



Computer
Science

CSC196: Analyzing Data

Probability

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Outline

- Random Events
- Counting Sample Points
- Random Events and Probability
- Conditional Probability & Independent Events

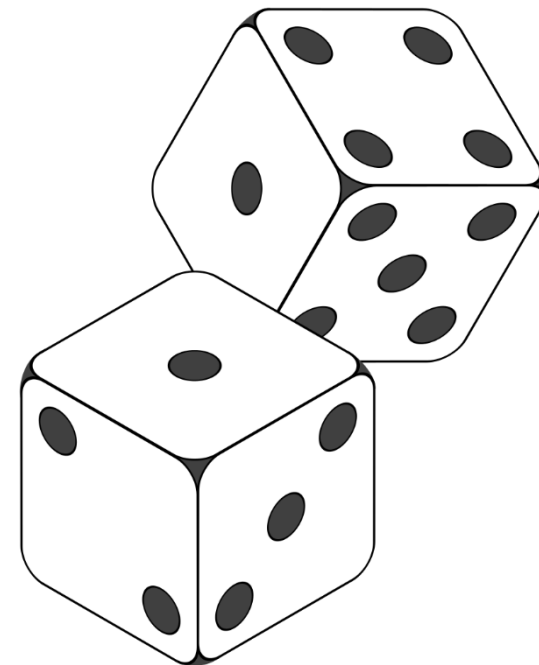
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Random Events and Probability

Suppose we roll two fair dice...

- What are the possible outcomes?
- What is the *probability* of rolling **even** numbers?
- What is the *probability* of rolling **odd** numbers?
- If one die rolls 1, then what is the probability of the second die also rolling 1?
- How to mathematically formulate outcomes and their probabilities?



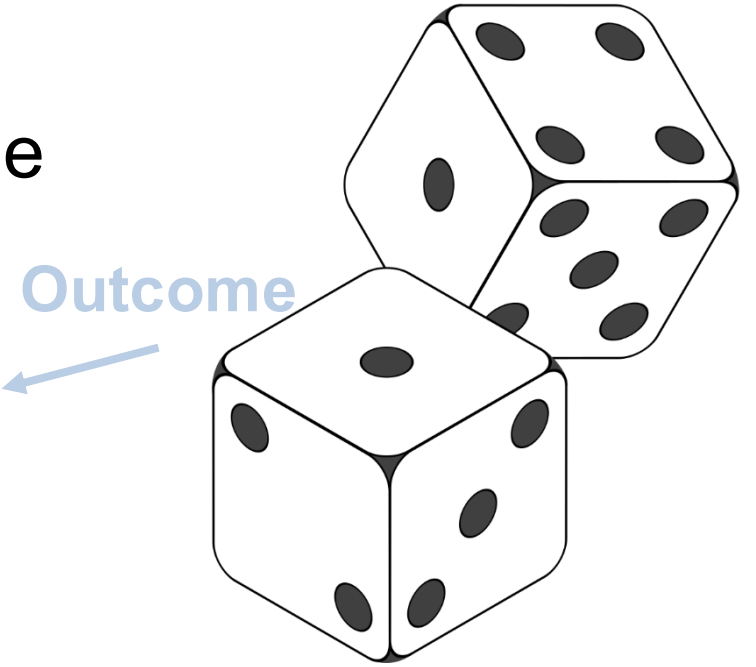
...this is an **experiment** or **random process**.

Random Events and Probability

Definition An **outcome** is a possible result of an experiment or trial, and the collection of all possible outcomes is the **sample space** of the experiment,

Example $(1,1), (1,2), \dots, (6,1), (6,2), \dots, (6,6)$

Sample Space



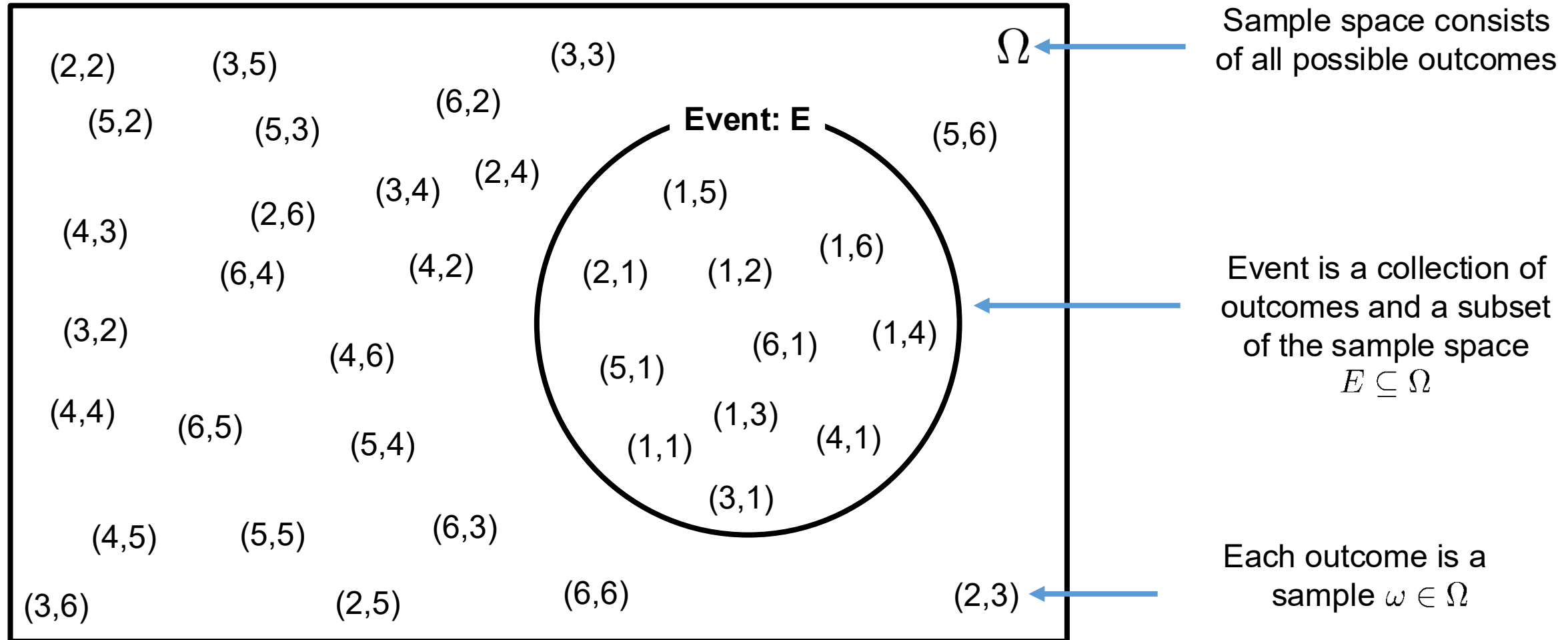
Definition An **event** is a *set* of outcomes (a subset of the sample space),

Example Event Roll at least a single 1

$\{(1,1), (1,2), (1,3), \dots, (1,6), \dots, (6,1)\}$

Random Events and Probability

Can formulate / visualize as a space of outcomes and events



Random Events and Probability

Some examples of events...

- Roll even numbers,

$$E^{\text{even}} = \{(2, 2), (2, 4), \dots, (6, 4), (6, 6)\}$$

- The sum of both dice is even,

$$E^{\text{sum even}} = \{(1, 1), (1, 3), (1, 5), \dots, (2, 2), (2, 4), \dots\}$$

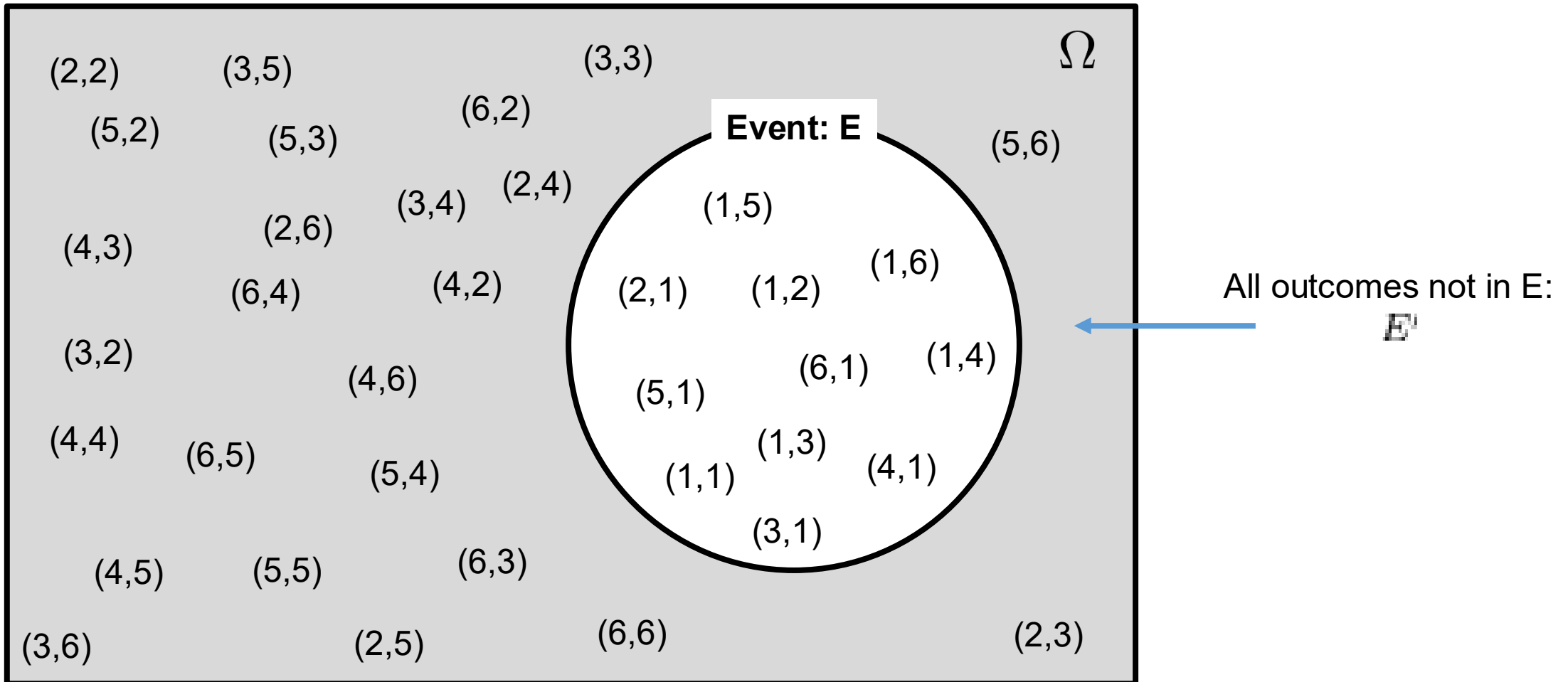
- The sum is greater than 12,

$$E^{\text{sum} > 12} = \emptyset$$

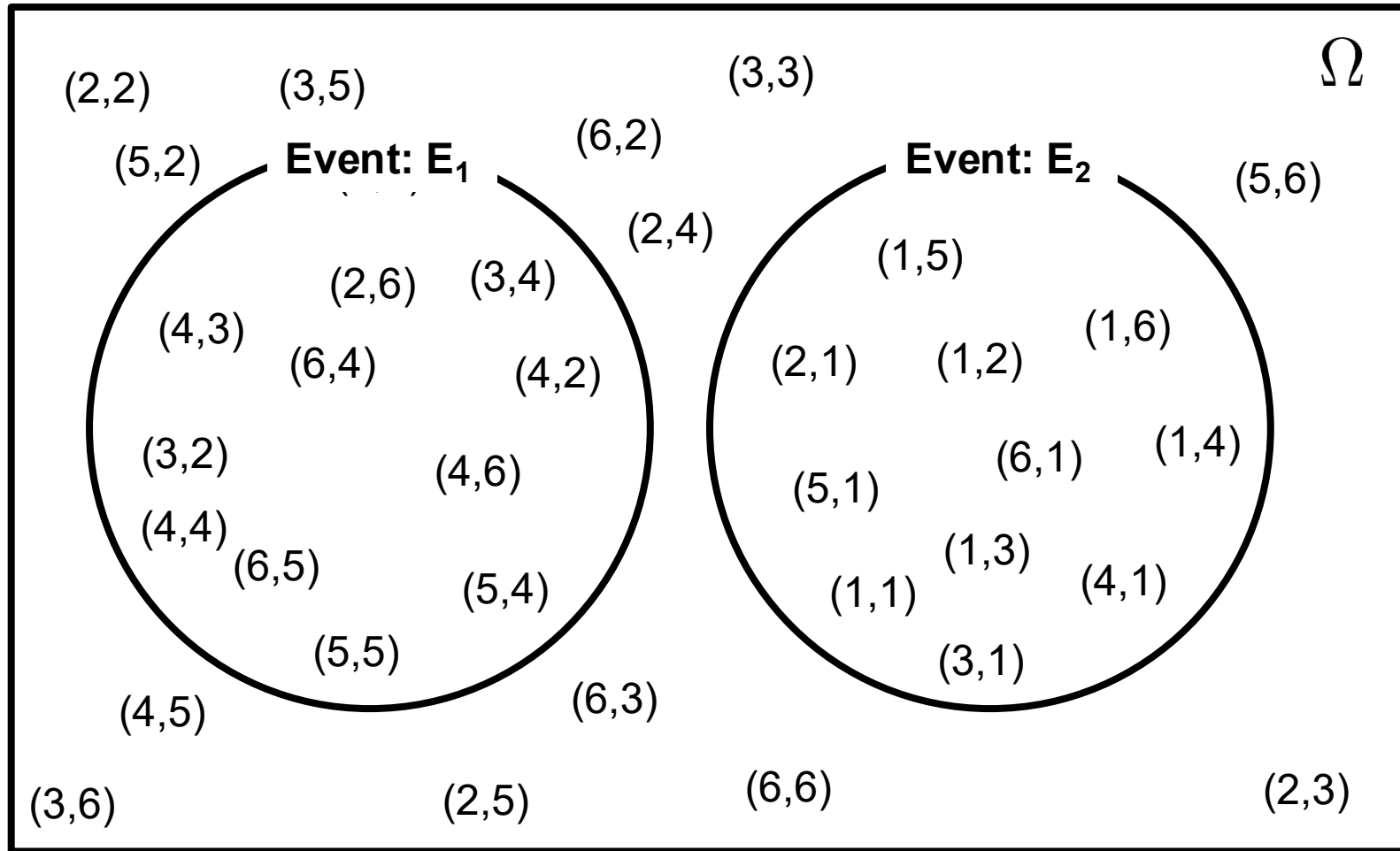
We can reason about impossible outcomes

Random Events and Probability

Definition The **complement** of an event E , denoted E' , is the subset of all elements of Ω that are not in E .



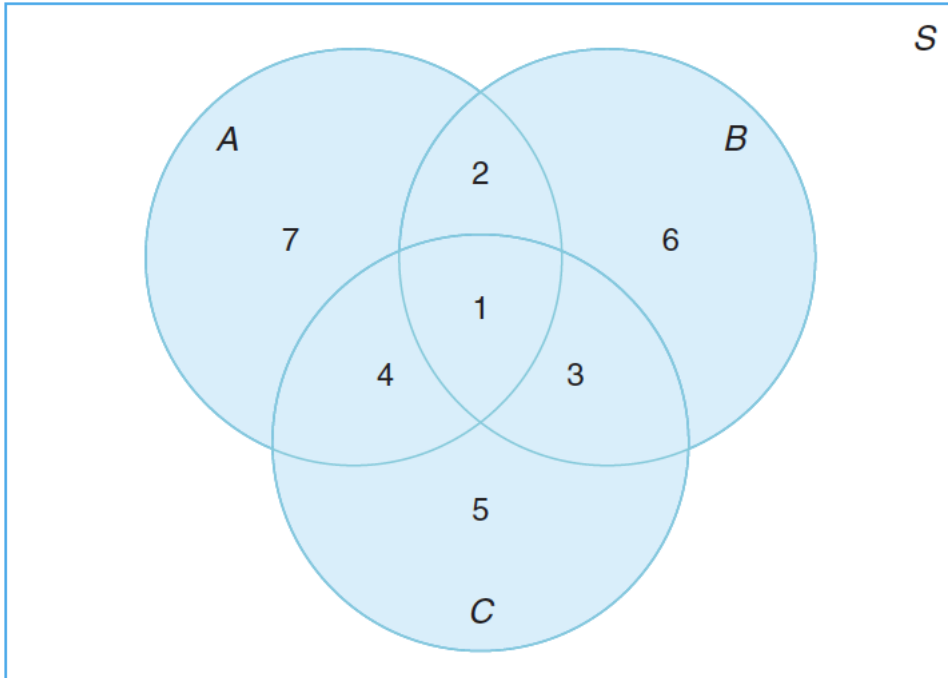
Random Events and Probability



Definition Two events E_1 and E_2 are called **mutually exclusive** if their intersection is the empty set:

$$E_1 \cap E_2 = \emptyset$$

Random Events and Probability



$A \cup C =$ regions 1, 2, 3, 4, 5, and 7,

$B' \cap A =$ regions 4 and 7,

$A \cap B \cap C =$ region 1,

$(A \cup B) \cap C' =$ regions 2, 6, and 7,

Random Events and Probability

Two dice example: If $E_1, E_2 \in \mathcal{F}$ where,

E_1 : First die equals 1

E_2 : Second die equals 1

$$E_1 = \{(1, 1), (1, 2), \dots, (1, 6)\}$$

$$E_2 = \{(1, 1), (2, 1), \dots, (6, 1)\}$$

Then we must include (at least) the following events...

Operation	Value	Interpretation
$E_1 \cup E_2$	$\{(1, 1), (1, 2), \dots, (1, 6), (2, 1), \dots, (6, 1)\}$	Any die rolls 1
$E_1 \cap E_2$	$\{(1, 1)\}$	Both dice roll 1
$E_1 - E_2$	$\{(1, 2), (1, 3), (1, 4), (1, 5), (1, 6)\}$	First die rolls 1 only
$(E_1 \cup E_2)'$	$\{(2, 2), (2, 3), \dots, (2, 6), (3, 2), \dots, (6, 6)\}$	No die rolls 1

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Counting Sample Points

Multiplication Rule If an operation can be performed n_1 ways, and if for each of these ways a second operation can be performed n_2 ways, then the two operations can be performed together in $n_1 n_2$ ways.

Example How many sample points are there in the sample space when a pair of dice is thrown once?

Solution First die can land face-up in $n_1=6$ ways. For each way, the second die can land face-up $n_2=6$ ways. So, the pair of dice can land in:

$$n_1 n_2 = (6)(6) = 36 \quad \text{possible ways.}$$

Counting Sample Points

We can extend this to more operations...

If the first operation can be performed in n_1 ways, and the second operation in n_2 ways, and the third operation for n_3 ways, and so on for k operations, then the sequence can be performed in:

$$n_1 n_2 n_3 \dots n_k \quad \text{ways}$$

Counting Sample Points

Example 2.16: Sam is going to assemble a computer by himself. He has the choice of chips from two brands, a hard drive from four, memory from three, and an accessory bundle from five local stores. How many different ways can Sam order the parts?

Solution: Since $n_1 = 2$, $n_2 = 4$, $n_3 = 3$, and $n_4 = 5$, there are

$$n_1 \times n_2 \times n_3 \times n_4 = 2 \times 4 \times 3 \times 5 = 120$$

different ways to order the parts.



Counting Sample Points

Definition A **permutation** is an arrangement of all or part of a set of objects.

Example Consider letters a, b, and c. How many possible permutations are there for the arrangement of these 3 letters?

$$n_1 n_2 n_3 = (3)(2)(1) = 6 \text{ ways}$$

Counting Sample Points

Example In general, n distinct objects can be arranged in:

$$n(n-1)(n-2)\dots(3)(2)(1) \text{ ways.}$$

There is a notation for such a number.

Definition For any nonnegative integer n , $n!$ called “ n factorial,” is defined as:

$$n! = n(n-1)(n-2)\dots(3)(2)(1)$$

with special case $0!=1$

Counting Sample Points

Theorem The number of permutations of n objects is $n!$.

Example The number of the four letters a, b, c , and d will be:

$$4! = (4)(3)(2)(1) = 24.$$

Example Consider the number of permutations by taking only 2 of these 4 letters. These would be:

$ab, ac, ad, ba, bc, bd, ca, cb, cd, da, db$, and dc

There are: $n_1 n_2 = (4)(3) = 12$ possible permutations.

Counting Sample Points

In general, n distinct objects taken r at a time can be arranged in

$n(n-1)(n-2)\dots(n-r+1)$ ways.

Theorem The number of permutations of n distinct objects taken r at a time is,

$${}_nP_r = \frac{n!}{(n-r)!}$$

Counting Sample Points

Example How many different ways can three awards (research, teaching, service) be given to a class of 25 graduate students where each student can receive at most one award?

$${}_{25}P_3 = \frac{25!}{22!} = (25)(24)(23) = 13,800$$

Counting Sample Points

Theorem 2.4: The number of distinct permutations of n things of which n_1 are of one kind, n_2 of a second kind, \dots , n_k of a k th kind is

$$\frac{n!}{n_1!n_2!\cdots n_k!}.$$

Example 2.20: In a college football training session, the defensive coordinator needs to have 10 players standing in a row. Among these 10 players, there are 1 freshman, 2 sophomores, 4 juniors, and 3 seniors. How many different ways can they be arranged in a row if only their class level will be distinguished?

Solution: Directly using Theorem 2.4, we find that the total number of arrangements is

$$\frac{10!}{1! 2! 4! 3!} = 12,600.$$



Counting Sample Points

We are often interested in selecting r objects from n *without regard to order*. We call such selections **combinations**.

Theorem The number of combinations of n distinct objects taken r at a time is,

$$\binom{n}{r} = \frac{n!}{r!(n-r)!}$$

Counting Sample Points

Example How many pairs of letters can we make from the letters a, b, c, and d?

$$\binom{4}{2} = \frac{4!}{2!(4-2)!} = 6$$

ab, ac, ad, bc, bd, cd

Note that we do not consider order so “ab” and “ba” are the same element.

Python Example: Permutations

Example Suppose a bin contains 50 balls, each numbered 1, 2, 3, ..., 50. Suppose we draw 5 balls at random in sequence. How many unique sequences of 5 balls can occur?

$${}_{50}P_5 = \frac{50!}{45!} = (50)(49)(48)(47)(46) = 254,251,200$$

```
import numpy as np
from scipy.special import perm

N = 50
k = 5
p = perm(N, k, exact=True)
print(f"There are {p} permutations.")
```

There are 254251200 permutations.

Python Example: Combinations

Example Suppose a bin contains 50 balls, each numbered 1, 2, 3, ..., 50. Suppose we draw 5 balls at random. Ignoring ordering, how many unique combinations of 5 balls can occur?

$$\binom{50}{5} = \frac{50!}{5!(50-5)!} = 2,118,760$$

```
import numpy as np
from scipy.special import comb

N = 50
r = 5
c = comb(N, r, exact=True)
print(f"There are {c} combinations.")
```

There are 2118760 combinations.

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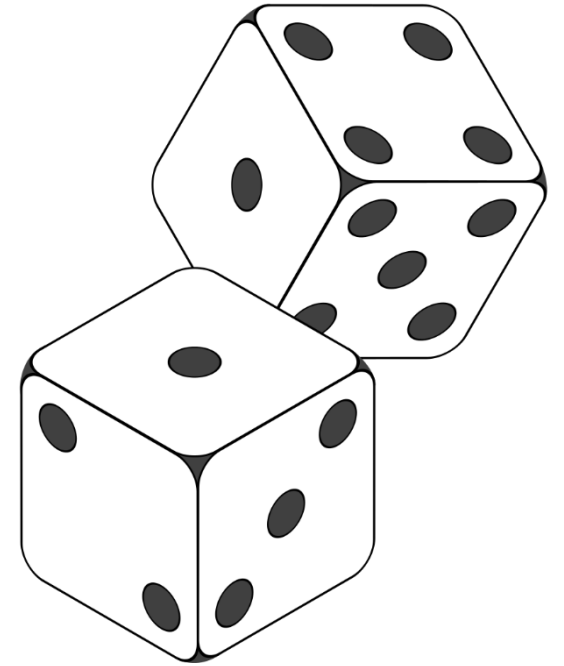
Random Events and Probability

Assume each outcome is equally likely, and sample space is finite, then the probability of event is:

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

Number of outcomes in event set

Number of possible outcomes in sample space



This is the **uniform probability distribution**

Example Probability that we roll *only* even numbers,

$$E^{\text{even}} = \{(2, 2), (2, 4), \dots, (6, 4), (6, 6)\}$$

$$P(E^{\text{even}}) = \frac{|E^{\text{even}}|}{|\Omega|} = \frac{9}{36}$$

Random Events and Probability

Example Probability that the *sum of both dice* is even,

$$E^{\text{sum even}} = \{(1, 1), (1, 3), (1, 5), \dots, (2, 2), (2, 4), \dots\}$$

$$P(E^{\text{sum even}}) = \frac{|E^{\text{sum even}}|}{|\Omega|} = \frac{18}{36} = \frac{1}{2}$$

Example Probability that the *sum of both dice* is greater than 12,

$$E^{>12} = \emptyset$$

$$P(E^{>12}) = \frac{|E^{>12}|}{|\Omega|} = 0$$

i.e. we can reason about the probability of impossible outcomes

Random Events and Probability

To measure the *probability* of an event...

- Function $P(E)$ maps events to probabilities in interval $[0,1]$
- $P(E)$ known as a **probability distribution**
- Follows the **axioms of probability**,
 1. For any event E , $0 \leq P(E) \leq 1$
 2. $P(\Omega) = 1$ and $P(\emptyset) = 0$
 3. For any *finite* or *countably infinite* sequence of pairwise mutually disjoint events E_1, E_2, E_3, \dots

$$P\left(\bigcup_{i \geq 1} E_i\right) = \sum_{i \geq 1} P(E_i)$$

How likely is it that two people share the same birthday here?



The probability of random events is not always intuitive.

Birthday Paradox

Assumptions

- 30 people in the room (there are more)
- Birthday uniformly distributed over 365 days (this is a simplification but easy)
- Ignore leap year effects

Number of ways to choose 30 different days from 365 is,

$$\binom{365}{30} \quad \text{where} \quad \binom{N}{k} = \frac{N!}{k! \cdot (N - k)!}$$

Binomial
coefficient

Let E' be event **no two people** share a birthday—number of ways is,

$$|E'| = 365 P_{30}$$

Birthday Paradox

Total number of possible combinations of birthdays among 30 people,

$$|\Omega| = 365^{30}$$

Probability of having **no two matching birthdays**,

$$P(E') = \frac{|E'|}{|\Omega|} = \frac{365 P_{30}}{365^{30}} = 0.294$$

Let E be the event that at least two people share a birthday,

$$P(E) = 1 - P(E') = 0.706$$

With the 58 people registered
 $P(E) = 0.992$

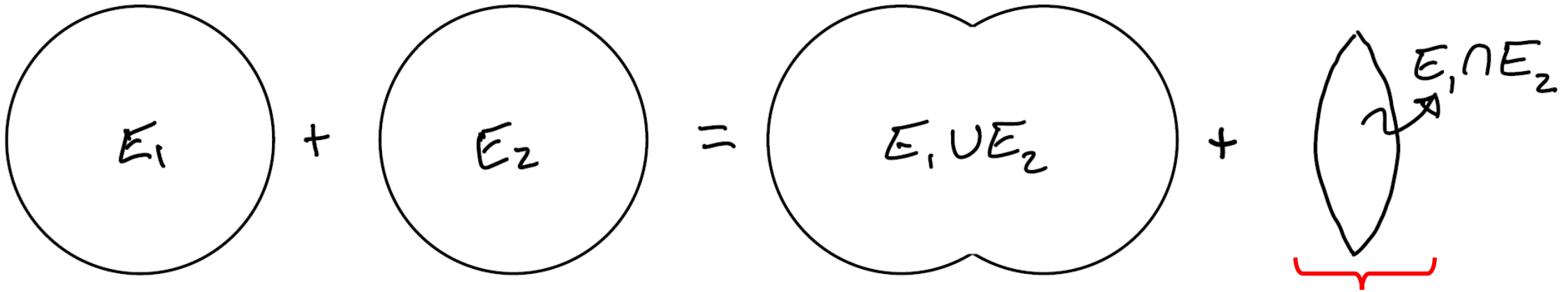
With only 30 people there is over 70% chance of shared birthdays

Random Events and Probability

Lemma: For any two events E_1 and E_2 ,

$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2)$$

Graphical Proof:



Subtract from both sides

Random Events and Probability

Lemma: For any two events E_1 and E_2 ,

$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2)$$

Proof:

$$P(E_1) = P(E_1 - (E_1 \cap E_2)) + P(E_1 \cap E_2)$$

$$P(E_2) = P(E_2 - (E_1 \cap E_2)) + P(E_1 \cap E_2)$$

$$P(E_1 \cup E_2) = P(E_1 - (E_1 \cap E_2)) + P(E_2 - (E_1 \cap E_2)) + P(E_1 \cap E_2)$$

Random Events and Probability

Theorem 2.8:

For three events A , B , and C ,

$$\begin{aligned} P(A \cup B \cup C) = & P(A) + P(B) + P(C) \\ & - P(A \cap B) - P(A \cap C) - P(B \cap C) + P(A \cap B \cap C). \end{aligned}$$

Corollary 2.2:

If A_1, A_2, \dots, A_n are mutually exclusive, then

$$P(A_1 \cup A_2 \cup \dots \cup A_n) = P(A_1) + P(A_2) + \dots + P(A_n).$$

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Conditional Probability

The probability of an event B occurring when it is known that some event A has occurred is called the **conditional probability** and is denoted,

$$P(B \mid A) = \frac{P(A \cap B)}{P(A)}$$

Usually read as “the probability of B, given A”.

Conditional Probability

Example Two dice are rolled, and the sum is equal to 6. What is the probability that the first die is 3?

Let S be the event that the sum is 6. We have,

$$|S| = |\{5,1\},\{1,5\},\{4,2\},\{2,4\},\{3,3\}| = 5$$

Let E be the event that the first die is a 3, then:

$$P(E \mid S) = \frac{P(E \cap S)}{P(S)} = \frac{1}{5}$$

Fundamental Rules of Probability

Given two random events A and B the **conditional distribution** is:

$$P(B \mid A) = \frac{P(A \cap B)}{P(A)}$$

1.13 Example. A medical test for a disease D has outcomes $+$ and $-$. The probabilities are:

	D	D^c
$+$.009	.099
$-$.001	.891

From the definition of conditional probability,

$$p(+ \mid D) = \frac{p(+, D)}{p(D)} = \frac{.009}{.009 + .001} = .9$$

and

$$p(- \mid D) = \frac{p(-, D)}{p(D)} = \frac{.891}{.891 + .099} \approx .9$$

Probability Chain Rule

The **probability chain rule** is,

$$P(X \cap Y) = P(Y)P(X | Y)$$

↑
Marginal

↑
Conditional

Proof By definition of the conditional distribution,

$$P(X | Y) = \frac{P(X \cap Y)}{P(Y)}$$

Multiply both sides by $P(Y)$,

$$P(X \cap Y) = P(Y)P(X | Y)$$

Probability Chain Rule

Suppose we have a collection of N random events,

$$X_1, X_2, \dots, X_N$$

The probability chain rule for these random variables is,

$$\begin{aligned} P(X_1 \cap X_2 \cap \dots \cap X_N) &= P(X_1)P(X_2 | X_1) \dots P(X_N | X_{N-1}, \dots, X_1) \\ &= P(X_1) \prod_{i=2}^N P(X_i | X_{i-1}, \dots, X_1) \end{aligned}$$

The chain rule is valid for any ordering of RVs, for example:

$$P(X_1 \cap \dots \cap X_N) = P(X_2)P(X_3 | X_2)P(X_1 | X_2, X_3) \dots P(X_7 | X_1, \dots, X_6, X_8, \dots, X_N)$$

Intuition Check

Question: Roll two dice and let their outcomes be $X_1, X_2 \in \{1, \dots, 6\}$ for die 1 and die 2, respectively. Recall the definition of conditional probability,

$$p(X_1 | X_2) = \frac{p(X_1 \cap X_2)}{p(X_2)}$$

Which of the following are true?

- a) $p(X_1 = 1 | X_2 = 1) > p(X_1 = 1)$
- b) $p(X_1 = 1 | X_2 = 1) = p(X_1 = 1)$
- c) $p(X_1 = 1 | X_2 = 1) < p(X_1 = 1)$

Intuition Check

Question: Let $X_1 \in \{1, \dots, 6\}$ be outcome of die 1, as before. Now let $X_3 \in \{2, 3, \dots, 12\}$ be the sum of both dice. Which of the following are true?

a) $p(X_1 = 1 | X_3 = 3) > p(X_1 = 1)$

b) $p(X_1 = 1 | X_3 = 3) = p(X_1 = 1)$

c) $p(X_1 = 1 | X_3 = 3) < p(X_1 = 1)$

Dependence of RVs

Intuition...

Consider $P(B|A)$ where you want to bet on B

Should you pay to know A ?

In general you would pay something for A if it changed your belief about B . In other words if,

$$P(B|A) \neq P(B)$$

Independent Events

There is a special case when,

$$P(A \mid B) = P(A)$$

In this case we refer to A and B as **independent events**.

Example Roll two fair dice. Let E_1 be the event that the first die is a 1. What is the probability that the second die is a 1 (denoted E_2)?

$$P(E_2 \mid E_1) = P(E_2) = \frac{6}{36} = 1/6$$