

## Lecture 1: Probabilistic Model

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EE210: Probability and Introductory Random Processes  
KAIST EE

MONTH DAY, 2021

- Probabilistic Model
- Sample Space, Event, Probability Law
- Probability Axioms

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## What Do We Want?

**Modeling:** Approximate reality with a simple (mathematical) model

- Experiment
  - Flip two coins
- Observation: a random outcome
  - for example,  $(H, H)$
- All outcomes
  - $\{(H, H), (H, T), (T, H), (T, T)\}$

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- **Our goal:** Build up a **probabilistic model** for an experiment with random outcomes
  - **Probabilistic model?**
    - Assign a number to each outcome or a set of outcomes
    - Mathematical description of an uncertain situation
  - Which model is good or bad?

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## Probabilistic Model

**Goal:** Build up a probabilistic model. Hmm... How?The first thing: What are the *elements* of a probabilistic model?

## Elements of Probabilistic Model

1. All outcomes of my interest: **Sample Space  $\Omega$**
2. Assigned numbers to each outcome of  $\Omega$ : **Probability Law  $\mathbb{P}(\cdot)$**

**Question:** What are the conditions of  $\Omega$  and  $\mathbb{P}(\cdot)$  under which their induced probability model becomes "legitimate"?

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## 1. Sample Space $\Omega$

The set of all outcomes of my interest

1. Mutually exclusive
2. Collectively exhaustive
3. At the right granularity (not too concrete, not too abstract)

1. Toss a coin. What about this?  
 $\Omega = \{H, T, HT\}$
2. Toss a coin. What about this?  $\Omega = \{H\}$
3. (a) Just figuring out prob. of H or T.  
 $\Rightarrow \Omega = \{H, T\}$   
  
 (b) The impact of the weather (rain or no rain) on the coin's behavior.  
  
 $\Rightarrow \Omega = \{(H, R), (T, R), (H, NR), (T, NR)\}$

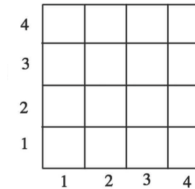
where R(Rain), NR(No Rain).

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## Examples: Sample Space $\Omega$

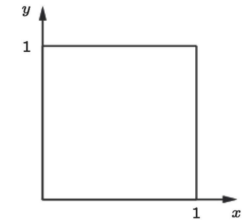
- *Discrete case*: Two rolls of a tetrahedral die

$$\Omega = \{(1, 1), (1, 2), \dots, (4, 4)\}$$



- *Continuous case*: Dropping a needle in a plain

$$\Omega = \{(x, y) \in \mathbb{R}^2 \mid 0 \leq x, y \leq 1\}$$



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## 2. Probability Law

### How should we construct $\mathbb{P}(\cdot)$ ?

- Assign numbers to what? Each outcome?
- What is the probability of dropping a needle at (0.5, 0.5) over the  $1 \times 1$  plane?
- Assign numbers to each subset of  $\Omega$
- A subset of  $\Omega$ : an event
- $\mathbb{P}(A)$ : Probability of an event  $A$ .
  - This is where probability meets set theory.
- Roll a dice. What is the probability of odd numbers?  
 $\mathbb{P}(\{1, 3, 5\})$ , where  $\{1, 3, 5\} \subset \Omega$  is an event.

- Need to construct  $\mathbb{P}(\cdot)$  that naturally satisfies the intention of a probability theory designer just like you. What about the followings as starting points?
  - $\mathbb{P}(A) \geq 0$  for any event  $A \subset \Omega$
  - $\mathbb{P}(A \cup B) = \mathbb{P}(A) + \mathbb{P}(B) - \mathbb{P}(A \cap B)$
  - $\mathbb{P}(A \cup B) \leq \mathbb{P}(A) + \mathbb{P}(B)$
  - For two disjoint events  $A$  and  $B$ ,  $\mathbb{P}(A \cup B) = \mathbb{P}(A) + \mathbb{P}(B)$
  - $\mathbb{P}(\Omega) = 1$  (Why not  $\mathbb{P}(\Omega) = 10$ ?)
  - $\mathbb{P}(\emptyset) = 0$
  - If  $A \subset B$ ,  $\mathbb{P}(A) \leq \mathbb{P}(B)$
  - many others

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- Surprisingly, we need just the following three rules (called axioms):

#### Probability Axioms: Version 1

A1. **Nonnegativity:**  $\mathbb{P}(A) \geq 0$  for any event  $A \subset \Omega$

A2. **Normalization:**  $\mathbb{P}(\Omega) = 1$

A3. **(Finite) additivity:** For two disjoint events  $A$  and  $B$ ,  $\mathbb{P}(A \cup B) = \mathbb{P}(A) + \mathbb{P}(B)$

- No other things are necessary, and we can prove all other things from the above axioms.
- Note that coming up with the above axioms is far from trivial.

Prove the following properties using the axioms:

- For any event  $A$ ,  $\mathbb{P}(A) \leq 1$

$$1 \stackrel{A2}{=} \mathbb{P}(\Omega) = \mathbb{P}(A \cup A^c) \stackrel{A3}{=} \mathbb{P}(A) + \mathbb{P}(A^c) \implies \mathbb{P}(A) = 1 - \mathbb{P}(A^c) \stackrel{A1}{\leq} 1$$

- $\mathbb{P}(\emptyset) = 0$

$$\mathbb{P}(\Omega \cup \emptyset) \stackrel{A3}{=} \mathbb{P}(\Omega) + \mathbb{P}(\emptyset) \stackrel{A2}{=} 1 + \mathbb{P}(\emptyset) \stackrel{\text{from 1.}}{\implies} \mathbb{P}(\emptyset) = 0$$

- If  $A \subset B$ ,  $\mathbb{P}(A) \leq \mathbb{P}(B)$

$$\mathbb{P}(B) \stackrel{A3}{=} \mathbb{P}(A) + \mathbb{P}(B \setminus A) \stackrel{A1}{\geq} \mathbb{P}(A)$$

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- Specify the sample space
- Specify a probability law  
- from my earlier belief, from data, from expert's opinion
- Identify an event of interest
- Calculate

Toss a (biased) coin

- $\Omega = \{H, T\}$
- $\mathbb{P}(\{H\}) = 1/4$ ,  $\mathbb{P}(\{T\}) = 3/4$ ,
- probability of head or tail
- 1/4, 3/4

- $\Omega = \{1, 2, 3, \dots\}$ ,  $\mathbb{P}(\{n\}) = \frac{1}{2^n}$ ,  $n = 1, 2, \dots$

- $\mathbb{P}(\text{even})$ ?

$$\begin{aligned} \mathbb{P}(\text{even}) &= \mathbb{P}(\{2, 4, 6, \dots\}) \\ &= \frac{1}{2^2} + \frac{1}{2^4} + \frac{1}{2^6} + \dots = 1/3 \end{aligned}$$

- Is the above right? If not, why?

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## Probability Axioms: Version 1.2

A1. Nonnegativity:  $\mathbb{P}(A) \geq 0$  for any event  $A \subset \Omega$

A2. Normalization:  $\mathbb{P}(\Omega) = 1$

A3. (Finite) additivity: For two disjoint events  $A$  and  $B$ ,  $\mathbb{P}(A \cup B) = \mathbb{P}(A) + \mathbb{P}(B)$

A4. Countable additivity: If  $A_1, A_2, A_3, \dots$  is an infinite sequence of disjoint events, then  $\mathbb{P}(A_1 \cup A_2 \cup \dots) = \mathbb{P}(A_1) + \mathbb{P}(A_2) + \dots$ .

- A narrow view: A branch of math
  - axioms  $\rightarrow$  theorems
- Frequencies:  $\mathbb{P}(H) = 1/2$
- Beliefs:  $\mathbb{P}(\text{He is reelected}) = 0.7$ 
  - Subjective, but providing numerical guidance

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## Questions?

Congratulations! You build up the very basics of a probabilistic model.

What else do we need to build up?

- 1) Please explain what a probabilistic model is and why we need it.
- 2) What is the mathematical definition of event?
- 3) What are the key elements of the probabilistic model?
- 4) Please list up the probability axioms and explain them.
- 5) Why do we need countable additivity in the probability axiom?

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