Lecture 10: 13 February, 2025

Madhavan Mukund

https://www.cmi.ac.in/~madhavan

Data Mining and Machine Learning
January–April 2025

Bayesian classifiers

- As before
  - Attributes $\{A_1, A_2, \ldots, A_k\}$ and
  - Classes $C = \{c_1, c_2, \ldots c_\ell\}$

Bayesian classifiers

- As before
  - Attributes $\{A_1, A_2, \ldots, A_k\}$ and
  - Classes $C = \{c_1, c_2, \ldots c_\ell\}$
- Each class c_i defines a probabilistic model for attributes
  - $Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i)$

Bayesian classifiers

- As before
  - Attributes $\{A_1, A_2, \ldots, A_k\}$ and
  - Classes $C = \{c_1, c_2, \ldots c_\ell\}$
- Each class c_i defines a probabilistic model for attributes
  - $Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i)$
- Given a data item $d = (a_1, a_2, \ldots, a_k)$, identify the best class c for d

Bayesian classifiers

- As before
  - Attributes $\{A_1, A_2, \ldots, A_k\}$ and
  - Classes $C = \{c_1, c_2, \ldots c_\ell\}$
- Each class c_i defines a probabilistic model for attributes
  - $Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i)$
- Given a data item $d = (a_1, a_2, \ldots, a_k)$, identify the best class c for d
- Maximize $Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$

Generative models

- To use probabilities, need to describe how data is randomly generated
  - Generative model

Generative models

- To use probabilities, need to describe how data is randomly generated
  - Generative model
- Typically, assume a random instance is created as follows
  - Choose a class c_j with probability $Pr(c_j)$
  - Choose attributes $a_1, \ldots, a_k$ with probability $Pr(a_1, \ldots, a_k \mid c_j)$

Generative models

- To use probabilities, need to describe how data is randomly generated
  - Generative model
- Typically, assume a random instance is created as follows
  - Choose a class c_j with probability $Pr(c_j)$
  - Choose attributes $a_1, \ldots, a_k$ with probability $Pr(a_1, \ldots, a_k \mid c_j)$

] Parameters

- Generative model has associated parameters $\theta = (\theta_1, \ldots, \theta_m)$
  - Each class probability $Pr(c_j)$ is a parameter
  - Each conditional probability $Pr(a_1, \ldots, a_k \mid c_j)$ is a parameter

Generative models

- To use probabilities, need to describe how data is randomly generated
  - Generative model
- Typically, assume a random instance is created as follows
  - Choose a class c_j with probability $Pr(c_j)$
  - Choose attributes $a_1, \ldots, a_k$ with probability $Pr(a_1, \ldots, a_k \mid c_j)$
- Generative model has associated parameters $\theta = (\theta_1, \ldots, \theta_m)$
  - Each class probability $Pr(c_j)$ is a parameter
  - Each conditional probability $Pr(a_1, \ldots, a_k \mid c_j)$ is a parameter
- We need to estimate these parameters

$P(c \mid data) = P(data \mid c)\, P(c)$

2^k per class

$2^k - 1$ parameters

Maximum Likelihood Estimators

- Our goal is to estimate parameters (probabilities) $\theta = (\theta_1, \ldots, \theta_m)$

Maximum Likelihood Estimators

- Our goal is to estimate parameters (probabilities) $\theta = (\theta_1, \ldots, \theta_m)$
- Law of large numbers allows us to estimate probabilities by counting frequencies

Maximum Likelihood Estimators

- Our goal is to estimate parameters (probabilities) $\theta = (\theta_1, \ldots, \theta_m)$
- Law of large numbers allows us to estimate probabilities by counting frequencies
- Example: Tossing a biased coin, single parameter $\theta = Pr(\text{heads})$
  - N coin tosses, H heads and T tails
  - Why is $\hat{\theta} = H/N$ the best estimate?

Maximum Likelihood Estimators

- Our goal is to estimate parameters (probabilities) $\theta = (\theta_1, \ldots, \theta_m)$
- Law of large numbers allows us to estimate probabilities by counting frequencies
- Example: Tossing a biased coin, single parameter $\theta = Pr(\text{heads})$
  - N coin tosses, H heads and T tails
  - Why is $\hat{\theta} = H/N$ the best estimate?
- Likelihood
  - Actual coin toss sequence is $\tau = t_1 t_2 \ldots t_N$
  - Given an estimate of θ, compute $Pr(\tau \mid \theta)$ — likelihood $L(\theta)$

$P(\text{outcome} \mid \theta)$

Likelihood

Maximum Likelihood Estimators

- Our goal is to estimate parameters (probabilities) $\theta = (\theta_1, \ldots, \theta_m)$
- Law of large numbers allows us to estimate probabilities by counting frequencies
- Example: Tossing a biased coin, single parameter $\theta = Pr(\text{heads})$
  - N coin tosses, H heads and T tails
  - Why is $\hat{\theta} = H/N$ the best estimate?
- Likelihood
  - Actual coin toss sequence is $\tau = t_1 t_2 \ldots t_N$
  - Given an estimate of θ, compute $Pr(\tau \mid \theta)$ — likelihood $L(\theta)$
- $\hat{\theta} = H/N$ maximizes this likelihood — $\arg\max_{\theta} L(\theta) = \hat{\theta} = H/N$
  - Maximum Likelihood Estimator (MLE)

Bayesian classification

- Maximize $Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$

Bayesian classification

- Maximize $Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$
- By Bayes' rule,

$$Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$$

$$= \frac{Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i)\, Pr(C = c_i)}{Pr(A_1 = a_1, \ldots, A_k = a_k)}$$

$P(C|A) = \frac{P(A|C) \cdot P(C)}{P(A)}$

$P(a_1 \ldots a_k | c_j)$

$Pr(c_j)$

$P(a_1 \ldots a_k)$

Bayesian classification

- Maximize $Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$
- By Bayes' rule,

$$Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$$

$$= \frac{Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i) \cdot Pr(C = c_i)}{Pr(A_1 = a_1, \ldots, A_k = a_k)}$$

$$= \frac{Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i) \cdot Pr(C = c_i)}{\sum_{j=1}^{\ell} Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_j) \cdot Pr(C = c_j)}$$

Bayesian classification

- Maximize $Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$

- By Bayes' rule,

$$Pr(C = c_i \mid A_1 = a_1, \ldots, A_k = a_k)$$

$$= \frac{Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i)\, Pr(C = c_i)}{Pr(A_1 = a_1, \ldots, A_k = a_k)}$$

← Same for all c_i

$$= \frac{Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i) \cdot Pr(C = c_i)}{\sum_{j=1}^{\ell} Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_j) \cdot Pr(C = c_j)}$$

- Denominator is the same for all c_i, so sufficient to maximize

$$Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i) \cdot Pr(C = c_i)$$

Example

- To classify $A = g, B = q$

$P(C \mid A=g, B=q)$

$P(C \mid data) = P(data \mid C) \cdot P(C)$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example

- To classify $A = g, B = q$

- $Pr(C = t) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = t) = 2/5$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example

- To classify $A = g, B = q$

- $Pr(C = t) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = t) = 2/5$
- $Pr(A = g, B = q \mid C = t) \cdot Pr(C = t) = 1/5$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example

- To classify $A = g, B = q$
- $Pr(C = t) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = t) = 2/5$
- $Pr(A = g, B = q \mid C = t) \cdot Pr(C = t) = 1/5$
- $Pr(C = f) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = f) = 1/5$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example

- To classify $A = g, B = q$

- $Pr(C = t) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = t) = 2/5$
- $Pr(A = g, B = q \mid C = t) \cdot Pr(C = t) = 1/5$

- $Pr(C = f) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = f) = 1/5$
- $Pr(A = g, B = q \mid C = f) \cdot Pr(C = f) = 1/10$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example

- To classify $A = g, B = q$

- $Pr(C = t) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = t) = 2/5$
- $Pr(A = g, B = q \mid C = t) \cdot Pr(C = t) = 1/5$

- $Pr(C = f) = 5/10 = 1/2$
- $Pr(A = g, B = q \mid C = f) = 1/5$
- $Pr(A = g, B = q \mid C = f) \cdot Pr(C = f) = 1/10$

- Hence, predict $C = t$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example ...

- What if we want to classify $A = m, B = q$?

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example . . .

- What if we want to classify $A = m, B = q$?
- $Pr(A = m, B = q \mid C = t) = 0$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

- What if we want to classify $A = m, B = q$?
- $Pr(A = m, B = q \mid C = t) = 0$
- Also $Pr(A = m, B = q \mid C = f) = 0$!

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

3 × 3 combinations = 9 parameters × 2

Example . . .

- What if we want to classify $A = m, B = q$?
- $Pr(A = m, B = q \mid C = t) = 0$
- Also $Pr(A = m, B = q \mid C = f) = 0$!
- To estimate joint probabilities across all combinations of attributes, we need a much larger set of training data

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Naïve Bayes classifier

- Strong simplifying assumption: attributes are pairwise independent

$$Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i) = \prod_{j=1}^{k} Pr(A_j = a_j \mid C = c_i)$$

  - $Pr(C = c_i)$ is fraction of training data with class c_i
  - $Pr(A_j = a_j \mid C = c_i)$ is fraction of training data labelled c_i for which $A_j = a_j$

$3 \times 3 \quad 3 \times 3 - 1 \qquad P(m, q \mid t) = P(m \mid t) \cdot P(q \mid t)$

$3 + 3 \quad (3-1) + (3-1)$

Naïve Bayes classifier

- Strong simplifying assumption: attributes are pairwise independent

$$Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i) = \prod_{j=1}^{k} Pr(A_j = a_j \mid C = c_i)$$

  - $Pr(C = c_i)$ is fraction of training data with class c_i
  - $Pr(A_j = a_j \mid C = c_i)$ is fraction of training data labelled c_i for which $A_j = a_j$

- Final classification is

$$\arg\max_{c_i} \; Pr(C = c_i) \prod_{j=1}^{k} Pr(A_j = a_j \mid C = c_i)$$

Instead of

$Pr(A_1 = a_1, \ldots, A_k = a_k \mid C = c_i)$

Naïve Bayes classifier . . .

- Conditional independence is not theoretically justified

Naïve Bayes classifier . . .

- Conditional independence is not theoretically justified
- For instance, text classification
  - Items are documents, attributes are words (absent or present)
  - Classes are topics
  - Conditional independence says that a document is a set of words: ignores sequence of words
  - Meaning of words is clearly affected by relative position, ordering

Naïve Bayes classifier . . .

- Conditional independence is not theoretically justified
- For instance, text classification
  - Items are documents, attributes are words (absent or present)
  - Classes are topics
  - Conditional independence says that a document is a set of words: ignores sequence of words
  - Meaning of words is clearly affected by relative position, ordering
- However, naive Bayes classifiers work well in practice, even for text classification!
  - Many spam filters are built using this model

Example revisited

- Want to classify $A = m, B = q$
- $Pr(A = m, B = q \mid C = t) = Pr(A = m, B = q \mid C = f) = 0$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

$P(m|t) = \frac{2}{5}$ $P(q|t) = \frac{2}{5}$ $P(t) = \frac{1}{2} = \frac{2}{25}$

$P(m|f) = \frac{1}{5}$ $P(q|f) = \frac{2}{5}$ $P(f) = \frac{1}{2} = \frac{1}{25}$

Example revisited

- Want to classify $A = m, B = q$
- $Pr(A = m, B = q \mid C = t) = Pr(A = m, B = q \mid C = f) = 0$
- $Pr(A = m \mid C = t) = 2/5$
- $Pr(B = q \mid C = t) = 2/5$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example revisited

- Want to classify $A = m, B = q$
- $Pr(A = m, B = q \mid C = t) = Pr(A = m, B = q \mid C = f) = 0$
- $Pr(A = m \mid C = t) = 2/5$
- $Pr(B = q \mid C = t) = 2/5$
- $Pr(A = m \mid C = f) = 1/5$
- $Pr(B = q \mid C = f) = 2/5$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example revisited

- Want to classify $A = m, B = q$
- $Pr(A = m, B = q \mid C = t) = Pr(A = m, B = q \mid C = f) = 0$
- $Pr(A = m \mid C = t) = 2/5$
- $Pr(B = q \mid C = t) = 2/5$
- $Pr(A = m \mid C = f) = 1/5$
- $Pr(B = q \mid C = f) = 2/5$
- $Pr(A = m \mid C = t) \cdot Pr(B = q \mid C = t) \cdot Pr(C = t) = 2/25$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example revisited

- Want to classify $A = m, B = q$
- $Pr(A = m, B = q \mid C = t) = Pr(A = m, B = q \mid C = f) = 0$
- $Pr(A = m \mid C = t) = 2/5$
- $Pr(B = q \mid C = t) = 2/5$
- $Pr(A = m \mid C = f) = 1/5$
- $Pr(B = q \mid C = f) = 2/5$
- $Pr(A = m \mid C = t) \cdot Pr(B = q \mid C = t) \cdot Pr(C = t) = 2/25$
- $Pr(A = m \mid C = f) \cdot Pr(B = q \mid C = f) \cdot Pr(C = f) = 1/25$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Example revisited

- Want to classify $A = m, B = q$
- $Pr(A = m, B = q \mid C = t) = Pr(A = m, B = q \mid C = f) = 0$
- $Pr(A = m \mid C = t) = 2/5$
- $Pr(B = q \mid C = t) = 2/5$
- $Pr(A = m \mid C = f) = 1/5$
- $Pr(B = q \mid C = f) = 2/5$
- $Pr(A = m \mid C = t) \cdot Pr(B = q \mid C = t) \cdot Pr(C = t) = 2/25$
- $Pr(A = m \mid C = f) \cdot Pr(B = q \mid C = f) \cdot Pr(C = f) = 1/25$
- Hence predict $C = t$

A	B	C
m	b	t
m	s	t
g	q	t
h	s	t
g	q	t
g	q	f
g	s	f
h	b	f
h	q	f
m	b	f

Zero counts

- Suppose $A = a$ never occurs in the test set with $C = c$

Zero counts

- Suppose $A = a$ never occurs in the test set with $C = c$

- Setting $Pr(A = a \mid C = c) = 0$ wipes out any product $\prod_{i=1}^{k} Pr(A_i = a_i \mid C = c)$ in which this term appears

Zero counts

- Suppose $A = a$ never occurs in the test set with $C = c$
- Setting $Pr(A = a \mid C = c) = 0$ wipes out any product $\prod_{i=1}^{k} Pr(A_i = a_i \mid C = c)$ in which this term appears
- Assume A_i takes m_i values $\{a_{i1}, \ldots, a_{im_i}\}$

Zero counts

- Suppose $A = a$ never occurs in the test set with $C = c$
- Setting $Pr(A = a \mid C = c) = 0$ wipes out any product $\prod_{i=1}^{k} Pr(A_i = a_i \mid C = c)$ in which this term appears
- Assume A_i takes m_i values $\{a_{i1}, \ldots, a_{im_i}\}$
- "Pad" training data with one sample for each value a_j — m_i extra data items

Zero counts

- Suppose $A = a$ never occurs in the test set with $C = c$
- Setting $Pr(A = a \mid C = c) = 0$ wipes out any product $\prod_{i=1}^{k} Pr(A_i = a_i \mid C = c)$ in which this term appears
- Assume A_i takes m_i values $\{a_{i1}, \ldots, a_{im_i}\}$
- "Pad" training data with one sample for each value a_j — m_i extra data items
- Adjust $Pr(A_i = a_i \mid C = c_j)$ to $\dfrac{n_{ij} + 1}{n_j + m_i}$ where
  - n_{ij} is number of samples with $A_i = a_i$, $C = c_j$
  - n_j is number of samples with $C = c_j$

$$\frac{n_{ij}}{n_j} \rightarrow \frac{n_{ij}+1}{n_j+m_i}$$

$$P(m|t) = \frac{2}{5} \rightarrow \frac{3}{7}$$

$$P(g|t) = \frac{3}{5} \rightarrow \frac{4}{7}$$

$$\frac{\frac{3}{7}}{\frac{2}{5}}$$

$$\frac{\frac{4}{7}}{\frac{3}{5}}$$

Smoothing

- Laplace's law of succession

$$Pr(A_i = a_i \mid C = c_j) = \frac{n_{ij} + 1}{n_j + m_i}$$

Smoothing

- Laplace's law of succession

$$Pr(A_i = a_i \mid C = c_j) = \frac{n_{ij} + 1}{n_j + m_i}$$

- More generally, Lidstone's law of succession, or smoothing

$$Pr(A_i = a_i \mid C = c_j) = \frac{n_{ij} + \lambda}{n_j + \lambda m_i}$$

Smoothing

- Laplace's law of succession

$$Pr(A_i = a_i \mid C = c_j) = \frac{n_{ij} + 1}{n_j + m_i}$$

- More generally, Lidstone's law of succession, or smoothing

$$Pr(A_i = a_i \mid C = c_j) = \frac{n_{ij} + \lambda}{n_j + \lambda m_i}$$

- $\lambda = 1$ is Laplace's law of succession

Text classification

- Classify text documents using topics

Text classification

- Classify text documents using topics
- Useful for automatic segregation of newsfeeds, other internet content

Text classification

- Classify text documents using topics
- Useful for automatic segregation of newsfeeds, other internet content
- Training data has a unique topic label per document — e.g., Sports, Politics, Entertainment

Text classification

- Classify text documents using topics
- Useful for automatic segregation of newsfeeds, other internet content
- Training data has a unique topic label per document — e.g., Sports, Politics, Entertainment
- Want to use a naïve Bayes classifier

Text classification

- Classify text documents using topics
- Useful for automatic segregation of newsfeeds, other internet content
- Training data has a unique topic label per document — e.g., Sports, Politics, Entertainment
- Want to use a naïve Bayes classifier
- Need to define a generative model

Text classification

- Classify text documents using topics
- Useful for automatic segregation of newsfeeds, other internet content
- Training data has a unique topic label per document — e.g., Sports, Politics, Entertainment
- Want to use a naïve Bayes classifier
- Need to define a generative model
- How do we represent documents?

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
- Topics come from a set $C = \{c_1, c_2, \ldots, c_k\}$

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \dots, w_m\}$
- Topics come from a set $C = \{c_1, c_2, \dots, c_k\}$
- Each topic c has probability $Pr(c)$

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
- Topics come from a set $C = \{c_1, c_2, \ldots, c_k\}$
- Each topic c has probability $Pr(c)$
- Each word $w_i \in V$ has conditional probability $Pr(w_i \mid c_j)$ with respect to each $c_j \in C$

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
- Topics come from a set $C = \{c_1, c_2, \ldots, c_k\}$
- Each topic c has probability $Pr(c)$
- Each word $w_i \in V$ has conditional probability $Pr(w_i \mid c_j)$ with respect to each $c_j \in C$
- Generating a random document d
  - Choose a topic c with probability $Pr(c)$
  - For each $w \in V$, toss a coin, include w in d with probability $Pr(w \mid c)$

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
- Topics come from a set $C = \{c_1, c_2, \ldots, c_k\}$
- Each topic c has probability $Pr(c)$
- Each word $w_i \in V$ has conditional probability $Pr(w_i \mid c_j)$ with respect to each $c_j \in C$
- Generating a random document d
  - Choose a topic c with probability $Pr(c)$
  - For each $w \in V$, toss a coin, include w in d with probability $Pr(w \mid c)$
- $Pr(d \mid c) = \prod_{w_i \in d} Pr(w_i \mid c) \prod_{w_i \notin d} (1 - Pr(w_i \mid c))$

$P(c \mid d)$

Set of words model

- Each document is a set of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
- Topics come from a set $C = \{c_1, c_2, \ldots, c_k\}$
- Each topic c has probability $Pr(c)$
- Each word $w_i \in V$ has conditional probability $Pr(w_i \mid c_j)$ with respect to each $c_j \in C$
- Generating a random document d
  - Choose a topic c with probability $Pr(c)$
  - For each $w \in V$, toss a coin, include w in d with probability $Pr(w \mid c)$
- $Pr(d \mid c) = \prod_{w_i \in d} Pr(w_i \mid c) \prod_{w_i \notin d} (1 - Pr(w_i \mid c))$
- $Pr(d) = \sum_{c \in C} Pr(d \mid c)$

Naïve Bayes classifier

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each $d_i \subseteq V$ is assigned a unique label from C

Naïve Bayes classifier

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each $d_i \subseteq V$ is assigned a unique label from C
- $Pr(c_j)$ is fraction of D labelled c_j

Naïve Bayes classifier

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each $d_i \subseteq V$ is assigned a unique label from C
- $Pr(c_j)$ is fraction of D labelled c_j
- $Pr(w_i \mid c_j)$ is fraction of documents labelled c_j in which w_i appears

Naïve Bayes classifier

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each $d_i \subseteq V$ is assigned a unique label from C
- $Pr(c_j)$ is fraction of D labelled c_j
- $Pr(w_i \mid c_j)$ is fraction of documents labelled c_j in which w_i appears
- Given a new document $d \subseteq V$, we want to compute $\arg\max_c Pr(c \mid d)$

Naïve Bayes classifier

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each $d_i \subseteq V$ is assigned a unique label from C
- $Pr(c_j)$ is fraction of D labelled c_j
- $Pr(w_i \mid c_j)$ is fraction of documents labelled c_j in which w_i appears
- Given a new document $d \subseteq V$, we want to compute $\arg\max_c Pr(c \mid d)$
- By Bayes' rule, $Pr(c \mid d) = \dfrac{Pr(d \mid c)Pr(c)}{Pr(d)}$
  - As usual, discard the common denominator and compute $\arg\max_c Pr(d \mid c)Pr(c)$

Naïve Bayes classifier

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each $d_i \subseteq V$ is assigned a unique label from C
- $Pr(c_j)$ is fraction of D labelled c_j
- $Pr(w_i \mid c_j)$ is fraction of documents labelled c_j in which w_i appears
- Given a new document $d \subseteq V$, we want to compute $\arg\max_c Pr(c \mid d)$
- By Bayes' rule, $Pr(c \mid d) = \dfrac{Pr(d \mid c)Pr(c)}{Pr(d)}$
  - As usual, discard the common denominator and compute $\arg\max_c Pr(d \mid c)Pr(c)$
- Recall $Pr(d \mid c) = \prod_{w_i \in d} Pr(w_i \mid c) \prod_{w_i \notin d} (1 - Pr(w_i \mid c))$

Bag of words model

- Each document is a multiset or bag of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
  - Count multiplicities of each word

Set + Count

a - 1
b - 3
c - 0
d - 4
⋮

Bag of words model

- Each document is a multiset or bag of words over a vocabulary $V = \{w_1, w_2, \ldots, w_m\}$
  - Count multiplicities of each word
- As before
  - Each topic c has probability $Pr(c)$
  - Each word $w_i \in V$ has conditional probability $Pr(w_i \mid c_j)$ with respect to each $c_j \in C$ (but we will estimate these differently)
  - Note that $\displaystyle\sum_{i=1}^{m} Pr(w_i \mid c_j) = 1$
  - Assume document length is independent of the class

Bag of words model

- Generating a random document d
  - Choose a document length ℓ with $Pr(\ell)$
  - Choose a topic c with probability $Pr(c)$
  - Recall $|V| = m$.
    - To generate a single word, throw an m-sided die that displays w with probability $Pr(w \mid c)$
    - Repeat ℓ times

Bag of words model

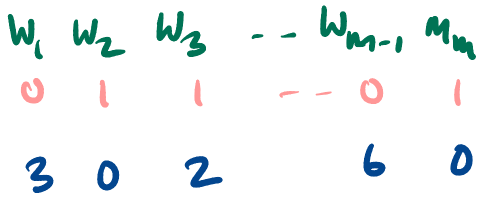
- Generating a random document d
  - Choose a document length ℓ with $Pr(\ell)$
  - Choose a topic c with probability $Pr(c)$
  - Recall $|V| = m$.
    - To generate a single word, throw an m-sided die that displays w with probability $Pr(w \mid c)$
    - Repeat ℓ times
- Let n_j be the number of occurrences of w_j in d

Bag of words model

- Generating a random document d
  - Choose a document length ℓ with $Pr(\ell)$
  - Choose a topic c with probability $Pr(c)$
  - Recall $|V| = m$.
    - To generate a single word, throw an m-sided die that displays w with probability $Pr(w \mid c)$
    - Repeat ℓ times
- Let n_j be the number of occurrences of w_j in d
- $Pr(d \mid c) = Pr(\ell)\ \ell! \prod_{j=1}^{m} \frac{Pr(w_j \mid c)^{n_j}}{n_j!}$

Parameter estimation

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each d_i is a multiset over V of size ℓ_i



Parameter estimation

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each d_i is a multiset over V of size ℓ_i
- As before, $Pr(c_j)$ is fraction of D labelled c_j

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each d_i is a multiset over V of size ℓ_i
- As before, $Pr(c_j)$ is fraction of D labelled c_j
- $Pr(w_i \mid c_j)$ — fraction of occurrences of w_i over documents $D_j \subseteq D$ labelled c_j
  - n_{id} — occurrences of w_i in d
  - $Pr(w_i \mid c_j) = \dfrac{\sum_{d \in D_j} n_{id}}{\sum_{t=1}^{m} \sum_{d \in D_j} n_{td}}$

number of w_i in all d labelled c_j

All words

in D_j

Parameter estimation

- Training set $D = \{d_1, d_2, \ldots, d_n\}$
  - Each d_i is a multiset over V of size ℓ_i
- As before, $Pr(c_j)$ is fraction of D labelled c_j
- $Pr(w_i \mid c_j)$ — fraction of occurrences of w_i over documents $D_j \subseteq D$ labelled c_j
  - n_{id} — occurrences of w_i in d
- $$Pr(w_i \mid c_j) = \frac{\sum_{d \in D_j} n_{id}}{\sum_{t=1}^{m} \sum_{d \in D_j} n_{td}} = \frac{\sum_{d \in D} n_{id} \; Pr(c_j \mid d)}{\sum_{t=1}^{m} \sum_{d \in D} n_{td} \; Pr(c_j \mid d)},$$

  since $Pr(c_j \mid d) = \begin{cases} 1 & \text{if } d \in D_j, \\ 0 & \text{otherwise} \end{cases}$

Classification

- $Pr(c \mid d) = \dfrac{Pr(d \mid c)\ Pr(c)}{Pr(d)}$

Classification

- $Pr(c \mid d) = \dfrac{Pr(d \mid c)\ Pr(c)}{Pr(d)}$
- Want $\arg\max_{c}\ Pr(c \mid d)$

Classification

- $Pr(c \mid d) = \dfrac{Pr(d \mid c)\ Pr(c)}{Pr(d)}$
- Want $\arg\max_c \ Pr(c \mid d)$
- As before, discard the denominator $Pr(d)$

Classification

- $Pr(c \mid d) = \dfrac{Pr(d \mid c)\ Pr(c)}{Pr(d)}$
- Want $\arg\max_c\ Pr(c \mid d)$
- As before, discard the denominator $Pr(d)$
- Recall, $Pr(d \mid c) = Pr(\ell)\ \ell! \prod_{j=1}^{m} \dfrac{Pr(w_j \mid c)^{n_j}}{n_j!}$, where $|d| = \ell$

Classification

- $Pr(c \mid d) = \dfrac{Pr(d \mid c)\ Pr(c)}{Pr(d)}$
- Want $\arg\max_c\ Pr(c \mid d)$
- As before, discard the denominator $Pr(d)$
- Recall, $Pr(d \mid c) = Pr(\ell)\ \ell! \displaystyle\prod_{j=1}^{m} \frac{Pr(w_j \mid c)^{n_j}}{n_j!}$, where $|d| = \ell$
- Discard $Pr(\ell), \ell!$ since they do not depend on c

Classification

- $Pr(c \mid d) = \dfrac{Pr(d \mid c)\, Pr(c)}{Pr(d)}$
- Want $\arg\max_c \; Pr(c \mid d)$
- As before, discard the denominator $Pr(d)$
- Recall, $Pr(d \mid c) = Pr(\ell)\; \ell! \displaystyle\prod_{j=1}^{m} \frac{Pr(w_j \mid c)^{n_j}}{n_j!}$, where $|d| = \ell$
- Discard $Pr(\ell), \ell!$ since they do not depend on c
- Compute $\arg\max_c \; Pr(c) \displaystyle\prod_{j=1}^{m} \frac{Pr(w_j \mid c)^{n_j}}{n_j!}$