



# Introduction to Topology -- 1

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This page contains a detailed introduction to basic [topology](#). Starting from scratch (required background is just a basic concept of [sets](#)), and amplifying motivation from [analysis](#), it first develops standard [point-set topology](#) ([topological spaces](#)). In passing, some basics of [category theory](#) make an informal appearance, used to transparently summarize some conceptually important aspects of the theory, such as [initial](#) and [final topologies](#) and the [reflection](#) into [Hausdorff](#) and [sober topological spaces](#). We close with discussion of the basics of [topological manifolds](#) and [differentiable manifolds](#), laying the foundations for [differential geometry](#). The second part introduces some basics of [homotopy theory](#), mostly the [fundamental group](#), and ends with their first application to the classification of [covering spaces](#).

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**this chapter:** *Introduction to Topology 1 – Point-set topology*

next chapter: [Introduction to Topology 2 -- Basic Homotopy Theory](#)

For introduction to more general and abstract [homotopy theory](#) see instead at [Introduction to Homotopy Theory](#).

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## Point-set Topology

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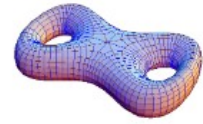
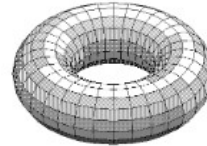
The idea of [topology](#) is to study “[spaces](#)” with “[continuous functions](#)” between them. Specifically one considers [functions](#) between [sets](#) (whence “[point-set topology](#)”, see [below](#)) such that there is a concept for what it means that these functions depend continuously on their arguments, in that their values do not “jump”. Such a concept of [continuity](#) is familiar from [analysis](#) on [metric spaces](#), (recalled [below](#)) but the definition in topology generalizes this analytic concept and renders it more foundational, generalizing the concept of [metric spaces](#) to that of [topological spaces](#). (def. [2.3](#) below).

Hence, [topology](#) is the study of the [category](#) whose [objects](#) are [topological spaces](#), and whose [morphisms](#) are [continuous functions](#) (see also remark [3.3](#) below). This category is much more flexible than that of [metric spaces](#), for example it admits the construction of arbitrary [quotients](#) and [intersections](#) of spaces. Accordingly, topology underlies or informs many and diverse areas of mathematics, such as [functional analysis](#), [operator algebra](#), [manifold/scheme](#) theory, hence [algebraic geometry](#) and [differential geometry](#), and the study of [topological groups](#), [topological vector spaces](#), [local rings](#), etc. Not the least, it gives rise to the field of [homotopy theory](#), where one considers also continuous deformations of continuous functions themselves (“[homotopies](#)”). Topology itself has many branches, such as [low-dimensional topology](#) or [topological domain theory](#).

A popular imagery for the concept of a [continuous function](#) is provided by deformations of [elastic](#) physical bodies, which may be deformed by stretching them without tearing. The canonical illustration is a continuous [bijective](#) function from the [torus](#) to the surface of a coffee mug, which maps half of the torus to the handle

of the coffee mug, and continuously deforms parts of the other half in order to form the actual cup. Since the [inverse function](#) to this function is itself continuous, the torus and the coffee mug, both regarded as [topological spaces](#), are “[the same](#)” for the purposes of [topology](#); one says they are [homeomorphic](#).

On the other hand, there is *no* [homeomorphism](#) from the [torus](#) to, for instance, the [sphere](#), signifying that these represent two topologically distinct spaces. Part of topology is concerned with studying [homeomorphism-invariants](#) of topological spaces



(“[topological properties](#)”) which allow to detect by means of [algebraic](#) manipulations whether two topological spaces are homeomorphic (or more generally [homotopy equivalent](#)) or not. This is called [algebraic topology](#). A basic algebraic invariant is the [fundamental group](#) of a topological space (discussed [below](#)), which measures how many ways there are to wind loops inside a topological space.

Beware the popular imagery of “[rubber-sheet geometry](#)”, which only captures part of the full scope of topology, in that it invokes spaces that *locally* still look like [metric spaces](#) (called [topological manifolds](#), see [below](#)). But the concept of topological spaces is a good bit more general. Notably, [finite topological spaces](#) are either [discrete](#) or very much unlike [metric spaces](#) (example 4.7 below); the former play a role in [categorical logic](#). Also, in [geometry](#), exotic topological spaces frequently arise when forming non-free [quotients](#). In order to gauge just how many of such “exotic” examples of topological spaces beyond locally [metric spaces](#) one wishes to admit in the theory, extra “[separation axioms](#)” are imposed on topological spaces (see [below](#)), and the flavour of topology as a field depends on this choice.

Among the separation axioms, the [Hausdorff space](#) axiom is the most popular (see [below](#)). But the weaker axiom of [sobriety](#) (see [below](#)) stands out, because on the one hand it is the weakest axiom that is still naturally satisfied in applications to [algebraic geometry](#) ([schemes are sober](#)) and [computer science](#) (Vickers 89), and on the other, it fully realizes the strong roots that topology has in [formal logic](#): [sober topological spaces](#) are entirely characterized by the union-, intersection- and inclusion-relations (logical [conjunction](#), [disjunction](#) and [implication](#)) among their [open subsets](#) ([propositions](#)). This leads to a natural and fruitful generalization of [topology](#) to more general “purely logic-determined spaces”, called [locales](#), and in yet more generality, [toposes](#) and [higher toposes](#). While the latter are beyond the scope of this introduction, their rich theory and relation to the [foundations](#) of mathematics and geometry provide an outlook on the relevance of the basic ideas of [topology](#).

In this first part we discuss the foundations of the concept of “sets equipped with topology” ([topological spaces](#)) and of [continuous functions](#) between them.

**(classical logic)**

The [proofs](#) in the following freely use the [principle of excluded middle](#), hence [proof by contradiction](#), and in a few places they also use the [axiom of choice/Zorn's lemma](#).

Hence we discuss [topology](#) in its traditional form with [classical logic](#).

We do however highlight the role of [frame](#) homomorphisms (def. 2.35 below) and that of [sober topological spaces](#) (def. 5.1 below). These concepts pave the way to a [constructive](#) formulation of [topology](#) in terms not of [topological spaces](#) but in terms of [locales](#), see remark 5.8 below. The reader interested in questions of [intuitionistic mathematics](#) in topology may benefit from looking at (Waldijk 96).

## 1. Metric spaces

The concept of continuity was first made precise in [analysis](#), in terms of [epsilon-delta analysis](#) on [metric spaces](#), recalled as def. 1.8 below. Then it was realized that this has a more elegant formulation in terms of the more general concept of [open sets](#), this is prop. 1.14 below. Adopting the latter as the definition leads to a more abstract concept of “continuous space”, this is the concept of [topological spaces](#), def. 2.3 below.

Here we briefly recall the relevant basic concepts from [analysis](#), as a motivation for various definitions in [topology](#). The reader who either already recalls these concepts in analysis or is content with ignoring the motivation coming from analysis should skip right away to the section [Topological spaces](#).

### Definition 1.1. ([metric space](#))

A [metric space](#) is

1. a [set](#)  $X$  (the “underlying set”);
2. a [function](#)  $d : X \times X \rightarrow [0, \infty)$  (the “distance function”) from the [Cartesian product](#) of the set with itself to the [non-negative real numbers](#)

such that for all  $x, y, z \in X$ :

1. (symmetry)  $d(x, y) = d(y, x)$
2. ([triangle inequality](#))  $d(x, z) \leq d(x, y) + d(y, z)$ .
3. (non-degeneracy)  $d(x, y) = 0 \iff x = y$

### Definition 1.2. ([open balls](#))

Let  $(X, d)$ , be a [metric space](#). Then for every element  $x \in X$  and every  $\epsilon \in \mathbb{R}_+$  a

positive real number, we write

$$B_x^\circ(\epsilon) := \{y \in X \mid d(x, y) < \epsilon\}$$

for the open ball of radius  $\epsilon$  around  $x$ . Similarly we write

$$B_x(\epsilon) := \{y \in X \mid d(x, y) \leq \epsilon\}$$

for the *closed ball* of radius  $\epsilon$  around  $x$ . Finally we write

$$S_x(\epsilon) := \{y \in X \mid d(x, y) = \epsilon\}$$

for the sphere of radius  $\epsilon$  around  $x$ .

For  $\epsilon = 1$  we also speak of the *unit open/closed ball* and the *unit sphere*.

**Definition 1.3.** For  $(X, d)$  a metric space (def. 1.1) then a subset  $S \subset X$  is called a bounded subset if  $S$  is contained in some open ball (def. 1.2)

$$S \subset B_x^\circ(r)$$

around some  $x \in X$  of some radius  $r \in \mathbb{R}$ .

A key source of metric spaces are normed vector spaces:

**Dedfinition 1.4. (normed vector space)**

A normed vector space is

1. a real vector space  $V$ ;
2. a function (the norm)

$$\|-\| : V \rightarrow \mathbb{R}_{\geq 0}$$

from the underlying set of  $V$  to the non-negative real numbers,

such that for all  $c \in \mathbb{R}$  with absolute value  $|c|$  and all  $v, w \in V$  it holds true that

1. (linearity)  $\|cv\| = |c|\|v\|$ ;
2. (triangle inequality)  $\|v + w\| \leq \|v\| + \|w\|$ ;
3. (non-degeneracy) if  $\|v\| = 0$  then  $v = 0$ .

**Proposition 1.5.** Every normed vector space  $(V, \|-\|)$  becomes a metric space according to def. 1.1 by setting

$$d(x, y) := \|x - y\| .$$

Examples of normed vector spaces (def. 1.4) and hence, via prop. 1.5, of metric spaces include the following:

**Example 1.6.** For  $n \in \mathbb{N}$ , the Cartesian space

$$\mathbb{R}^n = \{\vec{x} = (x_i)_{i=1}^n \mid x_i \in \mathbb{R}\}$$

carries a norm (the *Euclidean norm*) given by the square root of the sum of the squares of the components:

$$\|\vec{x}\| := \sqrt{\sum_{i=1}^n (x_i)^2}.$$

Via prop. 1.5 this gives  $\mathbb{R}^n$  the structure of a metric space, and as such it is called the Euclidean space of dimension  $n$ .

**Example 1.7.** More generally, for  $n \in \mathbb{N}$ , and  $p \in \mathbb{R}$ ,  $p \geq 1$ , then the Cartesian space  $\mathbb{R}^n$  carries the  $p$ -norm

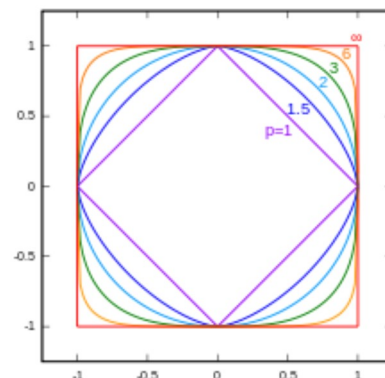
$$\|\vec{x}\|_p := \sqrt[p]{\sum_i |x_i|^p}$$

One also sets

$$\|\vec{x}\|_\infty := \max_{i \in I} |x_i|$$

and calls this the supremum norm.

The graphics on the right (grabbed from Wikipedia) shows unit circles (def. 1.2) in  $\mathbb{R}^2$  with respect to various  $p$ -norms.



By the Minkowski inequality, the  $p$ -norm generalizes to non-finite dimensional vector spaces such as sequence spaces and Lebesgue spaces.

## Continuity

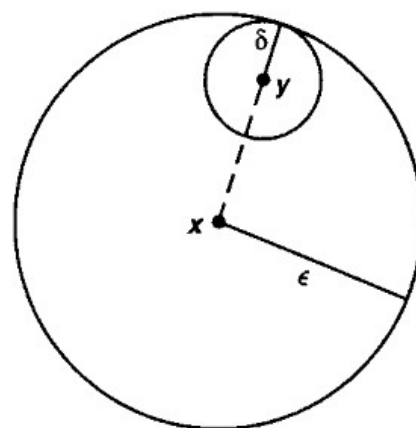
The following is now the fairly obvious definition of continuity for functions between metric spaces.

### Definition 1.8. (epsilontic definition of continuity)

For  $(X, d_X)$  and  $(Y, d_Y)$  two metric spaces (def. 1.1), then a function

$$f : X \rightarrow Y$$

is said to be *continuous at a point*  $x \in X$  if for every positive real number  $\epsilon$  there exists a positive real number  $\delta$  such that for all  $x' \in X$  that are a distance smaller than  $\delta$  from  $x$  then their image  $f(x')$  is a distance smaller than  $\epsilon$  from  $f(x)$ :



$$(f \text{ continuous at } x) := \forall_{\substack{\epsilon \in \mathbb{R} \\ \epsilon > 0}} \left( \exists_{\substack{\delta \in \mathbb{R} \\ \delta > 0}} ((d_X(x, x') < \delta) \Rightarrow (d_Y(f(x), f(x')) < \epsilon)) \right).$$

The function  $f$  is said to be *continuous* if it is continuous at every point  $x \in X$ .

### Example 1.9. (distance function from a subset is continuous)

Let  $(X, d)$  be a [metric space](#) (def. 1.1) and let  $S \subset X$  be a [subset](#) of the underlying set. Define then the function

$$d(S, -) : X \rightarrow \mathbb{R}$$

from the underlying set  $X$  to the [real numbers](#) by assigning to a point  $x \in X$  the [infimum](#) of the [distances](#) from  $x$  to  $s$ , as  $s$  ranges over the elements of  $S$ :

$$d(S, x) := \inf\{d(s, x) \mid s \in S\}.$$

This is a continuous function, with  $\mathbb{R}$  regarded as a [metric space](#) via its [Euclidean norm](#) (example 1.6).

In particular the original distance function  $d(x, -) = d(\{x\}, -)$  is continuous in both its arguments.

**Proof.** Let  $x \in X$  and let  $\epsilon$  be a positive real number. We need to find a positive real number  $\delta$  such that for  $y \in X$  with  $d(x, y) < \delta$  then  $|d(S, x) - d(S, y)| < \epsilon$ .

For  $s \in S$  and  $y \in X$ , consider the [triangle inequalities](#)

$$\begin{aligned} d(s, x) &\leq d(s, y) + d(y, x) \\ d(s, y) &\leq d(s, x) + d(x, y) \end{aligned}$$

Forming the [infimum](#) over  $s \in S$  of all terms appearing here yields

$$\begin{aligned} d(S, x) &\leq d(S, y) + d(y, x) \\ d(S, y) &\leq d(S, x) + d(x, y) \end{aligned}$$

which implies

$$|d(S, x) - d(S, y)| \leq d(x, y).$$

This means that we may take for instance  $\delta := \epsilon$ . ■

### Example 1.10. ([rational functions are continuous](#))

Consider the [real line](#)  $\mathbb{R}$  regarded as the 1-dimensional [Euclidean space](#)  $\mathbb{R}$  from example 1.6.

For  $P \in \mathbb{R}[X]$  a [polynomial](#), then the function

$$\begin{aligned} f_P &: \mathbb{R} \longrightarrow \mathbb{R} \\ x &\mapsto P(x) \end{aligned}$$



is a [continuous function](#) in the sense of def. 1.8. Hence [polynomials are continuous functions](#).

Similarly [rational functions are continuous](#) on their [domain](#) of definition: for  $P, Q \in \mathbb{R}[X]$  two polynomials, then  $\frac{f_P}{f_Q}: \mathbb{R} \setminus \{x \mid f_Q(x) = 0\} \rightarrow \mathbb{R}$  is a continuous function.

Also for instance forming the [square root](#) is a continuous function  $\sqrt{\phantom{x}}: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ .

On the other hand, a [step function](#) is continuous everywhere except at the [finite number](#) of points at which it changes its value, see example 1.15 below.

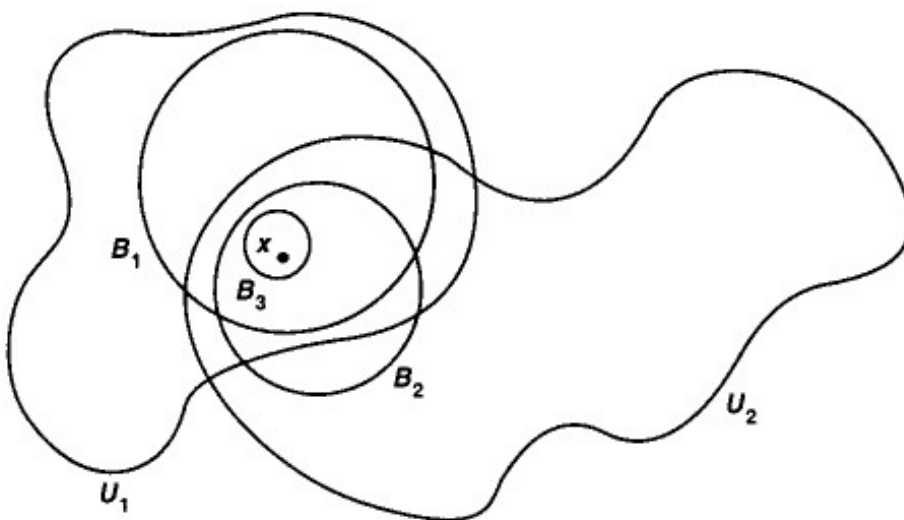
We now reformulate the analytic concept of continuity from def. 1.8 in terms of the simple but important concept of [open sets](#):

### Definition 1.11. (neighbourhood and open set)

Let  $(X, d)$  be a [metric space](#) (def. 1.1). Say that:

1. A [neighbourhood](#) of a point  $x \in X$  is a [subset](#)  $U_x \subset X$  which contains some [open ball](#)  $B_x^\circ(\epsilon) \subset U_x$  around  $x$  (def. 1.2).
2. An [open subset](#) of  $X$  is a [subset](#)  $U \subset X$  such that for every  $x \in U$  it also contains an [open ball](#)  $B_x^\circ(\epsilon)$  around  $x$  (def. 1.2).
3. An [open neighbourhood](#) of a point  $x \in X$  is a [neighbourhood](#)  $U_x$  of  $x$  which is also an open subset, hence equivalently this is any open subset of  $X$  that contains  $x$ .

The following picture shows a point  $x$ , some [open balls](#)  $B_i$  containing it, and two of its [neighbourhoods](#)  $U_i$ :



graphics grabbed from [Munkres 75](#)

### Example 1.12. (the empty subset is open)



Notice that for  $(X, d)$  a [metric space](#), then the [empty subset](#)  $\emptyset \subset X$  is always an [open subset](#) of  $(X, d)$  according to def. [1.11](#). This is because the clause for open subsets  $U \subset X$  says that “for every point  $x \in U$  there exists...”, but since there is no  $x$  in  $U = \emptyset$ , this clause is always satisfied in this case.

Conversely, the entire set  $X$  is always an open subset of  $(X, d)$ .

### Example 1.13. (open/closed [intervals](#))

Regard the [real numbers](#)  $\mathbb{R}$  as the 1-dimensional [Euclidean space](#) (example [1.6](#)).

For  $a < b \in \mathbb{R}$  consider the following [subsets](#):

1.  $(a, b) := \{x \in \mathbb{R} \mid a < x < b\}$  (*open interval*)
2.  $(a, b] := \{x \in \mathbb{R} \mid a < x \leq b\}$  (*half-open interval*)
3.  $[a, b) := \{x \in \mathbb{R} \mid a \leq x < b\}$  (*half-open interval*)
4.  $[a, b] := \{x \in \mathbb{R} \mid a \leq x \leq b\}$  (*closed interval*)

The first of these is an open subset according to def. [1.11](#), the other three are not. The first one is called an [open interval](#), the last one a [closed interval](#) and the middle two are called [half-open intervals](#).

Similarly for  $a, b \in \mathbb{R}$  one considers

1.  $(-\infty, b) := \{x \in \mathbb{R} \mid x < b\}$  (*unbounded open interval*)
2.  $(a, \infty) := \{x \in \mathbb{R} \mid a < x\}$  (*unbounded open interval*)
3.  $(-\infty, b] := \{x \in \mathbb{R} \mid x \leq b\}$  (*unbounded half-open interval*)
4.  $[a, \infty) := \{x \in \mathbb{R} \mid a \leq x\}$  (*unbounded half-open interval*)

The first two of these are open subsets, the last two are not.

For completeness we may also consider

- $(-\infty, \infty) = \mathbb{R}$
- $(a, a) = \emptyset$

which are both open, according to def. [2.3](#).

We may now rephrase the analytic definition of continuity entirely in terms of open subsets (def. [1.11](#)):

### Proposition 1.14. (rephrasing continuity in terms of open sets)

Let  $(X, d_X)$  and  $(Y, d_Y)$  be two [metric spaces](#) (def. [1.1](#)). Then a [function](#)  $f: X \rightarrow Y$  is [continuous](#) in the [epsilon-delta](#) sense of def. [1.8](#) precisely if it has the property that its [pre-images](#) of [open subsets](#) of  $Y$  (in the sense of def. [1.11](#)) are open subsets

of  $X$ :

$$(f \text{ continuous}) \Leftrightarrow ((O_Y \subset Y \text{ open}) \Rightarrow (f^{-1}(O_Y) \subset X \text{ open})).$$

### principle of continuity

*Continuous pre-Images of open subsets are open.*

**Proof.** Observe, by direct unwinding the definitions, that the epsilonic definition of continuity (def. 1.8) says equivalently in terms of [open balls](#) (def. 1.2) that  $f$  is continuous at  $x$  precisely if for every open ball  $B_{f(x)}^\circ(\epsilon)$  around an image point, there exists an open ball  $B_x^\circ(\delta)$  around the corresponding pre-image point which maps into it:

$$\begin{aligned} (f \text{ continuous at } x) &\Leftrightarrow \forall_{\epsilon > 0} \left( \exists_{\delta > 0} (f(B_x^\circ(\delta)) \subset B_{f(x)}^\circ(\epsilon)) \right) \\ &\Leftrightarrow \forall_{\epsilon > 0} \left( \exists_{\delta > 0} (B_x^\circ(\delta) \subset f^{-1}(B_{f(x)}^\circ(\epsilon))) \right). \end{aligned}$$

With this observation the proof immediate. For the record, we spell it out:

First assume that  $f$  is continuous in the epsilonic sense. Then for  $O_Y \subset Y$  any [open subset](#) and  $x \in f^{-1}(O_Y)$  any point in the pre-image, we need to show that there exists an [open neighbourhood](#) of  $x$  in  $f^{-1}(O_Y)$ .

That  $O_Y$  is open in  $Y$  means by definition that there exists an [open ball](#)  $B_{f(x)}^\circ(\epsilon)$  in  $O_Y$  around  $f(x)$  for some radius  $\epsilon$ . By the assumption that  $f$  is continuous and using the above observation, this implies that there exists an open ball  $B_x^\circ(\delta)$  in  $X$  such that  $f(B_x^\circ(\delta)) \subset B_{f(x)}^\circ(\epsilon) \subset Y$ , hence such that  $B_x^\circ(\delta) \subset f^{-1}(B_{f(x)}^\circ(\epsilon)) \subset f^{-1}(O_Y)$ . Hence this is an open ball of the required kind.

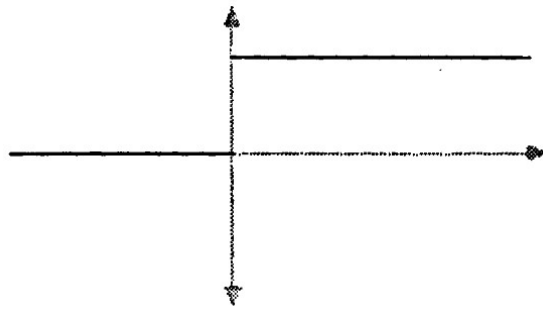
Conversely, assume that the pre-image function  $f^{-1}$  takes open subsets to open subsets. Then for every  $x \in X$  and  $B_{f(x)}^\circ(\epsilon) \subset Y$  an [open ball](#) around its image, we need to produce an open ball  $B_x^\circ(\delta) \subset X$  around  $x$  such that  $f(B_x^\circ(\delta)) \subset B_{f(x)}^\circ(\epsilon)$ .

But by definition of open subsets,  $B_{f(x)}^\circ(\epsilon) \subset Y$  is open, and therefore by assumption on  $f$  its pre-image  $f^{-1}(B_{f(x)}^\circ(\epsilon)) \subset X$  is also an open subset of  $X$ . Again by definition of open subsets, this implies that it contains an open ball as required. ■

### Example 1.15. ([step function](#))

Consider  $\mathbb{R}$  as the 1-dimensional [Euclidean space](#) (example 1.6) and consider the [step function](#)

$$\begin{aligned} \mathbb{R} &\xrightarrow{H} \mathbb{R} \\ x &\mapsto \begin{cases} 0 & | x \leq 0 \\ 1 & | x > 0 \end{cases} \end{aligned}$$



graphics grabbed from [Vickers 89](#)

Consider then for  $a < b \in \mathbb{R}$  the [open interval](#)  $(a, b) \subset \mathbb{R}$ , an [open subset](#) according to example 1.13. The [preimage](#)  $H^{-1}(a, b)$  of this open subset is

$$H^{-1} : (a, b) \mapsto \begin{cases} \emptyset & | a \geq 1 \text{ or } b \leq 0 \\ \mathbb{R} & | a < 0 \text{ and } b > 1 \\ \emptyset & | a \geq 0 \text{ and } b \leq 1 \\ (0, \infty) & | 0 \leq a < 1 \text{ and } b > 1 \\ (-\infty, 0] & | a < 0 \text{ and } b \leq 1 \end{cases}.$$

By example 1.13, all except the last of these pre-images listed are open subsets.

The failure of the last of the pre-images to be open witnesses that the step function is not continuous at  $x = 0$ .

## Compactness

A key application of [metric spaces](#) in [analysis](#) is that they allow a formalization of what it means for an infinite [sequence](#) of elements in the metric space (def. 1.16 below) to [converge](#) to a [limit of a sequence](#) (def. 1.17 below). Of particular interest are therefore those metric spaces for which each sequence has a converging subsequence: the [sequentially compact metric spaces](#) (def. 1.20).

We now briefly recall these concepts from [analysis](#). Then, in the above spirit, we reformulate their epsilon-delta definition in terms of [open subsets](#). This gives a useful definition that generalizes to [topological spaces](#), the [compact topological spaces](#) discussed further [below](#).

### Definition 1.16. ([sequence](#))

Given a [set](#)  $X$ , then a [sequence](#) of elements in  $X$  is a [function](#)

$$x_{(-)} : \mathbb{N} \rightarrow X$$

from the [natural numbers](#) to  $X$ .

A [sub-sequence](#) of such a sequence is a sequence of the form

$$x_{i(-)} : \mathbb{N} \xrightarrow{i} \mathbb{N} \xrightarrow{x_{(-)}} X$$

for some [injection](#)  $\iota$ .

### Definition 1.17. ([convergence to limit of a sequence](#))

Let  $(X, d)$  be a [metric space](#) (def. 1.1). Then a [sequence](#)

$$x_{(-)} : \mathbb{N} \rightarrow X$$

in the underlying set  $X$  (def. 1.16) is said to [converge](#) to a point  $x_\infty \in X$ , denoted

$$x_i \xrightarrow{i \rightarrow \infty} x_\infty$$

if for every [positive real number](#)  $\epsilon$ , there exists a [natural number](#)  $n$ , such that all elements in the sequence after the  $n$ th one have [distance](#) less than  $\epsilon$  from  $x_\infty$ .

$$\left( x_i \xrightarrow{i \rightarrow \infty} x_\infty \right) \Leftrightarrow \left( \bigvee_{\substack{\epsilon \in \mathbb{R} \\ \epsilon > 0}} \left( \bigvee_{n \in \mathbb{N}} \left( \bigvee_{\substack{i \in \mathbb{N} \\ i > n}} d(x_i, x_\infty) \leq \epsilon \right) \right) \right).$$

Here the point  $x_\infty$  is called the [limit of the sequence](#). Often one writes  $\lim_{i \rightarrow \infty} x_i$  for this point.

### Definition 1.18. ([Cauchy sequence](#))

Given a [metric space](#)  $(X, d)$  (def. 1.1), then a [sequence](#) of points in  $X$  (def. 1.16)

$$x_{(-)} : \mathbb{N} \rightarrow X$$

is called a [Cauchy sequence](#) if for every [positive real number](#)  $\epsilon$  there exists a [natural number](#)  $n \in \mathbb{N}$  such that the [distance](#) between any two elements of the sequence beyond the  $n$ th one is less than  $\epsilon$

$$(x_{(-)} \text{ Cauchy}) \Leftrightarrow \left( \bigvee_{\substack{\epsilon \in \mathbb{R} \\ \epsilon > 0}} \left( \bigvee_{N \in \mathbb{N}} \left( \bigvee_{\substack{i, j \in \mathbb{N} \\ i, j > N}} d(x_i, x_j) \leq \epsilon \right) \right) \right).$$

### Definition 1.19. ([complete metric space](#))

A [metric space](#)  $(X, d)$  (def. 1.1), for which every [Cauchy sequence](#) (def. 1.18) [converges](#) (def. 1.17) is called a [complete metric space](#).

A [normed vector space](#), regarded as a metric space via prop. 1.5 that is complete in this sense is called a [Banach space](#).

Finally recall the concept of [compactness](#) of [metric spaces](#) via [epsilon-delta analysis](#):

### Definition 1.20. ([sequentially compact metric space](#))

A [metric space](#)  $(X, d)$  (def. 1.1) is called [sequentially compact](#) if every [sequence](#) in  $X$  has a subsequence (def. 1.16) which [converges](#) (def. 1.17).

The key fact to translate this [epsilon-delta](#) definition of compactness to a concept that

makes sense for general [topological spaces](#) (below) is the following:

**Proposition 1.21. ([sequentially compact metric spaces are equivalently compact metric spaces](#))**

For a [metric space](#)  $(X, d)$  (def. 1.1) the following are equivalent:

1.  $X$  is [sequentially compact](#);
2. for every [set](#)  $\{U_i \subset X\}_{i \in I}$  of [open subsets](#)  $U_i$  of  $X$  (def. 1.11) which [cover](#)  $X$  in that  $X = \bigcup_{i \in I} U_i$ , then there exists a [finite subset](#)  $J \subset I$  of these open subsets which still covers  $X$  in that also  $X = \bigcup_{i \in J \subset I} U_i$ .

The **proof** of prop. 1.21 is most conveniently formulated with some of the terminology of topology in hand, which we introduce now. Therefore we postpone the proof to [below](#).

In **summary** prop. 1.14 and prop. 1.21 show that the purely combinatorial and in particular non-[epsilon](#) concept of [open subsets](#) captures a substantial part of the nature of [metric spaces](#) in [analysis](#). This motivates to reverse the logic and consider more general “[spaces](#)” which are *only* characterized by what counts as their open subsets. These are the [topological spaces](#) which we turn to now in def. 2.3 (or, more generally, these are the “[locales](#)”, which we briefly consider below in remark 5.8).

## 2. Topological spaces

Due to prop. 1.14 we should pay attention to [open subsets](#) in [metric spaces](#). It turns out that the following closure property, which follow directly from the definitions, is at the heart of the concept:

**Proposition 2.1. ([closure properties of open sets in a metric space](#))**

The collection of [open subsets](#) of a [metric space](#)  $(X, d)$  as in def. 1.11 has the following properties:

1. The [union](#) of any [set](#) of open subsets is again an open subset.
2. The [intersection](#) of any [finite number](#) of open subsets is again an open subset.

**Remark 2.2. ([empty union and empty intersection](#))**

Notice the degenerate case of [unions](#)  $\bigcup_{i \in I} U_i$  and [intersections](#)  $\bigcap_{i \in I} U_i$  of [subsets](#)  $U_i \subset X$  for the case that they are indexed by the [empty set](#)  $I = \emptyset$ :

1. the *empty union* is the empty set itself;

2. the *empty intersection* is all of  $X$ .

(The second of these may seem less obvious than the first. We discuss the general logic behind these kinds of phenomena [below](#).)

This way prop. [2.1](#) is indeed compatible with the degenerate cases of examples of open subsets in example [1.12](#).

Proposition [2.1](#) motivates the following generalized definition, which abstracts away from the concept of [metric space](#) just its system of [open subsets](#):

### Definition 2.3. ([topological spaces](#))

Given a [set](#)  $X$ , then a *topology* on  $X$  is a collection  $\tau$  of [subsets](#) of  $X$  called the [open subsets](#), hence a [subset](#) of the [power set](#)  $P(X)$

$$\tau \subset P(X)$$

such that this is closed under forming

1. finite [intersections](#);
2. arbitrary [unions](#).

In particular (by remark [2.2](#)):

- the [empty set](#)  $\emptyset \subset X$  is in  $\tau$  (being the union of no subsets)

and

- the whole set  $X \subset X$  itself is in  $\tau$  (being the intersection of no subsets).

A set  $X$  equipped with such a [topology](#) is called a [topological space](#).

**Remark 2.4.** In the field of [topology](#) it is common to eventually simply say “[space](#)” as shorthand for “[topological space](#)”. This is especially so as further qualifiers are added, such as “Hausdorff space” (def. [4.4](#) below). But beware that there are other kinds of [spaces](#) in mathematics.

**Remark 2.5.** The simple definition of [open subsets](#) in def. [2.3](#) and the simple implementation of the *principle of continuity* below in def. [3.1](#) gives the field of [topology](#) its fundamental and universal flavor. The combinatorial nature of these definitions makes [topology](#) be closely related to [formal logic](#). This becomes more manifest still for the “[sober topological space](#)” discussed [below](#). For more on this perspective see the remark on [locales](#) below, remark [5.8](#). An introductory textbook amplifying this perspective is ([Vickers 89](#)).

Before we look at first examples [below](#), here is some common **further terminology** regarding topological spaces:

There is an evident [partial ordering](#) on the set of topologies that a given set may carry:

**Definition 2.6. (finer/coarser topologies)**

Let  $X$  be a set, and let  $\tau_1, \tau_2 \in P(X)$  be two topologies on  $X$ , hence two choices of open subsets for  $X$ , making it a topological space. If

$$\tau_1 \subset \tau_2$$

hence if every open subset of  $X$  with respect to  $\tau_1$  is also regarded as open by  $\tau_2$ , then one says that

- the topology  $\tau_2$  is finer than the topology  $\tau_1$
- the topology  $\tau_1$  is coarser than the topology  $\tau_2$ .

With any kind of structure on sets, it is of interest how to “generate” such structures from a small amount of data:

**Definition 2.7. (basis for the topology)**

Let  $(X, \tau)$  be a topological space, def. 2.3, and let

$$\beta \subset \tau$$

be a subset of its set of open subsets. We say that

1.  $\beta$  is a basis for the topology  $\tau$  if every open subset  $O \in \tau$  is a union of elements of  $\beta$ ;
2.  $\beta$  is a sub-basis for the topology if every open subset  $O \in \tau$  is a union of finite intersections of elements of  $\beta$ .

Often it is convenient to *define* topologies by defining some (sub-)basis as in def. 2.7. Examples are the metric topology below, example 2.9, the binary product topology in def. 2.18 below, and the compact-open topology on mapping spaces below in def. 7.28. To make use of this, we need to recognize sets of open subsets that serve as the basis for some topology:

**Lemma 2.8. (recognition of topological bases)**

Let  $X$  be a set.

1. A collection  $\beta \subset P(X)$  of subsets of  $X$  is a basis for some topology  $\tau \subset P(X)$  (def. 2.7) precisely if
  1. every point of  $X$  is contained in at least one element of  $\beta$ ;
  2. for every two subsets  $B_1, B_2 \in \beta$  and for every point  $x \in B_1 \cap B_2$  in their intersection, then there exists a  $B \in \beta$  that contains  $x$  and is contained in the intersection:  $x \in B \subset B_1 \cap B_2$ .
2. A subset  $B \subset \tau$  of open subsets is a sub-basis for a topology  $\tau$  on  $X$  precisely if  $\tau$  is the coarsest topology (def. 2.6) which contains  $B$ .



## Examples

We discuss here some basic examples of [topological spaces](#) (def. 2.3), to get a feeling for the scope of the concept. But topological spaces are ubiquitous in [mathematics](#), so that there are many more examples and many more classes of examples than could be listed. As we further develop the theory below, we encounter more examples, and more classes of examples. Below in [Universal constructions](#) we discuss a very general construction principle of new topological space from given ones.

First of all, our motivating example from [above](#) now reads as follows:

### Example 2.9. ([metric topology](#))

Let  $(X, d)$  be a [metric space](#) (def. 1.1). Then the collection of its [open subsets](#) in def. 1.11 constitutes a [topology](#) on the set  $X$ , making it a [topological space](#) in the sense of def. 2.3. This is called the [metric topology](#).

The [open balls](#) in a metric space constitute a [basis of a topology](#) (def. 2.7) for the [metric topology](#).

While the example of [metric space](#) topologies (example 2.9) is the motivating example for the concept of [topological spaces](#), it is important to notice that the concept of topological spaces is considerably more general, as some of the following examples show.

The following simplistic example of a (metric) topological space is important for the theory (for instance in prop. 2.38):

### Example 2.10. ([empty space](#) and [point space](#))

On the [empty set](#) there exists a unique topology  $\tau$  making it a [topological space](#) according to def. 2.3. We write also

$$\emptyset := (\emptyset, \tau_{\emptyset} = \{\emptyset\})$$

for the resulting [topological space](#), which we call the [empty topological space](#).

On a [singleton](#) set  $\{1\}$  there exists a unique topology  $\tau$  making it a [topological space](#) according to def. 2.3, namely

$$\tau := \{\emptyset, \{1\}\}.$$

We write

$$* := (\{1\}, \tau := \{\emptyset, \{1\}\})$$

for this topological space and call it *the* [point topological space](#).

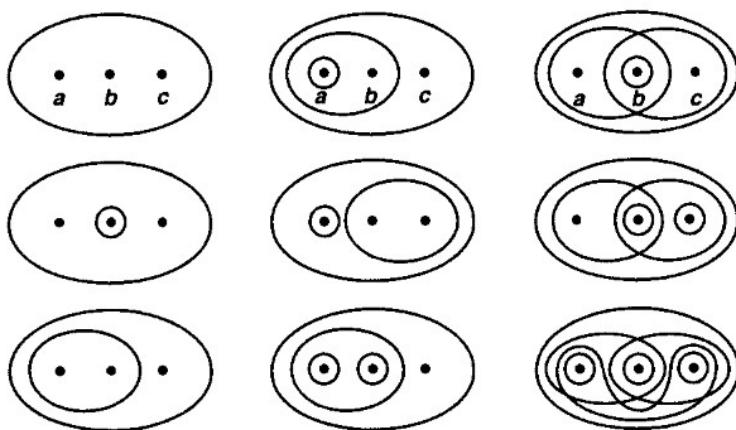
This is equivalently the [metric topology](#) (example 2.9) on  $\mathbb{R}^0$ , regarded as the

0-dimensional [Euclidean space](#) (example 1.6).

**Example 2.11.** On the 2-element set  $\{0, 1\}$  there are (up to [permutation](#) of elements) three distinct topologies:

1. the [codiscrete topology](#) (def. 2.13)  $\tau = \{\emptyset, \{0, 1\}\}$ ;
2. the [discrete topology](#) (def. 2.13),  $\tau = \{\emptyset, \{0\}, \{1\}, \{0, 1\}\}$ ;
3. the [Sierpinski space](#) topology  $\tau = \{\emptyset, \{1\}, \{0, 1\}\}$ .

**Example 2.12.** The following shows all the topologies on the 3-element set (up to [permutation](#) of elements)



graphics grabbed from [Munkres 75](#)

### Example 2.13. (discrete and co-discrete topology)

Let  $S$  be any [set](#). Then there are always the following two extreme possibilities of equipping  $X$  with a topology  $\tau \subset P(X)$  in the sense of def. 2.3, and hence making it a [topological space](#):

1.  $\tau := P(S)$  the set of *all* open subsets;

this is called the [discrete topology](#) on  $S$ , it is the [finest topology](#) (def. 2.6) on  $X$ ,

we write  $\text{Disc}(S)$  for the resulting topological space;

2.  $\tau := \{\emptyset, S\}$  the set containing only the [empty](#) subset of  $S$  and all of  $S$  itself;

this is called the [codiscrete topology](#) on  $S$ , it is the [coarsest topology](#) (def. 2.6) on  $X$ ,

we write  $\text{CoDisc}(S)$  for the resulting topological space.

The reason for this terminology is best seen when considering [continuous functions](#) into or out of these (co-)discrete topological spaces, we come to this in example 3.8 below.

**Example 2.14. (cofinite topology)**

Given a set  $X$ , then the cofinite topology or *finite complement topology* on  $X$  is the topology (def. 2.3) whose open subsets are precisely

1. all cofinite subsets  $S \subset X$  (i.e. those such that the complement  $X \setminus S$  is a finite set);
2. the empty set.

If  $X$  is itself a finite set (but not otherwise) then the cofinite topology on  $X$  coincides with the discrete topology on  $X$  (example 2.13).

We now consider basic construction principles of new topological spaces from given ones:

1. disjoint union spaces (example 2.15)
2. subspaces (example 2.16),
3. quotient spaces (example 2.17)
4. product spaces (example 2.18).

Below in Universal constructions we will recognize these as simple special cases of a general construction principle.

**Example 2.15. (disjoint union space)**

For  $\{(X_i, \tau_i)\}_{i \in I}$  a set of topological spaces, then their disjoint union

$$\bigsqcup_{i \in I} (X_i, \tau_i)$$

is the topological space whose underlying set is the disjoint union of the underlying sets of the summand spaces, and whose open subsets are precisely the disjoint unions of the open subsets of the summand spaces.

In particular, for  $I$  any index set, then the disjoint union of  $I$  copies of the point space (example 2.10) is equivalently the discrete topological space (example 2.13) on that index set:

$$\bigsqcup_{i \in I} * = \text{Disc}(I) .$$

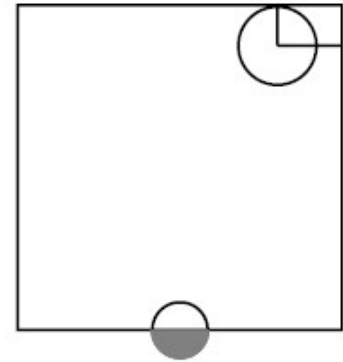
**Example 2.16. (subspace topology)**

Let  $(X, \tau_X)$  be a topological space, and let  $S \subset X$  be a subset of the underlying set. Then the corresponding topological subspace has  $S$  as its underlying set, and its open subsets are those subsets of  $S$  which arise as restrictions of open subsets of  $X$ .

$$(U_S \subset S \text{ open}) \Leftrightarrow \left( \bigcup_{U_X \in \tau_X} (U_S = U_X \cap S) \right).$$

(This is also called the *initial topology* of the inclusion map. We come back to this below in def. 6.17.)

The picture on the right shows two open subsets inside the square, regarded as a topological subspace of the plane  $\mathbb{R}^2$ :



graphics grabbed from Munkres 75

### Example 2.17. (quotient topological space)

Let  $(X, \tau_X)$  be a topological space (def. 2.3) and let

$$R_\sim \subset X \times X$$

be an equivalence relation on its underlying set. Then the quotient topological space has

- as underlying set the quotient set  $X / \sim$ , hence the set of equivalence classes,

and

- a subset  $O \subset X / \sim$  is declared to be an open subset precisely if its preimage  $\pi^{-1}(O)$  under the canonical projection map

$$\pi : X \rightarrow X / \sim$$

is open in  $X$ .

(This is also called the *final topology* of the projection  $\pi$ . We come back to this below in def. 6.17. )

Often one considers this with input datum not the equivalence relation, but any surjection

$$\pi : X \rightarrow Y$$

of sets. Of course this identifies  $Y = X / \sim$  with  $(x_1 \sim x_2) \Leftrightarrow (\pi(x_1) = \pi(x_2))$ . Hence the *quotient topology* on the codomain set of a function out of any topological space has as open subsets those whose pre-images are open.

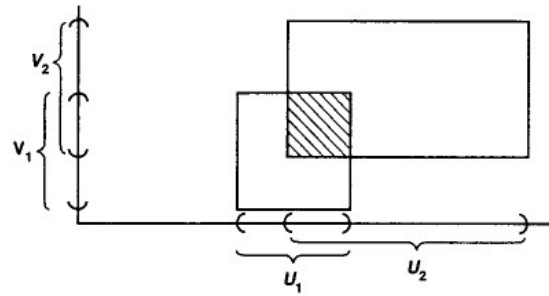
To see that this indeed does define a topology on  $X / \sim$  it is sufficient to observe that taking pre-images commutes with taking unions and with taking intersections.

### Example 2.18. (binary product topological space)

For  $(X_1, \tau_{X_1})$  and  $(X_2, \tau_{X_2})$  two topological spaces, then their binary product topological space has as underlying set the Cartesian product  $X_1 \times X_2$  of the

corresponding two underlying sets, and its topology is generated from the [basis](#) (def. 2.7) given by the Cartesian products  $U_1 \times U_2$  of the opens  $U_i \in \tau_i$ .

graphics grabbed from [Munkres 75](#)



Beware for non-[finite](#) products, the descriptions of the product topology is not as simple. This we turn to below in example 6.25, after introducing the general concept of [limits](#) in the [category of topological spaces](#).

The following examples illustrate how all these ingredients and construction principles may be combined.

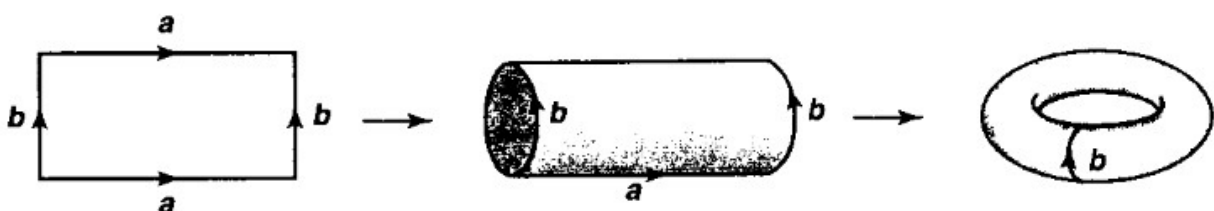
The following example we will examine in more detail below in example 3.30, after we have introduced the concept of [homeomorphisms](#) below.

**Example 2.19.** Consider the [real numbers](#)  $\mathbb{R}$  as the 1-dimensional [Euclidean space](#) (example 1.6) and hence as a [topological space](#) via the corresponding [metric topology](#) (example 2.9). Moreover, consider the [closed interval](#)  $[0, 1] \subset \mathbb{R}$  from example 1.13, regarded as a [subspace](#) (def. 2.16) of  $\mathbb{R}$ .

The [product space](#) (example 2.18) of this interval with itself

$$[0, 1] \times [0, 1]$$

is a topological space modelling the closed square. The [quotient space](#) (example 2.17) of that by the relation which identifies a pair of opposite sides is a model for the [cylinder](#). The further quotient by the relation that identifies the remaining pair of sides yields a model for the [torus](#).



graphics grabbed from [Munkres 75](#)

**Example 2.20. ([spheres](#) and disks)**

For  $n \in \mathbb{N}$  write

- $D^n$  for the [n-disk](#), the [closed unit ball](#) (def. 1.2) in the  $n$ -dimensional [Euclidean space](#)  $\mathbb{R}^n$  (example 1.6) and equipped with the induced [subspace topology](#) (example 2.16) of the corresponding [metric topology](#) (example 2.9);
- $S^{n-1}$  for the [\(n-1\)-sphere](#) (def. 1.2) also equipped with the corresponding

subspace topology;

- $i_n : S^{n-1} \hookrightarrow D^n$  for the continuous function that exhibits this boundary inclusion.

Notice that

- $S^{-1} = \emptyset$  is the empty topological space (example 2.10);
- $S^0 = * \sqcup *$  is the disjoint union space (example 2.15) of the point topological space (example 2.10) with itself, equivalently the discrete topological space on two elements (example 2.11).

The following important class of topological spaces form the foundation of algebraic geometry:

**Example 2.21. (Zariski topology on affine space)**

Let  $k$  be a field, let  $n \in \mathbb{N}$ , and write  $k[X_1, \dots, X_n]$  for the set of polynomials in  $n$  variables over  $k$ .

For  $\mathcal{F} \subset k[X_1, \dots, X_n]$  a subset of polynomials, let the subset  $V(\mathcal{F}) \subset k^n$  of the  $n$ -fold Cartesian product of the underlying set of  $k$  (the *vanishing set* of  $\mathcal{F}$ ) be the subset of points on which all these polynomials jointly vanish:

$$V(\mathcal{F}) := \left\{ (a_1, \dots, a_n) \in k^n \mid \forall_{f \in \mathcal{F}} f(a_1, \dots, a_n) = 0 \right\}.$$

These subsets are called the *Zariski closed subsets*.

Write

$$\tau_{\mathbb{A}_k^n} := \{ k^n \setminus V(\mathcal{F}) \subset k^n \mid \mathcal{F} \subset k[X_1, \dots, X_n] \}$$

for the set of complements of the Zariski closed subsets. These are called the *Zariski open subsets* of  $k^n$ .

The Zariski open subsets of  $k^n$  form a topology (def. 2.3), called the Zariski topology. The resulting topological space

$$\mathbb{A}_k^n := (k^n, \tau_{\mathbb{A}_k^n})$$

is also called the  $n$ -dimensional affine space over  $k$ .

More generally

**Example 2.22. (Zariski topology on the prime spectrum of a commutative ring)**

Let  $R$  be a commutative ring. Write  $\text{PrimeIdl}(R)$  for its set of prime ideals. For  $\mathcal{F} \subset R$  any subset of elements of the ring, consider the subsets of those prime ideals that contain  $\mathcal{F}$ :

$$V(\mathcal{F}) := \{p \in \text{PrimeIdl}(R) \mid \mathcal{F} \subset p\}.$$

These are called the *Zariski closed subsets* of  $\text{PrimeIdl}(R)$ . Their *complements* are called the *Zariski open subsets*.

Then the collection of Zariski open subsets in its set of *prime ideals*

$$\tau_{\text{Spec}(R)} \subset P(\text{PrimeIdl}(R))$$

satisfies the axioms of a *topology* (def. 2.3), the *Zariski topology*.

This *topological space*

$$\text{Spec}(R) := (\text{PrimeIdl}(R), \tau_{\text{Spec}(R)})$$

is called (the space underlying) the *prime spectrum of the commutative ring*.

## Closed subsets

The *complements* of *open subsets* in a *topological space* are called *closed subsets* (def. 2.23 below). This simple definition indeed captures the concept of closure in the *analytic* sense of *convergence* of *sequences* (prop. 2.29 below). Of particular interest for the theory of topological spaces in the discussion of *separation axioms* below are those closed subsets which are “*irreducible*” (def. 2.31 below). These happen to be equivalently the “*frame* homomorphisms” (def. 2.35) to the *frame of opens* of the point (prop. 2.38 below).

### Definition 2.23. (*closed subsets*)

Let  $(X, \tau)$  be a *topological space* (def. 2.3).

1. A *subset*  $S \subset X$  is called a *closed subset* if its *complement*  $X \setminus S$  is an *open subset*:

$$(S \subset X \text{ is closed}) \quad \Leftrightarrow \quad (X \setminus S \subset X \text{ is open}).$$

*graphics grabbed from Vickers 89*



open



closed



neither

2. If a *singleton* subset  $\{x\} \subset X$  is closed, one says that  $x$  is a *closed point* of  $X$ .
3. Given any subset  $S \subset X$ , then its *topological closure*  $\text{Cl}(S)$  is the smallest closed subset containing  $S$ :

$$\text{Cl}(S) := \bigcap_{\substack{C \subset X \text{ closed} \\ S \subset C}} (C).$$

4. A subset  $S \subset X$  such that  $\text{Cl}(S) = X$  is called a *dense subset* of  $(X, \tau)$ .

### Remark 2.24. (*de Morgan's law*)



In reasoning about [closed subsets](#) in [topology](#) (def. 2.23) we are concerned with [complements](#) of [unions](#) and [intersections](#) as well as with [unions/intersections](#) of [complements](#). Recall therefore that taking [complements](#) of [subsets](#) exchanges [unions](#) with [intersections](#) ([de Morgan's law](#)):

Given a [set](#)  $X$  and a set of subsets

$$\{S_i \subset X\}_{i \in I}$$

then

$$X \setminus \left( \bigcup_{i \in I} S_i \right) = \bigcap_{i \in I} (X \setminus S_i)$$

and

$$X \setminus \left( \bigcap_{i \in I} S_i \right) = \bigcup_{i \in I} (X \setminus S_i) .$$

Also notice that taking complements reverses inclusion relations:

$$(S_1 \subset S_2) \Leftrightarrow (X \setminus S_2 \subset X \setminus S_1) .$$

Often it is useful to reformulate def. 2.23 of [closed subsets](#) as follows:

**Lemma 2.25. ([alternative characterization of closed subsets](#))**

Let  $(X, \tau)$  be a [topological space](#) and let  $S \subset X$  be a [subset](#) of its underlying set. Then a point  $x \in X$  is contained in the [topological closure](#)  $\text{Cl}(S)$  (def. 2.23) precisely if every [open neighbourhood](#)  $U_x \subset X$  of  $x$  [intersects](#)  $S$ :

$$(x \in \text{Cl}(S)) \Leftrightarrow \neg \left( \bigcap_{\substack{U \subset X \setminus S \\ U \subset X \text{ open}}} (x \in U) \right) .$$

**Proof.** In view of remark 2.24 we may rephrase the definition of the [topological closure](#) as follows:

$$\begin{aligned} \text{Cl}(S) &:= \bigcap_{\substack{S \subset C \\ C \subset X \text{ closed}}} (C) \\ &= \bigcap_{\substack{U \subset X \setminus S \\ U \subset X \text{ open}}} (X \setminus U) \\ &= X \setminus \left( \bigcup_{\substack{U \subset X \setminus S \\ U \subset X \text{ open}}} U \right) \end{aligned}$$

■

**Definition 2.26. ([topological interior](#) and [boundary](#))**

Let  $(X, \tau)$  be a [topological space](#) (def. 2.3) and let  $S \subset X$  be a [subset](#). Then the [topological interior](#) of  $S$  is the largest [open subset](#)  $\text{Int}(S) \in \tau$  still contained in  $S$ ,

$\text{Int}(S) \subset S \subset X$ :

$$\text{Int}(S) := \bigcup_{\substack{O \subset S \\ O \subset X \text{ open}}} (O) .$$

The boundary  $\partial S$  of  $S$  is the complement of its interior inside its topological closure (def. 2.23):

$$\partial S := \text{Cl}(S) \setminus \text{Int}(S) .$$

**Lemma 2.27. (duality between closure and interior)**

Let  $(X, \tau)$  be a topological space and let  $S \subset X$  be a subset. Then the topological interior of  $S$  (def. 2.26) is the same as the complement of the topological closure  $\text{Cl}(X \setminus S)$  of the complement of  $S$ :

$$X \setminus \text{Int}(S) = \text{Cl}(X \setminus S)$$

and conversely

$$X \setminus \text{Cl}(S) = \text{Int}(X \setminus S) .$$

**Proof.** Using remark 2.24, we compute as follows:

$$\begin{aligned} X \setminus \text{Int}(S) &= X \setminus \left( \bigcup_{\substack{U \subset S \\ U \subset X \text{ open}}} U \right) \\ &= \bigcap_{\substack{U \subset S \\ U \subset X \text{ open}}} (X \setminus U) \\ &= \bigcap_{\substack{C \supset X \setminus S \\ C \text{ closed}}} (C) \\ &= \text{Cl}(X \setminus S) \end{aligned}$$

Similarly for the other case. ■

**Example 2.28. (topological closure and interior of closed and open intervals)**

Regard the real numbers as the 1-dimensional Euclidean space (example 1.6) and equipped with the corresponding metric topology (example 2.9) . Let  $a < b \in \mathbb{R}$ . Then the topological interior (def. 2.26) of the closed interval  $[a, b] \subset \mathbb{R}$  (example 1.13) is the open interval  $(a, b) \subset \mathbb{R}$ , moreover the closed interval is its own topological closure (def. 2.23) and the converse holds (by lemma 2.27):

$$\begin{aligned} \text{Cl}((a, b)) &= [a, b] & \text{Int}([a, b]) &= (a, b) \\ \text{Cl}([a, b]) &= [a, b] & \text{Int}([a, b]) &= (a, b) \end{aligned} .$$

Hence the boundary of the closed interval is its endpoints, while the boundary of the open interval is empty

$$\partial[a, b] = \{a\} \cup \{b\} \quad \partial(a, b) = \emptyset.$$

The terminology “closed” subspace for complements of opens is justified by the following statement, which is a further example of how the combinatorial concept of open subsets captures key phenomena in [analysis](#):

**Proposition 2.29. ([convergence in closed subspaces](#))**

Let  $(X, d)$  be a [metric space](#) (def. 1.1), regarded as a [topological space](#) via example 2.9, and let  $V \subset X$  be a [subset](#). Then the following are equivalent:

1.  $V \subset X$  is a [closed subspace](#) according to def. 2.23.
2. For every [sequence](#)  $x_i \in V \subset X$  (def. 1.16) with elements in  $V$ , which [converges](#) as a sequence in  $X$  (def. 1.17) to some  $x_\infty \in X$ , we have  $x_\infty \in V \subset X$ .

**Proof.** First assume that  $V \subset X$  is closed and that  $x_i \xrightarrow{i \rightarrow \infty} x_\infty$  for some  $x_\infty \in X$ . We need to show that then  $x_\infty \in V$ . Suppose it were not, hence that  $x_\infty \in X \setminus V$ . Since, by assumption on  $V$ , this [complement](#)  $X \setminus V \subset X$  is an [open subset](#), it would follow that there exists a [real number](#)  $\epsilon > 0$  such that the [open ball](#) around  $x$  of radius  $\epsilon$  were still contained in the complement:  $B_x^\circ(\epsilon) \subset X \setminus V$ . But since the sequence is assumed to converge in  $X$ , this would mean that there exists  $N_\epsilon$  such that all  $x_{i > N_\epsilon}$  are in  $B_x^\circ(\epsilon)$ , hence in  $X \setminus V$ . This contradicts the assumption that all  $x_i$  are in  $V$ , and hence we have [proved by contradiction](#) that  $x_\infty \in V$ .

Conversely, assume that for all sequences in  $V$  that converge to some  $x_\infty \in X$  then  $x_\infty \in V \subset X$ . We need to show that then  $V$  is closed, hence that  $X \setminus V \subset X$  is an open subset, hence that for every  $x \in X \setminus V$  we may find a real number  $\epsilon > 0$  such that the [open ball](#)  $B_x^\circ(\epsilon)$  around  $x$  of radius  $\epsilon$  is still contained in  $X \setminus V$ . Suppose on the contrary that such  $\epsilon$  did not exist. This would mean that for each  $k \in \mathbb{N}$  with  $k \geq 1$  then the [intersection](#)  $B_x^\circ(1/k) \cap V$  were [non-empty](#). Hence then we could [choose](#) points  $x_k \in B_x^\circ(1/k) \cap V$  in these intersections. These would form a sequence which clearly converges to the original  $x$ , and so by assumption we would conclude that  $x \in V$ , which violates the assumption that  $x \in X \setminus V$ . Hence we [proved by contradiction](#)  $X \setminus V$  is in fact open. ■

Often one considers closed subsets inside a closed subspace. The following is immediate, but useful.

**Lemma 2.30. ([subsets are closed in a closed subspace precisely if they are closed in the ambient space](#))**

Let  $(X, \tau)$  be a [topological space](#) (def. 2.3), and let  $C \subset X$  be a [closed subset](#) (def. 2.23), regarded as a [topological subspace](#)  $(C, \tau_{\text{sub}})$  (example 2.16). Then a [subset](#)  $S \subset C$  is a [closed subset](#) of  $(C, \tau_{\text{sub}})$  precisely if it is closed as a subset of  $(X, \tau)$ .

**Proof.** If  $S \subset C$  is closed in  $(C, \tau_{\text{sub}})$  this means equivalently that there is an open subset  $V \subset C$  in  $(C, \tau_{\text{sub}})$  such that

$$S = C \setminus V .$$

But by the definition of the subspace topology, this means equivalently that there is a subset  $U \subset X$  which is open in  $(X, \tau)$  such that  $V = U \cap C$ . Hence the above is equivalent to the existence of an open subset  $U \subset X$  such that

$$\begin{aligned} S &= C \setminus V \\ &= C \setminus (U \cap C) . \\ &= C \setminus U \end{aligned}$$

But now the condition that  $C$  itself is a closed subset of  $(X, \tau)$  means equivalently that there is an open subset  $W \subset X$  with  $C = X \setminus W$ . Hence the above is equivalent to the existence of two open subsets  $W, U \subset X$  such that

$$S = (X \setminus W) \setminus U = X \setminus (W \cup U) .$$

Since the union  $W \cup U$  is again open, this implies that  $S$  is closed in  $(X, \tau)$ .

Conversely, that  $S \subset X$  is closed in  $(X, \tau)$  means that there exists an open  $T \subset X$  with  $S = X \setminus T \subset X$ . This means that  $S = S \cap C = (X \setminus T) \cap C = C \setminus T = C \setminus (T \cap C)$ , and since  $T \cap C$  is open in  $(C, \tau_{\text{sub}})$  by definition of the subspace topology, this means that  $S \subset C$  is closed in  $(C, \tau_{\text{sub}})$ . ■

A special role in the theory is played by the “irreducible” closed subspaces:

### Definition 2.31. (**irreducible closed subspace**)

A closed subset  $S \subset X$  (def. 2.23) of a topological space  $X$  is called *irreducible* if it is non-empty and not the union of two closed proper (i.e. smaller) subsets. In other words, a non-empty closed subset  $S \subset X$  is irreducible if whenever  $S_1, S_2 \subset X$  are two closed subspace such that

$$S = S_1 \cup S_2$$

then  $S_1 = S$  or  $S_2 = S$ .

### Example 2.32. (**closures of points are irreducible**)

For  $x \in X$  a point inside a topological space, then the closure  $\text{Cl}(\{x\})$  of the singleton subset  $\{x\} \subset X$  is *irreducible* (def. 2.31).

### Example 2.33. (**no nontrivial closed irreducibles in metric spaces**)

Let  $(X, d)$  be a metric space, regarded as a topological space via its metric topology (example 2.9). Then every point  $x \in X$  is closed (def 2.23), hence every singleton subset  $\{x\} \subset X$  is irreducible according to def. 2.32.

Let  $\mathbb{R}$  be the 1-dimensional Euclidean space (example 1.6) with its metric topology (example 2.9). Then for  $a < c \in \mathbb{R}$  the closed interval  $[a, c] \subset \mathbb{R}$  (example 1.13 ) is *not* irreducible, since for any  $b \in \mathbb{R}$  with  $a < b < c$  it is the union of two smaller closed subintervals:

$$[a, c] = [a, b] \cup [b, c] .$$

In fact we will see below (prop. 5.3) that in a metric space the singleton subsets are precisely the only irreducible closed subsets.

Often it is useful to re-express the condition of irreducibility of closed subspaces in terms of complementary open subsets:

**Proposition 2.34. (irreducible closed subsets in terms of prime open subsets)**

Let  $(X, \tau)$  be a [topological space](#), and let  $P \in \tau$  be a proper [open subset](#) of  $X$ , hence so that the [complement](#)  $F := X \setminus P$  is a [non-empty closed subspace](#). Then  $F$  is [irreducible](#) in the sense of def. 2.31 precisely if whenever  $U_1, U_2 \in \tau$  are open subsets with  $U_1 \cap U_2 \subset P$  then  $U_1 \subset P$  or  $U_2 \subset P$ :

$$(X \setminus P \text{ irreducible}) \Leftrightarrow \left( \bigvee_{U_1, U_2 \in \tau} ((U_1 \cap U_2 \subset P) \Rightarrow (U_1 \subset P \text{ or } U_2 \subset P)) \right) .$$

The open subsets  $P \subset X$  with this property are also called the *prime open subsets* in  $\tau_X$ .

**Proof.** Observe that every [closed subset](#)  $F_i \subset F$  may be exhibited as the [complement](#)

$$F_i = F \setminus U_i$$

of some open subset  $U_i \in \tau$  with respect to  $F$ . Observe that under this identification the condition that  $U_1 \cap U_2 \subset P$  is equivalent to the condition that  $F_1 \cup F_2 = F$ , because it is equivalent to the equation labeled  $(*)$  in the following sequence of equations:

$$\begin{aligned} F_1 \cup F_2 &= (F \setminus U_1) \cup (F \setminus U_2) \\ &= (X \setminus (P \cup U_1)) \cup (X \setminus (P \cup U_2)) \\ &= X \setminus ((P \cup U_1) \cap (P \cup U_2)) \\ &= X \setminus (P \cup (U_1 \cap U_2)) \\ &\stackrel{(*)}{=} X \setminus P \\ &= F . \end{aligned}$$

Similarly, the condition that  $U_i \subset P$  is equivalent to the condition that  $F_i = F$ , because it is equivalent to the equality  $(*)$  in the following sequence of equalities:

$$\begin{aligned} F_i &= F \setminus U_i \\ &= X \setminus (P \cup U_i) \\ &\stackrel{(*)}{=} X \setminus P \\ &= F \end{aligned}$$

Under these identifications, the two conditions are manifestly the same. ■

We consider yet another equivalent characterization of irreducible closed subsets,

prop. 2.38 below, which will be needed in the discussion of the [separation axioms](#) further [below](#). Stating this requires the following concept of “[frame](#)” [homomorphism](#), the natural kind of [homomorphisms](#) between [topological spaces](#) if we were to forget the underlying set of points of a topological space, and only remember the set  $\tau_X$  with its operations induced by taking finite intersections and arbitrary unions:

**Definition 2.35. ([frame](#) homomorphisms)**

Let  $(X, \tau_X)$  and  $(Y, \tau_Y)$  be [topological spaces](#) (def. 2.3). Then a function

$$\tau_X \leftarrow \tau_Y : \phi$$

between their [sets of open subsets](#) is called a [frame homomorphism](#) if it preserves

1. arbitrary [unions](#);
2. [finite intersections](#).

In other words,  $\phi$  is a frame homomorphism precisely if

1. for every [set](#)  $I$  and every  $I$ -indexed set  $\{U_i \in \tau_Y\}_{i \in I}$  of elements of  $\tau_Y$ , then

$$\phi\left(\bigcup_{i \in I} U_i\right) = \bigcup_{i \in I} \phi(U_i) \in \tau_X,$$

2. for every [finite set](#)  $J$  and every  $J$ -indexed set  $\{U_j \in \tau_Y\}_{j \in J}$  of elements in  $\tau_Y$ , then

$$\phi\left(\bigcap_{j \in J} U_j\right) = \bigcap_{j \in J} \phi(U_j) \in \tau_X.$$

**Remark 2.36. ([frame](#) homomorphisms preserve inclusions)**

A [frame homomorphism](#)  $\phi$  as in def. 2.35 necessarily also preserves inclusions in that

- for every inclusion  $U_1 \subset U_2$  with  $U_1, U_2 \in \tau_Y \subset P(Y)$  then

$$\phi(U_1) \subset \phi(U_2) \in \tau_X.$$

This is because inclusions are witnessed by unions

$$(U_1 \subset U_2) \Leftrightarrow (U_1 \cup U_2 = U_2)$$

or alternatively because inclusions are witnessed by finite intersections:

$$(U_1 \subset U_2) \Leftrightarrow (U_1 \cap U_2 = U_1).$$

**Example 2.37. (pre-images of continuous functions are frame homomorphisms)**

Let  $(X, \tau_X)$  and  $(Y, \tau_Y)$  be two [topological spaces](#). One way to obtain a function

between their sets of open subsets

$$\tau_X \leftarrow \tau_Y : \phi$$

is to specify a function

$$f : X \rightarrow Y$$

of their underlying sets, and take  $\phi := f^{-1}$  to be the [pre-image](#) operation. A priori this is a function of the form

$$P(Y) \leftarrow P(X) : f^{-1}$$

and hence in order for this to co-restrict to  $\tau_X \subset P(X)$  when restricted to  $\tau_Y \subset P(Y)$  we need to demand that, under  $f$ , pre-images of open subsets of  $Y$  are open subsets of  $X$ . Below in def. [3.1](#) we highlight these as the [continuous functions](#) between topological spaces.

$$f : (X, \tau_X) \rightarrow (Y, \tau_Y)$$

In this case then

$$\tau_X \leftarrow \tau_Y : f^{-1}$$

is a frame homomorphism in the sense of def. [2.35](#).

For the following recall from example [2.10](#) the [point topological space](#)

$$* = (\{1\}, \tau_* = \{\emptyset, \{1\}\}).$$

**Proposition 2.38. (*irreducible closed subsets are equivalently frame homomorphisms to opens of the point*)**

For  $(X, \tau)$  a [topological space](#), then there is a [natural bijection](#) between the [irreducible closed subspaces](#) of  $(X, \tau)$  (def. [2.31](#)) and the [frame homomorphisms](#) from  $\tau_X$  to  $\tau_*$ , and this bijection is given by

$$\begin{array}{ccc} \text{FrameHom}(\tau_X, \tau_*) & \xrightarrow{\cong} & \text{IrrClSub}(X) \\ \phi & \mapsto & X \setminus (U_\emptyset(\phi)) \end{array}$$

where  $U_\emptyset(\phi)$  is the [union](#) of all elements  $U \in \tau_X$  such that  $\phi(U) = \emptyset$ :

$$U_\emptyset(\phi) := \bigcup_{\substack{U \in \tau_X \\ \phi(U) = \emptyset}} (U) .$$

See also ([Johnstone 82, II 1.3](#)).

**Proof.** First we need to show that the function is well defined in that given a frame homomorphism  $\phi : \tau_X \rightarrow \tau_*$  then  $X \setminus U_\emptyset(\phi)$  is indeed an irreducible closed subspace.

To that end observe that:

(\*) *If there are two elements  $U_1, U_2 \in \tau_X$  with  $U_1 \cap U_2 \subset U_\emptyset(\phi)$  then  $U_1 \subset U_\emptyset(\phi)$  or*



$$U_2 \subset U_\emptyset(\phi).$$

This is because

$$\begin{aligned}\phi(U_1) \cap \phi(U_2) &= \phi(U_1 \cap U_2) \\ &\subset \phi(U_\emptyset(\phi)) \quad , \\ &= \emptyset\end{aligned}$$

where the first equality holds because  $\phi$  preserves finite intersections by def. 2.35, the inclusion holds because  $\phi$  respects inclusions by remark 2.36, and the second equality holds because  $\phi$  preserves arbitrary unions by def. 2.35. But in  $\tau_* = \{\emptyset, \{1\}\}$  the intersection of two open subsets is empty precisely if at least one of them is empty, hence  $\phi(U_1) = \emptyset$  or  $\phi(U_2) = \emptyset$ . But this means that  $U_1 \subset U_\emptyset(\phi)$  or  $U_2 \subset U_\emptyset(\phi)$ , as claimed.

Now according to prop. 2.34 the condition  $(*)$  identifies the [complement](#)  $X \setminus U_\emptyset(\phi)$  as an [irreducible closed subspace](#) of  $(X, \tau)$ .

Conversely, given an irreducible closed subset  $X \setminus U_0$ , define  $\phi$  by

$$\phi : U \mapsto \begin{cases} \emptyset & | \text{ if } U \subset U_0 \\ \{1\} & | \text{ otherwise } \end{cases}.$$

This does preserve

#### 1. arbitrary unions

because  $\phi(\bigcup_i U_i) = \{\emptyset\}$  precisely if  $\bigcup_i U_i \subset U_0$  which is the case precisely if all  $U_i \subset U_0$ , which means that all  $\phi(U_i) = \emptyset$  and because  $\bigcup_i \emptyset = \emptyset$ ;

while  $\phi(\bigcup_i U_i) = \{1\}$  as soon as one of the  $U_i$  is not contained in  $U_0$ , which means that one of the  $\phi(U_i) = \{1\}$  which means that  $\bigcup_i \phi(U_i) = \{1\}$ ;

#### 2. finite intersections

because if  $U_1 \cap U_2 \subset U_0$ , then by  $(*)$   $U_1 \in U_0$  or  $U_2 \in U_0$ , whence  $\phi(U_1) = \emptyset$  or  $\phi(U_2) = \emptyset$ , whence with  $\phi(U_1 \cap U_2) = \emptyset$  also  $\phi(U_1) \cap \phi(U_2) = \emptyset$ ;

while if  $U_1 \cap U_2$  is not contained in  $U_0$  then neither  $U_1$  nor  $U_2$  is contained in  $U_0$  and hence with  $\phi(U_1 \cap U_2) = \{1\}$  also  $\phi(U_1) \cap \phi(U_2) = \{1\} \cap \{1\} = \{1\}$ .

Hence this is indeed a frame homomorphism  $\tau_X \rightarrow \tau_*$ .

Finally, it is clear that these two operations are inverse to each other. ■

## 3. Continuous functions

With the concept of [topological spaces](#) in hand (def. 2.3) it is now immediate to formally implement in abstract generality the statement of prop. 1.14:

**principle of continuity**

*Continuous pre-Images of open subsets are open.*

**Definition 3.1. (continuous function)**

A [continuous function](#) between [topological spaces](#) (def. 2.3)

$$f : (X, \tau_X) \rightarrow (Y, \tau_Y)$$

is a [function](#) between the underlying sets,

$$f : X \rightarrow Y$$

such that [pre-images](#) under  $f$  of open subsets of  $Y$  are open subsets of  $X$ .

We may equivalently state this in terms of [closed subsets](#):

**Proposition 3.2.** *Let  $(X_1, \tau_X)$  and  $(Y, \tau_Y)$  be two [topological spaces](#) (def. 2.3). Then a [function](#)*

$$f : X \rightarrow Y$$

*between the underlying [sets](#) is [continuous](#) in the sense of def. 3.1 precisely if [pre-images](#) under  $f$  of [closed subsets](#) of  $Y$  (def. 2.23) are closed subsets of  $X$ .*

**Proof.** This follows since taking [pre-images](#) commutes with taking [complements](#). ■

Before looking at first examples of continuous functions [below](#) we consider now an informal remark on the resulting global structure, the “[category of topological spaces](#)”, remark 3.3 below. This is a language that serves to make transparent key phenomena in [topology](#) which we encounter further below, such as the [Tn-reflection](#) (remark 4.24 below), and the [universal constructions](#).

**Remark 3.3. ([concrete category of topological spaces](#))**

For  $X_1, X_2, X_3$  three [topological spaces](#) and for

$$X_1 \xrightarrow{f} X_2 \quad \text{and} \quad X_2 \xrightarrow{g} X_3$$

two [continuous functions](#) (def. 3.1) then their [composition](#)

$$f_2 \circ f_1 : X_1 \xrightarrow{f} X_2 \xrightarrow{f_2} X_3$$

is clearly itself again a continuous function from  $X_1$  to  $X_3$ . Moreover, this composition operation is clearly [associative](#), in that for

$$X_1 \xrightarrow{f} X_2 \quad \text{and} \quad X_2 \xrightarrow{g} X_3 \quad \text{and} \quad X_3 \xrightarrow{h} X_4$$

three [continuous functions](#), then

$$f_3 \circ (f_2 \circ f_1) = (f_3 \circ f_2) \circ f_1 : X_1 \rightarrow X_3 .$$

Finally, the composition operation is also clearly [unital](#), in that for each topological space  $X$  there exists the [identity](#) function  $\text{id}_X : X \rightarrow X$  and for  $f : X_1 \rightarrow X_2$  any continuous function then

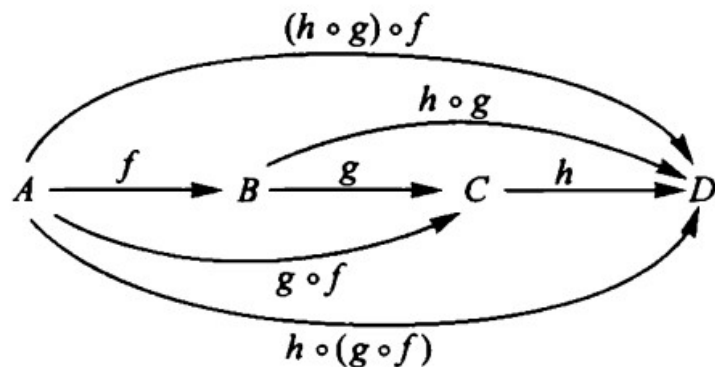
$$\text{id}_{X_2} \circ f = f = f \circ \text{id}_{X_1} .$$

One summarizes this situation by saying that:

1. [topological spaces](#) constitute the [objects](#),
2. [continuous functions](#) constitute the [morphisms](#) ([homomorphisms](#))

of a [category](#), called the [category of topological spaces](#) ("[Top](#)" for short).

It is useful to depict collections of [objects](#) with [morphisms](#) between them by [diagrams](#), like this one:



*graphics grabbed from [Lawvere-Schanuel 09](#).*

There are other categories. For instance there is the [category of sets](#) ("[Set](#)" for short) whose

1. [objects](#) are [sets](#),
2. [morphisms](#) are plain [functions](#) between these.

The two categories [Top](#) and [Set](#) are different, but related. After all,

1. an [object](#) of [Top](#) (hence a [topological space](#)) is an [object](#) of [Set](#) (hence a [set](#)) equipped with [extra structure](#) (namely with a [topology](#));
2. a [morphism](#) in [Top](#) (hence a [continuous function](#)) is a [morphism](#) in [Set](#) (hence a plain [function](#)) with the [extra property](#) that it preserves this extra structure.

Hence we have the *underlying set assigning function*

$$\text{Top} \xrightarrow{U} \text{Set}$$

$$(X, \tau) \longmapsto X$$

from the class of topological spaces to the class of sets. But more is true: every continuous function between topological spaces is, by definition, in particular a function on underlying sets:

$$\text{Top} \xrightarrow{U} \text{Set}$$

$$(X, \tau_X) \longmapsto X$$

$$f \downarrow \quad \mapsto \quad \downarrow f$$

$$(Y, \tau_Y) \longmapsto Y$$

and this assignment (trivially) respects the composition of morphisms and the identity morphisms.

Such a function between classes of objects of categories, which is extended to a function on the sets of homomorphisms between these objects in a way that respects composition and identity morphisms is called a functor. If we write an arrow between categories

$$U : \text{Top} \longrightarrow \text{Set}$$

then it is understood that we mean not just a function between their classes of objects, but a functor.

The functor  $U$  at hand has the special property that it does not do much except forgetting extra structure, namely the extra structure on a set  $X$  given by a choice of topology  $\tau_X$ . One also speaks of a forgetful functor.

This is intuitively clear, and we may easily formalize it: The functor  $U$  has the special property that as a function between sets of homomorphisms ("hom sets", for short) it is injective. More in detail, given topological spaces  $(X, \tau_X)$  and  $(Y, \tau_Y)$  then the component function of  $U$  from the set of continuous function between these spaces to the set of plain functions between their underlying sets

$$\left\{ (X, \tau_X) \xrightarrow[\text{function}]{\text{continuous}} (Y, \tau_Y) \right\} \xrightarrow{U} \left\{ X \xrightarrow{\text{function}} Y \right\}$$

is an injective function, including the continuous functions among all functions of underlying sets.

A functor with this property, that its component functions between all hom-sets are injective, is called a faithful functor.

A category equipped with a faithful functor to Set is called a concrete category.

Hence Top is canonically a concrete category.

**Example 3.4. (product topological space construction is functorial)**

For  $\mathcal{C}$  and  $\mathcal{D}$  two [categories](#) as in remark 3.3 (for instance [Top](#) or [Set](#)) then we obtain a new category denoted  $\mathcal{C} \times \mathcal{D}$  and called their [product category](#) whose

1. [objects](#) are [pairs](#)  $(c, d)$  with  $c$  an object of  $\mathcal{C}$  and  $d$  an object of  $\mathcal{D}$ ;
- [morphisms](#) are [pairs](#)  $(f, g) : (c, d) \rightarrow (c', d')$  with  $f : c \rightarrow c'$  a morphism of  $\mathcal{C}$  and  $g : d \rightarrow d'$  a morphism of  $\mathcal{D}$ ,
- [composition](#) of morphisms is defined pairwise  $(f', g') \circ (f, g) := (f' \circ f, g' \circ g)$ .

This concept secretly underlies the construction of [product topological spaces](#):

Let  $(X_1, \tau_{X_1})$ ,  $(X_2, \tau_{X_2})$ ,  $(Y_1, \tau_{Y_1})$  and  $(Y_2, \tau_{Y_2})$  be [topological spaces](#). Then for all [pairs](#) of [continuous functions](#)

$$f_1 : (X_1, \tau_{X_1}) \rightarrow (Y_1, \tau_{Y_1})$$

and

$$f_2 : (X_2, \tau_{X_2}) \rightarrow (Y_2, \tau_{Y_2})$$

the canonically induced function on [Cartesian products](#) of sets

$$\begin{array}{ccc} X_1 \times X_2 & \xrightarrow{f_1 \times f_2} & Y_1 \times Y_2 \\ (x_1, x_2) & \mapsto & (f_1(x_1), f_2(x_2)) \end{array}$$

is a [continuous function](#) with respect to the [binary product space topologies](#) (def. 2.18)

$$f_1 \times f_2 : (X_1 \times X_2, \tau_{X_1 \times X_2}) \rightarrow (Y_1 \times Y_2, \tau_{Y_1 \times Y_2}) .$$

Moreover, this construction respects [identity functions](#) and [composition](#) of functions in both arguments.

In the language of [category theory](#) (remark 3.3), this is summarized by saying that the [product topological space](#) construction  $(-) \times (-)$  extends to a [functor](#) from the [product category](#) of the [category Top](#) with itself to itself:

$$(-) \times (-) : \mathbf{Top} \times \mathbf{Top} \rightarrow \mathbf{Top} .$$

## Examples

We discuss here some basic examples of [continuous functions](#) (def. 3.1) between [topological spaces](#) (def. 2.3) to get a feeling for the nature of the concept. But as with topological spaces themselves, continuous functions between them are ubiquitous in mathematics, and no list will exhaust all classes of examples. Below in the section [Universal constructions](#) we discuss a general principle that serves to produce examples of continuous functions with prescribed "[universal properties](#)".

**Example 3.5. (point space is terminal)**

For  $(X, \tau)$  any topological space, then there is a *unique* continuous function

1. from the empty topological space (def. 2.10)  $\emptyset$

$$\emptyset \xrightarrow{\exists!} X$$

2. from  $X$  to the point topological space (def. 2.10).

$$X \xrightarrow{\exists!} *$$

In the language of category theory (remark 3.3), this says that

1. the empty topological space is the *initial object*
2. the point space  $*$  is the *terminal object*

in the category Top of topological spaces. We come back to this below in example 6.12.

**Example 3.6. (constant continuous functions)**

For  $(X, \tau)$  a topological space then for  $x \in X$  any element of the underlying set, there is a unique continuous function (which we denote by the same symbol)

$$x : * \rightarrow X$$

from the point topological space (def. 2.10), whose image in  $X$  is that element. Hence there is a natural bijection

$$\left\{ * \xrightarrow{f} X \mid f \text{ continuous} \right\} \simeq X$$

between the continuous functions from the point to any topological space, and the underlying set of that topological space.

More generally, for  $(X, \tau_X)$  and  $(Y, \tau_Y)$  two topological spaces, then a continuous function  $X \rightarrow Y$  between them is called a constant function with value some point  $y \in Y$  if it factors through the point spaces as

$$\text{const}_y : X \xrightarrow{\exists!} * \xrightarrow{y} Y.$$

**Definition 3.7. (locally constant function)**

For  $(X, \tau_X), (Y, \tau_Y)$  two topological spaces, then a continuous function  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  (def. 3.1) is called locally constant if every point  $x \in X$  has a neighbourhood on which the function is constant.

**Example 3.8. (continuous functions into and out of discrete and codiscrete spaces)**

Let  $S$  be a set and let  $(X, \tau)$  be a topological space. Recall from example 2.13

1. the [discrete topological space](#)  $\text{Disc}(S)$ ;
2. the [co-discrete topological space](#)  $\text{CoDisc}(S)$

on the underlying set  $S$ . Then [continuous functions](#) (def. 3.1) into/out of these satisfy:

1. every [function](#) (of sets)  $\text{Disc}(S) \rightarrow X$  out of a discrete space is [continuous](#);
2. every [function](#) (of sets)  $X \rightarrow \text{CoDisc}(S)$  into a codiscrete space is [continuous](#).

Also:

- every [continuous function](#)  $(X, \tau) \rightarrow \text{Disc}(S)$  into a discrete space is [locally constant](#) (def. 3.7).

### Example 3.9. ([diagonal](#))

For  $X$  a [set](#), its [diagonal](#)  $\Delta_X$  is the [function](#) from  $X$  to the [Cartesian product](#) of  $X$  with itself, given by

$$\begin{aligned} X &\xrightarrow{\Delta_X} X \times X \\ x &\mapsto (x, x) \end{aligned}$$

For  $(X, \tau)$  a [topological space](#), then the diagonal is a [continuous function](#) to the [product topological space](#) (def. 2.18) of  $X$  with itself.

$$\Delta_X : (X, \tau) \rightarrow (X \times X, \tau_{X \times X}) .$$

To see this, it is sufficient to see that the [preimages](#) of [basic opens](#)  $U_1 \times U_2$  in  $\tau_{X \times X}$  are in  $\tau_X$ . But these pre-images are the [intersections](#)  $U_1 \cap U_2 \subset X$ , which are open by the axioms on the topology  $\tau_X$ .

### Example 3.10. ([image factorization](#))

Let  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  be a [continuous function](#).

Write  $f(X) \subset Y$  for the [image](#) of  $f$  on underlying sets, and consider the resulting factorization of  $f$  through  $f(X)$  on underlying sets:

$$f : X \xrightarrow{\text{surjective}} f(X) \xrightarrow{\text{injective}} Y .$$

There are the following two ways to topologize the [image](#)  $f(X)$  such as to make this a sequence of two continuous functions:

1. By example 2.16  $f(X)$  inherits a [subspace topology](#) from  $(Y, \tau_Y)$  which evidently makes the inclusion  $f(X) \rightarrow Y$  a [continuous function](#).

Observe that this also makes  $X \rightarrow f(X)$  a continuous function: An open subset of  $f(X)$  in this case is of the form  $U_Y \cap f(X)$  for  $U_Y \in \tau_Y$ , and  $f^{-1}(U_Y \cap f(X)) = f^{-1}(U_Y)$ , which is open in  $X$  since  $f$  is continuous.



2. By example 2.17  $f(X)$  inherits a [quotient topology](#) from  $(X, \tau_X)$  which evidently makes the surjection  $X \rightarrow f(X)$  a [continuous function](#).

Observe that this also makes  $f(X) \rightarrow Y$  a continuous function: The preimage under this map of an open subset  $U_Y \in \tau_Y$  is the restriction  $U_Y \cap f(X)$ , and the pre-image of that under  $X \rightarrow f(X)$  is  $f^{-1}(U_Y)$ , as before, which is open since  $f$  is continuous, and therefore  $U_Y \cap f(X)$  is open in the quotient topology.

Beware, in general a continuous function itself (as opposed to its [pre-image](#) function) neither preserves [open subsets](#), nor [closed subsets](#), as the following examples show:

**Example 3.11.** Regard the [real numbers](#)  $\mathbb{R}$  as the 1-dimensional [Euclidean space](#) (example 1.6) equipped with the [metric topology](#) (example 2.9). For  $a \in \mathbb{R}$  the [constant function](#) (example 3.6)

$$\begin{array}{ccc} \mathbb{R} & \xrightarrow{\text{const}_a} & \mathbb{R} \\ x & \mapsto & a \end{array}$$

maps every [open subset](#)  $U \subset \mathbb{R}$  to the [singleton set](#)  $\{a\} \subset \mathbb{R}$ , which is not open.

**Example 3.12.** Write  $\text{Disc}(\mathbb{R})$  for the set of [real numbers](#) equipped with its [discrete topology](#) (def. 2.13) and  $\mathbb{R}$  for the set of [real numbers](#) equipped with its [Euclidean metric topology](#) (example 1.6, example 2.9). Then the [identity function](#) on the underlying sets

$$\text{id}_{\mathbb{R}} : \text{Disc}(\mathbb{R}) \rightarrow \mathbb{R}$$

is a [continuous function](#) (a special case of example 3.8). A [singleton subset](#)  $\{a\} \in \text{Disc}(\mathbb{R})$  is open, but regarded as a subset  $\{a\} \in \mathbb{R}$  it is not open.

**Example 3.13.** Consider the set of [real numbers](#)  $\mathbb{R}$  equipped with its [Euclidean metric topology](#) (example 1.6, example 2.9). The [exponential function](#)

$$\exp(-) : \mathbb{R} \rightarrow \mathbb{R}$$

maps all of  $\mathbb{R}$  (which is a closed subset, since  $\mathbb{R} = \mathbb{R} \setminus \emptyset$ ) to the [open interval](#)  $(0, \infty) \subset \mathbb{R}$ , which is not closed.

Those continuous functions that do happen to preserve open or closed subsets get a special name:

**Definition 3.14. ([open maps](#) and [closed maps](#))**

A [continuous function](#)  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  (def. 3.1) is called

- an [open map](#) if the [image](#) under  $f$  of an [open subset](#) of  $X$  is an open subset of  $Y$ ;

- a [closed map](#) if the [image](#) under  $f$  of a [closed subset](#) of  $X$  (def. 2.23) is a closed subset of  $Y$ .

**Example 3.15. ([image](#) projections of [open/closed maps](#) are themselves open/closed)**

If a [continuous function](#)  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  is an [open map](#) or [closed map](#) (def. 3.14) then so its [image](#) projection  $X \rightarrow f(X) \subset Y$ , respectively, for  $f(X) \subset Y$  regarded with its [subspace topology](#) (example 3.10).

**Proof.** If  $f$  is an open map, and  $O \subset X$  is an open subset, so that  $f(O) \subset Y$  is also open in  $Y$ , then, since  $f(O) = f(O) \cap f(X)$ , it is also still open in the subspace topology, hence  $X \rightarrow f(X)$  is an open map.

If  $f$  is a closed map, and  $C \subset X$  is a closed subset so that also  $f(C) \subset Y$  is a closed subset, then the [complement](#)  $Y \setminus f(C)$  is open in  $Y$  and hence  $(Y \setminus f(C)) \cap f(X) = f(X) \setminus f(C)$  is open in the subspace topology, which means that  $f(C)$  is closed in the subspace topology. ■

**Example 3.16. ([projections](#) are [open continuous functions](#) )**

For  $(X_1, \tau_{X_1})$  and  $(X_2, \tau_{X_2})$  two [topological spaces](#), then the projection maps

$$\text{pr}_i : (X_1 \times X_2, \tau_{X_1 \times X_2}) \rightarrow (X_i, \tau_{X_i})$$

out of their [product topological space](#) (def. 2.18)

$$\begin{array}{ccc} X_1 \times X_2 & \xrightarrow{\text{pr}_1} & X_1 \\ (x_1, x_2) & \longmapsto & x_1 \\ X_1 \times X_2 & \xrightarrow{\text{pr}_2} & X_2 \\ (x_1, x_2) & \longmapsto & x_2 \end{array}$$

are [open continuous functions](#) (def. 3.14).

This is because, by definition, every open subset  $O \subset X_1 \times X_2$  in the product space topology is a union of products of open subsets  $U_i \in X_1$  and  $V_i \in X_2$  in the factor spaces

$$O = \bigcup_{i \in I} (U_i \times V_i)$$

and because taking the image of a function preserves unions of subsets

$$\begin{aligned} \text{pr}_1 \left( \bigcup_{i \in I} (U_i \times V_i) \right) &= \bigcup_{i \in I} \text{pr}_1 (U_i \times V_i) \\ &= \bigcup_{i \in I} U_i \end{aligned}$$

Below in prop. 7.41 we find a large supply of [closed maps](#).

Sometimes it is useful to recognize [quotient topological space](#) projections via [saturated subsets](#) (essentially another term for pre-images of underlying sets):

**Definition 3.17. ([saturated subset](#))**

Let  $f : X \rightarrow Y$  be a [function](#) of [sets](#). Then a [subset](#)  $S \subset X$  is called an *[f-saturated subset](#)* (or just *saturated subset*, if  $f$  is understood) if  $S$  is the [pre-image](#) of its [image](#):

$$(S \subset X \text{ f-saturated}) \Leftrightarrow (S = f^{-1}(f(S))) .$$

Here  $f^{-1}(f(S))$  is also called the *f-saturation* of  $S$ .

**Example 3.18. (pre-images are saturated subsets)**

For  $f : X \rightarrow Y$  any [function](#) of [sets](#), and  $S_Y \subset Y$  any [subset](#) of  $Y$ , then the [pre-image](#)  $f^{-1}(S_Y) \subset X$  is an *f-saturated subset* of  $X$  (def. 3.17).

Observe that:

**Lemma 3.19.** *Let  $f : X \rightarrow Y$  be a [function](#). Then a [subset](#)  $S \subset X$  is f-saturated (def. 3.17) precisely if its [complement](#)  $X \setminus S$  is saturated.*

**Proposition 3.20. (recognition of quotient topologies)**

A [continuous function](#) (def. 3.1)

$$f : (X, \tau_X) \rightarrow (Y, \tau_Y)$$

whose underlying function  $f : X \rightarrow Y$  is [surjective](#) exhibits  $\tau_Y$  as the corresponding [quotient topology](#) (def. 2.17) precisely if  $f$  sends open and *f-saturated subsets* in  $X$  (def. 3.17) to open subsets of  $Y$ . By lemma 3.19 this is the case precisely if it sends closed and *f-saturated subsets* to closed subsets.

We record the following technical lemma about saturated subspaces, which we will need below to prove prop. 7.46.

**Lemma 3.21. (saturated open neighbourhoods of saturated closed subsets under closed maps)**

Let

1.  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  be a [closed map](#) (def. 3.14);
2.  $C \subset X$  be a [closed subset](#) of  $X$  (def. 2.23) which is *f-saturated* (def. 3.17);
3.  $U \supset C$  be an [open subset](#) containing  $C$ ;

then there exists a smaller open subset  $V$  still containing  $C$

$$U \supset V \supset C$$

and such that  $V$  is still *f-saturated*.

**Proof.** We claim that the [complement](#) of  $X$  by the  $f$ -saturation (def. [3.17](#)) of the complement of  $X$  by  $U$

$$V := X \setminus (f^{-1}(f(X \setminus U)))$$

has the desired properties. To see this, observe first that

1. the [complement](#)  $X \setminus U$  is closed, since  $U$  is assumed to be open;
2. hence the image  $f(X \setminus U)$  is closed, since  $f$  is assumed to be a closed map;
3. hence the pre-image  $f^{-1}(f(X \setminus U))$  is closed, since  $f$  is continuous (using prop. [3.2](#)), therefore its complement  $V$  is indeed open;
4. this pre-image  $f^{-1}(f(X \setminus U))$  is saturated (by example [3.18](#)) and hence also its complement  $V$  is saturated (by lemma [3.19](#)).

Therefore it now only remains to see that  $U \supset V \supset C$ .

By [de Morgan's law](#) (remark [2.24](#)) the inclusion  $U \supset V$  is equivalent to the inclusion  $f^{-1}(f(X \setminus U)) \supset X \setminus U$ , which is clearly the case.

The inclusion  $V \supset C$  is equivalent to  $f^{-1}(f(X \setminus U)) \cap C = \emptyset$ . Since  $C$  is saturated by assumption, this is equivalent to  $f^{-1}(f(X \setminus U)) \cap f^{-1}(f(C)) = \emptyset$ . This in turn holds precisely if  $f(X \setminus U) \cap f(C) = \emptyset$ . Since  $C$  is saturated, this holds precisely if  $X \setminus U \cap C = \emptyset$ , and this is true by the assumption that  $U \supset C$ . ■

## Homeomorphisms

With the [objects](#) ([topological spaces](#)) and the [morphisms](#) ([continuous functions](#)) of the [category Top](#) thus defined (remark [3.3](#)), we obtain the concept of “sameness” in topology. To make this precise, one says that a [morphism](#)

$$X \xrightarrow{f} Y$$

in a [category](#) is an [isomorphism](#) if there exists a morphism going the other way around

$$X \xleftarrow{g} Y$$

which is an [inverse](#) in the sense that both its [compositions](#) with  $f$  yield an [identity morphism](#):

$$f \circ g = \text{id}_Y \quad \text{and} \quad g \circ f = \text{id}_X .$$

Since such  $g$  is unique if it exists, one often writes “ $f^{-1}$ ” for this [inverse morphism](#). However, in the context of [topology](#) then  $f^{-1}$  usually refers to the [pre-image](#) function of a given [function](#)  $f$ , and in these notes we will stick to this usage and never use “ $(-)^{-1}$ ” to denote [inverses](#).

**Definition 3.22. (homeomorphisms)**

An isomorphism in the category Top (remark 3.3) of topological spaces (def. 2.3) with continuous functions between them (def. 3.1) is called a homeomorphism.

Hence a homeomorphism is a continuous function

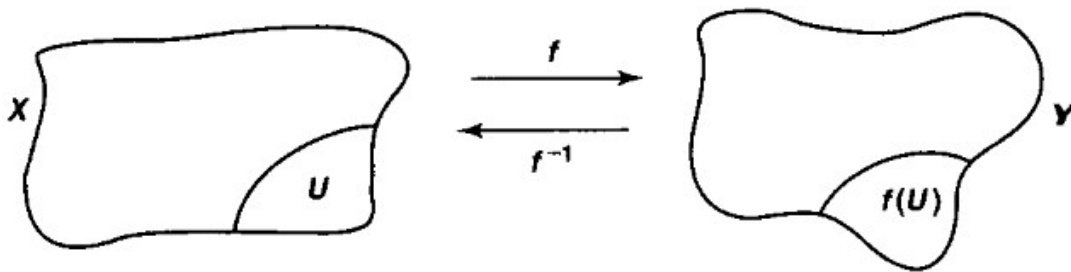
$$f : (X, \tau_X) \rightarrow (Y, \tau_Y)$$

between two topological spaces  $(X, \tau_X)$ ,  $(Y, \tau_Y)$  such that there exists another continuous function the other way around

$$(X, \tau_X) \leftarrow (Y, \tau_Y) : g$$

such that their composites are the identity functions on  $X$  and  $Y$ , respectively:

$$f \circ g = \text{id}_Y \quad \text{and} \quad g \circ f = \text{id}_X .$$



*graphics grabbed from Munkres 75*

We notationally indicate that a continuous function is a homeomorphism by the symbol " $\simeq$ ".

$$f : (X, \tau_X) \xrightarrow{\simeq} (Y, \tau_Y) .$$

If there is *some*, possibly unspecified, homeomorphism between topological spaces  $(X, \tau_X)$  and  $(Y, \tau_Y)$ , then we also write

$$(X, \tau_X) \simeq (Y, \tau_Y)$$

and say that the two topological spaces *are homeomorphic*.

A property/predicate  $P$  of topological spaces which is invariant under homeomorphism in that

$$((X, \tau_X) \simeq (Y, \tau_Y)) \Rightarrow (P(X, \tau_X) \Leftrightarrow P(Y, \tau_Y))$$

is called a topological property or *topological invariant*.

**Remark 3.23.** If  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  is a homeomorphism (def. 3.22) with inverse continuous function  $g$ , then

1. also  $g$  is a homeomorphism, with inverse continuous function  $f$ ;

- the underlying function of sets  $f: X \rightarrow Y$  of a homeomorphism  $f$  is necessarily a [bijection](#), with inverse bijection  $g$ .

But beware that not every [continuous function](#) which is [bijective](#) on underlying sets is a homeomorphism. While an [inverse function](#)  $g$  will exist on the level of functions of sets, this inverse may fail to be continuous:

**Counter Example 3.24.** Consider the [continuous function](#)

$$\begin{aligned} [0, 2\pi) &\rightarrow S^1 \subset \mathbb{R}^2 \\ t &\mapsto (\cos(t), \sin(t)) \end{aligned}$$

from the [half-open interval](#) (def. 1.13) to the unit circle  $S^1 := S_0(1) \subset \mathbb{R}^2$  (def. 1.2), regarded as a [topological subspace](#) (example 2.16) of the [Euclidean plane](#) (example 1.6).

The underlying function of sets of  $f$  is a [bijection](#). The [inverse function](#) of sets however fails to be continuous at  $(1, 0) \in S^1 \subset \mathbb{R}^2$ . Hence this  $f$  is *not* a [homeomorphism](#).

Indeed, below we see that the two topological spaces  $[0, 2\pi)$  and  $S^1$  are distinguished by [topological invariants](#), meaning that they cannot be homeomorphic via *any* (other) choice of homeomorphism. For example  $S^1$  is a [compact topological space](#) (def. 7.2) while  $[0, 2\pi)$  is not, and  $S^1$  has a non-trivial [fundamental group](#), while that of  $[0, 2\pi)$  is trivial ([this prop.](#)).

Below in example 7.47 we discuss a practical criterion under which continuous bijections are homeomorphisms after all. But immediate from the definitions is the following characterization:

**Proposition 3.25.** ([homeomorphisms are the continuous and open bijections](#))

Let  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  be a [continuous function](#) between [topological spaces](#) (def. 3.1). Then the following are equivalence:

- $f$  is a [homeomorphism](#);
- $f$  is a [bijection](#) and an [open map](#) (def. 3.14);
- $f$  is a [bijection](#) and a [closed map](#) (def. 3.14).

**Proof.** It is clear from the definition that a homeomorphism in particular has to be a bijection. The condition that the [inverse function](#)  $Y \leftarrow X: g$  be continuous means that the [pre-image](#) function of  $g$  sends open subsets to open subsets. But by  $g$  being the inverse to  $f$ , that pre-image function is equal to  $f$ , regarded as a function on subsets:

$$g^{-1} = f : P(X) \rightarrow P(Y) .$$

Hence  $g^{-1}$  sends opens to opens precisely if  $f$  does, which is the case precisely if  $f$

is an open map, by definition. This shows the equivalence of the first two items. The equivalence between the first and the third follows similarly via prop. 3.2. ■

Now we consider some actual **examples** of [homeomorphisms](#):

### Example 3.26. (concrete point homeomorphic to abstract point space)

Let  $(X, \tau_X)$  be a [non-empty topological space](#), and let  $x \in X$  be any point. Regard the corresponding [singleton subset](#)  $\{x\} \subset X$  as equipped with its [subspace topology](#)  $\tau_{\{x\}}$  (example 2.16). Then this is [homeomorphic](#) (def. 3.22) to the abstract [point space](#) from example 2.10:

$$(\{x\}, \tau_{\{x\}}) \simeq * .$$

### Example 3.27. (open interval homeomorphic to the real line)

Regard the [real line](#) as the 1-dimensional [Euclidean space](#) (example 1.6) with its [metric topology](#) (example 2.9).

Then the open [interval](#)  $(-1, 1) \subset \mathbb{R}$  (def. 1.13) regarded with its [subspace topology](#) (example 2.16) is [homeomorphic](#) (def. 3.22) to all of the [real line](#)

$$(-1, 1) \simeq \mathbb{R}^1 .$$

An [inverse](#) pair of [continuous functions](#) is for instance given (via example 1.10) by

$$\begin{aligned} f &: \mathbb{R}^1 \longrightarrow (-1, +1) \\ x &\longmapsto \frac{x}{\sqrt{1+x^2}} \end{aligned}$$

and

$$\begin{aligned} g &: (-1, +1) \longrightarrow \mathbb{R}^1 \\ x &\longmapsto \frac{x}{\sqrt{1-x^2}} . \end{aligned}$$

But there are many other choices for  $f$  and  $g$  that yield a homeomorphism.

Similarly, for all  $a < b \in \mathbb{R}$

1. the [open intervals](#)  $(a, b) \subset \mathbb{R}$  (example 1.13) equipped with their [subspace topology](#) are all homeomorphic to each other,
2. the closed intervals  $[a, b]$  are all homeomorphic to each other,
3. the half-open intervals of the form  $[a, b)$  are all homeomorphic to each other;
4. the half-open intervals of the form  $(a, b]$  are all homeomorphic to each other.

Generally, every [open ball](#) in  $\mathbb{R}^n$  (def. 1.2) is [homeomorphic](#) to all of  $\mathbb{R}^n$ :



$$(B_0^\circ(\epsilon) \subset \mathbb{R}^n) \simeq \mathbb{R}^n .$$

While mostly the interest in a given homeomorphism is in it being non-obvious from the definitions, many homeomorphisms that appear in practice exhibit “obvious re-identifications” for which it is of interest to leave them *consistently implicit*:

### Example 3.28. (homeomorphisms between iterated product spaces)

Let  $(X, \tau_X)$ ,  $(Y, \tau_Y)$  and  $(Z, \tau_Z)$  be [topological spaces](#).

Then:

1. There is an evident [homeomorphism](#) between the two ways of bracketing the three factors when forming their [product topological space](#) (def. 2.18), called the [associator](#):

$$\alpha_{X,Y,Z} : ((X, \tau_X) \times (Y, \tau_Y)) \times (Z, \tau_Z) \xrightarrow{\simeq} (X, \tau_X) \times ((Y, \tau_Y) \times (Z, \tau_Z)) .$$

2. There are evident [homeomorphism](#) between  $(X, \tau)$  and its [product topological space](#) (def. 2.18) with the [point space](#)  $*$  (example 2.10), called the left and right [unitors](#):

$$\lambda_X : * \times (X, \tau_X) \xrightarrow{\simeq} (X, \tau_X)$$

and

$$\rho_X : (X, \tau_X) \times * \xrightarrow{\simeq} (X, \tau_X) .$$

3. There is an evident [homeomorphism](#) between the results of the two orders in which to form their [product topological spaces](#) (def. 2.18), called the [braiding](#):

$$\beta_{X,Y} : (X, \tau_X) \times (Y, \tau_Y) \xrightarrow{\simeq} (Y, \tau_Y) \times (X, \tau_X) .$$

Moreover, all these homeomorphisms are compatible with each other, in that they make the following [diagrams commute](#) (recall remark 3.3):

1. (triangle identity)

$$\begin{array}{ccc} (X \times *) \times Y & \xrightarrow{\alpha_{X,*,Y}} & X \times (* \times Y) \\ \rho_X \times \text{id}_Y \searrow & & \swarrow \text{id}_X \times \lambda_Y \\ & X \times Y & \end{array}$$

2. ([pentagon identity](#))

$$\begin{array}{ccc}
 & (W \times X) \times (Y \times Z) & \\
 \alpha_{W \times X, Y, Z} \nearrow & & \searrow \alpha_{W, X, Y \times Z} \\
 ((W \times X) \times Y) \times Z & & (W \times (X \times (Y \times Z))) \\
 \alpha_{W, X, Y \times \text{id}_Z} \downarrow & & \uparrow \text{id}_W \times \alpha_{X, Y, Z} \\
 (W \times (X \times Y)) \times Z & \xrightarrow{\alpha_{W, X \times Y, Z}} & W \times ((X \times Y) \times Z)
 \end{array}$$

### 3. (hexagon identities)

$$\begin{array}{ccccc}
 (X \times Y) \times Z & \xrightarrow{\alpha_{X, Y, Z}} & X \times (Y \times Z) & \xrightarrow{\beta_{X, Y \times Z}} & (Y \times Z) \times X \\
 \downarrow \beta_{X, Y \times \text{id}_Z} & & & & \downarrow \alpha_{Y, Z, X} \\
 (Y \times X) \times Z & \xrightarrow{\alpha_{Y, X, Z}} & Y \times (X \times Z) & \xrightarrow{\text{id}_Y \times \beta_{X, Y}} & Y \times (Z \times X)
 \end{array}$$

and

$$\begin{array}{ccccc}
 X \times (Y \times Z) & \xrightarrow{\alpha_{X, Y, Z}^{\text{inv}}} & (X \times Y) \times Z & \xrightarrow{\beta_{X \times Y, Z}} & Z \times (X \times Y) \\
 \downarrow \text{id}_X \times \beta_{Y, Z} & & & & \downarrow \alpha_{Z, X, Y}^{\text{inv}} \\
 X \times (Z \times Y) & \xrightarrow{\alpha_{X, Z, Y}^{\text{inv}}} & (X \times Z) \times Y & \xrightarrow{\beta_{X, Z \times Y}^{\text{inv}}} & (Z \times X) \times Y
 \end{array}$$

### 4. (symmetry)

$$\beta_{Y, X} \circ \beta_{X, Y} = \text{id} : (X_1 \times X_2 \tau_{X_1 \times X_2}) \rightarrow (X_1 \times X_2 \tau_{X_1 \times X_2}).$$

In the language of [category theory](#) (remark 3.3), all this is summarized by saying that the [functorial](#) construction  $(-) \times (-)$  of [product topological spaces](#) (example 3.4) gives the [category Top](#) of [topological spaces](#) the [structure](#) of a [monoidal category](#) which moreover is [symmetrically braided](#).

From this, a basic result of [category theory](#), the [MacLane coherence theorem](#), guarantees that there is no essential ambiguity re-bracketing arbitrary iterations of the binary product topological space construction, as long as the above homeomorphisms are understood.

Accordingly, we may write

$$(X_1, \tau_1) \times (X_2, \tau_2) \times \cdots \times (X_n, \tau_n)$$

for iterated [product topological spaces](#) without putting parenthesis.

The following are a sequence of examples all of the form that an abstractly constructed topological space is homeomorphic to a certain subspace of a Euclidean space. These examples are going to be useful in further developments below, for example in the [proof below](#) of the [Heine-Borel theorem](#) (prop. 7.39).

- [Products of intervals](#) are homeomorphic to [hypercubes](#) (example 3.29).

- The [closed interval](#) glued at its endpoints is homeomorphic to the [circle](#) (example 3.30).
- The [cylinder](#), the [Möbius strip](#) and the [torus](#) are all homeomorphic to [quotients](#) of the square (example 3.31).

### Example 3.29. (product of closed intervals homeomorphic to hypercubes)

Let  $n \in \mathbb{N}$ , and let  $[a_i, b_i] \subset \mathbb{R}$  for  $i \in \{1, \dots, n\}$  be  $n$  [closed intervals](#) in the [real line](#) (example 1.13), regarded as [topological subspaces](#) of the 1-dimensional [Euclidean space](#) (example 1.6) with its [metric topology](#) (example 2.9). Then the [product topological space](#) (def. 2.18, example 3.28) of all these intervals is [homeomorphic](#) (def. 3.22) to the corresponding [topological subspace](#) of the  $n$ -dimensional [Euclidean space](#) (example 1.6):

$$[a_1, b_1] \times [a_2, b_2] \times \dots \times [a_n, b_n] \simeq \left\{ \vec{x} \in \mathbb{R}^n \mid \forall_i (a_i \leq x_i \leq b_i) \right\} \subset \mathbb{R}^n.$$

**Proof.** There is a canonical [bijection](#) between the underlying sets. It remains to see that this, as well as its inverse, are [continuous functions](#). For this it is sufficient to see that under this bijection the defining [basis](#) (def. 2.7) for the [product topology](#) is also a basis for the [subspace topology](#). But this is immediate from lemma 2.8. ■

### Example 3.30. (closed interval glued at endpoints homeomorphic circle)

As topological spaces, the [closed interval](#)  $[0, 1]$  (def. 1.13) with its two endpoints identified is [homeomorphic](#) (def. 3.22) to the standard [circle](#):

$$[0, 1]_{/(0 \sim 1)} \simeq S^1.$$

More in detail: let

$$S^1 \hookrightarrow \mathbb{R}^2$$

be the unit [circle](#) in the [plane](#)

$$S^1 = \{(x, y) \in \mathbb{R}^2, x^2 + y^2 = 1\}$$

equipped with the [subspace topology](#) (example 2.16) of the plane  $\mathbb{R}^2$ , which is itself equipped with its standard [metric topology](#) (example 2.9).

Moreover, let

$$[0, 1]_{/(0 \sim 1)}$$

be the [quotient topological space](#) (example 2.17) obtained from the [interval](#)  $[0, 1] \subset \mathbb{R}^1$  with its [subspace topology](#) by applying the [equivalence relation](#) which identifies the two endpoints (and nothing else).

Consider then the function

$$f : [0, 1] \rightarrow S^1$$

given by

$$t \mapsto (\cos(t), \sin(t)) .$$

This has the property that  $f(0) = f(1)$ , so that it descends to the [quotient topological space](#)

$$\begin{array}{ccc} [0, 1] & \rightarrow & [0, 1]_{/(0 \sim 1)} \\ f \searrow & & \downarrow \tilde{f} \\ & & S^1 \end{array} .$$

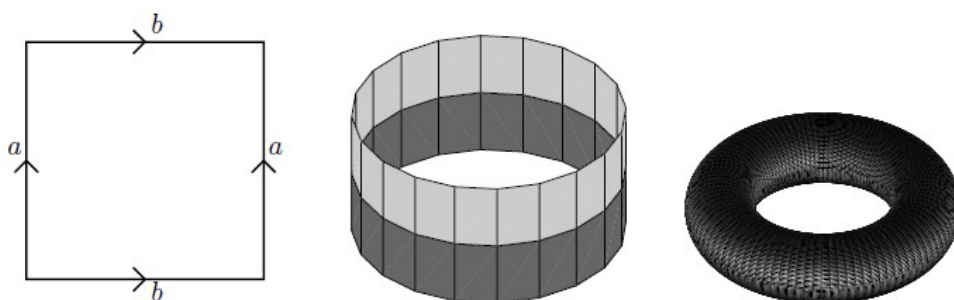
We claim that  $\tilde{f}$  is a [homeomorphism](#) (definition [3.22](#)).

First of all it is immediate that  $\tilde{f}$  is a [continuous function](#). This follows immediately from the fact that  $f$  is a [continuous function](#) and by definition of the [quotient topology](#) (example [2.17](#)).

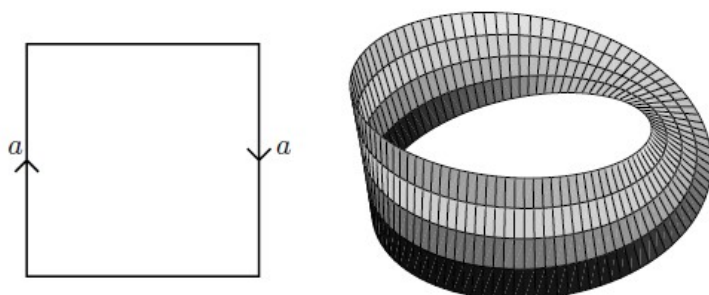
So we need to check that  $\tilde{f}$  has a continuous inverse function. Clearly the restriction of  $f$  itself to the open interval  $(0, 1)$  has a continuous inverse. It fails to have a continuous inverse on  $[0, 1)$  and on  $(0, 1]$  and fails to have an inverse at all on  $[0, 1]$ , due to the fact that  $f(0) = f(1)$ . But the relation quotiented out in  $[0, 1]_{/(0 \sim 1)}$  is exactly such as to fix this failure.

### Example 3.31. (cylinder, Möbius strip and torus homeomorphic to quotients of the square)

The [square](#)  $[0, 1]^2$  with two of its sides identified is the [cylinder](#), and with also the other two sides identified is the [torus](#):



If the sides are identified with opposite orientation, the result is the [Möbius strip](#):



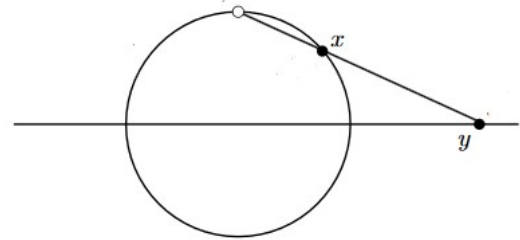
graphics grabbed from [Lawson 03](#)

### Example 3.32. ([stereographic projection](#))

For  $n \in \mathbb{N}$  then there is a [homeomorphism](#) (def. 3.22) between between the [n-sphere](#)  $S^n$  (example 2.20) with one point  $p \in S^n$  removed and the  $n$ -dimensional [Euclidean space](#)  $\mathbb{R}^n$  (example 1.6) with its [metric topology](#) (example 2.9):

$$S^n \setminus \{p\} \xrightarrow{\cong} \mathbb{R}^n.$$

This homeomorphism is given by "[stereographic projection](#)": One thinks of both the  $n$ -sphere as well as the Euclidean space  $\mathbb{R}^n$  as [topological subspaces](#) (example 2.16) of  $\mathbb{R}^{n+1}$  in the standard way (example 2.20), such that they [intersect](#) in the [equator](#) of the  $n$ -sphere.



For  $p \in S^n$  one of the corresponding poles, then the homeomorphism is the function which sends a point  $x \in S^n \setminus \{p\}$  along the line connecting it with  $p$  to the point  $y$  where this line intersects the equatorial plane.

In the canonical ambient [coordinates](#) this [stereographic projection](#) is given as follows:

$$\begin{array}{ccccc} \mathbb{R}^{n+1} \supset & S^n \setminus (1, 0, \dots, 0) & \xrightarrow{\cong} & \mathbb{R}^n & \subset \mathbb{R}^{n+1} \\ & (x_1, x_2, \dots, x_{n+1}) & \longmapsto & \frac{1}{1-x_1} (0, x_2, \dots, x_{n+1}) & \end{array}.$$

Important examples of pairs of spaces that are *not* homeomorphic include the following:

### Theorem 3.33. ([topological invariance of dimension](#))

For  $n_1, n_2 \in \mathbb{N}$  but  $n_1 \neq n_2$ , then the [Euclidean spaces](#)  $\mathbb{R}^{n_1}$  and  $\mathbb{R}^{n_2}$  (example 1.6, example 2.9) are not [homeomorphic](#).

More generally, an [open subset](#) in  $\mathbb{R}^{n_1}$  is never homeomorphic to an open subset in  $\mathbb{R}^{n_2}$  if  $n_1 \neq n_2$ .

The proofs of theorem 3.33 are not elementary, in contrast to how obvious the statement seems to be intuitively. One approach is to use tools from [algebraic topology](#): One assigns [topological invariants](#) to topological spaces, notably classes in [ordinary cohomology](#) or in [topological K-theory](#), quantities that are [invariant](#) under [homeomorphism](#), and then shows that these classes coincide for  $\mathbb{R}^{n_1} - \{0\}$  and for  $\mathbb{R}^{n_2} - \{0\}$  precisely only if  $n_1 = n_2$ .

One indication that [topological invariance of dimension](#) is not an *elementary* consequence of the axioms of topological spaces is that a related "intuitively

obvious" statement is in fact false: One might think that there is no [surjective continuous function](#)  $\mathbb{R}^{n_1} \rightarrow \mathbb{R}^{n_2}$  if  $n_1 < n_2$ . But there are: these are called the [Peano curves](#).

Often it is important to know whether a given space is homeomorphism to its *image*, under some continuous function, in some other space:

**Definition 3.34. ([embedding of topological spaces](#))**

Let  $(X, \tau_X)$  and  $(Y, \tau_Y)$  be [topological spaces](#). A [continuous function](#)  $f : X \rightarrow Y$  is called an [embedding of topological spaces](#) if in its [image factorization](#) (example 3.10)

$$f : X \xrightarrow{\cong} f(X) \hookrightarrow Y$$

with the image  $f(X) \hookrightarrow Y$  equipped with the [subspace topology](#), we have that  $X \rightarrow f(X)$  is a [homeomorphism](#).

**Proposition 3.35. ([open/closed continuous injections are embeddings](#))**

A [continuous function](#)  $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$  which is

1. an [injective function](#)
2. an [open map](#) or a [closed map](#) (def. 3.14)

is an [embedding of topological spaces](#) (def. 3.34).

This is called a *closed embedding* if the [image](#)  $f(X) \subset Y$  is a [closed subset](#).

**Proof.** If  $f$  is injective, then the map onto its [image](#)  $X \rightarrow f(X) \subset Y$  is a [bijection](#). Moreover, it is still continuous with respect to the subspace topology on  $f(X)$  (example 3.10). Now a bijective continuous function is a homeomorphism precisely if it is an [open map](#) or a [closed map](#) prop. 3.25 . But the image projection of  $f$  has this property, respectively, if  $f$  does, by prop 3.15. ■

## 4. Separation axioms

The plain definition of [topological space](#) (above) happens to admit examples where distinct points or distinct subsets of the underlying set appear as more-or-less unseparable as seen by the topology on that set.

The extreme class of examples of topological spaces in which the open subsets do not distinguish distinct underlying points, or in fact any distinct subsets, are the [codiscrete spaces](#) (example 2.13). This does occur in practice:

**Example 4.1. ([real numbers](#) quotiented by [rational numbers](#))**

Consider the [real line](#)  $\mathbb{R}$  regarded as the 1-dimensional [Euclidean space](#) (example 1.6) with its [metric topology](#) (example 2.9) and consider the [equivalence relation](#)

$\sim$  on  $\mathbb{R}$  which identifies two [real numbers](#) if they differ by a [rational number](#):

$$(x \sim y) \Leftrightarrow \left( \exists_{p/q \in \mathbb{Q} \subset \mathbb{R}} (x = y + p/q) \right).$$

Then the [quotient topological space](#) (def. 2.17)

$$\mathbb{R}/\mathbb{Q} := \mathbb{R}/\sim$$

is a [codiscrete topological space](#) (def. 2.13), hence its topology does not distinguish any distinct proper subsets.

Here are some less extreme examples:

#### Example 4.2. (open neighbourhoods in the Sierpinski space)

Consider the [Sierpinski space](#) from example 2.11, whose underlying set consists of two points  $\{0, 1\}$ , and whose open subsets form the set  $\tau = \{\emptyset, \{1\}, \{0, 1\}\}$ . This means that the only (open) neighbourhood of the point  $\{0\}$  is the entire space. Incidentally, also the [topological closure](#) of  $\{0\}$  (def. 2.23) is the entire space.

#### Example 4.3. (line with two origins)

Consider the [disjoint union space](#)  $\mathbb{R} \sqcup \mathbb{R}$  (example 2.15) of two copies of the [real line](#)  $\mathbb{R}$  regarded as the 1-dimensional [Euclidean space](#) (example 1.6) with its [metric topology](#) (example 2.9), which is equivalently the [product topological space](#) (example 2.18) of  $\mathbb{R}$  with the [discrete topological space](#) on the 2-element set (example 2.13):

$$\mathbb{R} \sqcup \mathbb{R} \simeq \mathbb{R} \times \text{Disc}(\{0, 1\})$$

Moreover, consider the [equivalence relation](#) on the underlying set which identifies every point  $x_i$  in the  $i$ th copy of  $\mathbb{R}$  with the corresponding point in the other, the  $(1 - i)$ th copy, except when  $x = 0$ :

$$(x_i \sim y_j) \Leftrightarrow ((x = y) \text{ and } ((x \neq 0) \text{ or } (i = j))) .$$

The [quotient topological space](#) by this equivalence relation (def. 2.17)

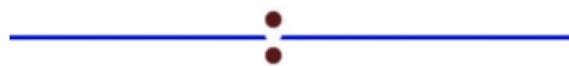
$$(\mathbb{R} \sqcup \mathbb{R})/\sim$$

is called the **line with two origins**. These “two origins” are the points  $0_0$  and  $0_1$ .

We claim that in this space *every neighbourhood of  $0_0$  intersects every neighbourhood of  $0_1$* .

Because, by definition of the [quotient space topology](#), the [open neighbourhoods](#) of  $0_i \in (\mathbb{R} \sqcup \mathbb{R})/\sim$  are precisely those that contain subsets of the form

$$(-\epsilon, \epsilon)_i := (-\epsilon, 0) \cup \{0_i\} \cup (0, \epsilon) .$$





But this means that the “two origins”  $0_0$  and  $0_1$  may not be separated by neighbourhoods, since the intersection of  $(-\epsilon, \epsilon)_0$  with  $(-\epsilon, \epsilon)_1$  is always non-empty:

$$(-\epsilon, \epsilon)_0 \cap (-\epsilon, \epsilon)_1 = (-\epsilon, 0) \cup (0, \epsilon) .$$

In many applications one wants to exclude at least some such exotic examples of topological spaces from the discussion and instead concentrate on those examples for which the topology recognizes the separation of distinct points, or of more general disjoint subsets. The relevant conditions to be imposed on top of the plain axioms of a topological space are hence known as separation axioms which we discuss in the following.

These axioms are all of the form of saying that two subsets (of certain kinds) in the topological space are ‘separated’ from each other in one sense if they are ‘separated’ in a (generally) weaker sense. For example the weakest axiom (called  $T_0$ ) demands that if two points are distinct as elements of the underlying set of points, then there exists at least one open subset that contains one but not the other.

In this fashion one may impose a hierarchy of stronger axioms. For example demanding that given two distinct points, then each of them is contained in some open subset not containing the other ( $T_1$ ) or that such a pair of open subsets around two distinct points may in addition be chosen to be disjoint ( $T_2$ ). Below in  $T_n$ -spaces we discuss the following hierarchy:

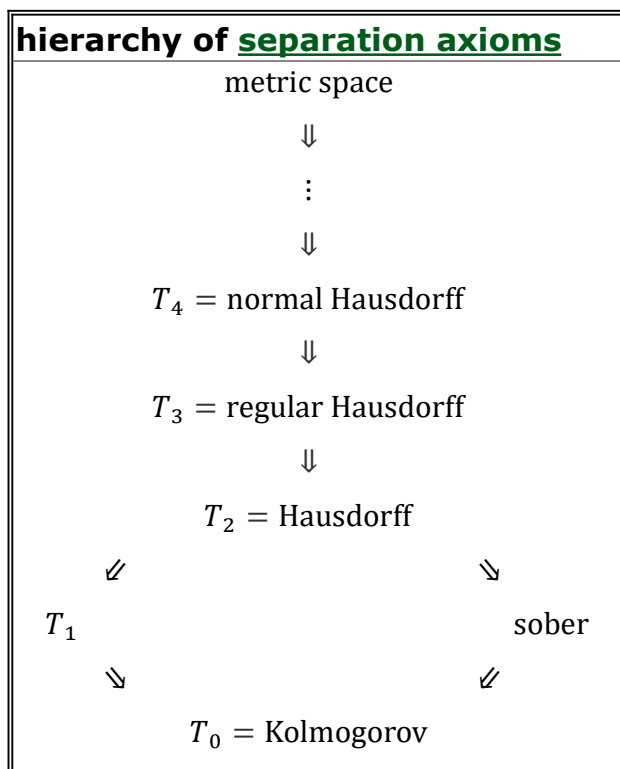
the **main separation axioms**

number	name	statement	reformulation
$T_0$	<u>Kolmogorov</u>	given two distinct points, at least one of them has an <u>open neighbourhood</u> not containing the other point	every <u>irreducible closed subset</u> is the <u>closure</u> of at most one point
$T_1$		given two distinct points, both have an <u>open neighbourhood</u> not containing the other point	all points are <u>closed</u>
$T_2$	<u>Hausdorff</u>	given two distinct points, they have <u>disjoint open neighbourhoods</u>	the <u>diagonal</u> is a <u>closed map</u>
$T_{>2}$		$T_1$ and...	all points are <u>closed</u> and...
$T_3$	<u>regular Hausdorff</u>	...given a point and a <u>closed subset</u> not containing it, they have <u>disjoint open neighbourhoods</u>	...every <u>neighbourhood</u> of a point contains the <u>closure</u> of an <u>open neighbourhood</u>
$T_4$	<u>normal Hausdorff</u>	...given two <u>disjoint closed subsets</u> , they have <u>disjoint open neighbourhoods</u>	...every <u>neighbourhood</u> of a <u>closed set</u> also contains the <u>closure</u> of an <u>open neighbourhood</u> ... every pair of <u>disjoint</u>

number	name	statement	reformulation
			<u>closed subsets</u> is separated by an <u>Urysohn function</u>

The condition,  $T_2$ , also called the Hausdorff condition is the most common among all separation axioms. Historically this axiom was originally taken as part of the definition of topological spaces, and it is still often (but by no means always) considered by default.

However, there are respectable areas of mathematics that involve topological spaces where the Hausdorff axiom fails, but a weaker axiom is still satisfied, called sobriety. This is the case notably in algebraic geometry (schemes are sober) and in computer science (Vickers 89). These sober topological spaces are singled out by the fact that they are entirely characterized by their sets of open subsets with their union and intersection structure (as in def. 2.35) and may hence be understood independently from their underlying sets of points. This we discuss further below.



All separation axioms are satisfied by metric spaces (example 4.8, example 4.14 below), from whom the concept of topological space was originally abstracted above. Hence imposing some of them may also be understood as gauging just how far one allows topological spaces to generalize away from metric spaces

## $T_n$ spaces

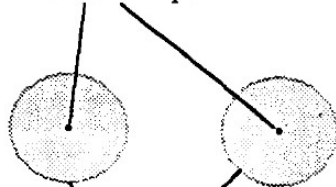
There are many variants of separation axioms. The classical ones are labeled  $T_n$  (for German "Trennungsaxiom") with  $n \in \{0, 1, 2, 3, 4, 5\}$  or higher. These we now introduce in def. 4.4 and def. 4.13.

**Definition 4.4. (the first three separation axioms)**

Let  $(X, \tau)$  be a [topological space](#) (def. 2.3).

For  $x \neq y \in X$  any two points in the underlying set of  $X$  which are not [equal](#) as elements of this set, consider the following [propositions](#):

two distinct points



disjoint open sets

- **(T0)** There exists a [neighbourhood](#) of one of the two points which does not contain the other point.
- **(T1)** There exist [neighbourhoods](#) of both points which do not contain the other point.
- **(T2)** There exists [neighbourhoods](#) of both points which do not intersect each other.

graphics grabbed from [Vickers 89](#)

The topological space  $X$  is called a  $T_n$ -topological space or just  $T_n$ -space, for short, if it satisfies condition  $T_n$  above for all pairs of distinct points.

A  $T_0$ -topological space is also called a [Kolmogorov space](#).

A  $T_2$ -topological space is also called a [Hausdorff topological space](#).

For definiteness, we re-state these conditions formally. Write  $x, y \in X$  for points in  $X$ , write  $U_x, U_y \in \tau$  for open [neighbourhoods](#) of these points. Then:

- **(T0)**  $\forall_{x \neq y} \left( \left( \exists_{U_y} (\{x\} \cap U_y = \emptyset) \right) \text{ or } \left( \exists_{U_x} (U_x \cap \{y\} = \emptyset) \right) \right)$
- **((T1))**  $\forall_{x \neq y} \left( \exists_{U_x, U_y} ((\{x\} \cap U_y = \emptyset) \text{ and } (U_x \cap \{y\} = \emptyset)) \right)$
- **(T2)**  $\forall_{x \neq y} \left( \exists_{U_x, U_y} (U_x \cap U_y = \emptyset) \right)$

The following is evident but important:

**Proposition 4.5.** ( $T_n$  are [topological properties of increasing strength](#))

The separation properties  $T_n$  from def. 4.4 are [topological properties](#) in that if two topological spaces are [homeomorphic](#) (def. 3.22) then one of them satisfies  $T_n$  precisely if the other does.

Moreover, these properties imply each other as

$$T_2 \Rightarrow T_1 \Rightarrow T_0 .$$

**Example 4.6.** Examples of topological spaces that are *not* [Hausdorff](#) (def. 4.4) include

1. the [Sierpinski space](#) (example 4.2),

2. the [line with two origins](#) (example 4.3),
3. the [quotient topological space](#)  $\mathbb{R}/\mathbb{Q}$  (example 4.1).

### Example 4.7. (finite $T_1$ -spaces are discrete)

For a [finite topological space](#)  $(X, \tau)$ , hence one for which the underlying set  $X$  is a [finite set](#), the following are equivalent:

1.  $(X, \tau)$  is  $T_1$  (def. 4.4);
2.  $(X, \tau)$  is a [discrete topological space](#) (def. 2.13).

### Example 4.8. ([metric spaces](#) are [Hausdorff](#))

Every [metric space](#) (def 1.1), regarded as a [topological space](#) via its [metric topology](#) (example 2.9) is a [Hausdorff topological space](#) (def. 4.4).

Because for  $x \neq y \in X$  two distinct points, then the [distance](#)  $d(x, y)$  between them is [positive number](#), by the non-degeneracy axiom in def. 1.1. Accordingly the [open balls](#) (def. 1.2)

$$B_x^\circ(d(x, y)) \supset \{x\} \quad \text{and} \quad B_y^\circ(d(x, y)) \supset \{y\}$$

are disjoint open neighbourhoods.

### Example 4.9. (subspace of $T_n$ -space is $T_n$ )

Let  $(X, \tau)$  be a [topological space](#) satisfying the  $T_n$  [separation axiom](#) for some  $n \in \{0, 1, 2\}$  according to def. 4.4. Then also every [topological subspace](#)  $S \subset X$  (example 2.16) satisfies  $T_n$ .

## Separation in terms of topological closures

The conditions  $T_0$ ,  $T_1$  and  $T_2$  have the following equivalent formulation in terms of [topological closures](#) (def. 2.23).

### Proposition 4.10. ( $T_0$ in terms of topological closures)

*A [topological space](#)  $(X, \tau)$  is  $T_0$  (def. 4.4) precisely if the function  $\text{Cl}(\{-\})$  that forms [topological closures](#) (def. 2.23) of [singleton subsets](#) from the underlying set of  $X$  to the set of [irreducible closed subsets](#) of  $X$  (def. 2.31, which is well defined according to example 2.32), is [injective](#):*

$$\text{Cl}(\{-\}) : X \hookrightarrow \text{IrrClSub}(X)$$

**Proof.** Assume first that  $X$  is  $T_0$ . Then we need to show that if  $x, y \in X$  are such that  $\text{Cl}(\{x\}) = \text{Cl}(\{y\})$  then  $x = y$ . Hence assume that  $\text{Cl}(\{x\}) = \text{Cl}(\{y\})$ . Since the closure of a point is the [complement](#) of the union of the open subsets not containing the point (lemma 2.25), this means that the union of open subsets that do not contain  $x$  is

the same as the union of open subsets that do not contain  $y$ :

$$\bigcup_{\substack{U \subset X \text{ open} \\ U \subset X \setminus \{x\}}} (U) = \bigcup_{\substack{U \subset X \text{ open} \\ U \subset X \setminus \{y\}}} (U)$$

But if the two points were distinct,  $x \neq y$ , then by  $T_0$  one of the above unions would contain  $x$  or  $y$ , while the other would not, in contradiction to the above equality. Hence we have a [proof by contradiction](#).

Conversely, assume that  $(\text{Cl}\{x\} = \text{Cl}\{y\}) \Rightarrow (x = y)$ , and assume that  $x \neq y$ . Hence by [contraposition](#)  $\text{Cl}(\{x\}) \neq \text{Cl}(\{y\})$ . We need to show that there exists an open set which contains one of the two points, but not the other.

Assume there were no such open subset, hence that every open subset containing one of the two points would also contain the other. Then by lemma 2.25 this would mean that  $x \in \text{Cl}(\{y\})$  and that  $y \in \text{Cl}(\{x\})$ . But this would imply that  $\text{Cl}(\{x\}) \subset \text{Cl}(\{y\})$  and that  $\text{Cl}(\{y\}) \subset \text{Cl}(\{x\})$ , hence that  $\text{Cl}(\{x\}) = \text{Cl}(\{y\})$ . This is a [proof by contradiction](#). ■

### Proposition 4.11. ( $T_1$ in terms of topological closures)

A [topological space](#)  $(X, \tau)$  is  $T_1$  (def. 4.4) precisely if all its points are [closed points](#) (def. 2.23).

**Proof.** We have

$$\begin{aligned} \text{all points in } (X, \tau) \text{ are closed} &:= \bigvee_{x \in X} (\text{Cl}(\{x\}) = \{x\}) \\ &\Leftrightarrow X \setminus \left( \bigcup_{\substack{U \subset X \text{ open} \\ x \notin U}} (U) \right) = \{x\} \\ &\Leftrightarrow \left( \bigcup_{\substack{U \subset X \text{ open} \\ x \notin U}} (U) \right) = X \setminus \{x\} \\ &\Leftrightarrow \bigvee_{y \in Y} \left( \left( \bigcup_{\substack{U \subset X \text{ open} \\ x \notin U}} (y \in U) \right) \Leftrightarrow (y \neq x) \right) \\ &\Leftrightarrow (X, \tau) \text{ is } T_1 \end{aligned}$$

Here the first step is the reformulation of closure from lemma 2.25, the second is another application of the [de Morgan law](#) (remark 2.24), the third is the definition of union and complement, and the last one is manifestly by definition of  $T_1$ . ■

### Proposition 4.12. ( $T_2$ in terms of topological closures)

A [topological space](#)  $(X, \tau_X)$  is  $T_2$  = [Hausdorff](#) precisely if the [image](#) of the [diagonal](#)

$$\begin{aligned} X &\xrightarrow{\Delta_X} X \times X \\ x &\longmapsto (x, x) \end{aligned}$$

is a closed subset in the product topological space  $(X \times X, \tau_{X \times X})$ .

**Proof.** Observe that the Hausdorff condition is equivalently rephrased in terms of the product topology as: *Every point  $(x, y) \in X$  which is not on the diagonal has an open neighbourhood  $U_{(x,y)} \times V_{(x,y)}$  which still does not intersect the diagonal, hence:*

$$(X, \tau) \text{ Hausdorff} \\ \Leftrightarrow \forall_{(x,y) \in (X \times X) \setminus \Delta_X(X)} \left( \exists_{\substack{U_{(x,y)} \times V_{(x,y)} \in \tau_{X \times X} \\ (x,y) \in U_{(x,y)} \times V_{(x,y)}}} (U_{(x,y)} \times V_{(x,y)} \cap \Delta_X(X) = \emptyset) \right)$$

Therefore if  $X$  is Hausdorff, then the diagonal  $\Delta_X(X) \subset X \times X$  is the complement of a union of such open sets, and hence is closed:

$$(X, \tau) \text{ Hausdorff} \Rightarrow \Delta_X(X) = X \setminus \left( \bigcup_{(x,y) \in (X \times X) \setminus \Delta_X(X)} U_{(x,y)} \times V_{(x,y)} \right).$$

Conversely, if the diagonal is closed, then (by lemma 2.25) every point  $(x, y) \in X \times X$  not on the diagonal, hence with  $x \neq y$ , has an open neighbourhood  $U_{(x,y)} \times V_{(x,y)}$  still not intersecting the diagonal, hence so that  $U_{(x,y)} \cap V_{(x,y)} = \emptyset$ . Thus  $(X, \tau)$  is Hausdorff. ■

## Further separation axioms

Clearly one may and does consider further variants of the separation axioms  $T_0$ ,  $T_1$  and  $T_2$  from def. 4.4. Here we discuss two more:

**Definition 4.13.** Let  $(X, \tau)$  be topological space (def. 4.4).

Consider the following conditions

- **(T3)** The space  $(X, \tau)$  is  $T_1$  (def. 4.4) and for  $x \in X$  a point and  $C \subset X$  a closed subset (def. 2.23) not containing  $x$ , then there exist disjoint open neighbourhoods  $U_x \supset \{x\}$  and  $U_C \supset C$ .
- **(T4)** The space  $(X, \tau)$  is  $T_1$  (def. 4.4) and for  $C_1, C_2 \subset X$  two disjoint closed subsets (def. 2.23) then there exist disjoint open neighbourhoods  $U_{C_i} \supset C_i$ .

If  $(X, \tau)$  satisfies  $T_3$  it is said to be a  $T_3$ -space also called a regular Hausdorff topological space.

If  $(X, \tau)$  satisfies  $T_4$  it is to be a  $T_4$ -space also called a normal Hausdorff topological space.

## Example 4.14. (metric spaces are normal Hausdorff)

Let  $(X, d)$  be a metric space (def. 1.1) regarded as a topological space via its metric topology (example 2.9). Then this is a normal Hausdorff space (def. 4.13).

**Proof.** By example 4.8 metric spaces are  $T_2$ , hence in particular  $T_1$ . What we need to show is that given two disjoint closed subsets  $C_1, C_2 \subset X$  then there exists disjoint open neighbourhoods  $U_{C_1} \subset C_1$  and  $U_{C_2} \supset C_2$ .

Recall the function

$$d(S, -): X \rightarrow \mathbb{R}$$

computing distances from a subset  $S \subset X$  (example 1.9). Then the unions of open balls (def. 1.2)

$$U_{C_1} := \bigcup_{x_1 \in C_1} B_{x_1}^\circ(d(C_2, x_1)/2)$$

and

$$U_{C_2} := \bigcup_{x_2 \in C_2} B_{x_2}^\circ(d(C_1, x_2)/2) .$$

have the required properties. ■

Observe that:

**Proposition 4.15. ( $T_n$  are topological properties of increasing strength)**

The separation axioms from def. 4.4, def. 4.13 are topological properties (def. 3.22) which imply each other as

$$T_4 \Rightarrow T_3 \Rightarrow T_2 \Rightarrow T_1 \Rightarrow T_0 .$$

**Proof.** The implications

$$T_2 \Rightarrow T_1 \Rightarrow T_0$$

and

$$T_4 \Rightarrow T_3$$

are immediate from the definitions. The remaining implication  $T_3 \Rightarrow T_2$  follows with prop. 4.11: This says that by assumption of  $T_1$  then all points in  $(X, \tau)$  are closed, and with this the condition  $T_2$  is manifestly a special case of the condition for  $T_3$ . ■

Hence instead of saying “ $X$  is  $T_1$  and ...” one could just as well phrase the conditions  $T_3$  and  $T_4$  as “ $X$  is  $T_2$  and ...”, which would render the proof of prop. 4.15 even more trivial.

The following shows that not every  $T_2$ -space/Hausdorff space is  $T_3$ /regular

**Example 4.16. (K-topology)**

Write

$$K := \{1/n \mid n \in \mathbb{N}_{\geq 1}\} \subset \mathbb{R}$$

for the subset of natural fractions inside the real numbers.



Define a [topological basis](#)  $\beta \subset P(\mathbb{R})$  on  $\mathbb{R}$  consisting of all the [open intervals](#) as well as the [complements](#) of  $K$  inside them:

$$\beta := \{(a, b), \mid a < b \in \mathbb{R}\} \cup \{(a, b) \setminus K, \mid a < b \in \mathbb{R}\} .$$

The [topology](#)  $\tau_\beta \subset P(\mathbb{R})$  which is generated from this [topological basis](#) is called the *K-topology*.

We may denote the resulting [topological space](#) by

$$\mathbb{R}_K := (\mathbb{R}, \tau_\beta) .$$

This is a [Hausdorff topological space](#) (def. 4.4) which is not a [regular Hausdorff space](#), hence (by prop. 4.15) in particular not a [normal Hausdorff space](#) (def. 4.13).

## Further separation axioms in terms of topological closures

As before we have equivalent reformulations of the further separation axioms.

### Proposition 4.17. ( $T_3$ in terms of topological closures)

A [topological space](#)  $(X, \tau)$  is a [regular Hausdorff space](#) (def. 4.13), precisely if all points are closed and for all points  $x \in X$  with [open neighbourhood](#)  $U \supset \{x\}$  there exists a smaller open neighbourhood  $V \supset \{x\}$  whose [topological closure](#)  $\text{Cl}(V)$  is still contained in  $U$ :

$$\{x\} \subset V \subset \text{Cl}(V) \subset U .$$

The **proof** of prop. 4.17 is the direct specialization of the following proof for prop. 4.18 to the case that  $C = \{x\}$  (using that by  $T_1$ , which is part of the definition of  $T_3$ , the singleton subset is indeed closed, by prop. 4.11).

### Proposition 4.18. ( $T_4$ in terms of topological closures)

A [topological space](#)  $(X, \tau)$  is [normal Hausdorff space](#) (def. 4.13), precisely if all points are closed and for all [closed subsets](#)  $C \subset X$  with [open neighbourhood](#)  $U \supset C$  there exists a smaller open neighbourhood  $V \supset C$  whose [topological closure](#)  $\text{Cl}(V)$  is still contained in  $U$ :

$$C \subset V \subset \text{Cl}(V) \subset U .$$

**Proof.** In one direction, assume that  $(X, \tau)$  is normal, and consider

$$C \subset U .$$

It follows that the [complement](#) of the open subset  $U$  is closed and disjoint from  $C$ :

$$C \cap X \setminus U = \emptyset .$$

Therefore by assumption of normality of  $(X, \tau)$ , there exist open neighbourhoods



with

$$V \supset C, \quad W \supset X \setminus U \quad \text{with} \quad V \cap W = \emptyset.$$

But this means that

$$V \subset X \setminus W$$

and since the [complement](#)  $X \setminus W$  of the open set  $W$  is closed, it still contains the closure of  $V$ , so that we have

$$C \subset V \subset \text{Cl}(V) \subset X \setminus W \subset U$$

as required.

In the other direction, assume that for every open neighbourhood  $U \supset C$  of a closed subset  $C$  there exists a smaller open neighbourhood  $V$  with

$$C \subset V \subset \text{Cl}(V) \subset U.$$

Consider disjoint closed subsets

$$C_1, C_2 \subset X, \quad C_1 \cap C_2 = \emptyset.$$

We need to produce disjoint open neighbourhoods for them.

From their disjointness it follows that

$$X \setminus C_2 \supset C_1$$

is an open neighbourhood. Hence by assumption there is an open neighbourhood  $V$  with

$$C_1 \subset V \subset \text{Cl}(V) \subset X \setminus C_2.$$

Thus

$$V \supset C_1, \quad X \setminus \text{Cl}(V) \supset C_2$$

are two disjoint open neighbourhoods, as required. ■

But the  $T_4$ /normality axiom has yet another equivalent reformulation, which is of a different nature, and will be important when we discuss [paracompact topological spaces](#) below:

The following concept of [Urysohn functions](#) is another approach of thinking about separation of subsets in a topological space, not in terms of their neighbourhoods, but in terms of continuous real-valued “indicator functions” that take different values on the subsets. This perspective will be useful when we consider [paracompact topological spaces](#) below.

But the [Urysohn lemma](#) (prop. 4.20 below) implies that this concept of separation is in fact equivalent to that of normality of Hausdorff spaces.

**Definition 4.19. ([Urysohn function](#))**

Let  $(X, \tau)$  be a [topological space](#), and let  $A, B \subset X$  be disjoint [closed subsets](#). Then an *Urysohn function separating  $A$  from  $B$*  is

- a [continuous function](#)  $f: X \rightarrow [0, 1]$

to the [closed interval](#) equipped with its [Euclidean metric topology](#) (example [1.6](#), example [2.9](#)), such that

- it takes the value 0 on  $A$  and the value 1 on  $B$ :

$$f(A) = \{0\} \quad \text{and} \quad f(B) = \{1\} .$$

**Proposition 4.20. ([Urysohn's lemma](#))**

Let  $X$  be a [normal Hausdorff topological space](#) (def. [4.13](#)), and let  $A, B \subset X$  be two [disjoint closed subsets](#) of  $X$ . Then there exists an [Urysohn function](#) separating  $A$  from  $B$  (def. [4.19](#)).

**Remark 4.21.** Beware, the Urysohn function in prop. [4.20](#) may take the values 0 or 1 even outside of the two subsets. The condition that the function takes value 0 or 1, respectively, *precisely* on the two subsets corresponds to “[perfectly normal spaces](#)”.

**Proof.** of [Urysohn's lemma](#), prop. [4.20](#)

Set

$$C_0 := A \quad U_1 := X \setminus B .$$

Since by assumption

$$A \cap B = \emptyset .$$

we have

$$C_0 \subset U_1 .$$

That  $(X, \tau)$  is normal implies, by lemma [4.18](#), that every open neighbourhood  $U \supset C$  of a closed subset  $C$  contains a smaller neighbourhood  $V$  together with its [topological closure](#)  $\text{Cl}(V)$

$$U \subset V \subset \text{Cl}(V) \subset C .$$

Apply this fact successively to the above situation to obtain the following infinite sequence of nested open subsets  $U_r$  and closed subsets  $C_r$

$$\begin{array}{ccccccc} C_0 & & & & & & U_1 \\ C_0 & \subset & & U_{1/2} \subset C_{1/2} & \subset & & U_1 \\ C_0 \subset U_{1/4} \subset C_{1/4} \subset U_{1/2} \subset C_{1/2} \subset U_{3/4} \subset C_{3/4} \subset U_1 \end{array}$$

and so on, labeled by the [dyadic rational numbers](#)  $\mathbb{Q}_{\text{dy}} \subset \mathbb{Q}$  within  $(0, 1]$

$$\{U_r \subset X\}_{r \in (0,1] \cap \mathbb{Q}_{\text{dy}}}$$

with the property

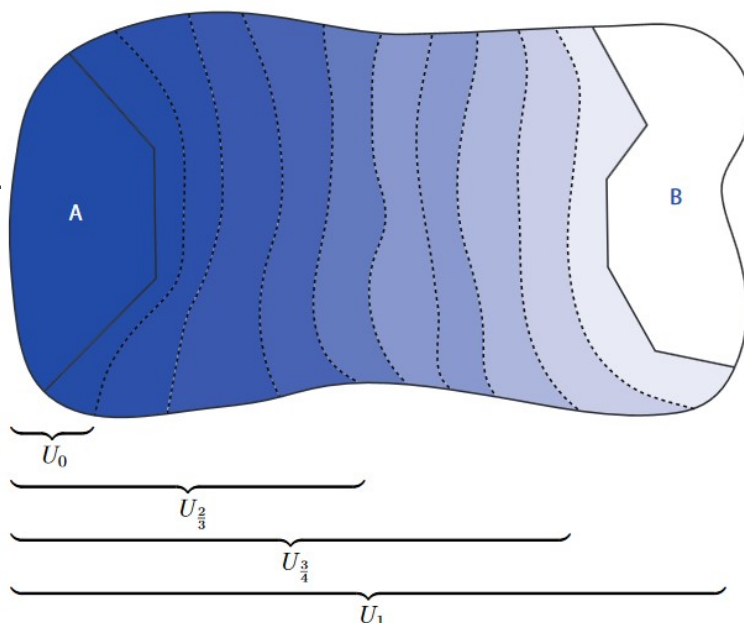
$$r_1 < r_2 \in (0,1] \cap \mathbb{Q}_{\text{dy}} \quad (U_{r_1} \subset \text{Cl}(U_{r_1}) \subset U_{r_2}) .$$

Define then the function

$$f : X \rightarrow [0,1]$$

to assign to a point  $x \in X$  the infimum of the labels of those open subsets in this sequence that contain  $x$ :

$$f(x) := \lim_{U_r \supset \{x\}} r$$



Here the limit is over the directed set of those  $U_r$  that contain  $x$ , ordered by reverse inclusion.

This function clearly has the property that  $f(A) = \{0\}$  and  $f(B) = \{1\}$ . It only remains to see that it is continuous.

To this end, first observe that

$$\begin{aligned} (\star) \quad (x \in \text{Cl}(U_r)) &\Rightarrow (f(x) \leq r) \\ (\star \star) \quad (x \in U_r) &\Leftarrow (f(x) < r) \end{aligned} .$$

Here it is immediate from the definition that  $(x \in U_r) \Rightarrow (f(x) \leq r)$  and that  $(f(x) < r) \Rightarrow (x \in U_r \subset \text{Cl}(U_r))$ . For the remaining implication, it is sufficient to observe that

$$(x \in \partial U_r) \Rightarrow (f(x) = r) ,$$

where  $\partial U_r := \text{Cl}(U_r) \setminus U_r$  is the boundary of  $U_r$ .

This holds because the dyadic numbers are dense in  $\mathbb{R}$ . (And this would fail if we stopped the above decomposition into  $U_{a/2^n}$ -s at some finite  $n$ .) Namely, in one direction, if  $x \in \partial U_r$  then for every small positive real number  $\epsilon$  there exists a dyadic rational number  $r'$  with  $r < r' < r + \epsilon$ , and by construction  $U_{r'} \supset \text{Cl}(U_r)$  hence  $x \in U_{r'}$ . This implies that  $\lim_{U_r \supset \{x\}} r = r$ .

Now we claim that for all  $\alpha \in [0,1]$  then

$$1. \ f^{-1}((\alpha, 1]) = \bigcup_{r > \alpha} (X \setminus \text{Cl}(U_r))$$

$$2. \ f^{-1}([0, \alpha)) = \bigcup_{r < \alpha} U_r$$

Thereby  $f^{-1}((\alpha, 1])$  and  $f^{-1}([0, \alpha))$  are exhibited as unions of open subsets, and

hence they are open.

Regarding the first point:

$$\begin{aligned}
 & x \in f^{-1}((\alpha, 1]) \\
 \Leftrightarrow & f(x) > \alpha \\
 \Leftrightarrow & \exists_{r > \alpha} (f(x) > r) \\
 \stackrel{(*)}{\Rightarrow} & \exists_{r > \alpha} (x \notin \text{Cl}(U_r)) \\
 \Leftrightarrow & x \in \bigcup_{r > \alpha} (X \setminus \text{Cl}(U_r))
 \end{aligned}$$

and

$$\begin{aligned}
 & x \in \bigcup_{r > \alpha} (X \setminus \text{Cl}(U_r)) \\
 \Leftrightarrow & \exists_{r > \alpha} (x \notin \text{Cl}(U_r)) \\
 \Rightarrow & \exists_{r > \alpha} (x \notin U_r) \\
 \stackrel{(**)}{\Rightarrow} & \exists_{r > \alpha} (f(x) \geq r) \\
 \Leftrightarrow & f(x) > \alpha \\
 \Leftrightarrow & x \in f^{-1}((\alpha, 1])
 \end{aligned}$$

Regarding the second point:

$$\begin{aligned}
 & x \in f^{-1}([0, \alpha)) \\
 \Leftrightarrow & f(x) < \alpha \\
 \Leftrightarrow & \exists_{r < \alpha} (f(x) < r) \\
 \stackrel{(**)}{\Rightarrow} & \exists_{r < \alpha} (x \in U_r) \\
 \Leftrightarrow & x \in \bigcup_{r < \alpha} U_r
 \end{aligned}$$

and

$$\begin{aligned}
 & x \in \bigcup_{r < \alpha} U_r \\
 \Leftrightarrow & \exists_{r < \alpha} (x \in U_r) \\
 \Rightarrow & \exists_{r < \alpha} (x \in \text{Cl}(U_r)) \\
 \stackrel{(*)}{\Rightarrow} & \exists_{r < \alpha} (f(x) \leq r) \\
 \Leftrightarrow & f(x) < \alpha \\
 \Leftrightarrow & x \in f^{-1}([0, \alpha))
 \end{aligned}$$

(In these derivations we repeatedly use that  $(0, 1] \cap \mathbb{Q}_{\text{dy}}$  is [dense](#) in  $[0, 1]$  (def. 2.23), and we use the [contrapositions](#) of  $(*)$  and  $(**)$ .)

Now since the subsets  $\{[0, \alpha), (\alpha, 1]\}_{\alpha \in [0, 1]}$  form a [sub-base](#) (def. 2.7) for the Euclidean metric topology on  $[0, 1]$ , it follows that all pre-images of  $f$  are open, hence that  $f$  is continuous. ■

As a corollary of [Urysohn's lemma](#) we obtain yet another equivalent reformulation of the normality of topological spaces, this one now of a rather different character than the re-formulations in terms of explicit topological closures considered above:

**Proposition 4.22. (normality equivalent to existence of Urysohn functions)**

*A  $T_1$ -space (def. 4.4) is [normal](#) (def. 4.13) precisely if it admits [Urysohn functions](#) (def 4.19) separating every pair of disjoint closed subsets.*

**Proof.** In one direction this is the statement of the [Urysohn lemma](#), prop. 4.20.

In the other direction, assume the existence of [Urysohn functions](#) (def. 4.19) separating all disjoint closed subsets. Let  $A, B \subset X$  be disjoint closed subsets, then we need to show that these have disjoint open neighbourhoods.

But let  $f: X \rightarrow [0, 1]$  be an Urysohn function with  $f(A) = \{0\}$  and  $f(B) = \{1\}$  then the [pre-images](#)

$$U_A := f^{-1}([0, 1/3]) \quad U_B := f^{-1}((2/3, 1])$$

are disjoint open neighbourhoods as required. ■

## $T_n$ reflection

While the [topological subspace](#) construction preserves the  $T_n$ -property for  $n \in \{0, 1, 2\}$  (example 4.9) the construction of [quotient topological spaces](#) in general does not, as shown by examples 4.1 and 4.3.

Further [below](#) we will see that, generally, among all [universal constructions](#) in the [category Top](#) of all [topological spaces](#) those that are [limits](#) preserve the  $T_n$  property, while those that are [colimits](#) in general do not.

But at least for  $T_0$ ,  $T_1$  and  $T_2$  there is a universal way, called [reflection](#) (prop. 4.23 below), to approximate any topological space “from the left” by a  $T_n$  topological spaces

Hence if one wishes to work within the [full subcategory](#) of the  $T_n$ -spaces among all [topological space](#), then the correct way to construct quotients and other [colimits](#) (see [below](#)) is to first construct them as usual [quotient topological spaces](#) (example 2.17), and then apply the  $T_n$ -reflection to the result.

**Proposition 4.23. ( $T_n$ -reflection)**

*Let  $n \in \{0, 1, 2\}$ . Then for every [topological space](#)  $X$  there exists*

1. a  $T_n$ -topological space  $T_n X$

2. a continuous function

$$t_n(X) : X \rightarrow T_n X$$

called the  $T_n$ -reflection of  $X$ ,

which is the "closest approximation from the left" to  $X$  by a  $T_n$ -topological space, in that for  $Y$  any  $T_n$ -space, then continuous functions of the form

$$f : X \rightarrow Y$$

are in bijection with continuous function of the form

$$\tilde{f} : T_n X \rightarrow Y$$

and such that the bijection is constituted by

$$f = \tilde{f} \circ t_n(X) : X \xrightarrow{t_n(X)} T_n X \xrightarrow{\tilde{f}} Y \quad \text{i.e.:} \quad \begin{array}{ccc} X & \xrightarrow{f} & Y \\ & t_n(X) \searrow & \nearrow \tilde{f} \\ & T_n X & \end{array} .$$

- For  $n = 0$  this is known as the Kolmogorov quotient construction (see prop. 4.26 below).
- For  $n = 2$  this is known as Hausdorff reflection or Hausdorffication or similar.

Moreover, the operation  $T_n(-)$  extends to continuous functions  $f : X \rightarrow Y$

$$(X \xrightarrow{f} Y) \mapsto (T_n X \xrightarrow{T_n f} T_n Y)$$

such as to preserve composition of functions as well as identity functions:

$$T_n g \circ T_n f = T_n (g \circ f) \quad , \quad T_n \text{id}_X = \text{id}_{T_n X}$$

Finally, the comparison map is compatible with this in that

$$t_n(Y) \circ f = T_n(f) \circ t_n(X) \quad \text{i.e.:} \quad \begin{array}{ccc} X & \xrightarrow{f} & Y \\ & t_n(X) \downarrow & \downarrow t_n(Y) \\ T_n X & \xrightarrow{T_n(f)} & T_n Y \end{array}$$

We **prove** this via a concrete construction of  $T_n$ -reflection in prop. 4.25 below. But first we pause to comment on the bigger picture of the  $T_n$ -reflection:

#### Remark 4.24. (reflective subcategories)

In the language of category theory (remark 3.3) the  $T_n$ -reflection of prop. 4.23 says that

1.  $T_n(-)$  is a [functor](#)  $T_n : \mathbf{Top} \rightarrow \mathbf{Top}_{T_n}$  from the [category Top](#) of [topological spaces](#) to the [full subcategory](#)  $\mathbf{Top}_{T_n} \xrightarrow{\iota} \mathbf{Top}$  of Hausdorff topological spaces;
2.  $t_n(X) : X \rightarrow T_n X$  is a [natural transformation](#) from the [identity functor](#) on [Top](#) to the functor  $\iota \circ T_n$
3.  $T_n$ -topological spaces form a [reflective subcategory](#) of all [topological spaces](#) in that  $T_n$  is [left adjoint](#) to the inclusion functor  $\iota$ ; this situation is denoted as follows:

$$\mathbf{Top}_{T_n} \begin{array}{c} \xleftarrow{H} \\ \perp \\ \xrightarrow{\iota} \end{array} \mathbf{Top} .$$

Generally, an [adjunction](#) between two [functors](#)

$$L : \mathcal{C} \leftrightarrow \mathcal{D} : R$$

is for all pairs of objects  $c \in \mathcal{C}$ ,  $d \in \mathcal{D}$  a [bijection](#) between sets of [morphisms](#) of the form

$$\{L(c) \rightarrow d\} \leftrightarrow \{c \rightarrow R(d)\} .$$

i.e.

$$\mathrm{Hom}_{\mathcal{D}}(L(c), d) \xrightarrow[\simeq]{\phi_{c,d}} \mathrm{Hom}_{\mathcal{C}}(c, R(d))$$

and such that these bijections are “[natural](#)” in that they for all pairs of morphisms  $f : c' \rightarrow c$  and  $g : d \rightarrow d'$  then the following [diagram commutes](#):

$$\begin{array}{ccc} \mathrm{Hom}_{\mathcal{D}}(L(c), d) & \xrightarrow[\simeq]{\phi_{c,d}} & \mathrm{Hom}_{\mathcal{C}}(c, R(d)) \\ g \circ (-) \circ L(f) \downarrow & & \downarrow R(g) \circ (-) \circ f \\ \mathrm{Hom}_{\mathcal{C}}(L(c'), d') & \xrightarrow[\simeq]{\phi_{c',d'}} & \mathrm{Hom}_{\mathcal{D}}(c', R(d')) \end{array}$$

One calls the image under  $\phi_{c,L(c)}$  of the [identity morphism](#)  $\mathrm{id}_{L(c)}$  the [unit of the adjunction](#), written

$$\eta_x : c \rightarrow R(L(c)) .$$

One may show that it follows that the image  $\tilde{f}$  under  $\phi_{c,d}$  of a general morphism  $f : c \rightarrow d$  (called the [adjunct](#) of  $f$ ) is given by this [composite](#):

$$\tilde{f} : c \xrightarrow{\eta_c} R(L(c)) \xrightarrow{R(f)} R(d) .$$

In the case of the [reflective subcategory](#) inclusion  $(T_n \dashv \iota)$  of the category of  $T_n$ -spaces into the category [Top](#) of all topological spaces this adjunction unit is precisely the  $T_n$ -reflection  $t_n(X) : X \rightarrow \iota(T_n(X))$  (only that we originally left the re-embedding  $\iota$  notationally implicit).

There are various ways to see the existence and to construct the  $T_n$ -reflections. The following is the quickest way to see the existence, even though it leaves the actual construction rather implicit.

**Proposition 4.25. ( $T_n$ -reflection via explicit quotients)**

Let  $n \in \{0, 1, 2\}$ . Let  $(X, \tau)$  be a [topological space](#) and consider the [equivalence relation](#)  $\sim$  on the underlying set  $X$  for which  $x_1 \sim x_2$  precisely if for every [surjective continuous function](#)  $f: X \rightarrow Y$  into any  $T_n$ -topological space  $Y$  (def. 4.4) we have  $f(x_1) = f(x_2)$ :

$$(x_1 \sim x_2) := \bigvee_{\substack{Y \in \mathbf{Top}_{T_n} \\ X \xrightarrow[\text{surjective}]{f} Y}} (f(x_1) = f(x_2)) .$$

Then

1. the set of [equivalence classes](#)

$$T_n X := X / \sim$$

equipped with the [quotient topology](#) (example 2.17) is a  $T_n$ -topological space,

2. the quotient projection

$$\begin{aligned} X &\xrightarrow{t_n(X)} X / \sim \\ x &\longmapsto [x] \end{aligned}$$

exhibits the  $T_n$ -reflection of  $X$ , according to prop. 4.23.

**Proof.** First we observe that every continuous function  $f: X \rightarrow Y$  into a  $T_n$ -topological space  $Y$  factors uniquely, via  $t_n(X)$  through a continuous function  $\tilde{f}$  (this makes use of the “[universal property](#)” of the quotient topology, which we dwell on a bit more below in example 6.3):

$$f = \tilde{f} \circ t_n(X)$$

Clearly this continuous function  $\tilde{f}$  is unique if it exists, because its underlying function of sets must be given by

$$\tilde{f}: [x] \mapsto f(x) .$$

First observe that this is indeed well defined as a function of underlying sets. To that end, factor  $f$  through its [image](#)  $f(X)$

$$f : X \rightarrow f(X) \hookrightarrow Y$$

equipped with its [subspace topology](#) as a subspace of  $Y$  (example 3.10). By prop.



4.9 also the image  $f(X)$  is a  $T_n$ -topological space, since  $Y$  is. This means that if two elements  $x_1, x_2 \in X$  have the same equivalence class, then, by definition of the equivalence relation, they have the same image under *all* continuous surjective functions into a  $T_n$ -space, hence in particular they have the same image under  $f: X \xrightarrow{\text{surjective}} f(X) \hookrightarrow Y$ :

$$\begin{aligned} ([x_1] = [x_2]) &\Leftrightarrow (x_1 \sim x_2) \\ &\Rightarrow (f(x_1) = f(x_2)) . \end{aligned}$$

This shows that  $\tilde{f}$  is well defined as a function between sets.

To see that  $\tilde{f}$  is also continuous, consider  $U \in Y$  an open subset. We need to show that the pre-image  $\tilde{f}^{-1}(U)$  is open in  $X/\sim$ . But by definition of the [quotient topology](#) (example 2.17), this is open precisely if its pre-image under the quotient projection  $t_n(X)$  is open, hence precisely if

$$\begin{aligned} (t_n(X))^{-1}(\tilde{f}^{-1}(U)) &= (\tilde{f} \circ t_n(X))^{-1}(U) \\ &= f^{-1}(U) \end{aligned}$$

is open in  $X$ . But this is the case by the assumption that  $f$  is continuous. Hence  $\tilde{f}$  is indeed the unique continuous function as required.

What remains to be seen is that  $T_n X$  as constructed is indeed a  $T_n$ -topological space. Hence assume that  $[x] \neq [y] \in T_n X$  are two distinct points. Depending on the value of  $n$ , need to produce open neighbourhoods around one or both of these points not containing the other point and possibly disjoint to each other.

Now by definition of  $T_n X$  the assumption  $[x] \neq [y]$  means that there exists a  $T_n$ -topological space  $Y$  and a surjective continuous function  $f: X \xrightarrow{\text{surjective}} Y$  such that  $f(x) \neq f(y) \in Y$ :

$$([x_1] \neq [x_2]) \Leftrightarrow \exists_{\substack{Y \in \text{Top}_{T_n} \\ X \xrightarrow[\text{surjective}]{f} Y}} (f(x_1) \neq f(x_2)) .$$

Accordingly, since  $Y$  is  $T_n$ , there exist the respective kinds of neighbourhoods around  $f(x_1)$  and  $f(x_2)$  in  $Y$ . Moreover, by the previous statement there exists the continuous function  $\tilde{f}: T_n X \rightarrow Y$  with  $\tilde{f}([x_1]) = f(x_1)$  and  $\tilde{f}([x_2]) = f(x_2)$ . By the nature of continuous functions, the pre-images of these open neighbourhoods in  $Y$  are still open in  $X$  and still satisfy the required disjunction properties. Therefore  $T_n X$  is a  $T_n$ -space. ■

Here are alternative constructions of the reflections:

### Proposition 4.26. ([Kolmogorov quotient](#))

Let  $(X, \tau)$  be a [topological space](#). Consider the [relation](#) on the underlying set by which  $x_1 \sim x_2$  precisely if neither  $x_i$  has an [open neighbourhood](#) not containing the

other. This is an [equivalence relation](#). The [quotient topological space](#)  $X \rightarrow X / \sim$  by this equivalence relation (def. [2.17](#)) exhibits the  $T_0$ -reflection of  $X$  according to prop. [4.23](#).

A more explicit construction of the Hausdorff quotient than given by prop. [4.25](#) is rather more involved. The issue is that the relation “ $x$  and  $y$  are not separated by disjoint open neighbourhoods” is not [transitive](#);

**Proposition 4.27. (more explicit [Hausdorff reflection](#))**

For  $(Y, \tau_Y)$  a [topological space](#), write  $r_Y \subset Y \times Y$  for the [transitive closure](#) of the [relation](#) given by the [topological closure](#)  $\text{Cl}(\Delta_Y)$  of the [image](#) of the [diagonal](#)  $\Delta_Y: Y \hookrightarrow Y \times Y$ .

$$r_Y := \text{Trans}(\text{Cl}(\Delta_Y)) .$$

Now for  $(X, \tau_X)$  a [topological space](#), define by [induction](#) for each [ordinal number](#)  $\alpha$  an [equivalence relation](#)  $r^\alpha$  on  $X$  as follows, where we write  $q^\alpha: X \rightarrow H^\alpha(X)$  for the corresponding [quotient topological space](#) projection:

We start the induction with the trivial equivalence relation:

- $r_X^0 := \Delta_X$ ;

For a [successor ordinal](#) we set

- $r_X^{\alpha+1} := \{(a, b) \in X \times X \mid (q^\alpha(a), q^\alpha(b)) \in r_{H^\alpha(X)}\}$

and for a [limit ordinal](#)  $\alpha$  we set

- $r_X^\alpha := \bigcup_{\beta < \alpha} r_X^\beta$ .

Then:

1. there exists an ordinal  $\alpha$  such that  $r_X^\alpha = r_X^{\alpha+1}$
2. for this  $\alpha$  then  $H^\alpha(X) = H(X)$  is the Hausdorff reflection from prop. [4.25](#).

A detailed **proof** is spelled out in ([vanMunster 14](#), section 4).

**Example 4.28. ([Hausdorff reflection](#) of the [line with two origins](#))**

The [Hausdorff reflection](#) ( $T_2$ -reflection, prop. [4.23](#))

$$T_2 : \text{Top} \rightarrow \text{Top}_{\text{Haus}}$$

of the [line with two origins](#) from example [4.3](#) is the [real line](#) itself:

$$T_2((\mathbb{R} \sqcup \mathbb{R}) / \sim) \simeq \mathbb{R} .$$

## 5. Sober spaces

While the original formulation of the [separation axioms](#)  $T_n$  from [def. 4.4](#) and [def. 4.13](#) clearly does follow some kind of pattern, its equivalent reformulation in terms of closure conditions in [prop. 4.10](#), [prop. 4.11](#), [prop. 4.12](#), [prop. 4.17](#) and [prop. 4.18](#) suggests rather different patterns. Therefore it is worthwhile to also consider separation-like axioms that are not among the original list.

In particular, the alternative characterization of the  $T_0$ -condition in [prop. 4.10](#) immediately suggests the following strengthening, different from the  $T_1$ -condition (see [example 5.5](#) below):

### Definition 5.1. ([sober topological space](#))

A [topological space](#)  $(X, \tau)$  is called a [sober topological space](#) precisely if every [irreducible closed subspace](#) ([def. 2.32](#)) is the [topological closure](#) ([def. 2.23](#)) of a unique point, hence precisely if the function

$$\text{Cl}(\{-\}) : X \rightarrow \text{IrrClSub}(X)$$

from the underlying set of  $X$  to the set of [irreducible closed subsets](#) of  $X$  ([def. 2.31](#), well defined according to [example 2.32](#)) is [bijective](#).

### Proposition 5.2. ([sober implies](#) $T_0$ )

Every [sober topological space](#) ([def. 5.1](#)) is  $T_0$  ([def. 4.4](#)).

**Proof.** By [prop. 4.10](#). ■

### Proposition 5.3. ([Hausdorff spaces are sober](#))

Every [Hausdorff topological space](#) ([def. 4.4](#)) is a [sober topological space](#) ([def. 5.1](#)).

More specifically, in a Hausdorff topological space the [irreducible closed subspaces](#) ([def. 2.31](#)) are precisely the [singleton subspaces](#) ([def. 2.16](#)).

Hence, by [example 4.8](#), in particular every [metric space](#) with its [metric topology](#) ([example 2.9](#)) is sober.

**Proof.** The second statement clearly implies the first. To see the second statement, suppose that  $F$  is an irreducible closed subspace which contained two distinct points  $x \neq y$ . Then by the Hausdorff property there would be disjoint neighbourhoods  $U_x, U_y$ , and hence it would follow that the relative [complements](#)  $F \setminus U_x$  and  $F \setminus U_y$  were distinct closed proper subsets of  $F$  with

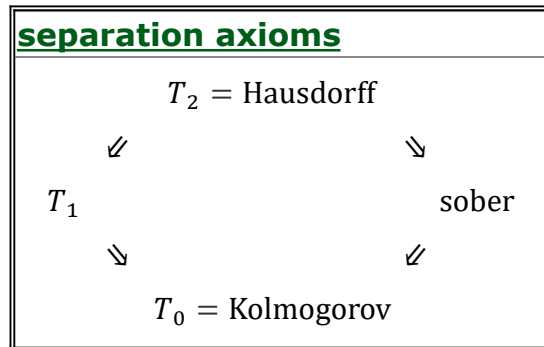
$$F = (F \setminus U_x) \cup (F \setminus U_y)$$

in contradiction to the assumption that  $F$  is irreducible.

This [proves by contradiction](#) that every irreducible closed subset is a singleton. Conversely, generally the [topological closure](#) of every singleton is irreducible

closed, by example 2.32. ■

By prop. 5.2 and prop. 5.3 we have the implications on the right of the following diagram:



But there there is no implication between  $T_1$  and sobriety:

**Proposition 5.4.** The [intersection](#) of the [classes](#) of [sober topological spaces](#) (def. 5.1) and  $T_1$ -topological spaces (def. 4.4) is not [empty](#), but neither class is contained within the other.

That the intersection is not empty follows from prop. 5.3. That neither class is contained in the other is shown by the following counter-examples:

**Example 5.5. ( $T_1$  neither implies nor is implied by sobriety)**

- The [Sierpinski space](#) (def. 2.11) is sober, but not  $T_1$ .
- The [cofinite topology](#) (example 2.14) on a non-[finite set](#) is  $T_1$  but not sober.

Finally, sobriety is indeed strictly weaker than Hausdorffness:

**Example 5.6. ([schemes are sober](#) but in general not [Hausdorff](#))**

The [Zariski topology](#) on an [affine space](#) (example 2.21) or more generally on the [prime spectrum of a commutative ring](#) (example 2.22) is

1. [sober](#) (def 5.1);
2. in general not [Hausdorff](#) (def. 4.4).

For details see at [Zariski topology](#) this prop and this example.

## Frames of opens

What makes the concept of [sober topological spaces](#) special is that for them the concept of [continuous functions](#) may be expressed entirely in terms of the relations between their [open subsets](#), disregarding the underlying set of points of which these opens are in fact subsets.

Recall from example 2.37 that for every [continuous function](#)  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  the [pre-image](#) function  $f^{-1}: \tau_Y \rightarrow \tau_X$  is a [frame homomorphism](#) (def. 2.35).

For sober topological spaces the converse holds:

**Proposition 5.7.** *If  $(X, \tau_X)$  and  $(Y, \tau_Y)$  are [sober topological spaces](#) (def. 5.1), then for every [frame homomorphism](#) (def. 2.35)*

$$\tau_X \leftarrow \tau_Y : \phi$$

*there is a unique [continuous function](#)  $f: X \rightarrow Y$  such that  $\phi$  is the function of forming [pre-images](#) under  $f$ :*

$$\phi = f^{-1}.$$

**Proof.** We first consider the special case of frame homomorphisms of the form

$$\tau_* \leftarrow \tau_X : \phi$$

and show that these are in bijection to the underlying set  $X$ , identified with the continuous functions  $* \rightarrow (X, \tau)$  via example 3.6.

By prop. 2.38, the frame homomorphisms  $\phi: \tau_X \rightarrow \tau_*$  are identified with the irreducible closed subspaces  $X \setminus U_\emptyset(\phi)$  of  $(X, \tau_X)$ . Therefore by assumption of [sobriety](#) of  $(X, \tau)$  there is a unique point  $x \in X$  with  $X \setminus U_\emptyset = \text{Cl}(\{x\})$ . In particular this means that for  $U_x$  an open neighbourhood of  $x$ , then  $U_x$  is not a subset of  $U_\emptyset(\phi)$ , and so it follows that  $\phi(U_x) = \{1\}$ . In conclusion we have found a unique  $x \in X$  such that

$$\phi : U \mapsto \begin{cases} \{1\} & | \text{ if } x \in U \\ \emptyset & | \text{ otherwise } \end{cases}.$$

This is precisely the [inverse image](#) function of the continuous function  $* \rightarrow X$  which sends  $1 \mapsto x$ .

Hence this establishes the bijection between frame homomorphisms of the form  $\tau_* \leftarrow \tau_X$  and continuous functions of the form  $* \rightarrow (X, \tau)$ .

With this it follows that a general frame homomorphism of the form  $\tau_X \xleftarrow{\phi} \tau_Y$  defines a function of sets  $X \xrightarrow{f} Y$  by [composition](#):

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ (\tau_* \leftarrow \tau_X) & \mapsto & (\tau_* \leftarrow \tau_X \xleftarrow{\phi} \tau_Y) \end{array}.$$

By the previous analysis, an element  $U_Y \in \tau_Y$  is sent to  $\{1\}$  under this composite precisely if the corresponding point  $* \rightarrow X \xrightarrow{f} Y$  is in  $U_Y$ , and similarly for an element  $U_X \in \tau_X$ . It follows that  $\phi(U_Y) \in \tau_X$  is precisely that subset of points in  $X$  which are sent by  $f$  to elements of  $U_Y$ , hence that  $\phi = f^{-1}$  is the [pre-image](#) function of  $f$ . Since  $\phi$  by definition sends open subsets of  $Y$  to open subsets of  $X$ , it follows that  $f$  is indeed a continuous function. This proves the claim in generality. ■

**Remark 5.8.** ([locales](#))

Proposition 5.7 is often stated as saying that sober topological spaces are equivalently the “locales with enough points” (Johnstone 82, II 1.). Here “locale” refers to a concept akin to topological spaces where one considers *just* a “frame of open subsets”  $\tau_X$ , without requiring that its elements be actual subsets of some ambient set. The natural notion of homomorphism between such generalized topological spaces are clearly the frame homomorphisms  $\tau_X \leftarrow \tau_Y$  from def. 2.35.

From this perspective, prop. 5.7 says that sober topological spaces  $(X, \tau_X)$  are entirely characterized by their frames of opens  $\tau_X$  and just so happen to “have enough points” such that these are actual open subsets of some ambient set, namely of  $X$ .

## Sober reflection

We saw above in prop. 4.23 that every  $T_n$ -topological space for  $n \in \{0, 1, 2\}$  has a “best approximation from the left” by a  $T_n$ -topological space (for  $n = 2$ : “Hausdorff reflection”). We now discuss the analogous statement for sober topological spaces.

Recall again the point topological space  $\ast := (\{1\}, \tau_\ast = \{\emptyset, \{1\}\})$  (example 2.10).

### Definition 5.9. (sober reflection)

Let  $(X, \tau)$  be a topological space.

Define  $SX$  to be the set

$$SX := \text{FrameHom}(\tau_X, \tau_\ast)$$

of frame homomorphisms (def. 2.35) from the frame of opens of  $X$  to that of the point. Define a topology  $\tau_{SX} \subset P(SX)$  on this set by declaring it to have one element  $\tilde{U}$  for each element  $U \in \tau_X$  and given by

$$\tilde{U} := \{\phi \in SX \mid \phi(U) = \{1\}\}.$$

Consider the function

$$\begin{array}{ccc} X & \xrightarrow{s_X} & SX \\ x & \mapsto & (\text{const}_x)^{-1} \end{array}$$

which sends an element  $x \in X$  to the function which assigns inverse images of the constant function  $\text{const}_x : \{1\} \rightarrow X$  on that element.

We are going to call this function the sober reflection of  $X$ .

### Lemma 5.10. (sober reflection is well defined)

*The construction  $(SX, \tau_{SX})$  in def. 5.9 is a topological space, and the function  $s_X : X \rightarrow SX$  is a continuous function*

$$s_X : (X, \tau_X) \rightarrow (SX, \tau_{SX})$$

**Proof.** To see that  $\tau_{SX} \subset P(SX)$  is closed under arbitrary unions and finite intersections, observe that the function

$$\begin{array}{ccc} \tau_X & \xrightarrow{(\quad)^{-}} & \tau_{SX} \\ U & \mapsto & \tilde{U} \end{array}$$

in fact preserves arbitrary unions and finite intersections. Whith this the statement follows by the fact that  $\tau_X$  is closed under these operations.

To see that  $(\quad)^{-}$  indeed preserves unions, observe that (e.g. [Johnstone 82, II 1.3 Lemma](#))

$$\begin{aligned} p \in \bigcup_{i \in I} \tilde{U}_i &\Leftrightarrow \exists_{i \in I} p(U_i) = \{1\} \\ &\Leftrightarrow \bigcup_{i \in I} p(U_i) = \{1\} \\ &\Leftrightarrow p\left(\bigcup_{i \in I} U_i\right) = \{1\} \\ &\Leftrightarrow p \in \overline{\bigcup_{i \in I} U_i} \end{aligned}$$

where we used that the frame homomorphism  $p: \tau_X \rightarrow \tau_*$  preserves unions. Similarly for intersections, now with  $I$  a [finite set](#):

$$\begin{aligned} p \in \bigcap_{i \in I} \tilde{U}_i &\Leftrightarrow \forall_{i \in I} p(U_i) = \{1\} \\ &\Leftrightarrow \bigcap_{i \in I} p(U_i) = \{1\} \\ &\Leftrightarrow p\left(\bigcap_{i \in I} U_i\right) = \{1\} \\ &\Leftrightarrow p \in \overline{\bigcap_{i \in I} U_i} \end{aligned}$$

where we used that the frame homomorphism  $p$  preserves finite intersections.

To see that  $s_X$  is continuous, observe that  $s_X^{-1}(\tilde{U}) = U$ , by construction. ■

**Lemma 5.11. ([sober reflection detects  \$T\_0\$  and sobriety](#))**

For  $(X, \tau_X)$  a [topological space](#), the function  $s_X: X \rightarrow SX$  from [def. 5.9](#) is

1. an [injection](#) precisely if  $(X, \tau_X)$  is  $T_0$  ([def. 4.4](#));
2. a [bijection](#) precisely if  $(X, \tau_X)$  is [sober](#) ([def. 5.1](#)), in which case  $s_X$  is in fact a [homeomorphism](#) ([def. 3.22](#)).

**Proof.** By lemma [2.38](#) there is an identification  $SX \simeq \text{IrrClSub}(X)$  and via this  $s_X$  is identified with the map  $x \mapsto \text{Cl}(\{x\})$ .

Hence the second statement follows by definition, and the first statement by [prop. 4.10](#).

That in the second case  $s_X$  is in fact a homeomorphism follows from the definition of the opens  $\tilde{U}$ : they are identified with the opens  $U$  in this case (...expand...). ■

**Lemma 5.12. (*soberification lands in sober spaces, e.g. Johnstone 82, lemma II 1.7*)**

For  $(X, \tau)$  a *topological space*, then the topological space  $(SX, \tau_{SX})$  from def. 5.9, lemma 5.10 is sober.

**Proof.** Let  $SX \setminus \tilde{U}$  be an *irreducible closed subspace* of  $(SX, \tau_{SX})$ . We need to show that it is the *topological closure* of a unique element  $\phi \in SX$ .

Observe first that also  $X \setminus U$  is irreducible.

To see this use prop. 2.34, saying that irreducibility of  $X \setminus U$  is equivalent to  $U_1 \cap U_2 \subset U \Rightarrow (U_1 \subset U) \text{ or } (U_2 \subset U)$ . But if  $U_1 \cap U_2 \subset U$  then also  $\tilde{U}_1 \cap \tilde{U}_2 \subset \tilde{U}$  (as in the proof of lemma 5.10) and hence by assumption on  $\tilde{U}$  it follows that  $\tilde{U}_1 \subset \tilde{U}$  or  $\tilde{U}_2 \subset \tilde{U}$ . By lemma 2.38 this in turn implies  $U_1 \subset U$  or  $U_2 \subset U$ . In conclusion, this shows that also  $X \setminus U$  is irreducible .

By lemma 2.38 this irreducible closed subspace corresponds to a point  $p \in SX$ . By that same lemma, this frame homomorphism  $p: \tau_X \rightarrow \tau_*$  takes the value  $\emptyset$  on all those opens which are inside  $U$ . This means that the *topological closure* of this point is just  $SX \setminus \tilde{U}$ .

This shows that there exists at least one point of which  $X \setminus \tilde{U}$  is the topological closure. It remains to see that there is no other such point.

So let  $p_1 \neq p_2 \in SX$  be two distinct points. This means that there exists  $U \in \tau_X$  with  $p_1(U) \neq p_2(U)$ . Equivalently this says that  $\tilde{U}$  contains one of the two points, but not the other. This means that  $(SX, \tau_{SX})$  is **T0**. By prop. 4.10 this is equivalent to there being no two points with the same topological closure. ■

**Proposition 5.13. (*unique factorization through soberification*)**

For  $(X, \tau_X)$  any *topological space*, for  $(Y, \tau_Y^{\text{sob}})$  a sober topological space, and for  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  a *continuous function*, then it factors uniquely through the *soberification*  $s_X: (X, \tau_X) \rightarrow (SX, \tau_{SX})$  from def. 5.9, lemma 5.10

$$\begin{array}{ccc} (X, \tau_X) & \xrightarrow{f} & (Y, \tau_Y^{\text{sob}}) \\ s_X \downarrow & \nearrow_{\exists!} & \\ (SX, \tau_{SX}) & & \end{array} .$$

**Proof.** By the construction in def. 5.9, we find that the outer part of the following square *commutes*:



$$\begin{array}{ccc}
 (X, \tau_X) & \xrightarrow{f} & (Y, \tau_Y^{\text{sob}}) \\
 s_X \downarrow & \nearrow & \downarrow s_{SX} \\
 (SX, \tau_{SX}) & \xrightarrow{s_f} & (SSX, \tau_{SSX})
 \end{array}
 .$$

By lemma 5.12 and lemma 5.11, the right vertical morphism  $s_{SX}$  is an isomorphism (a [homeomorphism](#)), hence has an [inverse morphism](#). This defines the diagonal morphism, which is the desired factorization.

To see that this factorization is unique, consider two factorizations

$\tilde{f}, \bar{f} : (SX, \tau_{SX}) \rightarrow (Y, \tau_Y^{\text{sob}})$  and apply the soberification construction once more to the triangles

$$\begin{array}{ccc}
 (X, \tau_X) & \xrightarrow{f} & (Y, \tau_Y^{\text{sob}}) \\
 s_X \downarrow & \nearrow_{\tilde{f}, \bar{f}} & \\
 (SX, \tau_{SX}) & & 
 \end{array}
 \mapsto
 \begin{array}{ccc}
 (SX, \tau_{SX}) & \xrightarrow{s_f} & (Y, \tau_Y^{\text{sob}}) \\
 \simeq \downarrow & \nearrow_{\tilde{f}, \bar{f}} & \\
 (SX, \tau_{SX}) & & 
 \end{array}
 .$$

Here on the right we used again lemma 5.11 to find that the vertical morphism is an isomorphism, and that  $\tilde{f}$  and  $\bar{f}$  do not change under soberification, as they already map between sober spaces. But now that the left vertical morphism is an isomorphism, the commutativity of this triangle for both  $\tilde{f}$  and  $\bar{f}$  implies that  $\tilde{f} = \bar{f}$ . ■

In **summary** we have found

**Proposition 5.14. ([sober reflection](#))**

For every [topological space](#)  $X$  there exists

1. a [sober topological spaces](#)  $SX$ ;
2. a [continuous function](#)  $s_X : X \rightarrow SX$

such that ...

As before for the  $T_n$ -reflection in remark 4.24, the statement of prop. 5.14 may neatly be re-packaged:

**Remark 5.15. ([sober topological spaces](#) are a [reflective subcategory](#))**

In the language of [category theory](#) (remark 3.3) and in terms of the concept of [adjoint functors](#) (remark 4.24), proposition 5.14 simply says that [sober topological spaces](#) form a [reflective subcategory](#)  $\text{Top}_{\text{sob}}$  of the category [Top](#) of all topological spaces

$$\text{Top}_{\text{sob}} \xrightleftharpoons[s]{s} \text{Top} .$$

## 6. Universal constructions

We have seen [above](#) various construction principles for [topological spaces](#) [above](#), such as [topological subspaces](#) and [topological quotient spaces](#). It turns out that these constructions enjoy certain “[universal properties](#)” which allow us to find [continuous functions](#) into or out of these spaces, respectively (examples [6.1](#), example [6.2](#) and [6.3](#) below).

Since this is useful for handling topological spaces (we secretly used the universal property of the quotient space construction already in the proof of prop. [4.25](#)), we next consider, in def. [6.11](#) below, more general “[universal constructions](#)” of topological spaces, called [limits](#) and [colimits](#) of topological spaces (and to be distinguished from limits *in* topological spaces, in the sense of [convergence](#) of [sequences](#) as in def. [1.17](#)).

Moreover, we have seen [above](#) that the [quotient space](#) construction in general does not preserve the  $T_n$ -[separation](#) property or [sobriety](#) property of topological spaces, while the [topological subspace](#) construction does. The same turns out to be true for the more general “colimiting” and “limiting” universal constructions. But we have also seen that we may universally “reflect” any topological space to becomes a  $T_n$ -space or sober space. The remaining question then is whether this reflection breaks the desired universal property. We discuss that this is not the case, that instead the universal construction in all topological spaces followed by these reflections gives the correct universal constructions in  $T_n$ -separated and sober topological spaces, respectively (remark [6.22](#) below).

After these general considerations, we finally discuss a [list of examples](#) of universal constructions in topological spaces.

To motivate the following generalizations, first observe the [universal properties](#) enjoyed by the basic construction principles of topological spaces from [above](#)

### Example 6.1. ([universal property of binary product topological space](#))

Let  $X_1, X_2$  be [topological spaces](#). Consider their [product topological space](#)  $X_1 \times X_2$  from example [2.18](#). By example [3.16](#) the two [projections](#) out of the product space are [continuous functions](#)

$$X_1 \xleftarrow{\text{pr}_1} X_1 \times X_2 \xrightarrow{\text{pr}_2} X_2 .$$

Now let  $Y$  be any other [topological space](#). Then, by [composition](#), every [continuous function](#)  $Y \rightarrow X_1 \times X_2$  into the product space yields two continuous component functions  $f_1$  and  $f_2$ :

$$\begin{array}{ccccc} & & Y & & \\ f_1 \swarrow & & \downarrow & & \searrow f_2 \\ X_1 & \xleftarrow{\text{pr}_1} & X_1 \times X_2 & \xrightarrow{\text{pr}_2} & X_2 \end{array} .$$

But in fact these two components completely characterize the function into the product: There is a ([natural](#)) [bijection](#) between continuous functions into the product space and pairs of continuous functions into the two factor spaces:

$$\{Y \rightarrow X_1 \times X_2\} \simeq \left\{ \begin{pmatrix} Y \rightarrow X_1, \\ Y \rightarrow X_2 \end{pmatrix} \right\}$$

i.e.:

$$\mathrm{Hom}(Y, X_1 \times X_2) \simeq \mathrm{Hom}(Y, X_1) \times \mathrm{Hom}(Y, X_2)$$

### Example 6.2. ([universal property of disjoint union spaces](#))

Let  $X_1, X_2$  be [topological spaces](#). Consider their [disjoint union space](#)  $X_1 \sqcup X_2$  from example 2.15. By definition, the two inclusions into the disjoint union space are clearly [continuous functions](#)

$$X_1 \xrightarrow{i_1} X_1 \sqcup X_2 \xleftarrow{i_2} X_2.$$

Now let  $Y$  be any other [topological space](#). Then by [composition](#) a [continuous function](#)  $X_1 \sqcup X_2 \rightarrow Y$  out of the disjoint union space yields two continuous component functions  $f_1$  and  $f_2$ :

$$\begin{array}{ccccc} X_1 & \xleftarrow{i_1} & X_1 \sqcup X_2 & \xrightarrow{i_2} & X_2 \\ & \searrow f_1 & \downarrow & \swarrow f_2 & \\ & & Y & & \end{array}.$$

But in fact these two components completely characterize the function out of the disjoint union: There is a ([natural](#)) [bijection](#) between continuous functions out of disjoint union spaces and pairs of continuous functions out of the two summand spaces:

$$\{X_1 \sqcup X_2 \rightarrow Y\} \simeq \left\{ \begin{pmatrix} X_1 \rightarrow Y, \\ X_2 \rightarrow Y \end{pmatrix} \right\}$$

i.e.:

$$\mathrm{Hom}(X_1 \sqcup X_2, Y) \simeq \mathrm{Hom}(X_1, Y) \times \mathrm{Hom}(X_2, Y)$$

### Example 6.3. ([universal property of quotient topological spaces](#))

Let  $X$  be a [topological space](#), and let  $\sim$  be an [equivalence relation](#) on its underlying set. Then the corresponding [quotient topological space](#)  $X/\sim$  together with the corresponding quotient [continuous function](#)  $p:X \rightarrow X/\sim$  has the following [universal property](#):

Given  $f:X \rightarrow Y$  any [continuous function](#) out of  $X$  with the property that it respects the given [equivalence relation](#), in that

$$(x_1 \sim x_2) \Rightarrow (f(x_1) = f(x_2))$$

then there is a unique [continuous function](#)  $\tilde{f}:X/\sim \rightarrow Y$  such that

$$\begin{array}{ccc}
 X & \xrightarrow{f} & Y \\
 f = \tilde{f} \circ p & i.e. & p \downarrow \nearrow \exists! \tilde{f} \\
 X / \sim & & 
 \end{array}$$

(We already made use of this universal property in the construction of the  $T_n$ -reflection in the proof of prop. 4.25.)

**Proof.** First observe that there is a unique function  $\tilde{f}$  as claimed on the level of functions of the underlying sets: In order for  $f = \tilde{f} \circ p$  to hold,  $\tilde{f}$  must send an equivalence class in  $X / \sim$  to one of its members

$$\tilde{f} : [x] \mapsto x$$

and that this is well defined and independent of the choice of representative  $x$  is guaranteed by the condition on  $f$  above.

Hence it only remains to see that  $\tilde{f}$  defined this way is continuous, hence that for  $U \subset Y$  an open subset, then its pre-image  $\tilde{f}^{-1}(U) \subset X / \sim$  is open in the quotient topology. By definition of the quotient topology (example 2.17), this is the case precisely if its further pre-image under  $p$  is open in  $X$ . But by the fact that  $f = \tilde{f} \circ p$ , this is the case by the continuity of  $f$ :

$$\begin{aligned}
 p^{-1}(\tilde{f}^{-1}(U)) &= (\tilde{f} \circ p)^{-1}(U) \\
 &= f^{-1}(U)
 \end{aligned}$$

■

This kind of example we now generalize.

## Limits and colimits

We consider now the general definition of [free diagrams](#) of [topological spaces](#) (def. 6.4 below), their [cones](#) and [co-cones](#) (def. 6.9) as well as [limiting cones](#) and [colimiting cocones](#) (def. 6.11 below).

Then we use these concepts to see generally (remark 6.22 below) why [limits](#) (such as [product spaces](#) and [subspaces](#)) of  $T_{n \leq 2}$ -spaces and of [sober spaces](#) are again  $T_n$  or sober, respectively, and to see that the correct [colimits](#) (such as [disjoint union spaces](#) and [quotient spaces](#)) of  $T_n$ - or sober spaces are instead the  $T_n$ -*reflection* (prop. 4.23) or sober reflection (prop. 5.14), respectively, of these colimit constructions performed in the context of unconstrained topological spaces.

### Definition 6.4. ([free diagram](#) of [sets/topological spaces](#))

A [free diagram](#)  $X$ . of [sets](#) or of [topological spaces](#) is

1. a set  $\{X_i\}_{i \in I}$  of sets or of topological spaces, respectively;
2. for every pair  $(i, j) \in I \times I$  of labels, a set  $\{X_i \xrightarrow{f_\alpha} X_j\}_{\alpha \in I_{i,j}}$  of functions of of continuous functions, respectively, between these.

Here is a list of basic and important examples of free diagrams

- *discrete diagrams and the empty diagram* (example 6.5);
- *pairs of parallel morphisms* (example 6.6);
- *span and cospan diagram* (example 6.7);
- *tower and cotower diagram* (example 6.8).

### Example 6.5. (discrete diagram and empty diagram)

Let  $I$  be any set, and for each  $(i, j) \in I \times I$  let  $I_{i,j} = \emptyset$  be the empty set.

The corresponding free diagrams (def. 6.4) are simply a set of sets/topological spaces with no specified (continuous) functions between them. This is called a discrete diagram.

For example for  $I = \{1, 2, 3\}$  the set with 3-elements, then such a diagram looks like this:

$$X_1 \quad X_2 \quad X_3 .$$

Notice that here the index set may be empty set,  $I = \emptyset$ , in which case the corresponding diagram consists of no data. This is also called the empty diagram.

### Definition 6.6. (parallel morphisms diagram)

Let  $I = \{a, b\}$  be the set with two elements, and consider the sets

$$I_{i,j} := \left\{ \begin{array}{ll} \{1, 2\} & | \quad (i = a) \text{ and } (j = b) \\ \emptyset & | \quad \text{otherwise} \end{array} \right\} .$$

The corresponding free diagrams (def. 6.4) are called pairs of parallel morphisms. They may be depicted like so:

$$X_a \begin{array}{c} \xrightarrow{f_1} \\ \xrightarrow{f_2} \end{array} X_b .$$

### Example 6.7. (span and cospan diagram)

Let  $I = \{a, b, c\}$  the set with three elements, and set

$$I_{i,j} = \begin{cases} \{f_1\} & | \quad (i = c) \text{ and } (j = a) \\ \{f_2\} & | \quad (i = c) \text{ and } (j = b) \\ \emptyset & | \quad \text{otherwise} \end{cases}$$

The corresponding [free diagrams](#) (def. 6.4) look like so:

$$\begin{array}{ccc} & X_c & \\ f_1 \swarrow & & \searrow f_2 \\ X_a & & X_b \end{array} .$$

These are called [span diagrams](#).

Similary, there is the [cospan](#) diagram of the form

$$\begin{array}{ccc} & X_c & \\ f_1 \nearrow & & \nwarrow f_2 \\ X_a & & X_b \end{array} .$$

### Example 6.8. ([tower diagram](#))

Let  $I = \mathbb{N}$  be the set of [natural numbers](#) and consider

$$I_{i,j} := \begin{cases} \{f_{i,j}\} & | \quad j = i + 1 \\ \emptyset & | \quad \text{otherwise} \end{cases}$$

The corresponding [free diagrams](#) (def. 6.4) are called [tower diagrams](#). They look as follows:

$$X_0 \xrightarrow{f_{0,1}} X_1 \xrightarrow{f_{1,2}} X_2 \xrightarrow{f_{2,3}} X_3 \longrightarrow \dots .$$

Similarly there are co-tower diagram

$$X_0 \xleftarrow{f_{0,1}} X_1 \xleftarrow{f_{1,2}} X_2 \xleftarrow{f_{2,3}} X_3 \longleftarrow \dots .$$

### Definition 6.9. ([cone over a free diagram](#))

Consider a [free diagram](#) of sets or of topological spaces (def. 6.4)

$$X_\bullet = \left\{ X_i \xrightarrow{f_\alpha} X_j \right\}_{i,j \in I, \alpha \in I_{i,j}} .$$

Then

1. a [cone](#) over this diagram is
  1. a [set](#) or [topological space](#)  $\tilde{X}$  (called the *tip* of the cone);
  2. for each  $i \in I$  a [function](#) or [continuous function](#)  $\tilde{X} \xrightarrow{p_i} X_i$

such that

- for all  $(i, j) \in I \times I$  and all  $\alpha \in I_{i,j}$  then the condition

$$f_\alpha \circ p_i = p_j$$

holds, which we depict as follows:

$$\begin{array}{ccc} & \tilde{X} & \\ p_i \swarrow & & \searrow p_j \\ X_i & \xrightarrow{f_\alpha} & X_j \end{array}$$

2. a [co-cone](#) over this diagram is

1. a set or topological space  $\tilde{X}$  (called the *tip* of the co-cone);
2. for each  $i \in I$  a function or continuous function  $q_i: X_i \rightarrow \tilde{X}$ ;

such that

- for all  $(i, j) \in I \times I$  and all  $\alpha \in I_{i,j}$  then the condition

$$q_j \circ f_\alpha = q_i$$

holds, which we depict as follows:

$$\begin{array}{ccc} X_i & \xrightarrow{f_\alpha} & X_j \\ q_i \searrow & & \swarrow q_j \\ & \tilde{X} & \end{array} .$$

### Example 6.10. ([solutions](#) to [equations](#) are [cones](#))

Let  $f, g: \mathbb{R} \rightarrow \mathbb{R}$  be two [functions](#) from the [real numbers](#) to themselves, and consider the corresponding [parallel morphism diagram](#) of sets (example 6.6):

$$\begin{array}{ccc} \mathbb{R} & \xrightarrow{f_1} & \mathbb{R} \\ & \xrightarrow{f_2} & \end{array} .$$

Then a [cone](#) (def. 6.9) over this free diagram with tip the [singleton](#) set  $*$  is a [solution](#) to the [equation](#)  $f(x) = g(x)$

$$\begin{array}{ccc} & * & \\ \text{const}_x \swarrow & & \searrow \text{const}_y \\ \mathbb{R} & \begin{array}{c} \xrightarrow{f_1} \\ \xrightarrow{f_2} \end{array} & \mathbb{R} \end{array} .$$

Namely the components of the cone are two functions of the form

$$\text{cont}_x, \text{const}_y : * \rightarrow \mathbb{R}$$

hence equivalently two [real numbers](#), and the conditions on these are

$$f_1 \circ \text{const}_x = \text{const}_y \quad f_2 \circ \text{const}_x = \text{const}_y .$$

**Definition 6.11. ([limiting cone](#) over a [diagram](#))**

Consider a [free diagram](#) of sets or of topological spaces (def. [6.4](#)):

$$\left\{ X_i \xrightarrow{f_\alpha} X_j \right\}_{i,j \in I, \alpha \in I_{i,j}} .$$

Then

1. its [limiting cone](#) (or just [limit](#) for short, also “[inverse limit](#)”, for historical reasons) is [the cone](#)

$$\left\{ \begin{array}{ccc} & \varprojlim_k X_k & \\ p_i \swarrow & & \searrow p_j \\ X_i & \xrightarrow{f_\alpha} & X_j \end{array} \right\}$$

over this diagram (def. [6.9](#)) which is [universal](#) among all possible cones, in that for

$$\left\{ \begin{array}{ccc} & \tilde{X} & \\ p'_i \swarrow & & \searrow p'_j \\ X_i & \xrightarrow{f_\alpha} & X_j \end{array} \right\}$$

any other [cone](#), then there is a unique function or continuous function, respectively

$$\phi : \tilde{X} \rightarrow \varprojlim_i X_i$$

that factors the given cone through the limiting cone, in that for all  $i \in I$  then

$$p'_i = p_i \circ \phi$$

which we depict as follows:

$$\begin{array}{ccc} \tilde{X} & & \\ \exists ! \phi \downarrow & & \searrow p'_i \\ \varprojlim_i X_i & \xrightarrow{p_i} & X_i \end{array}$$

2. its [colimiting cocone](#) (or just [colimit](#) for short, also “[direct limit](#)”, for historical reasons) is [the cocone](#)



$$\left\{ \begin{array}{ccc} X_i & \xrightarrow{f_\alpha} & X_j \\ & q_i \searrow & \swarrow q_j \\ & \varinjlim X_i & \end{array} \right\}$$

under this diagram (def. 6.9) which is [universal](#) among all possible co-cones, in that it has the property that for

$$\left\{ \begin{array}{ccc} X_i & \xrightarrow{f_\alpha} & X_j \\ & q'_i \searrow & \swarrow q'_j \\ & \tilde{X} & \end{array} \right\}$$

any other [cocone](#), then there is a unique function or continuous function, respectively

$$\phi : \varinjlim X_i \longrightarrow \tilde{X}$$

that factors the given co-cone through the co-limiting cocone, in that for all  $i \in I$  then

$$q'_i = \phi \circ q_i$$

which we depict as follows:

$$\begin{array}{ccc} X_i & \xrightarrow{q_i} & \varinjlim X_i \\ & q'_i \searrow & \downarrow \exists! \phi \\ & & \tilde{X} \end{array}$$

We now briefly mention the names and comment on the general nature of the limits and colimits over the free diagrams from the list of examples [above](#). Further [below](#) we discuss examples in more detail.

### shapes of [free diagrams](#) and the names of their [limits/colimits](#)

<a href="#">free diagram</a>	<a href="#">limit/colimit</a>
<a href="#">empty diagram</a>	<a href="#">terminal object/initial object</a>
<a href="#">discrete diagram</a>	<a href="#">product/coproduct</a>
<a href="#">parallel morphisms</a>	<a href="#">equalizer/coequalizer</a>
<a href="#">span/cospan</a>	<a href="#">pullback, fiber product/pushout</a>
<a href="#">tower/cotower</a>	<a href="#">sequential limit/sequential colimit</a>

#### Example 6.12. ([initial object](#) and [terminal object](#))

Consider the [empty diagram](#) (def. 6.5).

1. A **cone** over the empty diagram is just an object  $X$ , with no further structure or condition. The **universal property** of the **limit** " $\top$ " over the empty diagram is hence that for every object  $X$ , there is a unique map of the form  $X \rightarrow \top$ , with no further condition. Such an object  $\top$  is called a **terminal object**.
2. A **co-cone** over the empty diagram is just an object  $X$ , with no further structure or condition. The **universal property** of the **colimit** " $\perp$ " over the empty diagram is hence that for every object  $X$ , there is a unique map of the form  $\perp \rightarrow X$ . Such an object  $\perp$  is called an **initial object**.

### Example 6.13. (**Cartesian product** and **coproduct**)

Let  $\{X_i\}_{i \in I}$  be a **discrete diagram** (example 6.5), i.e. just a set of objects.

1. The **limit** over this diagram is called the **Cartesian product**, denoted  $\prod_{i \in I} X_i$ ;
2. The **colimit** over this diagram is called the **coproduct**, denoted  $\coprod_{i \in I} X_i$ .

### Example 6.14. (**equalizer**)

Let

$$X_1 \begin{array}{c} \xrightarrow{f_1} \\ \xrightarrow{f_2} \end{array} X_2$$

be a **free diagram** of the shape "**pair of parallel morphisms**" (example 6.6).

A **limit** over this diagram according to def. 6.11 is also called the **equalizer** of the maps  $f_1$  and  $f_2$ . This is a set or topological space  $\text{eq}(f_1, f_2)$  equipped with a map  $\text{eq}(f_1, f_2) \xrightarrow{p_1} X_1$ , so that  $f_1 \circ p_1 = f_2 \circ p_1$  and such that if  $Y \rightarrow X_1$  is any other map with this property

$$\begin{array}{ccccc} & & Y & & \\ & & \downarrow & \searrow & \\ \text{eq}(f_1, f_2) & \xrightarrow{p_1} & X_1 & \begin{array}{c} \xrightarrow{f_1} \\ \xrightarrow{f_2} \end{array} & X_2 \end{array}$$

then there is a unique factorization through the equalizer:

$$\begin{array}{ccccc} & & Y & & \\ & \exists! \swarrow & \downarrow & \searrow & \\ \text{eq}(f_1, f_2) & \xrightarrow{p_1} & X_1 & \begin{array}{c} \xrightarrow{f_1} \\ \xrightarrow{f_2} \end{array} & X_2 \end{array} .$$

In example 6.10 we have seen that a cone over such a pair of parallel morphisms is a **solution** to the equation  $f_1(x) = f_2(x)$ .

The equalizer above is the *space of all solutions* of this equation.

**Example 6.15. (pullback/fiber product and coproduct)**

Consider a cospan diagram (example 6.7)

$$\begin{array}{ccc} & Y & \\ & \downarrow f & \\ X & \xrightarrow[g]{} & Z \end{array}$$

The limit over this diagram is also called the fiber product of  $X$  with  $Y$  over  $Z$ , and denoted  $X \times_Z Y$ . Thought of as equipped with the projection map to  $X$ , this is also called the pullback of  $f$  along  $g$

$$\begin{array}{ccc} X \times_Z Y & \rightarrow & Y \\ \downarrow & \text{(pb)} & \downarrow f \\ X & \xrightarrow[g]{} & Z \end{array}$$

Dually, consider a span diagram (example 6.7)

$$\begin{array}{ccc} Z & \xrightarrow{g} & Y \\ f \downarrow & & \\ X & & \end{array}$$

The colimit over this diagram is also called the pushout of  $f$  along  $g$ , denoted  $X \sqcup_Z Y$ :

$$\begin{array}{ccc} Z & \xrightarrow{g} & Y \\ f \downarrow & \text{(po)} & \downarrow \\ X & \rightarrow & X \sqcup_Z Y \end{array}$$

Often the defining universal property of a limit/colimit construction is all that one wants to know. But sometimes it is useful to have an explicit description of the limits/colimits, not the least because this proves that these actually exist. Here is the explicit description of the (co-)limiting cone over a diagram of sets:

**Proposition 6.16. (limits and colimits of sets)**

Let

$$\left\{ X_i \xrightarrow{f_\alpha} X_j \right\}_{i,j \in I, \alpha \in I_{i,j}}$$

be a free diagram of sets (def. 6.4). Then

1. its limit cone (def. 6.11) is given by the following subset of the Cartesian product  $\prod_{i \in I} X_i$  of all the sets  $X_i$  appearing in the diagram

$$\lim_{\longleftarrow i} X_i \hookrightarrow \prod_{i \in I} X_i$$

on those tuples of elements which match the graphs of the functions appearing in the diagram:

$$\lim_{\longleftarrow i} X_i \simeq \left\{ (x_i)_{i \in I} \mid \bigvee_{\substack{i, j \in I \\ \alpha \in I_{i, j}}} (f_\alpha(x_i) = x_j) \right\}$$

and the projection functions are  $p_i : (x_j)_{j \in I} \mapsto x_i$ .

2. its colimiting co-cone (def. 6.11) is given by the quotient set of the disjoint union  $\bigsqcup_{i \in I} X_i$  of all the sets  $X_i$  appearing in the diagram

$$\bigsqcup_{i \in I} X_i \longrightarrow \lim_{\longrightarrow i \in I} X_i$$

with respect to the equivalence relation which is generated from the graphs of the functions in the diagram:

$$\lim_{\longrightarrow i} X_i \simeq (\bigsqcup_{i \in I} X_i) / \left( (x \sim x') \Leftrightarrow \left( \bigvee_{\substack{i, j \in I \\ \alpha \in I_{i, j}}} (f_\alpha(x) = x') \right) \right)$$

and the injection functions are the evident maps to equivalence classes:

$$q_i : x_i \mapsto [x_i] .$$

**Proof.** We discuss the proof of the first case. The second is directly analogous.

First observe that indeed, by construction, the projection maps  $p_i$  as given do make a cone over the free diagram, by the very nature of the relation that is imposed on the tuples:

$$\begin{array}{ccc} & \left\{ (x_k)_{k \in I} \mid \bigvee_{\substack{i, j \in I \\ \alpha \in I_{i, j}}} (f_\alpha(x_i) = x_j) \right\} & \\ p_i \swarrow & & \searrow p_j \\ X_i & \xrightarrow{f_\alpha} & X_j \end{array}$$

We need to show that this is universal, in that every other cone over the free diagram factors universally through this one. First consider the case that the tip of a given cone is a singleton:

$$\begin{array}{ccc} & * & \\ p'_i \swarrow & & \searrow p'_j \\ X_i & \xrightarrow{f_\alpha} & X_j \end{array} = \begin{array}{ccc} & * & \\ \text{const}_{x'_i} \swarrow & & \searrow \text{const}_{x'_j} \\ X_i & \xrightarrow{f_\alpha} & X_j \end{array}$$

As shown on the right, the data in such a cone is equivalently: for each  $i \in I$  an element  $x'_i \in X_i$ , such that for all  $i, j \in I$  and  $\alpha \in I_{i,j}$  then  $f_\alpha(x'_i) = x'_j$ . But this is precisely the relation used in the construction of the limit above and hence there is a unique map

$$* \xrightarrow{(x'_i)_{i \in I}} \left\{ (x_k)_{k \in I} \mid \bigvee_{\substack{i, j \in I \\ \alpha \in I_{i,j}}} (f_\alpha(x_i) = x_j) \right\}$$

such that for all  $i \in I$  we have

$$\begin{array}{ccc} * & & \\ \downarrow & & \searrow^{p'_i} \\ \left\{ (x_k)_{k \in I} \mid \bigvee_{\substack{i, j \in I \\ \alpha \in I_{i,j}}} (f_\alpha(x_i) = x_j) \right\} & \xrightarrow[p_i]{} & X_i \end{array}$$

namely that map is the one that picks the element  $(x'_i)_{i \in I}$ .

This shows that every cone with tip a singleton factors uniquely through the claimed limiting cone. But then for a cone with tip an arbitrary set  $Y$ , this same argument applies to all the single elements of  $Y$ . ■

It will turn out below in prop. 6.20 that limits and colimits of diagrams of topological spaces are computed by first applying prop. 6.16 to the underlying diagram of underlying sets, and then equipping the result with a topology as follows:

### Definition 6.17. (**initial topology** and **final topology**)

Let  $\{(X_i, \tau_i)\}_{i \in I}$  be a [set](#) of [topological spaces](#), and let  $S$  be a bare [set](#). Then

- For

$$\{S \xrightarrow{p_i} X_i\}_{i \in I}$$

a set of [functions](#) out of  $S$ , the [initial topology](#)  $\tau_{\text{initial}}(\{p_i\}_{i \in I})$  is the [coarsest](#) topology on  $S$  (def. 6.17) such that all  $f_i: (S, \tau_{\text{initial}}(\{p_i\}_{i \in I})) \rightarrow X_i$  are [continuous](#).

By lemma 2.8 this is equivalently the topology whose open subsets are the unions of finite intersections of the preimages of the open subsets of the component spaces under the projection maps, hence the topology generated from the [sub-base](#)

$$\beta_{\text{ini}}(\{p_i\}) = \{p_i^{-1}(U_i) \mid i \in I, U_i \subset X_i \text{ open}\}.$$

- For

$$\{X_i \xrightarrow{f_i} S\}_{i \in I}$$

a set of [functions](#) into  $S$ , the [final topology](#)  $\tau_{\text{final}}(\{f_i\}_{i \in I})$  is the [finest](#) topology on  $S$  (def. [6.17](#)) such that all  $q_i : X_i \rightarrow (S, \tau_{\text{final}}(\{f_i\}_{i \in I}))$  are [continuous](#).

Hence a subset  $U \subset S$  is open in the final topology precisely if for all  $i \in I$  then the [pre-image](#)  $q_i^{-1}(U) \subset X_i$  is open.

Beware a variation of synonyms that is in use:

<a href="#">limit topology</a>	<a href="#">colimit topology</a>
<a href="#">initial topology</a>	<a href="#">final topology</a>
weak topology	strong topology
coarse topology	fine topology

We have already seen [above](#) simple examples of initial and final topologies:

**Example 6.18. ([subspace topology](#) as an [initial topology](#))**

For  $(X, \tau)$  a single [topological space](#), and  $q : S \hookrightarrow X$  a [subset](#) of its underlying set, then the [initial topology](#)  $\tau_{\text{initial}}(p)$ , def. [6.17](#), is the [subspace topology](#) from example [2.16](#), making

$$p : (S, \tau_{\text{initial}}(p)) \hookrightarrow X$$

a [topological subspace](#) inclusion.

**Example 6.19. ([quotient topology](#) as a [final topology](#))**

Conversely, for  $(X, \tau)$  a [topological space](#) and for  $q : X \rightarrow S$  a [surjective function](#) out of its underlying set, then the [final topology](#)  $\tau_{\text{final}}(q)$  on  $S$ , from def. [6.17](#), is the [quotient topology](#) from example [2.17](#), making  $q$  a continuous function:

$$q : (X, \tau) \rightarrow (S, \tau_{\text{final}}(q)) .$$

Now we have all the ingredients to explicitly construct limits and colimits of diagrams of topological spaces:

**Proposition 6.20. ([limits and colimits of topological spaces](#))**

Let

$$\left\{ (X_i, \tau_i) \xrightarrow{f_\alpha} (X_j, \tau_j) \right\}_{i, j \in I, \alpha \in I_{i, j}}$$

be a [free diagram](#) of [topological spaces](#) (def. [6.4](#)).

1. The [limit](#) over this free diagram (def. [6.11](#)) is given by [the](#) topological space
  1. whose underlying set is [the](#) limit of the underlying sets according to prop. [6.16](#);

2. whose topology is the [initial topology](#), def. 6.17, for the functions  $p_i$  which are the limiting [cone](#) components:

$$\begin{array}{ccc} & \varprojlim_{k \in I} X_k & \\ p_i \swarrow & & \searrow p_j \\ X_i & \longrightarrow & X_j \end{array}$$

Hence

$$\varprojlim_{i \in I} (X_i, \tau_i) \simeq \left( \varprojlim_{i \in I} X_i, \tau_{\text{initial}}(\{p_i\}_{i \in I}) \right)$$

2. The [colimit](#) over the free diagram (def. 6.11) is [the](#) topological space

- whose underlying set is the colimit of sets of the underlying diagram of sets according to prop. 6.16,
- whose topology is the [final topology](#), def. 6.17 for the component maps  $q_i$  of the colimiting [cocone](#)

$$\begin{array}{ccc} X_i & \longrightarrow & X_j \\ q_i \searrow & & \swarrow q_j \\ & \varinjlim_{k \in I} X_k & \end{array}$$

Hence

$$\varinjlim_{i \in I} (X_i, \tau_i) \simeq \left( \varinjlim_{i \in I} X_i, \tau_{\text{final}}(\{q_i\}_{i \in I}) \right)$$

(e.g. [Bourbaki 71](#), section I.4)

**Proof.** We discuss the first case, the second is directly analogous:

Consider any [cone](#) over the given free diagram:

$$\begin{array}{ccc} & (\tilde{X}, \tau_{\tilde{X}}) & \\ p'_i \swarrow & & \searrow p'_j \\ (X_i, \tau_i) & \longrightarrow & (X_j, \tau_j) \end{array}$$

By the nature of the limiting cone of the underlying diagram of underlying sets, which always exists by prop. 6.16, there is a unique function of underlying sets of the form

$$\phi : \tilde{X} \longrightarrow \varprojlim_{i \in I} S_i$$

satisfying the required conditions  $p_i \circ \phi = p'_i$ . Since this is already unique on the underlying sets, it is sufficient to show that this function is always [continuous](#) with respect to the [initial topology](#).

Hence let  $U \subset \varprojlim_i X_i$  be in  $\tau_{\text{initial}}(\{p_i\})$ . By def. 6.17, this means that  $U$  is a union of finite intersections of subsets of the form  $p_i^{-1}(U_i)$  with  $U_i \subset X_i$  open. But since taking pre-images preserves unions and intersections, and since unions and intersections of opens in  $(\tilde{X}, \tau_{\tilde{X}})$  are again open, it is sufficient to consider  $U$  of the form  $U = p_i^{-1}(U_i)$ . But then by the condition that  $p_i \circ \phi = p'_i$  we find

$$\begin{aligned}\phi^{-1}(p_i^{-1}(U_i)) &= (p_i \circ \phi)^{-1}(U_i) \\ &= (p'_i)^{-1}(U_i),\end{aligned}$$

and this is open by the assumption that  $p'_i$  is continuous. ■

We discuss a list of examples of (co-)limits of topological spaces in a moment [below](#), but first we conclude with the main theoretical impact of the concept of topological (co-)limits for our purposes.

Here is a key property of (co-)limits:

**Proposition 6.21. (functions into a limit cone are the limit of the functions into the diagram)**

Let  $\{X_i \xrightarrow{f_\alpha} X_j\}_{i,j \in I, \alpha \in I_{i,j}}$  be a [free diagram](#) (def. 6.4) of sets or of topological spaces.

1. If the [limit](#)  $\varprojlim_i X_i \in \mathcal{C}$  exists (def. 6.11), then the [set](#) of (continuous) function into this limiting object is the limit over the sets  $\text{Hom}(-, -)$  of (continuous) functions ("[homomorphisms](#)") into the components  $X_i$ :

$$\text{Hom}\left(Y, \varprojlim_i X_i\right) \simeq \varprojlim_i (\text{Hom}(Y, X_i)).$$

Here on the right we have the limit over the free diagram of sets given by the operations  $f_\alpha \circ (-)$  of post-composition with the maps in the original diagram:

$$\left\{ \text{Hom}(Y, X_i) \xrightarrow{f_\alpha \circ (-)} \text{Hom}(Y, X_j) \right\}_{i,j \in I, \alpha \in I_{i,j}}.$$

2. If the [colimit](#)  $\varinjlim_i X_i \in \mathcal{C}$  exists, then the [set](#) of (continuous) functions out of this colimiting object is the limit over the sets of morphisms out of the components of  $X_i$ :

$$\text{Hom}\left(\varinjlim_i X_i, Y\right) \simeq \varprojlim (\text{Hom}(X_i, Y)).$$

Here on the right we have the colimit over the free diagram of sets given by the operations  $(-) \circ f_\alpha$  of pre-composition with the original maps:



$$\left\{ \mathrm{Hom}(X_i, Y) \xrightarrow{(-) \circ f_\alpha} \mathrm{Hom}(X_j, Y) \right\}_{i,j \in I, \alpha \in I_{i,j}}.$$

**Proof.** We give the proof of the first statement. The proof of the second statement is directly analogous (just reverse the direction of all maps).

First observe that, by the very definition of limiting cones, maps out of some  $Y$  into them are in natural bijection with the set  $\mathrm{Cones}\left(Y, \{X_i \xrightarrow{f_\alpha} X_j\}\right)$  of cones over the corresponding diagram with tip  $Y$ :

$$\mathrm{Hom}\left(Y, \varprojlim_i X_i\right) \simeq \mathrm{Cones}\left(Y, \{X_i \xrightarrow{f_\alpha} X_j\}\right).$$

Hence it remains to show that there is also a natural bijection like so:

$$\mathrm{Cones}\left(Y, \{X_i \xrightarrow{f_\alpha} X_j\}\right) \simeq \varprojlim_i (\mathrm{Hom}(Y, X_i)).$$

Now, again by the very definition of limiting cones, a single element in the limit on the right is equivalently a cone of the form

$$\left\{ \begin{array}{ccc} & * & \\ \mathrm{const}_{p_i} \swarrow & & \searrow \mathrm{const}_{p_j} \\ \mathrm{Hom}(Y, X_i) & \xrightarrow{f_\alpha \circ (-)} & \mathrm{Hom}(Y, X_j) \end{array} \right\}.$$

This is equivalently for each  $i \in I$  a choice of map  $p_i: Y \rightarrow X_i$ , such that for each  $i, j \in I$  and  $\alpha \in I_{i,j}$  we have  $f_\alpha \circ p_i = p_j$ . And indeed, this is precisely the characterization of an element in the set  $\mathrm{Cones}\left(Y, \{X_i \xrightarrow{f_\alpha} X_j\}\right)$ . ■

Using this, we find the following:

**Remark 6.22. (limits and colimits in categories of [nice topological spaces](#))**

Recall from remark [4.24](#) the concept of [adjoint functors](#)

$$\mathcal{C} \begin{array}{c} \xleftarrow{L} \\ \perp \\ \xrightarrow{R} \end{array} \mathcal{D}$$

witnessed by [natural isomorphisms](#)

$$\mathrm{Hom}_{\mathcal{D}}(L(c), d) \simeq \mathrm{Hom}_{\mathcal{C}}(c, R(d)).$$

Then:

1. the [left adjoint functor](#)  $L$  preserve [colimits](#) (def. [6.11](#))

in that for every [diagram](#)  $\{X_i \xrightarrow{f_\alpha} X_j\}$  in  $\mathcal{D}$  there is a [natural isomorphism](#) of the form

$$L\left(\varinjlim_i X_i\right) \simeq \varinjlim_i L(X_i)$$

2. the [right adjoint functor](#)  $R$  preserve [limits](#) (def. 6.11)

in that for every [diagram](#)  $\{X_i \xrightarrow{f_\alpha} X_j\}$  in  $\mathcal{C}$  there is a [natural isomorphism](#) of the form

$$R\left(\varprojlim_i X_i\right) \simeq \varprojlim_i R(X_i) .$$

This implies that if we have a [reflective subcategory](#) of topological spaces

$$\text{Top}_{\text{nice}} \begin{array}{c} \xleftarrow{L} \\ \xrightarrow[\iota]{1} \end{array} \text{Top}$$

(such as with  $T_{n \leq 2}$ -spaces according to remark 4.24 or with sober spaces according to remark 5.15)

then

1. limits in  $\text{Top}_{\text{nice}}$  are computed as limits in  $\text{Top}$ ;
2. colimits in  $\text{Top}_{\text{nice}}$  are computed as the reflection  $L$  of the colimit in  $\text{Top}$ .

For example let  $\{(X_i, \tau_i) \xrightarrow{f_\alpha} (X_j, \tau_j)\}$  be a diagram of Hausdorff spaces, regarded as a diagram of general topological spaces. Then

1. not only is the limit of topological spaces  $\varprojlim_i (X_i, \tau_i)$  according to prop. 6.20 again a Hausdorff space, but it also satisfies its universal property with respect to the category of Hausdorff spaces;
2. not only is the reflection  $T_2\left(\varinjlim_i X_i\right)$  of the colimit as topological spaces a Hausdorff space (while the colimit as topological spaces in general is not), but this reflection does satisfy the universal property of a colimit with respect to the category of Hausdorff spaces.

**Proof.** First to see that right/left adjoint functors preserve limits/colimits: We discuss the case of the right adjoint functor preserving limits. The other case is directly analogous (just reverse the direction of all arrows).

So let  $\varprojlim_i X_i$  be the limit over some diagram  $\{X_i \xrightarrow{f_\alpha} X_j\}_{i,j \in I, \alpha \in I_{i,j}}$ . To test what a right adjoint functor does to this, we may map any object  $Y$  into it. Using prop. 6.21 this yields

$$\begin{aligned}
 \mathrm{Hom}(Y, R(\varprojlim_i X_i)) &\simeq \mathrm{Hom}(L(Y), \varprojlim_i X_i) \\
 &\simeq \varprojlim_i \mathrm{Hom}(L(Y), X_i) \\
 &\simeq \varprojlim_i \mathrm{Hom}(Y, R(X_i)) \\
 &\simeq \mathrm{Hom}(Y, \varprojlim_i R(X_i)) .
 \end{aligned}$$

Since this is true for all  $Y$ , it [follows](#) that

$$R(\varprojlim_i X_i) \simeq \varprojlim_i R(X_i) .$$

Now to see that limits/colimits in the reflective subcategory are computed as claimed;

(...) ■

## Examples

We now discuss a list of examples of [universal constructions](#) of [topological spaces](#) as introduced in generality [above](#).

### examples of [universal constructions of topological spaces](#):

<a href="#">limits</a>	<a href="#">colimits</a>
<a href="#">point space</a>	<a href="#">empty space</a>
<a href="#">product topological space</a>	<a href="#">disjoint union topological space</a>
<a href="#">topological subspace</a>	<a href="#">quotient topological space</a>
<a href="#">fiber space</a>	<a href="#">space attachment</a>
<a href="#">mapping cocylinder</a> , <a href="#">mapping cocone</a>	<a href="#">mapping cylinder</a> , <a href="#">mapping cone</a> , <a href="#">mapping telescope</a>
	<a href="#">cell complex</a> , <a href="#">CW-complex</a>

### Example 6.23. ([empty space](#) and [point space](#) as empty [colimit](#) and [limit](#))

Consider the [empty diagram](#) (example 6.5) as a diagram of [topological spaces](#). By example 6.12 the limit and colimit (def. 6.11) over this type of diagram are the [terminal object](#) and [initial object](#), respectively. Applied to topological spaces we find:

1. The [limit](#) of topological spaces over the [empty diagram](#) is the [point space](#) \* (example 2.10).
2. The [colimit](#) of topological spaces over the [empty diagram](#) is the [empty topological space](#)  $\emptyset$  (example 2.10).

This is because for an empty diagram, the a (co-)cone is just a topological space,

without any further data or properties, and it is universal precisely if there is a unique continuous function to (respectively from) this space to any other space  $X$ . This is the case for the point space (respectively empty space) by example 3.5:

$$\emptyset \xrightarrow{\exists!} (X, \tau) \xrightarrow{\exists!} * .$$

**Example 6.24. (binary product topological space and disjoint union space as limit and colimit)**

Consider a discrete diagram consisting of two topological spaces  $(X, \tau_X), (Y, \tau_Y)$  (example 6.5). Generally, its limit and colimit is the product  $X \times Y$  and coproduct  $X \sqcup Y$ , respectively (example 6.13).

1. In topological space this product is the binary product topological space from example 2.18, by the universal property observed in example 6.1:

$$(X, \tau_X) \times (Y, \tau_Y) \simeq (X \times Y, \tau_{X \times Y}) .$$

2. In topological spaces, this coproduct is the disjoint union space from example 2.15, by the universal property observed in example 6.2:

$$(X, \tau_X) \sqcup (Y, \tau_Y) \simeq (X \sqcup Y, \tau_{X \sqcup Y}) .$$

So far these examples just reproduces simple constructions which we already considered. Now the first important application of the general concept of limits of diagrams of topological spaces is the following example 6.25 of product spaces with an non-finite set of factors. It turns out that the correct topology on the underlying infinite Cartesian product of sets is *not* the naive generalization of the binary product topology, but instead is the corresponding weak topology, which in this case is called the Tychonoff topology:

**Example 6.25. (general product topological spaces with Tychonoff topology)**

Consider an arbitrary discrete diagram of topological spaces (def. 6.5), hence a set  $\{(X_i, \tau_i)\}_{i \in I}$  of topological spaces, indexed by any set  $I$ , not necessarily a finite set.

The limit over this diagram (a Cartesian product, example 6.13) is called the product topological space of the spaces in the diagram, and denoted

$$\prod_{i \in I} (X_i, \tau_i) .$$

By prop. 6.16 and prop. 6.18, the underlying set of this product space is just the Cartesian product of the underlying sets, hence the set of tuples  $(x_i \in X_i)_{i \in I}$ . This comes for each  $i \in I$  with the projection map

$$\begin{array}{ccc} \prod_{j \in I} X_j & \xrightarrow{\text{pr}_i} & X_i \\ (x_j)_{j \in I} & \longmapsto & x_i \end{array}.$$

By prop. 6.18 and def. 6.17, the topology on this set is the [coarsest](#) topology such that the [pre-images](#)  $\text{pr}_i(U)$  of open subsets  $U \subset X_i$  under these projection maps are open. Now one such pre-image is a [Cartesian product](#) of open subsets of the form

$$p_i^{-1}(U_i) = U_i \times \left( \prod_{j \in I \setminus \{i\}} X_j \right) \subset \prod_{j \in I} X_j.$$

The [coarsest topology](#) that contains these open subsets is that generated by these subsets regarded as a [sub-basis for the topology](#) (def. 2.7), hence the arbitrary unions of finite intersections of subsets of the above form.

Observe that a binary intersection of these generating open is (for  $i \neq j$ ):

$$p_i^{-1}(U_i) \cap p_j^{-1}(U_j) \simeq U_i \times U_j \times \left( \prod_{k \in I \setminus \{i, j\}} X_k \right)$$

and generally for a [finite subset](#)  $J \subset I$  then

$$\bigcap_{j \in J \subset I} p_i^{-1}(U_i) = \left( \prod_{j \in J \subset I} U_j \right) \times \left( \prod_{i \in I \setminus J} X_i \right).$$

Therefore the open subsets of the product topology are unions of those of this form. Hence the product topology is equivalently that generated by these subsets when regarded as a [basis for the topology](#) (def. 2.7).

This is also known as the [Tychonoff topology](#).

Notice the subtlety: Naively we could have considered as open subsets the unions of products  $\prod_{i \in I} U_i$  of open subsets of the factors, without the constraint that only finitely many of them differ from the corresponding total space. This also defines a topology, called the [box topology](#). For a [finite index set](#)  $I$  the box topology coincides with the product space (Tychonoff) topology, but for non-finite  $I$  it is strictly [finer](#) (def. 2.6).

### Example 6.26. ([equalizer](#) of [continuous functions](#))

The [equalizer](#) (example 6.14) of two [continuous functions](#)  $f, g: (X, \tau_X) \rightrightarrows (Y, \tau_Y)$  is the equalizer of the underlying functions of sets

$$\text{eq}(f, g) \hookrightarrow X \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} Y$$

(hence the largest subset of  $Y$  on which both functions coincide) and equipped with the [subspace topology](#) from example 2.16.

### Example 6.27. ([coequalizer](#) of [continuous functions](#))

The **coequalizer** of two **continuous functions**  $f, g: (X, \tau_X) \rightrightarrows (Y, \tau_Y)$  is the coequalizer of the underlying functions of sets

$$X \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} Y \longrightarrow \operatorname{coeq}(f, g)$$

(hence the **quotient set** by the **equivalence relation** generated by the **relation**  $f(x) \sim g(x)$  for all  $x \in X$ ) and equipped with the **quotient topology**, example 2.17.

### Example 6.28. (**space attachments**)

Consider a **cospan diagram** (example 6.7) of continuous functions

$$\begin{array}{ccc} (A, \tau_A) & \xrightarrow{g} & (Y, \tau_Y) \\ f \downarrow & & \\ (X, \tau_X) & & \end{array}$$

The **colimit** under this diagram called the **pushout** (example 6.15)

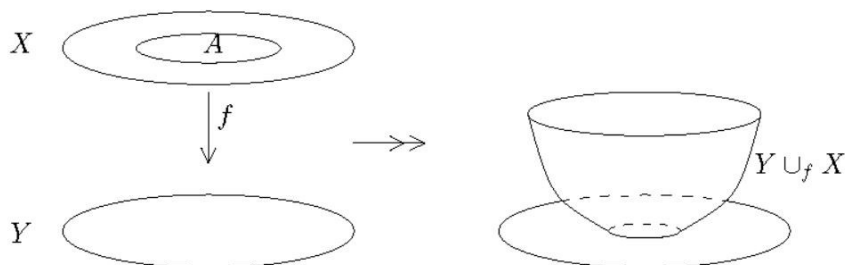
$$\begin{array}{ccccc} (A, \tau_A) & \xrightarrow{g} & & (Y, \tau_Y) & \\ f \downarrow & (\text{po}) & & \downarrow g_* f & . \\ (X, \tau_X) & \longrightarrow & (X, \tau_X) \sqcup_{(A, \tau_A)} (Y, \tau_Y) & . & \end{array}$$

Consider on the **disjoint union** set  $X \sqcup Y$  the **equivalence relation** generated by the **relation**

$$(x \sim y) \Leftrightarrow \left( \exists_{a \in A} (x = f(a) \text{ and } y = g(a)) \right) .$$

Then prop. 6.20 implies that the pushout is equivalently the **quotient topological space** (example 2.17) by this equivalence relation of the **disjoint union space** (example 2.15) of  $X$  and  $Y$ :

$$(X, \tau_X) \sqcup_{(A, \tau_A)} (Y, \tau_Y) \simeq ((X \sqcup Y, \tau_{X \sqcup Y})) / \sim .$$



If  $g$  is an **topological subspace inclusion**  $A \subset X$ , then in **topology** its pushout along  $f$  is traditionally written as

$$X \cup_f Y := (X, \tau_X) \sqcup_{(A, \tau_A)} (Y, \tau_Y)$$

and called the **space attachment** (sometimes: **attaching space** or **adjunction space**) of  $A \subset X$  along  $f$ .

(graphics from Aguilar-Gitler-Prieto 02)

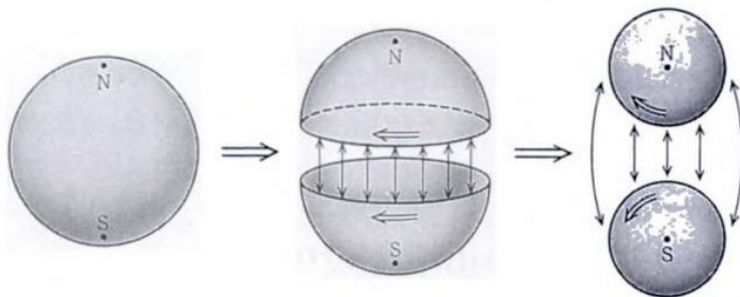
### Example 6.29. (**n-sphere** as **pushout** of the **equator** inclusions into its

## hemispheres)

As an important special case of example 6.28, let

$$i_n : S^{n-1} \rightarrow D^n$$

be the canonical inclusion of the standard [\(n-1\)-sphere](#) as the [boundary](#) of the standard [n-disk](#) (example 2.20).



Then the colimit of topological spaces under the [span diagram](#),

$$D^n \xleftarrow{i_n} S^{n-1} \xrightarrow{i_n} D^n,$$

is the topological [n-sphere](#)  $S^n$  (example 2.20):

$$\begin{array}{ccc} S^{n-1} & \xrightarrow{i_n} & D^n \\ i_n \downarrow & (\text{po}) & \downarrow \\ D^n & \longrightarrow & S^n \end{array}$$

(graphics from Ueno-Shiga-Morita 95)

In generalization of this example, we have the following important concept:

### Definition 6.30. (single cell [attachment](#))

For  $X$  any [topological space](#) and for  $n \in \mathbb{N}$ , then an  $n$ -cell [attachment](#) to  $X$  is the result of gluing an [n-disk](#) to  $X$ , along a prescribed image of its bounding [\(n-1\)-sphere](#) (def. 2.20):

Let

$$\phi : S^{n-1} \rightarrow X$$

be a [continuous function](#), then the [space attachment](#) (example 6.28)

$$X \cup_{\phi} D^n \in \text{Top}$$

is the topological space which is the [pushout](#) of the boundary inclusion of the  $n$ -sphere along  $\phi$ , hence the universal space that makes the following [diagram commute](#):

$$\begin{array}{ccc} S^{n-1} & \xrightarrow{\phi} & X \\ i_n \downarrow & (\text{po}) & \downarrow \\ D^n & \longrightarrow & X \cup_{\phi} D^n \end{array}$$

### Example 6.31. ([discrete topological spaces](#) from 0-cell [attachment](#) to the [empty space](#))

A single cell [attachment](#) of a 0-cell, according to example [6.30](#) is the same as forming the [disjoint union space](#)  $X \sqcup *$  with the [point space](#)  $*$ :

$$\begin{array}{ccc} (S^{-1} = \emptyset) & \xrightarrow{\exists!} & X \\ \downarrow & (\text{po}) & \downarrow \\ (D^0 = *) & \rightarrow & X \sqcup * \end{array} .$$

In particular if we start with the [empty topological space](#)  $X = \emptyset$  itself (example [2.10](#)), then by [attaching](#) 0-cells we obtain a [discrete topological space](#). To this then we may attach higher dimensional cells.

**Definition 6.32. ([attaching](#) many cells at once)**

If we have a [set](#) of [attaching maps](#)  $\{S^{n_i-1} \xrightarrow{\phi_i} X\}_{i \in I}$  (as in def. [6.30](#)), all to the same space  $X$ , we may think of these as one single continuous function out of the [disjoint union space](#) of their [domain](#) spheres

$$(\phi_i)_{i \in I} : \bigsqcup_{i \in I} S^{n_i-1} \rightarrow X .$$

Then the result of attaching *all* the corresponding  $n$ -cells to  $X$  is the pushout of the corresponding [disjoint union](#) of boundary inclusions:

$$\begin{array}{ccc} \bigsqcup_{i \in I} S^{n_i-1} & \xrightarrow{(\phi_i)_{i \in I}} & X \\ \downarrow & (\text{po}) & \downarrow \\ \bigsqcup_{i \in I} D^{n_i} & \rightarrow & X \cup_{(\phi_i)_{i \in I}} \left( \bigsqcup_{i \in I} D^{n_i} \right) \end{array} .$$

Apart from attaching a set of cells all at once to a fixed base space, we may “attach cells to cells” in that after forming a given cell attachment, then we further attach cells to the resulting attaching space, and ever so on:

**Definition 6.33. ([relative cell complexes](#) and [CW-complexes](#))**

Let  $X$  be a topological space, then A *topological [relative cell complex](#)* of countable height based on  $X$  is a [continuous function](#)

$$f: X \rightarrow Y$$

and a [sequential diagram](#) of [topological space](#) of the form

$$X = X_0 \hookrightarrow X_1 \hookrightarrow X_2 \hookrightarrow X_3 \hookrightarrow \dots$$

such that

1. each  $X_k \hookrightarrow X_{k+1}$  is exhibited as a cell attachment according to def. [6.32](#), hence presented by a [pushout](#) diagram of the form



$$\begin{array}{ccc}
 \bigsqcup_{i \in I} S^{n_i-1} & \xrightarrow{(\phi_i)_{i \in I}} & X_k \\
 \downarrow & \text{(po)} & \downarrow \\
 \bigsqcup_{i \in I} D^{n_i} & \longrightarrow & X_{k+1}
 \end{array}$$

2.  $Y = \bigcup_{k \in \mathbb{N}} X_k$  is the [union](#) of all these cell attachments, and  $f: X \rightarrow Y$  is the canonical inclusion; or stated more abstractly: the map  $f: X \rightarrow Y$  is the inclusion of the first component of the diagram into its [colimiting cocone](#)  $\varinjlim_k X_k$ :

$$\begin{array}{ccccccc}
 X = X_0 & \longrightarrow & X_1 & \longrightarrow & X_2 & \longrightarrow & \dots \\
 f \searrow & & \downarrow & & \swarrow & & \dots \\
 & & Y = \varinjlim X & & & & 
 \end{array}$$

If here  $X = \emptyset$  is the [empty space](#) then the result is a map  $\emptyset \hookrightarrow Y$ , which is equivalently just a space  $Y$  built from “attaching cells to nothing”. This is then called just a *topological cell complex* of countable height.

Finally, a topological (relative) cell complex of countable height is called a **CW-complex** is the  $(k+1)$ -st cell attachment  $X_k \rightarrow X_{k+1}$  is entirely by  $(k+1)$ -cells, hence exhibited specifically by a pushout of the following form:

$$\begin{array}{ccc}
 \bigsqcup_{i \in I} S^k & \xrightarrow{(\phi_i)_{i \in I}} & X_k \\
 \downarrow & \text{(po)} & \downarrow \\
 \bigsqcup_{i \in I} D^{k+1} & \longrightarrow & X_{k+1}
 \end{array}$$

A [finite CW-complex](#) is one which admits a presentation in which there are only finitely many attaching maps, and similarly a *countable CW-complex* is one which admits a presentation with countably many attaching maps.

Given a CW-complex, then  $X_n$  is also called its  $n$ -[skeleton](#).

## 7. Compact spaces

We discuss [compact topological spaces](#) (def 7.2 below), the generalization of compact metric spaces [above](#). Compact spaces are in some sense the “small” objects among topological spaces, analogous in [topology](#) to what [finite sets](#) are in [set theory](#), or what [finite-dimensional vector spaces](#) are in [linear algebra](#), and equally important in the theory.

Prop. 1.21 suggests the following simple definition 7.2:

**Definition 7.1. ([open cover](#))**

An [open cover](#) of a [topological space](#)  $(X, \tau)$  (def. 2.3) is a [set](#)  $\{U_i \subset X\}_{i \in I}$  of [open](#)

subsets  $U_i$  of  $X$ , indexed by some set  $I$ , such that their union is all of  $X$ :

$$\bigcup_{i \in I} U_i = X.$$

A *subcover* of a cover is a subset  $J \subset I$  such that  $\{U_i \subset X\}_{i \in J \subset I}$  is still a cover.

### Definition 7.2. (compact topological space)

A topological space  $X$  (def. 2.3) is called a compact topological space if every open cover  $\{U_i \subset X\}_{i \in I}$  (def. 7.1) has a finite subcover in that there is a finite subset  $J \subset I$  such that  $\{U_i \subset X\}_{i \in J}$  is still a cover of  $X$  in that also  $\bigcup_{i \in J} U_i = X$ .

### Remark 7.3. (terminology issue regarding “compact”)

Beware the following terminology issue which persists in the literature:

Some authors use “compact” to mean “Hausdorff and compact”. To disambiguate this, some authors (mostly in algebraic geometry, but also for instance Waldhausen) say “quasi-compact” for what we call “compact” in def. 7.2.

There are several equivalent reformulations of the compactness condition. An immediate reformulation is prop. 7.4, a more subtle one is prop. 7.13 further below.

### Proposition 7.4. (compactness in terms of closed subsets)

Let  $(X, \tau)$  be a topological space. Then the following are equivalent:

1.  $(X, \tau)$  is compact in the sense of def. 7.2.
2. Let  $\{C_i \subset X\}_{i \in I}$  be a set of closed subsets (def. 2.23) such that their intersection is empty  $\bigcap_{i \in I} C_i = \emptyset$ , then there is a finite subset  $J \subset I$  such that the corresponding finite intersection is still empty  $\bigcap_{i \in J \subset I} C_i = \emptyset$ .
3. Let  $\{C_i \subset X\}_{i \in I}$  be a set of closed subsets (def. 2.23) such that it enjoys the finite intersection property, meaning that for every finite subset  $J \subset I$  then the corresponding finite intersection is non-empty  $\bigcap_{i \in J \subset I} C_i \neq \emptyset$ . Then also the total intersection is non-empty,  $\bigcap_{i \in I} C_i \neq \emptyset$ .

**Proof.** The equivalence between the first and the second statement is immediate from the definitions after expressing open subsets as complements of closed subsets  $U_i = X \setminus C_i$  and applying de Morgan's law (remark 2.24).

We discuss the equivalence between the first and the third statement:

In one direction, assume that  $(X, \tau)$  is compact in the sense of def. 7.2, and that  $\{C_i \subset X\}_{i \in I}$  satisfies the finite intersection property. We need to show that then  $\bigcap_{i \in I} C_i \neq \emptyset$ .

Assume that this were not the case, hence assume that  $\bigcap_{i \in I} C_i = \emptyset$ . This would imply

that the open [complements](#) were an [open cover](#) of  $X$  (def. [7.1](#))

$$\{U_i := X \setminus C_i\}_{i \in I},$$

because (using [de Morgan's law](#), remark [2.24](#))

$$\begin{aligned} \bigcup_{i \in I} U_i &:= \bigcup_{i \in I} X \setminus C_i \\ &= X \setminus \left( \bigcap_{i \in I} C_i \right) \\ &= X \setminus \emptyset \\ &= X \end{aligned}$$

But then by compactness of  $(X, \tau)$  there were a finite subset  $J \subset I$  such that  $\{U_i \subset X\}_{i \in J \subset I}$  were still an open cover, hence that  $\bigcup_{i \in J \subset I} U_i = X$ . Translating this back through the [de Morgan's law](#) again this would mean that

$$\begin{aligned} \emptyset &= X \setminus \left( \bigcup_{i \in J \subset I} U_i \right) \\ &:= X \setminus \left( \bigcup_{i \in J \subset I} X \setminus C_i \right) \\ &= \bigcap_{i \in J \subset I} X \setminus (X \setminus C_i) \\ &= \bigcap_{i \in J \subset I} C_i. \end{aligned}$$

This would be in contradiction with the finite intersection property of  $\{C_i \subset X\}_{i \in I}$ , and hence we have [proof by contradiction](#).

Conversely, assume that every set of closed subsets in  $X$  with the finite intersection property has non-empty total intersection. We need to show that the every open cover  $\{U_i \subset X\}_{i \in I}$  of  $X$  has a finite subcover.

Write  $C_i := X \setminus U_i$  for the closed complements of these open subsets.

Assume on the contrary that there were no finite subset  $J \subset I$  such that  $\bigcup_{i \in J \subset I} U_i = X$ , hence no finite subset such that  $\bigcap_{i \in J \subset I} C_i = \emptyset$ . This would mean that  $\{C_i \subset X\}_{i \in I}$  satisfied the finite intersection property.

But by assumption this would imply that  $\bigcap_{i \in I} C_i \neq \emptyset$ , which, again by de Morgan, would mean that  $\bigcup_{i \in I} U_i \neq X$ . But this contradicts the assumption that the  $\{U_i \subset X\}_{i \in I}$  are a cover. Hence we have a [proof by contradiction](#). ■

### Example 7.5. ([finite discrete spaces](#) are [compact](#))

A [discrete topological space](#) (def. [2.13](#)) is [compact](#) (def. [7.2](#)) precisely if its underlying set is a [finite set](#).

### Example 7.6. ([closed intervals](#) are [compact](#))

For any  $a < b \in \mathbb{R}$  the [closed interval](#) (example [1.13](#))

$$[a, b] \subset \mathbb{R}$$

regarded with its [subspace topology](#) of [Euclidean space](#) (example 1.6) with its [metric topology](#) (example 2.9) is a [compact topological space](#) (def. 7.2).

**Proof.** Since all the closed intervals are [homeomorphic](#) (by example 3.27) it is sufficient to show the statement for  $[0, 1]$ . Hence let  $\{U_i \subset [0, 1]\}_{i \in I}$  be an [open cover](#) (def. 7.1). We need to show that it has an open subcover.

Say that an element  $x \in [0, 1]$  is *admissible* if the closed sub-interval  $[0, x]$  is covered by finitely many of the  $U_i$ . In this terminology, what we need to show is that 1 is admissible.

Observe from the definition that

1. 0 is admissible,
2. if  $y < x \in [0, 1]$  and  $x$  is admissible, then also  $y$  is admissible.

This means that the set of admissible  $x$  forms either

1. an [open interval](#)  $[0, g)$
2. or a [closed interval](#)  $[0, g]$ ,

for some  $g \in [0, 1]$ . We need to show that the latter is true, and for  $g = 1$ . We do so by observing that the alternatives lead to contradictions:

1. Assume that the set of admissible values were an open interval  $[0, g)$ . Pick an  $i_0 \in I$  such that  $g \in U_{i_0}$  (this exists because of the covering property). Since such  $U_{i_0}$  is an open neighbourhood of  $g$ , there is a positive real number  $\epsilon$  such that the open ball  $B_g^\circ(\epsilon) \subset U_{i_0}$  is still contained in the patch. It follows that there is an element  $x \in B_g^\circ(\epsilon) \cap [0, g) \subset U_{i_0} \cap [0, g)$  and such that there is a finite subset  $J \subset I$  with  $\{U_i \subset [0, 1]\}_{i \in J \subset I}$  a finite open cover of  $[0, x]$ . It follows that  $\{U_i \subset [0, 1]\}_{i \in J \subset I} \sqcup \{U_{i_0}\}$  were a finite open cover of  $[0, g]$ , hence that  $g$  itself were still admissible, in contradiction to the assumption.
2. Assume that the set of admissible values were a closed interval  $[0, g]$  for  $g < 1$ . By assumption there would then be a finite set  $J \subset I$  such that  $\{U_i \subset [0, 1]\}_{i \in J \subset I}$  were a finite cover of  $[0, g]$ . Hence there would be an index  $i_g \in J$  such that  $g \in U_{i_g}$ . But then by the nature of open subsets in the Euclidean space  $\mathbb{R}$ , this  $U_{i_g}$  would also contain an open ball  $B_g^\circ(\epsilon) = (g - \epsilon, g + \epsilon)$ . This would mean that the set of admissible values includes the open interval  $[0, g + \epsilon)$ , contradicting the assumption.

This gives a [proof by contradiction](#). ■

In contrast:

**Nonexample 7.7. ([Euclidean space](#) is non-compact)**

For all  $n \in \mathbb{N}$ ,  $n > 0$ , the [Euclidean space](#)  $\mathbb{R}^n$  (example 1.6), regarded with its [metric topology](#) (example 2.9), is *not* a [compact topological space](#) (def. 7.2).

**Proof.** Pick any  $\epsilon \in (0, 1/2)$ . Consider the open cover of  $\mathbb{R}^n$  given by

$$\{U_n := (n - \epsilon, n + 1 + \epsilon) \times \mathbb{R}^{n-1} \subset \mathbb{R}^{n+1}\}_{n \in \mathbb{Z}}.$$

This is not a finite cover, and removing any one of its patches  $U_n$ , it ceases to be a cover, since the points of the form  $(n + \epsilon, x_2, x_3, \dots, x_n)$  are contained only in  $U_n$  and in no other patch. ■

Below we prove the [Heine-Borel theorem](#) (prop. 7.39) which generalizes example 7.6 and example 7.7.

In [analysis](#), the [extreme value theorem](#) (example 7.11 below) asserts that a [real-valued continuous function](#) on the [bounded closed interval](#) (def. 1.13) attains its [maximum](#) and [minimum](#). The following is the generalization of this statement to general topological spaces, cast in terms of the more abstract concept of compactness from def. 7.2:

**Lemma 7.8. ([continuous surjections out of compact spaces have compact codomain](#))**

Let  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  be a [continuous function](#) between [topological spaces](#) such that

1.  $(X, \tau_X)$  is a [compact topological space](#) (def. 7.2);
2.  $f: X \rightarrow Y$  is a [surjective function](#).

Then also  $(Y, \tau_Y)$  is [compact](#).

**Proof.** Let  $\{U_i \subset Y\}_{i \in I}$  be an [open cover](#) of  $Y$  (def. 7.1). We need show that this has a finite sub-cover.

By continuity of  $f$ , the [pre-images](#)  $f^{-1}(U_i)$  are [open subsets](#) of  $X$ , and by the surjectivity of  $f$  they form an [open cover](#)  $\{f^{-1}(U_i) \subset X\}_{i \in I}$  of  $X$ . Hence by compactness of  $X$ , there exists a [finite subset](#)  $J \subset I$  such that

$$\{f^{-1}(U_i) \subset X\}_{i \in J \subset I}$$

is still an open cover of  $X$ . Finally, using again that  $f$  is assumed to be surjective, it follows that

$$\begin{aligned} Y &= f(X) \\ &= f\left(\bigcup_{i \in J} f^{-1}(U_i)\right) \\ &= \bigcup_{i \in J} U_i. \end{aligned}$$

This means that also  $\{U_i \subset Y\}_{i \in J \subset I}$  is still an open cover of  $Y$ , and in particular a

finite subcover of the original cover. ■

As a direct corollary of lemma 7.8 we obtain:

**Proposition 7.9. (continuous images of compact spaces are compact)**

If  $f: X \rightarrow Y$  is a continuous function out of a compact topological space  $X$  (def. 7.2) which is not necessarily surjective, then we may consider its image factorization

$$f : X \longrightarrow f(X) \hookrightarrow Y$$

as in example 3.10. Now by construction  $X \rightarrow f(X)$  is surjective, and so lemma 7.8 implies that  $f(X)$  is compact.

The converse to cor. 7.9 does not hold in general: the pre-image of a compact subset under a continuous function need not be compact again. If this is the case, then we speak of proper maps:

**Definition 7.10. (proper maps)**

A continuous function  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  is called proper if for  $C \in Y$  a compact topological subspace of  $Y$ , then also its pre-image  $f^{-1}(C)$  is compact in  $X$ .

As a first useful application of the topological concept of compactness we obtain a quick proof of the following classical result from analysis:

**Proposition 7.11. (extreme value theorem)**

Let  $C$  be a compact topological space (def. 7.2), and let

$$f : C \rightarrow \mathbb{R}$$

be a continuous function to the real numbers equipped with their Euclidean metric topology.

Then  $f$  attains is maximum and its minimum in that there exist  $x_{\min}, x_{\max} \in C$  such that

$$f(x_{\min}) \leq f(x) \leq f(x_{\max}) .$$

**Proof.** Since continuous images of compact spaces are compact (prop. 7.9) the image  $f([a, b]) \subset \mathbb{R}$  is a compact subspace.

Suppose this image did not contain its maximum. Then  $\{(-\infty, x)\}_{x \in f([a, b])}$  were an open cover of the image, and hence, by its compactness, there would be a finite subcover, hence a finite set  $(x_1 < x_2 < \dots < x_n)$  of points  $x_i \in f([a, b])$ , such that the union of the  $(-\infty, x_i)$  and hence the single set  $(-\infty, x_n)$  alone would cover the image. This were in contradiction to the assumption that  $x_n \in f([a, b])$  and hence we have a proof by contradiction.

Similarly for the minimum. ■

And as a special case:

**Example 7.12. (traditional extreme value theorem)**

Let

$$f : [a, b] \rightarrow \mathbb{R}$$

be a continuous function from a bounded closed interval ( $a < b \in \mathbb{R}$ ) (def. 1.13) regarded as a topological subspace (example 2.16) of real numbers to the real numbers, with the latter regarded with their Euclidean metric topology (example 1.6, example 2.9).

Then  $f$  attains its maximum and minimum: there exists  $x_{\max}, x_{\min} \in [a, b]$  such that for all  $x \in [a, b]$  we have

$$f([a, b]) = [f(x_{\min}), f(x_{\max})] .$$

**Proof.** Since continuous images of compact spaces are compact (prop. 7.9) the image  $f([a, b]) \subset \mathbb{R}$  is a compact subspace (def. 7.2, example 2.16). By the Heine-Borel theorem (prop. 7.39) this is a bounded closed subset (def. 1.3, def. 2.23). By the nature of the Euclidean metric topology, the image is hence a union of closed intervals. Finally by continuity of  $f$  it needs to be a single closed interval, hence (being bounded) of the form

$$f([a, b]) = [f(x_{\min}), f(x_{\max})] \subset \mathbb{R} .$$

■

There is also the following more powerful equivalent reformulation of compactness:

**Proposition 7.13. (closed-projection characterization of compactness)**

Let  $(X, \tau_X)$  be a topological space. The following are equivalent:

1.  $(X, \tau_X)$  is a compact topological space according to def. 7.2;
2. For every topological space  $(Y, \tau_Y)$  then the projection map out of the product topological space (example 2.18, example 6.25)

$$\pi_Y : (Y, \tau_Y) \times (X, \tau_X) \rightarrow (Y, \tau_Y)$$

is a closed map.

**Proof.** (due to Todd Trimble)

In one direction, assume that  $(X, \tau_X)$  is compact and let  $C \subset Y \times X$  be a closed subset. We need to show that  $\pi_Y(C) \subset Y$  is closed.

By lemma 2.25 this is equivalent to showing that every point  $y \in Y \setminus \pi_Y(C)$  in the complement of  $\pi_Y(C)$  has an open neighbourhood  $V_y \supset \{y\}$  which does not intersect  $\pi_Y(C)$ :

$$V_y \cap \pi_Y(C) = \emptyset .$$

This is clearly equivalent to

$$(V_y \times X) \cap C = \emptyset$$

and this is what we will show.

To this end, consider the set

$$\left\{ U \subset X \text{ open} \mid \begin{array}{c} \exists_{V \subset Y \text{ open}} \\ V \supset \{y\} \end{array} ((V \times U) \cap C = \emptyset) \right\}$$

Observe that this is an [open cover](#) of  $X$ : For every  $x \in X$  then  $(y, x) \notin C$  by assumption of  $Y$ , and by closure of  $C$  this means that there exists an open neighbourhood of  $(y, x)$  in  $Y \times X$  not intersecting  $C$ , and by nature of the [product topology](#) this contains an open neighbourhood of the form  $V \times U$ .

Hence by compactness of  $X$ , there exists a finite subcover  $\{U_j \subset X\}_{j \in J}$  of  $X$  and a corresponding set  $\{V_j \subset Y\}_{j \in J}$  with  $V_j \times U_j \cap C = \emptyset$ .

The resulting open neighbourhood

$$V := \bigcap_{j \in J} V_j$$

of  $y$  has the required property:

$$\begin{aligned} V \times X &= V \times \left( \bigcup_{j \in J} U_j \right) \\ &= \bigcup_{j \in J} (V \times U_j) \\ &\subset \bigcup_{j \in J} (V_j \times U_j) \\ &\subset (Y \times X) \setminus C . \end{aligned}$$

Now for the converse:

Assume that  $\pi_Y: Y \times X \rightarrow X$  is a closed map for all  $Y$ . We need to show that  $X$  is compact. By prop. [7.4](#) this means equivalently that for every set  $\{C_i \subset X\}_{i \in I}$  of closed subsets and satisfying the [finite intersection property](#), we need to show that  $\bigcap_{i \in I} C_i \neq \emptyset$ .

So consider such a set  $\{C_i \subset X\}_{i \in I}$  of closed subsets satisfying the [finite intersection property](#). Construct a new topological space  $(Y, \tau_Y)$  by setting

1.  $Y := X \sqcup \{\infty\}$ ;
2.  $\beta_Y := P(X) \sqcup \{(C_i \cup \{\infty\}) \subset Y\}_{i \in I}$  a [sub-base](#) for  $\tau_Y$  (def. [2.7](#)).

Then consider the [topological closure](#)  $\text{Cl}(\Delta)$  of the “diagonal”  $\Delta$  in  $Y \times X$



$$\Delta := \{(x, x) \in Y \times X \mid x \in X\}.$$

We claim that there exists  $x \in X$  such that

$$(\infty, x) \in \text{Cl}(\Delta).$$

This is because

$$\pi_Y(\text{Cl}(\Delta)) \subset Y \text{ is closed}$$

by the assumption that  $\pi_Y$  is a closed map, and

$$X \subset \pi_Y(\text{Cl}(\Delta))$$

by construction. So if  $\infty$  were not in  $\pi_Y(\text{Cl}(\Delta))$ , then, by lemma 2.25, it would have an open neighbourhood not intersecting  $X$ . But by definition of  $\tau_Y$ , the open neighbourhoods of  $\infty$  are the unions of finite intersections of  $C_i \cup \{\infty\}$ , and by the assumed [finite intersection property](#) all their finite intersections do still intersect  $X$ .

Since thus  $(\infty, x) \in \text{Cl}(\Delta)$ , lemma 2.25 gives again that all of its open neighbourhoods intersect the diagonal. By the nature of the [product topology](#) (example 2.18) this means that for all  $i \in I$  and all open neighbourhoods  $U_x \supset \{x\}$  we have that

$$((C_i \cup \{\infty\}) \times U_x) \cap \Delta \neq \emptyset.$$

By definition of  $\Delta$  this means equivalently that

$$C_i \cap U_x \neq \emptyset$$

for all open neighbourhoods  $U_x \supset \{x\}$ .

But by closure of  $C_i$  and using lemma 2.25, this means that

$$x \in C_i$$

for all  $i$ , hence that

$$\bigcap_{i \in I} C_i \neq \emptyset$$

as required. ■

This [closed-projection characterization of compactness](#) from prop. 7.13 is most useful, for instance it yields direct proof of the following important facts in [topology](#):

- The [tube lemma](#), prop. 7.14 below,
- The [Tychonoff theorem](#), prop. 7.15 below.

**Lemma 7.14. ([tube lemma](#))**

Let

1.  $(X, \tau_X)$  be a [topological space](#),
2.  $(Y, \tau_Y)$  a [compact topological space](#) (def. 7.2),
3.  $x \in X$  a point,
4.  $W \subset_{\text{open}} X \times Y$  an open subset in the [product topology](#) (example 2.18, example 7.15),

such that the  $Y$ -[fiber](#) over  $x$  is contained in  $W$ :

$$\{x\} \times Y \subseteq W .$$

Then there exists an [open neighborhood](#)  $U_x$  of  $x$  such that the "tube"  $U_x \times Y$  around the fiber  $\{x\} \times Y$  is still contained:

$$U_x \times Y \subseteq W .$$

**Proof.** Let

$$C := (X \times Y) \setminus W$$

be the [complement](#) of  $W$ . Since this is closed, by prop. 7.13 also its projection  $p_X(C) \subset X$  is closed.

Now

$$\begin{aligned} \{x\} \times Y \subset W &\Leftrightarrow \{x\} \times Y \cap C = \emptyset \\ &\Rightarrow \{x\} \cap p_X(C) = \emptyset \end{aligned}$$

and hence by the closure of  $p_X(C)$  there is (by lemma 2.25) an open neighbourhood  $U_x \supset \{x\}$  with

$$U_x \cap p_X(C) = \emptyset .$$

This means equivalently that  $U_x \times Y \cap C = \emptyset$ , hence that  $U_x \times Y \subset W$ . ■

**Proposition 7.15. ([Tychonoff theorem](#) – the [product space of compact spaces is compact](#))**

Let  $\{(X_i, \tau_i)\}_{i \in I}$  be a [set of compact topological spaces](#) (def. 7.2). Then also their [product space](#)  $\prod_{i \in I} (X_i, \tau_i)$  (example 6.25) is compact.

We give a proof of the finitary case of the Tychonoff theorem using the [closed-projection characterization of compactness](#) from prop. 7.13. This elementary proof generalizes fairly directly to an elementary proof of the general case: see [here](#).

**Proof of the finitary case.** By prop. 7.13 it is sufficient to show that for every topological space  $(Y, \tau_Y)$  then the projection

$$\pi_Y : (Y, \tau_Y) \times \left( \prod_{i \in \{1, \dots, n\}} (X_i, \tau_i) \right) \rightarrow (Y, \tau_Y)$$

is a closed map. We proceed by [induction](#). For  $n = 0$  the statement is obvious. Suppose it has been proven for some  $n \in \mathbb{N}$ . Then the projection for  $n + 1$  factors is the composite of two consecutive projections

$$\pi_Y : Y \times \left( \prod_{i \in \{1, \dots, n+1\}} X_i \right) = Y \times \left( \prod_{i \in \{1, \dots, n\}} X_i \right) \times X_{n+1} \rightarrow Y \times \left( \prod_{i \in \{1, \dots, n\}} X_i \right) \rightarrow Y.$$

By prop. [7.13](#), the first map here is closed since  $(X_{n+1}, \tau_{n+1})$  is compact by the assumption of the proposition, and similarly the second is closed by induction assumption. Hence the composite is a closed map. ■

Of course we also want to claim that [sequentially compact metric spaces](#) (def. [1.20](#)) are compact as topological spaces when regarded with their [metric topology](#) (example [2.9](#)):

**Definition 7.16. ([converging sequence in a topological space](#))**

Let  $(X, \tau)$  be a [topological space](#) (def. [2.3](#)) and let  $(x_n)_{n \in \mathbb{N}}$  be a [sequence](#) of points  $(x_n)$  in  $X$  (def. [1.16](#)). We say that this sequence [converges](#) in  $(X, \tau)$  to a point  $x_\infty \in X$ , denoted

$$x_n \xrightarrow{n \rightarrow \infty} x_\infty$$

if for each [open neighbourhood](#)  $U_{x_\infty}$  of  $x_\infty$  there exists a  $k \in \mathbb{N}$  such that for all  $n \geq k$  then  $x_n \in U_{x_\infty}$ :

$$\left( x_n \xrightarrow{n \rightarrow \infty} x_\infty \right) \Leftrightarrow \left( \bigwedge_{\substack{U_{x_\infty} \in \tau_X \\ x_\infty \in U_{x_\infty}}} \left( \exists_{k \in \mathbb{N}} \left( \bigwedge_{n \geq k} x_n \in U_{x_\infty} \right) \right) \right).$$

Accordingly it makes sense to consider the following:

**Definition 7.17. ([sequentially compact topological space](#))**

Let  $(X, \tau)$  be a [topological space](#) (def. [2.3](#)). It is called [sequentially compact](#) if for every [sequence](#) of points  $(x_n)$  in  $X$  (def. [1.16](#)) there exists a sub-sequence  $(x_{n_k})_{k \in \mathbb{N}}$  which [converges](#) according to def. [7.16](#).

**Proposition 7.18. ([sequentially compact metric spaces are equivalently compact metric spaces](#))**

If  $(X, d)$  is a [metric space](#) (def. [1.1](#)), regarded as a [topological space](#) via its [metric topology](#) (example [2.9](#)), then the following are equivalent:

1.  $(X, d)$  is a [compact topological space](#) (def. [7.2](#)).
2.  $(X, d)$  is a [sequentially compact metric space](#) (def. [1.20](#)) hence a [sequentially](#)

compact topological space (def. 7.17).

**Proof.** of prop. 1.21 and prop. 7.18

Assume first that  $(X, d)$  is a compact topological space. Let  $(x_k)_{k \in \mathbb{N}}$  be a sequence in  $X$ . We need to show that it has a sub-sequence which converges.

Consider the topological closures of the sub-sequences that omit the first  $n$  elements of the sequence

$$F_n := \text{Cl}(\{x_k \mid k \geq n\})$$

and write

$$U_n := X \setminus F_n$$

for their open complements.

Assume now that the intersection of all the  $F_n$  were empty

$$(*) \quad \bigcap_{n \in \mathbb{N}} F_n = \emptyset$$

or equivalently that the union of all the  $U_n$  were all of  $X$

$$\bigcup_{n \in \mathbb{N}} U_n = X,$$

hence that  $\{U_n \subset X\}_{n \in \mathbb{N}}$  were an open cover. By the assumption that  $X$  is compact, this would imply that there were a finite subset  $\{i_1 < i_2 < \dots < i_k\} \subset \mathbb{N}$  with

$$\begin{aligned} X &= U_{i_1} \cup U_{i_2} \cup \dots \cup U_{i_k} \\ &= U_{i_k} \end{aligned}.$$

This in turn would mean that  $F_{i_k} = \emptyset$ , which contradicts the construction of  $F_{i_k}$ .

Hence we have a proof by contradiction that assumption  $(*)$  is wrong, and hence that there must exist an element

$$x \in \bigcap_{n \in \mathbb{N}} F_n.$$

By definition of topological closure this means that for all  $n$  the open ball  $B_x^\circ(1/(n+1))$  around  $x$  of radius  $1/(n+1)$  must intersect the  $n$ th of the above subsequences:

$$B_x^\circ(1/(n+1)) \cap \{x_k \mid k \geq n\} \neq \emptyset.$$

If we choose one point  $(x'_n)$  in the  $n$ th such intersection for all  $n$  this defines a sub-sequence, which converges to  $x$ .

In summary this proves that *compact* implies *sequentially compact* for metric spaces.

For the converse, assume now that  $(X, d)$  is sequentially compact. Let  $\{U_i \subset X\}_{i \in I}$  be

an [open cover](#) of  $X$ . We need to show that there exists a finite sub-cover.

Now by the [Lebesgue number lemma](#), there exists a positive real number  $\delta > 0$  such that for each  $x \in X$  there is  $i_x \in I$  such that  $B_x^\circ(\delta) \subset U_{i_x}$ . Moreover, since [sequentially compact metric spaces are totally bounded](#), there exists then a [finite set](#)  $S \subset X$  such that

$$X = \bigcup_{s \in S} B_s^\circ(\delta).$$

Therefore  $\{U_{i_s} \rightarrow X\}_{s \in S}$  is a finite sub-cover as required. ■

**Remark 7.19. (neither [compactness](#) nor [sequential compactness](#) implies the other)**

Beware, in contrast to prop. 7.18, general topological spaces being [sequentially compact](#) neither implies nor is implied by being [compact](#).

1. The [product topological space](#) (example 6.25)  $\prod_{r \in [0,1]} \text{Disc}(\{0,1\})$  of copies of the [discrete topological space](#) (example 2.13) indexed by the elements of the [half-open interval](#) is compact by the [Tychonoff theorem](#) (prop. 7.15), but the sequence  $x_n$  with

$$\pi_r(x_n) = \text{nth digit of the binary expansion of } r$$

has no convergent subsequence.

2. conversely, there are spaces that are sequentially compact, but not compact, see for instance [Vermeeren 10](#), prop. 18.

**Remark 7.20. ([nets](#) fix the shortcomings of [sequences](#))**

That [compactness](#) of topological spaces is not detected by [convergence](#) of [sequences](#) (remark 7.19) may be regarded as a shortcoming of the concept of [sequence](#). While a sequence is indexed over the [natural numbers](#), the concept of [convergence](#) of sequences only invokes that the natural numbers form a [directed set](#). Hence the concept of convergence immediately generalizes to sets of points in a space which are indexed over an arbitrary [directed set](#). This is called a [net](#).

And with these the expected statement does become true (for a [proof](#) see [here](#)):

*A [topological space](#)  $(X, \tau)$  is [compact](#) precisely if every [net](#) in  $X$  has a [converging subnet](#).*

In fact convergence of nets also detects [closed subsets](#) in topological spaces (hence their topology as such), and it detects the continuity of functions between topological spaces. It also detects for instance the Hausdorff property. (For detailed statements and proofs see [here](#).) Hence when [analysis](#) is cast in terms of [nets](#) instead of just sequences, then it raises to the same level of generality as topology.

# Locally compact spaces

## Definition 7.21. (locally compact topological space)

A topological space  $X$  is called locally compact if for every point  $x \in X$  and every open neighbourhood  $U_x \supset \{x\}$  there exists a smaller open neighbourhood  $V_x \subset U_x$  whose topological closure is compact (def. 7.2) and still contained in  $U$ :

$$\{x\} \subset V_x \subset \underset{\text{compact}}{\text{Cl}(V_x)} \subset U_x .$$

## Remark 7.22. (terminology issue regarding “locally compact”)

On top of the terminology issue inherited from that of “compact”, remark 7.3 (regarding whether or not to require “Hausdorff” with “compact”; we do not), the definition of “locally compact” is subject to further ambiguity in the literature. There are various definitions of locally compact spaces alternative to def. 7.21. For Hausdorff topological spaces all these definitions happen to be equivalent, but in general they are not. The version we state in def. 7.21 is the one that gives various results (such as the universal property of the mapping space, prop. 7.29 below) *without* requiring the Hausdorff property.

## Example 7.23. (discrete spaces are locally compact)

Every discrete topological space (example 2.13) is locally compact (def. 7.21).

## Example 7.24. (metric spaces are locally compact)

Every metric space (def. 1.1), regarded as a topological space via its metric topology (def. 2.9), is locally compact (def. 7.21).

## Example 7.25. (open subspaces of compact Hausdorff spaces are locally compact)

Every open topological subspace  $X \subset_{\text{open}} K$  of a compact (def. 7.2) Hausdorff space (def. 4.4) is a locally compact topological space (def. 7.21).

In particular compact Hausdorff spaces themselves are locally compact.

We **prove** this below as prop. 7.44, after having established a list of convenient general facts about compact Hausdorff spaces.

## Example 7.26. (finite product space of locally compact spaces is locally compact)

The product topological space (example 6.25)  $\prod_{i \in I} (X_i, \tau_i)$  of a finite set  $\{(X_i, \tau_i)\}_{i \in I}$  of locally compact topological spaces  $(X_i, \tau_i)$  (def. 7.21) is itself locally compact.

## Nonexample 7.27. (countably infinite products of non-compact spaces are not locally compact)

Let  $X$  be a topological space which is *not* compact (def. 7.2). Then the product

topological space (example 6.25) of a countably infinite set of copies of  $X$

$$\prod_{n \in \mathbb{N}} X$$

is *not* a locally compact space (def. 7.21).

**Proof.** Since the continuous image of a compact space is compact (prop. 7.9), and since the projection maps  $p_i : \prod_{\mathbb{N}} X \rightarrow X$  are continuous (by nature of the initial topology/Tychonoff topology), it follows that every compact subspace of the product space is contained in one of the form

$$\prod_{i \in \mathbb{N}} K_i$$

for  $K_i \subset X$  compact.

But by the nature of the Tychonoff topology, a base for the topology on  $\prod_{\mathbb{N}} X$  is given by subsets of the form

$$\left( \prod_{i \in \{1, \dots, n\}} U_i \right) \times \left( \prod_{j \in \mathbb{N}_{>n}} X \right)$$

with  $U_i \subset X$  open. Hence every compact neighbourhood in  $\prod_{\mathbb{N}} X$  contains a subset of this kind, but if  $X$  itself is non-compact, then none of these is contained in a product of compact subsets. ■

A key application of locally compact spaces is that the space of maps out of them into any given topological space (example 7.28 below) satisfies the expected universal property of a mapping space (prop. 7.29 below).

### Example 7.28. (topological mapping space with compact-open topology)

For

1.  $(X, \tau_X)$  a locally compact topological space (def. 7.21)
2.  $(Y, \tau_Y)$  any topological space

then the mapping space

$$\mathrm{Maps}((X, \tau_X), (Y, \tau_Y)) := (\mathrm{Hom}_{\mathrm{Top}}(X, Y), \tau_{\mathrm{cpt-op}})$$

is the topological space

- whose underlying set  $\mathrm{Hom}_{\mathrm{Top}}(X, Y)$  is the set of continuous functions  $X \rightarrow Y$ ;
- whose topology  $\tau_{\mathrm{cpt-op}}$  is generated from the sub-basis for the topology (def. 2.7) which is given by subsets to denoted

$U^K \subset \text{Hom}_{\text{Top}}(X, Y)$  for labels

- $K \subset Y$  a [compact](#) subset,
- $U \subset X$  an [open subset](#)

and defined to be those subsets of all those [continuous functions](#)  $f$  that take  $K$  to  $U$ :

$$U^K := \left\{ f: X \xrightarrow{\text{continuous}} Y \mid \begin{array}{ccc} K & \hookrightarrow & X \\ \downarrow & & \downarrow f \\ U & \hookrightarrow & Y \end{array} \right\}.$$

Accordingly this topology  $\tau_{\text{cpt-op}}$  is called the [compact-open topology](#) on the set of functions.

**Proposition 7.29.** ([universal property of the mapping space](#))

Let  $(X, \tau_X)$ ,  $(Y, \tau_Y)$ ,  $(Z, \tau_Z)$  be [topological spaces](#), with  $X$  [locally compact](#) (def. 7.21). Then

1. The [evaluation](#) function

$$\begin{array}{ccc} (X, \tau_X) \times \text{Maps}((X, \tau_X), (Y, \tau_Y)) & \xrightarrow{\text{ev}} & (Y, \tau_Y) \\ (x, f) & \longmapsto & f(x) \end{array}$$

is a [continuous function](#).

2. The [natural bijection of function sets](#)

$$\begin{array}{ccc} \underbrace{\{X \times Y \rightarrow Y\}}_{\text{Hom}_{\text{Set}}(X \times Z, Y)} & \xrightarrow{\cong} & \underbrace{\{Z \rightarrow \text{Hom}_{\text{Set}}(X, Y)\}}_{\text{Hom}_{\text{Set}}(Z, \text{Hom}_{\text{Set}}(X, Y))} \\ (f: (x, z) \mapsto f(x, z)) & \longmapsto & \tilde{f}: z \mapsto (x \mapsto f(x, z)) \end{array}$$

restricts to a [natural bijection](#) between sets of [continuous functions](#)

$$\underbrace{\{(X, \tau_X) \times (Z, \tau_Z) \xrightarrow{\text{cts}} (Y, \tau_Y)\}}_{\text{Hom}_{\text{Top}}((X, \tau_X) \times (Z, \tau_Z), (Y, \tau_Y))} \xrightarrow{\cong} \underbrace{\{(Z, \tau_Z) \xrightarrow{\text{cts}} \text{Maps}((X, \tau_X), (Y, \tau_Y))\}}_{\text{Hom}_{\text{Top}}((Z, \tau_Z), \text{Maps}((X, \tau_X), (Y, \tau_Y)))}.$$

Here  $\text{Maps}((X, \tau_X), (Y, \tau_Y))$  is the [mapping space](#) with [compact-open topology](#) from example 7.28 and  $(-) \times (-)$  denotes forming the [product topological space](#) (example 2.18, example 6.25).

**Proof.** To see the continuity of the evaluation map:

Let  $V \subset Y$  be an open subset. We need to show that  $\text{ev}^{-1}(V) = \{(x, f) \mid f(x) \in V\}$  is a union of products of the form  $U \times V^K$  with  $U \subset X$  open and  $U^K \subset \text{Hom}_{\text{Set}}(K, U)$  a basic open according to def. 7.28.



For  $(x, f) \in \text{ev}^{-1}(V)$ , the preimage  $f^{-1}(V) \subset X$  is an open neighbourhood of  $x$  in  $X$ , by continuity of  $f$ . By local compactness of  $X$ , there is a compact subset  $K \subset f^{-1}(V)$  which is still a neighbourhood of  $x$ . Since  $f$  also still takes that into  $V$ , we have found an open neighbourhood

$$(x, f) \in K \times V^K \underset{\text{open}}{\subset} \text{ev}^{-1}(V)$$

with respect to the product topology. Since this is still contained in  $\text{ev}^{-1}(V)$ , for all  $(x, f)$  as above,  $\text{ev}^{-1}(V)$  is exhibited as a union of opens, and is hence itself open.

Regarding the second point:

In one direction, let  $f: (X, \tau_X) \times (Y, \tau_Y) \rightarrow (Z, \tau_Z)$  be a continuous function, and let  $U^K \subset \text{Maps}(X, Y)$  be a sub-basic open. We need to show that the set

$$\tilde{f}^{-1}(U) = \{z \in Z \mid f(K, z) \subset U\} \subset Z$$

is open. To that end, observe that  $f(K, z) \subset U$  means that  $K \times \{z\} \subset f^{-1}(U)$ , where  $f^{-1}(U) \subset X \times Y$  is open by the continuity of  $f$ . Hence in the [topological subspace](#)  $K \times Z \subset X \times Y$  the inclusion

$$K \times \{z\} \subset (f^{-1}(U) \cap (K \times Z))$$

is an open neighbourhood. Since  $K$  is compact, the [tube lemma](#) (prop. 7.14) gives an open neighbourhood  $V_z \supset \{z\}$  in  $Y$ , hence an open neighbourhood  $K \times V_z \subset K \times Y$ , which is still contained in the original pre-image:

$$K \times V_z \subset f^{-1}(U) \cap (K \times Z) \subset f^{-1}(U) .$$

This shows that with every point  $z \in \tilde{f}^{-1}(U^K)$  also an open neighbourhood of  $z$  is contained in  $\tilde{f}^{-1}(U^K)$ , hence that the latter is a union of open subsets, and hence itself open.

In the other direction, assume that  $\tilde{f}: Z \rightarrow \text{Maps}((X, \tau_X), (Y, \tau_Y))$  is continuous: We need to show that  $f$  is continuous. But observe that  $f$  is the [composite](#)

$$f = (X, \tau_X) \times (Z, \tau_Z) \xrightarrow{\text{id}_{(X, \tau_X)} \times \tilde{f}} (X, \tau_X) \times \text{Maps}((X, \tau_X), (Y, \tau_Y)) \xrightarrow{\text{ev}} (X, \tau_X) .$$

Here the first function  $\text{id} \times \tilde{f}$  is continuous since  $\tilde{f}$  is by assumption since the product of two continuous functions is again continuous (example 3.4). The second function  $\text{ev}$  is continuous by the first point above. hence  $f$  is continuous. ■

**Remark 7.30. ([topological mapping space](#) is [exponential object](#))**

In the language of [category theory](#) (remark 3.3), prop. 7.29 says that the [mapping space](#) construction with its [compact-open topology](#) from def. 7.28 is an [exponential object](#) or [internal hom](#). This just means that it behaves in all abstract ways just as a [function set](#) does for plain functions, but it does so for continuous functions and being itself equipped with a topology.

Moreover, the construction of topological mapping spaces in example 7.28 extends to a [functor](#) (remark 3.3)

$$(-)^{(-)} : \mathbf{Top}_{\text{lcp}}^{\text{op}} \times \mathbf{Top} \rightarrow \mathbf{Top}$$

from the [product category](#) of the category [Top](#) of all [topological spaces](#) (remark 3.3) with the [opposite category](#) of the [subcategory](#) of [locally compact topological spaces](#).

**Example 7.31. ([topological mapping space](#) construction out of the [point space](#) is the identity)**

The [point space](#)  $*$  (example 2.10) is clearly a [locally compact topological space](#). Hence for every [topological space](#)  $(X, \tau)$  the [mapping space](#)  $\text{Maps}(*, (X, \tau))$  (example 7.28) exists. This is [homeomorphic](#) (def. 3.22) to the space  $(X, \tau)$  itself:

$$\text{Maps}(*, (X, \tau)) \simeq (X, \tau) .$$

**Example 7.32. ([loop space](#) and [path space](#))**

Let  $(X, \tau)$  be any [topological space](#).

1. The [circle](#)  $S^1$  (example 2.20) is a [compact Hausdorff space](#) (example 7.40) hence, by prop. 7.25, a [locally compact topological space](#) (def. 7.21). Accordingly the [mapping space](#)

$$\mathcal{L}X := \text{Maps}(S^1, (X, \tau))$$

exists (def. 7.28). This is called the [free loop space](#) of  $(X, \tau)$ .

If both  $S^1$  and  $X$  are equipped with a choice of point ("[basepoint](#)")  $s_0 \in S^1$ ,  $x_0 \in X$ , then the [topological subspace](#)

$$\Omega X \subset \mathcal{L}X$$

on those functions which take the basepoint of  $S^1$  to that of  $X$ , is called the [loop space](#) of  $X$ , or sometimes [based loop space](#), for emphasis.

2. Similarly the [closed interval](#) is a [compact Hausdorff space](#) (example 7.40) hence, by prop. 7.25, a [locally compact topological space](#) (def. 7.21). Accordingly the [mapping space](#)

$$\text{Maps}([0, 1], (X, \tau))$$

exists (def. 7.28). Again if  $X$  is equipped with a choice of basepoint  $x_0 \in X$ , then the [topological subspace](#) of those functions that take  $0 \in [0, 1]$  to that chosen basepoint is called the [path space](#) of  $(X, \tau)$ :

$$PX \subset \text{Maps}([0, 1], (X, \tau)) .$$

Notice that we may encode these subspaces more abstractly in terms of [universal properties](#):

The path space and the loop space are characterized, up to homeomorphisms, as being the limiting cones in the following pullback diagrams of topological spaces (example 6.15):

1. loop space:

$$\begin{array}{ccc} \Omega X & \longrightarrow & \text{Maps}(S^1, (X, \tau)) \\ \downarrow \text{ (pb) } & & \downarrow \text{Maps}(\text{const}_{s_0}, \text{id}_{(X, \tau)}) \\ * & \xrightarrow{\text{const}_{x_0}} & X \simeq \text{Maps}(*, (X, \tau)) \end{array}$$

2. path space:

$$\begin{array}{ccc} PX & \longrightarrow & \text{Maps}([0, 1], (X, \tau)) \\ \downarrow \text{ (pb) } & & \downarrow \text{Maps}(\text{const}_x, \text{id}_{(X, \tau)}) \\ * & \xrightarrow{\text{const}_{x_0}} & X \simeq \text{Maps}(*, (X, \tau)) \end{array}$$

Here on the right we are using that the mapping space construction is a functor as shown in remark 7.30, and we are using example 7.31 in the identification on the bottom right mapping space out of the point space.

**Proposition 7.33.** (proper maps to locally compact spaces are closed)

Let

1.  $(X, \tau_X)$  be a topological space,
2.  $(Y, \tau_Y)$  a locally compact topological space according to def. 7.21,
3.  $f: X \rightarrow Y$  a continuous function.

Then:

If  $f$  is a proper map, then it is a closed map.

**Proof.** Let  $C \subset X$  be a closed subset. We need to show that every  $y \in Y \setminus f(C)$  has an open neighbourhood  $U_y \supset \{y\}$  not intersecting  $f(C)$  (by lemma 2.25).

By local compactness of  $(Y, \tau_Y)$  (def. 7.21),  $y$  has an open neighbourhood  $V_y$  whose topological closure  $\text{Cl}(V_y)$  is compact. Hence since  $f$  is proper, also  $f^{-1}(\text{Cl}(V_y)) \subset X$  is compact. Then also the intersection  $C \cap f^{-1}(\text{Cl}(V_y))$  is compact, and hence so is

$$f(C \cap f^{-1}(\text{Cl}(V_y))) = f(C) \cap (\text{Cl}(V_y)) \subset Y.$$

This is also a closed subset, since compact subspaces of Hausdorff spaces are closed. Therefore

$$U_y := V_y \setminus (f(C) \cap (\text{Cl}(V_y))) = V_y \setminus f(C)$$

is an open neighbourhood of  $y$  not intersecting  $f(C)$ . ■

**Proposition 7.34. (injective proper maps to locally compact spaces are equivalently the closed embeddings)**

Let

1.  $X$  be a topological space
2.  $Y$  a locally compact topological space
3.  $f: X \rightarrow Y$  be a continuous function.

Then the following are equivalent

1.  $f$  is an injective proper map,
2.  $f$  is a closed embedding of topological spaces (def. 3.34).

**Proof.** In one direction, if  $f$  is an injective proper map, then since proper maps to locally compact spaces are closed, it follows that  $f$  is also closed map. The claim then follows since closed injections are embeddings (prop. 3.35), and since the image of a closed map is closed.

Conversely, if  $f$  is a closed embedding, we only need to show that the embedding map is proper. So for  $C \subset Y$  a compact subspace, we need to show that the pre-image  $f^{-1}(C) \subset X$  is also compact. But since  $f$  is an injection (being an embedding), that pre-image is just the intersection  $f^{-1}(C) \simeq C \cap f(X)$ . By the nature of the subspace topology, this is compact if  $C$  is. ■

## Compact Hausdorff spaces

We discuss some important relations between the concepts of compact topological spaces (def. 7.2) and of Hausdorff topological spaces (def. 4.4).

**Proposition 7.35. (closed subspaces of compact Hausdorff spaces are equivalently compact subspaces)**

Let

1.  $(X, \tau)$  be a compact Hausdorff topological space (def. 4.4, def. 7.2)
2.  $Y \subset X$  be a topological subspace (example 2.16).

Then the following are equivalent:

1.  $Y \subset X$  is a closed subspace (def. 2.23);
2.  $Y$  is a compact topological space (def. 7.2).

**Proof.** By lemma 7.36 and lemma 7.38 below. ■

**Lemma 7.36. (closed subspaces of compact spaces are compact)**

Let

1.  $(X, \tau)$  be a compact topological space (def. 7.2),
2.  $Y \subset X$  be a closed topological subspace (def. 2.23, example 2.16).

Then also  $Y$  is compact.

**Proof.** Let  $\{V_i \subset Y\}_{i \in I}$  be an open cover of  $Y$  (def. 7.1). We need to show that this has a finite sub-cover.

By definition of the subspace topology, there exist open subsets  $U_i$  of  $X$  with

$$V_i = U_i \cap Y.$$

By the assumption that  $Y$  is closed, the complement  $X \setminus Y$  is an open subset of  $X$ , and therefore

$$\{X \setminus Y \subset X\} \cup \{U_i \subset X\}_{i \in I}$$

is an open cover of  $X$  (def. 7.1). Now by the assumption that  $X$  is compact, this latter cover has a finite subcover, hence there exists a finite subset  $J \subset I$  such that

$$\{X \setminus Y \subset X\} \cup \{U_i \subset X\}_{i \in J \subset I}$$

is still an open cover of  $X$ , hence in particular restricts to a finite open cover of  $Y$ . But since  $Y \cap (X \setminus Y) = \emptyset$ , it follows that indeed

$$\{V_i \subset Y\}_{i \in J \subset I}$$

is a cover of  $Y$ , and in indeed a finite subcover of the original one. ■

**Lemma 7.37. (separation by neighbourhoods of points from compact subspaces in Hausdorff spaces)**

Let

1.  $(X, \tau)$  be a Hausdorff topological space (def. 4.4);
2.  $Y \subset X$  a compact subspace (def. 7.2, example 2.16).

Then for every  $x \in X \setminus Y$  there exists

1. an open neighbourhood  $U_x \supset \{x\}$ ;
2. an open neighbourhood  $U_Y \supset Y$

such that

- they are still disjoint:  $U_x \cap U_Y = \emptyset$ .

**Proof.** By the assumption that  $(X, \tau)$  is Hausdorff, we find for every point  $y \in Y$  disjoint open neighbourhoods  $U_{x,y} \supset \{x\}$  and  $U_y \supset \{y\}$ . By the nature of the [subspace topology](#) of  $Y$ , the restriction of all the  $U_y$  to  $Y$  is an [open cover](#) of  $Y$ :

$$\{(U_y \cap Y) \subset Y\}_{y \in Y}.$$

Now by the assumption that  $Y$  is compact, there exists a finite subcover, hence a [finite set](#)  $S \subset Y$  such that

$$\{(U_y \cap Y) \subset Y\}_{y \in S \subset Y}$$

is still a cover.

But the finite intersection

$$U_x := \bigcap_{s \in S \subset Y} U_{x,s}$$

of the corresponding open neighbourhoods of  $x$  is still open, and by construction it is disjoint from all the  $U_s$ , hence also from their union

$$U_Y := \bigcup_{s \in S \subset Y} U_s.$$

Therefore  $U_x$  and  $U_Y$  are two open subsets as required. ■

Lemma [7.37](#) immediately implies the following:

**Lemma 7.38. ([compact subspaces of Hausdorff spaces are closed](#))**

Let

1.  $(X, \tau)$  be a [Hausdorff topological space](#) (def. [4.4](#))
2.  $C \subset X$  be a [compact](#) (def. [7.2](#)) [topological subspace](#) (example [2.16](#)).

Then  $C \subset X$  is also a [closed subspace](#) (def. [2.23](#)).

**Proof.** Let  $x \in X \setminus C$  be any point of  $X$  not contained in  $C$ . By lemma [2.25](#) we need to show that there exists an [open neighbourhood](#) of  $x$  in  $X$  which does not [intersect](#)  $C$ . This is implied by lemma [7.37](#). ■

**Proposition 7.39. ([Heine-Borel theorem](#))**

For  $n \in \mathbb{N}$ , regard  $\mathbb{R}^n$  as the  $n$ -dimensional [Euclidean space](#) via example [1.6](#), regarded as a [topological space](#) via its [metric topology](#) (example [2.9](#)).

Then for a [topological subspace](#)  $S \subset \mathbb{R}^n$  the following are equivalent:

1.  $S$  is [compact](#) (def. [7.2](#));
2.  $S$  is [closed](#) (def. [2.23](#)) and [bounded](#) (def. [1.3](#)).

**Proof.** First consider a [subset](#)  $S \subset \mathbb{R}^n$  which is closed and bounded. We need to

show that regarded as a [topological subspace](#) it is [compact](#).

The assumption that  $S$  is bounded by (hence contained in) some [open ball](#)  $B_x^\circ(\epsilon)$  in  $\mathbb{R}^n$  implies that it is contained in  $\{(x_i)_{i=1}^n \in \mathbb{R}^n \mid -\epsilon \leq x_i \leq \epsilon\}$ . By example [3.29](#), this topological subspace is homeomorphic to the  $n$ -cube

$$[-\epsilon, \epsilon]^n = \prod_{i \in \{1, \dots, n\}} [-\epsilon, \epsilon],$$

hence to the [product topological space](#) (example [6.25](#)) of  $n$  copies of the closed interval with itself.

Since the closed interval  $[-\epsilon, \epsilon]$  is compact by example [7.6](#), the binary [Tychonoff theorem](#) (prop. [7.15](#)) implies that this  $n$ -cube is compact.

Since [subsets are closed in a closed subspace precisely if they are closed in the ambient space](#), lemma [2.30](#), the closed subset  $S \subset \mathbb{R}^n$  is also closed as a subset  $S \subset [-\epsilon, \epsilon]^n$ . Since [closed subspaces of compact spaces are compact](#) (lemma [7.36](#)) this implies that  $S$  is compact.

Conversely, assume that  $S \subset \mathbb{R}^n$  is a compact subspace. We need to show that it is closed and bounded.

The first statement follows since the [Euclidean space](#)  $\mathbb{R}^n$  is [Hausdorff](#) (example [4.8](#)) and since [compact subspaces of Hausdorff spaces are closed](#) (prop. [7.38](#)).

Hence what remains is to show that  $S$  is bounded.

To that end, choose any [positive real number](#)  $\epsilon \in \mathbb{R}_{>0}$  and consider the [open cover](#) of all of  $\mathbb{R}^n$  by the open [n-cubes](#)

$$(k_1 - \epsilon, k_1 + 1 + \epsilon) \times (k_2 - \epsilon, k_2 + 1 + \epsilon) \times \cdots \times (k_n - \epsilon, k_n + 1 + \epsilon)$$

for [n-tuples](#) of [integers](#)  $(k_1, k_2, \dots, k_n) \in \mathbb{Z}^n$ . The restrictions of these to  $S$  hence form an open cover of the subspace  $S$ . By the assumption that  $S$  is compact, there is then a finite subset of  $n$ -tuples of integers such that the corresponding  $n$ -cubes still cover  $S$ . But the union of any finite number of bounded closed  $n$ -cubes in  $\mathbb{R}^n$  is clearly a bounded subset, and hence so is  $S$ . ■

For the record, we list some examples of [compact Hausdorff spaces](#) that are immediately identified by the [Heine-Borel theorem](#) (prop. [7.39](#)):

#### **Example 7.40. (examples of [compact Hausdorff spaces](#))**

We list some basic examples of [compact Hausdorff spaces](#) (def. [4.4](#), def. [7.2](#))

1. For  $n \in \mathbb{N}$ , the [n-sphere](#)  $S^n$  may canonically be regarded as a [topological subspace](#) of [Euclidean space](#)  $\mathbb{R}^{n+1}$  (example [2.20](#)).

These are clearly closed and bounded subspaces of Euclidean space, hence they are [compact topological space](#), by the [Heine-Borel theorem](#), prop. 7.39.

**Proposition 7.41. ([maps from compact spaces to Hausdorff spaces are closed and proper](#))**

Let  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  be a [continuous function](#) between [topological spaces](#) such that

1.  $(X, \tau_X)$  is a [compact topological space](#) (def. 7.2);
2.  $(Y, \tau_Y)$  is a [Hausdorff topological space](#) (def. 4.4).

Then  $f$  is

1. a [closed map](#) (def. 3.14);
2. a [proper map](#) (def. 7.10).

**Proof.** For the first statement, we need to show that if  $C \subset X$  is a [closed subset](#) of  $X$ , then also  $f(C) \subset Y$  is a closed subset of  $Y$ .

Now

1. since [closed subsets of compact spaces are compact](#) (lemma 7.36) it follows that  $C \subset X$  is also compact;
2. since [continuous images of compact spaces are compact](#) (cor. 7.9) it then follows that  $f(C) \subset Y$  is compact;
3. since [compact subspaces of Hausdorff spaces are closed](#) (prop. 7.38) it finally follow that  $f(C)$  is also closed in  $Y$ .

For the second statement we need to show that if  $C \subset Y$  is a [compact subset](#), then also its [pre-image](#)  $f^{-1}(C)$  is compact.

Now

1. since [compact subspaces of Hausdorff spaces are closed](#) (prop. 7.38) it follows that  $C \subset Y$  is closed;
2. since [pre-images](#) under continuous functions of closed subsets are closed (prop. 3.2), also  $f^{-1}(C) \subset X$  is closed;
3. since [closed subsets of compact spaces are compact](#) (lemma 7.36), it follows that  $f^{-1}(C)$  is compact.

■

As an immediate corollary we record this useful statement:



**Proposition 7.42. (continuous bijections from compact spaces to Hausdorff spaces are homeomorphisms)**

Let  $f: (X, \tau_X) \rightarrow (Y, \tau_Y)$  be a continuous function between topological spaces such that

1.  $(X, \tau_X)$  is a compact topological space (def. 7.2);
2.  $(Y, \tau_Y)$  is a Hausdorff topological space (def. 4.4).
3.  $f: X \rightarrow Y$  is a bijection of sets.

Then  $f$  is a homeomorphism (def. 3.22)

In particular then both  $(X, \tau_X)$  and  $(Y, \tau_Y)$  are compact Hausdorff spaces.

**Proof.** By prop. 3.25 it is sufficient to show that  $f$  is a closed map. This is the case by prop. 7.41. ■

**Proposition 7.43. (compact Hausdorff spaces are normal)**

Every compact Hausdorff topological space (def. 7.2, def. 4.4) is a normal topological space (def. 4.13).

**Proof.** First we claim that  $(X, \tau)$  is regular. To show this, we need to find for each point  $x \in X$  and each disjoint closed subset  $Y \in X$  disjoint open neighbourhoods  $U_x \supset \{x\}$  and  $U_Y \supset Y$ . But since closed subspaces of compact spaces are compact (lemma 7.36), the subset  $Y$  is in fact compact, and hence this is the statement of lemma 7.37.

Next to show that  $(X, \tau)$  is indeed normal, we apply the idea of the proof of lemma 7.37 once more:

Let  $Y_1, Y_2 \subset X$  be two disjoint closed subspaces. By the previous statement then for every point  $y_1 \in Y_1$  we find disjoint open neighbourhoods  $U_{y_1} \supset \{y_1\}$  and  $U_{Y_2, y_1} \supset Y_2$ . The union of the  $U_{y_1}$  is a cover of  $Y_1$ , and by compactness of  $Y_1$  there is a finite subset  $S \subset Y_1$  such that

$$U_{Y_1} := \bigcup_{s \in S \subset Y_1} U_{y_1}$$

is an open neighbourhood of  $Y_1$  and

$$U_{Y_2} := \bigcap_{s \in S \subset Y_1} U_{Y_2, s}$$

is an open neighbourhood of  $Y_2$ , and both are disjoint. ■

With these statements in hand, the remaining proof of example 7.25 is immediate:

**Proposition 7.44. (open subspaces of compact Hausdorff spaces are locally compact)**

Every open topological subspace  $X \subset_{\text{open}} K$  (def. 2.16) of a compact (def. 7.2) Hausdorff space  $K$  (def. 4.4) is a locally compact topological space (def. 7.21).

**Proof.** Let  $X$  be a topological space such that it arises as a topological subspace  $X \subset K$  of a compact Hausdorff space. We need to show that  $X$  is a locally compact topological space (def. 7.21).

Let  $x \in X$  be a point and let  $U_x \subset X$  an open neighbourhood. We need to produce a smaller open neighbourhood whose closure is compact and still contained in  $U_x$ .

By the nature of the subspace topology there exists an open subset  $V_x \subset K$  such that  $U_x = X \cap V_x$ . Since  $X$  is assumed to be open, it follows that  $U$  is also open as a subset of  $K$ . Since compact Hausdorff spaces are normal (prop. 7.43) it follows by prop. 4.18 that there exists a smaller open neighbourhood  $W_x \subset K$  whose topological closure is still contained in  $U_x$ , and since closed subspaces of compact spaces are compact (prop. 7.36), this topological closure is compact:

$$\{x\} \subset W_x \subset \underset{\text{cpt}}{\text{Cl}}(W_x) \subset V_x \subset K .$$

The intersection of this situation with  $X$  is the required smaller compact neighbourhood  $\text{Cl}(W_x) \cap X$ :

$$\{x\} \subset W_x \cap X \subset \underset{\text{cpt}}{\text{Cl}}(W_x) \cap X \subset U_x \subset X .$$

■

We discuss some important relations between the concept of compact topological spaces and that of quotient topological spaces.

**Proposition 7.45. (continuous surjections from compact spaces to Hausdorff spaces are quotient projections)**

Let

$$\pi : (X, \tau_X) \longrightarrow (Y, \tau_Y)$$

be a continuous function between topological spaces such that

1.  $(X, \tau_X)$  is a compact topological space (def. 7.2);
2.  $(Y, \tau_Y)$  is a Hausdorff topological space (def. 4.4);
3.  $\pi : X \rightarrow Y$  is a surjective function.

Then  $\tau_Y$  is the quotient topology inherited from  $\tau_X$  via the surjection  $f$  (def. 2.17).

**Proof.** We need to show that a subset  $U \subset Y$  is an open subset of  $(Y, \tau_Y)$  precisely if

its [pre-image](#)  $\pi^{-1}(U) \subset X$  is an open subset in  $(X, \tau_X)$ . Equivalently, as in prop. [3.2](#), we need to show that  $U$  is a [closed subset](#) precisely if  $\pi^{-1}(U)$  is a closed subset. The implication

$$(U \text{ closed}) \Rightarrow (f^{-1}(U) \text{ closed})$$

follows via prop. [3.2](#) from the continuity of  $\pi$ . The implication

$$(f^{-1}(U) \text{ closed}) \Rightarrow (U \text{ closed})$$

follows since  $\pi$  is a [closed map](#) by prop. [7.41](#). ■

The following proposition allows to recognize when a [quotient space](#) of a compact Hausdorff space is itself still Hausdorff.

**Proposition 7.46. (*quotient projections out of compact Hausdorff spaces are closed precisely if the codomain is Hausdorff*)**

Let

$$\pi : (X, \tau_X) \rightarrow (Y, \tau_Y)$$

be a [continuous function](#) between [topological spaces](#) such that

1.  $(X, \tau)$  is a [compact Hausdorff topological space](#) (def. [7.2](#), def. [4.4](#));
2.  $\pi$  is a [surjection](#) and  $\tau_Y$  is the corresponding [quotient topology](#) (def. [2.17](#)).

Then the following are equivalent

1.  $(Y, \tau_Y)$  is itself a [Hausdorff topological space](#) (def. [4.4](#));
2.  $\pi$  is a [closed map](#) (def. [3.14](#)).

**Proof.** The implicaton  $((Y, \tau_Y) \text{ Hausdorff}) \Rightarrow (\pi \text{ closed})$  is given by prop. [7.41](#). We need to show the converse.

Hence assume that  $\pi$  is a closed map. We need to show that for every pair of distinct point  $y_1 \neq y_2 \in Y$  there exist [open neighbourhoods](#)  $U_{y_1}, U_{y_2} \in \tau_Y$  which are disjoint,  $U_{y_1} \cap U_{y_2} = \emptyset$ .

Therefore consider the [pre-images](#)

$$C_1 := \pi^{-1}(\{y_1\}) \quad C_2 := \pi^{-1}(\{y_2\}) .$$

Observe that these are [closed subsets](#), because in the Hausdorff space  $(Y, \tau_Y)$ , which is in particular  $T_1$  by lemma [4.5](#), the singleton subsets  $\{y_i\}$  are closed by prop. [4.11](#), and since pre-images under continuous functions preserves closed subsets by prop. [3.2](#).

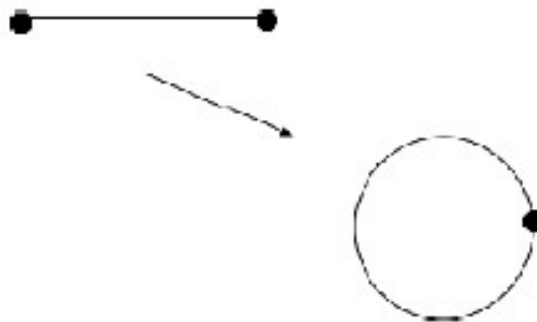
Now since [compact Hausdorff spaces are normal](#) (prop. [7.43](#)) it follows (by def. [4.13](#)) that we may find disjoint open subset  $U_1, U_2 \in \tau_X$  such that

$$C_1 \subset U_1 \quad C_2 \subset U_2 .$$

Moreover, by lemma 3.21 we may find these  $U_i$  such that they are both [saturated subsets](#) (def. 3.17). Therefore finally lemma 3.20 says that the images  $\pi(U_i)$  are open in  $(Y, \tau_Y)$ . These are now clearly disjoint open neighbourhoods of  $y_1$  and  $y_2$ . ■

**Example 7.47.** Consider the function

$$\begin{aligned} [0, 2\pi] / \sim &\longrightarrow S^1 \subset \mathbb{R}^2 \\ t &\mapsto (\cos(t), \sin(t)) \end{aligned}$$



- from the [quotient topological space](#) (def. 2.17) of the [closed interval](#) (def. 1.13) by the [equivalence relation](#) which identifies the two endpoints

$$(x \sim y) \Leftrightarrow ((x = y) \text{ or } ((x \in \{0, 2\pi\}) \text{ and } (y \in \{0, 2\pi\})))$$

- to the unit [circle](#)  $S^1 = S_0(1) \subset \mathbb{R}^2$  (def. 1.2) regarded as a [topological subspace](#) of the 2-dimensional [Euclidean space](#) (example 1.6) equipped with its [metric topology](#) (example 2.9).

This is clearly a [continuous function](#) and a [bijection](#) on the underlying sets. Moreover, since [continuous images of compact spaces are compact](#) (cor. 7.9) and since the closed interval  $[0, 1]$  is compact (example 7.6) we also obtain another proof that the [circle](#) is compact.

Hence by prop. 7.42 the above map is in fact a [homeomorphism](#)

$$[0, 2\pi] / \sim \simeq S^1 .$$

Compare this to the counter-example 3.24, which observed that the analogous function

$$\begin{aligned} [0, 2\pi) &\longrightarrow S^1 \subset \mathbb{R}^2 \\ t &\mapsto (\cos(t), \sin(t)) \end{aligned}$$

is *not* a homeomorphism, even though this, too, is a bijection on the the underlying sets. But the [half-open interval](#)  $[0, 2\pi)$  is not compact (for instance by the [Heine-Borel theorem](#), prop. 7.39), and hence prop. 7.42 does not apply.

## 8. Paracompact spaces

The concept of [compactness](#) in topology ([above](#)) has several evident weakenings of interest. One is that of [paracompactness](#) (def. 8.3 below).

A key property is that [paracompact Hausdorff spaces](#) are equivalently those (prop. 8.17) all whose [open covers](#) admit a subordinate [partition of unity](#) (def. 8.15 below), namely a set of [real-valued continuous functions](#) each of which is

[supported](#) in only one patch of the cover, but whose [sum](#) is the unit function. Existence of such partitions implies that structures on topological spaces which are glued together via [linear maps](#) (such as [vector bundles](#)) are well behaved.

(In [algebraic topology](#) paracompact spaces are important as for them [abelian sheaf cohomology](#) may be computed in terms of [Čech cohomology](#).)

### Definition 8.1. ([locally finite cover](#))

Let  $(X, \tau)$  be a [topological space](#).

An [open cover](#)  $\{U_i \subset X\}_{i \in I}$  of  $X$  is called *locally finite* if for all point  $x \in X$ , there exists a [neighbourhood](#)  $U_x \supset \{x\}$  such that it [intersects](#) only finitely many elements of the cover, hence such that  $U_x \cap U_i \neq \emptyset$  for only a [finite number](#) of  $i \in I$ .

### Definition 8.2. ([refinement of open covers](#))

Let  $(X, \tau)$  be a [topological space](#), and let  $\{U_i \subset X\}_{i \in I}$  be a [open cover](#).

Then a [refinement](#) of this open cover is a set of open subsets  $\{V_j \subset X\}_{j \in J}$  which is still an [open cover](#) in itself and such that for each  $j \in J$  there exists an  $i \in I$  with  $V_j \subset U_i$ .

### Definition 8.3. ([paracompact topological space](#))

A [topological space](#)  $(X, \tau)$  is called *paracompact* if every [open cover](#) of  $X$  has a [refinement](#) (def. 8.2) by a [locally finite open cover](#) (def. 8.1).

The definition is closely related to the following two:

### Definition 8.4. ([second-countable topological space](#))

A [topological space](#) is called *second countable* if it admits a [base for its topology](#)  $\beta_X$  which is a [countable set](#) of open subsets.

### Example 8.5. ([sigma-compact topological space](#))

A [topological space](#) is called *sigma-compact* if it is the [union](#) of a [countable set](#) of [compact subsets](#).

## Properties

### Proposition 8.6. ([paracompact Hausdorff spaces are normal](#))

Every [paracompact Hausdorff space](#) is [normal](#).

In particular [compact Hausdorff spaces are normal](#).

**Proof.** Let  $(X, \tau)$  be a paracompact Hausdorff space

We first show that it is [regular](#): To that end, let  $x \in X$  be a point, and let  $C \subset X$  be a [closed subset](#) not containing  $x$ . We need to find disjoint open neighbourhoods  $U_x \supset \{x\}$  and  $U_C \supset C$ .

First of all, by the Hausdorff property there exists for each  $c \in C$  disjoint open neighbourhoods  $U_{x,c} \supset \{x\}$  and  $U_c \supset C$ . As  $c$  ranges, the latter clearly form an open cover  $\{U_c \subset X\}_{c \in C}$  of  $C$ , and so the union

$$\{U_c \subset X\}_{c \in C} \cup X \setminus C$$

is an open cover of  $X$ . By paracompactness of  $(X, \tau)$ , there exists a locally finite refinement, and by [this lemma](#) we may assume its elements to share the original index set and be contained in the original elements of the same index. Hence

$$\{V_c \subset U_c \subset X\}_{c \in C}$$

is a locally finite collection of subsets, such that

$$U_C := \bigcup_{c \in C} U_c$$

is an open neighbourhood of  $C$ .

Now by definition of local finiteness there exists an open neighbourhood  $W_x \supset \{x\}$  and a finite subset  $K \subset C$  such that

$$\forall_{c \in C \setminus K} (W_x \cap V_c = \emptyset) .$$

Consider then

$$U_x := W_x \cap \left( \bigcap_{k \in K} (U_{x,k}) \right) .$$

which is an open neighbourhood of  $x$ , by the finiteness of  $K$ .

It thus only remains to see that

$$U_x \cap U_C = \emptyset .$$

But this holds because the only  $V_c$  that intersect  $W_x$  are the  $V_k \subset U_k$  and each of these is by construction disjoint from  $U_{x,k}$  and hence from  $U_x$ .

This establishes that  $(X, \tau)$  is regular. Now we prove that it is normal. For this we use the same approach as before:

Let  $C, D \subset X$  be two disjoint closed subsets. By need to produce disjoint open neighbourhoods for these.

By the previous statement of regularity, we may find for each  $c \in C$  disjoint open neighbourhoods  $U_c \subset \{c\}$  and  $U_{D,c} \supset D$ . Hence the union

$$\{U_c \subset X\}_{c \in \mathcal{C}} \cup X \setminus C$$

is an open cover of  $X$ , and thus by paracompactness has a locally finite refinement, whose elements we may, again by [this lemma](#), assume to have the same index set as before and be contained in the previous elements with the same index. Hence we obtain a locally finite collection of subsets

$$\{V_c \subset U_c \subset X\}_{c \in \mathcal{C}}$$

such that

$$U_C := \bigcup_{c \in \mathcal{C}} V_c$$

is an open neighbourhood of  $C$ .

It is now sufficient to see that every point  $d \in D$  has an open neighbourhood  $U_d$  not intersecting  $U_C$ , for then

$$U_D := \bigcup_{d \in D} U_d$$

is the required open neighbourhood of  $D$  not intersecting  $U_C$ .

Now by local finiteness of  $\{V_c \subset X\}_{c \in X}$ , every  $d \in D$  has an open neighbourhood  $W_d$  such that there is a finite set  $K_d \subset \mathcal{C}$  so that

$$\forall_{c \in \mathcal{C} \setminus K_d} (V_c \cap W_d = \emptyset).$$

Accordingly the intersection

$$U_d := W_d \cap \left( \bigcap_{c \in K_d} U_{D,c} \right)$$

is still open and disjoint from the remaining  $V_k$ , hence disjoint from all of  $U_C$ . ■

The following will be useful for identifying [manifolds](#) below:

**Proposition 8.7. ([locally compact and sigma-compact spaces are paracompact](#))**

Let  $X$  be a [topological space](#) which is

1. [locally compact](#);
2. [sigma-compact](#).

Then  $X$  is also [paracompact](#).

**Proposition 8.8. ([second-countable regular spaces are paracompact](#))**

Let  $X$  be a [topological space](#) which is

1. [second-countable](#);

## 2. regular.

Then  $X$  is paracompact topological space.

We consider now a couple of technical lemmas related to locally finite covers which will be needed in the proof of prop. 8.17 below:

1. every locally finite refinement induces one with the original index set,
2. every locally finite cover of a normal space contains the closure of one with smaller patches ("shrinking lemma").

**Lemma 8.9. (every locally finite refinement induces one with the original index set)**

Let  $(X, \tau)$  be a topological space, let  $\{U_i \subset X\}_{i \in I}$  be an open cover, and let  $(\phi: J \rightarrow I, \{V_j \subset X\}_{j \in J})$ , be a refinement to a locally finite cover.

Then  $\{W_i \subset X\}_{i \in I}$  with

$$W_i := \left\{ \bigcup_{j \in \phi^{-1}(\{i\})} V_j \right\}$$

is still a refinement of  $\{U_i \subset X\}_{i \in I}$  to a locally finite cover.

**Proof.** It is clear by construction that  $W_i \subset U_i$ , hence that we have a refinement. We need to show local finiteness.

Hence consider  $x \in X$ . By the assumption that  $\{V_j \subset X\}_{j \in J}$  is locally finite, it follows that there exists an open neighbourhood  $U_x \supset \{x\}$  and a finite subset  $K \subset J$  such that

$$\forall_{j \in J \setminus K} (U_x \cap V_j = \emptyset) .$$

Hence by construction

$$\forall_{i \in I \setminus \phi(K)} (U_x \cap W_i = \emptyset) .$$

Since the image  $\phi(K) \subset I$  is still a finite set, this shows that  $\{W_i \subset X\}_{i \in I}$  is locally finite. ■

**Lemma 8.10. (shrinking lemma for locally finite covers)**

Let  $X$  be a topological space which is normal and let  $\{U_i \subset X\}_{i \in I}$  be a locally finite open cover.

Then there exists another open cover  $\{V_i \subset X\}_{i \in I}$  such that the topological closure  $\text{Cl}(V_i)$  of its elements is contained in the original patches:



$$\forall_{i \in I} (V_i \subset \text{Cl}(V_i) \subset U_i) .$$

We now **prove** this in increasing generality; first for binary open covers (lemma [8.11](#) below), then for finite covers (lemma [8.12](#)), then for locally finite countable covers (lemma [8.14](#)), and finally for general locally finite covers (lemma [8.10](#), proof [below](#)). The last statement needs the [axiom of choice](#).

**Lemma 8.11. ([shrinking lemma for binary covers](#))**

Let  $(X, \tau)$  be a [normal topological space](#) and let  $\{U \subset X\}_{i \in \{1,2\}}$  an [open cover](#) by two [open subsets](#).

Then there exists an open set  $V_1 \subset X$  whose [topological closure](#) is contained in  $U_1$

$$V_1 \subset \text{Cl}(V_1) \subset U_1$$

and such that  $\{V_1, U_2\}$  is still an open cover of  $X$ .

**Proof.** Since  $U_1 \cup U_2 = X$  it follows (by [de Morgan's law](#)) that their [complements](#)  $X \setminus U_i$  are [disjoint closed subsets](#). Hence by normality of  $(X, \tau)$  there exist disjoint open subsets

$$V_1 \supset X \setminus U_2 \quad V_2 \supset X \setminus U_1 .$$

By their disjointness, we have the following inclusions:

$$V_1 \subset X \setminus V_2 \subset U_1 .$$

In particular, since  $X \setminus V_2$  is closed, this means that  $\text{Cl}(V_1) \subset X \setminus (V_2)$ .

Hence it only remains to observe that  $V_1 \cup U_2 = X$ , by definition of  $V_1$ . ■

**Lemma 8.12. ([shrinking lemma for finite covers](#))**

Let  $(X, \tau)$  be a [normal topological space](#), and let  $\{U_i \subset X\}_{i \in \{1, \dots, n\}}$  be an [open cover](#) with a [finite number](#)  $n \in \mathbb{N}$  of patches. Then there exists another open cover  $\{V_i \subset X\}_{i \in I}$  such that  $\text{Cl}(V_i) \subset U_i$  for all  $i \in I$ .

**Proof.** By [induction](#) using lemma [8.11](#).

To begin with, consider  $\{U_1, \bigcup_{i=2}^n U_i\}$ . This is a binary open cover, and hence lemma [8.11](#) gives an open subset  $V_1 \subset X$  with  $V_1 \subset \text{Cl}(V_1) \subset U_1$  such that  $\{V_1, \bigcup_{i=2}^n U_i\}$  is still an open cover, and accordingly so is

$$\{V_1\} \cup \{U_i\}_{i \in \{2, \dots, n\}} .$$

Similarly we next find an open subset  $V_2 \subset X$  with  $V_2 \subset \text{Cl}(V_2) \subset U_2$  and such that

$$\{V_1, V_2\} \cup \{U_i\}_{i \in \{3, \dots, n\}}$$

is an open cover. After  $n$  such steps we are left with an open cover  $\{V_i \subset X\}_{i \in \{1, \dots, n\}}$  as required. ■

**Remark 8.13.** Beware the [induction](#) in lemma 8.12 does *not* give the statement for infinite [countable covers](#). The issue is that it is not guaranteed that  $\bigcup_{i \in \mathbb{N}} V_i$  is a cover.

And in fact, assuming the [axiom of choice](#), then there exists a counter-example of a countable cover on a normal spaces for which the shrinking lemma fails (a [Dowker space](#) due to [Beslagic 85](#)).

This issue is evaded if we consider [locally finite covers](#):

**Lemma 8.14. ([shrinking lemma](#) for locally finite countable covers)**

*Let  $(X, \tau)$  be a [normal topological space](#) and  $\{U_i \subset X\}_{i \in \mathbb{N}}$  a [locally finite countable cover](#). Then there exists [open subsets](#)  $V_i \subset X$  for  $i \in \mathbb{N}$  such that  $V_i \subset \text{Cl}(V_i) \subset U_i$  and such that  $\{V_i \subset X\}_{i \in \mathbb{N}}$  is still a cover.*

**Proof.** As in the proof of lemma 8.12, there exist  $V_i$  for  $i \in \mathbb{N}$  such that  $V_i \subset \text{Cl}(V_i) \subset U_i$  and such that for every finite number, hence every  $n \in \mathbb{N}$ , then

$$\bigcup_{i=0}^n V_i = \bigcup_{i=0}^n U_i .$$

Now the extra assumption that  $\{U_i \subset X\}_{i \in I}$  is [locally finite](#) implies that every  $x \in X$  is contained in only finitely many of the  $U_i$ , hence that for every  $x \in X$  there exists  $n_x \in \mathbb{N}$  such that

$$x \in \bigcup_{i=0}^{n_x} U_i .$$

This implies that for every  $x$  then

$$x \in \bigcup_{i=0}^{n_x} V_i \subset \bigcup_{i \in \mathbb{N}} V_i$$

hence that  $\{V_i \subset X\}_{i \in \mathbb{N}}$  is indeed a cover of  $X$ . ■

We now invoke [Zorn's lemma](#) to generalize the shrinking lemma for finitely many patches (lemma 8.12) to arbitrary sets of patches:

**Proof.** of the general [shrinking lemma 8.10](#)

Let  $\{U_i \subset X\}_{i \in I}$  be the given locally finite cover of the normal space  $(X, \tau)$ . Consider the set  $S$  of [pairs](#)  $(J, \mathcal{V})$  consisting of

1. a [subset](#)  $J \subset I$ ;
2. an  $I$ -indexed set of open subsets  $\mathcal{V} = \{V_i \subset X\}_{i \in I}$

with the property that

1.  $(i \in J \subset I) \Rightarrow (\text{Cl}(V_i) \subset U_i)$ ;
2.  $(i \in I \setminus J) \Rightarrow (V_i = U_i)$ .
3.  $\{V_i \subset X\}_{i \in I}$  is an open cover of  $X$ .

Equip the set  $S$  with a [partial order](#) by setting

$$((J_1, \mathcal{V}) \leq (J_2, \mathcal{V})) \Leftrightarrow \left( (J_1 \subset J_2) \text{ and } \left( \bigvee_{i \in J_1} (V_i = W_i) \right) \right).$$

By definition, an element of  $S$  with  $J = I$  is an open cover of the required form.

We claim now that a [maximal element](#)  $(J, \mathcal{V})$  of  $(S, \leq)$  has  $J = I$ .

For assume on the contrary that there were  $i \in I \setminus J$ . Then we could apply the construction in lemma [8.11](#) to replace that single  $V_i$  with a smaller open subset  $V'_i$  to obtain  $\mathcal{V}'$  such that  $\text{Cl}(V'_i) \subset V_i$  and such  $\mathcal{V}'$  is still an open cover. But that would mean that  $(J, \mathcal{V}) < (J \cup \{i\}, \mathcal{V}')$ , contradicting the assumption that  $(J, \mathcal{V})$  is maximal. This [proves by contradiction](#) that a maximal element of  $(S, \leq)$  has  $J = I$  and hence is an open cover as required.

We are reduced now to showing that a maximal element of  $(S, \leq)$  exists. To achieve this we invoke [Zorn's lemma](#). Hence we have to check that every [chain](#) in  $(S, \leq)$ , hence every [totally ordered subset](#) has an [upper bound](#).

So let  $T \subset S$  be a [totally ordered](#) subset. Consider the union of all the index sets appearing in pairs in this subset:

$$K := \bigcup_{(J, \mathcal{V}) \in T} J.$$

Now define open subsets  $\mathcal{W}_i$  for  $i \in K$  picking any  $(J, \mathcal{V})$  in  $T$  with  $i \in J$  and setting

$$\mathcal{W}_i := V_i \quad i \in K.$$

This is independent of the choice of  $(J, \mathcal{V})$ , hence well defined, by the assumption that  $(T, \leq)$  is totally ordered.

Moreover, for  $i \in I \setminus K$  define

$$\mathcal{W}_i := U_i \quad i \in I \setminus K.$$

We claim now that  $\{\mathcal{W}_i \subset X\}_{i \in I}$  thus defined is a cover of  $X$ . Because by assumption that  $\{U_i \subset X\}_{i \in I}$  is locally finite, also all the  $\{V_i \subset X\}_{i \in I}$  are locally finite, hence for every point  $x \in X$  there exists a finite set  $J_x \subset I$  such that  $(i \in I \setminus J_x) \Rightarrow (i \notin U_i)$ . Since  $(T, \leq)$  is a total order, it must contain an element  $(J, \mathcal{V})$  such that  $J_x \cap K \subset J$ . Since that  $\mathcal{V}$  is a cover, it follows that  $x \in \bigcup_{i \in I} V_i$ , hence in  $\bigcup_{i \in I} \mathcal{W}_i$ .

This shows that  $(K, \mathcal{W})$  is indeed an element of  $S$ . It is clear by construction that it is an upper bound for  $(T, \leq)$ . Hence we have shown that every [chain](#) in  $(S, \leq)$  has an

upper bound, and so Zorn's lemma implies the claim. ■

## Partitions of unity

### Definition 8.15. (partition of unity)

Let  $(X, \tau)$  be a topological space, and let  $\{U_i \subset X\}_{i \in I}$  be an open cover. Then a partition of unity subordinate to the cover is

- a set  $\{f_i\}_{i \in I}$  of continuous functions

$$f_i : U_i \rightarrow [0, 1]$$

(where  $U_i \subset X$  and  $[0, 1] \subset \mathbb{R}$  are equipped with their subspace topology, the real numbers  $\mathbb{R}$  is regarded as the 1-dimensional Euclidean space equipped with its metric topology);

such that with

$$\text{Supp}(f_i) := \text{Cl}(f_i^{-1}((0, 1]))$$

denoting the support of  $f_i$  (the topological closure of the subset of points on which it does not vanish) then

1.  $\forall_{i \in I} (\text{Supp}(f_i) \subset U_i)$ ;
2.  $\{\text{Supp}(f_i) \subset X\}_{i \in I}$  is a locally finite cover (def. 8.1);
3.  $\forall_{x \in X} (\sum_{i \in I} f_i(x) = 1)$ .

**Remark 8.16.** Due to the second clause in def. 8.15, the sum in the third clause involves only a finite number of elements not equal to zero, and therefore is well defined.

### Proposition 8.17. (paracompact Hausdorff spaces equivalently admit subordinate partitions of unity)

Let  $(X, \tau)$  be a topological space. Then the following are equivalent:

1.  $(X, \tau)$  is a paracompact Hausdorff space (def. 4.4, def. 8.3).
2. Every open cover of  $(X, \tau)$  admits a subordinate partition of unity (def. 8.15).

**Proof.** One direction is immediate: Assume that every open cover  $\{U_i \subset X\}_{i \in I}$  admits a subordinate partition of unity  $\{f_i\}_{i \in I}$ . Then by definition (def. 8.15)  $\{\text{Int}(\text{Supp}(f_i)) \subset X\}_{i \in I}$  is a locally finite open cover refining the original one.

We need to show the converse: If  $(X, \tau)$  is a paracompact topological space, then for

every [open cover](#)  $\{U_i \subset X\}_{i \in I}$  there is a subordinate [partition of unity](#) (def. 8.15).

To that end, first apply the [shrinking lemma 8.10](#) to the given locally finite open cover  $\{U_i \subset X\}$ , to obtain a smaller locally finite open cover  $\{V_i \subset X\}_{i \in I}$ , and then apply the lemma once more to that result to get a yet smaller open cover  $\{W_i \subset X\}_{i \in I}$ , so that now

$$\forall_{i \in I} (W_i \subset \text{Cl}(W_i) \subset V_i \subset \text{Cl}(V_i) \subset U_i) .$$

It follows that for each  $i \in I$  we have two disjoint [closed subsets](#), namely the [topological closure](#)  $\text{Cl}(W_i)$  and the [complement](#)  $X \setminus V_i$

$$\text{Cl}(W_i) \cap X \setminus V_i = \emptyset .$$

Now since [paracompact Hausdorff spaces are normal](#) (prop. 8.6), [Urysohn's lemma](#) (prop. 4.20) says that there exist [continuous functions](#) of the form

$$h_i : X \rightarrow [0, 1]$$

with the property that

$$h_i(\text{Cl}(W_i)) = \{1\}, \quad h_i(X \setminus V_i) = \{0\} .$$

This means in particular that  $h_i^{-1}((0, 1]) \subset V_i$  and hence that

$$\text{Supp}(h_i) = \text{Cl}(h_i^{-1}((0, 1])) \subset \text{Cl}(V_i) \subset U_i .$$

By construction, the set of function  $\{h_i\}_{i \in I}$  already satisfies two of the three conditions on a partition of unity subordinate to  $\{U_i \subset X\}_{i \in I}$  from def. 8.15. It just remains to normalize these functions so that they indeed sum to unity. To that end, consider the continuous function

$$h : X \rightarrow [0, 1]$$

defined on  $x \in X$

$$h(x) := \sum_{i \in I} h_i(x) .$$

Notice that the [sum](#) on the right has only a [finite number](#) of non-zero summands, due to the local finiteness of the cover, so that this is well-defined.

Then set

$$f_i := g_i / g .$$

This is now manifestly such that  $\sum_{i \in I} f_i = 1$ , and so

$$\{f_i\}_{i \in I}$$

is a partition of unity as required. ■

## 9. Manifolds

A [topological manifold](#) is a [topological space](#) which is *locally homeomorphic* to a [Euclidean space](#) (def. 9.3 below), but which may globally look very different. These are the kinds of topological spaces that are really meant when people advertise [topology](#) as “[rubber-sheet geometry](#)”.

If the [gluing functions](#) which relate the Euclidean [local charts](#) of topological manifolds to each other are [differentiable functions](#), for a fixed degree of differentiability, then one speaks of [differentiable manifolds](#) (def 9.7 below) or of [smooth manifolds](#) if the gluing functions are arbitrarily differentiable.

Accordingly, a differentiable manifold is a space to which the tools of ([infinitesimal analysis](#)) may be applied *locally*. Notably we may ask whether a [continuous function](#) between differentiable manifolds is [differentiable](#) by computing its [derivatives](#) pointwise in any of the Euclidean [coordinate charts](#). This way differential and smooth manifolds are the basis for much of [differential geometry](#). They are the analogs in differential geometry of what [schemes](#) are in [algebraic geometry](#).

### Definition 9.1. ([locally Euclidean topological space](#))

A [topological space](#)  $X$  is [locally Euclidean](#) if every point  $x \in X$  has an [open neighbourhood](#)  $U_x \supset \{x\}$  which is [homeomorphic](#) to the [Euclidean space](#)  $\mathbb{R}^n$  with its [metric topology](#).

### Remark 9.2. (locally Euclidean spaces are $T_1$ and locally compact, but not necessarily $T_2$ )

It might superficially seem that every locally Euclidean space (def. 9.1) is necessarily a [Hausdorff topological space](#), since [Euclidean space](#), like any [metric space](#), is Hausdorff, and since by definition the neighbourhood of every point in a locally Euclidean spaces looks like Euclidean space.

But this is not so, see the counter-example 9.5 below, Hausdorffness is a “non-local condition”, as opposed to the  $T_0$  and  $T_1$  [separation axioms](#).

Every locally Euclidean space is  $T_1$ : Let  $x \neq y$  be two distinct points in the locally Euclidean space. We need to show that there is an open neighbourhood  $U_x$  around  $x$  that does not contain  $y$ . By definition there is a Euclidean open neighbourhood  $E_x$  around  $x$ . If this does not contain  $y$ , then we may set  $U_x := E_x$ . If it does, then  $x \neq y$  are two distinct point in this Euclidean space  $E_x \simeq \mathbb{R}^n$ . But Euclidean space is  $T_1$ , and hence we may find an open neighbourhood  $U_x \subset E_x$  not intersecting  $y$ .

Similarly every locally Euclidean space is a [locally compact topological space](#).

### Definition 9.3. ([topological manifold](#))

A *topological manifold* (also "*n*-fold") is a topological space which is

1. locally Euclidean,
2. paracompact Hausdorff.

**Remark 9.4. (varying terminology)**

There is some variance in the choice of regularity condition in def. 9.3. Often it is required in addition to being a paracompact Hausdorff space that a manifold have a countable set of connected components, which then means that it is sigma-compact.

This is the relevant condition for the Whitney embedding theorem to apply.

Very rarely one considers non-Hausdorff topological spaces as manifolds, see example 9.5.

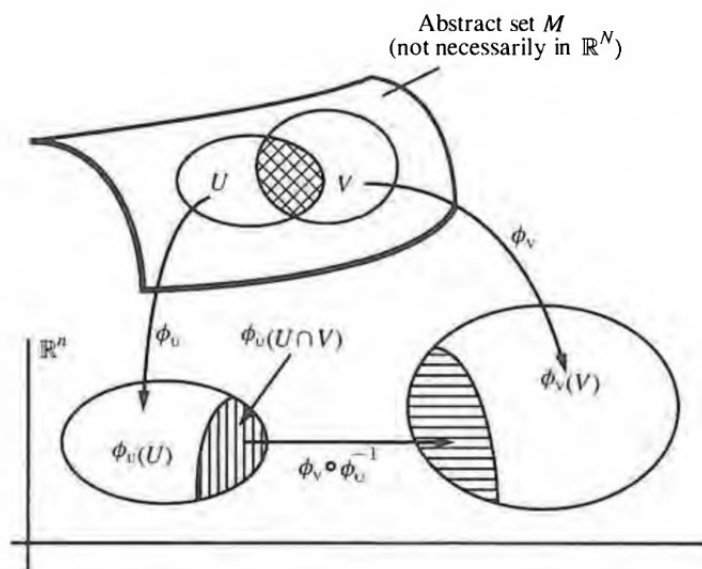
**Nonexample 9.5. (non-Hausdorff manifolds)**

An example of a topological space which is locally Euclidean as in def. 9.3 but a non-Hausdorff topological space, and hence not a topological manifold in the sense of def. 9.3, is the line with two origins (example 4.3).

**Definition 9.6. (local chart, atlas and gluing function)**

Given an  $n$ -dimensional topological manifold  $X$  (def. 9.3), then

1. an open subset  $U \subset X$  and a homeomorphism  $\phi: \mathbb{R}^n \xrightarrow{\sim} U$  is also called a local coordinate chart of  $X$ .
2. an open cover of  $X$  by local charts  $\{\mathbb{R}^n \xrightarrow{\phi_i} U_i \subset X\}_{i \in I}$  is called an atlas of the topological manifold.
3. denoting for each  $i, j \in I$  the intersection of the  $i$ th chart with the  $j$ th chart in such an atlas by



$$U_{ij} := U_i \cap U_j$$

then the induced homeomorphism

$$\mathbb{R}^n \supset \phi_i^{-1}(U_{ij}) \xrightarrow{\phi_i} U_{ij} \xrightarrow{\phi_j^{-1}} \phi_j^{-1}(U_{ij}) \subset \mathbb{R}^n$$

is called the gluing function from chart  $i$  to chart  $j$ .



graphics grabbed from [Frankel](#)

### Definition 9.7. ([differentiable manifold](#))

For  $p \in \mathbb{N} \cup \{\infty\}$  then a  $p$ -fold [differentiable manifold](#) or  $C^p$ -manifold for short is

1. a [topological manifold](#)  $X$  (def. 9.3);
2. an [atlas](#)  $\{\mathbb{R}^n \xrightarrow{\phi_i} X\}$  (def. 9.6) all whose [gluing functions](#) are  $p$  times continuously [differentiable](#).

A  $p$ -fold [differentiable function](#) between  $p$ -fold differentiable manifolds

$$\left( X, \{\mathbb{R}^n \xrightarrow{\phi_i} U_i \subset X\}_{i \in I} \right) \xrightarrow{f} \left( Y, \{\mathbb{R}^{n'} \xrightarrow{\psi_j} V_j \subset Y\}_{j \in J} \right)$$

is

- a [continuous function](#)  $f: X \rightarrow Y$

such that

- for all  $i \in I$  and  $j \in J$  then

$$\mathbb{R}^n \supset (f \circ \phi_i)^{-1}(V_j) \xrightarrow{\phi_i} f^{-1}(V_j) \xrightarrow{f} V_j \xrightarrow{\psi_j^{-1}} \mathbb{R}^{n'}$$

is a  $p$ -fold [differentiable function](#) between open subsets of [Euclidean space](#).

Notice that this is in general a non-trivial condition even if  $X = Y$  and  $f$  is the identity function. In this case the above exhibits a passage to a different, but equivalent, differentiable atlas.

### Remark 9.8. ([category Diff](#) of [differentiable manifolds](#))

In analogy to remark 3.3 there is a [category](#) called  $\mathbf{Diff}_p$  (or similar) whose [objects](#) are  $C^p$ -[differentiable manifolds](#) and whose [morphisms](#) are  $C^p$ -[differentiable functions](#).

### Example 9.9. ([Cartesian space](#) as a [smooth manifold](#))

For  $n \in \mathbb{N}$  then the [Cartesian space](#)  $\mathbb{R}^n$  equipped with the [atlas](#) consisting of the single [chart](#)  $\mathbb{R}^n \xrightarrow{\text{id}} \mathbb{R}^n$  is a [smooth manifold](#), in particular a  $p$ -fold differentiable manifold for every  $p \in \mathbb{N}$  according to def. 9.7.

Similarly the [open disk](#)  $D^n$  becomes a [smooth manifold](#) when equipped with the atlas whose single chart is the [homeomorphism](#)  $\mathbb{R}^n \rightarrow D^n$ .

### Example 9.10. ([n-sphere](#) as a [smooth manifold](#))

For all  $n \in \mathbb{N}$ , the [n-sphere](#)  $S^n$  becomes a smooth manifold, with [atlas](#) consisting of the two [local charts](#) that are given by the [inverse functions](#) of the [stereographic](#)



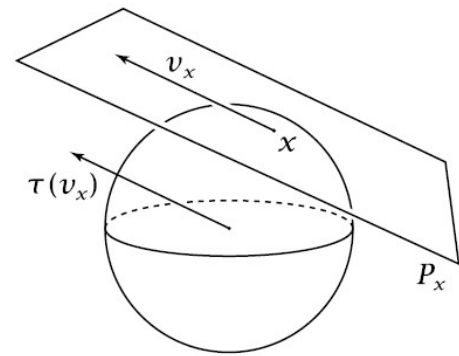
[projection](#) from the two poles of the sphere onto the [equatorial](#) hyperplane

$$\left\{ \mathbb{R}^n \xrightarrow[\simeq]{\sigma_i^{-1}} S^n \right\}_{i \in \{+, -\}}.$$

By the formulas given in [this prop.](#) the induced [gluing function](#)  $\mathbb{R}^n \setminus \{0\} \rightarrow \mathbb{R}^n \setminus \{0\}$  is smooth.

## Tangent bundles

Since [differentiable manifolds](#) are [locally Euclidean spaces](#) whose [gluing functions](#) respect the [infinitesimal analysis](#) on [Euclidean space](#), they constitute a globalization of [infinitesimal analysis](#) from [Euclidean space](#) to more general [topological spaces](#). In particular a [differentiable manifold](#) has associated to each point a [tangent space](#) of [vectors](#) that linearly approximate the manifold in the [infinitesimal neighbourhood](#) of that point. The union of all these [tangent spaces](#) is called the [tangent bundle](#) of the [differentiable manifold](#).



The tangent bundle, via the [frame bundle](#) that is [associated](#) to it is the basis for all actual [geometry](#): By equipping tangent bundles with ([torsion-free](#)) “[G-structures](#)” one encodes all sorts of flavors of geometry, such as [Riemannian geometry](#), [conformal geometry](#), [complex geometry](#), [symplectic geometry](#), and generally [Cartan geometry](#).

### Definition 9.11. (tangency relation on smooth curves)

Let  $X$  be a [differentiable manifold](#) of [dimension](#)  $n$  and let  $x \in X$  be a point. On the set of [smooth functions](#) of the form

$$\gamma : \mathbb{R}^1 \rightarrow X$$

such that

$$\gamma(0) = x$$

define the [relations](#)

$$(\gamma_1 \sim \gamma_2) := \exists_{\substack{\mathbb{R}^n \xrightarrow{\phi_{\text{chart}}} U_i \subset X \\ U_i \ni \{x\}}} \left( \frac{d}{dt}(\phi^{-1} \circ \gamma_1)(0) = \frac{d}{dt}(\phi^{-1} \circ \gamma_2)(0) \right)$$

and

$$(\gamma_1 \sim' \gamma_2) := \forall_{\substack{\mathbb{R}^n \xrightarrow{\phi_{\text{chart}}} U_i \subset X \\ U_i \ni \{x\}}} \left( \frac{d}{dt}(\phi^{-1} \circ \gamma_1)(0) = \frac{d}{dt}(\phi^{-1} \circ \gamma_2)(0) \right)$$

saying that two such functions are related precisely if either there exists a chart

around  $x$  such that (or else for all charts around  $x$  it is true that) the first [derivative](#) of the two functions regarded via the given chart as functions  $\mathbb{R}^1 \rightarrow \mathbb{R}^n$ , coincide at  $t = 0$  (with  $t$  denoting the canonical [coordinate](#) function on  $\mathbb{R}$ ).

**Lemma 9.12. (*tangency is equivalence relation*)**

The two relations in def. 9.11 are [equivalence relations](#) and they coincide.

**Proof.** First to see that they coincide, we need to show that if the derivatives in question coincide in one chart  $\mathbb{R}^n \xrightarrow[\cong]{\phi} U_i \subset X$ , that then they coincide also in any other chart  $\mathbb{R}^n \xrightarrow[\cong]{\psi} U_j \subset X$ .

Write

$$U_{ij} := U_i \cap U_j$$

for the intersection of the two charts.

First of all, since the derivative may be computed in any [open neighbourhood](#) around  $t = 0$ , and since the differentiable functions  $\gamma_i$  are in particular [continuous functions](#), we may restrict to the open neighbourhood

$$V := \gamma_1^{-1}(U_{ij}) \cap \gamma_2^{-1}(U_{ij}) \subset \mathbb{R}$$

of  $0 \in \mathbb{R}$  and consider the derivatives of the functions

$$\gamma_i^\phi := (\phi|_{U_{ij}} \circ \gamma_i|_V) : V \rightarrow \phi^{-1}(U_{ij}) \subset \mathbb{R}^n$$

and

$$\gamma_i^\psi := (\psi|_{U_{ij}} \circ \gamma_i|_V) : V \rightarrow \psi^{-1}(U_{ij}) \subset \mathbb{R}^n.$$

But then by definition of the differentiable [atlas](#), there is the differentiable function

$$\alpha := \phi^{-1}(U_{ij}) \xrightarrow[\cong]{\phi} U_{ij} \xrightarrow[\cong]{\psi^{-1}} \psi^{-1}(U_{ij})$$

such that

$$\gamma_i^\psi = \alpha \circ \gamma_i^\phi$$

for  $i \in \{1, 2\}$ . The [chain rule](#) now relates the derivatives of these functions as

$$\frac{d}{dt} \gamma_i^\psi = (D\alpha) \circ \left( \frac{d}{dt} \gamma_i^\phi \right).$$

Since  $\alpha$  is a [diffeomorphism](#) and since derivatives of diffeomorphisms are linear isomorphisms, this says that the derivative of  $\gamma_i^\phi$  is related to that of  $\gamma_i^\psi$  by a linear isomorphism, and hence

$$\left( \frac{d}{dt}(\gamma_1)^\phi = \frac{d}{dt}(\gamma_2^\phi) \right) \Leftrightarrow \left( \frac{d}{dt}(\gamma_1)^\psi = \frac{d}{dt}(\gamma_2^\psi) \right).$$

Finally, that either relation is an equivalence relation is immediate. ■

### Definition 9.13. ([tangent vector](#))

Let  $X$  be a [differentiable manifold](#) and  $x \in X$  a point. Then a *tangent vector* on  $X$  at  $x$  is an [equivalence class](#) of the tangency equivalence relation (def. [9.11](#), lemma [9.12](#)).

The set of all tangent vectors at  $x \in X$  is denoted  $T_x X$ .

### Lemma 9.14. ([real vector space structure on tangent vectors](#))

For  $X$  a [differentiable manifold](#) of [dimension](#)  $n$  and  $x \in X$  any point, let  $\mathbb{R}^n \xrightarrow[\cong]{\phi} U_i \subset X$  be a [chart](#) with  $x \in U_i$ .

Then there is induced a [bijection](#) of sets

$$\mathbb{R}^n \xrightarrow{\cong} T_x X$$

from the  $n$ -dimensional [Cartesian space](#) to the set of tangent vectors at  $x$  (def. [9.13](#)) given by sending  $\vec{v} \in \mathbb{R}^n$  to the equivalence class of the following smooth curve:

$$\begin{array}{ccccc} \mathbb{R}^1 & \xrightarrow{\gamma_{(-)}^\phi} & \mathbb{R}^n & \xrightarrow[\cong]{\phi} & U_i \subset X \\ t & \longmapsto & t\vec{v} + \phi(x) & \longmapsto & \phi^{-1}(t\vec{v} + \phi(x)) \end{array}.$$

Moreover, the structure of a [real vector space](#) inherited by  $T_x X$  from  $\mathbb{R}^n$  via  $\phi$  this way is independent of the choice of  $\phi$ .

**Proof.** The bijectivity of the map is immediate from the fact that the first derivative of  $\gamma_{\vec{v}}^\phi$  is  $\vec{v}$ . The independency from the choice of chart follows as in the proof of lemma [9.12](#). ■

### Remark 9.15. ([notation for tangent vectors in a chart](#))

Under the bijection of lemma [9.14](#) one often denotes the tangent vector corresponding to the the  $i$ -th canonical [basis](#) vector of  $\mathbb{R}^n$  by

$$\frac{\partial}{\partial x^i} \quad \text{or just} \quad \partial_i$$

because under the identification of tangent vectors with [derivations](#) on the algebra of [differentiable functions](#) on  $X$  as above then it acts as the operation of taking the  $i$ th [partial derivative](#). The general tangent vector corresponding to  $v \in \mathbb{R}^n$  is then denoted by

$$\sum_{i=1}^n v^i \frac{\partial}{\partial x^i} \quad \text{or just} \quad \sum_{i=1}^n v^i \partial_i .$$

Notice that this identification depends on the choice of [chart](#), which is left implicit in this notation.

Sometimes, notably in texts on [thermodynamics](#), one augments this notation to indicate the chart being used by listing the remaining coordinate functions as subscripts. For instance if two functions  $f, g$  on a 2-dimensional manifold are used as coordinate functions for a local chart (i.e. so that  $x^1 = f$  and  $x^2 = g$ ), then one write

$$(\partial / \partial f)_g \quad (\partial / \partial g)_f$$

for the tangent vectors  $\frac{\partial}{\partial x^1}$  and  $\frac{\partial}{\partial x^2}$ , respectively.

### Definition 9.16. ([tangent space](#))

For  $X$  a [differentiable manifold](#) and  $x \in X$  a point, then the [tangent space](#) of  $X$  at  $x$  is the set  $T_x X$  of [tangent vectors](#) at  $x$  (def. 9.13) regarded as a [real vector space](#) via lemma 9.14.

### Definition 9.17. ([tangent bundle](#))

Let  $X$  be a [differentiable manifold](#) with [atlas](#)  $\left\{ \mathbb{R}^n \xrightarrow[\simeq]{\phi_i} U_i \subset X \right\}_{i \in I}$ .

Equip the set of all tangent vectors (def. 9.13)

$$TX := \bigsqcup_{x \in X} T_x X$$

with a [topology](#)  $\tau_{TX}$  by declaring a [subset](#)  $U \subset TX$  to be an [open subset](#) precisely if for all [charts](#)  $\mathbb{R}^n \xrightarrow[\simeq]{\phi_i} U_i \subset X$  then its [preimage](#) under

$$\begin{aligned} \mathbb{R}^{2n} \simeq \mathbb{R}^n \times \mathbb{R}^n &\xrightarrow{d\phi} TX \\ (x, \vec{v}) &\longmapsto \frac{d}{dv} \phi(x) \end{aligned}$$

is open in the [Euclidean space](#)  $\mathbb{R}^{2n}$  with its [metric topology](#).

Define an [atlas](#) on this topological space by

$$\left\{ \mathbb{R}^{2n} \xrightarrow[\simeq]{d\phi_i} T(U_i) \subset TX \right\}_{i \in I} .$$

The resulting [differentiable manifold](#)  $TX$  is called the *total space of the tangent bundle* of  $X$ .

Equipped with the [function](#)

$$\begin{array}{ccc} TX & \xrightarrow{p_X} & X \\ (x, v) & \longmapsto & x \end{array}$$

this is called the *tangent bundle* of  $X$ .

**Lemma 9.18. (*tangent bundle is differentiable vector bundle*)**

The total space of the tangent bundle def. 9.17 is a differentiable manifold in that

1.  $(TX, \tau_{TX})$  is a paracompact Hausdorff space;
2. The gluing functions of the atlas  $\left\{ \mathbb{R}^{2n} \xrightarrow[\cong]{d\phi_i} TU_i \subset TX \right\}_{i \in I}$  are differentiable.

Moreover, the function  $p_X: TX \rightarrow X$  is continuous and of the same degree of differentiability as the differentiable structure on  $X$ .

Finally, this makes the tangent bundle into a real vector bundle over  $X$ .

**Proof.** (...) pretty straightforward (...) ■

**Proposition 9.19. (*differentials of differentiable functions between differentiable manifolds*)**

Let  $X$  and  $Y$  be differentiable manifolds and let  $f: X \rightarrow Y$  be a differentiable function. Then the operation of postcomposition which takes differentiable curves in  $X$  to differentiable curves in  $Y$

$$\begin{array}{ccc} \mathrm{Hom}_{\mathrm{Diff}}(\mathbb{R}^1, X) & \xrightarrow{f \circ (-)} & \mathrm{Hom}_{\mathrm{Diff}}(\mathbb{R}^1, Y) \\ \left( \mathbb{R}^1 \xrightarrow{\gamma} X \right) & \longmapsto & \left( \mathbb{R}^1 \xrightarrow{f \circ \gamma} Y \right) \end{array}$$

descends at each point  $x \in X$  to the tangency equivalence relation (def. 9.11, lemma 9.12) to yield a function on sets of tangent vectors (def. 9.13), called the differential  $df|_x$  of  $f$  at  $x$

$$df|_x : T_x X \rightarrow T_{f(x)} Y .$$

Moreover:

1. (linear dependence on the tangent vector) these differentials are linear functions with respect to the vector space structure on the tangent spaces from lemma 9.14, def. 9.16;
2. (differentiable dependence on the base point) globally they yield a homomorphism of differentiable real vector bundles between the tangent bundles (def. 9.17, lemma 9.18), called the global differential  $df$  of  $f$

$$df : TX \rightarrow TY .$$

3. (chain rule) The assignment  $f \mapsto df$  respects composition in that for  $X, Y, Z$

three differentiable manifolds and for

$$X \xrightarrow{f} Y \xrightarrow{g} Z$$

two composable differentiable functions then their differentials satisfy

$$d(g \circ f) = (dg) \circ (df) .$$

**Remark 9.20.** In the language of category theory the statement of prop. 9.19 says that forming tangent bundles  $TX$  of differentiable manifolds  $X$  and differentials  $df$  of differentiable functions  $f:X \rightarrow Y$  constitutes a functor

$$T : \text{Diff} \rightarrow \text{Vect}(\text{Diff})$$

from the category Diff of differentiable manifolds to the category of differentiable real vector bundles.

## Embeddings

**Definition 9.21. (immersion and submersion of differentiable manifolds)**

Let  $f:X \rightarrow Y$  be a differentiable function between differentiable manifolds.

If for each  $x \in X$  the differential (prop. 9.19)

$$df|_x : T_x X \rightarrow T_{f(x)} Y$$

is...

1. ...an injective function then  $f$  is called an immersion of differentiable manifolds
2. ...a surjective function then  $f$  is called a submersion of differentiable manifolds.

**Definition 9.22. (embedding of smooth manifolds)**

An embedding of smooth manifolds is a smooth function  $f:X \hookrightarrow Y$  between smooth manifolds  $X$  and  $Y$  such that

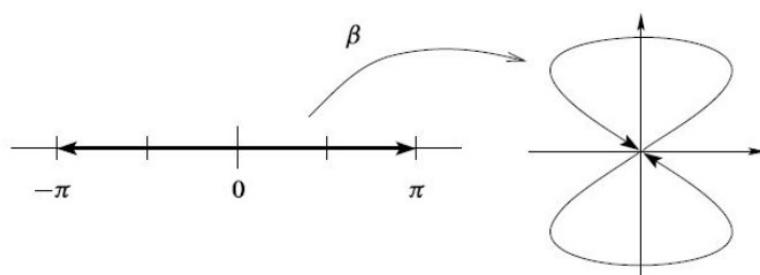
1.  $f$  is an immersion;
2. the underlying continuous function is an embedding of topological spaces.

A closed embedding is an embedding such that the image  $f(X) \subset Y$  is a closed subset.

**Nonexample 9.23. (immersions that are not embeddings)**

Consider an immersion  $f : (a, b) \rightarrow \mathbb{R}^2$  of an open interval into the Euclidean plane (or the 2-sphere) as shown on the right. This is not a embedding of smooth

**manifolds**: around the points where the image crosses itself, the function is not even injective, but even at the points where it just touches itself, the pre-images under  $f$  of open subsets of  $\mathbb{R}^2$  do not exhaust the open subsets of  $(a, b)$ , hence do not yield the **subspace topology**.

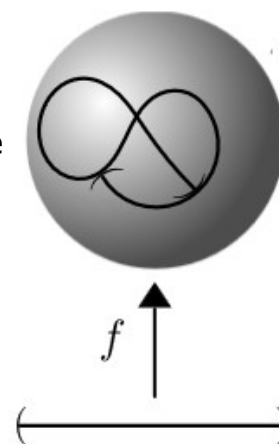


As a concrete examples, consider the function

$$(\sin(2 -), \sin(-)) : (-\pi, \pi) \rightarrow \mathbb{R}^2.$$

While this is an immersion and **injective**, it fails to be an

embedding due to the points at  $t = \pm \pi$  "touching" the point at  $t = 0$ .



graphics grabbed from [Lee](#)

**Proposition 9.24. (proper injective immersions are equivalently the closed embeddings)**

Let  $X$  and  $Y$  be **smooth manifolds**, and let  $f : X \rightarrow Y$  be a **smooth function**. Then the following are equivalent

1.  $f$  is a **proper injective immersion**;
2.  $f$  is a **closed embedding** (def. 9.22).

**Proof.** Since topological manifolds are **locally compact topological spaces** (remark \ref{TopologicalManifoldsAreLocallyCompact}), this follows directly since [injective proper maps into locally compact spaces are equivalently closed embeddings by prop. .] ■

**Proposition 9.25.** For every **compact smooth manifold**  $X$  (of **finite dimension**), there exists some  $k \in \mathbb{N}$  such that  $X$  has an embedding (def. 9.22) into the **Euclidean space** of dimension  $k$ :

$$X \xrightarrow{\text{embd}} \mathbb{R}^k$$

**Proof.** Let

$$\{\mathbb{R}^n \xrightarrow{\phi_i} U_i \subset X\}_{i \in I}$$

be an **atlas** exhibiting the **smooth structure** of  $X$ . In particular this is an **open cover**, and hence by compactness there exists a **finite subset**  $J \subset I$  such that

$$\{\mathbb{R}^n \xrightarrow{\phi_i} U_i \subset X\}_{i \in J \subset I}$$

is still an open cover.

Since  $X$  is a [smooth manifold](#), there exists a [partition of unity](#)  $\{f_i \in C^\infty(X, \mathbb{R})\}_{i \in J}$  subordinate to this cover with [smooth functions](#)  $f_i$  (by [this prop.](#)).

This we may use to extend the inverse [chart](#) identifications

$$X \supset U_i \xrightarrow[\simeq]{\psi_i} \mathbb{R}^n$$

to smooth functions

$$\hat{\psi}_i : X \rightarrow \mathbb{R}^n$$

by setting

$$\hat{\phi}_i : x \mapsto \begin{cases} f_i(x) \cdot \psi_i(x) & | \ x \in U_i \subset X \\ 0 & | \ \text{otherwise} \end{cases}.$$

The idea now is to combine all these functions to obtain an injective function

$$(\hat{\psi}_i)_{i \in J} : X \rightarrow (\mathbb{R}^n)^{|J|} \simeq \mathbb{R}^{n \cdot |J|}.$$

But while this is injective, it need not be an [immersion](#), since the [derivatives](#) of the product functions  $f_i \cdot \psi_i$  may vanish, even though the derivatives of the two factors do not vanish separately. However this is readily fixed by adding yet more ambient coordinates and considering the function

$$(\hat{\psi}_i, f_i)_{i \in J} : X \rightarrow (\mathbb{R}^{n+1})^{|J|} \simeq \mathbb{R}^{(n+1) \cdot |J|}.$$

This is an immersion. Hence it remains to see that it is also an [embedding of topological spaces](#).

By [this prop](#) it is sufficient to see that the injective continuous function is a [closed map](#). But this follows generally since  $X$  is a [compact topological space](#) by assumption, and since  $Y$  is a [Hausdorff topological space](#) by definition of manifolds, and since [maps from compact spaces to Hausdorff spaces are closed and proper](#). ■

This concludes *Section 1 [Point-set topology](#)*.

For the next section see *[Section 2 -- Basic homotopy theory](#)*.

## 10. References



## General

A canonical compendium is

- [Nicolas Bourbaki](#), chapter 1 *Topological Structures* in *Elements of Mathematics III: General topology*, Springer (1971, 1990)

Introductory textbooks include

- [John Kelley](#) *General Topology*, Graduate Texts in Mathematics, Springer (1955)
- [James Munkres](#), *Topology*, Prentice Hall (1975, 2000)

Lecture notes include

- [Friedhelm Waldhausen](#), *Topologie* ([pdf](#))

See also the references at [algebraic topology](#).

## Special topics

The standard literature typically omits the following important topics:

Discussion of [sober topological spaces](#) is briefly in

- [Peter Johnstone](#), section II 1. of [Stone Spaces](#), Cambridge Studies in Advanced Mathematics **3**, Cambridge University Press 1982. xxi+370 pp. [MR85f:54002](#), reprinted 1986.

An introductory textbook that takes sober spaces, and their relation to logic, as the starting point for topology is

- [Steven Vickers](#), *Topology via Logic*, Cambridge University Press (1989)

Detailed discussion of the [Hausdorff reflection](#) is in

- Bart van Munster, *The Hausdorff quotient*, 2014 ([pdf](#))

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