

# Lecture 1: Probabilistic Model

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## Roadmap

- (1) Probabilistic Model
  - Mathematical description of uncertain situations
- (2) Sample Space, Event, Probability Law
  - Elements of probability theory
- (3) Probability Axioms
  - 3 axioms for the completeness of a theory

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- (1) Probabilistic Model
- (2) Sample Space, Event, Probability Law
- (3) Probability Axioms

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## What Do We Want?

**Modeling:** Understand 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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**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) Probabilistic Model
- (2) Sample Space, Event, Probability Law
- (3) Probability Axioms

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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.  
  
 $\Rightarrow \Omega = \{(H, R), (T, R), (H, NR), (T, NR)\},$   
  
R(Rain), NR(No Rain).

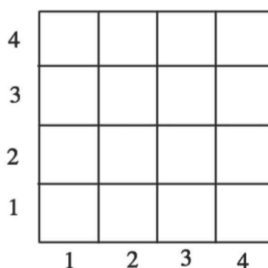
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## Examples: Sample Space $\Omega$

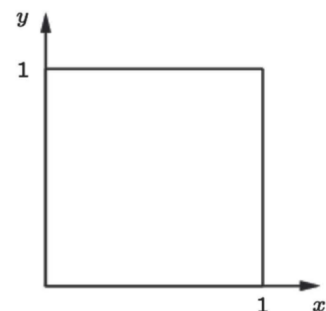
- *Discrete case:* Two rolls of a tetrahedral die

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



- *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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- 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.

- (1) Probabilistic Model
- (2) Sample Space, Event, Probability Law
- (3) **Probability Axioms**

- 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<sup>1</sup> 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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<sup>1</sup>Their intersection is empty.

- 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.

A1: Nonnegativity, A2: Normalization, A3: Finite additivity

Prove the following properties using the axioms:

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

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

2.  $\mathbb{P}(\emptyset) = 0$

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

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

Toss a (biased) coin

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

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- $\Omega = \{1, 2, 3, \dots\}$ ,  $\mathbb{P}(\{n\}) = \frac{1}{2^n}$ ,  $n = 1, 2, \dots$
- Is the above probability law legitimate? seems OK

$$\mathbb{P}(\Omega) = \frac{1}{2} + \frac{1}{2^2} + \dots = \frac{1/2}{1 - 1/2} = 1$$

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

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

- Is the above right? If not, why?
  - Wrong: Finite additivity axiom does not allow this.

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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  $\mathbb{P}(A_1 \cup A_2 \cup \dots) = \mathbb{P}(A_1) + \mathbb{P}(A_2) + \dots$ .

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- A narrow view: A branch of math
  - axioms  $\rightarrow$  theorems
  - Mathematicians work very hard to find the smallest set of necessary axioms (just like atoms in physics)
- Frequencies:  $\mathbb{P}(H) = 1/2$ 
  - Understanding an uncertain situation: fractions of successes out of many experiments
- Beliefs:  $\mathbb{P}(\text{He is reelected}) = 0.7$

Anyway, we believe that probabilistic reasoning is very helpful to understand the world with many uncertain situations.

## Questions?

You build up the very basics of a probabilistic model.

What else do we need to build up?

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## Review Questions

- 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 axioms?

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