

# Random Process Background

Young W Lim

Jun 12, 2023

Copyright (c) 2023 - 2018 Young W. Lim. Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.2 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts. A copy of the license is included in the section entitled "GNU Free Documentation License".

This work is licensed under a Creative Commons  
"Attribution-NonCommercial-ShareAlike 3.0 Unported"  
license.



Based on  
Probability, Random Variables and Random Signal Principles,  
P.Z. Peebles, Jr. and B. Shi

# Outline

- 1 Measurable Space
  - Measurable Space
  - Sigma Alebra
  - Topological Space
  - Open Set
  
- 2 Stochastic Process

# Outline

- 1 Measurable Space
  - Measurable Space
  - Sigma Alebra
  - Topological Space
  - Open Set
- 2 Stochastic Process

# Space (1)

- A **space** consists of selected **mathematical objects** that are treated as **points**, and selected **relationships** between these **points**.
  - the nature of the **points** can vary widely:  
for example, the points can be
    - elements of a set
    - functions on another space
    - subspaces of another space
  - It is the **relationships** that define the nature of the space.

[https://en.wikipedia.org/wiki/Space\\_\(mathematics\)](https://en.wikipedia.org/wiki/Space_(mathematics))

## Space (2)

- While modern mathematics uses many types of **spaces**, such as
  - Euclidean spaces
  - linear spaces
  - topological spaces
  - Hilbert spaces
  - probability spaces
- it does not define the notion of **space** itself.

[https://en.wikipedia.org/wiki/Space\\_\(mathematics\)](https://en.wikipedia.org/wiki/Space_(mathematics))

## Space (3)

- a **space** is
  - a **set** (or a **universe**) with some added **structure**
- It is not always clear whether a given **mathematical object** should be considered as a geometric **space**, or an algebraic **structure**
- A general definition of **structure** embraces all common types of **space**

[https://en.wikipedia.org/wiki/Space\\_\(mathematics\)](https://en.wikipedia.org/wiki/Space_(mathematics))

# Mathematical objects (1)

- A **mathematical object** is an **abstract concept** arising in mathematics.
- an **mathematical object** is anything that has been (or could be) **formally defined**, and with which one may do
  - **deductive reasoning**
  - **mathematical proofs**

[https://en.wikipedia.org/wiki/Mathematical\\_object](https://en.wikipedia.org/wiki/Mathematical_object)



## Mathematical objects (2)

- Typically, a **mathematical object**
  - can be a **value** that can be assigned to a **variable**
  - therefore can be involved in **formulas**

[https://en.wikipedia.org/wiki/Mathematical\\_object](https://en.wikipedia.org/wiki/Mathematical_object)

## Mathematical objects (3)

- Commonly encountered **mathematical objects** include
  - numbers
  - sets
  - functions
  - expressions
  - geometric objects
  - transformations of other mathematical objects
  - spaces

[https://en.wikipedia.org/wiki/Mathematical\\_object](https://en.wikipedia.org/wiki/Mathematical_object)

## Mathematical objects (4)

- **Mathematical objects** can be very *complex*;
  - for example, the followings are considered as **mathematical objects** in **proof theory**.
    - theorems
    - proofs
    - theories

[https://en.wikipedia.org/wiki/Mathematical\\_object](https://en.wikipedia.org/wiki/Mathematical_object)

# Structure (1)

- a **structure** is a **set** endowed with some *additional features* on the **set**
  - e.g. an *operation*
  - *relation*
  - *metric*
  - *topology*
- Often, the *additional features* are attached or related to the set, so as to provide it with some *additional meaning* or *significance*.

<https://www.localmaxradio.com/questions/what-is-a-mathematical-space>

## Structure (2)

- A partial list of possible **structures** are
  - measures
  - algebraic structures (groups, fields, etc.)
  - topologies
  - metric structures (geometries)
  - orders
  - events
  - equivalence relations
  - differential structures
  - categories.

<https://www.localmaxradio.com/questions/what-is-a-mathematical-space>

# Mathematical space (1)

- A **mathematical space** is, informally, a **collection** of **mathematical objects** under consideration.
- The **universe** of **mathematical objects** within a **space** are *precisely defined entities* whose **rules** of *interaction* come baked into the **rules** of the **space**.

<https://www.localmaxradio.com/questions/what-is-a-mathematical-space>

## Mathematical space (2)

- A **space** differs from a **mathematical set** in several important ways:
  - A **mathematical set** is also a **collection** of **objects**
  - but these **objects** are being pulled from a **space** (or **universe**) of **objects** where the **rules** and **definitions** have already been agreed upon

<https://www.localmaxradio.com/questions/what-is-a-mathematical-space>

## Mathematical space (3)

- A **space** differs from a **mathematical set** in several important ways:
  - A **mathematical set** has no **internal structure**,
  - whereas a **space** usually has some **internal structure**.

<https://www.localmaxradio.com/questions/what-is-a-mathematical-space>



## Mathematical space (4)

- having some **internal structure** could mean a variety of things, but typically it involves
  - *interactions* and *relationships* between **elements** of the **space**
  - *rules* on how to *create* and *define* **new elements** of the **space**

<https://www.localmaxradio.com/questions/what-is-a-mathematical-space>

# Measurable space (1)

- A **measurable space** is any **space** with a **sigma-algebra** which can then be equipped with a **measure**
  - collection of **subsets** of the **space** following certain **rules** with a way to assign **sizes** to those sets.

<https://www.quora.com/What-is-a-measurable-space-and-probability-space-intuitively-What-differences-do-they-have>

## Measurable space (2)

- Intuitively, certain sets belonging to a **measurable space** can be given a **size** in a *consistent way*.

*consistent way* means that certain **axioms** are met:

- the **empty set** is given a **size** of zero
- if a measurable set is **contained** inside another one, then its **size** is **less than** or **equal to** the size of the **containing set**
- the size of a **disjoint union** of sets is the **sum** of the individual sets' **sizes**

<https://www.quora.com/What-is-a-measurable-space-and-probability-space-intuitively-What-differences-do-they-have>

# Probability space

- A **probability space** is simply a **measurable space** equipped with a **probability measure**.
- A **probability measure** has the special property of giving the entire space a size of **1**.
  - this then implies that the **size** of any disjoint union of sets (the sum of the **sizes** of the sets) in the **probability space** is less than or equal to 1

<https://www.quora.com/What-is-a-measurable-space-and-probability-space-intuitively-What-differences-do-they-have>

# Outline

- 1 Measurable Space
  - Measurable Space
  - **Sigma Alebra**
  - Topological Space
  - Open Set
- 2 Stochastic Process

# Sigma algebra (1)

- We term the **structures** which allow us to use **measure** to be **sigma algebras**
- the only requirements for **sigma algebras** (on a **set**  $X$ ) are:
  - the  $\{\}$  and  $X$  are in the **set**.
  - if  $A$  is in the **set**,  $\text{complement}(A)$  is in the **set**.
  - for any **sets**  $E_i$  in the set,  
 $\bigcup_i E_i$  is in the **set** (for countable  $i$ ).

<https://medium.com/intuition/measure-theory-for-beginners-an-intuitive-approach-f5cea0cc2e7>

## Sigma algebra (2)

- The most intuitive way to think about a **sigma algebra** is that it is the kind of **structure** we can do **probability** on.
  - for example, we can assign ratios of areas and length, so the **measure** on such a **set**  $X$  tells something about the **probability** of its **subsets**.
  - we can find the **probability** of **subsets**  $A$  and  $B$  because we know their ratios with respect to a **set**  $X$  ;
  - we also know that
    - (the measure of) their **complements** are defined, and
    - their **unions** and **intersections** are defined,
    - so we know how to find the **probability** of things in this set  $X$ .

<https://medium.com/intuition/measure-theory-for-beginners-an-intuitive-approach-f5cea0cc2e7>

## Sigma algebra (3)

- The **sigma algebra** which contains the **standard topology** on  $\mathbb{R}$  (that is, *all open sets* on  $\mathbb{R}$ ) is called the **Borel Sigma Algebra**, and the elements of this **set** are called **Borel sets**.
- What this gives us, is the set of **sets** on which outer measure gives our list of dreams. That is, if we take a **Borel set** and we check that length follows translation, additivity, and interval length, it will always hold.

[https://medium.com/intuition/measure-theory-for-beginners-an-intuitive-approach-](https://medium.com/intuition/measure-theory-for-beginners-an-intuitive-approach-f5cea0cc2e7)

f5cea0cc2e7



## Sigma algebra (4)

- The **set** of Lebesgue measurable sets is the **set** of **Borel sets**, along with (union) all the sets which differ from a Borel set by a **set of measure 0**.
- More intuitively, it is all the sets we can normally measure, plus a bunch of stuff that doesn't affect our ideas of area or volume (think about the **border** of the circle above).

<https://medium.com/intuition/measure-theory-for-beginners-an-intuitive-approach-f5cea0cc2e7>

## Borel Sets (1-1)

- a **Borel set** is any **set** in a **topological space** that can be formed from **open sets** (or, equivalently, from **closed sets**) through the operations of
  - countable union,
  - countable intersection, and
  - relative complement.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Borel Sets (1-2)

- For a **topological space  $X$** , the collection of all Borel sets on  $X$  forms a  $\sigma$ -algebra, known as the **Borel algebra** or **Borel  $\sigma$ -algebra**.
- The **Borel algebra on  $X$**  is the smallest  **$\sigma$ -algebra** containing all open sets (or, equivalently, all closed sets).

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Borel Sets (1-3)

- **Borel sets** are important in measure theory, since any measure defined on the open sets of a space, or on the closed sets of a space, must also be defined on all Borel sets of that space.
- Any measure defined on the Borel sets is called a **Borel measure**.
- **Borel sets** and the associated **Borel hierarchy** also play a fundamental role in descriptive set theory.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Borel Sets (2)

- **Borel sets** are those obtained from intervals by means of the operations allowed in a  **$\sigma$ -algebra**. So we may construct them in a (transfinite) "sequence" of steps:
- ... And again and again.

<https://math.stackexchange.com/questions/220248/understanding-borel-sets>

# Borel Sets (3-1)

1. Start with **finite unions** of **closed-open intervals**.  
These sets are completely **elementary**, and they form an **algebra**.
2. **Adjoin countable unions** and **intersections** of elementary sets.  
What you get already includes **open sets** and **closed sets**, **intersections** of an open set and a closed set, and so on.  
Thus you obtain an **algebra**, that is still not a  **$\sigma$ -algebra**.

<https://math.stackexchange.com/questions/220248/understanding-borel-sets>

## Borel Sets (3)

3. Again, **adjoin countable unions** and **intersections** to 2.  
Observe that you get a strictly larger class, since a **countable intersection** of **countable unions** of intervals is not necessarily included in 2.  
Explicit examples of sets in 3 but not in 2 include  $F_\sigma$  sets, like, say, the set of *rational numbers*.
4. And do the same again.

<https://math.stackexchange.com/questions/220248/understanding-borel-sets>

## Borel Sets (4-1)

- And even after a sequence of steps we are not yet finished. Take, say, a countable union of a set constructed at step 1, a set constructed at step 2, and so on. This union may very well not have been constructed at any step yet. By axioms of  $\sigma$ -algebra, you should include it as well - if you want, as step  $\infty$

<https://math.stackexchange.com/questions/220248/understanding-borel-sets>



## Borel Sets (4-2)

- (or, technically, the first infinite ordinal, if you know what that means).
- And then continue in the same way until you reach the first uncountable ordinal. And only then will you finally obtain the generated  $\sigma$ -algebra.

<https://math.stackexchange.com/questions/220248/understanding-borel-sets>

# Outline

- 1 Measurable Space
  - Measurable Space
  - Sigma Alebra
  - **Topological Space**
  - Open Set
- 2 Stochastic Process

# Topology

- **topology**  
from the Greek words  
τόπος, 'place, location',  
and λόγος, 'study'  
is concerned with the **properties** of a **geometric object**
  - that are *preserved* under continuous deformations,  
such as stretching, twisting, crumpling, and bending;
  - that is, without closing holes, opening holes,  
tearing, gluing, or passing through itself.

<https://en.wikipedia.org/wiki/Topology>

# Topological space (1)

- a **topological space** is, roughly speaking, a **geometrical space** in which **closeness** is defined but cannot necessarily be **measured** by a **numeric distance**.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Topological space (2)

- More specifically, a **topological space** is
- a set whose elements are called points,
- along with an additional structure called a topology,
  - which can be defined as
  - a set of neighbourhoods for each point
  - that satisfy some axioms
  - formalizing the concept of closeness.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Topological space (3)

- There are several equivalent **definitions** of a topology, the most commonly used of which is the **definition** through **open sets**, which is easier than the others to manipulate.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Topological space (4)

- A **topological space** is the most general type of a **mathematical space** that allows for the definition of
  - **limits**,
  - **continuity**, and
  - **connectedness**.
- Common types of **topological spaces** include
  - **Euclidean spaces**,
  - **metric spaces** and
  - **manifolds**.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)

## Topological space (5)

- Although very general, the concept of **topological spaces** is fundamental, and used in virtually every branch of modern mathematics.
- The study of **topological spaces** in their own right is called point-set topology or general topology.

[https://en.wikipedia.org/wiki/Borel\\_set](https://en.wikipedia.org/wiki/Borel_set)



# Open set (1)

- an **open set** is a generalization of an **open interval** in the real line.
- a **metric space** is a **set** along with a **distance** defined between any two **points**
- in a **metric space**, an **open set** is a **set** that, along with every **point**  $P$ , contains all **points** that are **sufficiently near** to  $P$ 
  - all **points** whose **distance** to  $P$  is less than some value depending on  $P$

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Open set (2)

- More generally, an **open set** is a **member** of a given **collection** of **subsets** of a given **set**, a **collection** that has the property of **containing**
  - every **union** of its **members**
  - every **finite intersection** of its members
  - the **empty set**
  - the **whole set** itself

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Open set (2)

- A **set** in which such a **collection** is given is called a **topological space**, and the **collection** is called a **topology**.
- These conditions are very loose, and allow enormous flexibility in the choice of **open sets**.
- For example,
  - every **subset** can be **open** (the discrete topology), or
  - no **subset** can be **open** (the indiscrete topology) except
    - the space itself and
    - the empty set .

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Open set (3)

Example:

- The *circle* represents the set of points  $(x, y)$  satisfying  $x^2 + y^2 = r^2$ .
- The *disk* represents the set of points  $(x, y)$  satisfying  $x^2 + y^2 < r^2$ .
- The *circle* set is an **open set**,
- the *disk* set is its **boundary set**, and
- the **union** of the *circle* and *disk* sets is a **closed set**.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Open set (4)

- A **set** is a **collection** of distinct **objects**.
- Given a **set**  $A$ , we say that  $a$  is an **element** of  $A$  if  $a$  is one of the distinct **objects** in  $A$ , and we write  $a \in A$  to denote this
- Given two **sets**  $A$  and  $B$ , we say that  $A$  is a **subset** of  $B$  if every element of  $A$  is also an element of  $B$  write  $A \subseteq B$  to denote this.

<https://ximera.osu.edu/mooculus/calculusE/continuityOfFunctionsOfSeveralVariables/digInOpenAnd>

## Open set (5) Open Balls

- We give these definitions in general, for when one is working in  $\mathbb{R}^n$  since they are really not all that different to define in  $\mathbb{R}^n$  than in  $\mathbb{R}^2$
- An **open ball**  $B_r(\mathbf{a})$  in  $\mathbb{R}^n$  centered at  $\mathbf{a} = (a_1, \dots, a_n) \in \mathbb{R}^n$  with radius  $r$  is the set of all points  $\mathbf{x} = (x_1, \dots, x_n) \in \mathbb{R}^n$  such that the distance between  $\mathbf{x}$  and  $\mathbf{a}$  is less than  $r$
- In  $\mathbb{R}^2$  an **open ball** is often called an **open disk**

<https://ximera.osu.edu/mooculus/calculusE/continuityOfFunctionsOfSeveralVariables/digInOpenAnd>

# Open set (6) Interior points

- Suppose that  $S \subseteq \mathbb{R}^n$ .
- A point  $\mathbf{p} \in S$  is an **interior point** of  $S$  if there exists an **open ball**  $B_r(\mathbf{p}) \subseteq S$ .
- Intuitively,  $\mathbf{p}$  is an **interior point** of  $S$  if we can *squeeze* an entire open ball centered at  $\mathbf{p}$  within  $S$

<https://ximera.osu.edu/mooculus/calculusE/continuityOfFunctionsOfSeveralVariables/digInOpenAnd>

## Open set (7) Boundary points

- A point  $p \in \mathbb{R}^n$  is a **boundary point** of  $S$  if all **open balls** centered at  $p$  contain both **points** in  $S$  and **points** not in  $S$ .
- The **boundary** of  $S$  is the **set**  $\partial S$  that consists of all of the **boundary points** of  $S$ .

<https://ximera.osu.edu/mooculus/calculusE/continuityOfFunctionsOfSeveralVariables/digInOpenAnd>



## Open set (8) Open and Closed Sets

- A set  $O \subseteq \mathbb{R}^n$  is **open**  
if every point in  $O$  is an **interior point**.
- A set  $C \subseteq \mathbb{R}^n$  is **closed**  
if it contains all of its **boundary points**.

<https://ximera.osu.edu/mooculus/calculusE/continuityOfFunctionsOfSeveralVariables/digInOpenAnd>

## Open set (8) Bounded and Unbounded

- A set  $S$  is **bounded** if there is an **open ball**  $B_M(0)$  such that

$$S \subseteq B.$$

- intuitively, this means that we can enclose all of the **set**  $S$  within a large enough ball centered at the origin.
- A **set** that is not **bounded** is called **unbounded**

<https://ximera.osu.edu/mooculus/calculusE/continuityOfFunctionsOfSeveralVariables/digInOpenAnd>

# Outline

- 1 Measurable Space
  - Measurable Space
  - Sigma Alebra
  - Topological Space
  - Open Set
- 2 Stochastic Process

# Topologically distinguishable points (1)

- Intuitively, an **open set** provides a *method* to *distinguish* two **points**.
- two **points** in a **topological space**, there exists an **open set**
  - containing one point but
  - not containing the other (distinct) point
  - the two points are topologically distinguishable.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Topologically distinguishable points (2)

- In this manner, one may speak of whether two **points**, or more generally two **subsets**, of a **topological space** are "**near**" without concretely defining a **distance**.
- Therefore, **topological spaces** may be seen as a generalization of **spaces** equipped with a notion of **distance**, which are called **metric spaces**.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Topologically distinguishable points (3)

- In the set of all real numbers, one has the natural **Euclidean metric**; that is, a function which *measures* the **distance** between two real numbers:  $d(x, y) = |x - y|$ .
- Therefore, given a real number  $x$ , one can speak of the **set** of all **points** close to that real number  $x$ ; that is, within  $\varepsilon$  of  $x$ .
- In essence, **points** within  $\varepsilon$  of  $x$  approximate  $x$  to an **accuracy** of **degree**  $\varepsilon$ .
- Note that  $\varepsilon > 0$  always, but as  $\varepsilon$  becomes *smaller* and *smaller*, one obtains **points** that approximate  $x$  to a *higher* and *higher* **degree** of **accuracy**.

# Topologically distinguishable points (4)

- For example, if  $x = 0$  and  $\varepsilon = 1$ ,  
the **points** within  $\varepsilon$  of  $x$  are precisely  
the **points** of the interval  $(-1, 1)$ ; that is,  
the **set** of all real numbers between  $-1$  and  $1$ .
- However, with  $\varepsilon = 0.5$ ,  
the **points** within  $\varepsilon$  of  $x$  are precisely  
the **points** of  $(-0.5, 0.5)$ .
- Clearly, these **points** approximate  $x$   
to a *greater* **degree** of **accuracy** than when  $\varepsilon = 1$ .

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

# Topologically distinguishable points (5)

- The previous discussion shows, for the case  $x = 0$ , that one may approximate  $x$  to *higher* and *higher* degrees of accuracy by defining  $\varepsilon$  to be *smaller* and *smaller*.
- In particular, sets of the form  $(-\varepsilon, \varepsilon)$  give us a lot of information about points close to  $x = 0$ .
- Thus, rather than speaking of a concrete Euclidean metric, one may use sets to describe points close to  $x$ .

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)



# Topologically distinguishable points (6)

- This innovative idea has far-reaching consequences; in particular, by defining different collections of sets containing 0 (distinct from the sets  $(-\varepsilon, \varepsilon)$ ), one may find different results regarding the distance between 0 and other real numbers.
- For example, if we were to define  $R$  as the only such set for "measuring distance", all points are close to 0 since there is only one possible degree of accuracy one may achieve in approximating 0: being a member of  $R$ .

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Topologically distinguishable points (7)

- Thus, we find that in some sense, every real number is **distance** 0 away from 0.
- It may help in this case to think of the **measure** as being a **binary condition**:  
all things in  $R$  are equally close to 0,  
while any item that is not in  $R$  is not close to 0.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

# Topologically distinguishable points (8)

- In general, one refers to the family of **sets** containing 0, used to approximate 0, as a **neighborhood basis**; a member of this **neighborhood basis** is referred to as an **open set**.
- In fact, one may generalize these notions to an arbitrary set ( $X$ ); rather than just the **real numbers**.
- In this case, given a **point** ( $x$ ) of that **set**, one may define a **collection** of **sets** "**around**" (that is, containing)  $x$ , used to approximate  $x$ .

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

# Topologically distinguishable points (9)

- Of course, this **collection** would have to satisfy certain properties (known as **axioms**) for otherwise we may not have a *well-defined method* to measure distance.
- For example, every **point** in  $X$  should approximate  $x$  to some **degree** of **accuracy**.
- Thus  $X$  should be in this **family**.
- Once we begin to define "smaller" **sets** containing  $x$ , we tend to approximate  $x$  to a greater **degree** of **accuracy**.
- Bearing this in mind, one may define the remaining **axioms** that the **family** of **sets** about  $x$  is required to satisfy.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

# Definitions (1) Euclidean space

- A **subset**  $U$  of the **Euclidean n-space**  $\mathbb{R}^n$  is **open** if, for every **point**  $x$  in  $U$ , there exists a positive **real number**  $\varepsilon$  (depending on  $x$ ) such that any **point** in  $\mathbb{R}^n$  whose **Euclidean distance** from  $x$  is smaller than  $\varepsilon$  belongs to  $U$
- Equivalently, a **subset**  $U$  of  $\mathbb{R}^n$  is **open** if every **point** in  $U$  is the **center** of an **open ball** contained in  $U$
- An example of a **subset** of  $\mathbb{R}$  that is not **open** is the **closed interval**  $[0, 1]$ , since neither  $0 - \varepsilon$  nor  $1 + \varepsilon$  belongs to  $[0, 1]$  for any  $\varepsilon > 0$ , no matter how small.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Definitions (2) Metric space

- A **subset**  $U$  of a **metric space**  $(M, d)$  is called **open** if, for any **point**  $x$  in  $U$ , there exists a **real number**  $\varepsilon > 0$  such that any **point**  $y \in M$  satisfying  $d(x, y) < \varepsilon$  belongs to  $U$ .
- Equivalently,  $U$  is **open** if every **point** in  $U$  has a **neighborhood** contained in  $U$ .
- This generalizes the **Euclidean space** example, since **Euclidean space** with the **Euclidean distance** is a **metric space**.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)

## Definitions (3) Topological space

- A **topology**  $\tau$  on a **set**  $X$  is a **set** of **subsets** of  $X$  with the *properties* below. Each **member** of  $\tau$  is called an **open set**. [3]
  - $X \in \tau$  and  $\emptyset \in \tau$
  - Any **union** of sets in  $\tau$  belong to  $\tau$  : if  $\{U_i : i \in I\} \subseteq \tau$  then

$$\bigcup_{i \in I} U_i \in \tau$$

- Any finite **intersection** of sets in  $\tau$  belong to  $\tau$  : if  $U_1, \dots, U_n \in \tau$  then

$$U_1 \cap \dots \cap U_n \in \tau$$

- $X$  together with  $\tau$  is called a **topological space**.

## Definitions (4) Topological space

- Infinite intersections of open sets need not be open.
- For example, the intersection of all intervals of the form  $(-1/n, 1/n)$ , where  $n$  is a positive integer, is the set  $\{0\}$  which is not open in the real line.
- A metric space is a topological space, whose topology consists of the collection of all subsets that are unions of open balls.
- There are, however, topological spaces that are not metric spaces.

[https://en.wikipedia.org/wiki/Open\\_set](https://en.wikipedia.org/wiki/Open_set)



# Topological space via neighborhoods (1)

- This axiomatization is due to Felix Hausdorff.
- Let  $X$  be a set;
- the elements of  $X$  are usually called points, though they can be any mathematical object.
- We allow  $X$  to be empty.
- Let  $\mathcal{N}$  be a function assigning to each  $x$  (point) in  $X$  a non-empty collection  $\mathcal{N}(x)$  of subsets of  $X$ .
- The elements of  $\mathcal{N}(x)$  will be called neighbourhoods of  $x$  with respect to  $\mathcal{N}$  (or, simply, neighbourhoods of  $x$ ).
- The function  $\mathcal{N}$  is called a neighbourhood topology if the axioms below[8] are satisfied; and
- then  $X$  with  $\mathcal{N}$  is called a topological space.

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

# Topological space via neighborhoods (2)

- If  $N$  is a neighbourhood of  $x$  (i.e.,  $N \in \mathcal{N}(x)$ ), then  $x \in N$ .  
In other words, each point belongs to every one of its neighbourhoods.
- If  $N$  is a subset of  $X$  and includes a neighbourhood of  $x$ , then  $N$  is a neighbourhood of  $x$ . I.e., every superset of a neighbourhood of a point  $x \in X$  is again a neighbourhood of  $x$ .
- The intersection of two neighbourhoods of  $x$  is a neighbourhood of  $x$ .
- Any neighbourhood  $\mathcal{N}$  of  $x$  includes a neighbourhood  $\mathcal{M}$  of  $x$  such that  $\mathcal{M}$  is a neighbourhood of each point of  $M$ .

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

# Topological space via neighborhoods (3)

- The first three axioms for neighbourhoods have a clear meaning.
- The fourth axiom has a very important use in the structure of the theory, that of linking together the neighbourhoods of different points of  $X$ .
- A standard example of such a system of neighbourhoods is for the real line  $\mathbb{R}$ , where a subset  $N$  of  $\mathbb{R}$  is defined to be a neighbourhood of a real number  $x$  if it includes an open interval containing  $x$ .

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

# Topological space via open sets (1)

- A **topology** on a set  $X$  may be defined as a **collection**  $\tau$  of **subsets** of  $X$ , called **open sets** and satisfying the following **axioms**:
  - The **empty set** and  $X$  itself belong to  $\tau$ .
  - Any arbitrary (**finite** or **infinite**) **union** of members of  $\tau$  belongs to  $\tau$ .
  - The **intersection** of any **finite** number of members of  $\tau$  belongs to  $\tau$ .

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

## Topological space via open sets (2)

- As this definition of a topology is the most commonly used, the set  $\tau$  of the **open sets** is commonly called a **topology** on  $X$ .
- A **subset**  $C \subseteq X$  is said to be **closed** in  $(X, \tau)$  if its complement  $X \setminus C$  is an **open set**.

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

# Topological space via neighborhoods (4)

- Given such a **structure**, a **subset**  $U$  of  $X$  is defined to be **open** if  $U$  is a **neighbourhood** of all **points** in  $U$ .
- The **open sets** then satisfy the **axioms** given below.
- Conversely, when given the **open sets** of a **topological space**, the **neighbourhoods** satisfying the above **axioms** can be recovered by defining  $N$  to be a **neighbourhood** of  $x$  if  $N$  includes an open set  $U$  such that  $x \in U$ .

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

# Examples of topology (1)

- Given  $X = \{1, 2, 3, 4\}$ ,  
the trivial or indiscrete topology on  $X$  is  
the family  $\tau = \{\{\}, \{1, 2, 3, 4\}\} = \{\emptyset, X\}$   
consisting of only the two subsets of  $X$   
required by the axioms  
forms a topology of  $X$ .
- Given  $X = \{1, 2, 3, 4\}$ ,  
the family  $\tau = \{\{\}, \{2\}, \{1, 2\}, \{2, 3\}, \{1, 2, 3\}, \{1, 2, 3, 4\}\}$   
 $= \{\emptyset, \{2\}, \{1, 2\}, \{2, 3\}, \{1, 2, 3\}, X\}$   
of six subsets of  $X$  forms another topology of  $X$ .

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

## Examples of topology (2)

- Let  $\tau$  be denoted with the circles, here are four examples and two non-examples of topologies on the three-point set  $\{1,2,3\}$ .
- The bottom-left example is not a topology because the union of  $\{2\}$  and  $\{3\}$  [i.e.  $\{2,3\}$ ] is missing;
- the bottom-right example is not a topology because the intersection of  $\{1,2\}$  and  $\{2,3\}$  [i.e.  $\{2\}$ ], is missing.

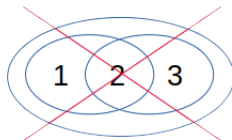
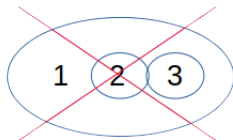
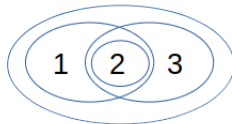
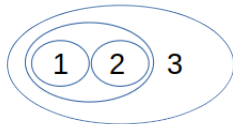
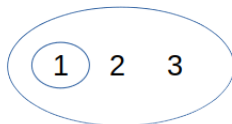
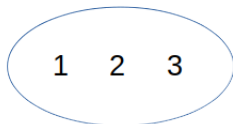
[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)



## Examples of topology (3)

- Given  $X = \{1, 2, 3, 4\}$ ,  
the discrete topology on  $X$  is  
the power set of  $X$ , which is the family  $\tau = \mathcal{P}(X)$   
consisting of all possible subsets of  $X$ .  
In this case the topological space  $(X, \tau)$   
is called a discrete space.
- Given  $X = \mathbb{Z}$ , the set of integers,  
the family  $\tau$  of all finite subsets  
of the integers plus  $\mathbb{Z}$  itself  
is not a topology,  
because (for example) the union of all finite sets  
not containing zero is not finite  
but is also not all of  $\mathbb{Z}$ , and so it cannot be in  $\tau$ .

## Examples of topology (3)



# Open)

- (Open and Closed Sets)

[https://en.wikipedia.org/wiki/Topological\\_space](https://en.wikipedia.org/wiki/Topological_space)

# Stochastic Process (1)

In probability theory and related fields, a **stochastic** (/stou'kæstɪk/) or **random** process is a mathematical object usually defined as a family of **random variables**.

The word stochastic in English was originally used as an adjective with the definition "pertaining to **conjecturing**", and stemming from a Greek word meaning "to aim at a mark, guess", and the Oxford English Dictionary gives the year 1662 as its earliest occurrence.

From Ancient Greek στοχαστικός (stokhastikós), from στοχάζομαι (stokhá-zomai, "aim at a target, guess"), from στόχος (stókchos, "an aim, a guess").

<https://en.wikipedia.org/wiki/Stochastic>  
<https://en.wiktionary.org/wiki/stochastic>

## Stochastic Process (2)

The definition of a **stochastic process** varies, but a **stochastic process** is *traditionally* defined as a collection of **random variables** indexed by some set.

The terms **random process** and **stochastic process** are considered synonyms and are used interchangeably, without the **index set** being precisely specified.

Both "**collection**", or "**family**" are used while instead of "**index set**", sometimes the terms "**parameter set**" or "**parameter space**" are used.

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Stochastic Process (3)

The term **random function** is also used to refer to a **stochastic** or **random process**, though sometimes it is only used when the stochastic process takes real values.

This term is also used when the **index sets** are **mathematical spaces** other than the **real line**,

while the terms **stochastic process** and **random process** are usually used when the **index set** is interpreted as time,

and other terms are used such as **random field** when the **index set** is  $n$ -dimensional **Euclidean space**  $\mathbb{R}^n$  or a manifold

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Stochastic Process (4)

A **stochastic process** can be denoted, by  $\{X(t)\}_{t \in T}$ ,  $\{X_t\}_{t \in T}$ ,  $\{X(t)\}$ ,  $\{X_t\}$  or simply as  $X$  or  $X(t)$ , although  $X(t)$  is regarded as an abuse of function notation.

For example,  $X(t)$  or  $X_t$  are used to refer to the **random variable** with the **index**  $t$ , and not the entire **stochastic process**.

If the **index set** is  $T = [0, \infty)$ , then one can write, for example,  $(X_t, t \geq 0)$  to denote the **stochastic process**.

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

# Stochastic Process Definition (1)

A **stochastic process** is defined as a collection of **random variables** defined on a common **probability space**  $(\Omega, \mathcal{F}, P)$ ,

- $\Omega$  is a **sample space**,
- $\mathcal{F}$  is a  $\sigma$ -**algebra**,
- $P$  is a **probability measure**;
- the **random variables**, indexed by some set  $T$ ,
- all take values in the same **mathematical space**  $S$ , which must be **measurable** with respect to some  $\sigma$ -algebra  $\Sigma$

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)



## Stochastic Process Definition (2)

In other words, for a given **probability space**  $(\Omega, \mathcal{F}, P)$  and a **measurable space**  $(S, \Sigma)$ , a **stochastic process** is a **collection** of  $S$ -valued **random variables**, which can be written as:

$$\{X(t) : t \in T\}.$$

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Stochastic Process Definition (3)

Historically, in many problems from the natural sciences a point  $t \in T$  had the meaning of time, so  $X(t)$  is a **random variable** representing a value observed at time  $t$ .

A **stochastic process** can also be written as  $\{X(t, \omega) : t \in T\}$  to reflect that it is actually a function of two variables,  $t \in T$  and  $\omega \in \Omega$ .

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Stochastic Process Definition (4)

There are other ways to consider a stochastic process, with the above definition being considered the traditional one.

For example, a stochastic process can be interpreted or defined as a  $S^T$ -valued **random variable**, where  $S^T$  is the space of all the possible functions from the set  $T$  into the space  $S$ .

However this alternative definition as a "**function-valued random variable**" in general requires additional regularity assumptions to be **well-defined**.

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Index set (1)

The set  $T$  is called the **index set** or **parameter set** of the **stochastic process**.

Often this set is some subset of the real line, such as the natural numbers or an interval, giving the set  $T$  the interpretation of time.

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Index set (2)

In addition to these sets, the index set  $T$  can be another set with a **total order** or a more general set, such as the Cartesian plane  $R^2$  or  $n$ -dimensional **Euclidean space**, where an element  $t \in T$  can represent a point in space.

That said, many results and theorems are only possible for **stochastic processes** with a **totally ordered index set**.

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

# State space

The **mathematical space**  $S$  of a **stochastic process** is called its **state space**.

This mathematical space can be defined using integers, real lines,  $n$ -dimensional Euclidean spaces, complex planes, or more abstract mathematical spaces.

The **state space** is defined using elements that reflect the different values that the **stochastic process** can take.

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

# Sample function (1)

A **sample function** is a single outcome of a **stochastic process**, so it is formed by taking a single possible value of each **random variable** of the **stochastic process**.

More precisely, if  $\{X(t, \omega) : t \in T\}$  is a **stochastic process**, then for any point  $\omega \in \Omega$ , the mapping  $X(\cdot, \omega) : T \rightarrow S$ , is called a **sample function**, a **realization**, or, particularly when  $T$  is interpreted as time, a **sample path** of the **stochastic process**  $\{X(t, \omega) : t \in T\}$ .

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)

## Sample function (2)

This means that for a fixed  $\omega \in \Omega$  ,  
there exists a **sample function**  
that maps the **index set**  $T$  to the **state space**  $S$ .

Other names for a **sample function** of a **stochastic process**  
include **trajectory**, **path function** or **path**

[https://en.wikipedia.org/wiki/Stochastic\\_process](https://en.wikipedia.org/wiki/Stochastic_process)



