11-755 Machine Learning for Signal Processing

# Expectation Maximization
# Mixture Models
# HMMs

Class 9. 21 Sep 2010



## Learning Distributions for Data

- Problem: Given a collection of examples from some data, estimate its distribution
  - Basic ideas of Maximum Likelihood and MAP estimation can be found in Aarti/Paris' slides
    - Pointed to in a previous class
- Solution: Assign a model to the distribution
  - Learn parameters of model from data
- Models can be arbitrarily complex
  - Mixture densities, Hierarchical models.
- Learning must be done using Expectation Maximization
- Following slides: An intuitive explanation using a simple example of multinomials



## A Thought Experiment

6 3 1 5 4 1 2 4 …

- A person shoots a loaded dice repeatedly
- You observe the series of outcomes
- **You can form a good idea of how the dice is loaded**
  - Figure out what the probabilities of the various numbers are for dice
- P(number) = count(number)/sum(rolls)
- This is a *maximum likelihood* estimate
  - Estimate that makes the observed sequence of numbers most probable



## The Multinomial Distribution

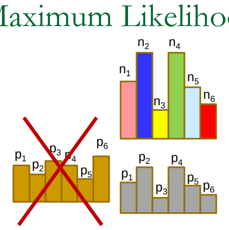
- A probability distribution over a discrete collection of items is a *Multinomial*

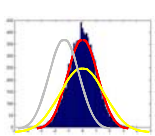
$$P(X : X \text{ belongs to a discrete set}) = P(X)$$

- E.g. the roll of dice
  - X : X in (1,2,3,4,5,6)
- Or the toss of a coin
  - X : X in (head, tails)



## Maximum Likelihood Estimation



- Basic principle: Assign a form to the distribution
  - E.g. a multinomial
  - Or a Gaussian
- Find the *distribution* that best fits the histogram of the data



## Defining "Best Fit"

- The data are generated by draws from the distribution
  - I.e. the generating process draws from the distribution
- Assumption: The distribution has a high probability of generating the observed data
  - Not necessarily true
- Select the distribution that has the *highest* probability of generating the data
  - Should assign lower probability to less frequent observations and vice versa

## Maximum Likelihood Estimation: Multinomial

- Probability of generating ($n_1$, $n_2$, $n_3$, $n_4$, $n_5$, $n_6$)

$$P(n_1, n_2, n_3, n_4, n_5, n_6) = Const \prod_i p_i^{n_i}$$

- Find $p_1$,$p_2$,$p_3$,$p_4$,$p_5$,$p_6$ so that the above is maximized
- Alternately maximize

$$\log\big(P(n_1, n_2, n_3, n_4, n_5, n_6)\big) = \log(Const) + \sum_i n_i \log(p_i)$$

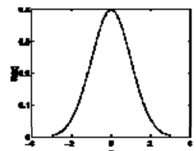
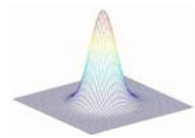
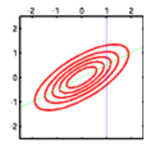
  - Log() is a monotonic function
    - $\text{argmax}_x f(x) = \text{argmax}_x \log(f(x))$
- Solving for the probabilities gives us
  - Requires constrained optimization to ensure probabilities sum to 1

$$p_i = \frac{n_i}{\sum_j n_j}$$

EVENTUALLY ITS JUST COUNTING!



## Segue: Gaussians

$$P(X) = N(X;\mu,\Theta) = \frac{1}{\sqrt{(2\pi)^d |\Theta|}} \exp\big(-0.5(X-\mu)^T \Theta^{-1} (X-\mu)\big)$$

- Parameters of a Gaussian:
  - Mean $\mu$, Covariance $\Theta$



## Maximum Likelihood: Gaussian

- Given a collection of observations ($X_1$, $X_2$,…), estimate mean $\mu$ and covariance $\Theta$

$$P(X_1, X_2, ...) = \prod_i \frac{1}{\sqrt{(2\pi)^d |\Theta|}} \exp\big(-0.5(X_i-\mu)^T \Theta^{-1} (X_i-\mu)\big)$$

$$\log\big(P(X_1, X_2, ...)\big) = C - 0.5 \sum_i \big(\log(|\Theta|) + (X_i-\mu)^T \Theta^{-1} (X_i-\mu)\big)$$

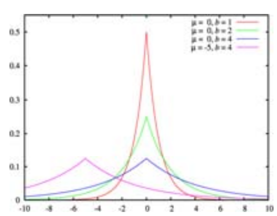
- Maximizing w.r.t $\mu$ and $\Theta$ gives us

$$\mu = \frac{1}{N}\sum_i X_i \qquad \Theta = \frac{1}{N}\sum_i (X_i-\mu)(X_i-\mu)^T$$

ITS STILL JUST COUNTING!



## Laplacian



$$P(x) = L(x;\mu,b) = \frac{1}{2b}\exp\left(-\frac{|x-\mu|}{b}\right)$$

- Parameters: Mean $\mu$, scale $b$ ($b > 0$)



## Maximum Likelihood: Laplacian

- Given a collection of observations ($x_1$, $x_2$,…), estimate mean $\mu$ and scale $b$

$$\log\big(P(x_1, x_2, ...)\big) = C - N\log(b) - \sum_i \frac{|x_i-\mu|}{b}$$

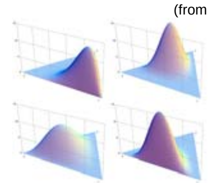
- Maximizing w.r.t $\mu$ and $b$ gives us

$$\mu = \frac{1}{N}\sum_i x_i \qquad b = \frac{1}{N}\sum_i |x_i-\mu|$$

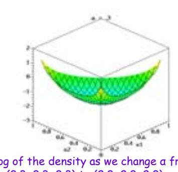


## Dirichlet

(from wikipedia)



K=3. Clockwise from top left: α=(6, 2, 2), (3, 7, 5), (6, 2, 6), (2, 3, 4)



log of the density as we change a from a=(0.3, 0.3, 0.3) to (2.0, 2.0, 2.0), keeping all the individual ai's equal to each other.

$$P(X) = D(X;\alpha) = \frac{\prod_i \Gamma(\alpha_i)}{\Gamma\left(\sum_i \alpha_i\right)} \prod_i x_i^{\alpha_i - 1}$$

- Parameters are $\alpha$s
  - Determine mode and curvature
- Defined only of probability vectors
  - $X = [x_1\ x_2\ ..\ x_K]$, $\Sigma_i\ x_i = 1$, $x_i >= 0$ for all i

## Maximum Likelihood: Dirichlet

- Given a collection of observations $(X_1, X_2, \ldots)$, estimate $\alpha$

$$\log(P(X_1, X_2, \ldots)) = \sum_j \sum_i (\alpha_i - 1)\log(X_{j,i}) + N\sum_i \log(\Gamma(\alpha_i)) - N\log\left(\Gamma\left(\sum_i \alpha_i\right)\right)$$

- No closed form solution for $\alpha$s.
  - Needs gradient ascent
- Several distributions have this property: the ML estimate of their parameters have no closed form solution



## Continuing the Thought Experiment

6 3 1 5 4 1 2 4 ... 4 4 1 6 3 2 1 2 ...

- Two persons shoot loaded dice repeatedly
  - The dice are differently loaded for the two of them
- We observe the series of outcomes for both persons
- **How to determine the probability distributions of the two dice?**



## Estimating Probabilities

- Observation: The sequence of numbers from the two dice
  - As indicated by the colors, we know who rolled what number

6 4 5 1 2 3 4 5 2 2 1 4 3 4 6 2 1 6...



## Estimating Probabilities

- Observation: The sequence of numbers from the two dice
  - As indicated by the colors, we know who rolled what number
- Segregation: Separate the blue observations from the red

6 4 5 1 2 3 4 5 2 2 1 4 3 4 6 2 1 6...

6 5 2 4 2 1 3 6 1.. 4 1 3 5 2 4 4 2 6..

Collection of "blue" numbers Collection of "red" numbers



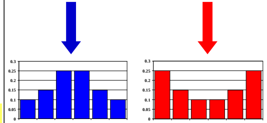
## Estimating Probabilities

- Observation: The sequence of numbers from the two dice
  - As indicated by the colors, we know who rolled what number
- Segregation: Separate the blue observations from the red
- From each set compute probabilities for each of the 6 possible outcomes

$$P(number) = \frac{\text{no. of times number was rolled}}{\text{total number of observed rolls}}$$

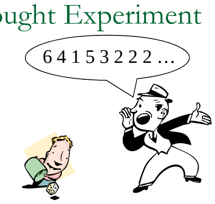
6 4 5 1 2 3 4 5 2 2 1 4 3 4 6 2 1 6...

6 5 2 4 2 1 3 6 1.. 4 1 3 5 2 4 4 2 6..





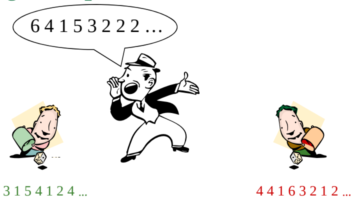
## A Thought Experiment




6 3 1 5 4 1 2 4 ... 4 4 1 6 3 2 1 2 ...

- Now imagine that you cannot observe the dice yourself
- Instead there is a "caller" who randomly calls out the outcomes
  - 40% of the time he calls out the number from the left shooter, and 60% of the time, the one from the right (and you know this)
- At any time, you do not know which of the two he is calling out
- How do you determine the probability distributions for the two dice?

## A Thought Experiment




- How do you now determine the probability distributions for the two sets of dice …
- .. If you do not even know what fraction of time the blue numbers are called, and what fraction are red?



## A Mixture Multinomial

- The caller will call out a number X in any given callout IF
  - He selects “RED”, and the Red die rolls the number X
  - OR
  - He selects “BLUE” and the Blue die rolls the number X
- P(X) = P(Red)P(X|Red) + P(Blue)P(X|Blue)
  - E.g. P(6) = P(Red)P(6|Red) + P(Blue)P(6|Blue)
- A distribution that *combines* (or *mixes*) multiple multinomials is a *mixture* multinomial

$$P(X) = \sum_Z P(Z)P(X \mid Z)$$

Mixture weights  Component multinomials



## Mixture Distributions

$$P(X) = \sum_Z P(Z)P(X \mid Z)$$

Mixture weights  Component distributions

Mixture Gaussian

$$P(X) = \sum_Z P(Z)N(X;\mu_z,\Theta_z)$$

Mixture of Gaussians and Laplacians

$$P(X) = \sum_Z P(Z)N(X;\mu_z,\Theta_z) + \sum_Z P(Z)\prod_i L(X_i;\mu_z,b_{z,i})$$

- Mixture distributions mix several component distributions
  - Component distributions may be of varied type
- Mixing weights must sum to 1.0
- Component distributions integrate to 1.0
- Mixture distribution integrates to 1.0



## Maximum Likelihood Estimation

- For our problem: $P(X) = \sum_Z P(Z)P(X \mid Z)$
  - Z = color of dice

$$P(n_1,n_2,n_3,n_4,n_5,n_6) = Const\prod_X P(X)^{n_X} = Const\prod_X \left(\sum_Z P(Z)P(X \mid Z)\right)^{n_X}$$

- Maximum likelihood solution: Maximize

$$\log(P(n_1,n_2,n_3,n_4,n_5,n_6)) = \log(Const) + \sum_X n_X \log\left(\sum_Z P(Z)P(X \mid Z)\right)$$

- No closed form solution (summation inside log)!
  - In general ML estimates for mixtures do not have a closed form
  - USE EM!



## Expectation Maximization

- It is possible to estimate all parameters in this setup using the Expectation Maximization (or EM) algorithm
- First described in a landmark paper by Dempster, Laird and Rubin
  - Maximum Likelihood Estimation from incomplete data, via the EM Algorithm, Journal of the Royal Statistical Society, Series B, 1977
- Much work on the algorithm since then
- The principles behind the algorithm existed for several years prior to the landmark paper, however.



## Expectation Maximization

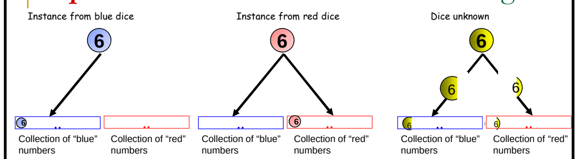
- Iterative solution
- Get some initial estimates for all parameters
  - Dice shooter example: This includes probability distributions for dice AND the probability with which the caller selects the dice
- Two steps that are iterated:
  - ***Expectation Step:*** Estimate statistically, the values of ***unseen*** variables
  - ***Maximization Step:*** Using the estimated values of the unseen variables as truth, estimates of the model parameters

## EM: The auxiliary function

- EM iteratively optimizes the following auxiliary function
- $Q(\theta, \theta') = \Sigma_Z P(Z|X,\theta') \log(P(Z,X \mid \theta))$
  - Z are the unseen variables
  - Assuming Z is discrete (may not be)
- θ' are the parameter estimates from the previous iteration
- θ are the estimates to be obtained in the current iteration



## Expectation Maximization as counting




- Hidden variable: *Z*
  - Dice: The identity of the dice whose number has been called out
- If we knew *Z* for every observation, we could estimate all terms
  - By adding the observation to the right bin
- Unfortunately, we do not know *Z* – it is hidden from us!
- Solution: FRAGMENT THE OBSERVATION



## Fragmenting the Observation

- EM is an iterative algorithm
  - At each time there is a *current* estimate of parameters
- The "size" of the fragments is proportional to the *a posteriori probability* of the component distributions
  - The *a posteriori* probabilities of the various values of *Z* are computed using Bayes' rule:

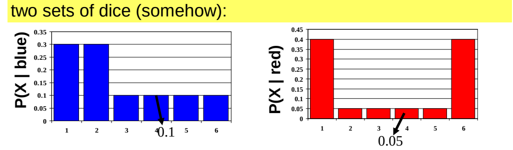
$$P(Z \mid X) = \frac{P(X \mid Z)P(Z)}{P(X)} = CP(X \mid Z)P(Z)$$

- Every dice gets a fragment of size P(dice | number)

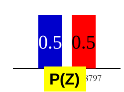


## Expectation Maximization

- Hypothetical Dice Shooter Example:
- We obtain an initial estimate for the probability distribution of the two sets of dice (somehow):




- We obtain an initial estimate for the probability with which the caller calls out the two shooters (somehow)






## Expectation Maximization

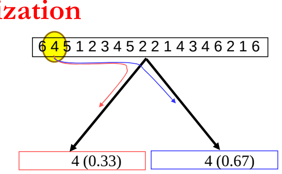
- Hypothetical Dice Shooter Example:
- Initial estimate:
  - P(blue) = P(red) = 0.5
  - P(4 | blue) = 0.1, for P(4 | red) = 0.05
- Caller has just called out 4
- Posterior probability of colors:

$$P(red \mid X=4) = CP(X=4 \mid Z=red)P(Z=red) = C \times 0.05 \times 0.5 = C0.025$$
$$P(blue \mid X=4) = CP(X=4 \mid Z=blue)P(Z=blue) = C \times 0.1 \times 0.5 = C0.05$$

$$\textbf{Normalizing: } P(red \mid X=4) = 0.33; \quad P(blue \mid X=4) = 0.67$$

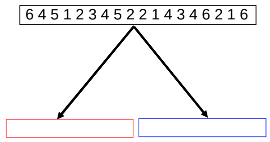


## Expectation Maximization



## Expectation **Maximization**

- Every observed roll of the dice contributes to both “Red” and “Blue”



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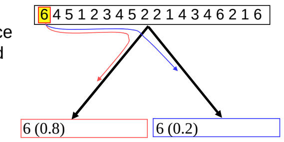




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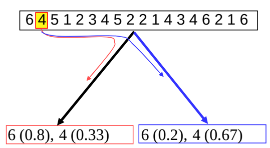




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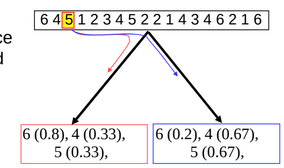
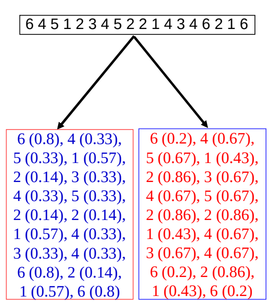





## Expectation **Maximization**

- Every observed roll of the dice contributes to both “Red” and “Blue”






## Expectation **Maximization**

- Every observed roll of the dice contributes to both “Red” and “Blue”
- Total count for “Red” is the sum of all the posterior probabilities in the red column
  - 7.31
- Total count for “Blue” is the sum of all the posterior probabilities in the blue column
  - 10.69
  - Note: 10.69 + 7.31 = 18 = the total number of instances

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |
| | 7.31 | 10.69 |

## Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
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| 4 | .33 | .67 |
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| 2 | .14 | .86 |
| 2 | .14 | .86 |
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| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71
  - Total count for 2: 0.56

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71
  - Total count for 2: 0.56
  - Total count for 3: 0.66

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71
  - Total count for 2: 0.56
  - Total count for 3: 0.66
  - Total count for 4: 1.32

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
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| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
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| 2 | .14 | .86 |
| 2 | .14 | .86 |
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| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71
  - Total count for 2: 0.56
  - Total count for 3: 0.66
  - Total count for 4: 1.32
  - Total count for 5: 0.66

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
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| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71
  - Total count for 2: 0.56
  - Total count for 3: 0.66
  - Total count for 4: 1.32
  - Total count for 5: 0.66
  - Total count for 6: 2.4

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
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| 5 | .33 | .67 |
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| 1 | .57 | .43 |
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7.31 10.69

# Expectation Maximization

- Total count for "Red" : 7.31
- Red:
  - Total count for 1: 1.71
  - Total count for 2: 0.56
  - Total count for 3: 0.66
  - Total count for 4: 1.32
  - Total count for 5: 0.66
  - Total count for 6: 2.4
- **Updated probability of Red dice:**
  - P(1 | Red) = 1.71/7.31 = 0.234
  - P(2 | Red) = 0.56/7.31 = 0.077
  - P(3 | Red) = 0.66/7.31 = 0.090
  - P(4 | Red) = 1.32/7.31 = 0.181
  - P(5 | Red) = 0.66/7.31 = 0.090
  - P(6 | Red) = 2.40/7.31 = 0.328

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



# Expectation Maximization

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



# Expectation Maximization

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29
  - Total count for 2: 3.44

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



# Expectation Maximization

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29
  - Total count for 2: 3.44
  - Total count for 3: 1.34

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



# Expectation Maximization

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29
  - Total count for 2: 3.44
  - Total count for 3: 1.34
  - Total count for 4: 2.68

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



# Expectation Maximization

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29
  - Total count for 2: 3.44
  - Total count for 3: 1.34
  - Total count for 4: 2.68
  - Total count for 5: 1.34

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69

## Expectation **Maximization**

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29
  - Total count for 2: 3.44
  - Total count for 3: 1.34
  - Total count for 4: 2.68
  - Total count for 5: 1.34
  - Total count for 6: 0.6

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation **Maximization**

- Total count for "Blue" : 10.69
- Blue:
  - Total count for 1: 1.29
  - Total count for 2: 3.44
  - Total count for 3: 1.34
  - Total count for 4: 2.68
  - Total count for 5: 1.34
  - Total count for 6: 0.6
- **Updated probability of Blue dice:**
  - P(1 | Blue) = 1.29/11.69 = 0.122
  - P(2 | Blue) = 0.56/11.69 = 0.322
  - P(3 | Blue) = 0.66/11.69 = 0.125
  - P(4 | Blue) = 1.32/11.69 = 0.250
  - P(5 | Blue) = 0.66/11.69 = 0.125
  - P(6 | Blue) = 2.40/11.69 = 0.056

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## Expectation **Maximization**

- Total count for "Red" : 7.31
- Total count for "Blue" : 10.69
- Total instances = 18
  - Note 7.31+10.69 = 18
- We also revise our estimate for the probability that the caller calls out Red or Blue
  - i.e the fraction of times that he calls Red and the fraction of times he calls Blue
- P(Z=Red) = 7.31/18 = 0.41
- P(Z=Blue) = 10.69/18 = 0.59

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

7.31 10.69



## The updated values

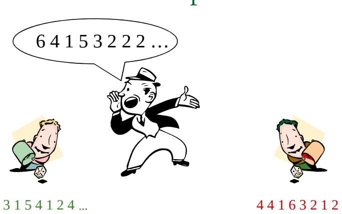
- Probability of Red dice:
  - P(1 | Red) = 1.71/7.31 = 0.234
  - P(2 | Red) = 0.56/7.31 = 0.077
  - P(3 | Red) = 0.66/7.31 = 0.090
  - P(4 | Red) = 1.32/7.31 = 0.181
  - P(5 | Red) = 0.66/7.31 = 0.090
  - P(6 | Red) = 2.40/7.31 = 0.328
- Probability of Blue dice:
  - P(1 | Blue) = 1.29/11.69 = 0.122
  - P(2 | Blue) = 0.56/11.69 = 0.322
  - P(3 | Blue) = 0.66/11.69 = 0.125
  - P(4 | Blue) = 1.32/11.69 = 0.250
  - P(5 | Blue) = 0.66/11.69 = 0.125
  - P(6 | Blue) = 2.40/11.69 = 0.056
- P(Z=Red) = 7.31/18 = 0.41
- P(Z=Blue) = 10.69/18 = 0.59

| Called | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6 | .8 | .2 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 1 | .57 | .43 |
| 2 | .14 | .86 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 5 | .33 | .67 |
| 2 | .14 | .86 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 4 | .33 | .67 |
| 3 | .33 | .67 |
| 4 | .33 | .67 |
| 6 | .8 | .2 |
| 2 | .14 | .86 |
| 1 | .57 | .43 |
| 6 | .8 | .2 |

**THE UPDATED VALUES CAN BE USED TO REPEAT THE PROCESS. ESTIMATION IS AN ITERATIVE PROCESS**



## The Dice Shooter Example




1. Initialize *P(Z)*, *P(X | Z)*
2. Estimate *P(Z | X)* for each *Z*, for each called out number
   - Associate *X* with each value of *Z*, with weight *P(Z | X)*
3. Re-estimate *P(X | Z)* for every value of *X* and *Z*
4. Re-estimate *P(Z)*
5. If not converged, return to 2



## In Squiggles

- Given a sequence of observations $O_1$, $O_2$, ..
  - $N_X$ is the number of observations of number X
- Initialize P(Z), P(X|Z) for dice Z and numbers X
- Iterate:
  - For each number X: $P(Z \mid X) = \frac{P(X \mid Z)P(Z)}{\sum_{Z'} P(Z')P(X \mid Z')}$
  - Update:

$$P(X \mid Z) = \frac{\sum_{O \text{ such that } O==X} P(Z \mid X)}{\sum_{O} P(Z \mid O)} = \frac{N_X P(Z \mid X)}{\sum_X N_X P(Z \mid X)} \qquad P(Z) = \frac{\sum_X N_X P(Z \mid X)}{\sum_{Z'} \sum_X N_X P(Z' \mid X)}$$

## Solutions may not be unique

- The EM algorithm will give us one of many solutions, all equally valid!
  - The probability of 6 being called out:

$$P(6) = \alpha P(6 \mid red) + \beta P(6 \mid blue) = \alpha P_r + \beta P_b$$

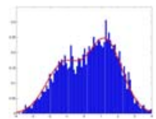
    - Assigns $P_r$ as the probability of 6 for the red die
    - Assigns $P_b$ as the probability of 6 for the blue die
  - The following too is a valid solution [FIX]

$$P(6) = 1.0(\alpha P_r + \beta P_b) + 0.0 anything$$

    - Assigns 1.0 as the a priori probability of the red die
    - Assigns 0.0 as the probability of the blue die
- The solution is NOT unique



## A More Complex Model



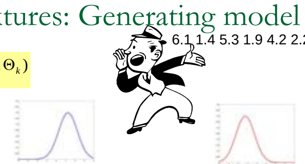
$$P(X) = \sum_k P(k) N(X; \mu_k, \Theta_k) = \sum_k \frac{P(k)}{\sqrt{(2\pi)^d \mid \Theta_k \mid}} \exp\left(-0.5 (X - \mu_k)^T \Theta_k^{-1} (X - \mu_k)\right)$$

- Gaussian mixtures are often good models for the distribution of multivariate data
- Problem: Estimating the parameters, given a collection of data



## Gaussian Mixtures: Generating model

$$P(X) = \sum_k P(k) N(X; \mu_k, \Theta_k)$$

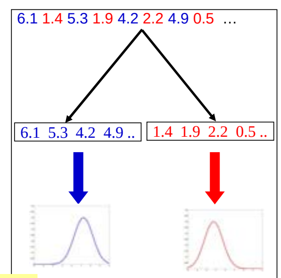



- The caller now has two Gaussians
  - At each draw he randomly selects a Gaussian, by the mixture weight distribution
  - He then draws an observation from that Gaussian
  - Much like the dice problem (only the outcomes are now real numbers and can be anything)



## Estimating GMM with complete information

- Observation: A collection of numbers drawn from a mixture of 2 Gaussians
  - As indicated by the colors, we know which Gaussian generated what number
- Segregation: Separate the blue observations from the red
- From each set compute parameters for that Gaussian

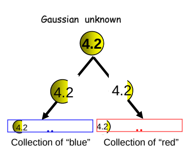



$$\mu_{red} = \frac{1}{N_{red}} \sum_{i \in red} X_i \qquad \Theta_{red} = \frac{1}{N_{red}} \sum_{i \in red} (X_i - \mu_{red})(X_i - \mu_{red})^T$$

$$P(red) = \frac{N_{red}}{N}$$



## Fragmenting the observation




- The identity of the Gaussian is not known!
- Solution: **Fragment the observation**
- Fragment size proportional to *a posteriori* probability

$$P(k \mid X) = \frac{P(X \mid k) P(k)}{\sum_{k'} P(k') P(X \mid k')} = \frac{P(k) N(X; \mu_k, \Theta_k)}{\sum_{k'} P(k') N(X; \mu_{k'}, \Theta_{k'})}$$



## Expectation **Maximization**

- Initialize P(k), $\mu_k$ and $\Theta_k$ for both Gaussians
  - Important how we do this
  - Typical solution: Initialize means randomly, $\Theta_k$ as the global covariance of the data and P(k) uniformly
- Compute fragment sizes for each Gaussian, for each observation

| Number | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6.1 | .81 | .19 |
| 1.4 | .33 | .67 |
| 5.3 | .75 | .25 |
| 1.9 | .41 | .59 |
| 4.2 | .64 | .36 |
| 2.2 | .43 | .57 |
| 4.9 | .66 | .34 |
| 0.5 | .05 | .95 |

$$P(k \mid X) = \frac{P(k) N(X; \mu_k, \Theta_k)}{\sum_{k'} P(k') N(X; \mu_{k'}, \Theta_{k'})}$$

## Expectation **Maximization**

- ***Each observation contributes only as much as its fragment size to each statistic***
- Mean(red) = (6.1*0.81 + 1.4*0.33 + 5.3*0.75 + 1.9*0.41 + 4.2*0.64 + 2.2*0.43 + 4.9*0.66 + 0.5*0.05 ) / (0.81 + 0.33 + 0.75 + 0.41 + 0.64 + 0.43 + 0.66 + 0.05) = 17.05 / 4.08 = 4.18

| Number | P(red\|X) | P(blue\|X) |
|---|---|---|
| 6.1 | .81 | .19 |
| 1.4 | .33 | .67 |
| 5.3 | .75 | .25 |
| 1.9 | .41 | .59 |
| 4.2 | .64 | .36 |
| 2.2 | .43 | .57 |
| 4.9 | .66 | .34 |
| 0.5 | .05 | .95 |
| | 4.08 | 3.92 |

- Var(red) = ((6.1-4.18)$^2$*0.81 + (1.4-4.18)$^2$*0.33 + (5.3-4.18)$^2$*0.75 + (1.9-4.18)$^2$*0.41 + (4.2-4.18)$^2$*0.64 + (2.2-4.18)$^2$*0.43 + (4.9-4.18)$^2$*0.66 + (0.5-4.18)$^2$*0.05 ) / (0.81 + 0.33 + 0.75 + 0.41 + 0.64 + 0.43 + 0.66 + 0.05)

$$P(red) = \frac{4.08}{8}$$



## EM for Gaussian Mixtures

1. Initialize P(k), $\mu_k$ and $\Theta_k$ for all Gaussians
2. For each observation X compute *a posteriori* probabilities for all Gaussian

$$P(k \mid X) = \frac{P(k)N(X;\mu_k,\Theta_k)}{\sum_{k'} P(k')N(X;\mu_{k'},\Theta_{k'})}$$

3. Update mixture weights, means and variances for all Gaussians

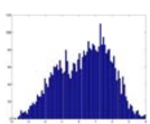
$$P(k) = \frac{\sum_X P(k|X)}{N} \qquad \mu_k = \frac{\sum_X P(k|X)\,X}{\sum_X P(k|X)} \qquad \Theta_k = \frac{\sum_X P(k|X)(X-\mu_k)^2}{\sum_X P(k|X)}$$

4. If not converged, return to 2

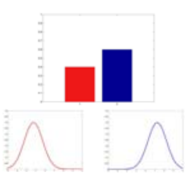


## EM estimation of Gaussian Mixtures

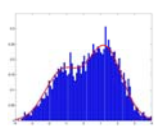
- An Example



Histogram of 4000 instances of a randomly generated data



Individual parameters of a two-Gaussian mixture estimated by EM



Two-Gaussian mixture estimated by EM



## Expectation Maximization

- The same principle can be extended to mixtures of other distributions.
- E.g. Mixture of Laplacians: Laplacian parameters become

$$\mu_k = \frac{1}{\sum_x P(k \mid x)} \sum_x P(k \mid x)x \qquad b_k = \frac{1}{\sum_x P(k \mid x)} \sum_x P(k \mid x) \mid x - \mu_k \mid$$

- In a mixture of Gaussians and Laplacians, Gaussians use the Gaussian update rules, Laplacians use the Laplacian rule



## Expectation Maximization

- The EM algorithm is used whenever proper statistical analysis of a phenomenon requires the knowledge of a hidden or missing variable (or a set of hidden/missing variables)
  - The hidden variable is often called a "latent" variable
- Some examples:
  - Estimating mixtures of distributions
    - Only data are observed. The individual distributions and mixing proportions must both be learnt.
  - Estimating the distribution of data, when some attributes are missing
  - Estimating the dynamics of a system, based only on observations that may be a complex function of system state

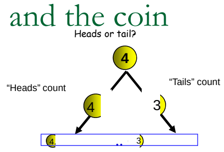


## Solve this problem:

- Caller rolls a dice and flips a coin
- He calls out the number rolled if the coin shows head
- Otherwise he calls the number+1
- Determine p(heads) and p(number) for the dice from a collection of ouputs

- Caller rolls two dice
- He calls out the sum
- Determine P(dice) from a collection of ouputs

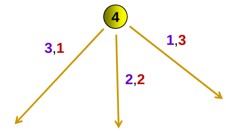
## The dice and the coin




- Unknown: Whether it was head or tails



## The two dice

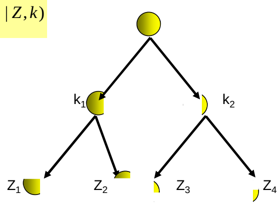



- Unknown: How to partition the number
- $Count_{blue}(3)$ += P(3,1 | 4)
- $Count_{blue}(2)$ += P(2,2 | 4)
- $Count_{blue}(1)$ += P(1,3 | 4)



## Fragmentation can be hierarchical

$$P(X) = \sum_k P(k) \sum_Z P(Z \mid k) P(X \mid Z, k)$$




- E.g. mixture of mixtures
- Fragments are further fragmented..
  - Work this out



## More later

- Will see a couple of other instances of the use of EM
- Work out HMM training
  - Assume state output distributions are multinomials
  - Assume they are Gaussian
  - Assume Gaussian mixtures