

[70240413 Statistical Machine Learning, Spring, 2015]

# Unsupervised Learning

## Clustering

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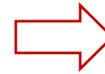
Tsinghua University

March 10, 2015

# Unsupervised Learning

- ◆ **Task:** learn an explanatory function  $f(x), x \in \mathcal{X}$
- ◆ Aka “Learning without a teacher”

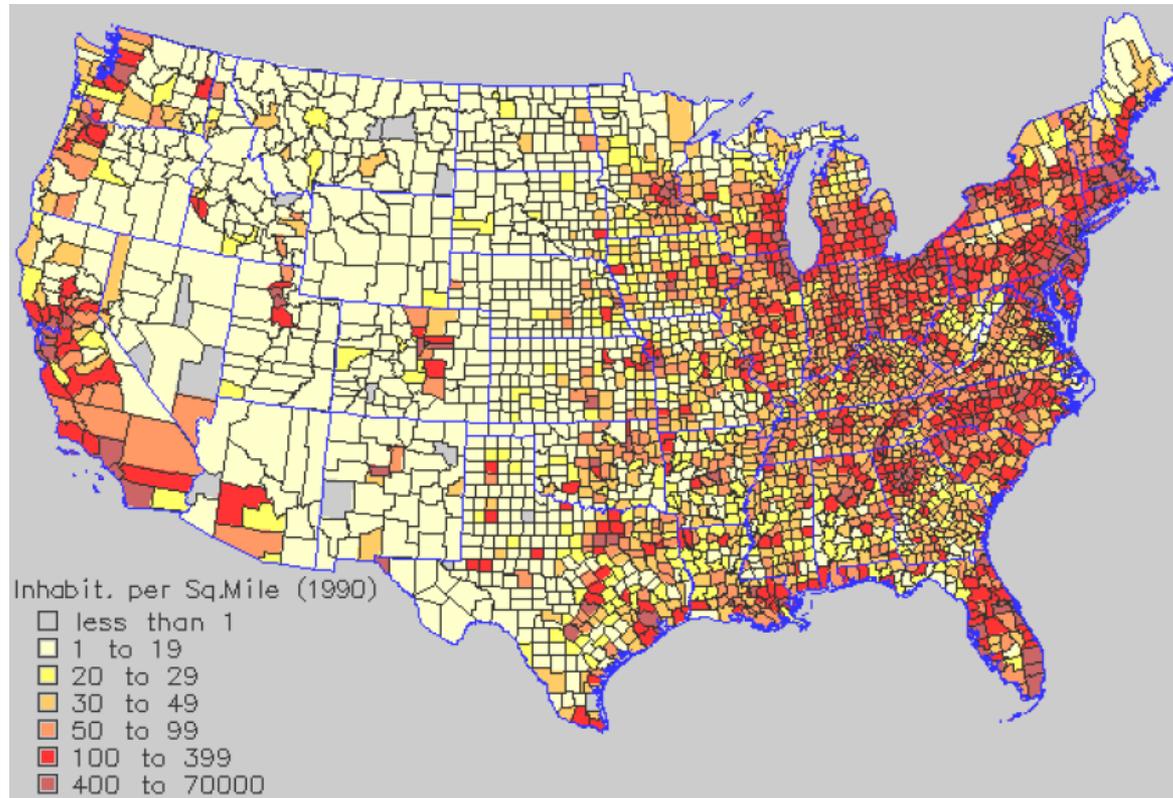
Feature space  $\mathcal{X}$



Word distribution  
(probability of a word)

- ◆ No training/test split

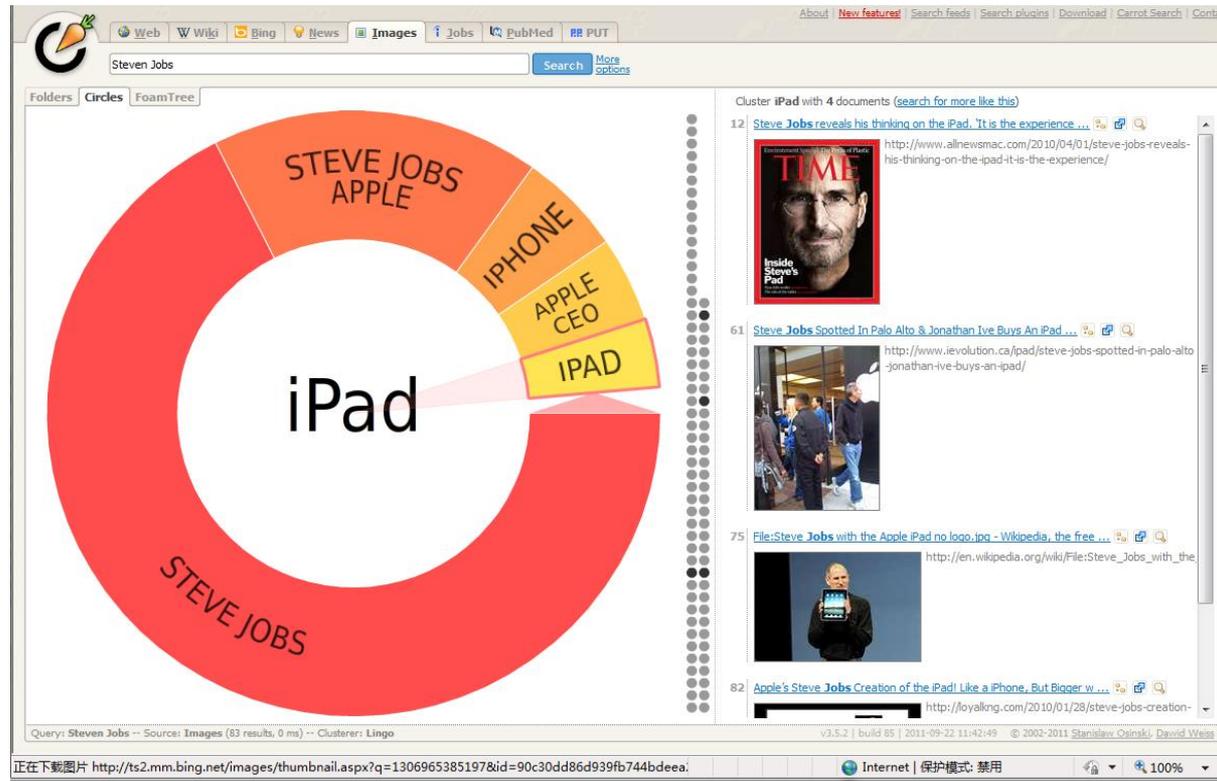
# Unsupervised Learning – density estimation



**Feature** space  $\mathcal{X}$   
geographical information of a location

Density function  
 $f(x), x \in \mathcal{X}$

# Unsupervised Learning – clustering



<http://search.carrot2.org/stable/search>

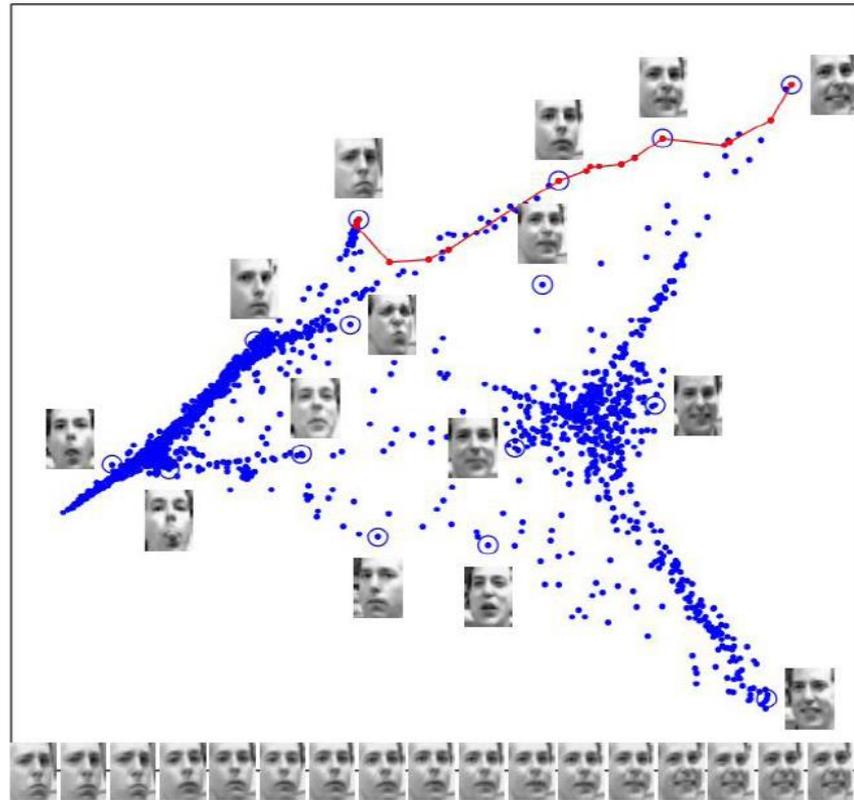
**Feature** space  $\mathcal{X}$   
Attributes (e.g., pixels & text) of images

Cluster assignment function  
 $f(x), x \in \mathcal{X}$

# Unsupervised Learning – dimensionality reduction

Images have thousands or millions of pixels

Can we give each image a coordinate, such that similar images are near each other ?



**Feature** space  $\mathcal{X}$   
pixels of images

Coordinate function in 2D space

$$f(x), x \in \mathcal{X}$$

# **Clustering**

## **(K-Means, Gaussian Mixtures)**

# What is clustering?

- ◆ Clustering: the process of grouping a set of objects into classes of similar objects
  - High intra-class similarity
  - Low inter-class similarity
- ◆ A common and important task that finds many applications in science, engineering, information science, etc
  - Group genes that perform the same function
  - Group individuals that has similar political view
  - Categorize documents of similar topics
  - Identify similar objects from pictures
  - ...

# The clustering problem

- ◆ **Input:** training data  $D = \{\mathbf{x}_1, \dots, \mathbf{x}_N\}$ , where  $\mathbf{x} \in \mathbb{R}^d$ , integer  $K$  clusters
- ◆ **Output:** a set of clusters  $C_1, \dots, C_K$

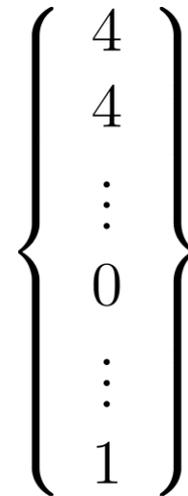
## Machine learning

From Wikipedia, the free encyclopedia

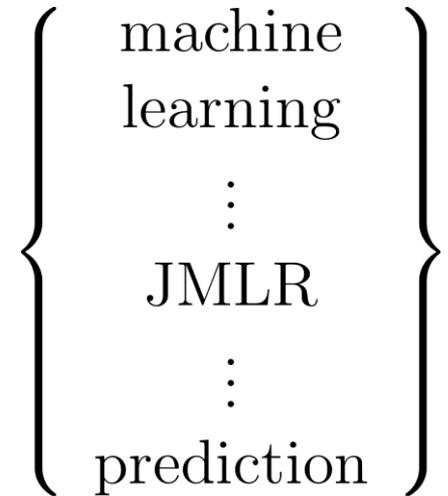
*For the journal, see [Machine Learning \(journal\)](#).*

*See also: [Pattern recognition](#)*

**Machine learning** is a scientific discipline that explores the construction and study of algorithms that can learn from data. [1] Such algorithms operate by building a model from example inputs and using that to make predictions or decisions, [2]:2 rather than following strictly static program instructions. Machine learning is closely related to and often overlaps with computational statistics; a discipline which also specializes in prediction-making.



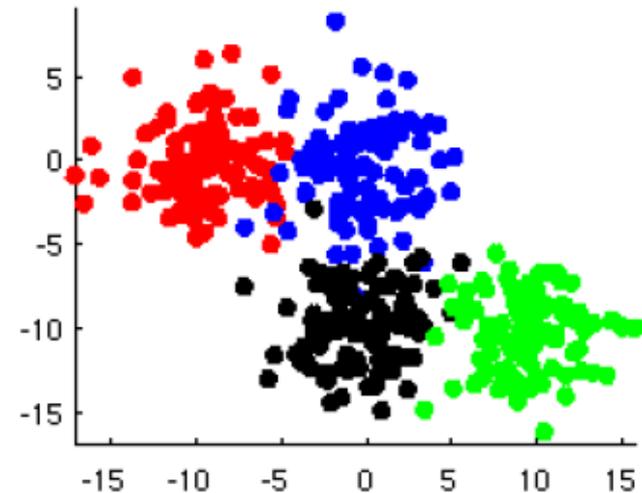
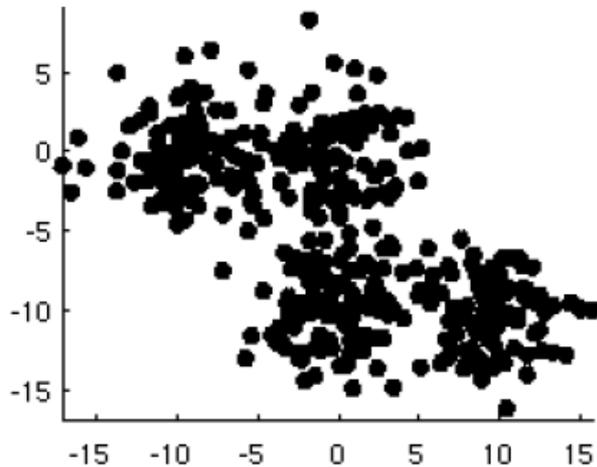
Word Vector Space



Vocabulary

# The clustering problem

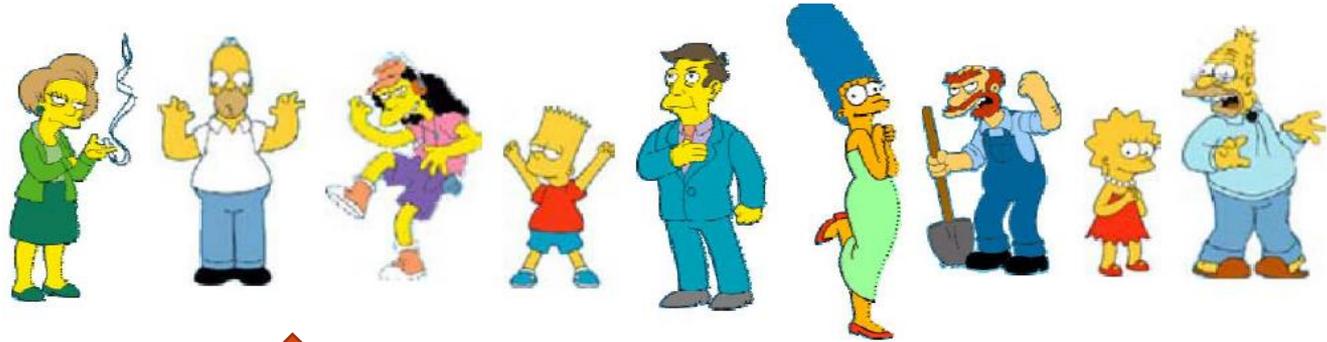
- ◆ **Input:** training data  $D = \{\mathbf{x}_1, \dots, \mathbf{x}_N\}$ , where  $\mathbf{x} \in \mathbb{R}^d$ , integer  $K$  clusters
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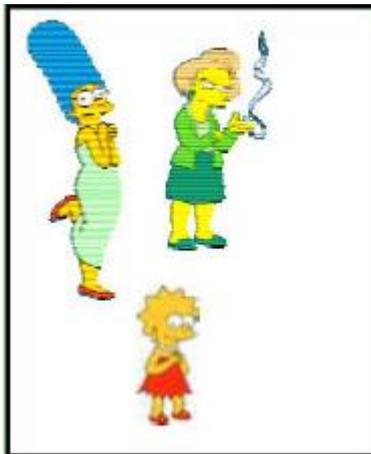
# Issues for clustering

- ◆ What is a natural grouping among these objects?
  - Definition of “groupness”
- ◆ What makes objects “related”?
  - Definition of “similarity/distance”
- ◆ Representation for objects
  - Vector space? Normalization?
- ◆ How many clusters?
  - Fixed a priori?
  - Completely data driven?
- ◆ Clustering algorithms
  - Partitional algorithms
  - Hierarchical algorithms
- ◆ Formal foundation and convergence

# What is a natural grouping among objects?



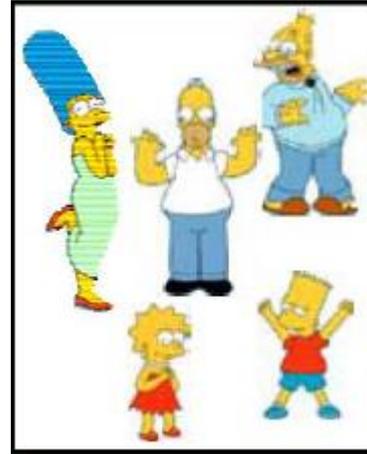
Clustering is subjective



Females



Males



Simpson's Family



School Employees

# What is similarity?



- ◆ The real meaning of similarity is a philosophical question.
- ◆ Depends on representation and algorithm. For many rep./alg., easier to think in terms of distance (rather than similarity) between vectors

# Desirable distance measure properties

- ◆  $d(A,B) = d(B,A)$  Symmetry
  - Otherwise you could claim “Alex looks like Bob, but Bob looks nothing like Alex”
- ◆  $d(A,A) = 0$  Constancy of Self-Similarity
  - Otherwise you could claim “Alex looks more like Bob, than Bob does”
- ◆  $d(A,B) = 0$  iff  $A=B$  Positivity Separation
  - Otherwise there are objects that are different, but you can't tell apart
- ◆  $d(A,B) \leq d(A,C)+d(B,C)$  Triangular Inequality
  - Otherwise you could claim “Alex is very like Bob, and Alex is very like Carl, but Bob is very unlike Carl”

# Minkowski Distance

$$\text{dist}(\mathbf{x}, \mathbf{y}) = \sqrt[r]{\sum_{i=1}^d |x_i - y_i|^r}$$

## ◆ Common Minkowski distances

- Euclidean distance ( $r=2$ ):

$$\text{dist}(\mathbf{x}, \mathbf{y}) = \sqrt{\sum_{k=1}^d (x_k - y_k)^2} = \|\mathbf{x} - \mathbf{y}\|_2$$

- Manhattan distance ( $r=1$ ):

$$\text{dist}(\mathbf{x}, \mathbf{y}) = \sum_{k=1}^d |x_k - y_k| = \|\mathbf{x} - \mathbf{y}\|_1$$

- “Sup” distance ( $r = \infty$ ):

$$\text{dist}(\mathbf{x}, \mathbf{y}) = \sup_{k=1}^d |x_k - y_k| = \|\mathbf{x} - \mathbf{y}\|_\infty$$

# Hamming distance

- ◆ Manhattan distance is called Hamming distance when all features are binary

- E.g., gene expression levels under 17 conditions (1-high; 0-low)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
<i>GeneA</i>	0	1	1	0	0	1	0	0	1	0	0	1	1	1	0	0	1
<i>GeneB</i>	0	1	1	1	0	0	0	0	1	1	1	1	1	1	0	1	1

- Hamming distance:  $\#(0\ 1) + \#(1\ 0) = 4 + 1 = 5$

# Correlation coefficient

◆ Pearson correlation coefficient

$$s(\mathbf{x}, \mathbf{y}) = \frac{(\mathbf{x} - \bar{x}\mathbf{1})^\top (\mathbf{y} - \bar{y}\mathbf{1})}{\|\mathbf{x} - \bar{x}\mathbf{1}\|_2 \|\mathbf{y} - \bar{y}\mathbf{1}\|_2}$$

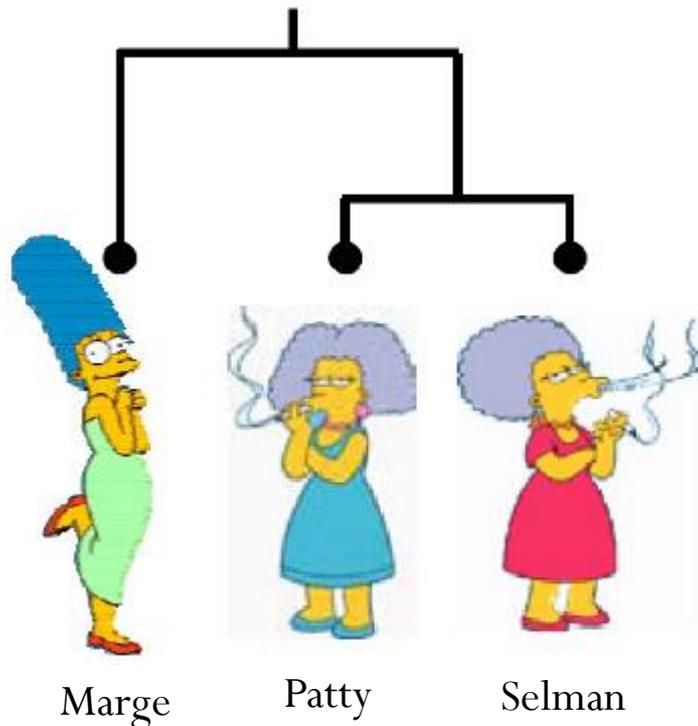
$$\text{where } \bar{x} = \frac{1}{d} \sum_i x_i, \quad \bar{y} = \frac{1}{d} \sum_i y_i$$

□ Cosine Similarity:

$$\cos(\mathbf{x}, \mathbf{y}) = \frac{\mathbf{x}^\top \mathbf{y}}{\|\mathbf{x}\|_2 \|\mathbf{y}\|_2}$$

# Edit Distance

- ◆ To measure the similarity between two objects, transform one into the other, and measure how much effort it took. The measure of effort becomes the distance measure



## The distance between Patty and Selma.

- Change dress color, 1 point
- Change earring shape, 1 point
- Change hair part, 1 point

$$D(\text{Patty}, \text{Selma}) = 3$$

## The distance between Marge and Selma

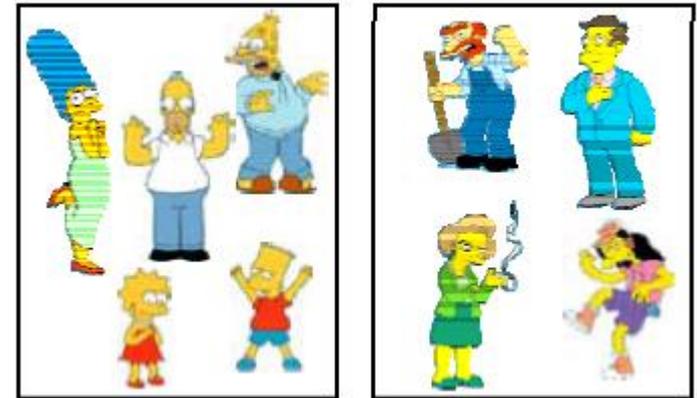
- Change dress color, 1 point
- Add earrings, 1 point
- Decrease height, 1 point
- Take up smoking, 1 point
- Loss weight, 1 point

$$D(\text{Marge}, \text{Selma}) = 5$$

# Clustering algorithms

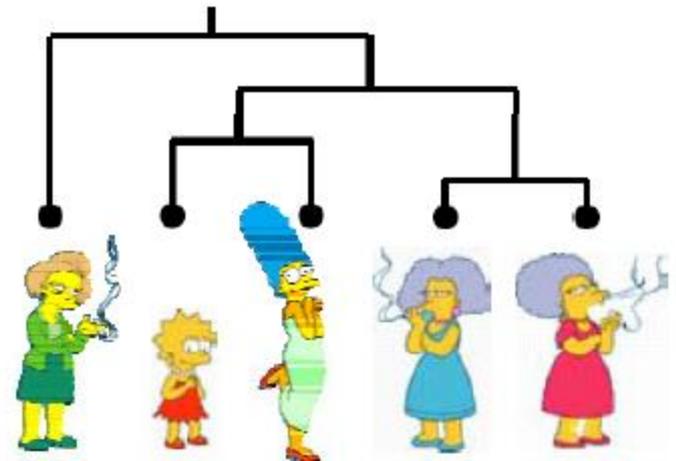
## ◆ Partitional algorithms

- Usually start with a random (partial) partitioning
- Refine it iteratively
  - K-means
  - Mixture-Model based clustering



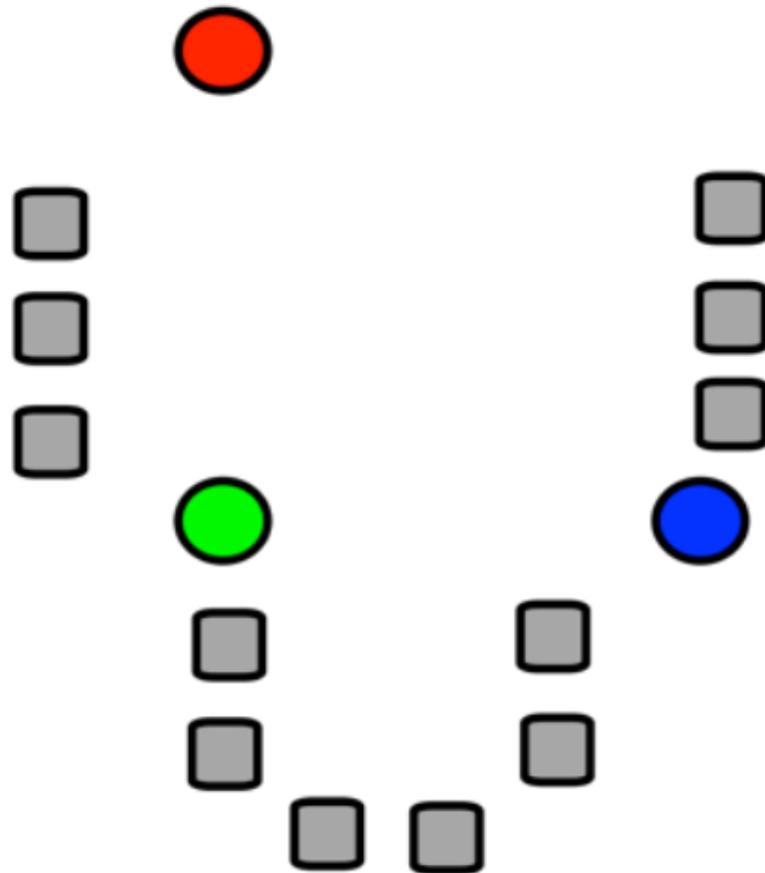
## ◆ Hierarchical algorithms

- Bottom-up, agglomerative
- Top-down, divisive



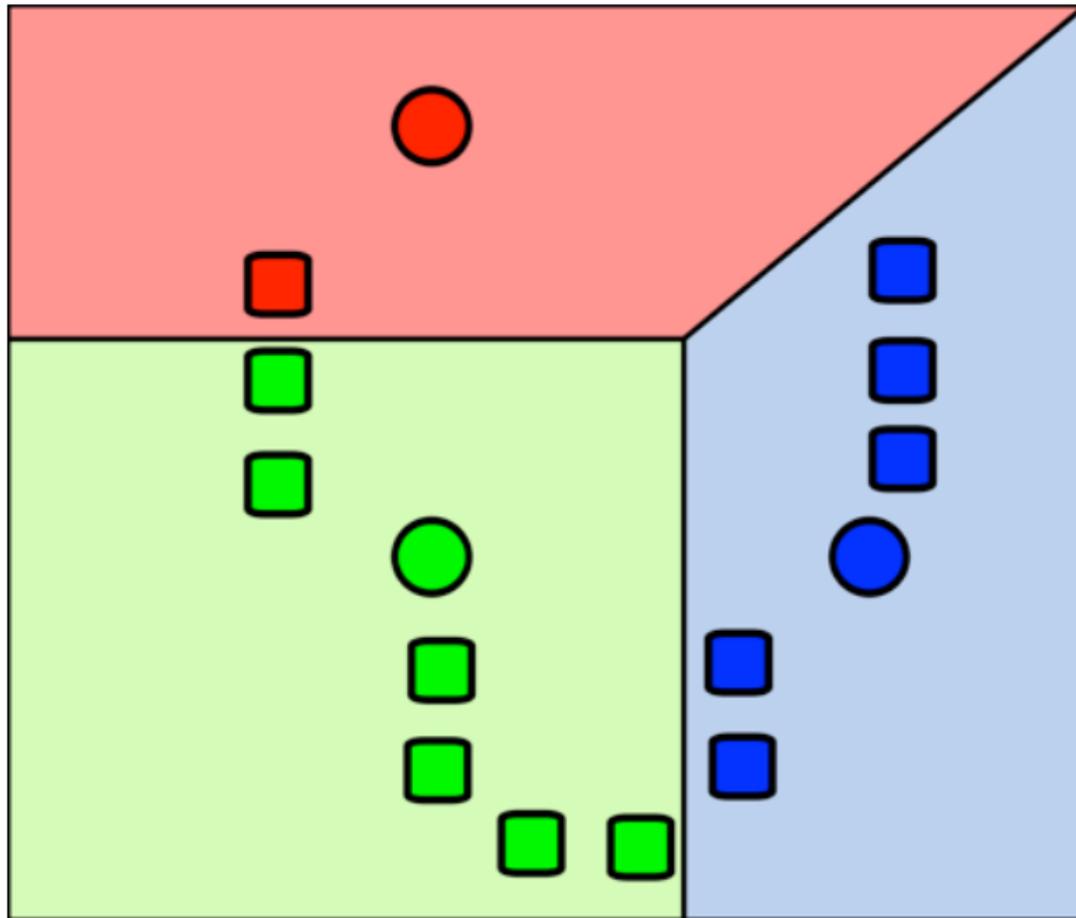
# K-means Algorithm

- ◆ 1. Initialize the centroids  $\mu_1, \dots, \mu_K$



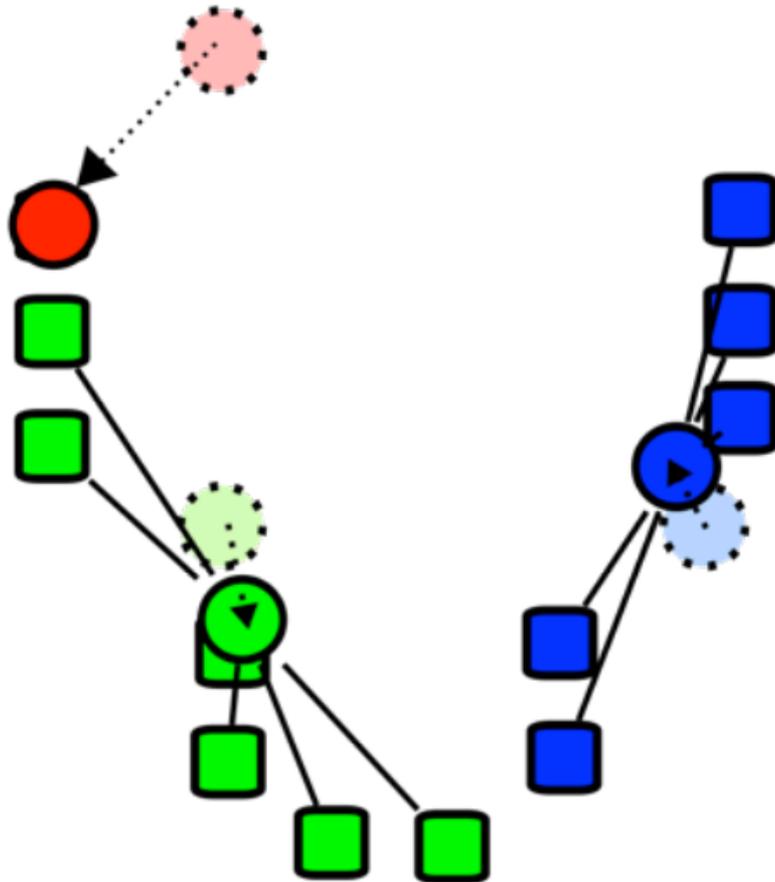
# K-means Algorithm

- ◆ 2. for each  $k$ ,  $C_k = \{i, \text{ s.t. } \mathbf{x}_i \text{ is closest to } \boldsymbol{\mu}_k\}$



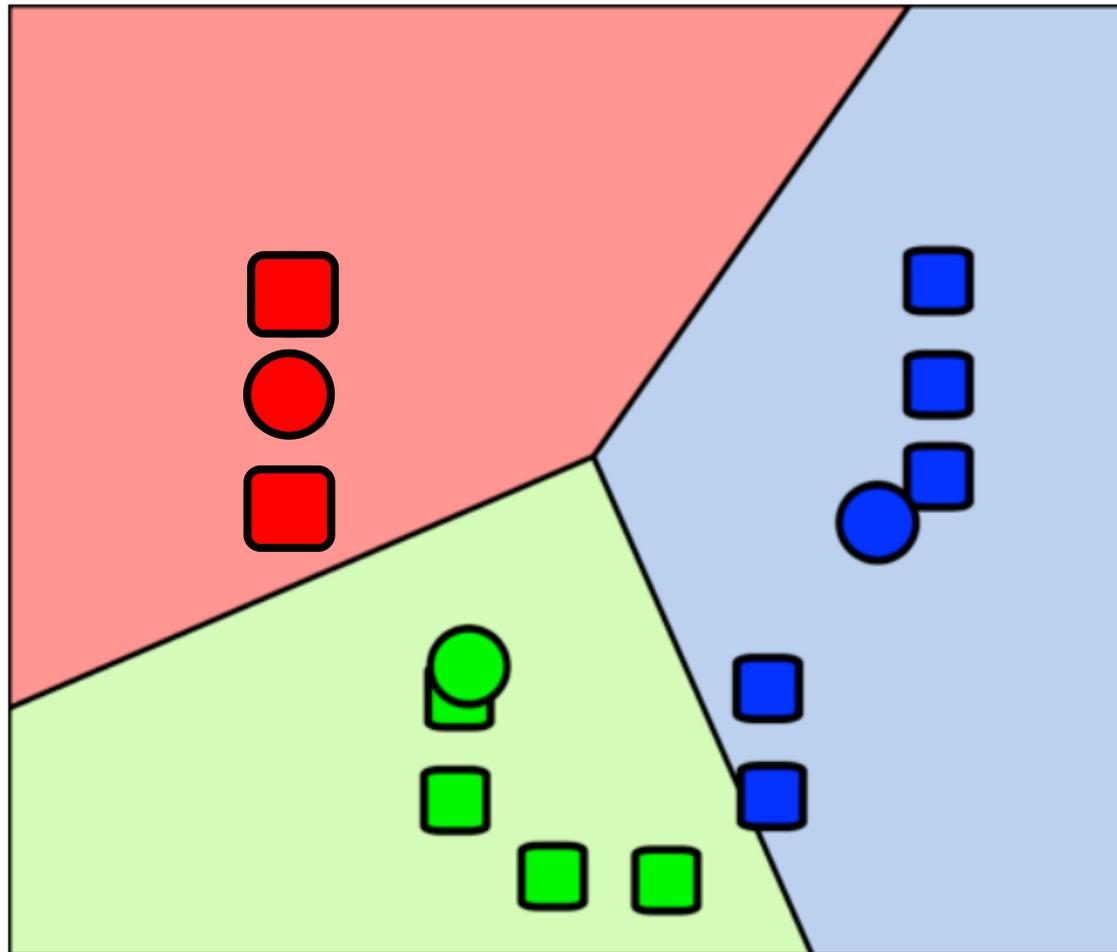
# K-means Algorithm

- ◆ 3. for each  $k$ ,  $\mu_k \leftarrow \frac{1}{|C_k|} \sum_{j \in C_k} \mathbf{x}_j$  (sample mean)



# K-means Algorithm

- ◆ Repeat until no further change in cluster assignment



# Summary of K-means Algorithm

- ◆ 1. Initialize centroids  $\mu_1, \dots, \mu_K$
- ◆ 2. Repeat until no change of cluster assignment

- (1) for each  $k$ :

$$C_k = \{i, \text{ s.t. } \mathbf{x}_i \text{ is closest to } \mu_k\}$$

- (2) for each  $k$ :

$$\mu_k \leftarrow \frac{1}{|C_k|} \sum_{j \in C_k} \mathbf{x}_j$$

- ◆ **Note:** each iteration requires  $O(NK)$  operations

# K-means Questions

- ◆ What is it trying to optimize?
- ◆ Are we sure it will terminate?
- ◆ Are we sure it will find an optimal clustering?
- ◆ How should we start it?
- ◆ How could we automatically choose the number of centers?

# Theory: K-Means as an Opt. Problem

◆ The opt. problem

$$\begin{aligned} \min_{\{C_k\}_{k=1}^K} \quad & \sum_{k=1}^K \sum_{\mathbf{x} \in C_k} \|\mathbf{x} - \boldsymbol{\mu}_k\|_2^2 \\ \text{s.t. :} \quad & \boldsymbol{\mu}_k = \frac{1}{|C_k|} \sum_{\mathbf{x} \in C_k} \mathbf{x} \end{aligned}$$

◆ **Theorem:** *K-means iteratively leads to a non-increasing of the objective, until local minimum is achieved*

□ *Proof ideas:*

- *Each operation leads to non-increasing of the objective*
- *The objective is bounded and the number of clusters is finite*

# K-means as gradient descent

- ◆ Find  $K$  prototypes to minimize the *quantization error* (i.e., the average distance between a data to its closest prototype):

$$\min_{\{\boldsymbol{\mu}_c\}_{c=1}^K} \sum_{i=1}^N \min_k \|\mathbf{x}_i - \boldsymbol{\mu}_k\|_2^2$$

- First-order gradient descent applies
- Newton method leads to the same update rule:

$$\boldsymbol{\mu}_k = \frac{1}{|C_k|} \sum_{\mathbf{x} \in C_k} \mathbf{x}$$

- ◆ See [Bottou & Bengio, NIPS'95] for more details

# Trying to find a good optimum

- ◆ **Idea 1:** Be careful about where you start
- ◆ **Idea 2:** Do many runs of k-means, each from a different random start configuration
- ◆ Many other ideas floating around.
  
- ◆ **Note:** *K*-means is often used to initialize other clustering methods

# Mixture of Gaussians and EM algorithm

# **Basics of Probability & MLE**



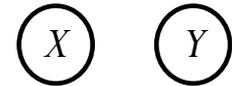
# Basics of Probabilities

# Independence

## ◆ Independent random variables:

$$P(X, Y) = P(X)P(Y)$$

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



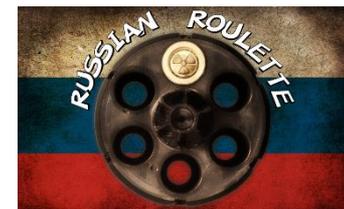
- Y and X don't contain information about each other

Observing Y doesn't help predicting X

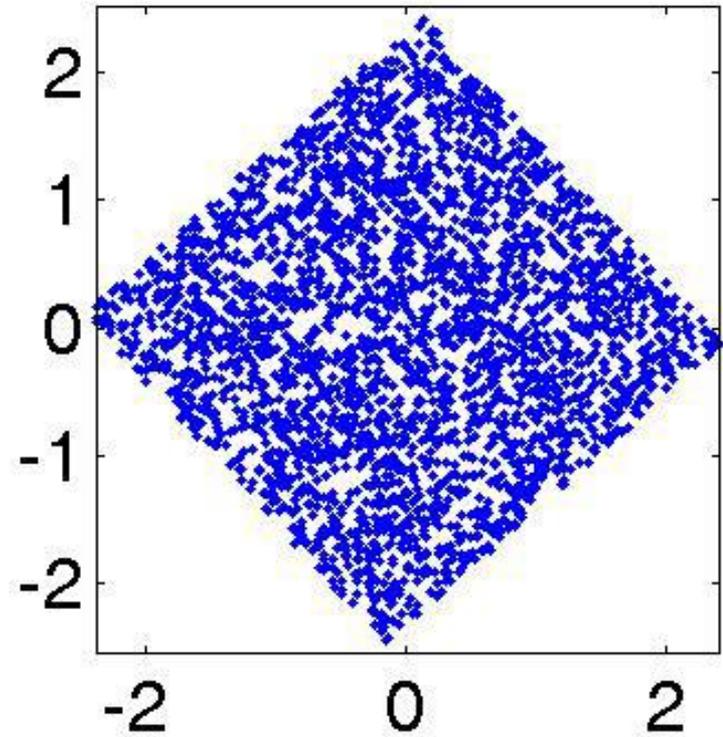
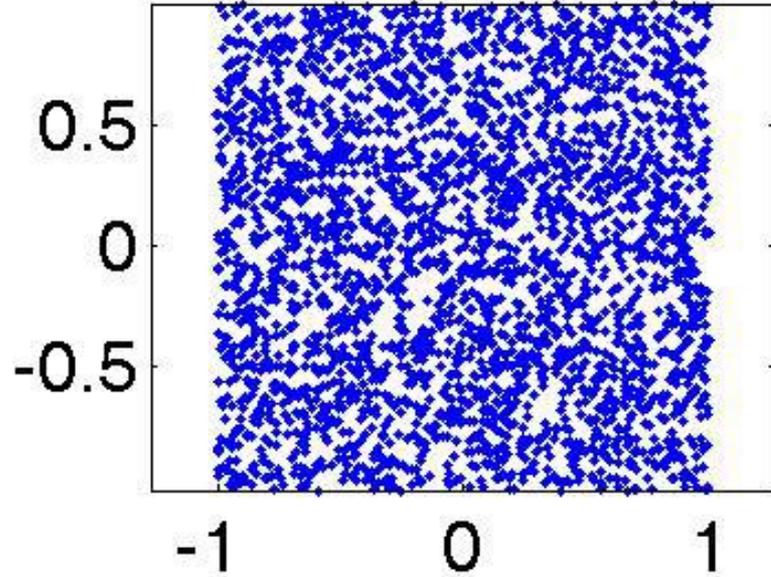
Observing X doesn't help predicting Y

## ◆ Examples:

- Independent:
  - winning on roulette this week and next week
- Dependent:
  - Russian roulette



# Dependent / Independent?

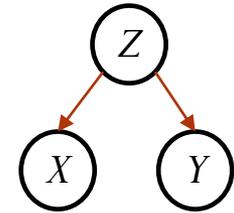


# Conditional Independence

◆ Conditionally independent:

$$P(X, Y|Z) = P(X|Z)P(Y|Z)$$

- knowing Z makes X and Y independent



◆ Examples:

**London taxi drivers:** A survey has pointed out a positive and significant correlation between the number of accidents and wearing coats. They concluded that coats could hinder movements of drivers and be the cause of accidents. A new law was prepared to prohibit drivers from wearing coats when driving.



Finally another study pointed out that people wear coats when it rains...

# Conditional Independence

◆ Conditionally independent:

$$P(X, Y | Z) = P(X | Z)P(Y | Z)$$

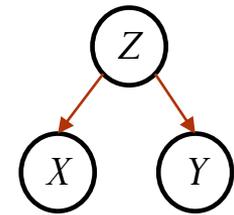
- knowing  $Z$  makes  $X$  and  $Y$  independent

◆ Equivalent to:

$$\forall(x, y, z): P(X = x | Y = y, Z = z) = P(X = x | Z = z)$$

- E.g.:

$$P(\textit{Thunder} | \textit{Rain}, \textit{Lightning}) = P(\textit{Thunder} | \textit{Lightning})$$



# Maximum Likelihood Estimation (MLE)

# Flipping a Coin

- ◆ What's the probability that a coin will fall with a head up (if flipped)?
- ◆ Let us flip it a few times to estimate the probability



The estimated probability is:  $3/5$  “frequency of heads”

# Questions:



The estimated probability is:  $3/5$  “frequency of heads”

- ◆ Why frequency of heads?
- ◆ How good is this estimation?
- ◆ Why is this a machine learning problem?

# Question (1)

- ◆ Why frequency of heads?
  - Frequency of heads is exactly the Maximum Likelihood Estimator for this problem
  - MLE has nice properties  
(interpretation, statistical guarantees, simple)

# MLE for Bernoulli Distribution

Data,  $D =$



$$D = \{X_i\}_{i=1}^n, X_i \in \{H, T\}$$

$$P(\text{Head}) = \theta \quad P(\text{Tail}) = 1 - \theta$$

- ◆ Flips are i.i.d:
  - ▣ **Independent** events that are **identically distributed** according to Bernoulli distribution
- ◆ **MLE**: choose  $\theta$  that maximizes the probability of observed data

# Maximum Likelihood Estimation (MLE)

- ◆ MLE: choose  $\theta$  that maximizes the probability of observed data

$$\hat{\theta}_{MLE} = \arg \max_{\theta} P(D|\theta)$$

$$= \arg \max_{\theta} \prod_{i=1}^n P(X_i|\theta) \quad \text{Independent draws}$$

$$= \arg \max_{\theta} \prod_{i:X_i=H} \theta \prod_{i:X_i=T} (1 - \theta) \quad \text{Identically distributed}$$

$$= \arg \max_{\theta} \theta^{N_H} (1 - \theta)^{N_T}$$

# Maximum Likelihood Estimation (MLE)

- ◆ MLE: choose  $\theta$  that maximizes the probability of observed data

$$\begin{aligned}\hat{\theta}_{MLE} &= \arg \max_{\theta} P(D|\theta) \\ &= \arg \max_{\theta} \theta^{N_H} (1 - \theta)^{N_T}\end{aligned}$$

- ◆ Solution?

$$\hat{\theta}_{MLE} = \frac{N_H}{N_H + N_T}$$

- Exactly the “**Frequency of heads**”

## Question (2)

◆ How good is the MLE estimation?

$$\hat{\theta}_{MLE} = \frac{N_H}{N_H + N_T}$$

□ Is it biased?

# How many flips do I need?

- ◆ I flipped the coins 5 times: 3 heads, 2 tails

$$\hat{\theta}_{MLE} = \frac{3}{5}$$

- ◆ What if I flipped 30 heads and 20 tails?

$$\hat{\theta}_{MLE} = \frac{30}{50}$$

- ◆ Which estimator should we trust more?

## A Simple Bound

◆ Let  $\theta^*$  be the true parameter. For  $n$  data points, and

$$\hat{\theta}_{MLE} = \frac{N_H}{N_H + N_T}$$

◆ Then, for any  $\epsilon > 0$ , we have the Hoeffding's Inequality:

$$P(|\hat{\theta} - \theta^*| \geq \epsilon) \leq 2e^{-2n\epsilon^2}$$

# Probably Approximately Correct (PAC) Learning

- ◆ I want to know the coin parameter  $\theta$ , within  $\epsilon=0.1$  error with probability at least  $1-\delta$  (e.g., 0.95)
- ◆ How many flips do I need?

$$P(|\hat{\theta} - \theta^*| \geq \epsilon) \leq 2e^{-2n\epsilon^2} \leq \delta$$

- ◆ Sample complexity:

$$n \geq \frac{\ln(2/\delta)}{2\epsilon^2}$$

## Question (3)

- ◆ Why is this a machine learning problem?
  - Improve their **performance** (accuracy of the estimated prob.)
  - At some **task** (estimating the probability of heads)
  - With **experience** (the more coin flips the better we are)

How about continuous features?

# Gaussian Distributions

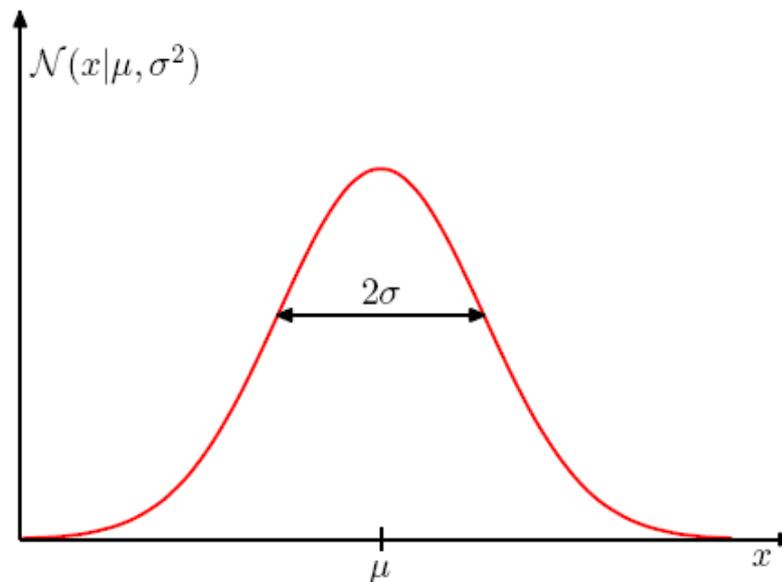
- ◆ Univariate Gaussian distribution

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



Carl F. Gauss (1777 – 1855)

- ◆ Given parameters, we can draw samples and plot distributions



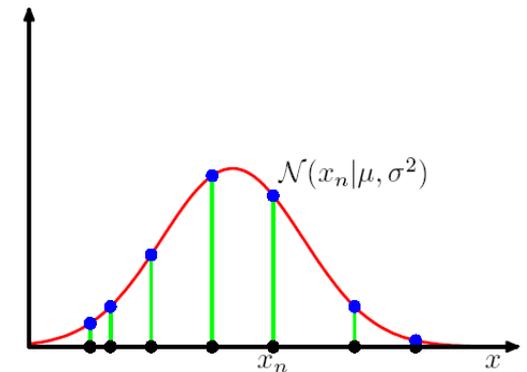
# Maximum Likelihood Estimation

◆ Given a data set  $\mathcal{D} = \{x_1, \dots, x_N\}$ , the likelihood is

$$p(\mathcal{D}|\mu, \sigma^2) = \prod_{n=1}^N p(x_n|\mu, \sigma^2)$$

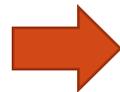
◆ MLE estimates the parameters as

$$(\mu_{\text{ML}}, \sigma_{\text{ML}}^2) = \underset{\mu, \sigma^2}{\operatorname{argmax}} \log p(\mathcal{D}|\mu, \sigma^2)$$



$$\mu_{\text{ML}} = \frac{1}{N} \sum_{n=1}^N x_n$$

sample mean



$$\sigma_{\text{ML}}^2 = \frac{1}{N} \sum_{n=1}^N (x_n - \mu_{\text{ML}})^2$$

sample variance

Note: MLE for the variance of a Gaussian is biased

# Gaussian Distributions

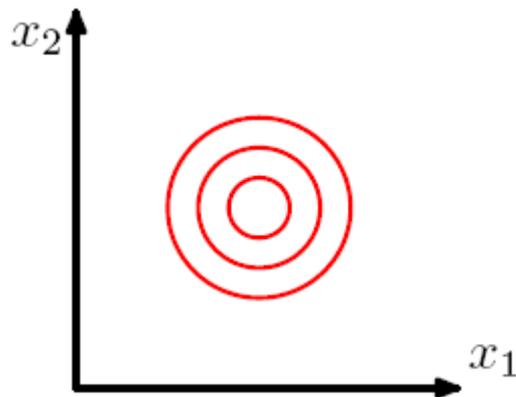


Carl F. Gauss (1777–1855)

◆  $d$ -dimensional multivariate Gaussian

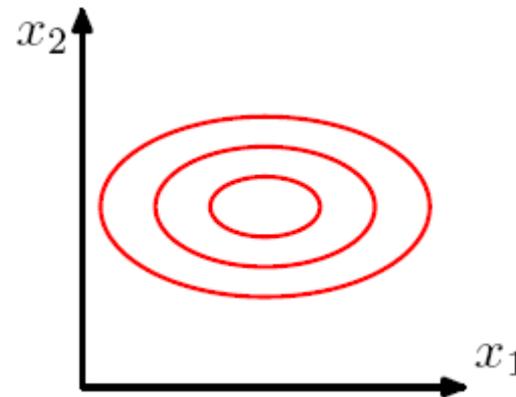
$$p(\mathbf{x}|\mu, \Sigma) = \frac{1}{(2\pi)^{d/2} |\Sigma|^{1/2}} \exp\left(-\frac{1}{2}(\mathbf{x} - \mu)\Sigma^{-1}(\mathbf{x} - \mu)\right)$$

◆ Given parameters, we can draw samples and plot distributions



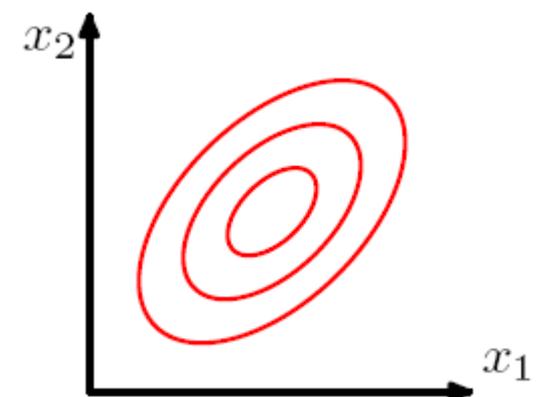
Isotropic

$$\Sigma = \sigma^2 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$



Diagonal

$$\Sigma = \begin{bmatrix} \sigma_1^2 & 0 \\ 0 & \sigma_2^2 \end{bmatrix}$$



General

$$\Sigma = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

# Maximum Likelihood Estimation

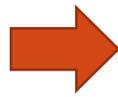
◆ Given a data set  $\mathcal{D} = \{\mathbf{x}_1, \dots, \mathbf{x}_N\}$ , the likelihood is

$$p(\mathcal{D}|\mu, \Sigma) = \prod_{n=1}^N p(\mathbf{x}_n|\mu, \Sigma)$$

◆ MLE estimates the parameters as

$$(\mu_{\text{ML}}, \Sigma_{\text{ML}}) = \underset{\mu, \Sigma}{\operatorname{argmax}} \log p(\mathcal{D}|\mu, \Sigma)$$

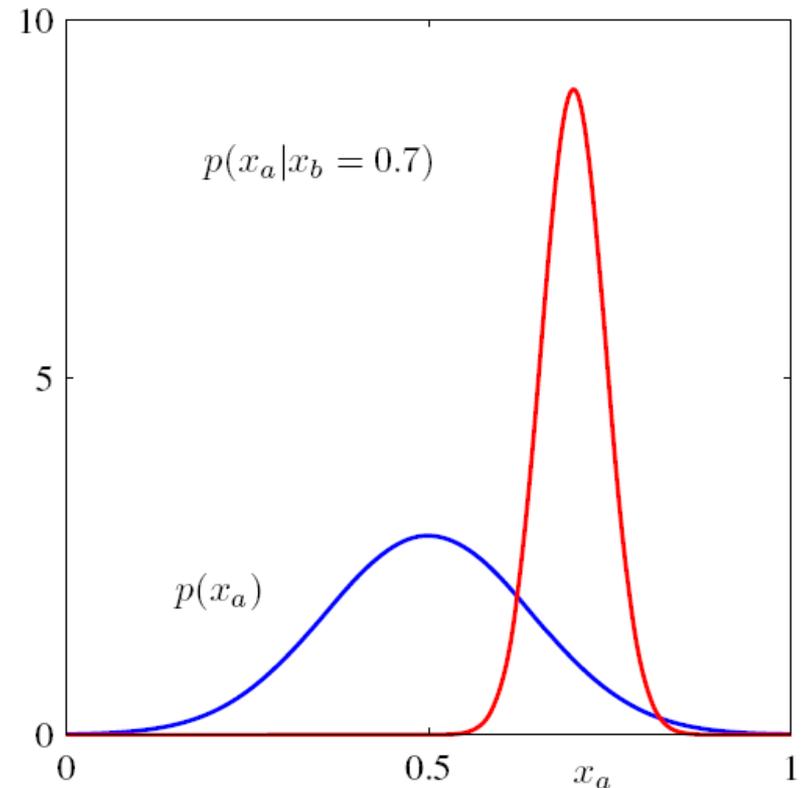
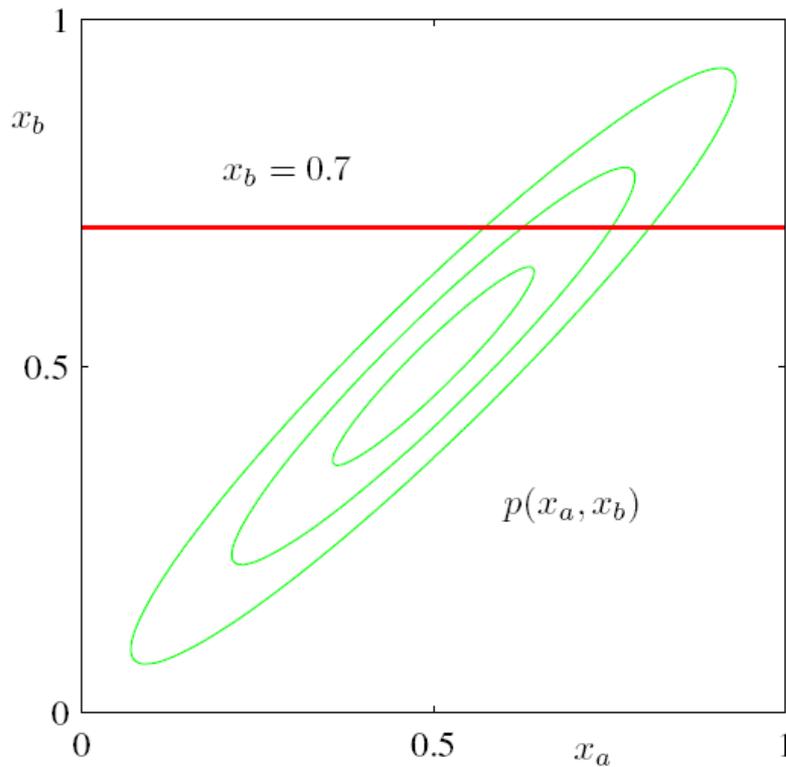
$$\mu_{\text{ML}} = \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n \quad \text{sample mean}$$



$$\Sigma_{\text{ML}}^2 = \frac{1}{N} \sum_{n=1}^N (\mathbf{x}_n - \mu_{\text{ML}})(\mathbf{x}_n - \mu_{\text{ML}})^\top \quad \text{sample covariance}$$

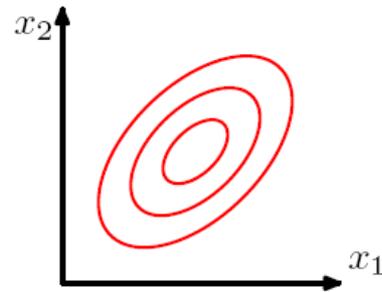
# Other Nice Analytic Properties

- ◆ Marginal is Gaussian
- ◆ Conditional is Gaussian

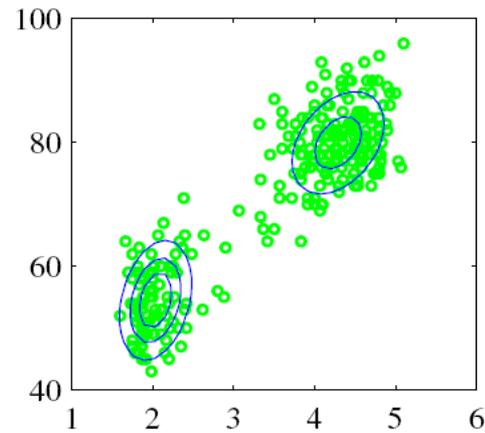
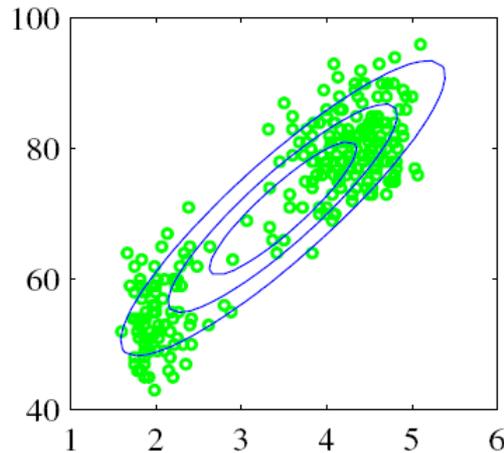


# Limitations of Single Gaussians

- ◆ Single Gaussian is unimodal



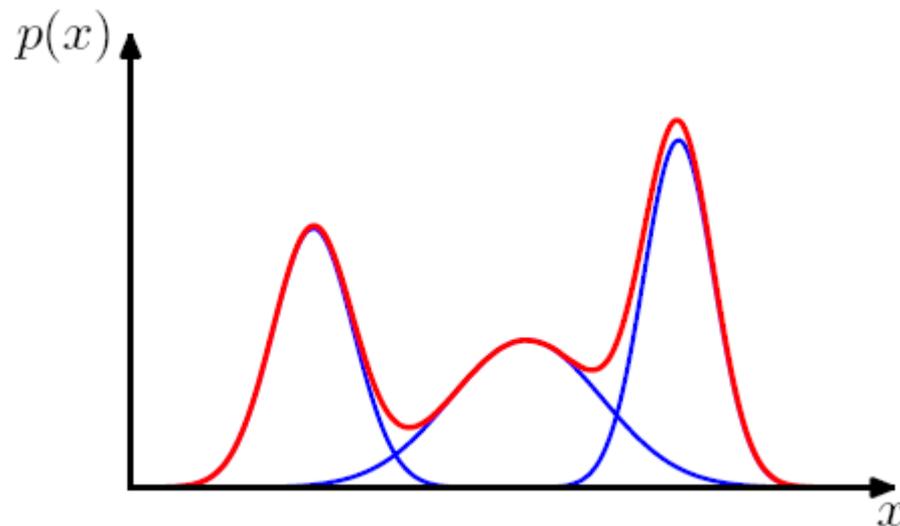
- ◆ ... can't fit well multimodal data, which is more realistic!



# Mixture of Gaussians

- ◆ A simple family of multi-modal distributions
  - treat unimodal Gaussians as **basis (or component) distributions**
  - superpose multiple Gaussians via **linear combination**

$$p(x) = \sum_{k=1}^K \pi_k \mathcal{N}(x | \mu_k, \sigma_k^2)$$

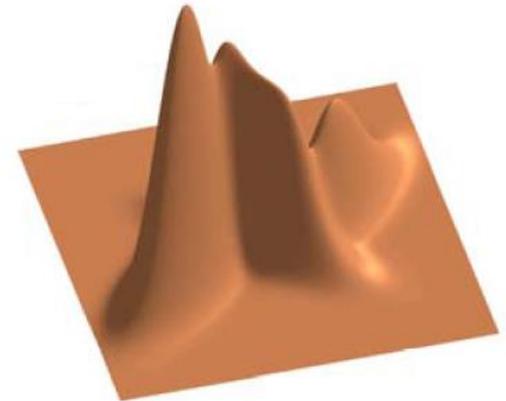
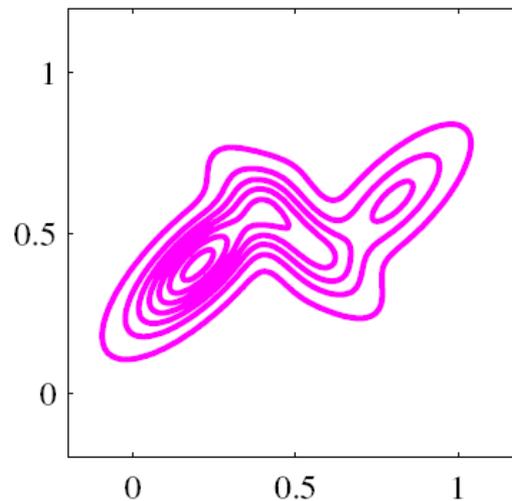
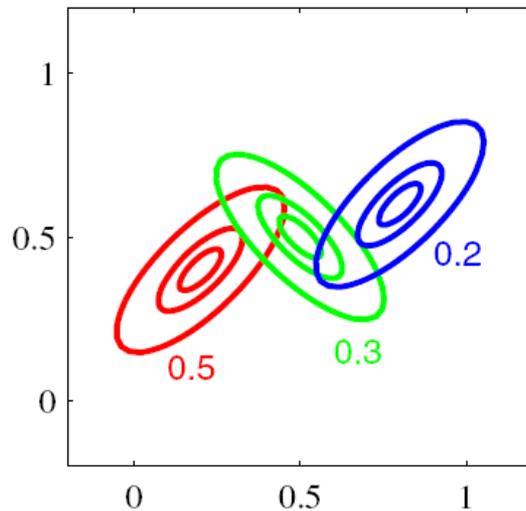


# Mixture of Gaussians

- ◆ A simple family of multi-modal distributions
  - ▣ treat unimodal Gaussians as **basis (or component) distributions**
  - ▣ superpose multiple Gaussians via **linear combination**

$$p(\mathbf{x}) = \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x} | \mu_k, \Sigma_k)$$

*What conditions should the mixing coefficients satisfy?*



# MLE for Mixture of Gaussians

## ◆ Log-likelihood

$$\log p(\mathcal{D}|\pi, \mu, \Sigma) = \sum_{n=1}^N \log \left( \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x}|\mu_k, \Sigma_k) \right)$$

- this is complicated ... 😞
- ... but, we know the MLE for single Gaussians are easy

## ◆ A heuristic procedure (can we iterate?)

- allocate data into different components
- estimate each component Gaussian analytically

# Optimal Conditions

◆ Some math

$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\Sigma}) = \log p(\mathcal{D}|\boldsymbol{\mu}, \boldsymbol{\Sigma}) = \sum_{n=1}^N \log \left( \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x}|\boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k) \right)$$

$$\frac{\partial \mathcal{L}}{\partial \boldsymbol{\mu}_k} = 0 \quad \rightarrow \quad \sum_{n=1}^N \frac{\pi_k \mathcal{N}(\mathbf{x}_n|\boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)}{\underbrace{\sum_j \pi_j \mathcal{N}(\mathbf{x}_n|\boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)}_{\gamma(z_{nk})}} \boldsymbol{\Sigma}_k^{-1} (\mathbf{x}_n - \boldsymbol{\mu}_k) = 0$$

$$\rightarrow \quad \boldsymbol{\mu}_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) \mathbf{x}_n \quad N_k = \sum_{n=1}^N \gamma(z_{nk})$$

*A weighted sample mean!*

# Optimal Conditions

◆ Some math

$$\mathcal{L}(\boldsymbol{\mu}, \Sigma) = \log p(\mathcal{D}|\boldsymbol{\mu}, \Sigma) = \sum_{n=1}^N \log \left( \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x}|\boldsymbol{\mu}_k, \Sigma_k) \right)$$

$$\frac{\partial \mathcal{L}}{\partial \Sigma_k} = 0 \quad \longrightarrow \quad \Sigma_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) (\mathbf{x}_n - \boldsymbol{\mu}_k) (\mathbf{x}_n - \boldsymbol{\mu}_k)^\top$$

*A weighted sample variance!*

# Optimal Conditions

◆ Some math

$$\mathcal{L}(\boldsymbol{\mu}, \Sigma) = \log p(\mathcal{D}|\boldsymbol{\mu}, \Sigma) = \sum_{n=1}^N \log \left( \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x}|\boldsymbol{\mu}_k, \Sigma_k) \right)$$

**Note: constraints exist for mixing coefficients!**

$$L = \mathcal{L}(\boldsymbol{\mu}, \Sigma) + \lambda \left( \sum_{k=1}^K \pi_k - 1 \right)$$

$$\frac{\partial L}{\partial \pi_k} = 0 \quad \longrightarrow \quad \sum_{n=1}^N \frac{\mathcal{N}(\mathbf{x}_n|\boldsymbol{\mu}_k, \Sigma_k)}{\sum_j \pi_j \mathcal{N}(\mathbf{x}_n|\boldsymbol{\mu}_j, \Sigma_j)} + \lambda = 0$$

$$\longrightarrow \quad \pi_k = \frac{N_k}{N}$$

*The ratio of data assigned to component  $k$ !*

# Optimal Conditions – summary

- ◆ The set of couple conditions

$$\boldsymbol{\mu}_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) \mathbf{x}_n$$

$$\boldsymbol{\Sigma}_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) (\mathbf{x}_n - \boldsymbol{\mu}_k)(\mathbf{x}_n - \boldsymbol{\mu}_k)^\top$$

$$\pi_k = \frac{N_k}{N}$$

- ◆ The key factor to get them coupled

$$\gamma(z_{nk}) = \frac{\pi_k \mathcal{N}(\mathbf{x}_n | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)}{\sum_j \pi_j \mathcal{N}(\mathbf{x}_n | \boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)}$$



- ◆ If we know  $\gamma(z_{nk})$ , each component Gaussian is easy to estimate!

# The EM Algorithm

◆ **E-step:** estimate the responsibilities

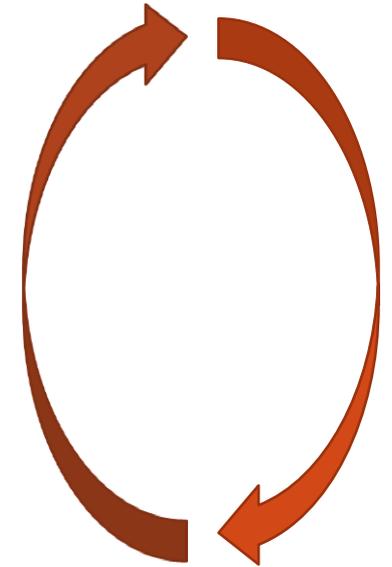
$$\gamma(z_{nk}) = \frac{\pi_k \mathcal{N}(\mathbf{x}_n | \boldsymbol{\mu}_k, \Sigma_k)}{\sum_j \pi_j \mathcal{N}(\mathbf{x}_n | \boldsymbol{\mu}_j, \Sigma_j)}$$

◆ **M-step:** re-estimate the parameters

$$\boldsymbol{\mu}_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) \mathbf{x}_n$$

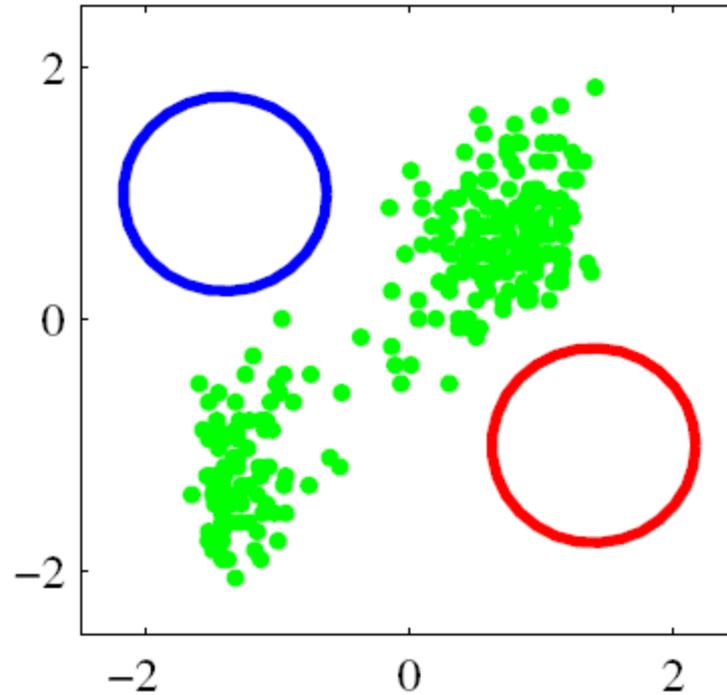
$$\Sigma_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) (\mathbf{x}_n - \boldsymbol{\mu}_k)(\mathbf{x}_n - \boldsymbol{\mu}_k)^\top$$

$$\pi_k = \frac{N_k}{N}$$



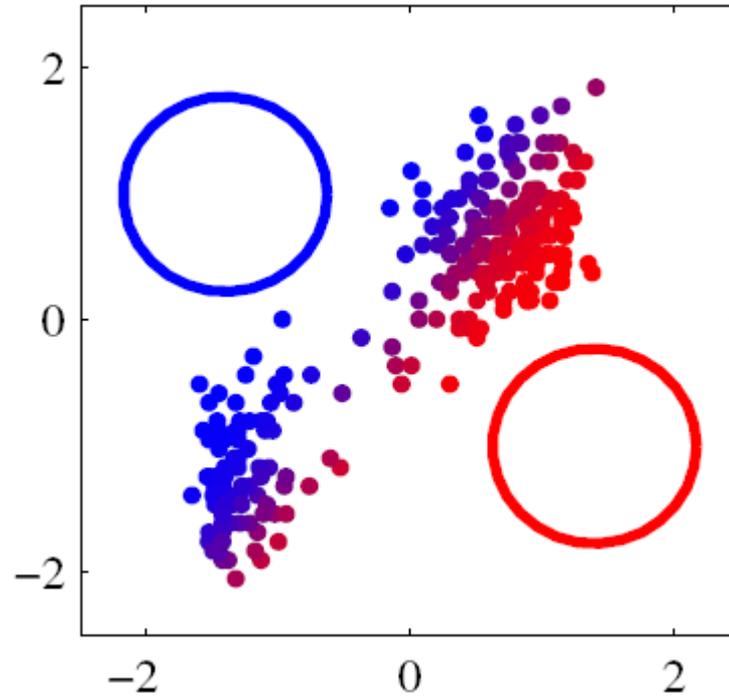
**Initialization plays a key role to succeed!**

# A Running Example



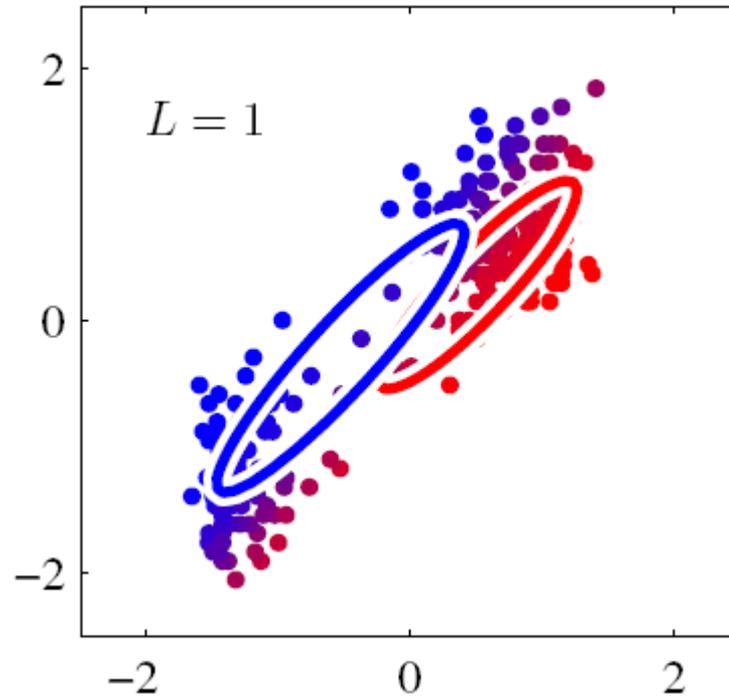
- ◆ The data and a mixture of two isotropic Gaussians

# A Running Example



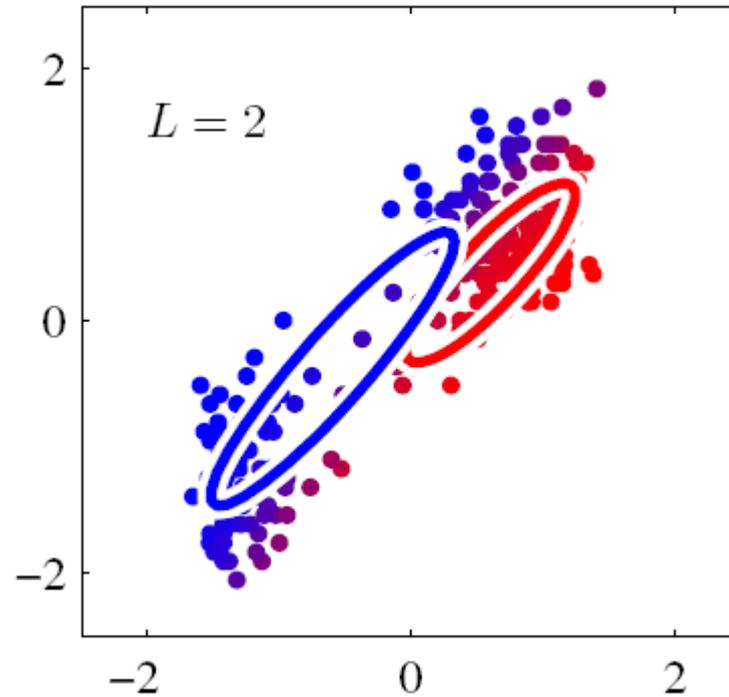
◆ Initial E-step

# A Running Example



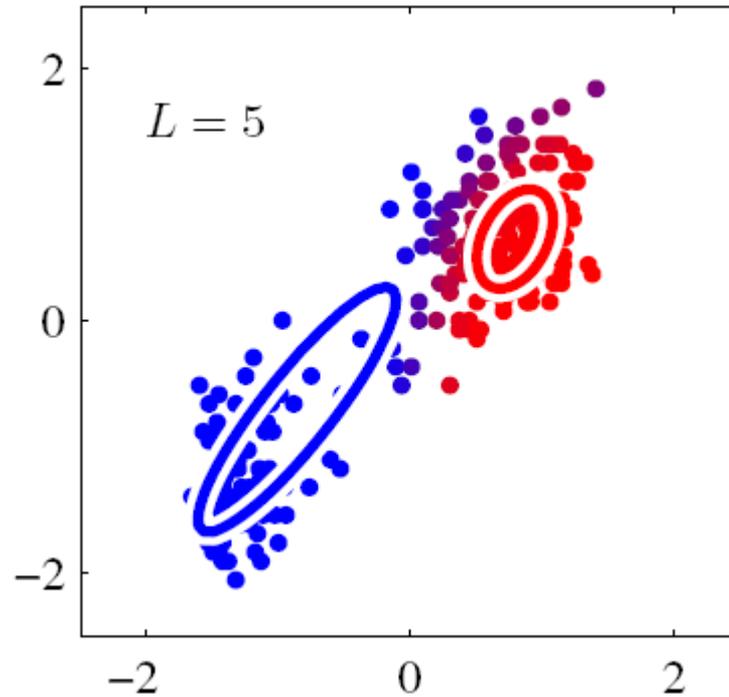
◆ Initial M-step

# A Running Example



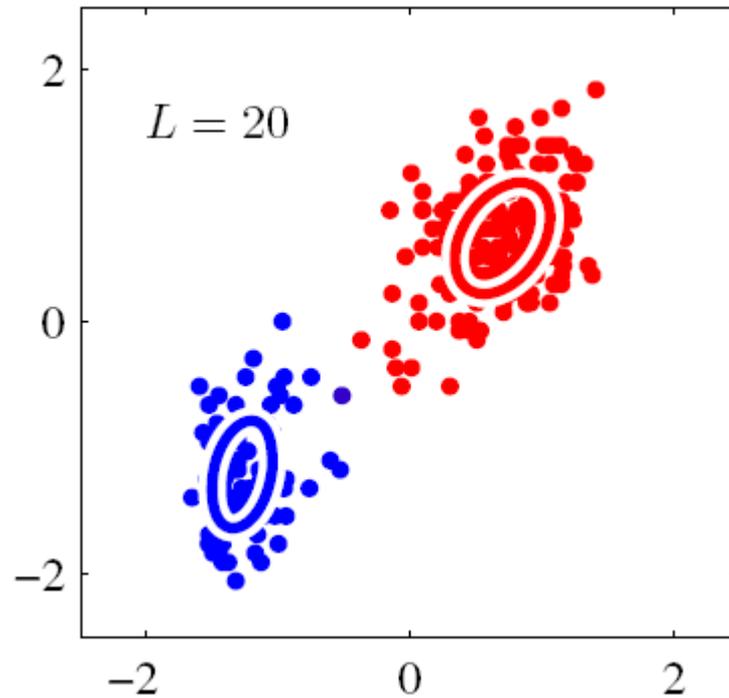
◆ The 2<sup>nd</sup> M-step

# A Running Example



◆ The 5<sup>th</sup> M-step

# A Running Example



◆ The 20<sup>th</sup> M-step

# Theory

◆ Let's take the latent variable view of mixture of Gaussians

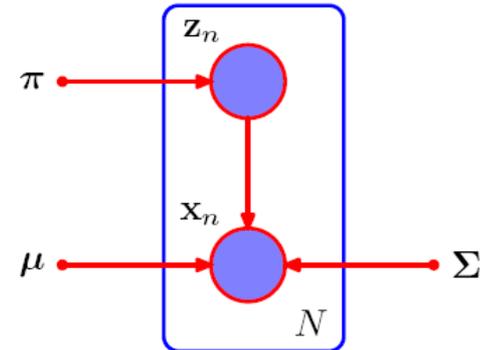
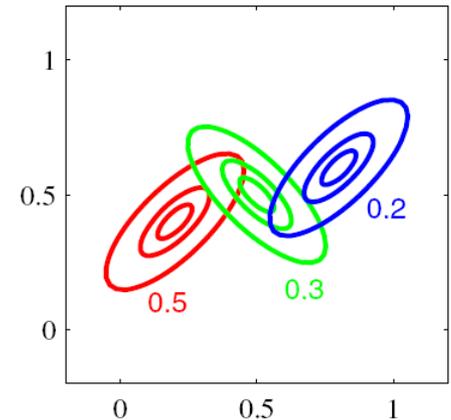
$$p(\mathbf{x}) = \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x} | \mu_k, \Sigma_k)$$

□ Indicator (selecting) variable

$$\mathbf{z} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

➔ 
$$p(\mathbf{x}, \mathbf{z}) = \prod_{k=1}^K \pi_k^{z_k} \mathcal{N}(\mathbf{x} | \mu_k, \Sigma_k)^{z_k}$$

➔ 
$$p(\mathbf{x}) = \sum_{\mathbf{z}} p(\mathbf{x}, \mathbf{z})$$



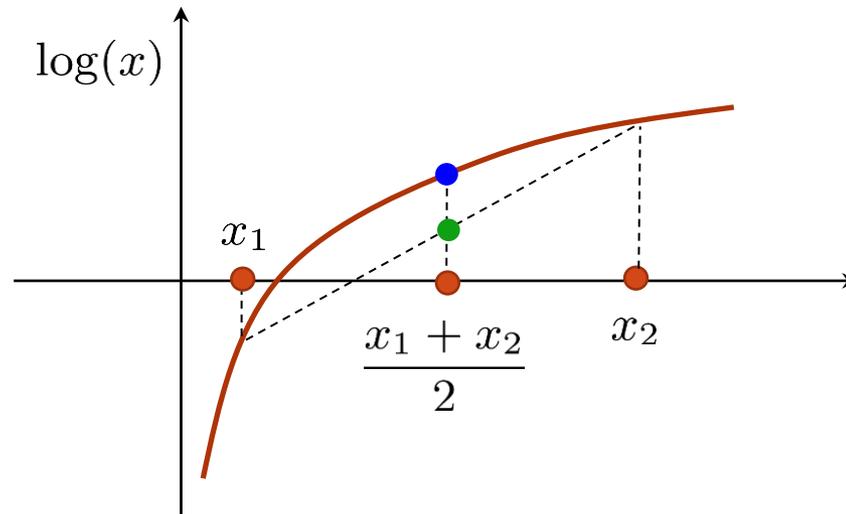
**Note: the idea of data augmentation is influential in statistics and machine learning!**

# Theory

◆ Re-visit the log-likelihood

$$\log p(\mathcal{D}|\Theta) = \sum_{n=1}^N \log \left( \sum_{\mathbf{z}_n} p(\mathbf{x}_n, \mathbf{z}_n) \right)$$

◆ Jensen's inequality



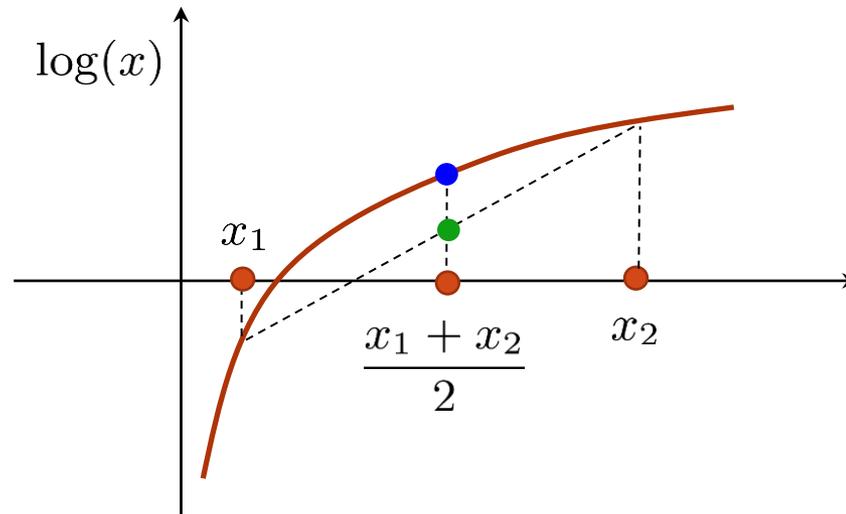
$$\log \frac{x_1 + x_2}{2} \geq \frac{\log x_1 + \log x_2}{2}$$

# Theory

- ◆ Re-visit the log-likelihood

$$\log p(\mathcal{D}|\Theta) = \sum_{n=1}^N \log \left( \sum_{\mathbf{z}_n} p(\mathbf{x}_n, \mathbf{z}_n) \right)$$

- ◆ Jensen's inequality



$$\log \mathbb{E}_{p(x)}[x] \geq \mathbb{E}_{p(x)}[\log x]$$

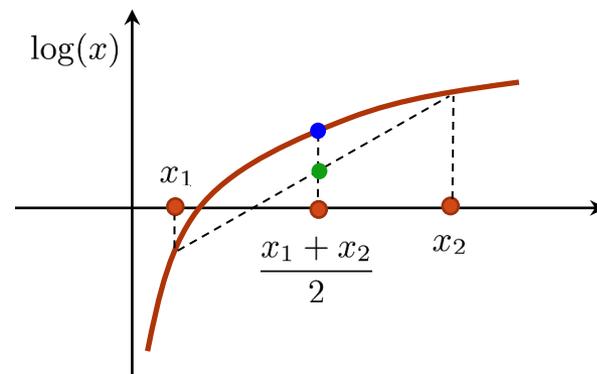
# Theory

- ◆ Re-visit the log-likelihood

$$\log p(\mathcal{D}|\Theta) = \sum_{n=1}^N \log \left( \sum_{\mathbf{z}_n} p(\mathbf{x}_n, \mathbf{z}_n) \right)$$

- ◆ Jensen's inequality

$$\log \mathbb{E}_{p(x)}[x] \geq \mathbb{E}_{p(x)}[\log x]$$



- ◆ How to apply?

$$\begin{aligned} \log p(\mathcal{D}|\Theta) &= \sum_{n=1}^N \log \left( \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \frac{p(\mathbf{x}_n, \mathbf{z}_n)}{q(\mathbf{z}_n)} \right) \\ &\geq \sum_{n=1}^N \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log \left( \frac{p(\mathbf{x}_n, \mathbf{z}_n)}{q(\mathbf{z}_n)} \right) \end{aligned}$$

# Theory

◆ What we have is a lower bound

$$\log p(\mathcal{D}|\Theta) \geq \sum_{n=1}^N \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log \left( \frac{p(\mathbf{x}_n, \mathbf{z}_n)}{q(\mathbf{z}_n)} \right) \triangleq \mathcal{L}(\Theta, q(\mathbf{Z}))$$

◆ What's the GAP?

$$\begin{aligned} \mathcal{L}(\Theta, q(\mathbf{Z})) &= \sum_{n=1}^N \left\{ \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log p(\mathbf{x}_n, \mathbf{z}_n) - \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log q(\mathbf{z}_n) \right\} \\ &= \sum_{n=1}^N \left\{ \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log \left( \frac{p(\mathbf{x}_n, \mathbf{z}_n)}{p(\mathbf{x}_n)} \right) + \log p(\mathbf{x}_n) - \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log q(\mathbf{z}_n) \right\} \\ &= \log p(\mathcal{D}|\Theta) + \sum_{n=1}^N \left\{ \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log p(\mathbf{z}_n|\mathbf{x}_n) - \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log q(\mathbf{z}_n) \right\} \\ &= \log p(\mathcal{D}|\Theta) - \text{KL}(q(\mathbf{Z})||p(\mathbf{Z}|\mathcal{D})) \end{aligned}$$

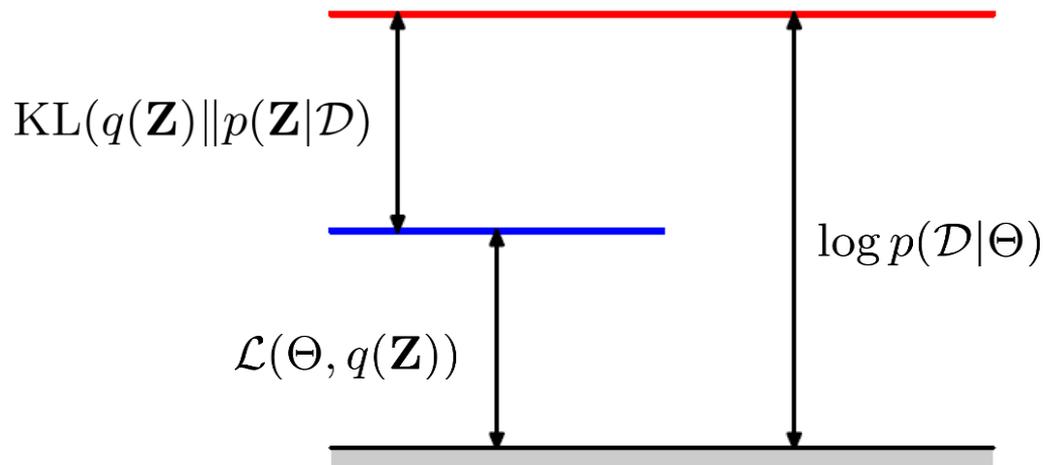
# Theory

- ◆ What we have is a lower bound

$$\log p(\mathcal{D}|\Theta) \geq \sum_{n=1}^N \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log \left( \frac{p(\mathbf{x}_n, \mathbf{z}_n)}{q(\mathbf{z}_n)} \right) \triangleq \mathcal{L}(\Theta, q(\mathbf{Z}))$$

- ◆ What's the GAP?

$$\log p(\mathcal{D}|\Theta) - \mathcal{L}(\Theta, q(\mathbf{Z})) = \text{KL}(q(\mathbf{Z})||p(\mathbf{Z}|\mathcal{D}))$$

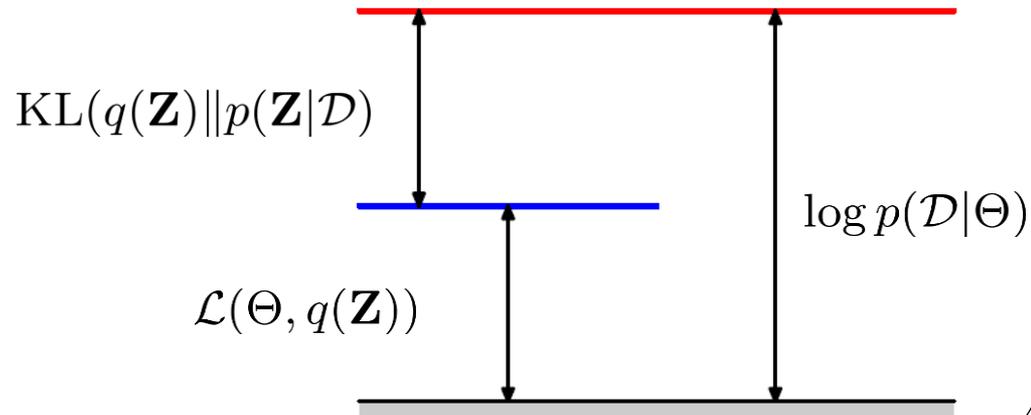


# EM-algorithm

- ◆ Maximize the lower bound or minimize the gap:

$$\log p(\mathcal{D}|\Theta) \geq \sum_{n=1}^N \sum_{\mathbf{z}_n} q(\mathbf{z}_n) \log \left( \frac{p(\mathbf{x}_n, \mathbf{z}_n)}{q(\mathbf{z}_n)} \right) \triangleq \mathcal{L}(\Theta, q(\mathbf{Z}))$$

- Maximize over  $q(\mathbf{Z}) \Rightarrow$  E-step
- Maximize over  $\Theta \Rightarrow$  M-step



# Convergence of EM

- ◆ Local optimum is guaranteed under mild conditions (Depster et al., 1977)
  - alternating minimization for a bi-convex problem

$$\mathcal{L}(\Theta_{t+1}) \geq \mathcal{L}(\Theta_t)$$

- ◆ Some special cases with global optimum (Wu, 1983)
- ◆ First-order gradient descent for log-likelihood
  - for comparison with other gradient ascent methods, see (Xu & Jordan, 1995)

# Relation between GMM and K-Means

◆ Small variance asymptotics:

- The EM algorithm for GMM reduces to K-Means under **certain conditions**:

E-step:

$$\gamma(z_{nk}) = \frac{\pi_k \mathcal{N}(\mathbf{x}_n | \boldsymbol{\mu}_k, \Sigma_k)}{\sum_j \pi_j \mathcal{N}(\mathbf{x}_n | \boldsymbol{\mu}_j, \Sigma_j)}$$

M-step:

$$\boldsymbol{\mu}_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) \mathbf{x}_n$$

$$\Sigma_k = \frac{1}{N_k} \sum_{n=1}^N \gamma(z_{nk}) (\mathbf{x}_n - \boldsymbol{\mu}_k)(\mathbf{x}_n - \boldsymbol{\mu}_k)^\top$$

$$\pi_k = \frac{N_k}{N}$$

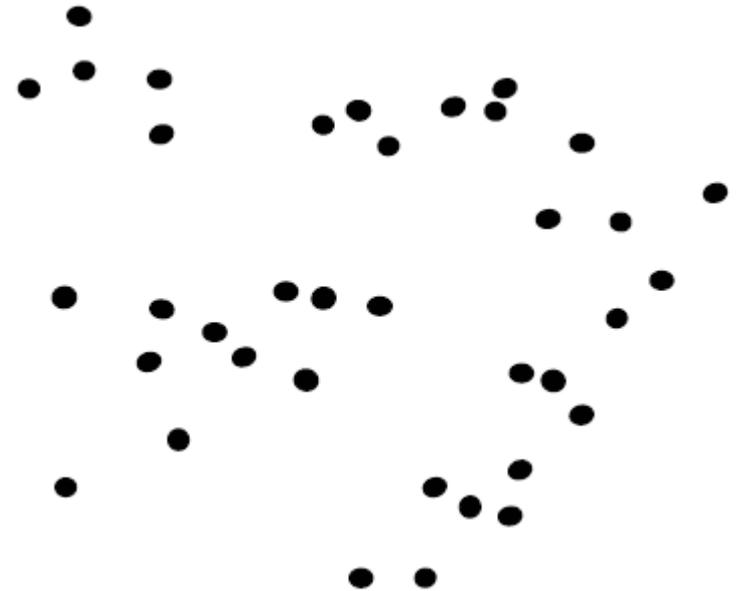
let  $\Sigma_k = \sigma I$  and  $\sigma \rightarrow 0$

$$\gamma(z_{nk}) = \frac{\pi_k \exp(-\frac{1}{2\sigma} \|\mathbf{x}_n - \boldsymbol{\mu}_k\|_2^2)}{\sum_j \pi_j \exp(-\frac{1}{2\sigma} \|\mathbf{x}_n - \boldsymbol{\mu}_j\|_2^2)}$$

$$= k^*, \text{ where } k^* = \operatorname{argmin}_k \|\mathbf{x}_n - \boldsymbol{\mu}_k\|_2^2$$

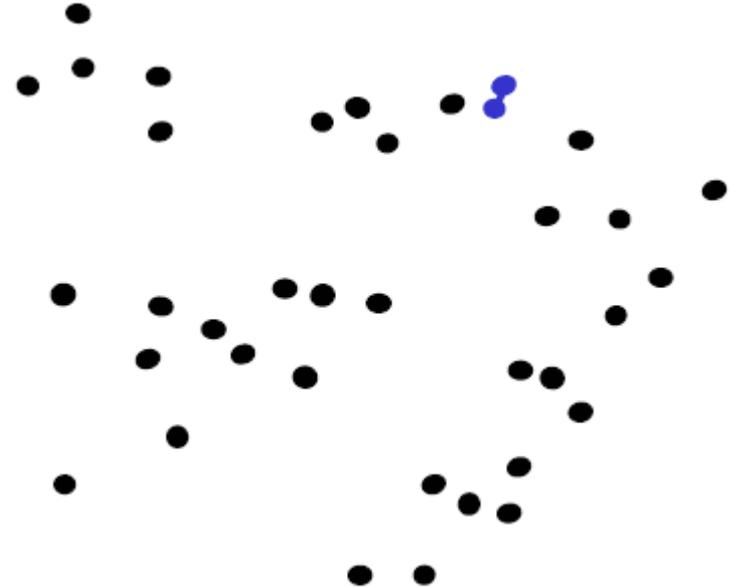
# Single Linkage Hierarchical Clustering

- ◆ Start with “every point is its own cluster”



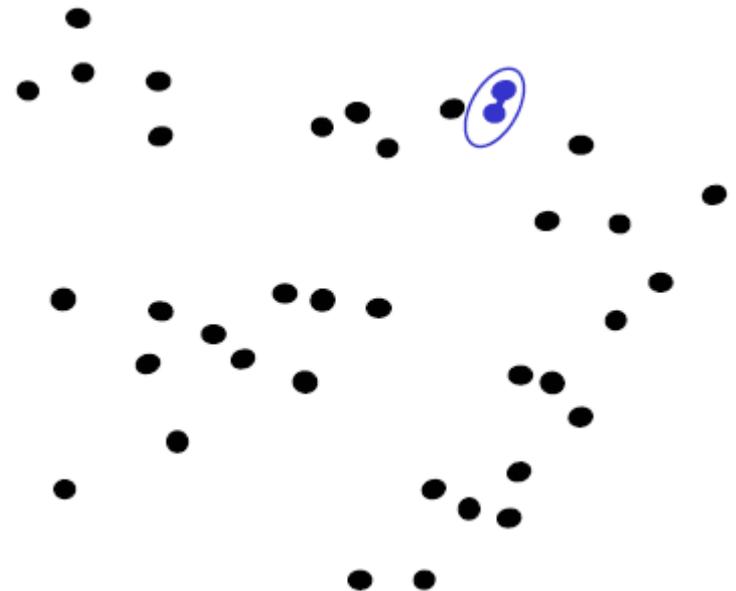
# Single Linkage Hierarchical Clustering

- ◆ Start with “every point is its own cluster”
- ◆ Find “most similar” pairs of clusters



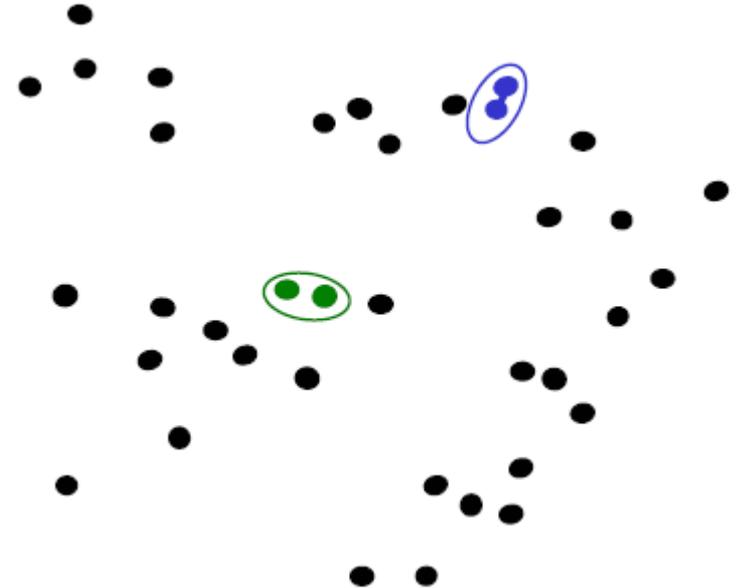
# Single Linkage Hierarchical Clustering

- ◆ Start with “every point is its own cluster”
- ◆ Find “most similar” pairs of clusters
- ◆ Merge it into a parent cluster



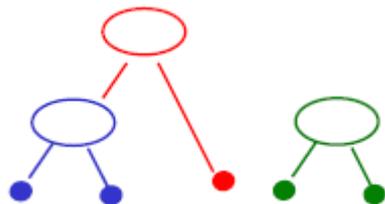
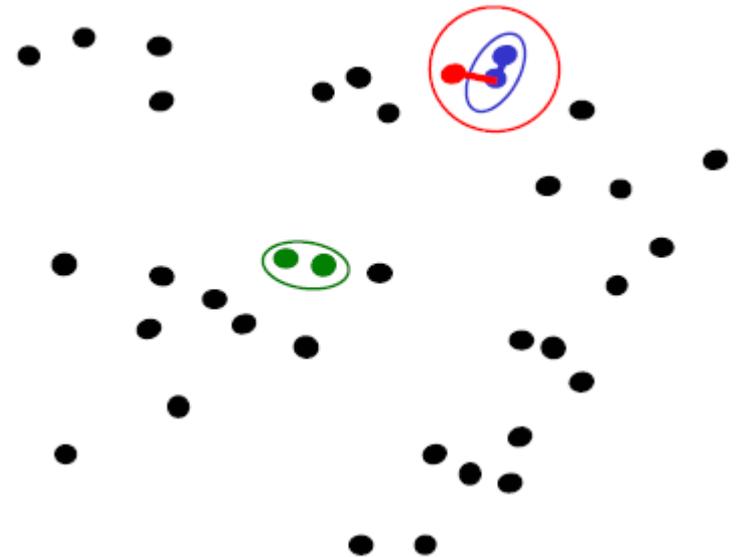
# Single Linkage Hierarchical Clustering

- ◆ Start with “every point is its own cluster”
- ◆ Find “most similar” pairs of clusters
- ◆ Merge it into a parent cluster
- ◆ Repeat



# Single Linkage Hierarchical Clustering

- ◆ Start with “every point is its own cluster”
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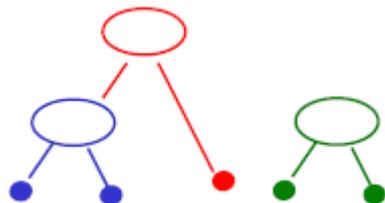
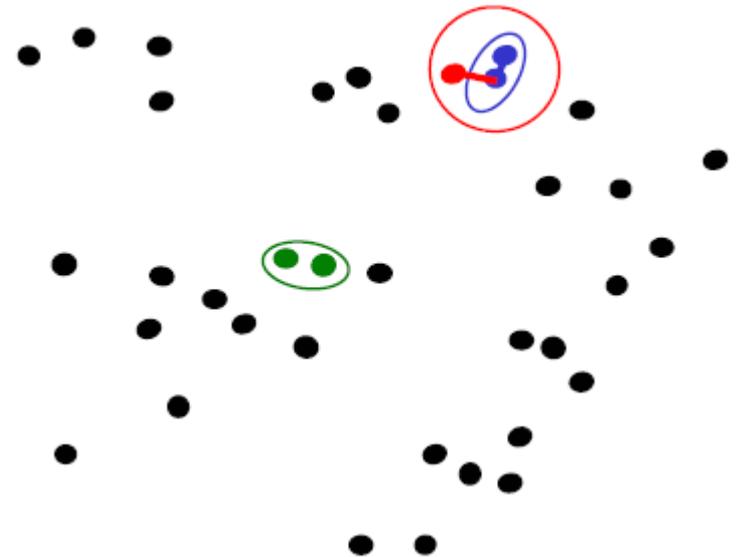
# Single Linkage Hierarchical Clustering

- ◆ Start with “every point is its own cluster”
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- ◆ Merge it into a parent cluster
- ◆ Repeat

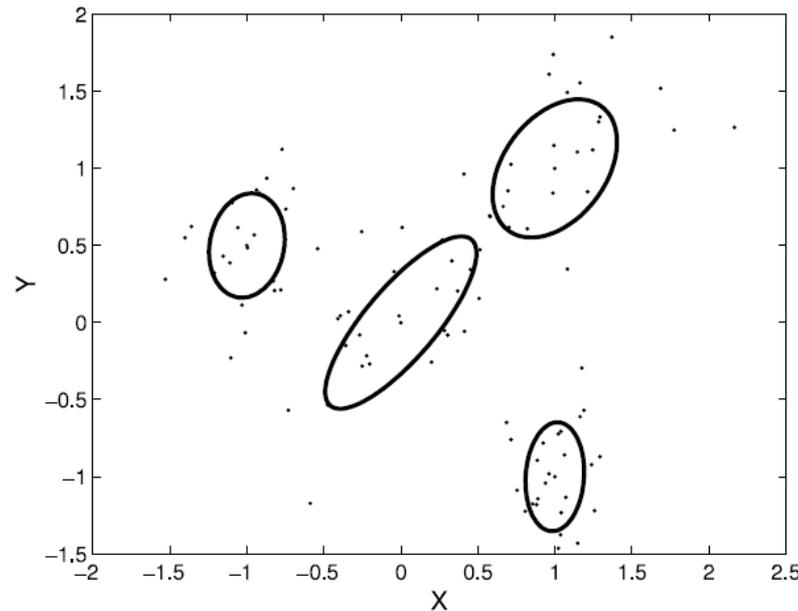
Key Question:

**How do we define similarity between clusters?**

=> **minimum, maximum, or average distance**  
**between points in clusters**

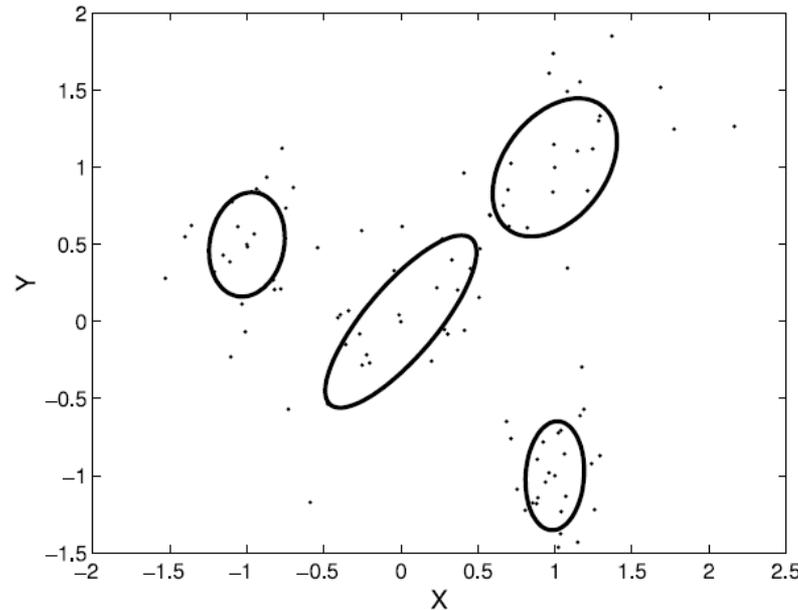


# How many components are good?



- ◆ Can we let the data speak for themselves?
  - let data determine model complexity (e.g., the number of components in mixture models)
  - allow model complexity to grow as more data observed

# How many components are good?



- ◆ Can we let the data speak for themselves?
  - we will talk about Dirichlet Process (DP) Mixtures
  - and nonparametric Bayesian models

# Summary

- ◆ Gaussian Mixtures and K-means are effective tools to discover clustering structures
- ◆ EM algorithms can be applied to do MLE for GMMs
- ◆ Relationships between GMMs and K-means are discussed
  
- ◆ Unresolved issues
  - How to determine the number of components for mixture models?
  - How to determine the number of components for K-means?

# Materials to Read

- ◆ Chap. 9 of Bishop's PRML book
- ◆ Bottou, L. & Bengio, Y. Convergence Properties of the K-means Algorithms, NIPS 1995.