

# Naïve Bayes classifiers

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# Common problem: detect spam tweets

- Q. Is the following tweet spam or ham (not spam)?



- Without knowledge of content, what's the best we can do?

# Common problem: detect spam tweets

- Q. Is the following tweet spam or ham (not spam)?



- Without knowledge of content, what's the best we can do?
- Use prior knowledge about relative likelihoods of spam/ham
- If *a priori*, we know 75% of tweets are spam, always guess spam
- (Note: we could also be solving topic classification not spam)

# Our base model

- If 75% of tweets are spam, always guessing spam gives us a lower bound of 75% accuracy
- *Accuracy* has formal definition: % correctly-identified tweets
- A superior model must do better than 75% accuracy
- What if a priori spam rate was 99%? Our model has 99% accuracy
- That hints that accuracy can be very misleading in isolation (more later)

# Better model using knowledge of content

- If we can see tweet words, we have more to go on; e.g.,

Viagra sale

Buy catfood

- Given “Viagra sale”, how do you know it’s spam?
- Because among spam emails you’ve received, those words are highly likely to appear
- Words like “Buy catfood” are unlikely to occur in spam email
- Vice versa: “Viagra sale” low likelihood in non-spam
- $P(\text{Viagra} \cap \text{sale} \mid \text{spam})$  is high,  $P(\text{Viagra} \cap \text{sale} \mid \text{ham})$  is low

# Model based upon tweet likelihoods

- Predict spam if:

$$P(\text{Viagra} \cap \text{sale} \mid \text{spam}) > P(\text{Viagra} \cap \text{sale} \mid \text{ham})$$

- Predict spam if:

$$P(\text{Buy} \cap \text{catfood} \mid \text{spam}) > P(\text{Buy} \cap \text{catfood} \mid \text{ham})$$

- This model works great but makes an assumption by not taking into consideration what knowledge? The *a priori* probabilities; assumes equal priors

# Model combining priors and content info

- Predict spam if:

$$P(\text{spam})P(\text{Viagra} \cap \text{sale} \mid \text{spam}) > P(\text{ham})P(\text{Viagra} \cap \text{sale} \mid \text{ham})$$

- Predict spam if:

$$P(\text{spam})P(\text{Buy} \cap \text{catfood} \mid \text{spam}) > P(\text{ham})P(\text{Buy} \cap \text{catfood} \mid \text{ham})$$

- We are weighting the content likelihoods by prior overall spam rate
- If spam-to-ham priors are .5-to-.5 the prior terms cancel out

# Are these computations probabilities?

- Are  $P(\text{spam})P(\text{Viagra} \cap \text{sale} \mid \text{spam})$  and  $P(\text{ham})P(\text{Viagra} \cap \text{sale} \mid \text{ham})$  probabilities after weighting?
- Nope. Sum over  $P(\text{spam})P(\text{wordsequence}_i \mid \text{spam}) > 1$   
(Imagine  $P(\text{spam})=1.0$  and 1000 different word sequences)
- Must normalize by likelihood of seeing specific word sequence:  
$$\frac{P(\text{spam})P(\text{Viagra} \cap \text{sale} \mid \text{spam})}{P(\text{Viagra} \cap \text{sale})} > \frac{P(\text{ham})P(\text{Viagra} \cap \text{sale} \mid \text{ham})}{P(\text{Viagra} \cap \text{sale})}$$
- Congrats: You've just reinvented *Bayes Theorem*
- I.e., how to adjust knowledge of spam rate with content evidence



# Maximum *a posteriori* classifier

- Choose class/category for document  $d$  with max likelihood:

$$c^* = \underset{c}{\operatorname{argmax}} P(c|d)$$

- Substitute Bayes' theorem:

$$c^* = \underset{c}{\operatorname{argmax}} \frac{P(c)P(d|c)}{P(d)}$$

Bayes' theorem

$$P(c|d) = \frac{P(c)P(d|c)}{P(d)}$$

# Simplifying the classifier

- $P(d)$  is constant on both sides so we can drop it for classification:

$$c^* = \underset{c}{\operatorname{argmax}} P(c)P(d|c)$$

- If  $P(c)$  is same for all  $c$  OR we don't know  $P(c)$ , we drop that too
- Another way to write the classification decision rule is  
*Bayes test for minimum error:*

$$P(c_1 | d) \geq P(c_2 | d)$$

# Training the classifier

- We need to estimate  $P(c)$  and  $P(d \mid c)$  for all  $c$  and  $d$
- Estimating  $P(c)$ ? The number of documents in class  $c$  divided by the total number of documents
- Estimating  $P(d \mid c)$ ? E.g., we need  $P(\text{Viagra} \cap \text{sale} \mid \text{spam})$
- That means considering all 2-word combinations (*bigrams*), which grows in size with the square!

# The naïve assumption

- Naïve assumption: conditional independence; Estimate  $P(\text{Viagra} \cap \text{sale} \mid \text{ham})$  as  $P(\text{Viagra} \mid \text{spam}) \times P(\text{sale} \mid \text{spam})$

$$P(d|c) = \prod_{w \in d} P(w|c)$$

- So, our classifier becomes

$$c^* = \underset{c}{\operatorname{argmax}} P(c) \prod_{w \in d} P(w|c)$$

- where  $w$  is each word in  $d$  not the unique vocabulary words

# Fixed-length word-count vectors

- Rather than arbitrary-length word vectors for each document  $d$ , it's much easier to use fixed-length vectors with word counts; this:

$$c^* = \underset{c}{\operatorname{argmax}} P(c) \prod_{w \in d} P(w|c)$$

becomes this

$$c^* = \underset{c}{\operatorname{argmax}} P(c) \prod_{\text{unique}(w) \in d} P(w|c)^{n_w(d)}$$

# Estimating $P(w | c)$

- We have  $P(c)$  so how do we estimate  $P(w | c)$ ?
- It's number of times  $w$  appears in all documents from class  $c$  divided by the total number of words (including repeats) in all documents from class  $c$

$$P(w|c) = \frac{\textit{count}(w, c)}{\textit{count}(c)}$$

# Laplace smoothing

- If  $P(w | c)=0$  then the entire product goes to zero. Ooops

$$c^* = \underset{c}{\operatorname{argmax}} P(c) \prod_{w \in d} P(w|c)$$

- To avoid, add 1 to each word count in numerator and compensate by adding  $|V|$  to denominator (to keep a probability)

$$P(w|c) = \frac{\text{count}(w, c) + 1}{\text{count}(c) + |V|}$$

- We have added +1 to each word count and there are  $|V|$  words in each word-count vector

# Dealing with misspelled or unknown words

- Laplace smoothing deals with  $w$  that are in the vocabulary but not in class  $c$ , which gives  $P(w | c) = 0$
- What should  $\text{count}(w, c)$  be for a word not in vocabulary? Zero doesn't seem right as we have no data but if  $\text{count}(w, c) = 0$  for all classes, classifier is not biased
- $\text{count}(w, c) = 0$  actually won't occur due to Laplace but it's like we map all unknown  $w$  to a wildcard word in vocabulary, which means  $|V|$  is one bigger
- Likely not a huge factor...

$$P(w|c) = \frac{\text{count}(w, c) + 1}{\text{count}(c) + |V| + 1}$$



# Avoiding floating point underflow

- In practice, multiplying lots of probabilities in  $[0,1]$  range tends to get too small to represent with finite floating-point numbers
- Take log (a monotonic function) and product becomes summation

$$c^* = \underset{c}{\operatorname{argmax}} P(c) \prod_{w \in d} P(w|c)$$

$$c^* = \underset{c}{\operatorname{argmax}} \left\{ \log(P(c)) + \sum_{\text{unique}(w) \in d} n_w(d) \times \log(P(w|c)) \right\}$$

# An example

# Documents as word-count vectors

- One column per vocab word, one row per document

d1 = "sale viagra sale"

d2 = "free viagra free viagra free viagra free"

d3 = "buy catfood and buy eggs"

d4 = "buy eggs"

$P(\text{spam}) = 2/4$

$P(\text{ham}) = 2/4$

column for  
unknown  
words

	unknown	buy	catfood	eggs	free	sale	viagra	spam
0	0	0	0	0	0	2	1	1
1	0	0	0	0	4	0	3	1
2	0	2	1	1	0	0	0	0
3	0	1	0	1	0	0	0	0

spam or ham

Note:

$|V|=7+1=8$

# Laplace smoothing

- Add +1 everywhere, even for unknown (just “df+1” in pandas)

	<i>spam</i>						
	unknown	buy	catfood	eggs	free	sale	viagra
0	1	1	1	1	1	3	2
1	1	1	1	1	5	1	4

	<i>ham</i>						
	unknown	buy	catfood	eggs	free	sale	viagra
2	1	3	2	2	1	1	1
3	1	2	1	2	1	1	1

Pandas query to get just spam rows: `df.query('spam==1')`



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# Estimating probabilities: $P(w \mid \text{spam})$

- 1<sup>st</sup>, get total word count in spam category: sum across rows or cols then sum that result; `count(spam) = spam.sum(axis=1).sum()`
- `count(spam)` includes  $|V|$  (smoothing) and +1 (unknown word) for denominator of  $P(w \mid \text{spam})$

		<i>spam</i>							
		unknown	buy	catfood	eggs	free	sale	viagra	
0		1	1	1	1	1	3	2	10
1		1	1	1	1	5	1	4	14

`count(spam) = 24`

$$P(w \mid c) = \frac{\text{count}(w, c) + 1}{\text{count}(c) + |V| + 1}$$

# Estimating probabilities: $P(w \mid \text{spam})$

- 2<sup>nd</sup>, get total count for each word in spam docs,  $\text{count}(w, \text{spam})$   
`spam.sum(axis=0)`
- 3<sup>rd</sup>, divide word count in each doc by  $\text{count}(\text{spam})=24$

	<i>spam</i>						
	unknown	buy	catfood	eggs	free	sale	viagra
0	1	1	1	1	1	3	2
1	1	1	1	1	5	1	4
	$\frac{2}{24}$	$\frac{2}{24}$	$\frac{2}{24}$	$\frac{2}{24}$	$\frac{6}{24}$	$\frac{4}{24}$	$\frac{6}{24}$

$$P(\text{unknown}|\text{spam})=1/12$$

$$P(\text{buy}|\text{spam})=1/12$$

...

$$P(\text{viagra}|\text{spam})=1/4$$

## Estimate $P(c|w)$ w/o $P(d)$ normalization

- $P(\text{spam}|\text{viagra sale}) = P(\text{spam})[P(\text{viagra}|\text{spam})P(\text{sale}|\text{spam})]$   
 $= 1/2 \times 6/24 \times 4/24 = 0.0208$
- $P(\text{ham}|\text{viagra sale}) = P(\text{ham})[P(\text{viagra}|\text{ham})P(\text{sale}|\text{ham})]$   
 $= 1/2 \times 2/20 \times 2/20 = 0.005$
- $P(\text{spam}|\text{viagra sale}) > P(\text{ham}|\text{viagra sale})$  so predict spam

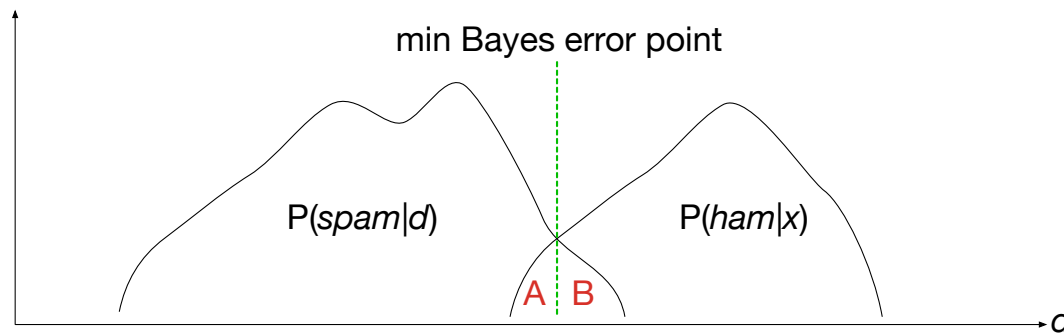
## Example with word count > 1

- $P(\text{spam}|\text{sale viagra sale}) = P(\text{spam})[P(\text{viagra}|\text{spam})P(\text{sale}|\text{spam})^2]$   
 $= 1/2 \times 6/24 \times 4/24 \times 4/24 = 0.0034$
- $P(\text{ham}|\text{sale viagra sale}) = P(\text{ham})[P(\text{viagra}|\text{ham})P(\text{sale}|\text{ham})^2]$   
 $= 1/2 \times 2/20 \times 2/20 \times 2/20 = 0.0005$
- Imagine “sale” or “viagra” repeated many times, all scores go down since  $P(w|c) < 1$  but  $P(\text{ham}|\text{sale viagra sale})$  drops much faster than  $P(\text{spam}|\text{sale viagra sale})$
- Ratio of those spam to ham will grow with added spam words



# Quick idea on Bayes error

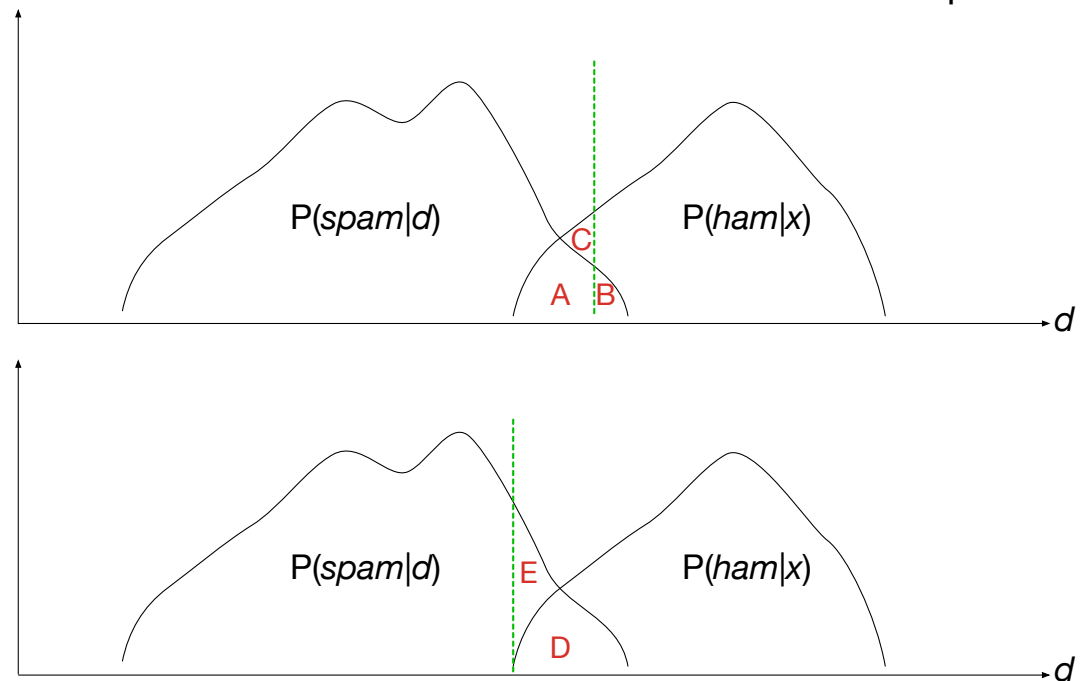
- Bayes error is the lowest possible total error from all classes
- Imagine squashing doc  $d$  down to single dimension
- Bayes error is area under  $P(\text{spam}|d)$  to right and  $P(\text{ham}|d)$  to left of decision point (**A** and **B** here)



# Preview AUC ROC / PR curves

- If our "utility function" values spam or ham differently, can shift boundary to left/right
- Tradeoff: to get 0 ham error, must accept many spam, area under  $P(\text{spam}|d)$  to right: D+E error
- Later we'll examine ROC/PR curves that summarize effect of shifting boundary all over

E.g., in disease testing, might value catching disease more than cost of false positive



# Key takeaways

- Naïve bayes is classifier often applied to text classification; e.g., spam/ham, topic labeling, etc...
- Less often used these days with rise of deep learning
- Fixed-length word-count vectors are the feature vectors per doc
- Bayes theorem gives formula for  $P(c|w)$
- Naïve assumption is conditional independence  $\longrightarrow P(d|c) = \prod_{w \in d} P(w|c)$
- Training estimates  $P(c)$ ,  $P(w|c)$  for each  $w$  and  $c$
- $P(c)$  is ratio of docs in  $c$  to overall number of docs
- $P(w|c)$  is ratio of word count of  $w$  in  $c$  to total word count in  $c$
- Classifier:
$$c^* = \underset{c}{\operatorname{argmax}} P(c) \prod_{\text{unique}(w) \in d} P(w|c)^{n_w(d)}$$

# Implementation takeaways

- Avoid vanishing floating-point values from product

$$c^* = \underset{c}{\operatorname{argmax}} \left\{ \log(P(c)) + \sum_{\text{unique}(w) \in d} n_w(d) \times \log(P(w|c)) \right\}$$

- Avoid  $P(w|c)=0$  via Laplace smoothing
  - add 1 to all word counts
  - adjust  $P(w|c)$  denominator with extra  $|V|$  since every doc now has every word
  - this is for missing words where  $w$  not in  $d$  but in  $V$
- Treat unknown words as  $1 / (\text{count}(c) + |V| + 1)$