  as  $b_n$ . Then  $X$  consist of the elements  $a_1, a_2, \dots, b_1, b_2, \dots$ .

Now take  $\{b_1\}$ , then any open set containing  $b_1$  must have a basis about  $b_1$ , and also contains points  $a_i$  with  $i \in \mathbb{Z}^+$ ; thus the order topology on  $X$  is not the discrete topology.

**Definition.** Let  $X$  be an ordered set, and let  $a \in X$ . There are two subsets in  $X$ ,  $(a, \infty) = \{x \in X : x > a\}$  and  $(-\infty, a) = \{x \in X : x < a\}$  called **open rays** of  $X$ . There are also two sets  $[a, \infty) = \{x \in X : x \geq a\}$  and  $(-\infty, a] = \{x \in X : x \leq a\}$  called **closed rays** of  $X$ .

**Theorem 1.3.2.** Let  $X$  be an ordered set. Then the collection of all open rays in  $X$  form a subbasis for the order topology on  $X$ .

*Proof.* Let  $\mathcal{S}$  be the collection of all open rays of  $X$ , let  $a < b$  and  $(a, \infty), (-\infty, b) \in \mathcal{S}$ , then  $(a, b) = (a, \infty) \cap (-\infty, b)$ . Now take:

$$S = \bigcup_{a, b \in X} (a, b)$$

then  $S \subseteq X$ , likewise, since  $S$  runs through all intersections of open rays of  $X$ , it contains all open intervals in  $X$ , hence  $X \subseteq S$ , and so  $X = S$  as required. ■

## 1.4 The Product Topology.

**Definition.** Let  $X$  and  $Y$  be topological spaces. We define the **product topology** on  $X \times Y$  to be the topology having as basis the collection

$$\mathcal{B} = \{U \times V \subseteq X \times Y : U \text{ is open in } X \text{ and } V \text{ is open in } Y\}$$

**Theorem 1.4.1.** The collection  $\mathcal{B} = \{U \times V \subseteq X \times Y : U \text{ is open in } X \text{ and } V \text{ is open in } Y\}$  forms a basis for the product topology on  $X \times Y$ .



*Proof.* Clearly, we have that  $X \times Y$  is a basis element of  $\mathcal{B}$ . Now take  $U_1 \times V_1$  and  $U_2 \times V_2$  in  $\mathcal{B}$ . Since  $U_1 \times V_1 \cap U_2 \times V_2 = U_1 \cap U_2 \times V_1 \cap V_2$ , since  $U_1 \cap U_2$  and  $V_1 \cap V_2$  are open in  $X$  and  $Y$  respectively, then we have that  $U_1 \times V_1 \cap U_2 \times V_2$  is a basis element as well. ■

**Theorem 1.4.2.** *If  $\mathcal{B}$  is the basis for a topology on  $X$ , and  $\mathcal{C}$  is the basis for a topology on  $Y$ , then the collection:*

$$\mathcal{D} = \{B \times C : B \in \mathcal{B} \text{ and } C \in \mathcal{C}\}$$

*Is a basis for the topology on  $X \times Y$ .*

*Proof.* By lemma 1.2.3, let  $W$  be an open set of  $X \times Y$ , and let  $x \times y \in W$ . Then there is a basis  $U \times V$  such that  $x \times y \in U \times V \subseteq W$ . Since  $\mathcal{B}$  and  $\mathcal{C}$  are bases of  $X$  and  $Y$  respectively, choosing  $B \in \mathcal{B}$  and  $C \in \mathcal{C}$ , we have that  $x \in B \subseteq U$ , and  $y \in C \subseteq V$ , thus  $x \times y \in B \times C \subseteq U \times V \subseteq W$ . Therefore,  $\mathcal{D}$  is the basis for a topology on  $X \times Y$ . ■

**Example 1.6.** The product of the standard topology on  $\mathbb{R}$  with itself is called the **standard topology on  $\mathbb{R} \times \mathbb{R}$** , and has as basis the collection of all products of open sets in  $\mathbb{R}$ . By theorem 1.4.2, if we take the collection of all open intervals  $(a, b) \times (c, d)$  in  $\mathbb{R} \times \mathbb{R}$ , we form a basis. Constructing this basis geometrically gives the interior of a rectangle, whose boundaries are the intervals  $(a, b)$  and  $(c, d)$ .

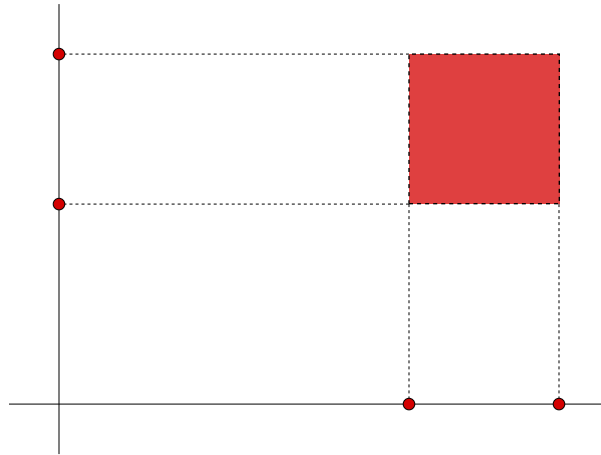


Figure 1.4: A basis element for  $\mathbb{R} \times \mathbb{R}$

**Definition.** Let  $\pi_1 : X \times Y \rightarrow X$  be defined such that  $\pi_1(x, y) = x$ , and define  $\pi_2 : X \times Y \rightarrow Y$  such that  $\pi_2(x, y) = y$ . We call  $\pi_1$  and  $\pi_2$  **projections** of  $X \times Y$  onto its first and second **factors**; that is onto  $X$  and  $Y$ , respectively.

Clearly,  $\pi_1$  and  $\pi_2$  are both onto. Now let  $U$  be open in  $X$ , then  $\pi_1^{-1}(U) = U \times Y$  is open in  $X \times Y$ ; similarly,  $\pi_2^{-1}(V) = X \times V$  is also open in  $X \times Y$ , for  $V$  open in  $Y$ .

**Example 1.7.** The maps  $\pi_1 : x \times y \rightarrow x$  and  $\pi_2 : x \times y \rightarrow y$  of  $X \times Y$  onto  $X$  and  $Y$ , respectively, are what we call “open maps”. Let  $U$  and  $V$  be open in  $X$  and  $Y$  respectively, then  $U \times V$  is open in  $X \times Y$ , and for every  $x \times y \in U \times V$ , we have  $\pi_1(x \times y) = x$  and  $\pi_2(x \times y) = y$ , so that  $\pi_1(U \times V) = U$  and  $\pi_2(U \times V) = V$  are open in  $X$  and  $Y$  respectively.

**Theorem 1.4.3.** *The collection  $\mathcal{S} = \{\pi_1^{-1}(U) : U \text{ is open in } X\} \cup \{\pi_2^{-1}(V) : V \text{ is open in } Y\}$  is a subbasis for the product topology on  $X \times Y$ .*

*Proof.* Let  $\mathcal{T}$  be the product topology on  $X \times Y$ , and let  $\mathcal{T}'$  be the topology generated by  $\mathcal{S}$ . Since every element of  $\mathcal{S}$  is open in  $\mathcal{T}$ ,  $\mathcal{T} \subseteq \mathcal{T}'$ . Conversely, consider the basis element  $U \times V$  of  $\mathcal{T}$ , then  $\pi_1^{-1}(U) \cap \pi_2^{-1}(V) = U \times Y \cap X \times V = U \times V$ , thus  $\mathcal{T} \subseteq \mathcal{T}'$ . Therefore,  $\mathcal{S}$  is a subbasis for the product topology. ■

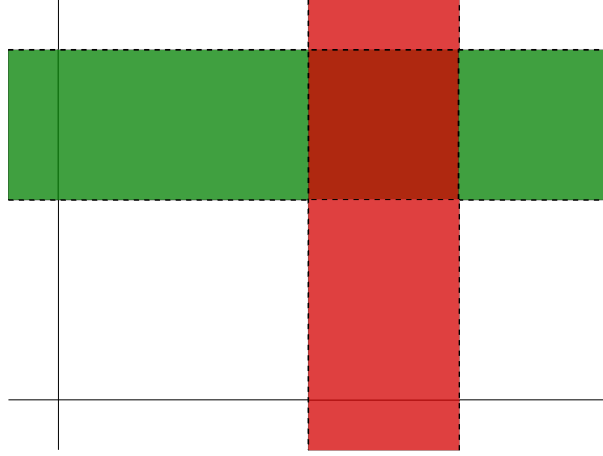


Figure 1.5: The inverse images,  $\pi_1^{-1}(U)$  and  $\pi_2^{-1}(V)$ , of the projections  $\pi_1$  and  $\pi_2$  onto the  $X \times Y$  plane.

## 1.5 The Subspace Topology.

**Theorem 1.5.1.** *Let  $X$  be a topological space with topology  $\mathcal{T}$ , and let  $Y \subseteq X$ . Then the collection:*

$$\mathcal{T}_Y = \{Y \cap U : U \in \mathcal{T}\}$$

*forms a topology on  $Y$ .*

*Proof.* Clearly,  $Y \cap \emptyset = \emptyset \in \mathcal{T}_Y$  and  $Y \cap X = Y \in \mathcal{T}_Y$ . Now consider the collection  $\{U_\alpha\}$ . Then  $\bigcup (Y \cap U_\alpha) = Y \cap \bigcup U_\alpha$ , similarly, for  $\{U_i\}_{i=1}^n$ ,  $\bigcap (Y \cap U_i) = Y \cap \bigcap U_i$ , hence  $\mathcal{T}_Y$  is a topology on  $Y$ . ■

**Definition.** Let  $X$  be a topological space, and let  $Y \subseteq X$ . We call the  $\mathcal{T}_Y$  defined in theorem 1.5.1 the **subspace topology** on  $Y$ . We say that  $U \subseteq Y$  is **open in  $Y$**  if  $U \in \mathcal{T}_Y$ .

**Lemma 1.5.2.** *Let  $\mathcal{B}$  be the basis for a topology on  $X$ . Then the collection  $\mathcal{B}_Y = \{B \cap Y : B \in \mathcal{B}\}$ , where  $Y \subseteq X$ , is a basis for the subspace topology on  $Y$ .*

*Proof.* Let  $U$  be open in  $X$ , and let  $y \in Y \cap U$ , and choose  $B \in \mathcal{B}$  such that  $y \in B \subseteq U$ , then  $y \in B \cap Y \subseteq U \cap Y$ , then by lemma 1.2.2,  $\mathcal{B}_Y$  is the basis for the subspace topology on  $Y$ . ■

**Lemma 1.5.3.** *Let  $Y$  be a subspace of  $X$ , If  $U \subseteq Y$  is open in  $Y$  and  $Y$  is open in  $X$ , then  $U$  is open in  $X$ .*

*Proof.* Let  $U \in \mathcal{T}_Y$ , then for some  $V \subseteq X$ ,  $U = Y \cap V$ . Now since  $Y$  is open in  $X$ , and so is  $V$ , then it follows that  $U$  is also open in  $X$ . ■

*Remark.* What this lemma says is that given a topological space  $X$ , and a subspace  $Y$  of  $X$ , then the subspace topology of  $Y$  is coarser than the topology on  $X$ , i.e.  $\mathcal{T}_Y \subseteq \mathcal{T}$ .

**Theorem 1.5.4.** *If  $A$  is a subspace of  $X$ , and  $B$  is a subspace of  $Y$ , then the product topology on  $A \times B$  is the topology that  $A \times B$  inherits as a subspace of  $X \times Y$ .*

*Proof.* We have that  $U \times V$  is the basis element for  $X \times Y$ , with  $U$  open in  $X$ , and  $V$  open in  $Y$ . Thus  $(U \times V) \cap (A \times B) = (U \cap A) \times (V \cap B)$  is a basis element for the subspace topology on  $X \times Y$ . Since  $U \cap A$  and  $V \cap B$  are open in the subspace topologies of  $A$  and  $B$  respectively, then  $(U \cap A) \times (V \cap B)$  is a basis for the product topology on  $A \times B$ . ■

**Example 1.8.** (1) Consider  $[0, 1] \subseteq \mathbb{R}$ . In the subspace topology of  $[0, 1]$ , we have as basis elements of the form  $(a, b) \cap [0, 1]$ , with  $(a, b) \subseteq \mathbb{R}$ . If we have that  $(a, b) \subseteq [0, 1]$ , then  $(a, b) \cap [0, 1] = (a, b)$ . On the other hand, if  $a \in [0, 1]$  or  $b \in [0, 1]$ , then we get  $(a, b) \cap [0, 1] = (a, 1]$  or  $(a, b) \cap [0, 1] = [0, b)$ , lastly if neither  $a$  nor  $b$  are in  $[0, 1]$ , then we have  $(a, b) \cap [0, 1] = [0, 1]$  only if  $[0, 1] \subseteq (a, b)$ , and  $(a, b) \cap [0, 1] = \emptyset$  otherwise.

The only one of these sets open in  $\mathbb{R}$  under the standard topology is  $(0, 1)$ .

(2) For  $[0, 1) \cup \{2\} \subseteq \mathbb{R}$ , the singleton  $\{2\}$  is open in the subspace topology on  $[0, 1) \cup \{2\}$ ; for observe, that  $(\frac{3}{5}, \frac{5}{2}) \cap ([0, 1) \cup \{2\}) = \{2\}$ , however, in the order topology, on that same set,  $\{2\}$  is not open. Any basis element on  $[0, 1) \cup \{2\}$  containing 2 is of the form  $(a, 2]$ , where  $a \in [0, 1) \cup \{2\}$ .

(3) The dictionary order on  $[0, 1] \times [0, 1]$  is a restriction of the dictionary order on  $\mathbb{R} \times \mathbb{R}$ . Now the set  $\{\frac{1}{2}\} \times (\frac{1}{2}, 1]$  is open in the subspace topology on  $[0, 1] \times [0, 1]$ , but it is not open in the dictionary order on the same set.

**Definition.** We call the set  $[0, 1] \times [0, 1]$  on the dictionary order the **ordered square**, and we denote it by  $I_0^2$ .

**Lemma 1.5.5.** *Let  $Y$  be a subspace of a topological space  $X$ , and let  $A \subseteq Y$ . Then the topology of  $A$  as a subspace of  $Y$  is the same as the topology of  $A$  as a subspace of  $X$ .*

*Proof.* Let  $V$  be open in  $Y$ , then  $V \cap A$  is open in  $A$  as a subspace of  $Y$ , however, since  $Y$  is a subspace of  $X$ ,  $V = U \cap Y$  for some  $U$  open in  $X$ , so  $V \cap A = (U \cap Y) \cap A = U \cap (A \cap Y) = U \cap A$ , making  $V \cap A$  open in  $A$  as a subspace of  $X$ .

Conversely, if  $U$  is open in  $X$ , then  $U \cap A$  is open in  $A$  as a subspace of  $X$ , additionally,  $U \cap Y$  is open in  $Y$  as a subspace of  $Y$ , so that  $(U \cap Y) \cap A = U \cap (A \cap Y) = U \cap A$ , which makes  $U \cap A$  open in  $A$  as a subspace of  $Y$ . ■

**Example 1.9.** Suppose that  $\mathcal{T}$  and  $\mathcal{T}'$  are topologies on a set  $X$ , with  $\mathcal{T} \subseteq \mathcal{T}'$ . Then if  $Y \subseteq X$ , then the topology of  $Y$  as a subspace of  $X$  under  $\mathcal{T}'$  is finer than the topology of  $Y$  as a subspace of  $X$  under  $\mathcal{T}$ ; for, if  $U$  is open in  $X$  under  $\mathcal{T}$ , then  $U \cap Y$  is open in  $Y$  under  $\mathcal{T}$ . But  $\mathcal{T} \subseteq \mathcal{T}'$ , which implies that  $U \cap Y$  is open in  $Y$  under  $\mathcal{T}'$ .

**Definition.** Let  $X$  be an ordered set. We say that a nonempty subset  $Y \subset X$  is **convex** in  $X$  if for each pair of points  $a, b \in Y$ , with  $a < b$ , then the open interval  $(a, b) \subseteq X$  is also contained in  $Y$ .

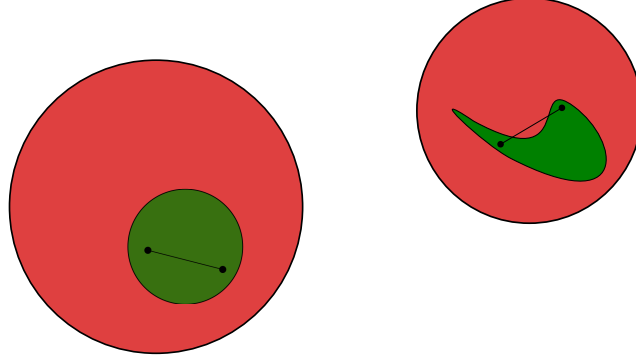


Figure 1.6: A convex set, and a nonconvex set.

**Example 1.10.** Let  $X$  be any ordered set. Then by definition, all open intervals and rays in  $X$  are convex in  $X$ .

**Theorem 1.5.6.** Let  $X$  be an ordered set on the order topology, and let  $Y \subseteq X$  be convex in  $X$ . Then the order topology on  $Y$  is the same as the subspace topology on  $Y$ .

*Proof.* Consider  $(a, \infty) \subseteq X$ . If  $a \in Y$ , then  $(a, \infty) \cap Y = \{x \in Y : x > a\}$ , which is by definition an open ray on  $Y$ . Now if  $a \notin Y$ , then  $a$  is either a lowerbound, or an upperbound. Then  $(a, \infty) \cap Y = \emptyset$  and  $(-\infty, a) \cap Y = Y$  if  $a$  is an upperbound, similarly, if  $a$  is a lowerbound we get  $(a, \infty) \cap Y = Y$  and  $(-\infty, a) \cap Y = \emptyset$ .

Since  $(a, \infty) \cap Y$  and  $(-\infty, a) \cap Y$  form a subbasis on the subspace topology on  $Y$ , and since they are also open in the order topology, then the order topology contains the subspace topology.

Now if  $(a, \infty)$  is an open ray in  $Y$ , then  $(a, \infty) = (b, \infty) \cap Y$ , with  $(b, \infty)$  some open ray in  $X$ , hence  $(a, \infty)$  is open in the subspace topology of  $Y$ , and since it also forms the subbasis for the order topology, we have that the order topology is contained within the subspace topology. Thus both topologies are equal. ■

## 1.6 Closed Sets and Limit Points.

**Definition.** A subset  $A$  of a topological space  $X$  is said to be **closed** if  $X \setminus A$  is open.

**Example 1.11.** (1) Consider  $[a, b] \subseteq \mathbb{R}$ , we have that  $\mathbb{R} \setminus [a, b] = (-\infty, a) \cup (b, \infty)$  which is open in  $\mathbb{R}$ . So  $[a, b]$  is closed.

(2) In  $\mathbb{R} \times \mathbb{R}$ , the set  $A = \{x \times y : x, y \geq 0\}$  (i.e the first quadrant of the plane) is closed, for  $\mathbb{R} \times \mathbb{R} \setminus A = ((-\infty, 0) \times \mathbb{R}) \cup (\mathbb{R} \times (-\infty, 0))$ , which is open in  $\mathbb{R} \times \mathbb{R}$ .

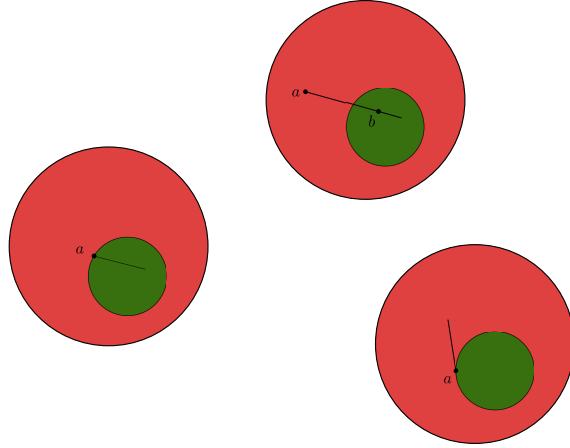


Figure 1.7: An illustration of theorem 1.5.6.

- (3) Consider the finite complement topology  $\mathcal{T}_f$  on a set  $X$ . We have that  $X \setminus X = \emptyset \in \mathcal{T}_f$ , so  $X$  is closed, similarly,  $\emptyset$  is also closed. Likewise, if  $A \subseteq X$  is a finite set, then  $X \setminus A$  is also finite, and hence  $A$  is also closed. Thus, we have that all the closed sets of  $\mathcal{T}_f$  are those finite subsets of  $X$ . As a consequence, this example also illustrates that sets can be both closed and open.
- (4) In the discrete topology  $2^X$ , every open set is closed. This is another example where open sets are also closed sets.
- (4) Consider  $[0, 1] \cup (2, 3)$  in the subspace topology on  $\mathbb{R}$ . We have that  $[0, 1]$  is open in the subspace topology on  $\mathbb{R}$ ;  $[0, 1] = [0, 1] \cup (2, 3) \cap (-\frac{2}{3}, \frac{3}{2})$ , similarly,  $(2, 3)$  is also open. Now taking  $[0, 1] \cup (2, 3) \setminus (2, 3) = [0, 1]$ , which is open, so  $[0, 1]$  is closed in the subspace topology on  $\mathbb{R}$ , by the same reasoning, so is  $(2, 3)$ .

**Theorem 1.6.1.** *Let  $X$  be a topological space. Then:*

- (1)  $\emptyset$  and  $X$  are closed.
- (2) Arbitrary intersections of closed sets are closed.
- (3) Finite unions of closed sets are closed.

*Proof.* We have that  $X \setminus \emptyset = X$  and  $X \setminus X = \emptyset$ , both of which are open in  $X$ , so they are also closed in  $X$ . Now let  $\{U_\alpha\}$  be a collection of closed sets of  $X$ . We have that:

$$X \setminus \bigcap_{\alpha} U_{\alpha} = \bigcup_{\alpha} X \setminus U_{\alpha}.$$

Similarly, for  $\{U_i\}_{i=1}^n$ , we have

$$X \setminus \bigcup_{i=1}^n U_i = \bigcap_{i=1}^n X \setminus U_i.$$

Both of which are open in  $X$ . This completes the proof. ■

**Example 1.12.** For the following examples, let  $X$  and  $Y$  be topological spaces.

- (1) If  $Y$  is a subspace of  $X$ , and  $A$  is closed in  $Y$ , and  $Y$  is closed in  $X$ , then by theorem 1.6.1,  $A = U \cap Y$ , where  $U$  is closed in  $X$ . Then by theorem 1.6.1, we get that  $A$  is closed in  $X$ .
- (2) Suppose that  $A$  is closed in  $X$  and  $B$  is closed in  $Y$ . Then  $X \setminus A$  and  $Y \setminus B$  are open in  $X$  and  $Y$ , respectively, so  $(X \setminus A) \times (Y \setminus B) = (X \times Y) \setminus (A \times B)$  is open in  $X \times Y$ . Therefore  $A \times B$  is closed in  $X \times Y$ .

**Definition.** If  $Y$  is a subspace of  $X$ , we say that  $A$  is **closed in  $Y$**  if  $A \subseteq Y$  and  $A$  is closed in the subspace topology on  $Y$ .

**Theorem 1.6.2.** *Let  $Y$  be a subspace of  $X$ . Then  $A$  is closed in  $Y$  if and only if  $A$  equals the intersection of a closed set of  $X$  with  $Y$ .*

*Proof.* Suppose that  $A$  is closed in  $Y$ , then  $Y \setminus A$  is open in  $Y$ , hence we have that  $Y \setminus A = U \cap Y$  for some open set  $U$  of  $X$ . Now  $X \setminus U$  is closed in  $X$ , and with  $A \subseteq Y$ , we have that  $A = Y \cap (X \setminus U)$ .

Conversely, suppose that  $A = C \cap Y$ , with  $C$  closed in  $X$ . Then  $X \setminus C$  is open in  $X$ , hence  $(X \setminus C) \cap Y$  is open in  $Y$ , now since  $(X \setminus C) \cap Y = Y \setminus A$ , which is open, we have that  $A$  is closed in  $Y$ . ■

**Theorem 1.6.3.** *Let  $Y$  be a subspace of  $X$ . If  $A$  is closed in  $Y$ , and  $Y$  is closed in  $X$ , then  $A$  is closed in  $X$ ; that is, closure is transitive.*

*Proof.* By theorem 1.6.2, if  $A$  is closed in  $Y$ , then  $A = C \cap Y$  with  $C$  closed in  $X$ , now since  $Y$  is closed in  $X$ , then  $Y = D \cap X$  with  $D$  closed in  $X$ . Thus  $A = (C \cap D) \cap X$ , therefore,  $A$  is closed in  $X$ . ■

We now go over the concepts of the closure, and the interior of a set.

**Definition.** Let  $A \subseteq X$ , with  $X$  a topological space. The **interior** of  $A$  is defined to be the union of all open sets in  $A$ . The **closure** of  $A$  is defined to be the intersection of all closed sets containing  $A$ . We denote the interior and the closure of  $A$  as  $\text{Int } A$  and  $\text{cl } A$  respectively

We have by the very definitions that  $\text{Int } A \subseteq A \subseteq \text{cl } A$

**Lemma 1.6.4.**  *$\text{Int } A = A$  only when  $A$  is open, and  $\text{cl } A = A$  only when  $A$  is closed.*

*Proof.* Now, if  $A$  is open, then it is in the union of all open sets of  $A$ , hence  $A \subseteq \text{Int } A$ , likewise, if  $A$  is closed, then since  $\text{cl } A$  is the intersection of all closed sets containing  $A$ , we get  $\text{cl } A \subseteq A$ . ■

**Corollary.**  *$A$  is closed and open if and only if  $\text{Int } A = \text{cl } A$ .*

**Theorem 1.6.5.** *Let  $Y$  be a subspace of  $X$ , and let  $A \subseteq Y$ . Then  $\text{cl } A \cap Y$  is the closure of  $A$  in  $Y$ .*

*Proof.* Let  $\text{cl } A$  be the closure of  $A$  in  $X$ . Since  $\text{cl } A$  is closed in  $X$ , by theorem 1.6.2,  $\text{cl } A \cap Y$  is closed in  $Y$ , now we have that  $A \subseteq \text{cl } A \cap Y$ , and since  $\text{cl } A = \bigcap U$ , then  $\text{cl } A \subseteq \text{cl } A \cap Y$ .

Conversely, suppose that  $\text{cl } A$  is closed in  $Y$ , again by theorem 1.6.2, we have that  $\text{cl } A = C \cap Y$ , where  $C$  is closed in  $X$ , since  $A \subseteq \text{cl } A$ , then  $A \subseteq C$ , and since  $C$  is closed, then  $\text{cl } A \subseteq C$ , thus  $\text{cl } A \cap Y \subseteq \text{cl } A$ . ■

**Definition.** Let  $X$  be a topological space, and let  $x \in X$ . We call an open set  $U$  of  $X$  a **neighborhood** of  $x$  if  $x \in U$ .

**Theorem 1.6.6.** *If  $A \subseteq X$ , with  $X$  a topological space, then  $\text{cl } A$  is a neighborhood of  $x \in X$  if and only if for every neighborhood  $U$  of  $x$ ,  $A \cap U \neq \emptyset$ .*

*Proof.* We prove the contrapositive. If  $x \notin \text{cl } A$ , then  $U = X \setminus \text{cl } A$  is an open set containing  $x$ , disjoint from  $A$ . Conversely, suppose there is a neighborhood  $U$  of  $x$ , with  $U$  disjoint from  $A$ , then  $X \setminus U$  is closed, and therefore contains the closure of  $A$ , thus  $x \notin \text{cl } A$ . ■

**Corollary.**  *$\text{cl } A$  is a neighborhood of  $x$  if and only if for every basis element  $B$  of  $X$ , containing  $x$ , intersects  $A$ .*

*Proof.* This is a direct application of theorem 1.6.6, since basis elements are open sets. ■

**Example 1.13.** (1) We have the closure of  $(0, 1]$  in  $\mathbb{R}$  is the closed interval  $[0, 1]$ , since every neighborhood of 0 intersects  $(0, 1]$ . Now every point outside of  $[0, 1]$  has a neighborhood disjoint from  $[0, 1]$  (take the neighborhood  $(2, 3)$  of 2).

$$(2) \text{cl } \frac{1}{\mathbb{Z}^+} = \{0\} \cup \frac{1}{\mathbb{Z}^+} \text{ and } \text{cl } \{0\} \cup (1, 2) = \{0\} \cup [1, 2].$$

$$(3) \text{cl } \mathbb{Q} = \mathbb{R}, \text{cl } \mathbb{Z}^+ = \mathbb{Z}^+, \text{cl } \mathbb{R}^+ = \mathbb{R}^+ \cup \{0\}. \text{ This first follows from the density of } \mathbb{Q} \text{ in } \mathbb{R}. \text{ Every neighborhood } n \in \mathbb{Z}^+ \text{ intersects } \mathbb{Z}^+, \text{ so } \text{cl } \mathbb{Z}^+ \subseteq \mathbb{Z}^+, \text{ and we have that the neighborhood } (0, 1) \text{ of } 0 \text{ intersects } \mathbb{R}^+, \text{ so } \text{cl } \mathbb{R}^+ \subseteq \mathbb{R}^+ \cup \{0\}.$$

**Definition.** If  $A \subseteq X$ , with  $X$  a topological space, and if  $x \in X$ , we say that  $x$  is a **limit point** of  $A$  if every neighborhood of  $x$  intersects  $A$  at some distinct point. That is:  $x \in \text{cl } X \setminus \{x\}$ .

**Example 1.14.** (1) Consider  $(0, 1]$ , we have that  $0 \in [0, 1] = \text{cl } (0, 1] = \text{cl } [0, 1] \setminus \{0\}$ , so 0 is a limit point of  $(0, 1]$ , the same can be said for any  $x \in (0, 1]$ .

(2) For  $\frac{1}{\mathbb{Z}^+}$ , 0 is once again a limit point. Let  $x \in \mathbb{R}$  be nonzero, and let  $[x, b)$  be the neighborhood of  $x$  in the lower limit topology. Then  $[x, b) \cap \frac{1}{\mathbb{Z}^+} = \emptyset$  or  $\{x\}$ , hence, 0 is the only limit point of  $\frac{1}{\mathbb{Z}^+}$ .

(3)  $\text{cl } \{0\} \cup (1, 2) = \{0\} \cup [1, 2]$  has all of its limit points in  $[1, 2]$ . Likewise, every point in  $\mathbb{R}$  is a limit point of  $\mathbb{Q}$ .  $\mathbb{Z}^+$  has no limit points in  $\mathbb{R}$ , and the limit points of  $\mathbb{R}^+$  are all the points of  $\text{cl } \mathbb{R}^+$ .

**Theorem 1.6.7.** *Let  $A \subseteq X$ ,  $X$  a topological space, and let  $A'$  be the set of all limit points in  $A$ . Then  $\text{cl } A = A \cup A'$ .*

*Proof.* Let  $x \in A'$ , then every neighborhood of  $x$  intersects  $A$  at some distinct point  $x'$ , by definition, so by theorem 1.6.6,  $x \in \text{cl } A$ , hence  $A' \subseteq \text{cl } A$ , so  $A \cup A' \subseteq \text{cl } A$ . Now, let  $x \in \text{cl } A$ . If  $x \in A$ , we are done. Otherwise, since every neighborhood of  $x$  intersects  $A$ , we have that they intersect at distinct points, thus  $x \in A'$ , therefore  $\text{cl } A \subseteq A \cup A'$ . ■

**Corollary.**  $A \subseteq X$  is closed if and only if  $A' \subseteq A$ .

*Proof.* If  $A$  is closed, then  $\text{cl } A = A = A \cup A'$ , thus  $A' \subseteq A$ . The converse is obvious. ■

**Example 1.15.** Let  $X$  and  $Y$  be topological spaces, and let  $A \subseteq X$  and  $B \subseteq Y$ . Then  $\text{cl}(A \times B) = \text{cl } A \times \text{cl } B$ . It suffices to show that limit points of one closure is in the other and vice versa as  $A \times B \subseteq \text{cl}(A \times B)$  and  $A \times B \subseteq \text{cl } A \times \text{cl } B$ .

Suppose  $x' \times y' \in (A \times B)'$  is a limit point of  $A \times B$ , then for a neighborhood  $U \times V$  of  $x' \times y'$ , we have  $(U \times V) \cap (A \times B) = (U \cap A) \times (V \cap B) \neq \emptyset$ . Therefore  $U \cap A \neq \emptyset$  and  $V \cap B \neq \emptyset$ . This makes  $x' \in A'$  and  $y' \in B'$ . Therefore  $\text{cl}(A \times B) \subseteq \text{cl } A \times \text{cl } B$ . By similar reasoning, we have the reverse inclusion so that equality is established.

**Definition.** Let  $X$  be a topological space. A sequence of points of  $X$   $\{x_n\}$  is said to **converge** to a point  $x \in X$  if for every neighborhood  $U$  of  $x$ , there is an  $N \in \mathbb{Z}^+$  such that  $x_n \in U$  for all  $n \geq N$ .

**Example 1.16.** (1) Consider the following topological space on  $\{a, b, c\}$  in figure ??, and

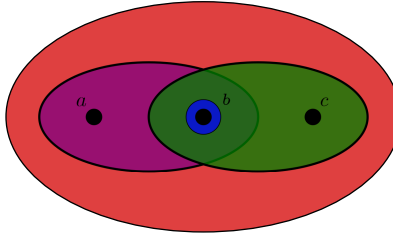


Figure 1.8: A topology on  $\{a, b, c\}$ , is not a Hausdorff space.

define the sequence  $\{x_n\}$  by  $x_n = b$  for all  $n \in \mathbb{Z}^+$ . The neighborhoods of  $a$ ,  $b$ , and  $c$  are  $U_a = \{a, b\}$ ,  $U_b = \{b\}$ , and  $U_c = \{b, c\}$ . Now let  $N > 0$ , then we see that for all  $n \geq N$ , that  $b \in U_a$ ,  $b \in U_b$ , and  $b \in U_c$  thus  $b$  converges to  $a$  and to  $c$ , and itself.

- (2) Consider the sequence of points  $\{\frac{1}{n}\}_{n \in \mathbb{Z}^+}$  of  $\mathbb{R}$  in the finite complement topology. Then for any neighborhood of  $x \in \mathbb{R}$ , which is of the form  $\mathbb{R} \setminus U$ , there are finitely many  $\frac{1}{n}$  not included. Thus we get that  $\lim_{n \rightarrow \infty} \frac{1}{n} = x$  for all  $x \in \mathbb{R}$ .

**Definition.** A topological space  $X$  is called a **Hausdorff space** if for each pair of distinct points  $x$  and  $y$ , there are neighborhoods  $U$  and  $V$  of  $x$  and  $y$  respectively such that  $U$  and  $V$  are disjoint.

**Example 1.17.** The topology of the previous example in figure 1.8 is not a Hausdorff space.

**Theorem 1.6.8.** Every finite point set in a Hausdorff space is closed.



*Proof.* Let  $X$  be a Hausdorff space, and let  $x_0 \in X$ . We have that  $\text{cl}\{x_0\} = \bigcap_{\{x_0\} \in U} U$ . Now let  $x \neq x_0 \in X$ . Since  $x \notin \{x_0\}$ , and  $X$  is Hausdorff, the intersections of the neighborhoods of  $x$  and  $x_0$  is empty, thus  $x \notin \text{cl}\{x_0\}$ , therefore  $\text{cl}\{x_0\} = \{x_0\}$ .

We can then extend this proof to finite point sets of size  $n$  by induction. ■

Now the condition that finite point sets be closed need not depend on whether or not  $X$  is a Hausdorff space. In fact, we can assume the following for some topological spaces.

**Axiom 1.6.1** (The  $T_1$  Axiom). *In any topological space, every finite point set of  $X$  is closed.*

**Theorem 1.6.9.** *Let  $X$  be a topological space satisfying the  $T_1$  axiom, and let  $A \subseteq X$ . Then a point  $x$  is a limit point of  $A$  if and only if every neighborhood of  $x$  contains infinitely many points of  $A$ .*

*Proof.* Let  $U_x$  be a neighborhood of  $x$ . If  $U_x$  intersects  $A$  at infinitely many points of  $A$ , then it intersects  $A$  at a point distinct from  $x$ , thus  $x$  is a limit point of  $A$ .

Conversely suppose that  $x$  is a limit point of  $A$ , and let  $U_x \cap A$  be finite, then  $U_x \cap (A \setminus \{x\})$  is also finite. Now let  $U_x \cap (A \setminus \{x\}) = \{x_1, \dots, x_m\}$ . By the  $T_1$  axiom,  $\{x_1, \dots, x_m\}$  is closed, so  $X \setminus \{x_1, \dots, x_m\}$  is open, thus  $U_x \cap (X \setminus \{x_1, \dots, x_m\})$  is a neighborhood of  $x$  that does not intersect  $A \setminus \{x\}$ , which contradicts that  $x$  is a limit point. ■

**Theorem 1.6.10.** *If  $X$  is a Hausdorff space, then a sequence of points of  $X$  converges to at most one point in  $X$ .*

*Proof.* Let  $\{x_n\}$  be a sequence of points converging to  $x$ , and let  $y \neq x$  and let  $U_x$  and  $U_y$  be neighborhoods of  $x$  and  $y$  respectively. Then  $U_x \cap U_y = \emptyset$ . Now since  $\{x_n\}$  converges to  $x$ , we have that for  $N > 0$ ,  $x_n \in U_x$  whenever  $n \geq N$ . Then  $x_n \notin U_y$ , and so  $\{x_n\}$  cannot converge to  $y$ . ■

**Definition.** Let  $\{x_n\}$  be a sequence in a Hausdorff space  $X$ . If  $\{x_n\}$  converges to a point  $x \in X$ , we call  $x$  the **limit** of  $\{x_n\}$  as  $n$  **approaches**  $\infty$  and we write  $\lim_{n \rightarrow \infty} x_n = x$  or  $\{x_n\} \rightarrow x$  as  $n \rightarrow \infty$ .

**Theorem 1.6.11.** *The following are true:*

- (1) *Every simply ordered set under the order topology is Hausdorff.*
- (2) *The product of two Hausdorff spaces is Hausdorff.*
- (3) *The subspace of a Hausdorff space is Hausdorff.*

*Proof.* (1) Let  $X$  be an ordered set under the order topology. Take  $x, y \in X$  distinct, and suppose without loss of generality that  $x < y$ . Then consider the neighborhoods  $(-\infty, x]$  and  $[y, \infty)$  of  $x$  and  $y$  respectively. Then  $(-\infty, x] \cap [y, \infty) = \emptyset$ .

- (2) Let  $X$  and  $Y$  be Hausdorff, and consider  $X \times Y$  in the product topology. Let  $x_1 \times y_1$  and  $x_2 \times y_2$  be distinct points, and let  $U_{x_1}, U_{x_2}, V_{y_1}$  and  $V_{y_2}$  be basis elements of  $x_1, x_2, y_1$ , and  $y_2$  respectively. Then they are neighborhoods of those elements respectively.

Now we have that  $U_{x_1} \times V_{y_1}$  and  $U_{x_2} \times V_{y_2}$  are basis elements of  $x_1 \times y_1$  and  $x_2 \times y_2$ , respectively, and hence neighborhoods of those elements respectively. Then we have  $(U_{x_1} \times V_{y_1}) \cap (U_{x_2} \times V_{y_2}) = (U_{x_1} \cap U_{x_2}) \times (V_{y_1} \cap V_{y_2}) = \emptyset \times \emptyset = \emptyset$ .

- (3) Let  $X$  be Hausdorff, and let  $Y$  be a subspace of  $X$ . Let  $x_1$  and  $x_2$  be distinct points, and let  $U_{x_1}$  and  $U_{x_2}$  be their neighborhoods. Since  $Y$  is open in  $X$ , then so are  $Y \cap U_{x_1}$  and  $Y \cap U_{x_2}$ , so they are also neighborhoods of  $x_1$  and  $x_2$  respectively. Then  $(Y \cap U_{x_1}) \cap (Y \cap U_{x_2}) = Y \cap (U_{x_1} \cap U_{x_2}) = \emptyset$ .

■

**Definition.** For any set  $X$ , we define the **diagonal** of  $X$  to be the set

$$\Delta(X) = \{x \times x : x \in X\} \quad (1.1)$$

**Theorem 1.6.12.** *A topological space  $X$  is Hausdorff if, and only if the diagonal  $\Delta(X)$  is closed.*

*Proof.* Suppose that  $X$  is Hausdorff, then for any  $x, y \in X$  distinct, there are neighborhoods  $U_x$  and  $U_y$  of  $x$  and  $y$  respectively with  $U_x$  and  $U_y$  disjoint. Notice then that  $X \setminus U_x$  and  $X \setminus U_y$  are closed in  $X$ , hence  $(X \times X) \setminus (U_x \times U_y)$  is also closed. Now, since  $x \neq y$  in the neighborhood of  $U_x \times U_y$  we get that the intersection:

$$\bigcap_{x, y \in X} (X \times X) \setminus (U_x \times U_y) = \Delta(X)$$

So  $\Delta(X)$  is closed.

Conversely, suppose that  $\Delta(X)$  is closed. Then  $(X \times X) \setminus \Delta(X) = \{x \times y : x \neq y\}$  is open. Now, let  $U \times V$  be a neighborhood for some  $x \times y \in (X \times X) \setminus \Delta(X)$  as a subspace of  $X \times X$ . Then  $U$  is a neighborhood for  $x$  and  $V$  is a neighborhood for  $y$ . Now, if  $U \cap V \neq \emptyset$ , there is some  $z \in U$  and  $z \in V$ , so that  $z \times z \in U \times V$ . But  $U \times V$  is a neighborhood contained in  $(X \times X) \setminus \Delta(X)$ , which contradicts  $z \times z \in U \times V$ . Therefore,  $U$  and  $V$  must be disjoint, which makes  $X$  into a Hausdorff space. ■

We conclude this section by looking at another characteristic of sets in topological spaces, closely related to the interior and closure of sets.

**Definition.** Let  $X$  be a topological space, and  $A \subseteq X$ . We define the **boundary** of  $A$

$$\partial A = \text{cl } A \cap \text{cl } (X \setminus A) \quad (1.2)$$

**Example 1.18.** The following are true about the boundary:

- (1)  $\text{int } A$  and  $\partial A$  are disjoint and  $\text{cl } A = \text{int } A \cup \partial A$ .
- (2) If  $A$  is open and closed, then  $\partial A = \emptyset$ .
- (3) If  $A$  is open, then  $\partial A = \text{cl } A \setminus A$ .

## 1.7 Continuous Functions.

**Definition.** Let  $X$  and  $Y$  be topological spaces. We say that a mapping  $f : X \rightarrow Y$  is **continuous** if for each open set  $V$  in  $Y$ ,  $f^{-1}(V)$  is open in  $X$ .

Now if  $f : X \rightarrow Y$  is continuous, then for every open set  $V$  of  $Y$ ,  $f^{-1}(V)$  is open in  $X$ . Now suppose that  $\mathcal{B}$  is a basis of  $Y$ , then  $V = B_\alpha$ , hence  $f^{-1}(B_\alpha)$  is open in  $X$ .

Similarly, if  $\mathcal{S}$  is a subbasis of  $Y$ , then for any basis element  $B$  of  $Y$ ,  $B = \bigcap_{i=1}^n S_i$ , which then implies that  $f^{-1}(B) = \bigcap_{i=1}^n f^{-1}(S_i)$ , thus  $f^{-1}(S_i)$  is also open in  $X$  for  $1 \leq i \leq n$ .

**Example 1.19.** (1) Let  $f : \mathbb{R} \rightarrow \mathbb{R}$  be a continuous realvalued function. Then for each open interval  $I \subseteq \mathbb{R}$ ,  $f^{-1}(I)$  is an open interval in  $\mathbb{R}$ , so take  $x_0 \in \mathbb{R}$  and  $\varepsilon > 0$ , and let  $I = (f(x_0) - \varepsilon, f(x_0) + \varepsilon)$ , then since  $x_0 \in f^{-1}(I)$ , there is a basis  $(a, b) \subseteq f^{-1}(I)$  about  $x_0$ . Then take  $\delta = \min\{x_0 - a, x_0 - b\}$ , then  $x \in (a, b)$  whenever  $0 < |x - x_0| < \delta$ , and we get that  $f(x) \in I$ , that is,  $|f(x) - f(x_0)| < \varepsilon$ . This is the definition of continuity defined in the real analysis. We can prove that the converse holds also.

If  $f : \mathbb{R} \rightarrow \mathbb{R}$  is continuous at a point  $x_0$ , then for every  $\varepsilon > 0$ , there is a  $\delta > 0$  such that  $|f(x) - f(x_0)| < \varepsilon$  whenever  $0 < |x - x_0| < \delta$ . Then we notice that  $x$  and  $x_0$  are distinct, furthermore,  $x_0 - \delta < x < x_0 + \delta$ , hence  $x \in (x_0 - \delta, x_0 + \delta)$  implies that  $f(x) \in (f(x_0) - \varepsilon, f(x_0) + \varepsilon)$ . Letting  $V_\delta(x_0) = (x_0 - \delta, x_0 + \delta)$  and  $V_\varepsilon(f(x_0)) = (f(x_0) - \varepsilon, f(x_0) + \varepsilon)$ , we have that whenever  $x \in V_\delta(x_0)$ , then  $f(x) \in V_\varepsilon(f(x_0)) \subseteq f^{-1}(V_\delta(x_0))$ . And so the topological definition of continuity is equivalent to the real analytic definition of continuity.

(2) Let  $f : \mathbb{R} \rightarrow \mathbb{R}_l$  be defined such that  $f(x) = x$  for all  $x \in \mathbb{R}$ . Take  $[a, b) \subseteq \mathbb{R}_l$ , we have that  $f^{-1}([a, b)) = [a, b)$ , which is not open in  $\mathbb{R}$  (under the standard topology), hence  $f$  is not continuous. However, the map  $g : \mathbb{R}_l \rightarrow \mathbb{R}$  defined the same way is continuous since  $g^{-1}([a, b))$  is open in  $\mathbb{R}_l$ .

**Theorem 1.7.1.** Let  $X$  and  $Y$  be topological spaces, and let  $f : X \rightarrow Y$  be a mapping of  $X$  into  $Y$ . Then the following are equivalent:

- (1)  $f$  is continuous.
- (2) For every  $A \subseteq X$ ,  $f(\text{cl } A) \subseteq \text{cl } f(A)$ .
- (3) For every closed set  $B \subseteq Y$ ,  $f^{-1}(B)$  is closed in  $X$ .
- (4) For each  $x \in X$  and each neighborhood  $V$  of  $f(x)$ , there is a neighborhood  $U$  of  $x$  such that  $f(U) \subseteq V$ .

*Proof.* Let  $f$  be continuous and let  $A \subseteq X$ . Consider the neighborhood  $V$  of  $f(x)$ , then  $f^{-1}(V)$  is open in  $X$ , and intersects  $A$  at a point  $y$ . Then  $V \cap f(A) = f(y)$ , thus  $f(x) \in \text{cl } f(A)$ .

Now let  $B$  be closed in  $Y$ , and let  $A = f^{-1}(B)$ . Then we have that  $f(A) = f(f^{-1}(B)) \subseteq B$ , thus  $x \in \text{cl } A$ .

Now let  $V$  be open in  $Y$ , so that  $B = Y \setminus V$  is closed in  $Y$ , and  $f^{-1}(B) = f^{-1}(Y) \setminus f^{-1}(V) = X \setminus f^{-1}(V)$  which is closed in  $X$ , hence  $f^{-1}(V)$  is open in  $X$ .

Now let  $x \in X$ , and let  $V$  be a neighborhood of  $f(x)$ . Then  $U = f^{-1}(V)$  is a neighborhood of  $x$  for which  $f(U) \subseteq V$ . Finally let  $V$  be open in  $Y$ , and let  $x \in f^{-1}(V)$ , then  $f(x) \in V$ , so there is a neighborhood  $U_x$  of  $x$  for which  $f(U_x) \subseteq V$ , then  $U_x \subseteq f^{-1}(V)$ , then  $f^{-1}(V)$  is a union of open sets, and hence open in  $X$ . ■

**Definition.** Let  $X$  and  $Y$  be topological spaces, and  $f : X \rightarrow Y$  be a 1 – 1 mapping of  $X$  onto  $Y$ . We call  $f$  a **homeomorphism** if both  $f$  and  $f^{-1}$  are continuous.

**Lemma 1.7.2.** *Let  $X$  and  $Y$  be topological spaces and let  $f : X \rightarrow Y$  be a homeomorphism. Then  $f(U)$  is open if and only if  $U$  is open.*

*Proof.* We have that both  $f : X \rightarrow Y$  and  $f^{-1} : Y \rightarrow X$  are continuous 1 – 1 of  $X$  and  $Y$  onto each other (respectively). Now let  $U$  be open in  $X$ , then  $U = f^{-1}(V)$ , for some set  $V$  open in  $Y$ . Notice then, that  $f(U) = f(f^{-1}(V)) = V$ , thus  $f(U)$  is open in  $Y$ . Conversely, let  $V = f(U)$  be open in  $Y$  for some open set  $U$  in  $X$ , then  $U = f^{-1}(V)$ , so by definition of continuity,  $U$  is open in  $X$ . ■

**Definition.** Let  $X$  and  $Y$  be topological spaces and let  $f : X \rightarrow Y$  be a continuous 1 – 1 mapping of  $X$  into  $Y$ , and consider  $f(X)$  as a subspace of  $Y$ . We call  $f : X \rightarrow f(X)$  a **topological imbedding** if  $f$  is a homeomorphism of  $X$  onto  $f(X)$ .

**Example 1.20.** (1) The map  $f : \mathbb{R} \rightarrow \mathbb{R}$  defined by  $f(x) = 3x + 1$  is a homeomorphism whose inverse is  $f^{-1}(y) = \frac{1}{3}(y - 1)$ , both  $f$  and  $f^{-1}$  are continuous.

(2) The map  $f : (-1, 1) \rightarrow \mathbb{R}$  defined by  $f(x) = \frac{x^2}{1-x^2}$  has as its inverse the map  $f : \mathbb{R} \rightarrow (-1, 1)$  defined by  $f^{-1}(y) = \frac{2y}{1+\sqrt{1+4y^2}}$ . Both  $f$  and  $f^{-1}$  are continuous, so  $f$  is a homeomorphism.

(3) The map  $g : \mathbb{R}_l \rightarrow \mathbb{R}$  defined by  $g(x) = x$  is not a homeomorphism, despite being continuous, as  $g^{-1}(1)$  is undefined.

(4) Let  $S^1$  be the unit circle in  $\mathbb{R}^2$ , which is a subspace of  $\mathbb{R}^2$ , and define  $f : [0, 1) \rightarrow S^1$  by  $f(t) = (\cos(2t\pi), \sin(2t\pi))$ . Clearly  $f$  is 1 – 1 onto  $S^1$ , and continuous, however  $f^{-1}$  is not continuous as  $f([0, \frac{1}{4}))$  is not open in  $S^1$  as  $f(0)$  is in no open set of  $\mathbb{R}^2$  such that  $U \cap S^1 = f([0, 1))$ .

(5) Consider the mappings  $g : [0, 1) \rightarrow \mathbb{R}^2$  by  $g(t) = (\cos(2t\pi), \sin(2t\pi))$ . Now  $g$  is 1 – 1 and continuous, and we have that  $g([0, 1)) \subseteq S^1$ , however since  $g$  is not a homeomorphism,  $g$  fails to be a topological embedding.

**Theorem 1.7.3** (Constructions for continuous functions.). *Let  $X$  and  $Y$  be topological spaces, then:*

(1) (Constant construction) *If  $f : X \rightarrow Y$  maps  $x \rightarrow y_0$  for all  $x \in X$ , then  $f$  is continuous.*

(2) (Inclusion) *If  $A \subseteq X$  is a subspace, then the inclusion mapping  $\iota : A \rightarrow X$  is continuous.*

- (3) (Construction by composition) If  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  are continuous, then  $f \circ g : X \rightarrow Z$  is also continuous.
- (4) (Domain restriction) If  $f : X \rightarrow Y$  is continuous and  $A \subseteq X$ , then  $f : A \rightarrow Y$  is continuous.
- (5) (Range restriction) if  $f : X \rightarrow Y$ , and  $Z \subseteq Y$  such that  $f(X) \subseteq Z$ , then  $f : X \rightarrow Z$  is continuous.
- (6) (Range expansion) If  $f : X \rightarrow Y$  is continuous, and  $Y \subseteq Z$  is a subspace of  $Z$ , then  $f : X \rightarrow Z$  is continuous.
- (7) (Local Formulation) The map  $f : X \rightarrow Y$  is continuous if  $X$  can be written as the union of open sets  $U_\alpha$  such that  $f : U_\alpha \rightarrow Y$  is continuous for all  $\alpha$ .

*Proof.* (1) Let  $f(x) = y_0$  for all  $x \in X$ , and let  $V$  be open in  $Y$ , then  $f^{-1}(V) = X$  or  $\emptyset$  depending on if  $y_0 \in V$  or not. In either case,  $f^{-1}(V)$  is open.

(2) If  $U$  is open in  $X$ , then  $f^{-1}(U) = U \cap A$  which is open in the subspace topology of  $X$ .

(3) If  $U$  is open in  $Z$ ,  $g^{-1}(U)$  is open in  $Y$ , hence  $f^{-1}g^{-1}(U)$  is open in  $X$ .

(4) Notice that  $f_A = \iota \circ f = f : A \rightarrow Y$  which is continuous by (2) and (3).

(5) Let  $f : A \rightarrow Y$  be continuous and let  $f(X) \subseteq Z \subseteq Y$ . Let  $B$  be open in  $Z$ , so  $B = Z \cap U$  for some  $U$  open in  $Y$ . Now by hypothesis, we have that  $f^{-1}(U) \subseteq f^{-1}(B)$ , hence  $f^{-1}(B)$  is open in  $X$ , thus  $f : X \rightarrow Z$  is continuous.

(6) Let  $f$  be as in (5), and let  $Y \subseteq Z$  be a subspace of  $Z$ . Then the mapping  $h : X \rightarrow Z$  defined by  $h = \iota \circ f$  is continuous.

(7) Let  $X = \bigcup U_\alpha$  where  $U_\alpha$  is open in  $X$ , and  $f : U_\alpha \rightarrow Y$  is continuous for all  $\alpha$ . Let  $V$  be open in  $Y$ , then  $f^{-1}(V) \cap U_\alpha = f_{U_\alpha}^{-1}(V)$ , and since  $f$  is continuous on  $U_\alpha$ , then  $f^{-1}(V) = \bigcup f_{U_\alpha}^{-1}(V)$  is open in  $X$ . ■

**Theorem 1.7.4** (The pasting lemma). Let  $X = A \cup B$  with  $A$  and  $B$  closed in  $X$ , and let  $f : A \rightarrow Y$  and  $g : B \rightarrow Y$  be continuous. If  $f(x) = g(x)$  for all  $x \in A \cap B$ , then we can construct a mapping  $h : X \rightarrow Y$  defined by  $h(x) = \begin{cases} f(x), & x \in A \\ g(x), & x \in B \end{cases}$ . Then  $h$  is continuous.

*Proof.* Let  $C$  be closed in  $Y$ , then  $h^{-1}(C) = f^{-1}(C) \cup g^{-1}(C)$ . Since  $f$  and  $g$  are continuous, then  $f^{-1}(C)$  and  $g^{-1}(C)$  are closed in  $A$  and  $B$ , respectively. Thus  $h^{-1}(C)$  is closed in  $X$ . ■

**Example 1.21.** Define  $h : \mathbb{R} \rightarrow \mathbb{R}$  by  $h(x) = \begin{cases} x, & x \leq 0 \\ \frac{x}{2}, & x \geq 0 \end{cases}$ . We have that  $x$  and  $\frac{x}{2}$  are continuous on their respective domains, intersecting at 0, i.e.  $x : (-\infty, 0] \rightarrow \mathbb{R}$ ,  $\frac{x}{2} : [0, \infty) \rightarrow \mathbb{R}$ , and  $\{0\} = (-\infty, 0] \cap [0, \infty)$ . Thus  $h$  is continuous on  $\mathbb{R}$ .

However,  $k, l : \mathbb{R} \rightarrow \mathbb{R}$  defined by  $k(x) = \begin{cases} x - 2, & x \leq 0 \\ x + 2, & x \geq 0 \end{cases}$  and  $l(x) = \begin{cases} x - 2, & x < 0 \\ x + 2, & x \geq 0 \end{cases}$  are not continuous. We have that their domains intersect at 0, but that  $k(0) = \pm 2$ , (so  $k$  isn't even a function). Likewise,  $(-\infty, 0) \cap [0, \infty) = \emptyset$ , which is open in  $\mathbb{R}$  see 1.9.

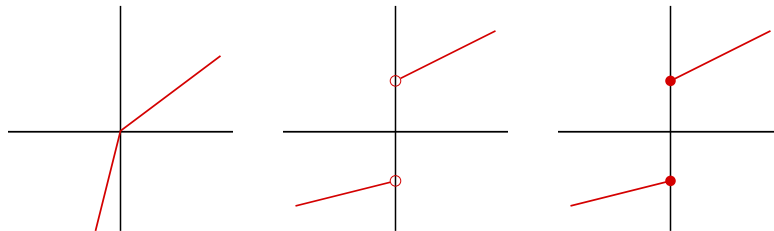


Figure 1.9: The mappings  $h$ ,  $k$ , and  $l$ .

**Theorem 1.7.5.** Let  $f : A \rightarrow X \times Y$  be defined by  $f(a) = (f_1(a), f_2(a))$ , where  $f_1 : A \rightarrow X$  and  $f_2 : A \rightarrow Y$ . Then  $f$  is continuous if and only if  $f_1$  and  $f_2$  are continuous.

*Proof.* Let  $\pi_1 : X \times Y \rightarrow X$  and  $\pi_2 : X \times Y \rightarrow Y$  be projections onto  $X$  and  $Y$  respectively. Since  $\pi_1^{-1}(U) = U \times Y$  and  $\pi_2^{-1}(V) = X \times V$  are both open in  $X \times Y$ ,  $\pi_1$  and  $\pi_2$  are continuous. Then notice that  $f_1(a) = \pi_1 \circ f(a)$  and  $f_2(a) = \pi_2 \circ f(a)$ , both of which are continuous.

Now suppose that  $f_1$  and  $f_2$  are continuous. We have that  $a \in f^{-1}(U \times V)$  if and only if  $f_1(a) \in U$  and  $f_2(a) \in V$ , then  $f_1^{-1}(U)$  and  $f_2^{-1}(V)$  are open in  $A$ , hence so is  $f^{-1}(U \times V) = f_1^{-1}(U) \cap f_2^{-1}(V)$ . ■

**Definition.** We define the **parametrized curve** of the plane  $\mathbb{R}^2$  to be the continuous function  $f : [a, b] \rightarrow \mathbb{R}^2$  defined by  $f(t) = (x(t), y(t))$ . If  $f$  is in a vector field, then we define  $f(t) = x(t)i + y(t)j$  where  $i = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$  and  $j = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ .

**Example 1.22.** The function  $f(t) = ((\cos(t)), \sin(t))$  is a parametrization of the curve  $x^2 + y^2 = 1$ , i.e. the unit circle  $S^1$ .

# Bibliography

- [1] J. Munkres, *Topology*. New York, NY: Pearson, 2018.