Introduction to Probability

Random Experiment

- Any well-defined procedure that produces an observable outcome that could not be perfectly predicted in advance
  - Tossing a coin
  - Rolling a dice twice
  - Goals scored in a soccer match
  - Rainfall today

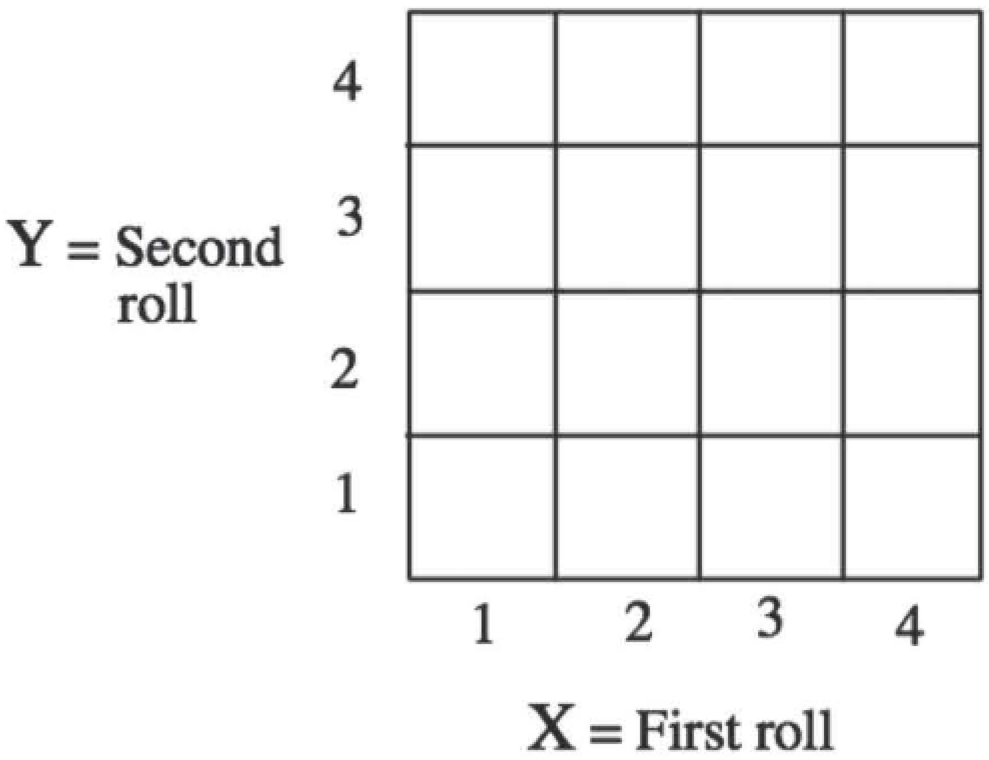
- Outcome: result of a random experiment
- Random variable: outcome mapped to a numerical value

Sample Space

- Set of all possible outcomes – Ω

- Elements of the set must be
  - Mutually exclusive
  - Collectively exhaustive

Sample Space: Two rolls of a 4 faced die



Probability Events

- Event: a subset of the sample space
- Probability of an event: Value P(A) assigned to an event A
- Event space (Σ): collection of all possible events

- σ-algebra on a set X is a nonempty collection Σ of subsets of X closed under complement, countable unions, and countable intersections. The ordered pair (X , Σ) is called a measurable space.
- (Ω , Σ , P) is a called probability space, with sample space Ω, event space Σ and probability measure P s.t. satisfying the axioms

Axioms of Probability

- Nonnegativity: $\mathbf{P}(A) \geq 0$
- Normalization: $\mathbf{P}(\Omega) = 1$
- (Finite) additivity: (to be strengthened later)
  If $A \cap B = \emptyset$, then $\mathbf{P}(A \cup B) = \mathbf{P}(A) + \mathbf{P}(B)$

Simple consequences (Theorems):

Axioms	Consequences
$\mathbf{P}(A) \geq 0$	$\mathbf{P}(A) \leq 1$
$\mathbf{P}(\Omega) = 1$	$\mathbf{P}(\varnothing) = 0$
For disjoint events:	$\mathbf{P}(A) + \mathbf{P}(A^c) = 1$
$\mathbf{P}(A \cup B) = \mathbf{P}(A) + \mathbf{P}(B)$	$\mathbf{P}(A \cup B \cup C) = \mathbf{P}(A) + \mathbf{P}(B) + \mathbf{P}(C)$

More consequences (Theorems):

- If $A \subset B$, then $\mathbf{P}(A) \leq \mathbf{P}(B)$
- $\mathbf{P}(A \cup B) = \mathbf{P}(A) + \mathbf{P}(B) - \mathbf{P}(A \cap B)$
- $\mathbf{P}(A \cup B) \leq \mathbf{P}(A) + \mathbf{P}(B)$

Probability Models

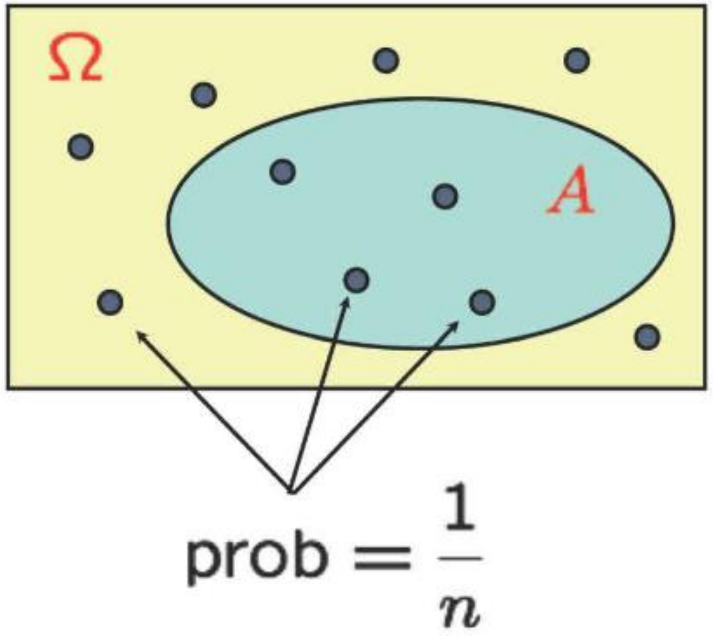
- Rules/mechanism for assigning probability values to events

- Should be faithful to real life phenomenon
- Should produce valid probability values

Discrete Uniform Law

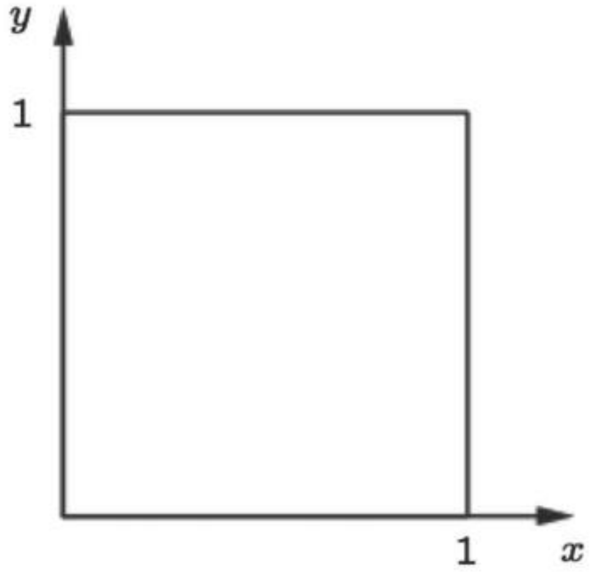
- Assume Ω consists of n equally likely elements
- Assume A consists of k elements

$$P(A) =$$



Continuous Uniform Law

- (x, y) such that $0 \leq x, y \leq 1$



- **Uniform** probability law: Probability = Area

$$\mathbf{P}\Big(\{(x,y) \mid x+y \leq 1/2\}\Big) =$$

$$\mathbf{P}\Big(\{(0.5, 0.3)\}\Big) =$$

Probability Calculation Steps

- Specify the sample space
- Specify a probability model
- Identify an event of interest
- Calculate ...

Building Probability Models

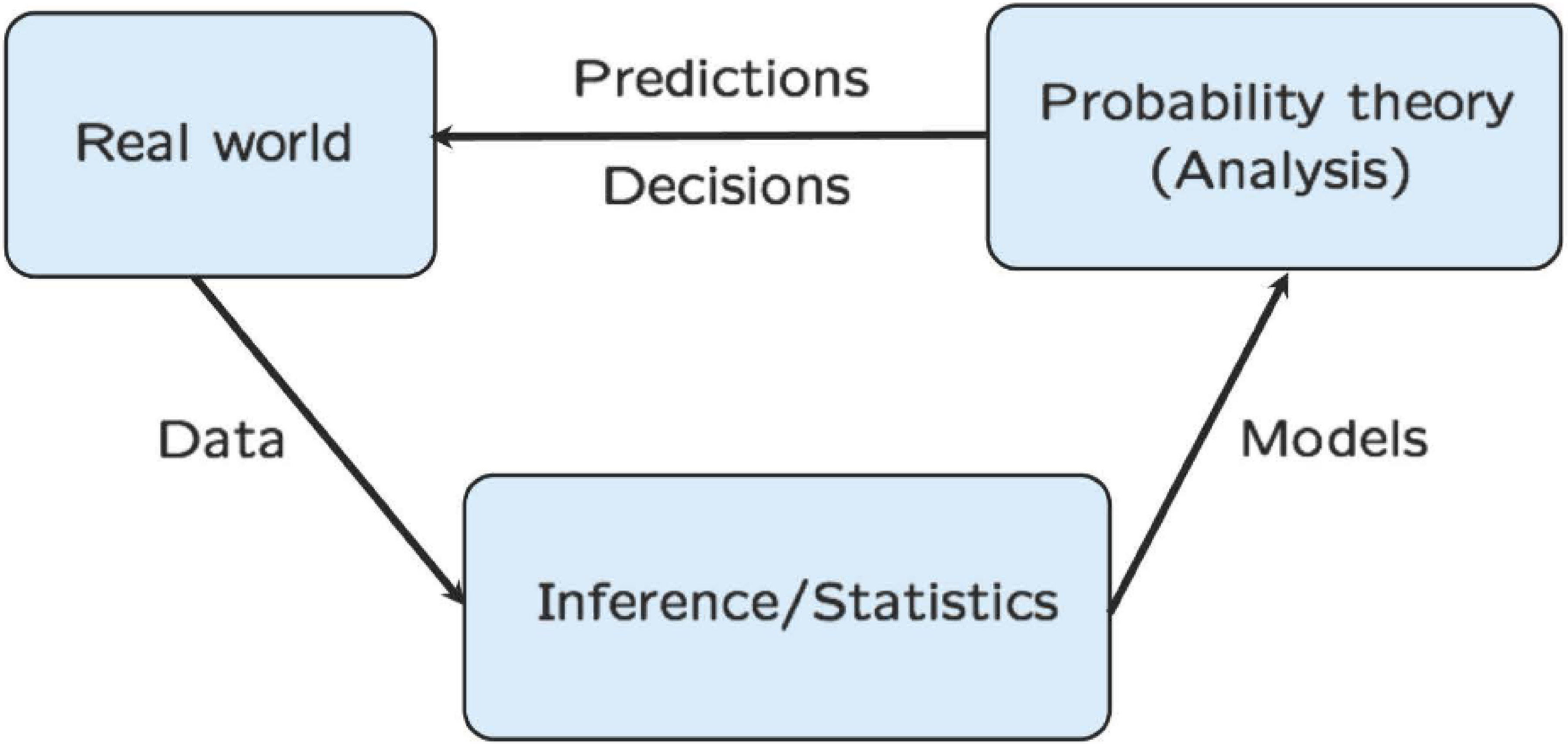
- Depends on interpretation of probability values

- Frequentist: (Theorem: “Frequency” of event A “is” P(A))
  - Are probabilities frequencies?

  - P(coin toss yields heads) = 1/2
  - P(the president of ... will be reelected) = 0.7

- Probabilities are often interpreted as:
  - Description of beliefs/knowledge

Building Probability Model: Statistical Inference/Learning

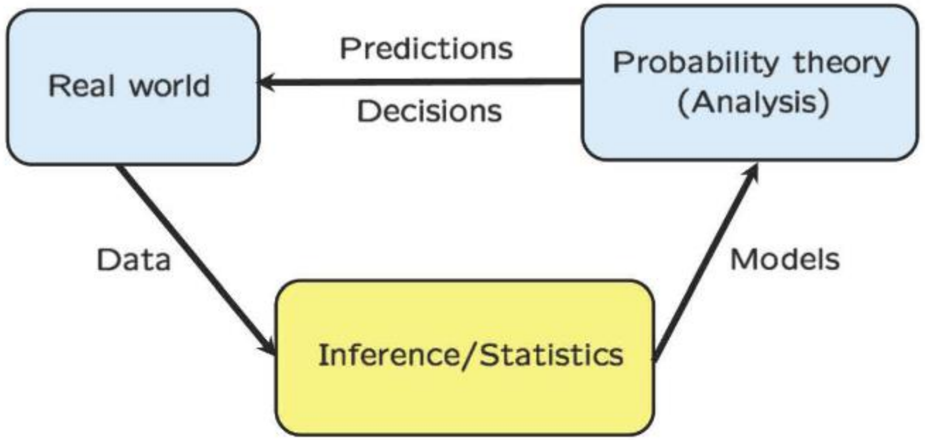


Model Inference vs Estimating a Variable

$X = aS + W$

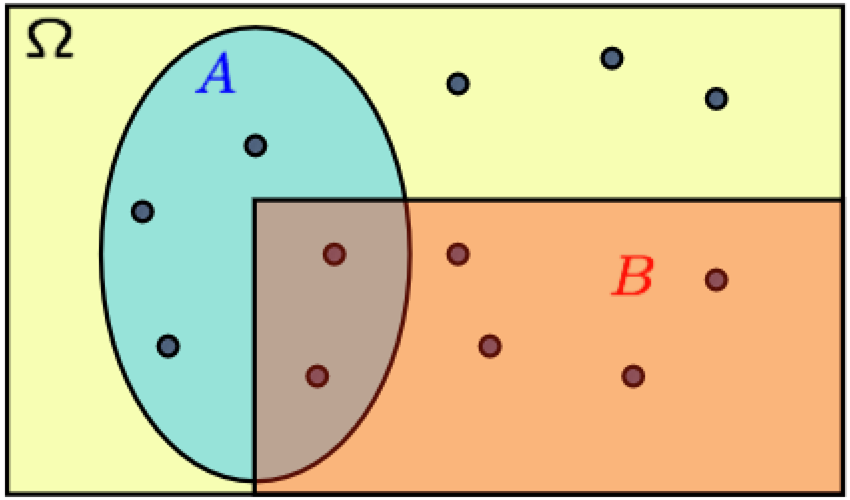
- Model building:
  - know "signal" S, observe X
  - infer a

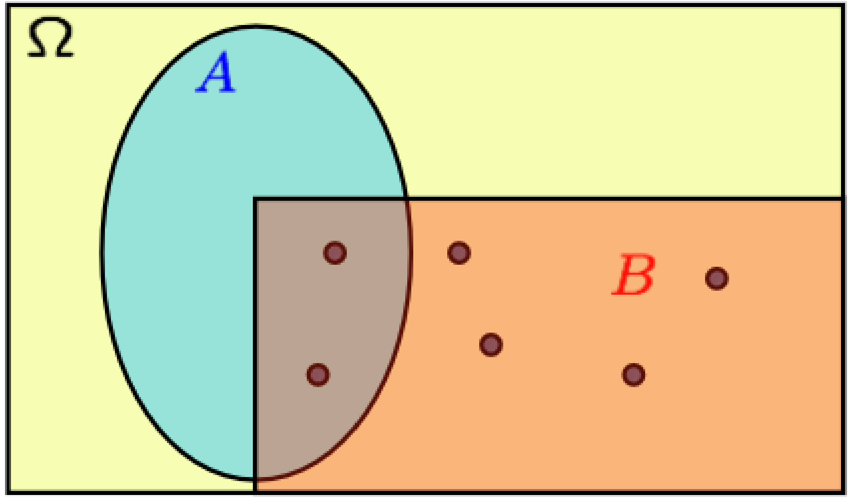
- Variable estimation:
  - know a, observe X
  - infer S



Conditioning

- Use new information to revise a model (12 equally likely outcomes)

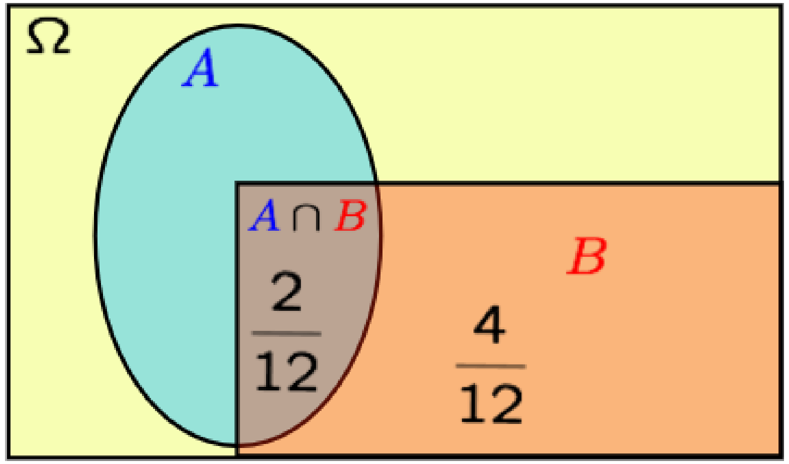




$\mathbf{P}(A) = \frac{5}{12}$ $\mathbf{P}(B) = \frac{6}{12}$

$\mathbf{P}(A \mid B) =$ $\mathbf{P}(B \mid B) =$

Conditional Probability

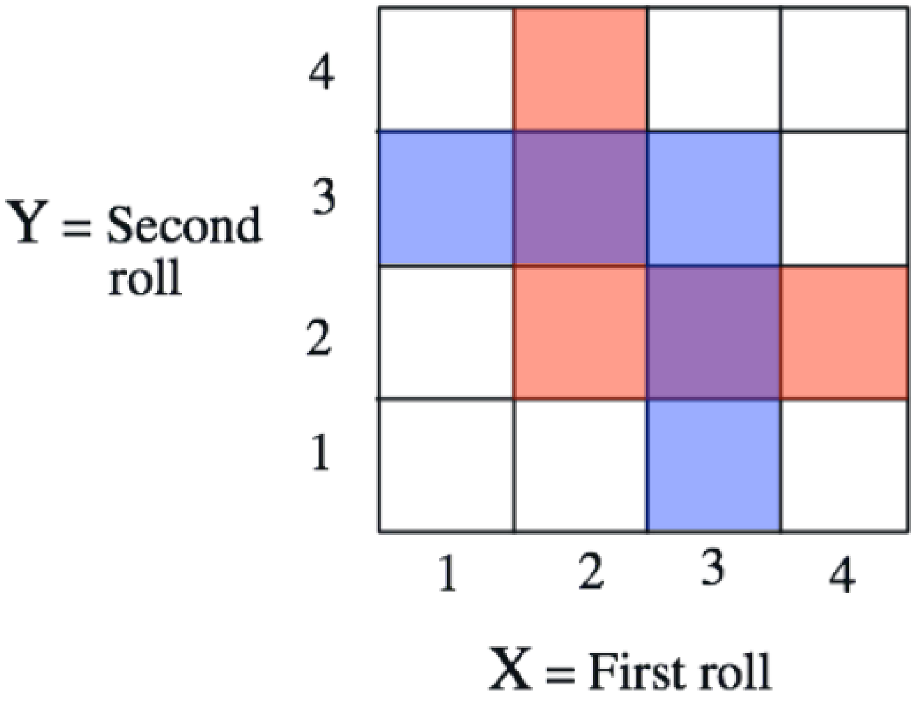


- $\mathbf{P}(A \mid B) =$ "probability of A, given that B occurred"

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

defined only when $\mathbf{P}(B) > 0$

Example: 2 rolls of a 4 sided die



- Let B be the event: $\min(X, Y) = 2$

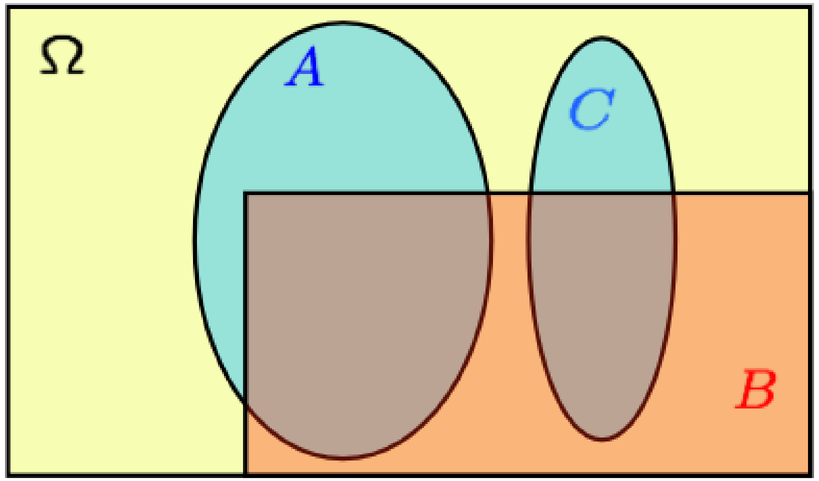
  Let $M = \max(X, Y)$

$\mathbf{P}(M = 1 \mid B) =$

$\mathbf{P}(M = 3 \mid B) =$

Conditional Probabilities Share Property of Original Probabilities

$\mathbf{P}(A \mid B) \geq 0$ assuming $\mathbf{P}(B) > 0$



$\mathbf{P}(\Omega \mid B) =$

$\mathbf{P}(B \mid B) =$

If $A \cap C = \emptyset$, then $\mathbf{P}(A \cup C \mid B) = \mathbf{P}(A \mid B) + \mathbf{P}(C \mid B)$

Model Based on Conditional Probability

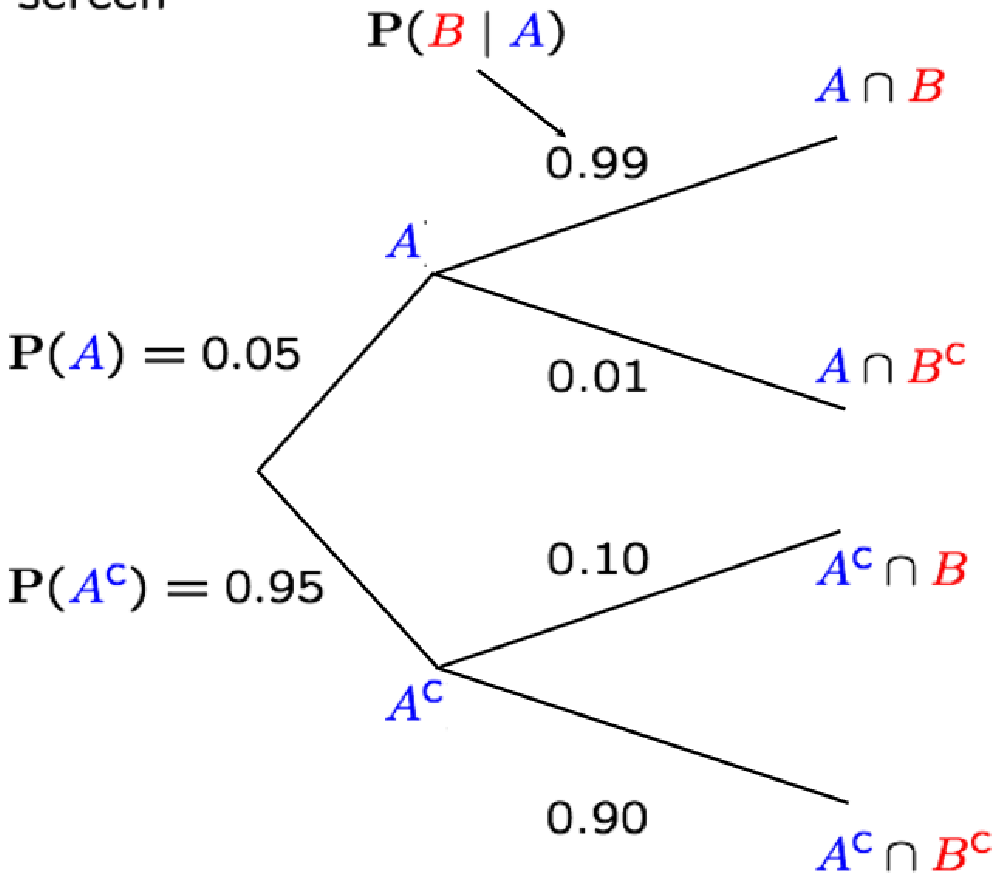
Event A: Airplane is flying above

Event B: Something registers on radar screen

- $\mathbf{P}(A \cap B) =$

- $\mathbf{P}(B) =$

- $\mathbf{P}(A \mid B) =$



Multiplication Rule

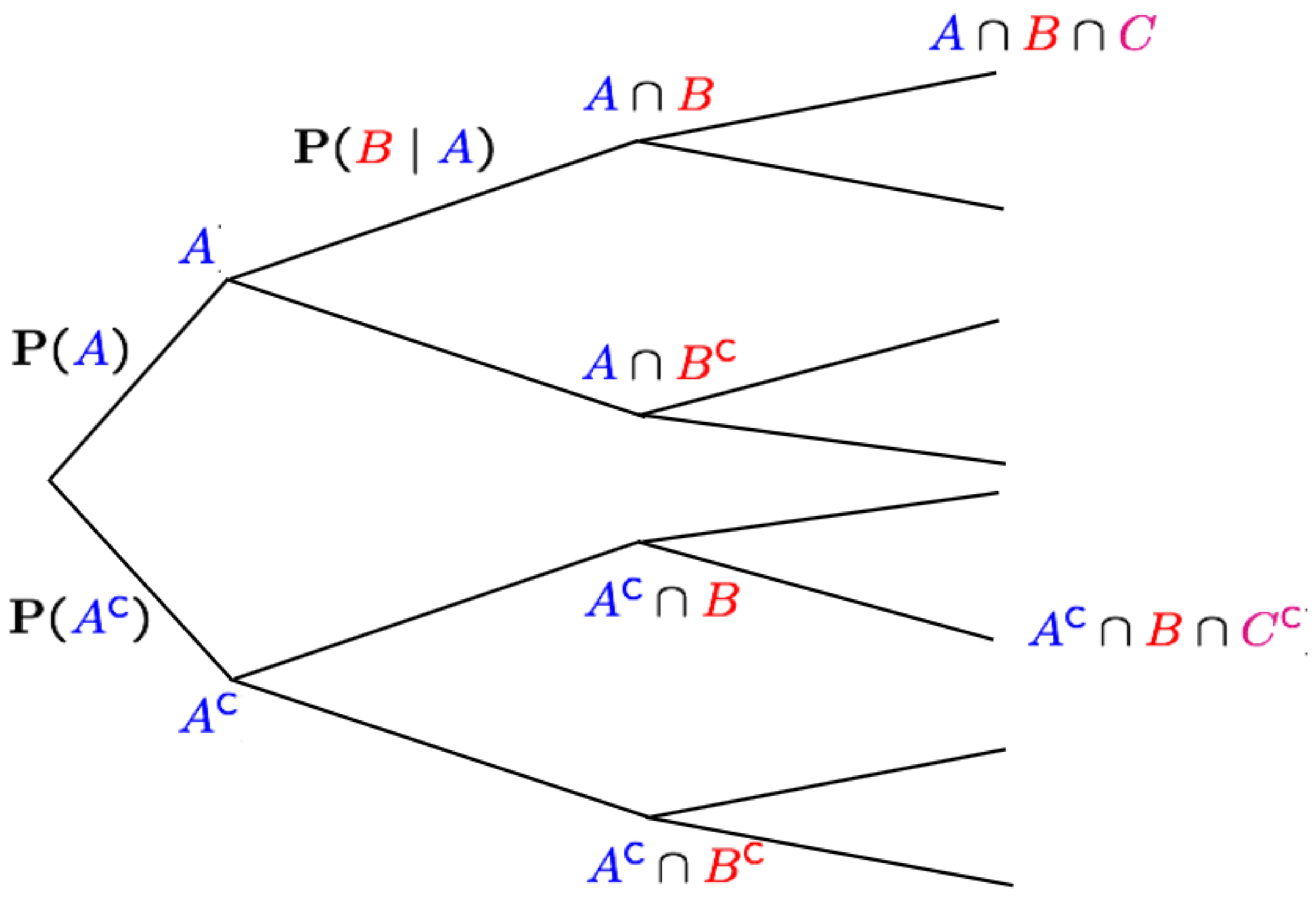
The multiplication rule

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

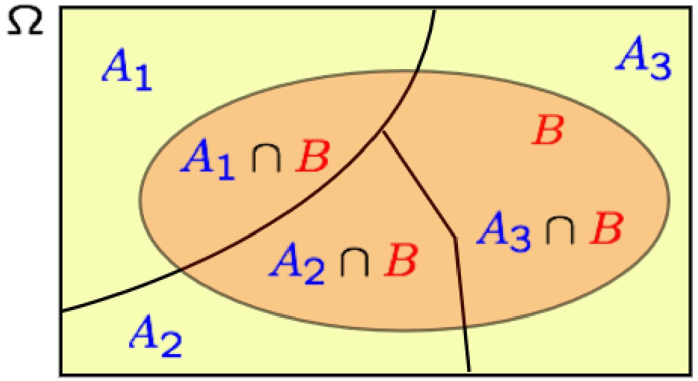
$$P(A \cap B) = P(B)\,P(A \mid B)$$

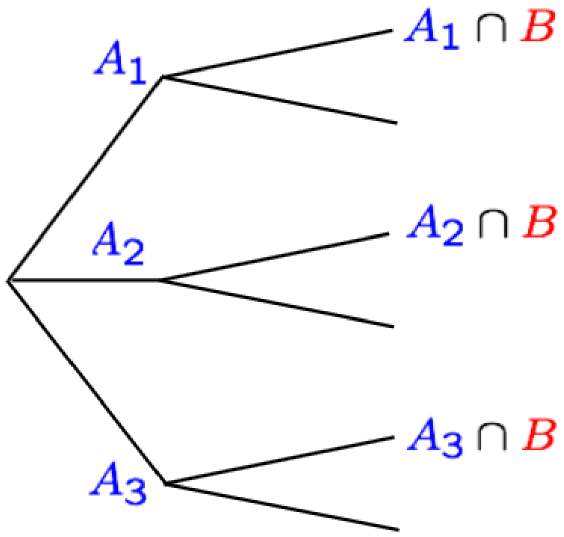
$$= P(A)\,P(B \mid A)$$

$$P(A^c \cap B \cap C^c) =$$



Total Probability Theorem



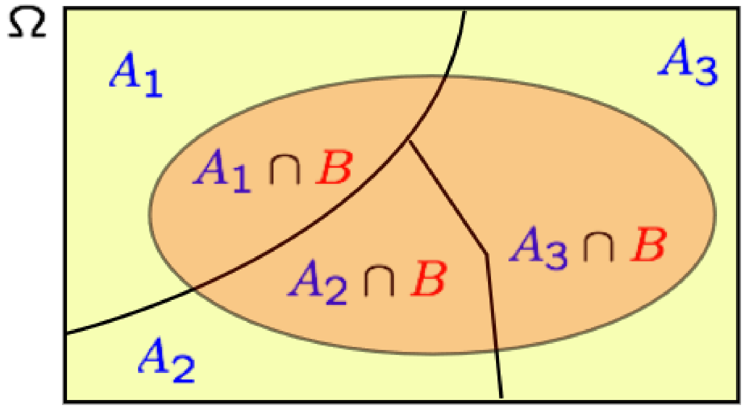


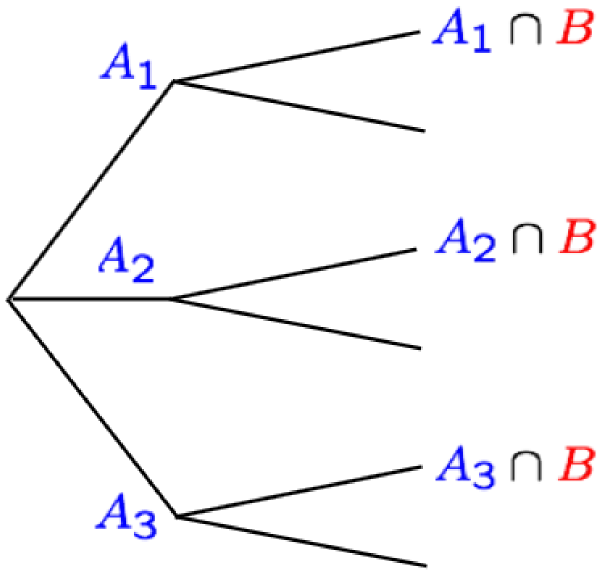
- Partition of sample space into A_1, A_2, A_3
- Have $\mathbf{P}(A_i)$, for every i
- Have $\mathbf{P}(B \mid A_i)$, for every i

$\mathbf{P}(B) =$

$$\mathbf{P}(B) = \sum_i \mathbf{P}(A_i)\,\mathbf{P}(B \mid A_i)$$

Bayes Rule





- Partition of sample space into A_1, A_2, A_3
- Have $\mathbf{P}(A_i)$, for every i — initial "beliefs"
- Have $\mathbf{P}(B \mid A_i)$, for every i

revised "beliefs," given that B occurred:

$$\mathbf{P}(A_i \mid B) =$$

$$\mathbf{P}(A_i \mid B) = \frac{\mathbf{P}(A_i)\mathbf{P}(B \mid A_i)}{\sum_j \mathbf{P}(A_j)\mathbf{P}(B \mid A_j)}$$

Bayesian Inference

- initial beliefs $\mathbf{P}(A_i)$ on possible causes of an observed event B
- model of the world under each A_i: $\mathbf{P}(B \mid A_i)$

$$A_i \xrightarrow[\mathbf{P}(B \mid A_i)]{\text{model}} B$$

- draw conclusions about causes

$$B \xrightarrow[\mathbf{P}(A_i \mid B)]{\text{inference}} A_i$$

Joint Probability

- For events A and B, **joint probability** Pr(AB) stands for the probability that both events happen.
- Example: A={HH}, B={HT, TH}, what is the joint probability Pr(AB)?

Independence

- Two events ***A and B are independent*** in case

$$\Pr(AB) = \Pr(A)\Pr(B)$$

- A set of events $\{A_i\}$ is independent in case

$$\Pr(\bigcap_i A_i) = \prod_i \Pr(A_i)$$

Random Variable and Distribution

- A ***random variable X*** is a numerical outcome of a random experiment
- The ***distribution*** of a random variable is the collection of possible outcomes along with their probabilities:
  - Discrete case:
  - Continuous case:
  - Probability density function
  - Probability mass function

$$\Pr(X = x) = p_\theta(x)$$

$$\Pr(a \le X \le b) = \int_a^b p_\theta(x)dx$$

Random Variable: Example

- Let S be the set of all sequences of three rolls of a die. Let X be the sum of the number of dots on the three rolls.
- What are the possible values for X?
- $\Pr(X = 5) = ?$, $\Pr(X = 10) = ?$

Expectation

- A random variable X~Pr(X=x). Then, its expectation is

$$E[X] = \sum_x x \Pr(X = x)$$

  - In an empirical sample, x1, x2,…, xN,

$$E[X] = \frac{1}{N} \sum_{i=1}^{N} x_i$$

- Continuous case: $$E[X] = \int_{-\infty}^{\infty} x p_\theta(x) dx$$

- Expectation of sum of random variables

$$E[X_1 + X_2] = E[X_1] + E[X_2]$$

Variance

- The variance of a random variable X is the expectation of $(X\text{-}E[x])^2$:

$$
\begin{aligned}
Var(X) &= E((X - E[X])^2) \\
&= E(X^2 + E[X]^2 - 2XE[X]) \\
&= E(X^2 - E[X]^2) \\
&= E[X^2] - E[X]^2
\end{aligned}
$$

Bernoulli Distribution

- The outcome of an experiment can either be success (i.e., 1) and failure (i.e., 0).
- Pr(X=1) = p, Pr(X=0) = 1-p, or
- E[X] = p, Var(X) = p(1-p)

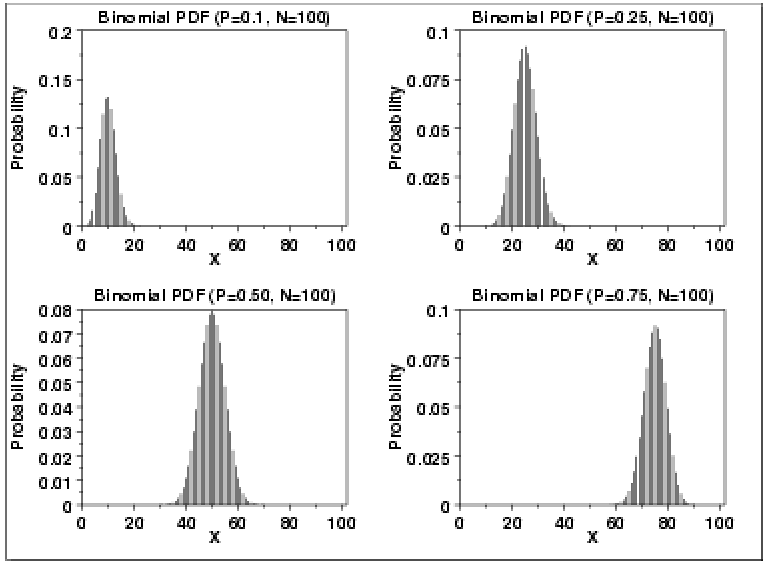
Binomial Distribution

- n draws of a Bernoulli distribution
  - X_i~Bernoulli(p), $X=\sum_{i=1}^{n} X_i$, X~Bin(p, n)
- Random variable X stands for the number of times that experiments are successful.

$$\Pr(X = x) = p_\theta(x) = \begin{cases} \binom{n}{x} p^x (1-p)^{n-x} & x = 1, 2, \ldots, n \\ 0 & \text{otherwise} \end{cases}$$

- E[X] = np, Var(X) = np(1-p)

Plots of Binomial Distribution



Poisson Distribution

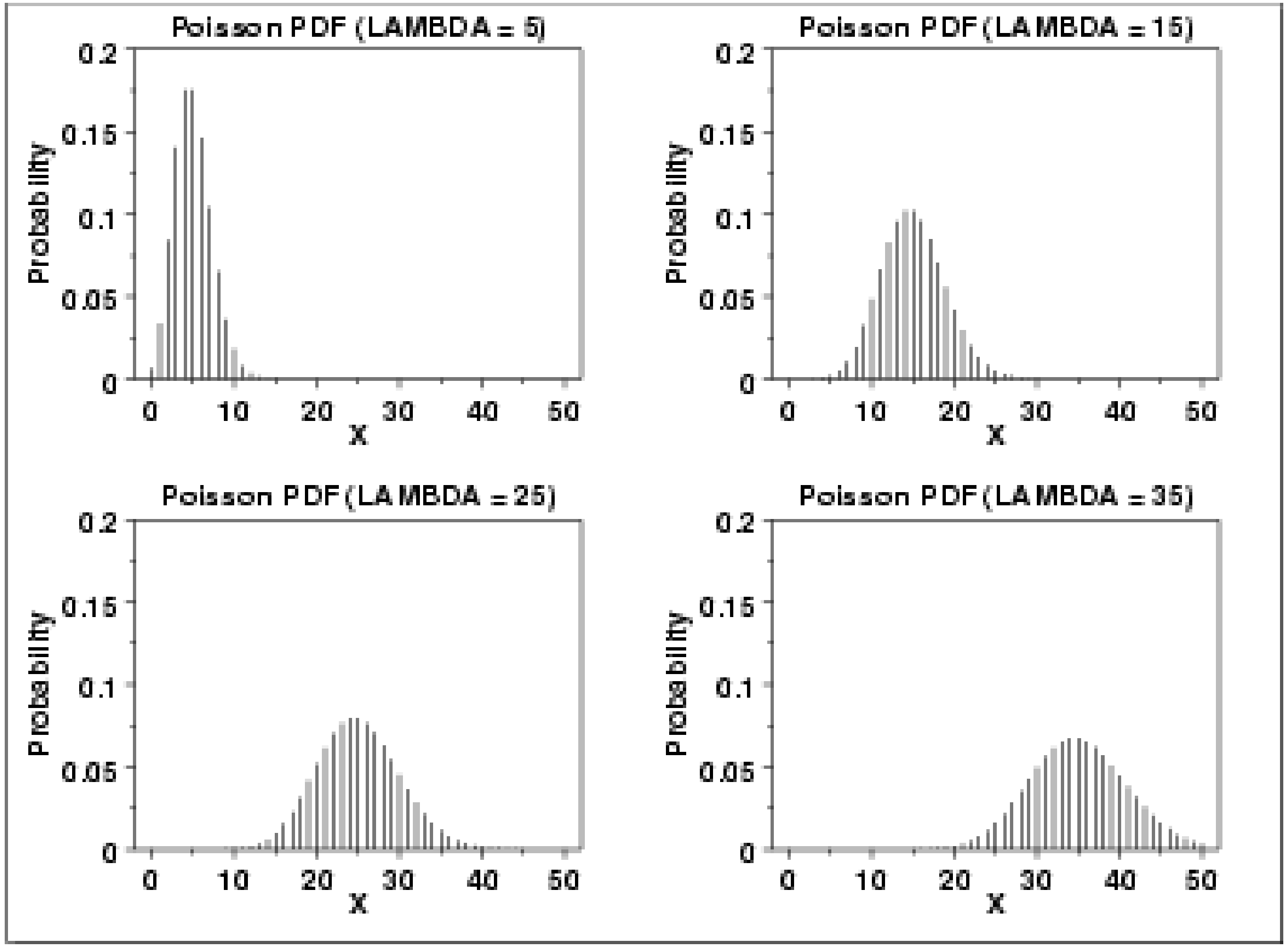
- Coming from Binomial distribution
  - Fix the expectation λ=np
  - Let the number of trials n$\rightarrow\infty$

  A Binomial distribution will become a Poisson distribution

$$\Pr(X = x) = p_\theta(x) = \begin{cases} \dfrac{\lambda^x}{x!} e^{-\lambda} & x \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

- E[X] = λ, Var(X) = λ

Plots of Poisson Distribution



Normal (Gaussian) Distribution

- $X \sim N(\mu,\sigma)$

$$p_\theta(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$$

$$\Pr(a \le X \le b) = \int_a^b p_\theta(x)dx = \int_a^b \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}dx$$

- $E[X]= \mu$, $Var(X)= \sigma^2$
- If $X_1 \sim N(\mu_1,\sigma_1)$ and $X_2 \sim N(\mu_2,\sigma_2)$, $X= X_1+ X_2$?