

Classification with Naive Bayes

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Mathematical basics

Random experiment

Statistics is about the probability of events:

Example: How likely is it to have six correct numbers in the lottery?

Random experiment: Experiment (trial) with several possible outputs
(*throw of two dices*)

Outcome: Result of an experiment (*3 eyes on dice 1 and 4 eyes on dice 2*)

Sample space Ω : Set of all possible outcomes

Event: Subset of the sample space (*7 eyes on two dices*)

Sample: Series of results in a repeated experiment

Probability distribution

Probability distribution: Function that assigns a value between 0 and 1 to each outcome, such that

$$\sum_{o \in \Omega} p(o) = 1$$

The probability of a **event** is the sum of the probabilities of the corresponding outcomes.

Example:

probability that the number of eyes when throwing a dice is an even number

Conditional and a priori probability

Conditional probability: Probability of an event A, if the event B is known:

$$P(A|B) = \frac{P(A \cap B)}{P(B)}$$

Example: Probability that the number of points in a dice is even if the number of points is greater than 3

A priori probability $P(A)$: Probability of event A without knowing event B

Random variables

Random variable: Function that assigns a real number to each outcome.

Example: Mapping of grades *very good, good, satisfactory, sufficient, poor, insufficient* to the numbers 1, 2, 3, 4, 5, 6

Example: Mapping of grades *very good, good, satisfactory, sufficient, poor, insufficient* to the numbers 0, 1 (non-pass, pass)

A random variable is called discrete if it takes only a finite number or countably infinite values.

The above examples thus describe a discrete random variables.

Probability of a value x of the random variable X :

$$P(X = x) = p(x) = P(A_x)$$

A random variable with only the values 0 and 1 is called **Bernoulli experiment**.

Joint distributions and marginal distributions

The **joint distribution** of two random variables X and Y :

$$p(x, y) = P(X = x, Y = y) = P(A_x \cap A_y)$$

The **marginal distribution** of two random variables X and Y :

$$p_X(x) = \sum_y p(x, y) \quad p_Y(y) = \sum_x p(x, y)$$

Independence: The random variables X and Y are statistically independent if:

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

Example: When throwing two dice, their numbers are statistically independent to each other.

Important rules

Chain rule: Some common probabilities can be converted into a product of conditional probabilities.

$$\begin{aligned}P(A_1 \cap A_2 \cap \dots \cap A_n) &= P(A_1)P(A_2|A_1)\dots P(A_n|A_1 \cap \dots \cap A_{n-1}) \\&= \prod_{i=1}^n P(A_i|A_1 \cap \dots \cap A_{i-1})\end{aligned}$$

Theorem of Bayes: allows to "reverse" a conditional probability

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Probability estimation

$$\tilde{p}(x) = \frac{n(x)}{N}$$

The **relative frequency** $n(x)/N$ is the number of occurrences (*counts*) $n(x)$ an event x divided by the sample size n .

With growing sample size n , the relative frequency converges to the actual probability of an event.

More precisely: the probability that the relative frequency differs more than ϵ from the actual probability converges to 0 for increasing sample size.

Probability estimation by relative frequency

Example:

- Random event: word occurrence is a specific word
- $n(x)$: Number of occurrences (*counts*) of the word in a corpus
- N : Number of word occurrences in the corpus.

word	$n(\text{word})$	$\tilde{p}(\text{word})$
meet		
deadline		
single		
...		

hot
stock
tip

reminder
deadline
meet
thanks

meet
hot
single

thanks
for
tip

deadline
approaching

Probability estimation by relative frequency

Example:

- Random event: word occurrence is a specific word
- $n(x)$: Number of occurrences (*counts*) of the word in a corpus
- N : Number of word occurrences in the corpus.

word	$n(\text{word})$	$\tilde{p}(\text{word})$
meet	2	$\frac{2}{15} \approx 0.133$
deadline	2	$\frac{2}{15} \approx 0.133$
single	1	$\frac{1}{15} \approx 0.067$
...		

hot
stock
tip

reminder
deadline
meet
thanks

meet
hot
single

thanks
for
tip

deadline
approaching

Relative frequency for conditional probabilities

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

Conditional probabilities can also be estimated from relative frequencies.

$n(x, y)$ here is the number of common occurrences of the events x and y .

n_y is the number of occurrences of the event y .

It applies: $n_y = \sum_{x'} n(x', y)$

Relative frequency for conditional probabilities

- Random event x : Word occurrence is a certain word
- Random event y : Word occurrence is in email of a certain category, e.g. HAM or SPAM (HAM = “no spam”)
- $n(x, y)$: Number of word occurrences in emails of a category in the corpus

word	$n(\text{word}, \text{HAM})$	$\tilde{p}(\text{word} \text{HAM})$	$n(\text{word}, \text{SPAM})$	$\tilde{p}(\text{word} \text{SPAM})$
meet				
deadline				
single				
...				

reminder
deadline
meet
thanks

thanks
for
tip

deadline
approaching

hot
stock
tip

meet
hot
single

Relative frequency for conditional probabilities

- Random event x : Word occurrence is a certain word
- Random event y : Word occurrence is in email of a certain category, e.g. HAM or SPAM (HAM = "no spam")
- $n(x, y)$: Number of word occurrences in emails of a category in the corpus

word	$n(\text{word}, \text{HAM})$	$\tilde{p}(\text{word} \text{HAM})$	$n(\text{word}, \text{SPAM})$	$\tilde{p}(\text{word} \text{SPAM})$
meet	1	$\frac{1}{9} \approx 0.111$	1	$\frac{1}{6} \approx 0.167$
deadline	2	$\frac{2}{9} \approx 0.222$	0	0
single	0	0	1	$\frac{1}{6} \approx 0.167$
...				

reminder
deadline
meet
thanks

thanks
for
tip

deadline
approaching

hot
stock
tip

meet
hot
single

Probability for word sequence

- So far we have only expressed and estimated probabilities of single words.
- How can we calculate the probabilities of whole texts (e.g. emails)?
- Application of conditional probability:

$$P(w_1, w_2, \dots, w_n)$$

$$= P(w_1)P(w_2|w_1)P(w_3|w_1, w_2) \dots P(w_n|w_1 \dots w_{n-1})$$

- \Rightarrow does not really solve the problem, because $P(w_n|w_1 \dots w_{n-1})$ can not be well estimated

Independence assumption: Bag of Words

- One solution: we make the statistical assumption that every word is independent of the occurrence of other words.
- This is also called bag-of-words (BOW) assumption, because the order of words becomes irrelevant.

$$\begin{aligned} &P(w_1, w_2, \dots, w_n) \\ &= P(w_1)P(w_2|w_1)P(w_3|w_1, w_2) \dots P(w_n|w_1 \dots w_{n-1}) \\ &\stackrel{\text{indep.}}{=} P(w_1)P(w_2)P(w_3) \dots P(w_n) \end{aligned}$$

Conditional independence

- For many machine-learning algorithms, **conditional independence** is the central concept:

If the value of a random variable y is known, random variables x_1, \dots, x_n are independent

- Middle ground between:
 - ▶ no independence
 - ▶ independence of all random variables
- In our case:

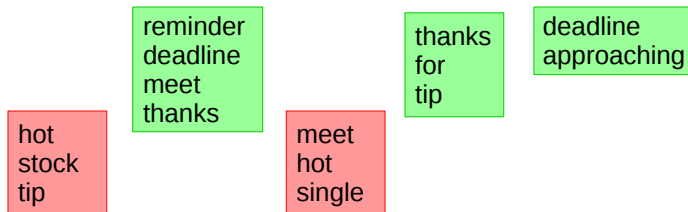
$$P(w_1, w_2, \dots, w_n | \text{SPAM})$$

$$\stackrel{\text{cond. indep.}}{=} P(w_1 | \text{SPAM}) P(w_2 | \text{SPAM}) P(w_3 | \text{SPAM}) \dots P(w_n | \text{SPAM})$$

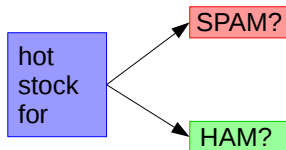
Naive Bayes Classifier

Task

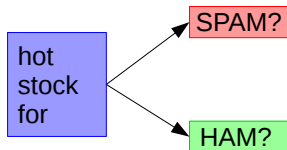
- Given a training corpus:



- Decide whether new (unseen) emails should be assigned to the category HAM or SPAM:



Decision criterion



- Given the content of the email, which category is more likely: SPAM or HAM?

$$P(HAM|text) > P(SPAM|text)$$

- Why isn't the decision criterion:

$$P(text|HAM) > P(text|SPAM)$$

?

Bayes rule

$$P(HAM|text) = \frac{P(text|HAM) * P(HAM)}{P(text)}$$

- $P(text|HAM)$: conditional BOW probability
- $P(HAM)$: Prior probability that an email is assigned to the category HAM (if the content of the email is not known). Estimation:

$$\tilde{p}(HAM) = \frac{\text{number of HAM-Mails}}{\text{number of all Mails}}$$

- $P(text)$: BOW probability of the content of the email without knowing the category.

Decision criterion

Email is HAM

\Leftrightarrow

$$P(\text{HAM}|\text{text}) > P(\text{SPAM}|\text{text})$$

\Leftrightarrow

$$\frac{P(\text{HAM}|\text{text})}{P(\text{SPAM}|\text{text})} > 1$$

\Leftrightarrow

Decision criterion

Email is HAM

\Leftrightarrow

$$P(\text{HAM}|\text{text}) > P(\text{SPAM}|\text{text})$$

\Leftrightarrow

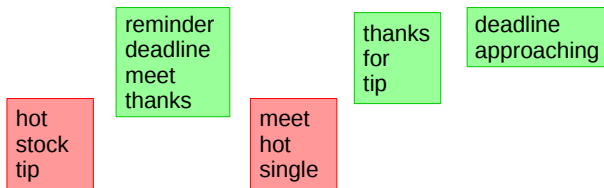
$$\frac{P(\text{HAM}|\text{text})}{P(\text{SPAM}|\text{text})} > 1$$

\Leftrightarrow

$$\frac{\cancel{\frac{1}{P(\text{text})}} P(\text{text}|\text{HAM}) * P(\text{HAM})}{\cancel{\frac{1}{P(\text{text})}} P(\text{text}|\text{SPAM}) * P(\text{SPAM})} > 1$$

What is a decision rule for more than two categories?

Example (preliminary)



- $\tilde{p}(HAM) = \frac{3}{5}$
- $\tilde{p}(SPAM) = \frac{2}{5}$
- $p(\text{hot stock for} | HAM)$

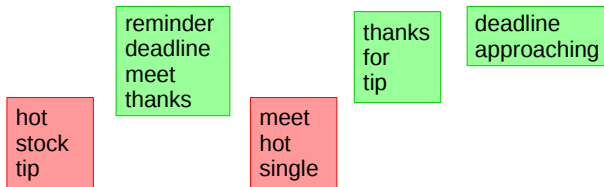
$$= \tilde{p}(\text{hot} | HAM) \tilde{p}(\text{stock} | HAM) \tilde{p}(\text{for} | HAM) = \dots$$

- $p(\text{hot stock for} | SPAM)$

$$= \tilde{p}(\text{hot} | SPAM) \tilde{p}(\text{stock} | SPAM) \tilde{p}(\text{for} | SPAM) = \dots$$

• ...

Example (preliminary)



- $\tilde{p}(HAM) = \frac{3}{5}$
- $\tilde{p}(SPAM) = \frac{2}{5}$
- $p(\text{hot stock for} | HAM)$

$$= \tilde{p}(\text{hot} | HAM) \tilde{p}(\text{stock} | HAM) \tilde{p}(\text{for} | HAM) = \frac{0 \cdot 0 \cdot 1}{9 \cdot 9 \cdot 9} = 0$$

- $p(\text{hot stock for} | SPAM)$

$$= \tilde{p}(\text{hot} | SPAM) p(\text{stock} | SPAM) \tilde{p}(\text{for} | SPAM) = \frac{2 \cdot 1 \cdot 0}{6 \cdot 6 \cdot 6} = 0$$

- Problem: Decision criterion is not defined ($\frac{0}{0}$)

Add-1 smoothing

Add-1 smooting (Laplace smoothing)

$$\tilde{p}(w) = \frac{n(w) + 1}{N + V}$$

(V = number of possible words; N = number of tokens)

- ... is optimal if the uniform distribution is most likely is what is rarely the case in text corpora \Rightarrow Zipf's distribution
- ... therefore, overestimates the probability of unseen words.

Add- λ smoothing

reduces the amount of smoothing

Add- λ smoothing

$$\tilde{p}(w) = \frac{n(w) + \lambda}{N + V\lambda}$$

Add- λ smoothing for conditional probabilities

$$\tilde{p}(w|y) = \frac{n(w, y) + \lambda}{n_y + V\lambda}$$

Example (with Add-1 smoothing)

hot
stock
tip

reminder
deadline
meet
thanks

meet
hot
single

thanks
for
tip

deadline
approaching

- $\tilde{p}(HAM) = \frac{3}{5}, \tilde{p}(SPAM) = \frac{2}{5}$
- Vocabulary contains $V = 10$ different words
- $p(\text{hot stock for} | HAM) = \tilde{p}(\text{hot} | HAM) \tilde{p}(\text{stock} | HAM) \tilde{p}(\text{for} | HAM)$
$$= \frac{(0 + 1) \cdot (0 + 1) \cdot (1 + 1)}{(9 + 10) \cdot (9 + 10) \cdot (9 + 10)} \approx 0.00029$$
- $p(\text{hot stock for} | SPAM) = \tilde{p}(\text{hot} | SPAM) \tilde{p}(\text{stock} | SPAM) \tilde{p}(\text{for} | SPAM)$
$$= \frac{(2 + 1) \cdot (1 + 1) \cdot (0 + 1)}{(6 + 10) \cdot (6 + 10) \cdot (6 + 10)} \approx 0.00146$$
- $\frac{P(\text{text} | HAM) \cdot P(HAM)}{P(\text{text} | SPAM) \cdot P(SPAM)} = \frac{0.00029 \cdot 0.6}{0.00146 \cdot 0.4} \approx 0.298 \Rightarrow \text{Category?}$

Example (with Add-1 smoothing)

hot
stock
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- $p(\text{hot stock for} | SPAM) = \tilde{p}(\text{hot} | SPAM) \tilde{p}(\text{stock} | SPAM) \tilde{p}(\text{for} | SPAM)$
$$= \frac{(2+1) \cdot (1+1) \cdot (0+1)}{(6+10) \cdot (6+10) \cdot (6+10)} \approx 0.00146$$
- $\frac{P(\text{text} | HAM) \cdot P(HAM)}{P(\text{text} | SPAM) \cdot P(SPAM)} = \frac{0.00029 \cdot 0.6}{0.00146 \cdot 0.4} \approx 0.298 < 1 \Rightarrow \text{Email is spam}$

Calculating with logarithms

- When multiplying many small probabilities (for example, all words in a long text), the result can quickly approach 0 and may not be represented correctly.
- That's why you always avoid the multiplication of probabilities.
- Instead, use the sum of the logarithmized probabilities.
- $\log(a \cdot b \cdot c \cdot \dots) = \log(a) + \log(b) + \log(c) + \dots$
- Example:

$$0.0001 * 0.001 * 0.00001 * 0.01 = 0.0000000000000001$$

$$\log_{10}(0.0001 * 0.001 * 0.00001 * 0.01) =$$

Calculating with logarithms

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- $\log(a \cdot b \cdot c \cdot \dots) = \log(a) + \log(b) + \log(c) + \dots$
- Example:

$$0.0001 * 0.001 * 0.00001 * 0.01 = 0.0000000000000001$$

$$\log_{10}(0.0001 * 0.001 * 0.00001 * 0.01) = -4 + (-3) + (-5) + (-2) = -14$$

- $\log(\frac{a}{b}) = ?$

Decision rule with logarithms

- The logarithm is increasing monotonically, i.e. we can apply it to inequalities on both sides.
- The decision rule is now:

$$P(HAM|text) > P(SPAM|text)$$

$$\Leftrightarrow$$

$$\log P(HAM|text) > \log P(SPAM|text)$$

$$\Leftrightarrow$$

Decision rule with logarithms

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- The decision rule is now:

$$P(HAM|text) > P(SPAM|text)$$

$$\Leftrightarrow$$

$$\log P(HAM|text) > \log P(SPAM|text)$$

$$\Leftrightarrow$$

$$\log P(HAM|text) - \log P(SPAM|text) > 0$$

$$\Leftrightarrow$$

$$\log P(text|HAM) + \log P(HAM) - \log P(text|SPAM) - \log P(SPAM) > 0$$

- The quotient of the probabilities of two complementary events is also called **Odds**.
- The logarithm of this quotient is called **Log-Odds**.

Naive Bayes with other distributions

- Depending on the problem, the distribution $P(X|category)$ can take various forms.
- In the case just discussed, the distribution is the **multinomial distribution** (probability that with text of length n exactly the observed numbers of words occur)
- If the observed values are floating point values (e.g., values from a meter), one can e.g. Use **Gauss Distributions**.
⇒ Smoothing is also important here (for example, what variance should be assumed for a category with little data?)
- For machine-learning software (such as Scikit-learn), you can choose the type of distribution as a hyper parameter.

Unknown words in the test data

- It may be that words appear in the test data that did not occur in the training data.
- The possible values of the random variable were chosen based on the training data, i.e. the probability of the new words is not defined.
- Two common solutions:
 - ▶ Words that do not occur in the training data are ignored (\Rightarrow Test documents are getting shorter)
 - ▶ Words that are rarely in the training data (for example, 1-2 times) or do not occur at all, (in training and testing) are replaced with a placeholder <UNK>.
- Advantages and disadvantages of the two methods?

Implementation

Training or test instance

In our case:

- Features = words (tokens)
- Label
 - ▶ Binary classification: HAM (True) vs SPAM (False)
 - ▶ Multi-Class Classification (Exercise Sheet): String for category("work", "social", "promotions", "spam", ...)

```
class DataInstance:
    def __init__(self, feature_counts, label):
        self.feature_counts = feature_counts
        self.label = label

#...
```

Training or test set

- Amount of possible feature values is e.g. important for smoothing.
- Sanity-check: What accuracy would result from predicting the most common category?
- Some learning algorithms require several training iterations between which the training set should be re-permuted (mixed).

```
class Dataset:
    def __init__(self, instance_list, feature_set):
        self.instance_list = instance_list
        self.feature_set = feature_set
    def most_frequent_sense_accuracy(self):
        # ...
    def shuffle(self):
        # ...
```

Classifier

What information do we need to create the Naive-Bayes model?

- ...

What information do we need to create the Naive-Bayes model?

- For the estimation of $P(w|HAM)$ or $P(w|SPAM)$
 - ▶ $n(w, HAM)$ or $n(w, SPAM)$:
One dictionary for each category, which maps each word to its frequency in the respective category.
 - ▶ n_{HAM} or n_{SPAM} :
The number of word occurrences per category
(can be summed up from the values of the dictionaries)
 - ▶ For smoothing: Parameters λ and size of the vocabulary V
- For the estimation of $P(HAM)$ or $P(SPAM)$
 - ▶ In each case the number of training emails per category.

Classifier: constructor

```
def __init__(self, positive_word_to_count, negative_word_to_count,\
             positive_counts, negative_counts, vocabsize, smoothing):\
    #  $n(\text{word}, \text{HAM})$  and  $n(\text{word}, \text{SPAM})$ \
    self.positive_word_to_count = positive_word_to_count\
    self.negative_word_to_count = negative_word_to_count\

    #  $n_{\text{HAM}}$  and  $n_{\text{SPAM}}$ \
    self.positive_total_wordcount = \
        sum(positive_word_to_count.values())\
    self.negative_total_wordcount = \
        sum(negative_word_to_count.values())\

    self.vocabsize = vocabsize\

    #  $P(\text{HAM})$  and  $P(\text{SPAM})$ \
    self.positive_prior = \
        positive_counts / (positive_counts + negative_counts)\
    self.negative_prior = \
        negative_counts / (positive_counts + negative_counts)\

    self.smoothing = smoothing
```

Classifier: Overview

```
class NaiveBayesWithLaplaceClassifier:
    def log_probability(self, word, is_positive_label):
        # ...
    def log_odds(self, feature_counts):
        # ...
    def prediction(self, feature_counts):
        # ...
    def prediction_accuracy(self, dataset):
        # ...
    def log_odds_for_word(self, word):
        # ...
    def features_for_class(self, is_positive_class, topn=10):
        # ...
```

Calculation of $P(w|HAM)$ or $P(w|SPAM)$

Probability estimation...

- ... smoothed
- ... is returned logarithmized

```
def log_probability(self, word, is_positive_label):  
    if is_positive_label:  
        wordcount = self.positive_word_to_count.get(word, 0)  
        total = self.positive_total_wordcount  
    else:  
        wordcount = self.negative_word_to_count.get(word, 0)  
        total = self.negative_total_wordcount  
    return math.log(wordcount + self.smoothing) \  
        - math.log(total + self.smoothing * self.vocabsize)
```

Calculation of Log-Odds

- What is calculated in the two sums?

```
def log_odds(self, feature_counts):  
    # language model probability  
    pos_logprob = sum([ count * self.log_probability(word, True) \  
        for word, count in feature_counts.items()])  
    # prior probability  
    pos_logprob += math.log(self.positive_prior)  
    # same for negative case  
    neg_logprob = sum([ count * self.log_probability(word, False) \  
        for word, count in feature_counts.items()])  
    neg_logprob += math.log(self.negative_prior)  
    return pos_logprob - neg_logprob
```

Applying the classifier, test accuracy

- Prediction

- ▶ Apply the model to the feature counts of a test instance
- ▶ Prediction of a category (HAM/True or SPAM/False) according to the decision rule

```
def prediction(self, feature_counts):  
    # ...
```

- Calculation of test accuracy

- ▶ First, prediction for all instances of the dataset
- ▶ Then compare with the correct category label

```
def prediction_accuracy(self, dataset):  
    # ...
```

Multi-class classification

Multi-class classification

- Extension: Classifier distinguishes n different categories ($n \geq 2$)
- \Rightarrow Exercise sheet
- Decision rule: choose category c^* , that maximizes probability $p(c^*|text)$.

$$c^* = \arg \max_c p(c|text)$$

- $\arg \max_x f(x)$ selects a value x (from the definition set) for which the function value $f(x)$ is maximal.
- By applying the calculation rules, the conditional independence assumption, and our estimation method (Laplace):

$$\begin{aligned} c^* &= \arg \max_c p(c)p(text|c) \\ &= \arg \max_c \log[p(c)] + \sum_{w \in text} \log[\tilde{p}(w|c)] \end{aligned}$$

Multi-class classification

- Decision rule: choose category c^* , that maximizes probability $p(c^*|text)$.

$$c^* = \arg \max_c p(c|text)$$

- Does the following implication apply?

$$c^* = \arg \max_c p(c|text) \Rightarrow \frac{p(c^*|text)}{1 - p(c^*|text)} \geq 1$$

- Does the following implication apply?

$$\frac{p(c^*|text)}{1 - p(c^*|text)} > 1 \Rightarrow c^* = \arg \max_c p(c|text)$$

Multi-class classification

- Does the following implication apply?

$$c^* = \arg \max_c p(c|text) \Rightarrow \frac{p(c^*|text)}{1 - p(c^*|text)} \geq 1$$

No. For 3 or more categories, the most likely category may be WK $p(c^|text) < 0.5$ and the Odds are < 1 .*

- Does the following implication apply?

$$\frac{p(c^*|text)}{1 - p(c^*|text)} > 1 \Rightarrow c^* = \arg \max_c p(c|text)$$

Yes. If the most likely category odds has > 1 , the WK $p(c^|text) > 0.5$, and all other categories must have a smaller WK.*

Multi-classes Naive Bayes: Implementation

- To calculate the values $\tilde{p}(w|c)$, we need the word frequencies per class $n(w, c)$
Solution: Dictionary
 $(\text{str}, \text{str}) \rightarrow \text{int}$
- For the priors $p(c)$ we need the number of instances per class:
 $\text{str} \rightarrow \text{int}$
- and the vocabulary size and the smoothing parameter

```
class NaiveBayesClassifier:
    def __init__(self, word_and_category_to_count, \
                  category_to_num_instances, vocabsize, smoothing):
        # ...
```

Log odds per word

⇒ Exercise sheet

- The log odds for a category c can also be calculated for only one word (instead of one whole document).
- Begin with $\log \frac{p(c|w)}{1-p(c|w)}$ and apply the calculation rules

$$\begin{aligned}\log \frac{p(c|w)}{1-p(c|w)} &= \dots \\ &= \log[\tilde{p}(w|c)] + \log[p(c)] - \log\left[\sum_{c' \neq c} \tilde{p}(w|c')p(c')\right]\end{aligned}$$

- The log odds per word indicate how strongly a word indicates the respective category
- You can then sort all words based on their log odds, and get an idea of what the model has learned (i.e., what's important for the model)

Train and evaluate a classifier

In order to train and evaluate a classifier, we need 3 datasets:

- ① Training data: On this data, the model estimates its parameters automatically (e.g., word probabilities and category priors).
- ② Development data: On this data, various model architectures and hyper-parameters¹ can be compared.

What, for example in our case?

- ③ Test data: An estimate of how well the model works on further unseen data can be obtained on this data, **after the development data finally determined a model architecture.**
 - ▶ Depending on the nature of the data (domain etc), this estimate can deviate very much from reality.
 - ▶ The estimate may also be very unreliable depending on the amount of test data (\Rightarrow significance tests).
 - ▶ **Why can not we use the performance on the development data?**

¹Parameters that are not automatically learned.

Summary

- Probability calculation
 - ▶ Theorem of Bayes
 - ▶ Conditional independence
- Naive Bayes classifier
 - ▶ Decision rule, and “flip” the formula by using theorem of Bayes
 - ▶ Smoothing the probabilities
 - ▶ Log-Odds
- Questions?