CSE 312

Foundations of Computing II

Lecture 4: Intro to Discrete Probability

Announcement

- PSet 1 due tonight
- PSet 2 posted this evening, due next Wednesday
- The in-lecture chats, so far, had few questions. We still have it today, but if it remains sparse, we will roll it out
- Interest form for forming study groups. Please fill in the form by the end of Sunday. We will help form the groups.

Before probability a quick wrap-up for counting…

Summary of Counting: Tools and concepts

- Sum rule, Product rule
- Permutations, combinations
- Inclusion-exclusion
- Binary encoding/stars and bars
- Pigeonhole principle
- Combinatorial proofs
- Binomial Theorem

Before you attempt the homework.
Make sure to understand examples on lecture slides and sections.

Agenda

- Events
- Probability
- Equally Likely Outcomes
- Probability Axioms and Beyond Equally Likely Outcomes
- Another Example

Probability

- We want to model a process that is not deterministic.
  - i.e., outcome not determined a-priori
  - E.g. throwing dice, flipping a coin…
  - We want to numerically measure likelihood of outcomes = probability.
  - We want to make complex statements about these likelihoods.
- We will not argue why a certain physical process realizes the probabilistic model we study
  - Why is the outcome of the coin flip really "random"?
- First part of class: "Discrete" probability theory
  - Experiment with finite / discrete set of outcomes.
  - Will explore countably infinite and continuous outcomes later

Sample Space

Definition. A **sample space** Ω is the set of all possible outcomes of an experiment.

Examples:

- Single coin flip: $\Omega = \{H, T\}$
- Two coin flips: $\Omega = \{HH, HT, TH, TT\}$
- Roll of a die: $\Omega = \{1, 2, 3, 4, 5, 6\}$

Events

Definition. An **event** $E \subseteq \Omega$ is a subset of possible outcomes.

Examples:

- Getting at least one head in two coin flips: $E = \{HH, HT, TH\}$
- Rolling an even number on a die : $E = \{2, 4, 6\}$

Definition. Events E and F are **mutually exclusive** if $E \cap F = \emptyset$
(i.e., E and F can't happen at same time)

Example:

- For dice rolls: If $E = \{2, 4, 6\}$ and $F = \{1, 5\}$, then $E \cap F = \emptyset$

Example: 4-sided Dice

Suppose I roll blue and red 4-sided dice. Let D1 be the value of the blue die and D2 be the value of the red die. To the right is the sample space (possible outcomes).

What outcomes match these events?

A. D1 = 1

B. D1 + D2 = 6

C. D1 = 2 * D2

Die 2 (D2)

Die 1 (D1)

	1	2	3	4
1	(1, 1)	(1, 2)	(1, 3)	(1, 4)
2	(2, 1)	(2, 2)	(2, 3)	(2, 4)
3	(3, 1)	(3, 2)	(3, 3)	(3, 4)
4	(4, 1)	(4, 2)	(4, 3)	(4, 4)

Example: 4-sided Dice

Suppose I roll blue and red 4-sided dice. Let D1 be the value of the blue die and D2 be the value of the red die. To the right is the sample space (possible outcomes).

What outcomes match these events?

A. D1 = 1

$$A = \{(1,1), (1,2), (1,3), (1,4)\}$$

B. D1 + D2 = 6

$$B = \{(2,4), (3,3), (4,2)\}$$

C. D1 = 2 * D2

$$C = \{(2,1), (4,2)\}$$

Die 2 (D2), Die 1 (D1)

	1	2	3	4
1	(1, 1)	(1, 2)	(1, 3)	(1, 4)
2	(2, 1)	(2, 2)	(2, 3)	(2, 4)
3	(3, 1)	(3, 2)	(3, 3)	(3, 4)
4	(4, 1)	(4, 2)	(4, 3)	(4, 4)

Example: 4-sided Dice, Mutual Exclusivity

Are A and B mutually exclusive?
How about B and C?
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	A & B	B & C
(a)	Yes	Yes
(b)	Yes	No
(c)	No	Yes
(d)	No	No

A. D1 = 1

$$A = \{(1,1), (1,2), (1,3), (1,4)\}$$

B. D1 + D2 = 6

$$B = \{(2,4), (3,3), (4,2)\}$$

C. D1 = 2 * D2

$$C = \{(2,1), (4,2)\}$$

Die 2 (D2)

Die 1 (D1)

	1	2	3	4
1	(1, 1)	(1, 2)	(1, 3)	(1, 4)
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- Probability Axioms and Beyond Equally Likely Outcomes
- More Examples

Idea: Probability

A **probability** is a number (between 0 and 1) describing how likely a particular outcome will happen.

Most written formal CS, math, or stats uses $\mathbb{P}$ or $\Pr$ but for slides we mostly use just P because it is easiest to read

Will define a function

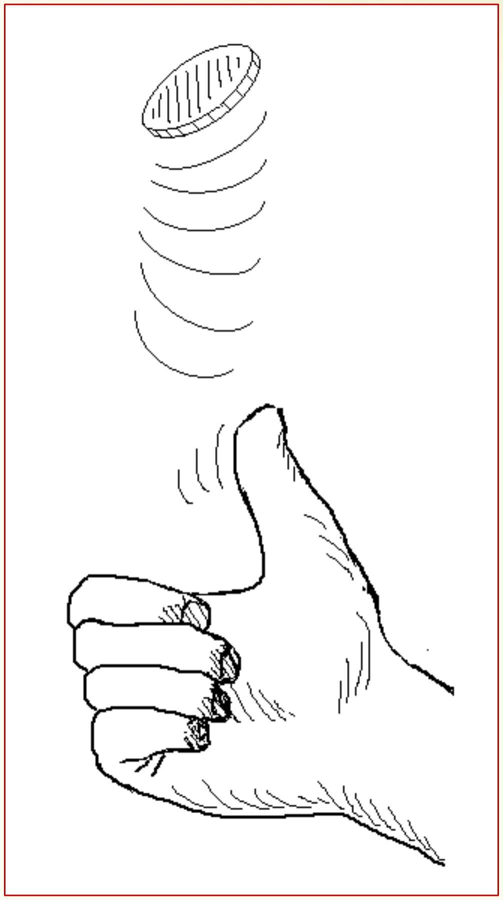
$$\mathbb{P} : \Omega \to [0,1]$$

that maps outcomes $\omega \in \Omega$ to probabilities $\mathbb{P}(\omega)$.

– Alternative notations: $\mathbb{P}(\omega) = P(\omega) = \Pr(\omega)$

Example – Coin Tossing

Imagine we toss one coin – outcome can be **heads** or **tails.**



$$\Omega = \{\mathrm{H}, \mathrm{T}\}$$

P**?** Depends! What do we want to model?!

Fair coin toss

$$P(\mathrm{H}) = P(\mathrm{T}) = \frac{1}{2} = 0.5$$

Example – Coin Tossing

Imagine we toss one coin – outcome can be **heads** or **tails.**

$$\Omega = \{\mathrm{H}, \mathrm{T}\}$$

P? Depends! What do we want to model?!

Bent coin toss (e.g., biased or unfair coin)

$$P(\mathrm{H}) = 0.85, \qquad P(\mathrm{T}) = 0.15$$

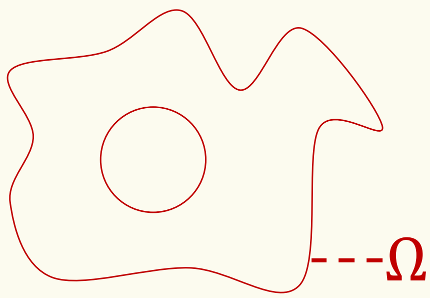
Probability space

Either finite or infinite countable (e.g., integers)

Definition. A (discrete) **probability space** is a pair (Ω, P) where:

- Ω is a set called the **sample space.**
- P is the **probability measure,** a function $P: \Omega \rightarrow [0,1]$ such that:
  - $P(x) \geq 0$ for all $x \in \Omega$
  - $\sum_{x \in \Omega} P(x) = 1$

Set of possible **elementary outcomes**



Specify Likelihood (or probability) of each **elementary outcome**

Some outcome must show up. Normalize the total probability to 1.

The likelihood (or probability) of each outcome is non-negative.

Uniform Probability Space

Definition. A **uniform probability space** is a pair (Ω, P) such that

$$P(x) = \frac{1}{|\Omega|}$$

for all $x \in \Omega$.

$\forall x, y \in \Omega$

$P(x) = P(y) = p^*$

$\sum_{x \in \Omega} P(x) = 1$

$= |\Omega| \cdot p^* = 1$

$p^* = \frac{1}{|\Omega|}$

Examples:

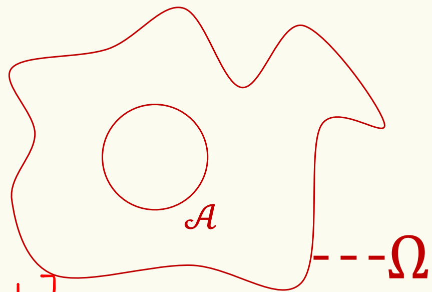
- Fair coin $P(x) = \frac{1}{2}$
- Fair 6-sided die $P(x) = \frac{1}{6}$

Events

Definition. An **event** in a probability space (Ω, P) is a subset $\mathcal{A} \subseteq \Omega$. Its probability is

$$P(\mathcal{A}) = \sum_{\omega \in \mathcal{A}} P(\omega)$$

$P: \Omega \to [0,1]$



Abuse of notation: When the event $\mathcal{A}$ is a set $\{\omega\}$ with just one outcome ω we write

$P(\omega)$ instead of $P(\{\omega\})$

But that is OK, because they are equal by definition.

Agenda

- Events
- Probability
- **Equally Likely Outcomes** ◀
- Probability Axioms and Beyond Equally Likely Outcomes
- More Examples

Example: 4-sided Dice, Event Probability

Think back to 4-sided die. Suppose each die is fair.

What is the probability of event B? $P(B) = ???$

B. D1 + D2 = 6

$B = \{(2,4), (3,3)(4,2)\}$

Die 2 (D2)

Die 1 (D1)

	1	2	3	4
1	(1, 1)	(1, 2)	(1, 3)	(1, 4)
2	(2, 1)	(2, 2)	(2, 3)	(2, 4)
3	(3, 1)	(3, 2)	(3, 3)	(3, 4)
4	(4, 1)	(4, 2)	(4, 3)	(4, 4)

$\frac{3}{16}$

Equally Likely Outcomes

If (Ω, P) is a **uniform** probability space, then for any event $E \subseteq \Omega$,

$$P(E) = \frac{|E|}{|\Omega|}$$

$$P(E) = \sum_{x \in E} P(x) = \sum_{x \in E} \frac{1}{|\Omega|} = \frac{|E|}{|\Omega|}$$

This follows from the definitions of the probability of an event and uniform probability spaces.

Example – Coin Tossing

Toss a coin 100 times. Each outcome is **equally likely** (and assume the outcome of one toss does not impact another).

What is the probability of seeing 50 heads?

(a) $\frac{1}{2}$ ~20

(b) $\frac{1}{2^{50}}$ 20

(c) $\frac{\binom{100}{50}}{2^{100}}$ 760

(d) Not sure

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$$\frac{|E|}{|\Omega|} = \frac{\binom{100}{50}}{2^{100}}$$

$\Omega = \{$100-length sequence from alphabet $\{H, T\}\}$

2^{100}

Brain Break

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- More Examples

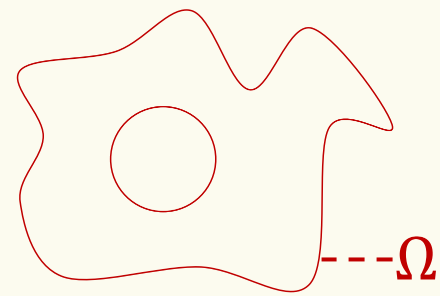
Review Probability space

Definition. A (discrete) **probability space** is a pair (Ω, P) where:

- Ω is a set called the **sample space.**
- P is the **probability measure,** a function $P: \Omega \rightarrow \mathbb{R}$ such that:
  - $P(x) \geq 0$ for all $x \in \Omega$
  - $\sum_{x \in \Omega} P(x) = 1$

Either finite or infinite countable (e.g., integers)

Set of possible **elementary outcomes**

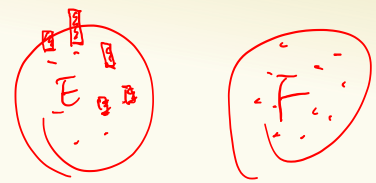


Specify Likelihood (or probability) of each **elementary outcome**

Some outcome must show up. Normalize the total probability to 1.

The likelihood (or probability) of each outcome is non-negative.

Axioms of Probability



Let (Ω, P) be a probability space. Then, the following properties hold for any events $E, F \subseteq \Omega$.

> Called "axioms" because all properties of P follow from them!

Axiom 1 (Non-negativity): $P(E) \geq 0$.
Axiom 2 (Normalization): $P(\Omega) = 1$.
Axiom 3 (Countable Additivity): If E and F are mutually exclusive, then $P(E \cup F) = P(E) + P(F)$ → sum rule

$|E^c| = |\Omega| - |E|$

Corollary 1 (Complementation): $P(E^c) = 1 - P(E)$.
Corollary 2 (Monotonicity): If $E \subseteq F$, $P(E) \leq P(F)$.
Corollary 3 (Inclusion-Exclusion): $P(E \cup F) = P(E) + P(F) - P(E \cap F)$.

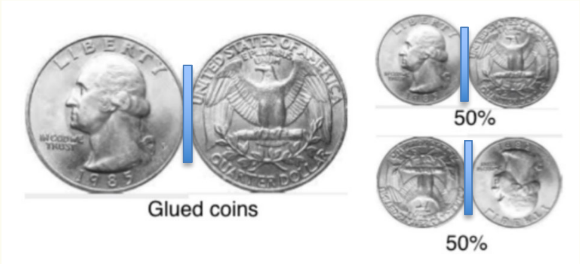
Non-equally Likely Outcomes

Many probability spaces can have **non-equally likely outcomes**.

Biased coin

$P(H) = p$
$P(T) = 1 - p$

Glued coins

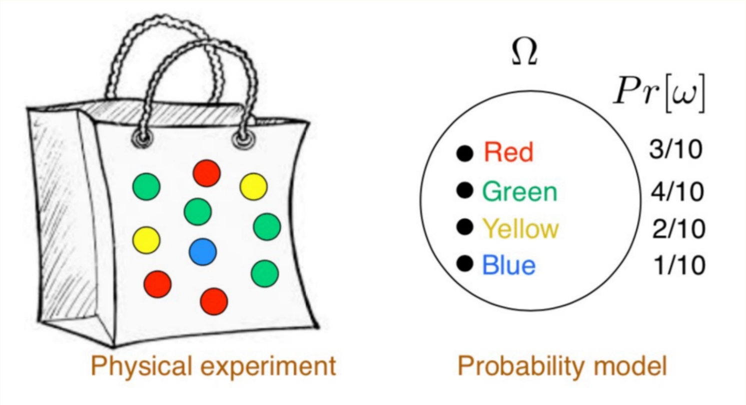


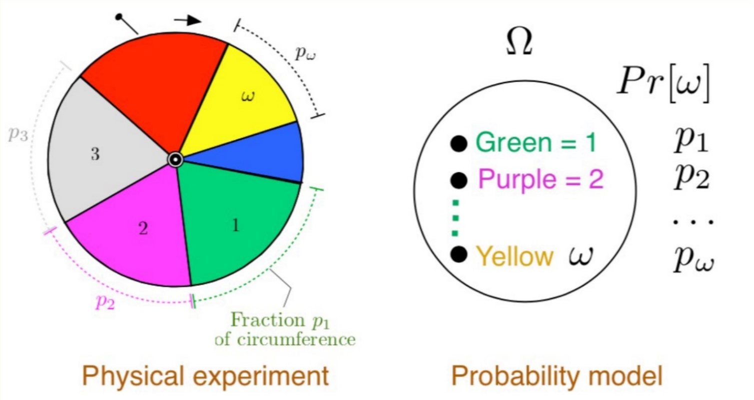
$P(HT) = P(TH) = 0.5$
$P(HH) = P(TT) = 0$

Attached coins

$P(HH) = P(TT) = 0.4$
$P(HT) = P(TH) = 0.1$

More Examples of Non-equally Likely Outcomes





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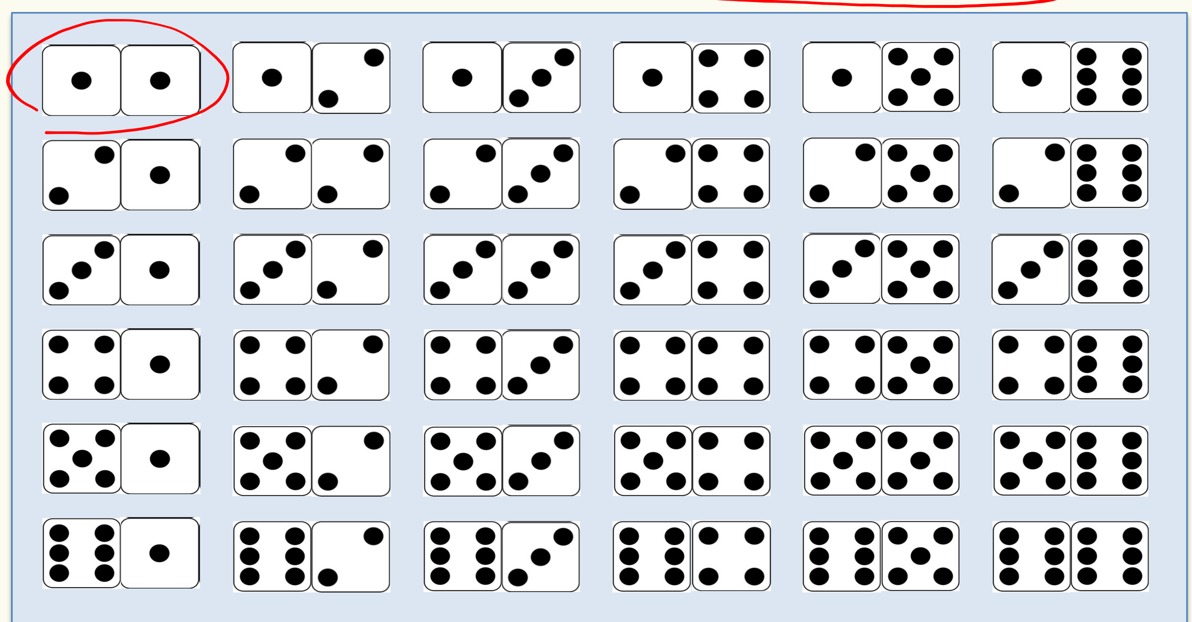
- Probability Axioms and Beyond Equally Likely Outcomes
- **Another Example (Equally Likely)** ◀

Example: Dice Rolls

$\frac{1}{36}$

Suppose I had two, fair, 6-sided dice that we roll once each. What is the probability that we see *at least one 3 in the two rolls*?



Example: Dice Rolls

Suppose I had two, fair, 6-sided dice that we roll once each.
What is the probability that we see *at least one 3 in the two rolls*?

Event has
$6 + 6 - 1 = 11$
outcomes

$|\Omega| = 36$

$P(\geq \text{one } 3) = \frac{11}{36}$