Bayesian Methods: Naïve Bayes

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based on the slides of Vibhav Gogate
Last Time

• Parameter learning
  • Learning the parameter of a simple coin flipping model
• Prior distributions
• Posterior distributions
• Today: more parameter learning and naïve Bayes
Maximum Likelihood Estimation (MLE)

- **Data:** Observed set of $\alpha_H$ heads and $\alpha_T$ tails
- **Hypothesis:** Coin flips follow a binomial distribution
- **Learning:** Find the “best” $\theta$
- **MLE:** Choose $\theta$ to maximize the likelihood (probability of $D$ given $\theta$)

$$\theta_{MLE} = \arg \max_{\theta} p(D|\theta)$$
MAP Estimation

• Choosing $\theta$ to maximize the posterior distribution is called maximum a posteriori (MAP) estimation

$$\theta_{MAP} = \arg \max_{\theta} p(\theta | D)$$

• The only difference between $\theta_{MLE}$ and $\theta_{MAP}$ is that one assumes a uniform prior (MLE) and the other allows an arbitrary prior
Sample Complexity

- How many coin flips do we need in order to guarantee that our learned parameter does not differ too much from the true parameter (with high probability)?

- Can use Chernoff bound (again!)

  - Suppose $Y_1, \ldots, Y_N$ are i.i.d. random variables taking values in $\{0, 1\}$ such that $E_p[Y_i] = y$. For $\epsilon > 0$,

    $$p \left( \left| y - \frac{1}{N} \sum_i Y_i \right| \geq \epsilon \right) \leq 2e^{-2N\epsilon^2}$$
Sample Complexity

• How many coin flips do we need in order to guarantee that our learned parameter does not differ too much from the true parameter (with high probability)?

• Can use Chernoff bound (again!)

  • For the coin flipping problem with $X_1, \ldots, X_n$ iid coin flips and $\epsilon > 0$,}

\[
p \left( \left| \theta_{true} - \frac{1}{N} \sum_{i} X_i \right| \geq \epsilon \right) \leq 2e^{-2N\epsilon^2}
\]
Sample Complexity

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  • For the coin flipping problem with $X_1, \ldots, X_n$ iid coin flips and $\epsilon > 0$,

    $$p(\mid \theta_{true} - \theta_{MLE} \mid \geq \epsilon) \leq 2e^{-2N\epsilon^2}$$
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$$p(|\theta_{true} - \theta_{MLE}| \geq \epsilon) \leq 2e^{-2N\epsilon^2}$$

$$\delta \geq 2e^{-2N\epsilon^2} \Rightarrow N \geq \frac{1}{2\epsilon^2 \ln \frac{2}{\delta}}$$
MLE for Gaussian Distributions

• Two parameter distribution characterized by a mean and a variance

\[ P(x \mid \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]
Some properties of Gaussians

- Affine transformation (multiplying by scalar and adding a constant) are Gaussian
  - \( X \sim N(\mu, \sigma^2) \)
  - \( Y = aX + b \Rightarrow Y \sim N(a\mu + b, a^2\sigma^2) \)
- Sum of Gaussians is Gaussian
  - \( X \sim N(\mu_X, \sigma_X^2), Y \sim N(\mu_Y, \sigma_Y^2) \)
  - \( Z = X + Y \Rightarrow Z \sim N(\mu_X + \mu_Y, \sigma_X^2 + \sigma_Y^2) \)
- Easy to differentiate, as we will see soon!
Learning a Gaussian

- Collect data
  - Hopefully, i.i.d. samples
  - e.g., exam scores
- Learn parameters
  - Mean: $\mu$
  - Variance: $\sigma$

\[
P(x \mid \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]
MLE for Gaussian:

- Probability of $N$ i.i.d. samples $D = x^{(1)}, \ldots, x^{(N)}$

$$p(D | \mu, \sigma) = \left( \frac{1}{\sqrt{2\pi\sigma^2}} \right)^N \prod_{i=1}^{N} e^{-\frac{(x^{(i)}-\mu)^2}{2\sigma^2}}$$

$$\mu_{MLE}, \sigma_{MLE} = \arg\max_{\mu, \sigma} P(D | \mu, \sigma)$$

- Log-likelihood of the data

$$\ln p(D | \mu, \sigma) = -\frac{N}{2} \ln 2\pi \sigma^2 - \sum_{i=1}^{N} \frac{(x^{(i)} - \mu)^2}{2\sigma^2}$$
MLE for the Mean of a Gaussian

\[
\frac{\partial}{\partial \mu} \ln p(D|\mu, \sigma) = \frac{\partial}{\partial \mu} \left[ -\frac{N}{2} \ln 2\pi \sigma^2 - \sum_{i=1}^{N} \frac{(x^{(i)} - \mu)^2}{2\sigma^2} \right]
\]

\[
= \frac{\partial}{\partial \mu} \left[ -\sum_{i=1}^{N} \frac{(x^{(i)} - \mu)^2}{2\sigma^2} \right]
\]

\[
= -\sum_{i=1}^{N} \frac{(x^{(i)} - \mu)}{\sigma^2}
\]

\[
= \left[ N\mu - \sum_{i=1}^{N} x^{(i)} \right] = 0
\]

\[
\mu_{MLE} = \frac{1}{N} \sum_{i=1}^{N} x^{(i)}
\]
MLE for Variance

\[
\frac{\partial}{\partial \sigma} \ln p(D|\mu, \sigma) = \frac{\partial}{\partial \sigma} \left[ -\frac{N}{2} \ln 2\pi \sigma^2 - \sum_{i=1}^{N} \frac{(x^{(i)} - \mu)^2}{2\sigma^2} \right] \\
= -\frac{N}{\sigma} + \frac{\partial}{\partial \sigma} \left[ -\sum_{i=1}^{N} \frac{(x^{(i)} - \mu)^2}{2\sigma^2} \right] \\
= -\frac{N}{\sigma} + \sum_{i=1}^{N} \frac{(x^{(i)} - \mu)^2}{\sigma^3} = 0
\]

\[
\sigma^2_{MLE} = \frac{1}{N} \sum_{i=1}^{N} (x^{(i)} - \mu_{MLE})^2
\]
Learning Gaussian parameters

\[
\mu_{MLE} = \frac{1}{N} \sum_{i=1}^{N} x(i)
\]

\[
\sigma_{MLE}^2 = \frac{1}{N} \sum_{i=1}^{N} (x(i) - \mu_{MLE})^2
\]

- MLE for the variance of a Gaussian is **biased**
  - Expected result of estimation is **not** true parameter!
  - Unbiased variance estimator

\[
\sigma_{unbiased}^2 = \frac{1}{N - 1} \sum_{i=1}^{N} (x(i) - \mu_{MLE})^2
\]
Bayesian Categorization/Classification

- Given features $x = (x_1, \ldots, x_m)$ predict a label $y$

- If we had a joint distribution over $x$ and $y$, given $x$ we could find the label using MAP inference

$$\arg \max_y p(y|x_1, \ldots, x_m)$$

- Can compute this in exactly the same way that we did before using Bayes rule:

$$p(y|x_1, \ldots, x_m) = \frac{p(x_1, \ldots, x_m|y)p(y)}{p(x_1, \ldots, x_m)}$$
Article Classification

• Given a collection of news articles labeled by topic goal is, given an unseen news article, to predict topic

• One possible feature vector:

  • One feature for each word in the document, in order
    
    – $x_i$ corresponds to the $i^{th}$ word
    
    – $x_i$ can take a different value for each word in the dictionary
Text Classification

Article from rec.sport.hockey

Path: cantaloupe.srv.cs.cmu.edu!das-news.harvard.edu
From: xxx@yyy.zzz.edu (John Doe)
Subject: Re: This year’s biggest and worst (opinion)
Date: 5 Apr 93 09:53:39 GMT

I can only comment on the Kings, but the most obvious candidate for pleasant surprise is Alex Zhitnik. He came highly touted as a defensive defenseman, but he’s clearly much more than that. Great skater and hard shot (though wish he were more accurate). In fact, he pretty much allowed the Kings to trade away that huge defensive liability Paul Coffey. Kelly Hrudey is only the biggest disappointment if you thought he was any good to begin with. But, at best, he’s only a mediocre goaltender. A better choice would be Tomas Sandstrom, though not through any fault of his own, but because some thugs in Toronto decided
• $x_1, x_2, \ldots$ is sequence of words in document

• The set of all possible features, and hence $p(y|x)$, is huge

  • Article at least 1000 words, $x = (x_1, \ldots, x_{1000})$

  • $x_i$ represents $i^{th}$ word in document

    • Can be any word in the dictionary – at least 10,000 words

    • $10,000^{1000} = 10^{4000}$ possible values

  • Atoms in Universe: $\sim 10^{80}$
Bag of Words Model

• Typically assume position in document doesn’t matter

\[ p(X_i = \text{"the"}|Y = y) = p(X_k = \text{"the"}|Y = y) \]

• All positions have the same distribution
• Ignores the order of words
• Sounds like a bad assumption, but often works well!

• Features

• Set of all possible words and their corresponding frequencies (number of times it occurs in the document)
Bag of Words

Our energy exploration, production, and distribution operations span the globe, with activities in more than 100 countries.

At TOTAL, we draw our greatest strength from our fast-growing oil and gas reserves. Our strategic emphasis on natural gas provides a strong position in a rapidly expanding market.

Our expanding refining and marketing operations in Asia and the Mediterranean Rim complement already solid positions in Europe, Africa, and the U.S.

Our growing specialty chemicals sector adds balance and profit to the core energy business.
Need to Simplify Somehow

- Even with the bag of words assumption, there are too many possible outcomes
  - Too many probabilities
    \[ p(x_1, ..., x_m | y) \]
  - Can we assume some are the same?
    \[ p(x_1, x_2 | y) = p(x_1 | y) p(x_2 | y) \]
    - This is a conditional independence assumption
Conditional Independence

• X is conditionally independent of Y given Z, if the probability distribution for X is independent of the value of Y, given the value of Z

\[ p(X|Y, Z) = P(X|Z) \]

• Equivalent to

\[ p(X, Y|Z) = p(X|Z)P(Y|Z) \]
Naïve Bayes

• Naïve Bayes assumption

  • Features are independent given class label

\[ p(x_1, x_2 | y) = p(x_1 | y) p(x_2 | y) \]

  • More generally

\[ p(x_1, \ldots, x_m | y) = \prod_{i=1}^{m} p(x_i | y) \]

• How many parameters now?

  • Suppose \( x \) is composed of \( d \) binary features
Naïve Bayes

• Naïve Bayes assumption

  • Features are independent given class label

\[ p(x_1, x_2 | y) = p(x_1 | y) \ p(x_2 | y) \]

  • More generally

\[ p(x_1, \ldots, x_m | y) = \prod_{i=1}^{m} p(x_i | y) \]

• How many parameters now?

  • Suppose \( x \) composed of \( d \) binary features \( \Rightarrow O(d \cdot L) \)
    where \( L \) is the number of class labels
The Naïve Bayes Classifier

• Given
  • Prior $p(y)$
  • $m$ conditionally independent features $X$ given the class $Y$
  • For each $X_i$, we have likelihood $P(X_i|Y)$

• Classify via

$$y^* = h_{NB}(x) = \arg\max_y p(y)p(x_1, ..., x_m|y)$$

$$= \arg\max_y p(y) \prod_{i=1}^{m} p(x_i|y)$$
MLE for the Parameters of NB

• Given dataset, count occurrences for all pairs
  
  • \( \text{Count}(X_i = x_i, Y = y) \) is the number of samples in which \( X_i = x_i \) and \( Y = y \)
  
• MLE for discrete NB

\[
p(Y = y) = \frac{\text{Count}(Y = y)}{\sum_{y'} \text{Count}(Y = y')}
\]

\[
p(X_i = x_i | Y = y) = \frac{\text{Count}(X_i = x_i, Y = y)}{\sum_{x_i'} \text{Count}(X_i = x_i', Y = y)}
\]
## Naïve Bayes Calculations

<table>
<thead>
<tr>
<th>Day</th>
<th>Outlook</th>
<th>Temperature</th>
<th>Humidity</th>
<th>Wind</th>
<th>PlayTennis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Sunny</td>
<td>Hot</td>
<td>High</td>
<td>Weak</td>
<td>No</td>
</tr>
<tr>
<td>D2</td>
<td>Sunny</td>
<td>Hot</td>
<td>High</td>
<td>Strong</td>
<td>No</td>
</tr>
<tr>
<td>D3</td>
<td>Overcast</td>
<td>Hot</td>
<td>High</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D4</td>
<td>Rain</td>
<td>Mild</td>
<td>High</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D5</td>
<td>Rain</td>
<td>Cool</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D6</td>
<td>Rain</td>
<td>Cool</td>
<td>Normal</td>
<td>Strong</td>
<td>No</td>
</tr>
<tr>
<td>D7</td>
<td>Overcast</td>
<td>Cool</td>
<td>Normal</td>
<td>Strong</td>
<td>Yes</td>
</tr>
<tr>
<td>D8</td>
<td>Sunny</td>
<td>Mild</td>
<td>High</td>
<td>Weak</td>
<td>No</td>
</tr>
<tr>
<td>D9</td>
<td>Sunny</td>
<td>Cool</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D10</td>
<td>Rain</td>
<td>Mild</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D11</td>
<td>Sunny</td>
<td>Mild</td>
<td>Normal</td>
<td>Strong</td>
<td>Yes</td>
</tr>
<tr>
<td>D12</td>
<td>Overcast</td>
<td>Mild</td>
<td>High</td>
<td>Strong</td>
<td>Yes</td>
</tr>
<tr>
<td>D13</td>
<td>Overcast</td>
<td>Hot</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D14</td>
<td>Rain</td>
<td>Mild</td>
<td>High</td>
<td>Strong</td>
<td>No</td>
</tr>
</tbody>
</table>
Subtleties of NB Classifier: #1

• Usually, features are not conditionally independent:

\[ p(x_1, ..., x_m | y) \neq \prod_{i=1}^{m} p(x_i | y) \]

• The naïve Bayes assumption is often violated, yet it performs surprisingly well in many cases

• Plausible reason: Only need the probability of the correct class to be the largest!

  • Example: binary classification; just need to figure out the correct side of 0.5 and not the actual probability (0.51 is the same as 0.99).
Subtleties of NB Classifier

• What if you never see a training instance \((X_1 = a, Y = b)\)

  • Example: you did not see the word “Nigerian” in spam

  • Then \(p(X_1 = a | Y = b) = 0\)

  • Thus no matter what values \(X_2, \ldots, X_m\) take

  \[ P(X_1 = a, X_2 = x_2, \ldots, X_m = x_m | Y = b) = 0 \]

• Why?
Subtleties of NB Classifier

• To fix this, use a prior!
  
  • Already saw how to do this in the coin-flipping example using the Beta distribution
  
  • For NB over discrete spaces, can use the Dirichlet prior
  
  • The Dirichlet distribution is a distribution over $z_1, \ldots, z_k \in (0,1)$ such that $z_1 + \cdots + z_k = 1$ characterized by $k$ parameters $\alpha_1, \ldots, \alpha_k$

\[
f(z_1, \ldots, z_k; \alpha_1, \ldots, \alpha_k) \propto \prod_{i=1}^{k} z_i^{\alpha_i-1}
\]

• Called smoothing, what are the MLE estimates under these kinds of priors?