

Human-Oriented Robotics

Probability Refresher

Kai Arras

Social Robotics Lab, University of Freiburg

- **Introduction to Probability**

- Random variables
- Joint distribution
- Marginalization
- Conditional probability
- Chain rule
- Bayes' rule
- Independence
- Conditional independence
- Expectation and Variance

- **Common Probability Distributions**

- Bernoulli distribution
- Binomial distribution
- Categorical distribution
- Multinomial distribution
- Poisson distribution
- Gaussian distribution
- Chi-squared distribution

We assume that you are familiar with the **fundamentals** of probability theory and probability distributions

This is a quick refresher, we aim at **ease of understanding** rather than formal depth

For a more comprehensive treatment, refer, e.g. to A. Papoulis or the references given on the last slide

Why probability theory?

- Consider a **human, animal, or robot** in the **real world** those task involves the solution of a set of problems (e.g. an animal looking for food, a robot serving coffee, ...)
- In order to be successful, it needs to **observe** and **estimate** the state of the world around it and **act** in an appropriate way
- **Uncertainty** is an **inescapable aspect** of the real world
- It is a consequence of several factors, for example,
 - Uncertainty from **partial, indirect** and **ambiguous** observations of the world
 - Uncertainty in the **values** of observations (e.g. sensor noise)
 - Uncertainty in the **origin** of observations (e.g. data association)
 - Uncertainty in **action** execution (e.g. from limitations in the control system)
- Probability theory is the **most powerful** (and accepted) **formalism** to deal with uncertainty

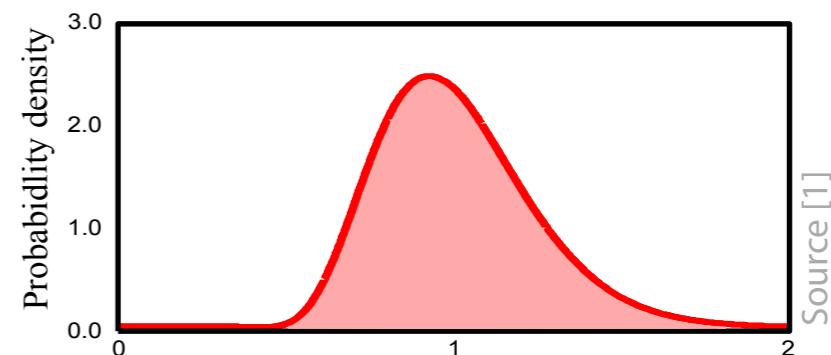
Random Variables

- A **random variable** x denotes an **uncertain quantity**
- x could be the **outcome of an experiment** such as rolling a dice (numbers from 1 to 6), flipping a coin (heads, tails), or measuring a temperature (value in degrees Celcius)
- If we observe several instances $\{x_i\}_{i=1}^I$ then it might take a different value each time, some values may occur more often than others. This information is captured by the **probability distribution** $p(x)$ of x
- A random variable may be **continuous** or **discrete**
- Continuous random variables take values that are **real numbers: finite** (e.g. time taken to finish 2-hour exam), **infinite** (time until next bus arrives)
- Discrete random variables take values from a **predefined set: ordered** (e.g. outcomes 1 to 6), **unordered** (e.g. “sunny”, “raining”, “cloudy”), **finite** or **infinite**.

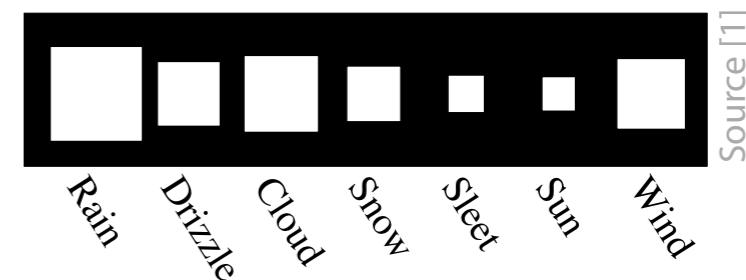
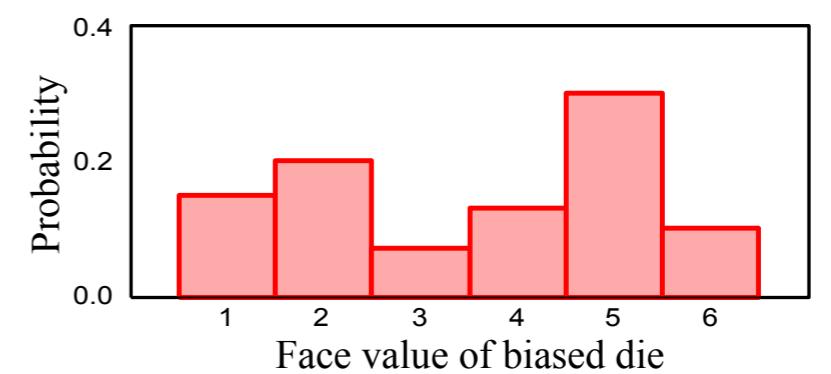
Random Variables

- The probability distribution $p(x)$ of a continuous random variable is called **probability density function** (pdf). This function may take **any** positive value, its integral always sums to **one**
- The probability distribution $p(x)$ of a discrete random variables is called **probability mass function** and can be visualized as a **histogram** (less often: Hinton diagram). Each outcome has a positive probability associated to it whose **sum** is always **one**

Continuous distribution



Discrete distribution



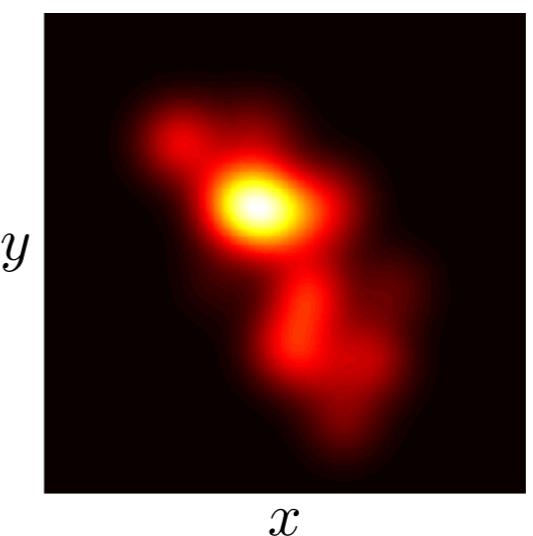
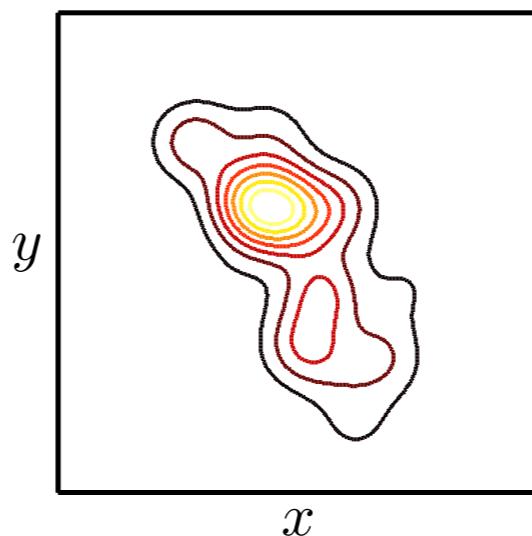
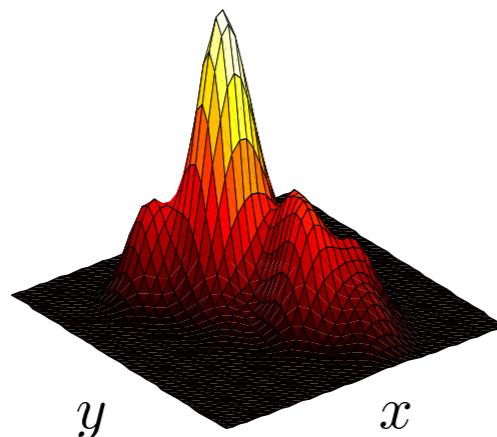
Joint Probability

- Consider two random variables x and y
- If we observe multiple paired instances of x and y , then some outcome combinations occur more frequently than others. This is captured in the **joint probability distribution** of x and y , written as $p(x,y)$
- A joint probability distribution may relate variables that are all discrete, all continuous, or mixed discrete-continuous
- Regardless – the **total probability** of all outcomes (obtained by summing or integration) is always **one**
- In general, we can have $p(x,y,z)$. We may also write $p(\mathbf{x})$ to represent the joint probability of all elements in **vector** $\mathbf{x} = [x_1, x_2, \dots, x_n]^T$
- We will write $p(\mathbf{x}, \mathbf{y})$ to represent the joint distribution of all elements from random vectors \mathbf{x} and \mathbf{y}

Joint Probability

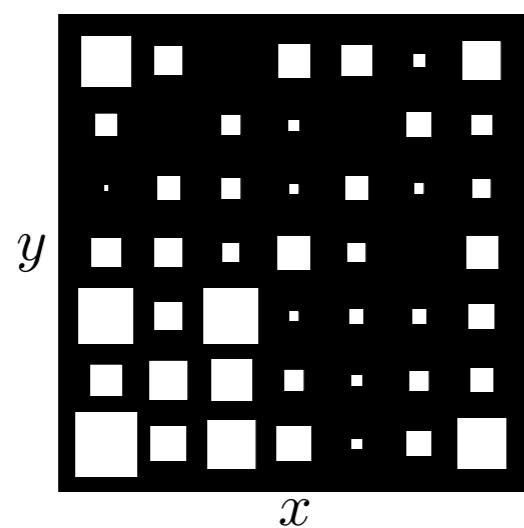
- Joint probability distribution $p(x,y)$ examples:

Continuous:

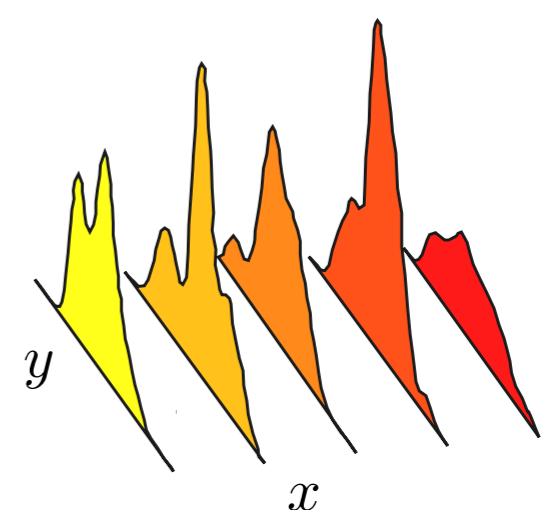
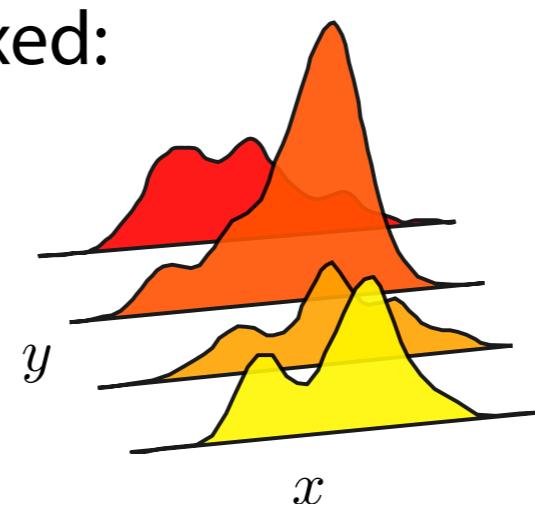


Source [1]

Discrete:



Mixed:



Source [1]

Marginalization

- We can recover the probability distribution of a **single variable** from a joint distribution by **summing over all the other variables**
- Given a continuous $p(x,y)$

$$p(x) = \int p(x, y) dy$$

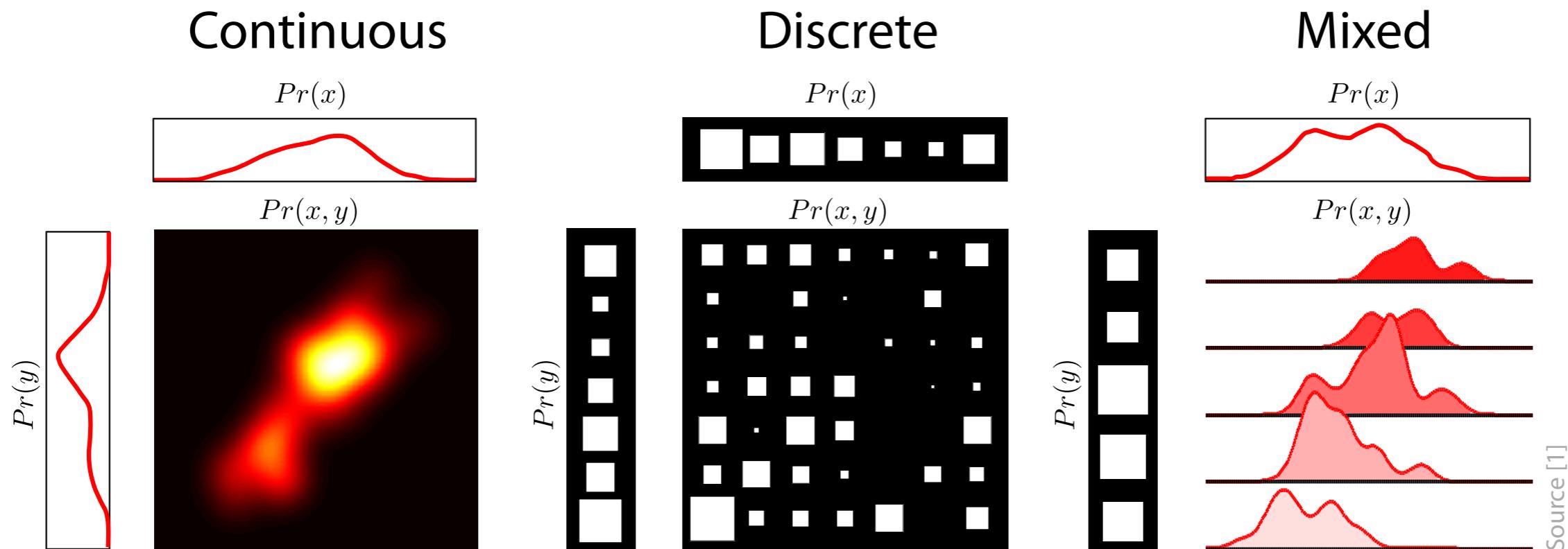
$$p(y) = \int p(x, y) dx$$

- The integral becomes a **sum** in the **discrete** case
- Recovered distributions are referred to as **marginal distributions**. The process of integrating/summing is called **marginalization**
- We can recover **any subset of variables**. E.g., given w, x, y, z where w is discrete

$$p(x, y) = \sum_w \int p(w, x, y, z) dz$$

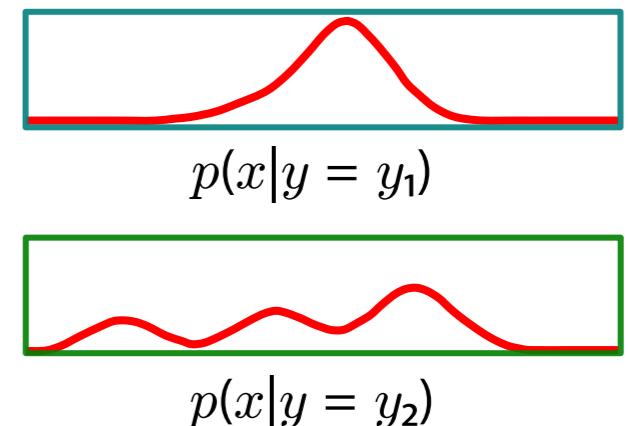
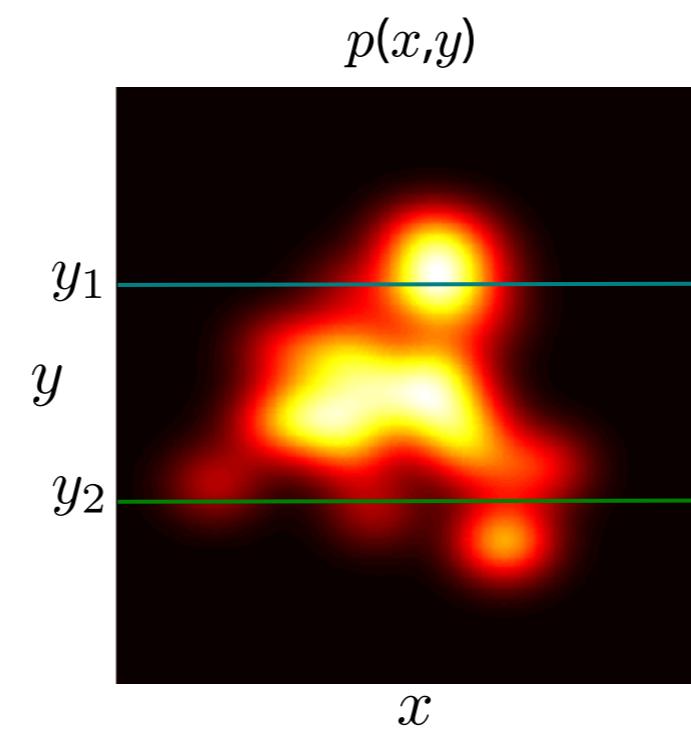
Marginalization

- Calculating the marginal distribution $p(x)$ from $p(x,y)$ has a **simple interpretation**: we are finding the probability distribution of x **regardless of** y (in absence of information about y)
- Marginalization is also known as **sum rule of law of total probability**



Conditional Probability

- The **probability of x given that y takes a fixed value y^*** tells us the relative frequency of x to take different outcomes given the conditioning event that y equal y^*
- This is written $p(x|y = y^*)$ and is called the **conditional probability** of x given y equals y^*
- The conditional probability $p(x|y)$ can be **recovered** from the **joint distribution** $p(x,y)$
- This can be visualized by a **slice** $p(x,y = y^*)$ **through the joint distribution**



Source [1]

Conditional Probability

- The values in the slice tell us about the **relative probability** of x given $y = y^*$, but they do not themselves form a valid probability distribution
- They **cannot sum to one** as they constitute only a small part of $p(x,y)$ which itself sums to one
- To calculate a **proper** conditional probability distribution, we hence **normalize by the total probability** in the slice

$$p(x|y = y^*) = \frac{p(x, y = y^*)}{\int p(x, y = y^*) dx} = \frac{p(x, y = y^*)}{p(y = y^*)}$$

where we use marginalization to simplify the denominator

Conditional Probability

- Instead of writing

$$p(x|y = y^*) = \frac{p(x, y = y^*)}{p(y = y^*)}$$

it is common to use a more compact notation and write the conditional probability relation **without explicitly defining the value** $y = y^*$

$$p(x|y) = \frac{p(x, y)}{p(y)}$$

- This can be **rearranged** to give $p(x, y) = p(x|y) p(y)$
- By **symmetry** we also have $p(x, y) = p(y|x) p(x)$

Bayes' Rule

- In the last two equations, we expressed the joint probability in two ways. When **combining them** we get a **relationship between $p(x|y)$ and $p(y|x)$**

$$p(x|y) p(y) = p(y|x) p(x)$$

- Rearranging gives

$$p(x|y) = \frac{p(y|x) p(x)}{p(y)}$$

$$= \frac{p(y|x) p(x)}{\int p(x, y) dx} = \frac{p(y|x) p(x)}{\int p(y|x) p(x) dx}$$

where we have expanded the denominator using the definition of marginal and conditional probability, respectively

Bayes' Rule

- In the last two equations, we expressed the joint probability in two ways. When **combining them** we get a **relationship between $p(x|y)$ and $p(y|x)$**

$$p(x|y) p(y) = p(y|x) p(x)$$

- Rearranging gives

$$p(x|y) = \frac{p(y|x) p(x)}{p(y)}$$

Bayes' rule

$$= \frac{p(y|x) p(x)}{\int p(x, y) dx} = \frac{p(y|x) p(x)}{\int p(y|x) p(x) dx}$$

where we have expanded the denominator using the definition of marginal and conditional probability, respectively

Bayes' Rule

- Each term in Bayes' rule has a name

$$p(x|y) = \frac{p(y|x) p(x)}{p(y)}$$

(a.k.a. marginal likelihood, evidence)

Diagram illustrating the components of Bayes' Rule:

- posterior** (green arrow pointing to $p(x|y)$)
- likelihood** (pink arrow pointing to $p(y|x)$)
- prior** (orange arrow pointing to $p(x)$)
- normalizer** (blue arrow pointing to $p(y)$)

- The **posterior** represents what we know about x given y
- Conversely, the **prior** is what is known about x **before** considering y
- Bayes' rule provides a way to **change your existing beliefs** in the **light of new evidence**. It allows us to combine new data with the existing knowledge or expertise
- Bayes' rule is important in that it allows us to **compute the conditional probability** $p(x|y)$ from the “**inverse**” conditional probability $p(y|x)$

Bayes' Rule Example

Suppose that a tuberculosis (TB) skin test is 95% accurate. That is, if the patient is TB-infected, then the test will be positive with probability 0.95, and if the patient is not infected, then the test will be negative with probability 0.95.

A person gets a positive test result. What is the probability that he is infected?

- **Wanted:** $p(\text{TB}|\text{Positive})$ given $p(\text{Positive}|\text{TB}) = 0.95$, $p(\text{Positive}|\neg\text{TB}) = 0.05$
- **Naive reasoning:** given that the test result is wrong 5% of the time, then the probability that the subject is infected is **0.95**
- **Bayes' rule:** we need to consider the prior probability of TB infection $p(\text{TB})$, and the probability of getting positive test result $p(\text{Positive})$

$$p(\text{TB}|\text{Positive}) = \frac{p(\text{Positive}|\text{TB}) p(\text{TB})}{p(\text{Positive})}$$

Bayes' Rule Example (cont.)

- What is the probability of getting a positive test result, $p(\text{Positive})$?
- Let's expand the denominator

$$\begin{aligned} p(\text{TB}|\text{Positive}) &= \frac{p(\text{Positive}|\text{TB}) p(\text{TB})}{p(\text{Positive})} \\ &= \frac{p(\text{Positive}|\text{TB}) p(\text{TB})}{p(\text{Positive}|\text{TB}) p(\text{TB}) + p(\text{Positive}|\neg\text{TB}) p(\neg\text{TB})} \end{aligned}$$

- Suppose that 1 in 1000 of subjects who get tested is infected: $p(\text{TB})$
- We see that $0.95 \cdot 0.001 = 0.00095$ infected subjects get a positive result, and $0.05 \cdot 0.999 = 0.04995$ uninfected subjects get a positive result. Thus, $p(\text{Positive}) = 0.00095 + 0.04995 = 0.0509$
- Applying Bayes' rule, we obtain $p(\text{TB}|\text{Positive}) = 0.95 \cdot 0.001 / 0.0509 \approx \mathbf{0.0187}$

Bayes' Rule Example (cont.)

- Wait, **only 2%**?
- This is much more than the prior infection probability of 0.001 but still... what if we needed a more accurate results?
- **Insights**
 - Our subject was a **random person** for which $p(\text{TB}) = 0.001$ is indeed low
 - Our clinical test is very **inaccurate**, in particular $p(\text{Positive}|\neg\text{TB})$ is high
 - If we set $p(\text{Positive}|\neg\text{TB}) = 0.0001$ (0.1 %) leaving all other values the same, we obtain a posterior probability of **0.90**
 - If we set $p(\text{Positive}|\text{TB}) = 0.9999$ leaving all other values the same, we obtain a posterior of **0.0196**
 - The **false positive rate** is important in this case (see also later in this course)

Chain Rule

- Another immediate result of the definition of conditional probability is the **chain rule**

$$p(x, y) = p(x|y) p(y)$$

- In general,

$$p(x_1, x_2, \dots, x_K) = p(x_1) p(x_2|x_1) p(x_3|x_1, x_2) \cdots p(x_k|x_1, x_2, \dots, x_{K-1})$$

compactly expressed as

$$p(x_1, x_2, \dots, x_K) = \prod_{i=1}^K p(x_i|x_1, \dots, x_{i-1})$$

Chain Rule

- In other words, we can express the **joint probability** of random variables in terms of the probability of the **first**, the probability of the **second given the first**, and so on
- Note that we can expand this expression using **any order of variables**, the result will be the same
- The chain rule is also known as the **product rule**

Independence

- Assume that the value of variable x **tells us nothing about variable y** and vice versa. Formally,

$$p(x|y) = p(x) \quad p(y|x) = p(y)$$

- Then, we say x and y are **independent**
- When substituting this into the conditional probability relation

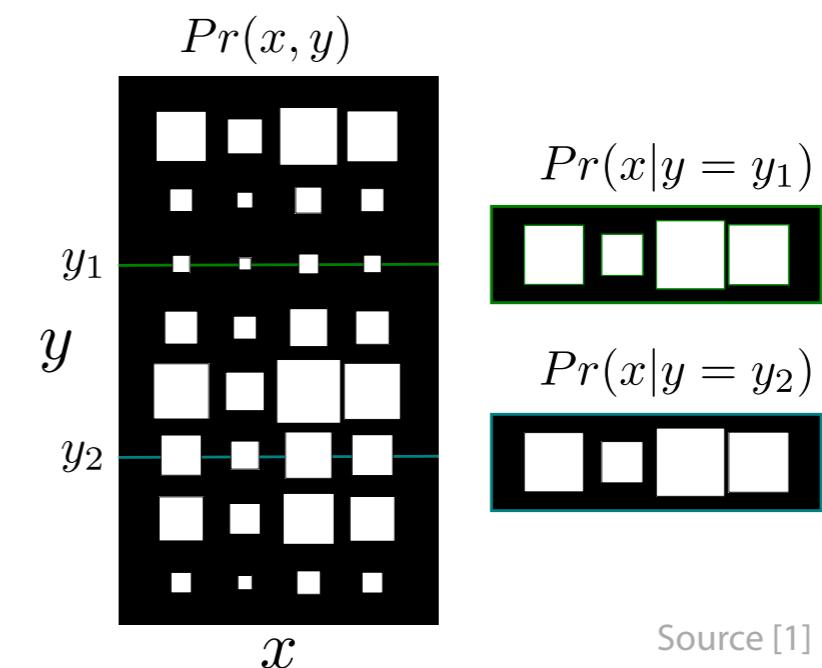
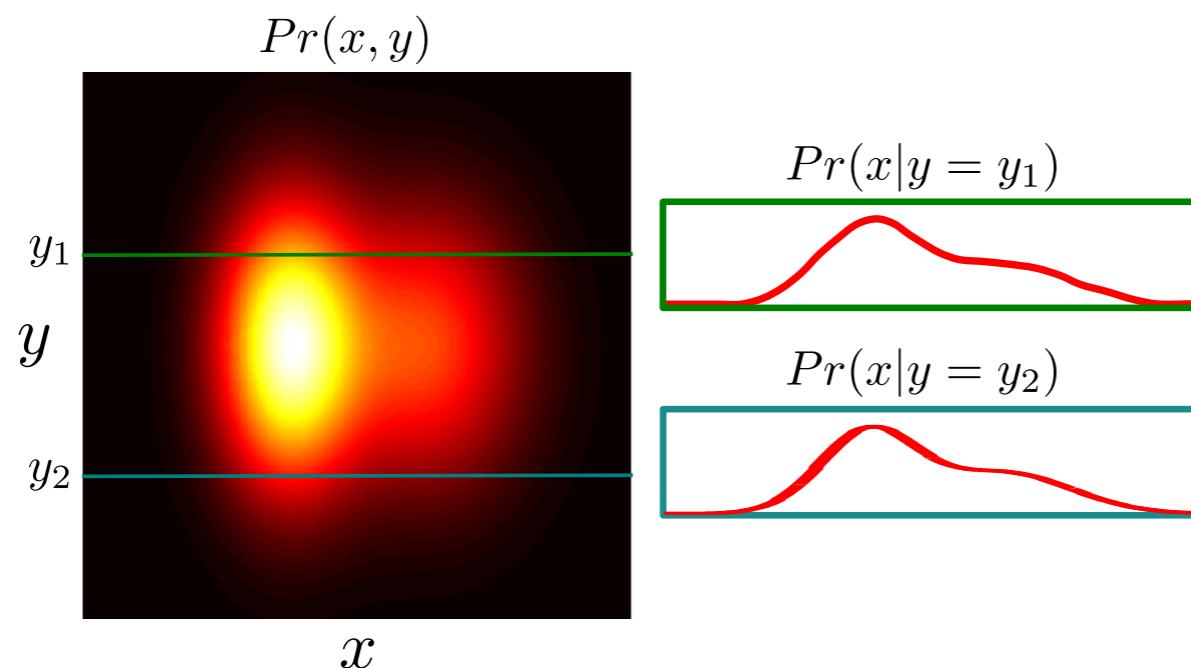
$$p(x, y) = p(x|y) p(y)$$

we see that for **independent variables** the joint probability is the **product of the marginal probabilities**

$$p(x, y) = p(x) p(y)$$

Independence

- Let us **visualize** this for the joint distribution of two independent variables x and y
- Independence** of x and y means that **every conditional distribution is the same** (recall that the conditional distribution is the “normalized version of the slice”)
- The value of y **tells us nothing** about x and vice versa



Source [1]

Conditional Independence

- While independence is a useful property, it is **not often** that we encounter two independent events. A more common situation is when **two variables are independent given a third one**
- Consider three variables x_1, x_2, x_3 . Conditional independence is written as

$$\begin{aligned} p(x_1|x_2, x_3) &= p(x_1|x_2) \\ p(x_3|x_1, x_2) &= p(x_3|x_2) \end{aligned}$$

- Conditional independence is **always symmetric**
- Note that when x_1 and x_3 are conditionally independent given x_2 , this **does not mean** that x_1 and x_3 are **themselves** independent. It implies that if we know x_2 , then x_1 provides no further information about x_3
- This typically occurs in **chain of events**: if x_1 causes x_2 and x_2 causes x_3 , then the dependence of x_3 on x_1 is entirely “contained” in x_2

Conditional Independence

- Example: entering a hip nightclub
 - Suppose we want to reason about the chance that a student enters the two hottest nightclubs in town. Denote A the event “student passes bouncer of club A”, and B the event “student passes bouncer of club B”
 - Usually, these two events are **not independent** because if we learn that the student could enter club B, then our estimate of his/her probability of entering club A is higher since it is a sign that the student is hip, properly dressed and not too drunk
 - Now suppose that the doormen base their decisions **only** on the looks of the student’s company, and we know their preferences. Thus, learning that event B has occurred should not change the probability of event A : the looks of the company contains **all relevant information** to his/her chances of passing. Finding out whether he/she could enter club B **does not change** that
 - Formally, $p(A|B, \text{Looks}) = p(A|\text{Looks})$
- In this case, we say A **is conditionally independent of B given Looks**



Conditional Independence

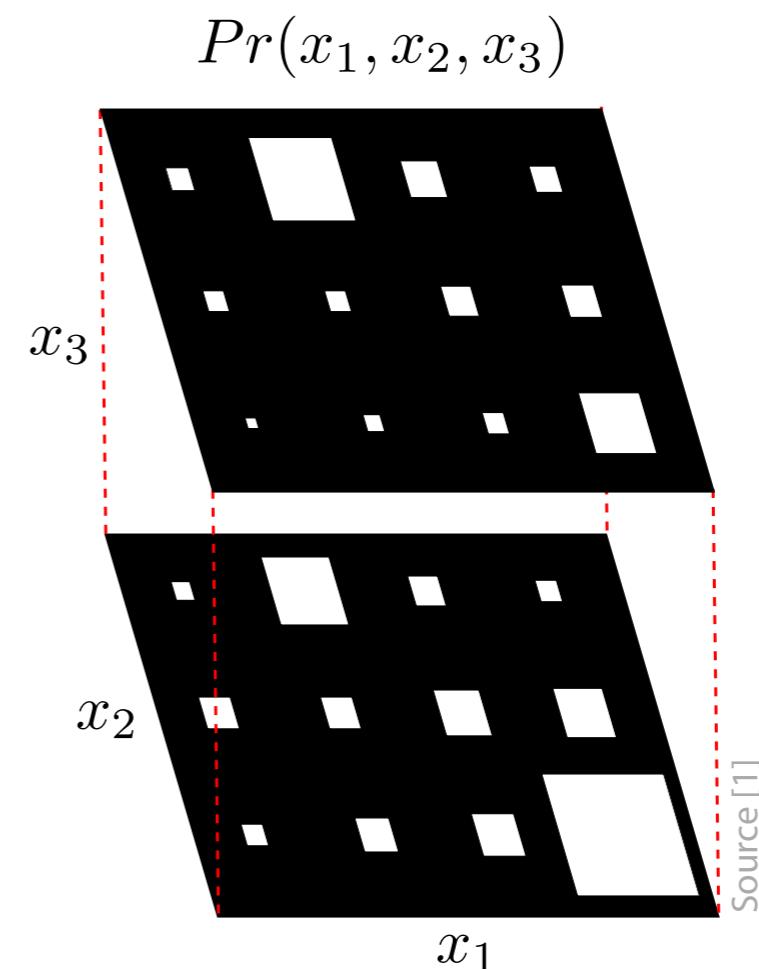
- Example: rolling a blue and red die
 - The two results are **independent** of each other
 - Now someone tells you "**the blue result isn't a 6 and the red result isn't a 1**"
 - From this information, you cannot gain any knowledge about the red die by looking at the blue die. The probability for each number except 1 on the red one is still 1/5
 - The information does not affect the independence of the results
 - Now someone tells you "**the sum of the two results is even**"
 - This allows you to learn a lot about the red die by looking at the blue die
 - For instance, if you see a 3 on the blue die, the red die can only be 1, 3 or 5
 - The result probabilities are **not conditionally independent** given this information
- Conditional independence is always **relative to the given condition**



Conditional Independence

- Variable x_1 is said to be **conditional independent of variable x_3 given variable x_2** if – given **any** value of x_2 – the probability distribution of x_1 is the same for all values of x_3 and the probability distribution of x_3 is the same for all values of x_1

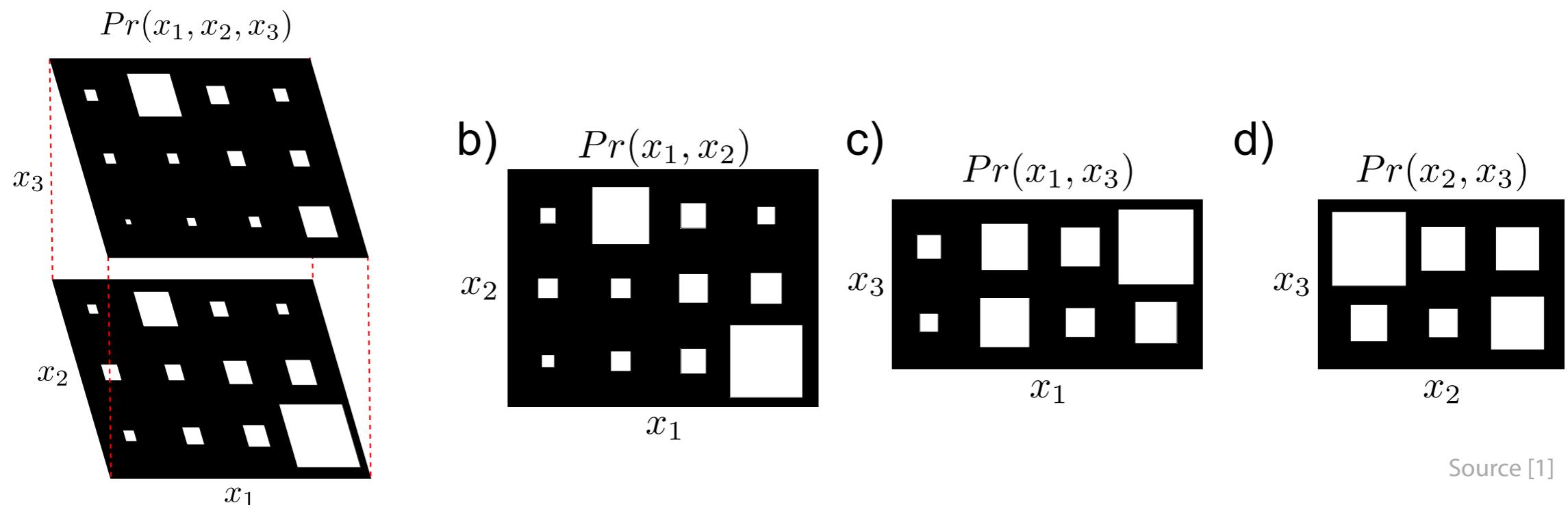
- Let us look at a **graphical example**
- Consider the joint density function of three discrete random variables x_1, x_2, x_3 which take 4, 3, and 2 possible values, respectively
- All 24 probabilities sum to **one**



Conditional Independence

First, let's consider independence:

- Figure b, marginalization of x_3 : no independence between x_1 and x_2
- Figure c, marginalization of x_2 : no independence between x_1 and x_3
- Figure d, marginalization of x_1 : no independence between x_2 and x_3

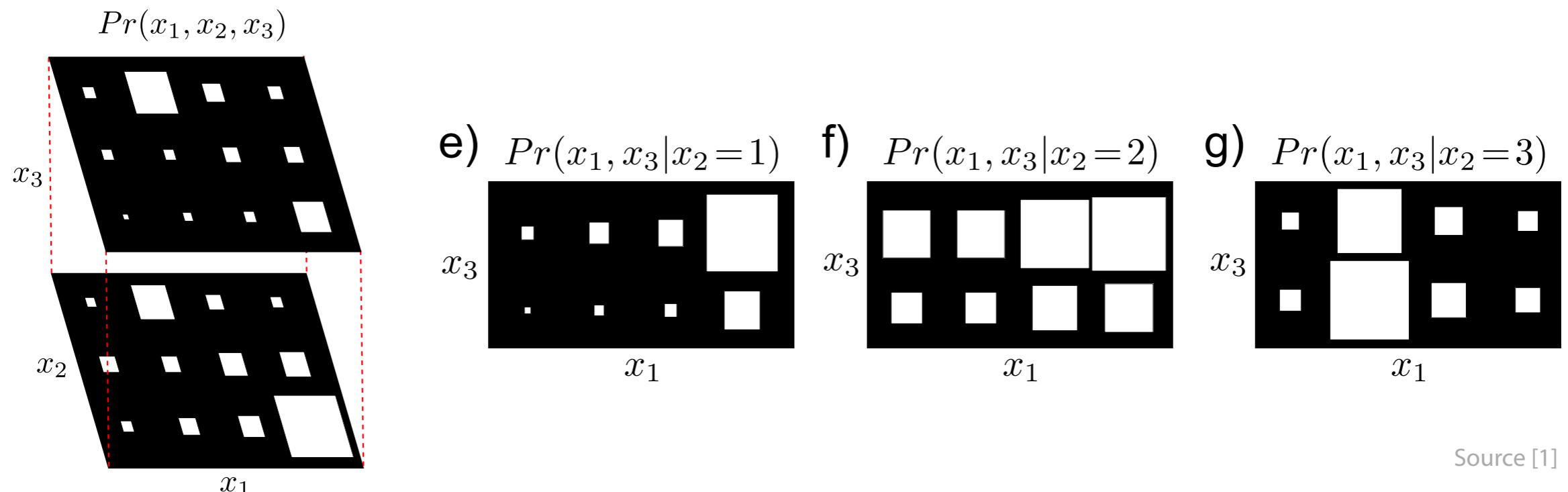


Source [1]

Conditional Independence

Now let's consider **conditional** independence given x_2

- Figures e, f, g: value of x_2 is fixed at 1, 2, 3 respectively



- For fixed x_2 , variable x_1 **tells us nothing more about x_3** and vice versa
- Thus, x_1 **and x_3 are conditionally independent given x_2**

Expectation

- Intuitively, the expected value of a random variable is the value one would “expect” to find if one could **repeat the random variable process an infinite number of times** and take the average of the values obtained
- Let x be a discrete random variable, then the **expectation of x under the distribution p** is

$$E[x] = \sum_x x \cdot p(x)$$

- In the continuous case, we use density functions and integrals

$$E[x] = \int x \cdot p(x) dx$$

- It is a **weighted average** of all possible values where the weights are the corresponding values of the probability mass/density function

Expectation

- For example, if x models the outcome of rolling a fair die, then

$$E[x] = 1 \cdot \frac{1}{6} + 2 \cdot \frac{1}{6} + \dots + 6 \cdot \frac{1}{6} = 3.5$$

- With a biased die where $p(x=6) = 0.5$ and $p(x=x^*) = 0.1$ for $x^* < 6$, then

$$E[x] = 1 \cdot 0.1 + \dots + 5 \cdot 0.1 + 6 \cdot 0.5 = 4.5$$

- Often, we are interested in expectations of a **function of random variables**. Thus, we extend the definition to

$$E[f(x)] = \sum_x f(x) \cdot p(x)$$

$$E[f(x)] = \int f(x) \cdot p(x) dx$$

Expectation

- This idea also generalizes to functions of **more than one** variable

$$E[f(x, y)] = \iint f(x, y) \cdot p(x, y) dx dy$$

- Note however, that any function g of a set of a random variable x , or a set of variables (x_1, x_2, \dots, x_k) is essentially a **new** random variable y
- For some choices of function f , the expectation is given a **special name**

| Function $f(x)$, $f(x, y)$ | Expectation | |
|-----------------------------|---------------------------|---|
| x | mean μ_x | |
| x^k | k -th moment about zero | |
| $(x - \mu_x)^k$ | k -th central moment | Skew and kurtosis are also defined as standardized moments |
| $(x - \mu_x)^2$ | variance | |
| $(x - \mu_x)^3$ | skew | |
| $(x - \mu_x)^4$ | kurtosis | |
| $(x - \mu_x)(y - \mu_y)$ | covariance of x and y | $\frac{(x - \mu_x)^k}{\sigma^k}$ |

Expectation

- The expected value of a specified integer power of the deviation of the random variable from the mean is called **central moment** or **moment about the mean** of a probability distribution

$$\mu_x^k = E[(x - E[x])^k] = \int_{-\infty}^{+\infty} (x - \mu_x)^k \cdot p(x) dx$$

- Ordinary moments (or raw moments) are defined **about zero**
- Moments are used to **characterize the shape** of a distribution
 - The mean is the first raw moment. It's actually a location measure
 - The variance describes the distribution's **width** or **spread**
 - The skew describes – loosely speaking – the extent to which a probability distribution **"leans" to one side** of the mean. A measure of asymmetry
 - The kurtosis is a measure of the **"peakedness"** of the probability distribution

Expectation

- There are four **rules for manipulating expectations**, which can be easily proved from the original definition
- Expected value of a **constant**

$$E[a] = a$$

- Expected value of a **constant times** a random variable

$$E[a \cdot x] = a E[x] \quad \text{thus} \quad E[a \cdot x + b] = a E[x] + b$$

- Expected value of the **sum** of two random variables

$$E[x + y] = E[x] + E[y]$$

- Expected value of the **product** of two random variables

$$E[x \cdot y] = E[x] \cdot E[y] \quad \text{if } x, y \text{ are independent}$$

Expectation

- These properties also apply to **functions of random variables**
- Expected value of a **constant**

$$E[a] = a$$

- Expected value of a **constant times** a function

$$E[a \cdot f(x)] = a E[f(x)] \quad \text{thus } E[af(x)+b] = a E[f(x)]+b$$

- Expected value of the **sum** of two functions

$$E[f(x) + g(x)] = E[f(x)] + E[g(x)]$$

- Expected value of the **product** of two functions

$$E[f(x) \cdot g(x)] = E[f(x)] \cdot E[g(x)] \quad \text{if } x,y \text{ are independent}$$

Variance

- The variance is the **second central moment**, defined as

$$\text{Var}[x] = \mathbb{E}[(x - \mathbb{E}[x])^2] = \int_{-\infty}^{+\infty} (x - \mu_x)^2 \cdot p(x) dx$$

- Alternative formulation $\text{Var}[x] = \mathbb{E}[x^2] - (\mathbb{E}[x])^2$
- Its square root is called the **standard deviation** $\sigma_x = \sqrt{\text{Var}[x]}$
- The **rules for manipulating variances** are as follows

Variance of a **linear function**

$$\text{Var}[a \cdot x + b] = a^2 \cdot \text{Var}[x]$$

Variance of a **sum** of random variables

$$\text{Var}[x + y] = \text{Var}[x] + \text{Var}[y] \quad \text{if } x, y \text{ are independent}$$

- **Introduction to Probability**

- Random variables
- Joint distribution
- Marginalization
- Conditional probability
- Chain rule
- Bayes' rule
- Independence
- Conditional independence
- Expectation and Variance

- **Common Probability Distributions**

- Bernoulli distribution
- Binomial distribution
- Categorical distribution
- Multinomial distribution
- Poisson distribution
- Gaussian distribution
- Chi-squared distribution

We assume that you are familiar with the **fundamentals** of probability theory and probability distributions

This is a quick refresher, we aim at **ease of understanding** rather than formal depth

For a more comprehensive treatment, refer, e.g. to A. Papoulis or the references on the last slide

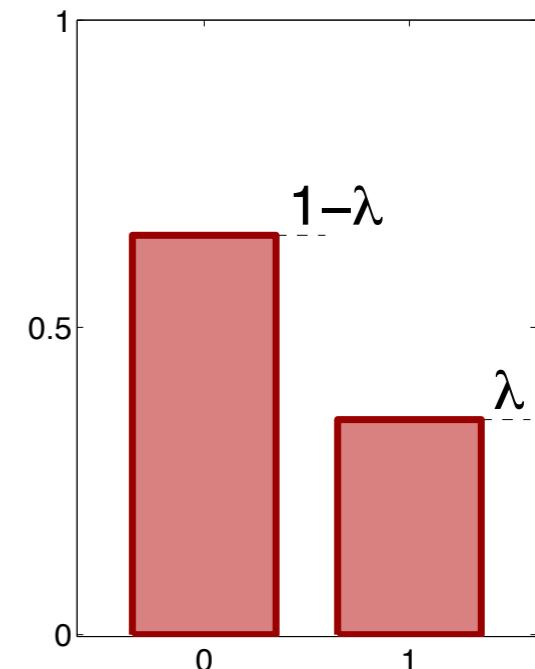
Bernoulli Distribution

- Given a **Bernoulli experiment**, that is, a **yes/no experiment** with outcomes **0** (“failure”) or **1** (“success”)
- The Bernoulli distribution is a **discrete** probability distribution, which takes value 1 with success probability λ and value 0 with failure probability $1 - \lambda$
- Probability mass function**

$$\left. \begin{array}{l} p(x=0) = 1 - \lambda \\ p(x=1) = \lambda \end{array} \right\} \quad p(x) = \lambda^x (1 - \lambda)^{1-x}$$

- Notation**

$$\text{Bern}_x(\lambda) = \lambda^x (1 - \lambda)^{1-x}$$



Parameters

- λ : probability of observing a success

Expectation

- $E[x] = \lambda$

Variance

- $\text{Var}[x] = \lambda(1 - \lambda)$

Common Probability Distributions

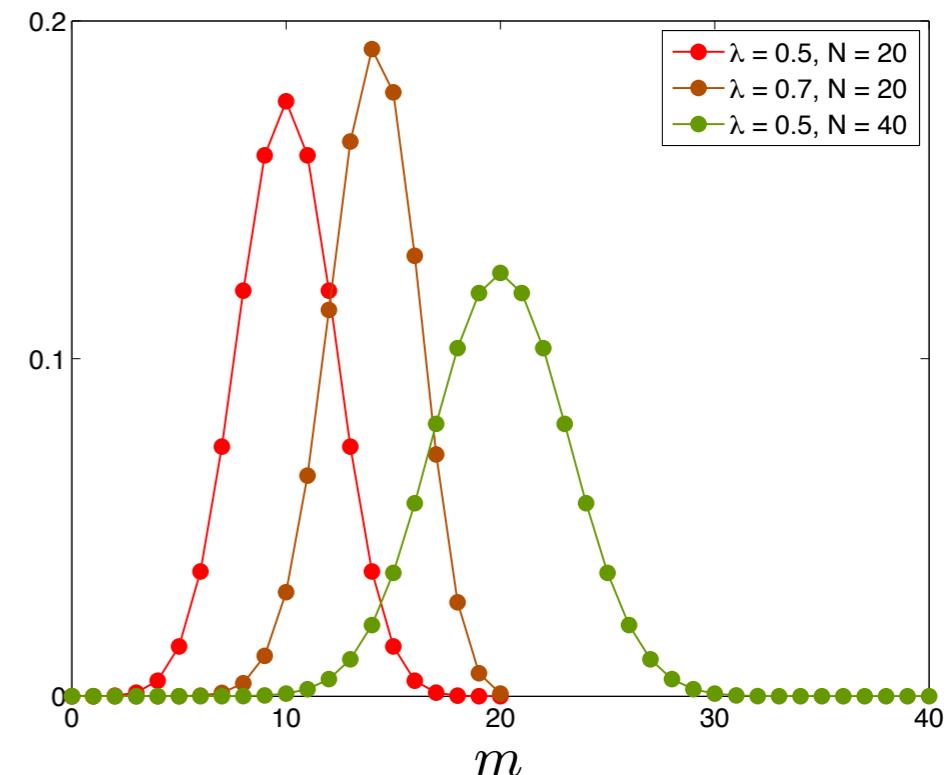
Binomial Distribution

- Given a **sequence** of Bernoulli experiments
- The binomial distribution is the **discrete** probability distribution of the **number of successes** m in a **sequence** of N independent yes/no experiments, each of which yields success with probability λ
- Probability mass function**

$$p(m) = \binom{N}{m} \lambda^m (1 - \lambda)^{N-m}$$

- Notation

$$\text{Bin}_m(N, \lambda) = \binom{N}{m} \lambda^m (1 - \lambda)^{N-m}$$



Parameters

- N : number of trials
- λ : success probability

Expectation

- $E[m] = N \lambda$

Variance

- $\text{Var}[m] = N \lambda(1 - \lambda)$

Common Probability Distributions

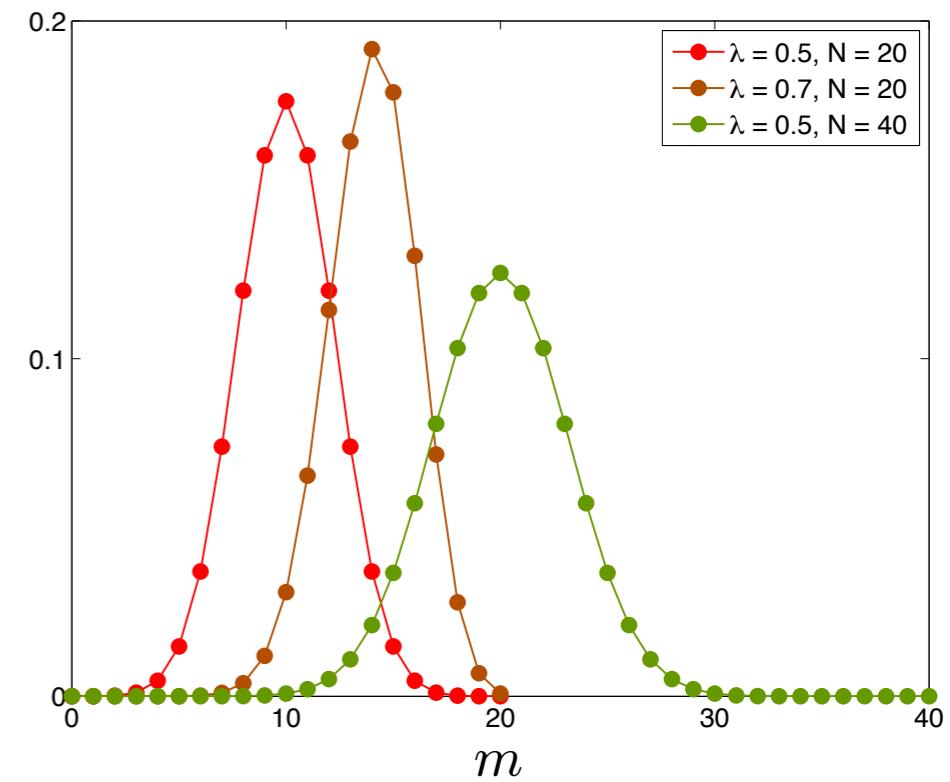
Binomial Distribution

- The quantity

$$\binom{N}{m} = \frac{N!}{m! (N - m)!}$$

is the binomial coefficient (" N choose m ") and denotes the **number of ways of choosing** m objects out of a total of N identical objects

- For $N = 1$, the binomial distribution is the **Bernoulli distribution**
- For fixed expectation $N \lambda$, the Binomial converges towards the **Poisson distribution** as N goes to infinity



Parameters

- N : number of trials
- λ : success probability

Expectation

- $E[m] = N \lambda$

Variance

- $\text{Var}[m] = N \lambda(1 - \lambda)$

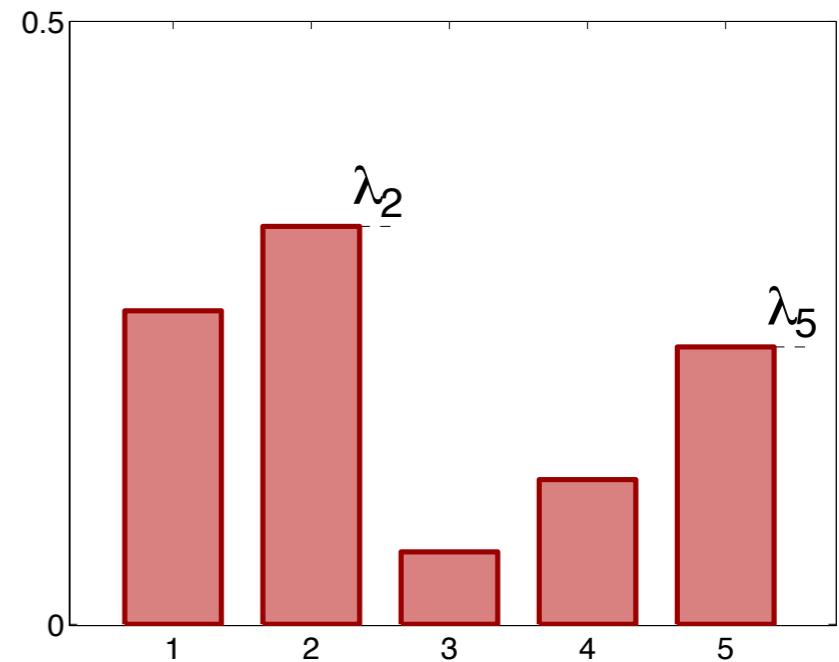
Categorial Distribution

- Considering a single experiment with K **possible outcomes**
- The categorial distribution is a **discrete** distribution that describes the probability of observing **one of K possible outcomes**
- **Generalizes** the Bernoulli distribution
- The probability of each outcome is specified as $\lambda = [\lambda_1, \lambda_2, \dots, \lambda_K]$ with $\sum_{k=1}^K \lambda_k = 1$
- **Probability mass function**

$$p(x = k) = \lambda_k$$

- Notation

$$\text{Cat}_x(\lambda) = p(x)$$



Parameters

- λ : vector of outcome probabilities

Expectation

- $E[x = k] = \lambda_k$

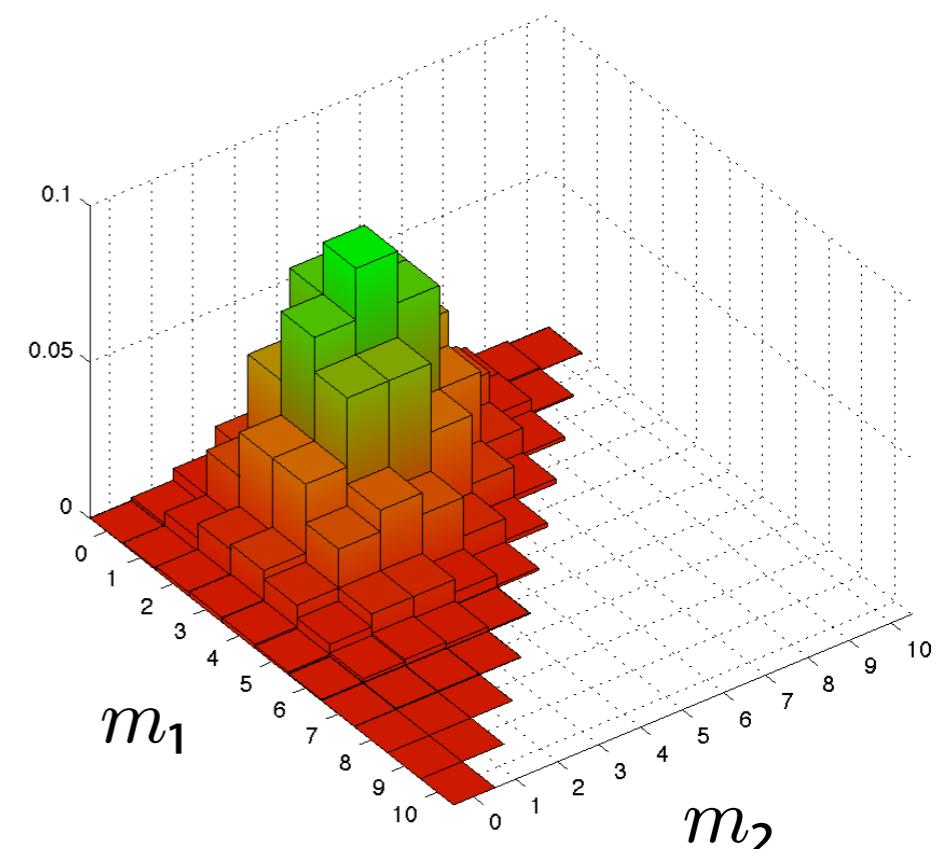
Variance

- $\text{Var}[x = k] = \lambda_k(1 - \lambda_k)$

Common Probability Distributions

Multinomial Distribution

- Given a **sequence** of experiments, each with K **possible outcomes**
- The multinomial distribution is the **discrete** probability distribution of the **number of observations of values** $\{1,2,\dots,K\}$ with **counts** $\{m_1, m_2, \dots, m_K\}$ in a **sequence** of N independent trials
- In other words:
For N independent trials each of which leads to a success for exactly one of K categories, the multinomial distribution gives the **probability of a combination of numbers of successes** for the various categories



Parameters

- N : number of trials
- λ : success probabilities

Expectation

- $E[m_k] = N\lambda_k$

Variance

- $\text{Var}[m_k] = N\lambda_k(1 - \lambda_k)$

Multinomial Distribution

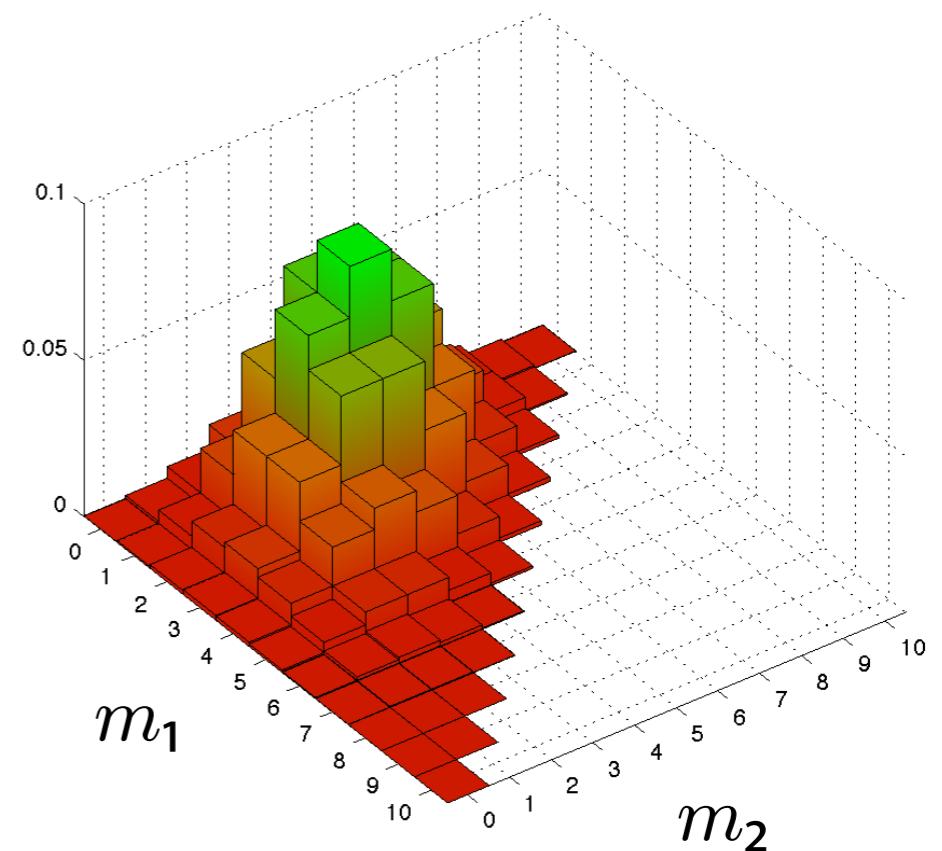
- Each category has a given fixed **success probability** $\lambda = [\lambda_1, \lambda_2, \dots, \lambda_K]$ subject to $\lambda_1 + \lambda_2 + \dots + \lambda_K = 1$
- **Probability mass function**

$$p(m) = \binom{N}{m_1 m_2 \cdots m_K} \lambda_1^{m_1} \lambda_2^{m_2} \cdots \lambda_K^{m_K}$$

- Notation

$$\text{Mult}_{\mathbf{m}}(N, \boldsymbol{\lambda}) = p(m)$$

with $\mathbf{m} = \{m_1, m_2, \dots, m_K\}$



Parameters

- N : number of trials
- $\boldsymbol{\lambda}$: success probabilities

Expectation

- $E[m_k] = N\lambda_k$

Variance

- $\text{Var}[m_k] = N\lambda_k(1 - \lambda_k)$

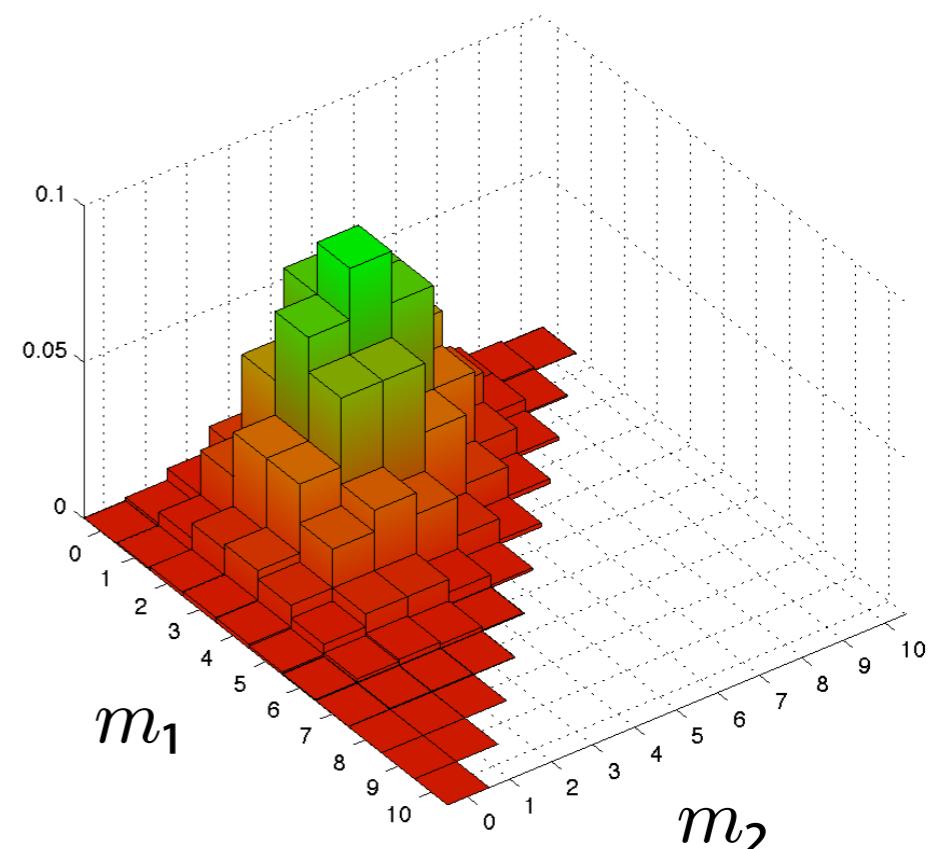
Multinomial Distribution

- The quantity

$$\binom{N}{m_1 m_2 \cdots m_K} = \frac{N!}{m_1! m_2! \cdots m_K!}$$

is the multinomial coefficient and denotes the **number of ways of taking** N identical objects and **assigning** m_k of them to bin k

- Generalizes** the **binomial** distribution to K outcomes
- Generalizes** the **categorical** distribution to sequences of N trials



Parameters

- N : number of trials
- λ : success probabilities

Expectation

- $E[m_k] = N\lambda_k$

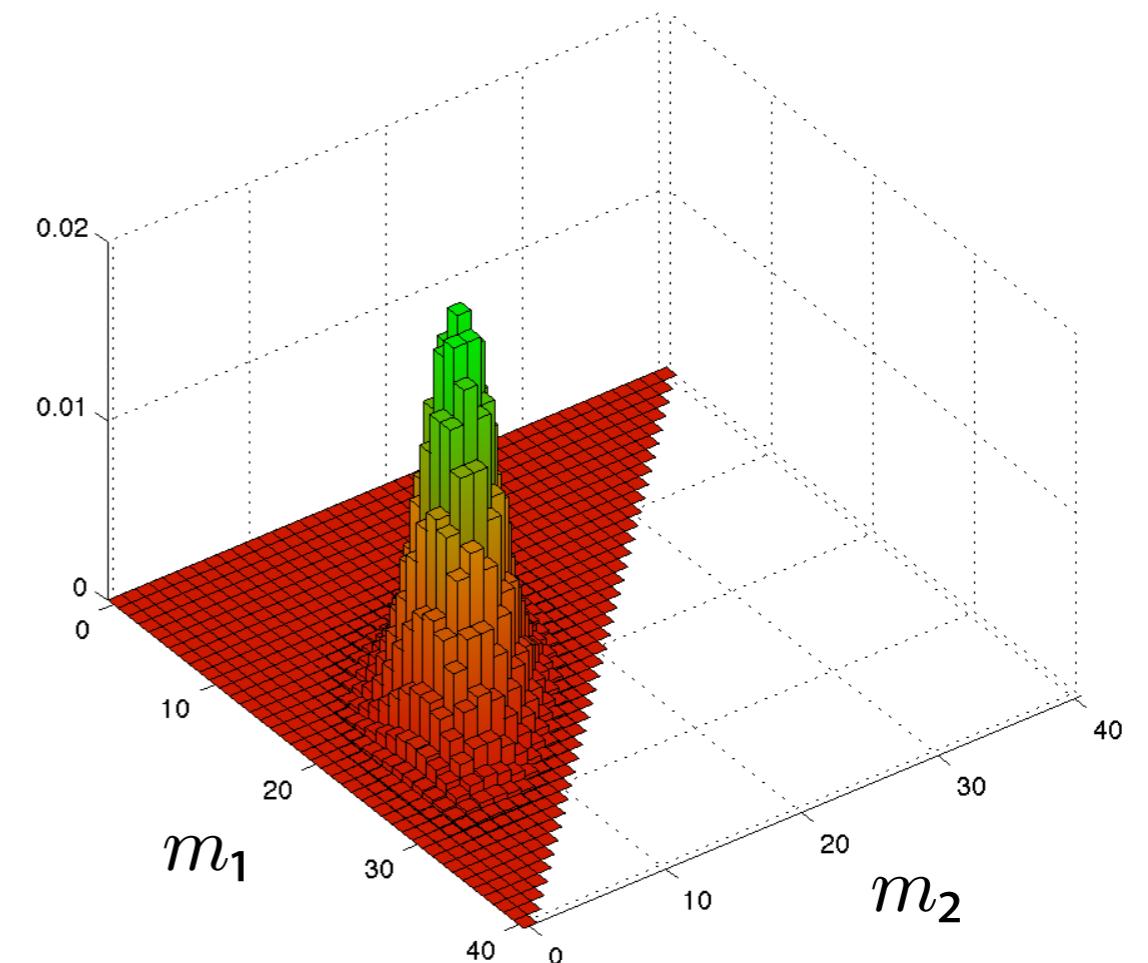
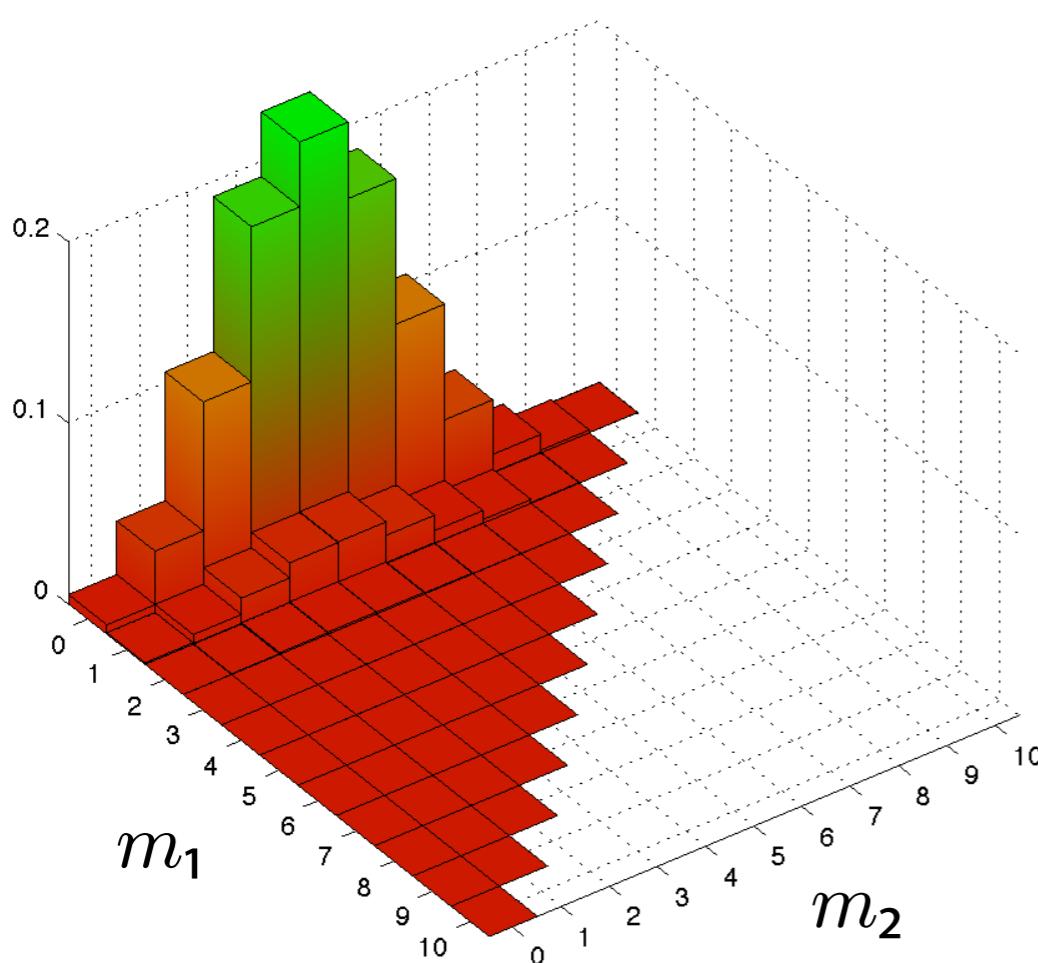
Variance

- $\text{Var}[m_k] = N\lambda_k(1 - \lambda_k)$

Common Probability Distributions

Multinomial Distribution

- $N = 10, \lambda_1 = 0.01, \lambda_2 = 0.4, \lambda_3 = 0.49$
- Maximum at $m_1 = 1, m_2 = 4$
- Showing successes for m_1, m_2
- $N = 40, \lambda_1 = 0.5, \lambda_2 = 0.25, \lambda_3 = 0.25$
- Maximum at $m_1 = 20, m_2 = 10$
- Showing successes for m_1, m_2



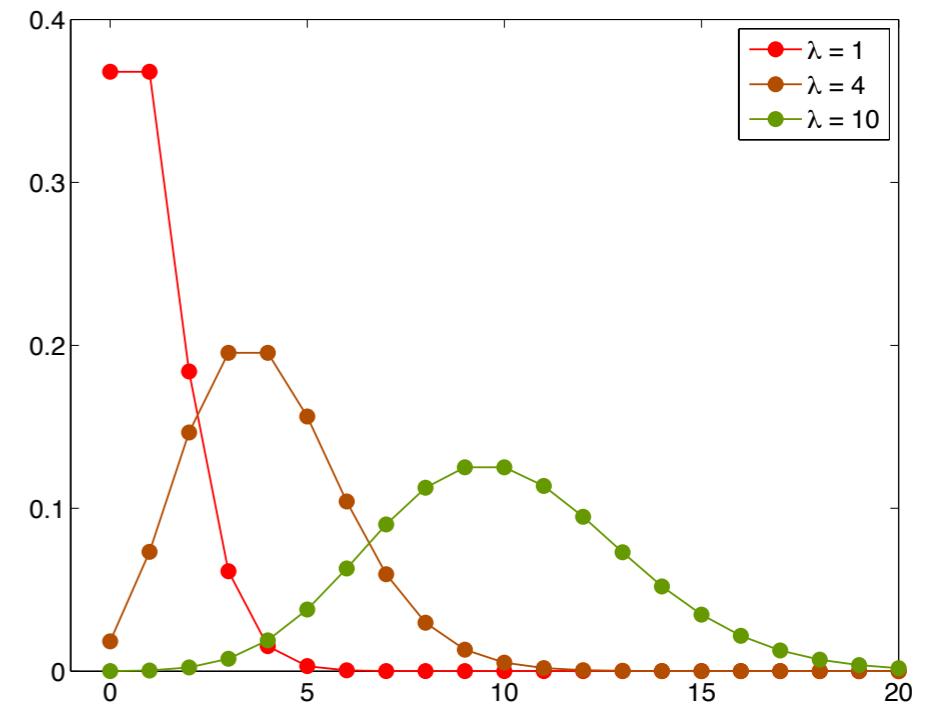
Poisson Distribution

- Consider independent **events** that **happen with an average rate** of λ over time
- The Poisson distribution is a **discrete** distribution that describes the **probability** of a **given number of events** occurring in a **fixed interval of time**
- Can also be defined over other intervals such as **distance, area or volume**
- Probability mass function**

$$p(x) = \frac{\lambda^k e^{-\lambda}}{k!}$$

- Notation

$$\text{Pois}_x(\lambda) = p(x)$$



Parameters

- λ : average rate of events over time or space

Expectation

- $E[x] = \lambda$

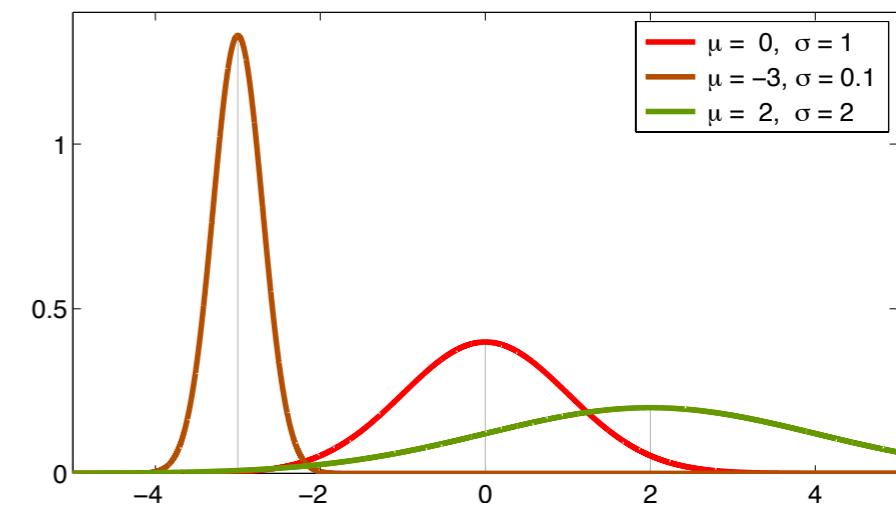
Variance

- $\text{Var}[x] = \lambda$

Gaussian Distribution

- **Most widely** used distribution for **continuous** variables
- Reasons: (i) **simplicity** (fully represented by only two moments, mean and variance) and (ii) the **central limit theorem** (CLT)
- The CLT states that, under mild conditions, the **mean** (or sum) of many independently drawn random variables is distributed approximately **normally**, irrespective of the form of the original distribution
- **Probability density function**

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



Parameters

- μ : mean
- σ^2 : variance

Expectation

- $E[x] = \mu$

Variance

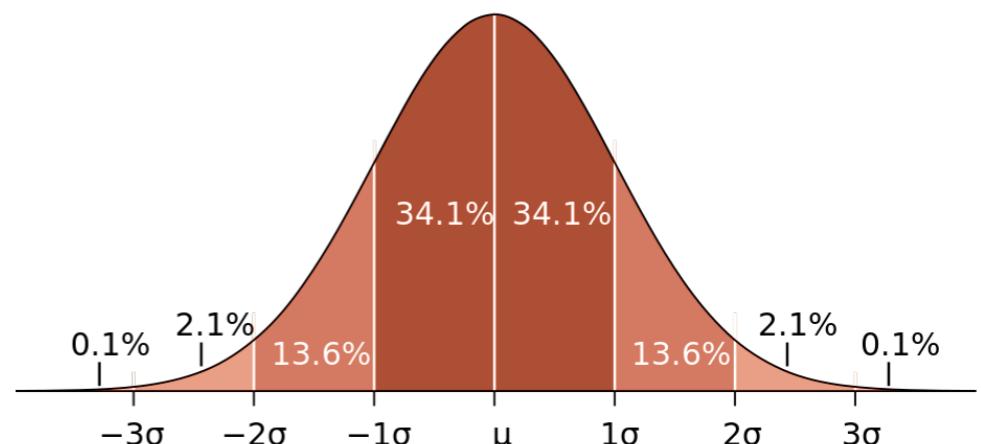
- $\text{Var}[x] = \sigma^2$

Gaussian Distribution

- Notation

$$\mathcal{N}_x(\mu, \sigma^2) = p(x)$$

- Called **standard normal distribution** for $\mu = 0$ and $\sigma = 1$
- About 68%** (~two third) of values drawn from a normal distribution are within a **range of ± 1 standard deviations** around the mean
- About 95%** of the values lie within a **range of ± 2 standard deviations** around the mean
- Important e.g. for **hypothesis testing**



Parameters

- μ : mean
- σ^2 : variance

Expectation

- $E[x] = \mu$

Variance

- $\text{Var}[x] = \sigma^2$

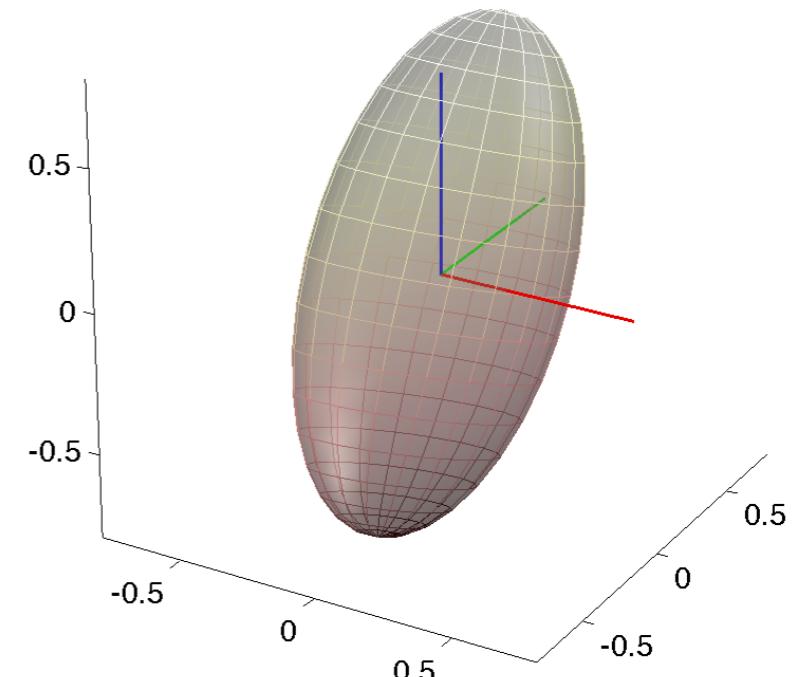
Multivariate Gaussian Distribution

- For d -dimensional random vectors, the **multivariate Gaussian distribution** is governed by a d -dimensional **mean vector** μ and a $D \times D$ **covariance matrix** Σ that must be symmetric and positive semi-definite
- Probability density function**

$$p(\mathbf{x}) = \frac{1}{(2\pi)^{D/2}|\Sigma|^{1/2}} \exp\left\{-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^T \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu})\right\}$$

- Notation

$$\mathcal{N}_x(\boldsymbol{\mu}, \boldsymbol{\Sigma}) = p(\mathbf{x})$$



Parameters

- $\boldsymbol{\mu}$: mean vector
- $\boldsymbol{\Sigma}$: covariance matrix

Expectation

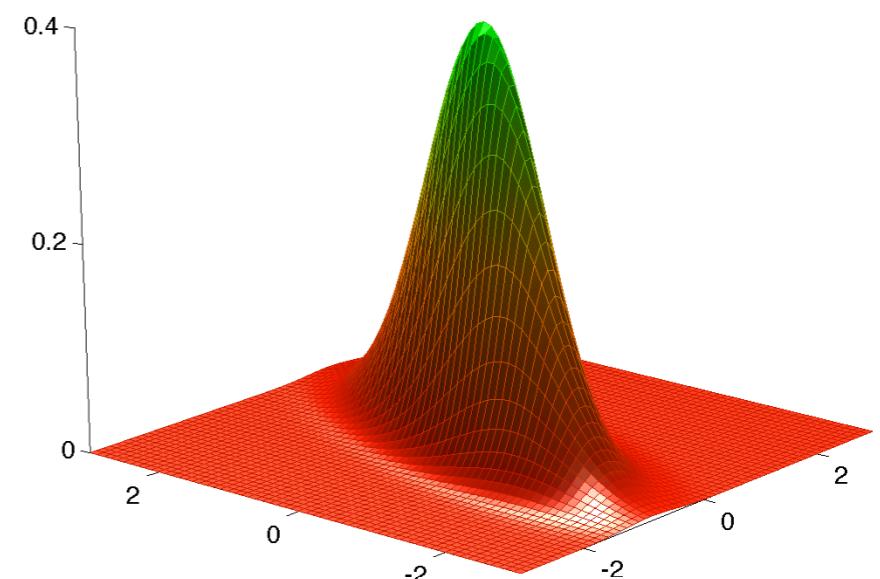
- $E[\mathbf{x}] = \boldsymbol{\mu}$

Variance

- $\text{Var}[\mathbf{x}] = \boldsymbol{\Sigma}$

Multivariate Gaussian Distribution

- For $d = 2$, we have the **bivariate** Gaussian distribution
- The covariance matrix Σ (often C) determines the **shape of the distribution** (video)



Parameters

- μ : mean vector
- Σ : covariance matrix

Expectation

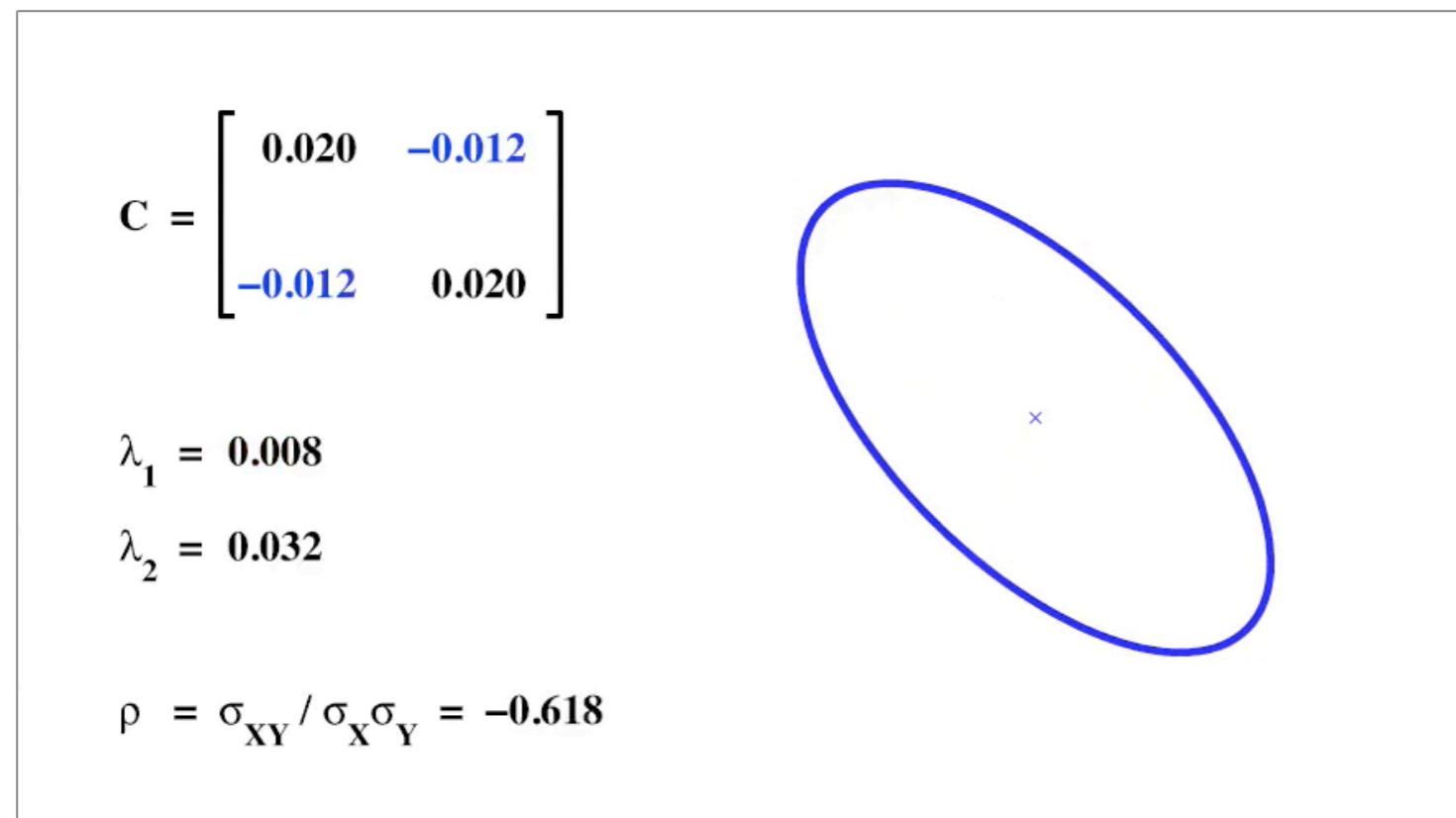
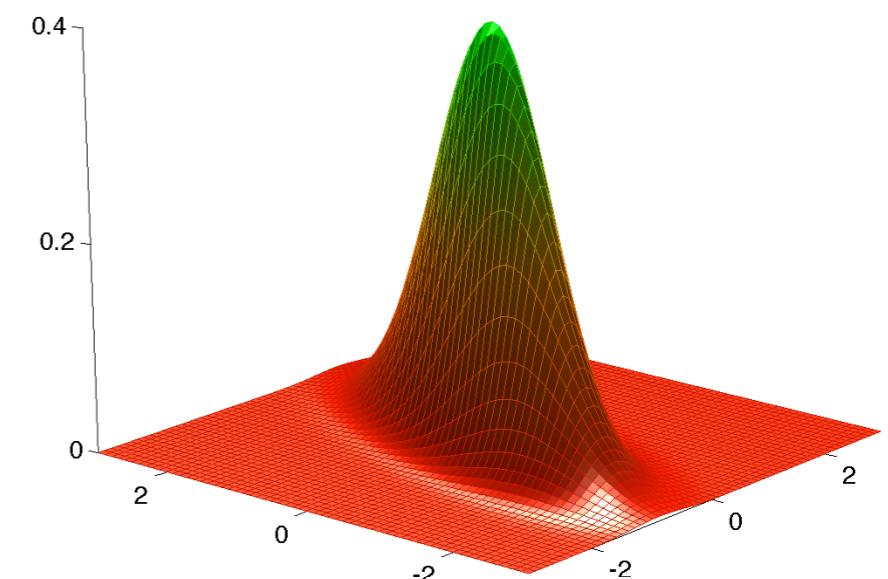
- $E[\mathbf{x}] = \mu$

Variance

- $\text{Var}[\mathbf{x}] = \Sigma$

Multivariate Gaussian Distribution

- For $d = 2$, we have the **bivariate** Gaussian distribution
- The covariance matrix Σ (often C) determines the **shape of the distribution** (video)



Parameters

- μ : mean vector
- Σ : covariance matrix

Expectation

- $E[\mathbf{x}] = \mu$

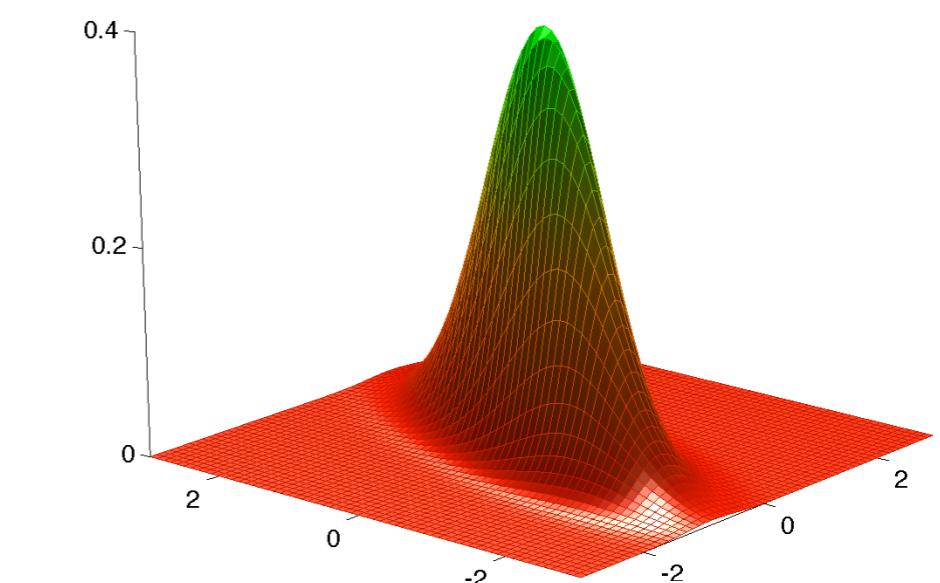
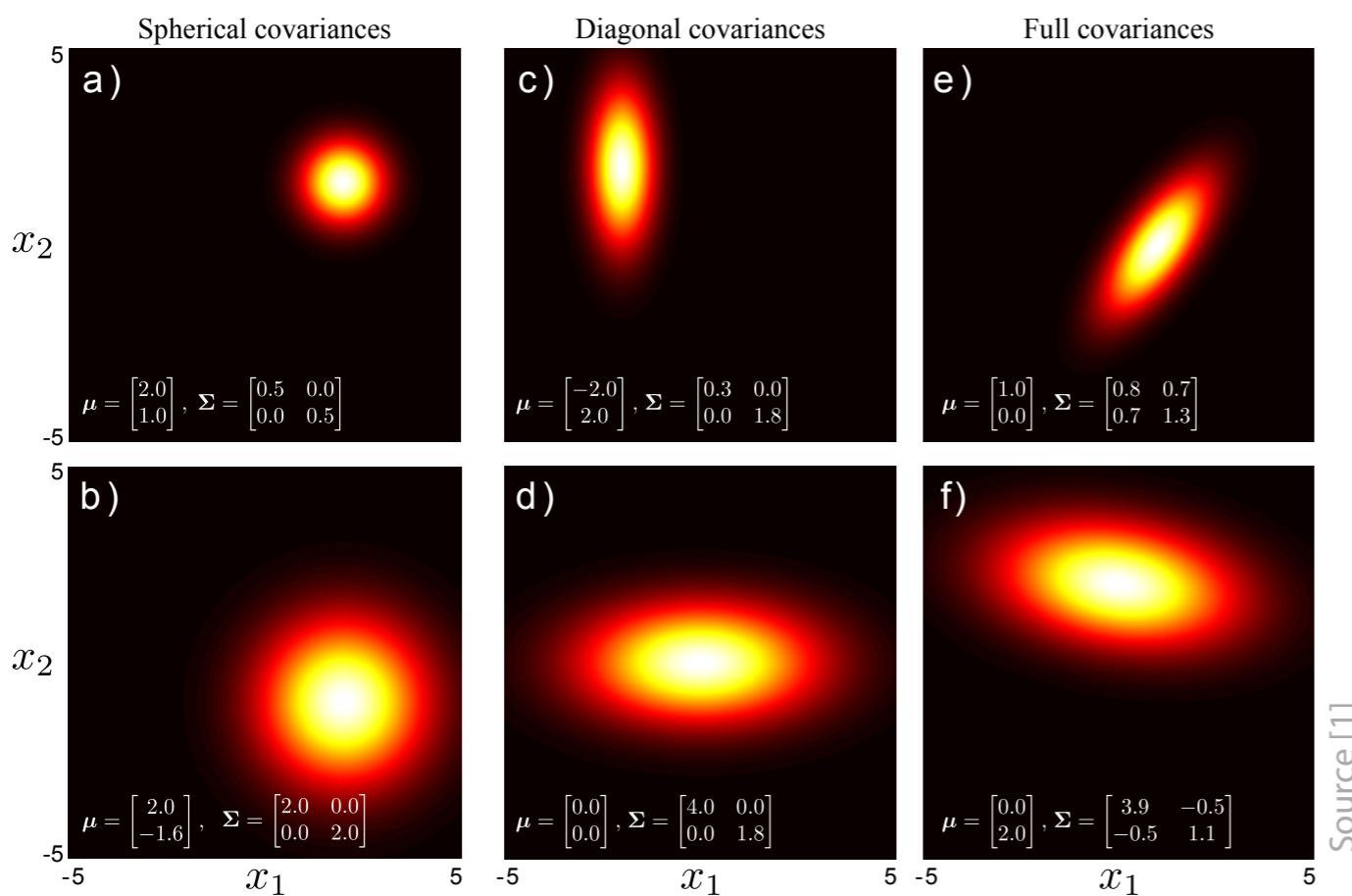
Variance

- $\text{Var}[\mathbf{x}] = \Sigma$

Common Probability Distributions

Multivariate Gaussian Distribution

- For $d = 2$, we have the **bivariate** Gaussian distribution
- The covariance matrix Σ (often C) determines the **shape of the distribution** (video)



Parameters

- μ : mean vector
- Σ : covariance matrix

Expectation

- $E[\mathbf{x}] = \mu$

Variance

- $\text{Var}[\mathbf{x}] = \Sigma$

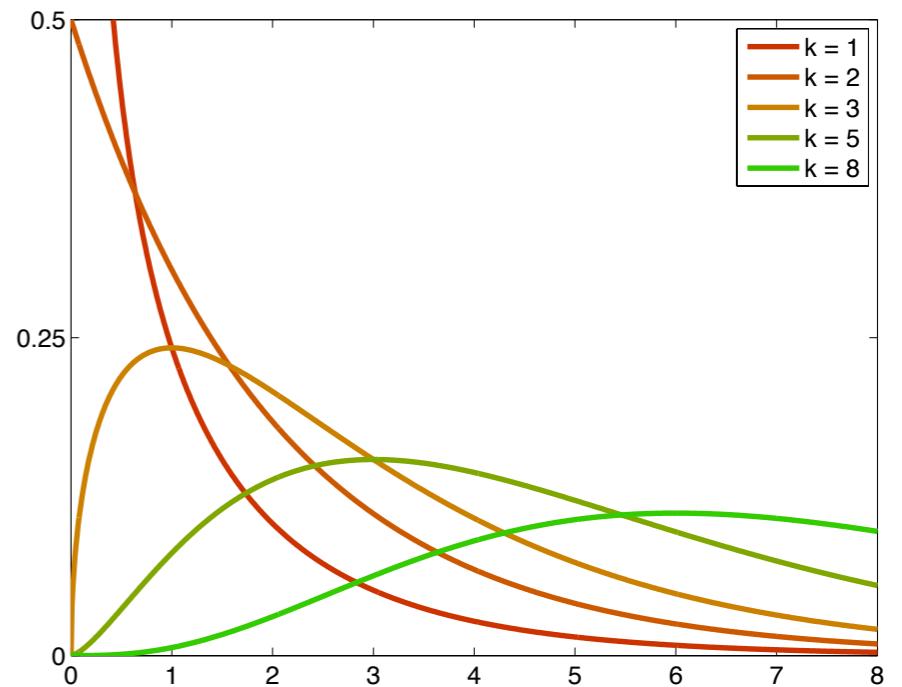
Source [1]

Chi-squared Distribution

- Consider k independent **standard normally distributed** random variables x_i
- The chi-squared distribution is the **continuous** distribution of a **sum of the squares** of k independent standard normal random variables

$$q = \sum_{i=1}^k x_i^2 \quad q \sim \chi_k^2$$

- Parameter** k is called the number of “degrees of freedom”
- It is one of the **most widely** used probability distributions in statistical inference, e.g., in hypothesis testing



Parameters

- k : degrees of freedom

Expectation

- $E[x] = k$

Variance

- $\text{Var}[x] = 2k$

Chi-squared Distribution

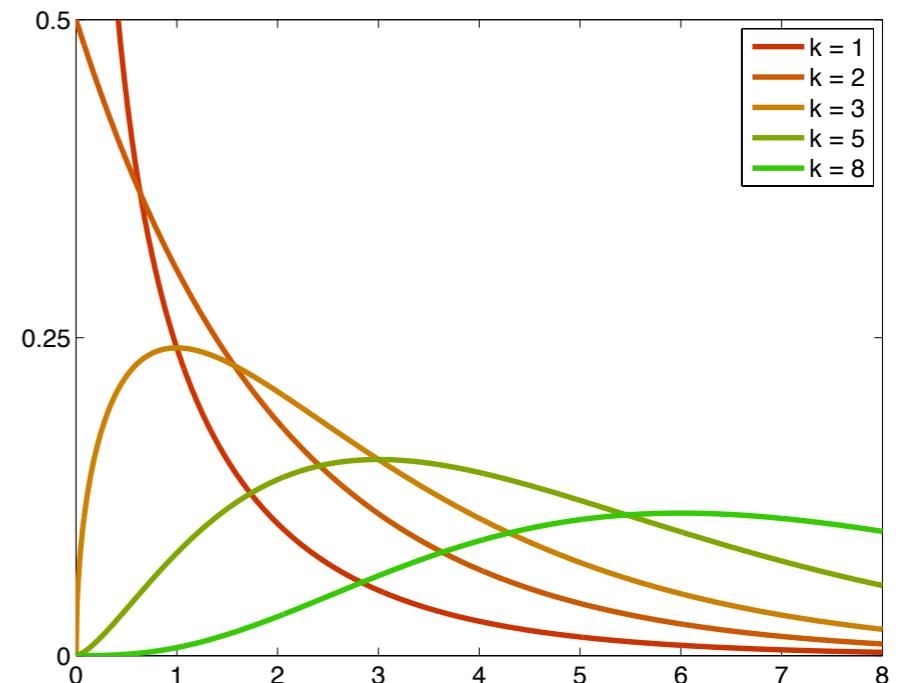
- **Probability density function** (for $x \geq 0$)

$$p(x) = \frac{x^{\frac{k}{2}-1} e^{-\frac{x}{2}}}{2^{\frac{k}{2}} \Gamma\left(\frac{k}{2}\right)}$$

- Notation

$$\chi_x^2(k) = \chi_k^2 = p(x)$$

- For **hypothesis testing**, values of the **cumulative distribution function** are taken, typically from tables in statistics text books or online sources



Parameters

- k : degrees of freedom

Expectation

- $E[x] = k$

Variance

- $\text{Var}[x] = 2k$

- **Uncertainty** is an **inescapable aspect** of every system in the real world
- Probability theory is a **very powerful framework** to represent, propagate, reduce and reason about uncertainty
- The rules of probability are **remarkably compact and simple**
- The concepts of **marginalization**, **joint** and **conditional probability**, **independence** and **conditional independence** underpin many today algorithms in robotics, machine learning, computer vision and AI
- Two immediate results of the definition of conditional probability are **Bayes' rule** and the **chain rule**
- Together with the **sum rule** (marginalization) they form the foundation of even the most advanced inference and learning methods. Memorize them!
- There are also **alternative approaches to uncertainty representation**
 - Fuzzy logic, possibility theory, set theory, belief functions, qualitative uncertainty representations

Sources Used for These Slides and Further Reading

The first section, Introduction to Probability, follows to large parts chapter 2 of Prince et al. [1], in particular also the nice figures are taken from this book. The section also contains material from chapters 1 and 2 in Koller and Friedman [2].

Another good compact summary of probability theory can be found in the book by Bishop [3]. A comprehensive treatment of probability theory is, for instance, the book by Papoulis and Pillai [4].

- [1] S.J.D. Prince, "Computer vision: models, learning and inference", Cambridge University Press, 2012. See www.computervisionmodels.com
- [2] D. Koller, N. Friedman, "Probabilistic graphical models: principles and techniques", MIT Press, 2009. See <http://pgm.stanford.edu>
- [3] C.M. Bishop, "Pattern Recognition and Machine Learning", Springer, 2nd ed., 2007. See <http://research.microsoft.com/en-us/um/people/cmbishop/prml>
- [4] A. Papoulis, S.U. Pillai, "Probability, Random Variables and Stochastic Processes", McGraw-Hill, 4th edition, 2002. See <http://www.mhhe.com/engcs/electrical/papoulis>