Ngrams

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A card deck

Let’s say we have a deck of standard cards and we are interesting in what suits and ranks we get when we draw a random card (returning the card to the deck after each experiment).

Our mathematical description is as follows:

1. We chose a variable—call it card—to denote the outcomes of our various card-drawing experiments.
2. There are 52 possible outcomes to an experiment:
   \[
   \{\spadesuit A, \spadesuit K, \ldots, \spadesuit Q, \ldots \}
   \]
3. The variable card is a random variable.
4. The important thing about a random variable is that it can take different values. For example:
   \[
   \text{card} = \diamond J
   \]
5. The term usually comes up when we know something or want to something about the probabilities of certain events.
There are numerous classes of outcomes of interest:

- **Suits**: ♠, ♦, ♣, ♥
- **Ranks**: Ace, King, Queen, Jack, 10, ...
Random Variables

Let \( \Omega \) be a set of outcomes (called the **sample space**): \( \Omega = \{x_1, x_2, \ldots, x_n\} \) and let \( \chi \) be some random variable that takes values in \( \Omega \):

\[
\chi = x_1, \chi = x_2, \ldots \chi = x_n
\]

\( P(\chi = x_i) \) is the probability that \( \chi \) is equal to \( x_i \):

\[
0 \leq P(\chi = x_i) \leq 1
\]

\[
\sum_{x_i \in \Omega} P(\chi = x_i) = 1
\]

Subsets of \( \Omega \) are called **events**. The probability of an event \( e_1 \) is defined:

\[
P(e_1) = \sum_{x_i \in e_1} P(\chi = x_i)
\]

For any two events \( e_1, e_2 \),

\[
P(e_1 \cup e_2) = \sum_{x_i \in e_1 \cup e_2} P(\chi = x_i)
\]

With \( e_1, e_2 \) disjoint,

\[
P(e_1 \cup e_2) = P(e_1) + P(e_2)
\]
Example

In our card-drawing example,

\[ \Omega = \{\spadesuit A, \spadesuit K, \spadesuit Q, \ldots \} \]

\(\chi\) the random variable, was card, and it took values in \(\Omega\)

\(\text{card} = \spadesuit A, \text{card} = \heartsuit Q, \text{card} = \diamondsuit 7, \ldots\)

Assuming the cards are being dealt fairly:

\[ P(\text{card} = \diamondsuit 7) = \frac{1}{52} = 0.019 \]

And similarly for any other card.

**Suit events** are subsets of \(\Omega\):

\(\clubsuit = \{\spadesuit A, \spadesuit K, \spadesuit Q, \ldots \}\)

**Rank events**:

\(\text{king} = \{\spadesuit K, \heartsuit K, \diamondsuit K, \spadesuit K\}\)
Example, ctd.

\[
P(\spadesuit) = \sum_{x_i \in \spadesuit} P(\chi = x_i) = \frac{13}{52} = \frac{1}{4} = .25 \\
P(\heartsuit) = \sum_{x_i \in \heartsuit} P(\chi = x_i) = \frac{13}{52} = \frac{1}{4} = .25 \\
P(\text{King}) = \sum_{x_i \in \text{King}} P(\chi = x_i) = \frac{4}{52} = \frac{1}{13} = .077
\]

For disjoint events \spadesuit, \heartsuit, we get

\[
P(\spadesuit \cup \heartsuit) = .25 + .25 = .5
\]

Compare \(P(\spadesuit \cup \text{king})\)

\[
P(\text{King} \cup \spadesuit) \neq \frac{4}{52} + \frac{13}{52} = \frac{17}{52} = .327 \\
P(\text{king} \cup \spadesuit) = \frac{16}{52} = .308
\]

\(\spadesuit = \{ \spadesuit A, \spadesuit K, \spadesuit Q, \ldots \}\)  
king = \{ \text{King}, \heartsuit K, \diamondsuit K, \spadesuit K \}
Example, ctd.

\[
\begin{align*}
P(\spadesuit) &= \sum_{x_i \in \spadesuit} P(\chi = x_i) = \frac{13}{52} = \frac{1}{4} = .25 \\
P(\heartsuit) &= \sum_{x_i \in \heartsuit} P(\chi = x_i) = \frac{13}{52} = \frac{1}{4} = .25 \\
P(\text{King}) &= \sum_{x_i \in \text{King}} P(\chi = x_i) = \frac{4}{52} = \frac{1}{13} = .077
\end{align*}
\]

For disjoint events \( \spadesuit, \heartsuit \), we get

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P(\text{king} \cup \spadesuit) &= \frac{16}{52} = .308
\end{align*}
\]

\( \spadesuit = \{ \spadesuit A, \spadesuit K, \spadesuit Q, \ldots \} \)
\( \text{king} = \{ \spadesuit K, \heartsuit K, \diamondsuit K, \clubsuit K \} \)
Consider $P(\heartsuit \cap \text{king}) = P(\heartsuit, \text{king})$

$$P(\text{king} \cap \heartsuit) = \frac{1}{52} + \frac{13}{52} = .019$$

$\heartsuit = \{\heartsuit A, \heartsuit K, \heartsuit Q, \ldots\}$

king = $\{\spadesuit K, \heartsuit K, \diamondsuit K, \clubsuit K\}$
Binomial Distribution

Suppose you toss a coin 100 times and you get 45 Heads.

\[ \Omega = \{ \text{H, T} \} \]

Our sample size is 100. The count of heads events is 45. Using relative frequency to estimate the probability of heads, we get:

\[ \hat{P}(\chi = \text{head}) = \frac{45}{100} = .45 \]

Given that the coin has this probability for heads, we can ask, what is the probability of getting exactly 45 heads:

\[
P(r \mid p) = \binom{n}{r} p^r (1 - p)^{n-r}
\]

\[
P(45 \mid p) = \binom{100}{45} p^{45} (1 - p)^{55} = 0.08
\]

Here \( p \) is the probability of heads, \( r \) the number of heads in the sample, and \( n \) the total sample size. This is called a **binomial distribution**, because there are only two outcomes.
Binomial Distribution

We have 6 coin flips (fair coin \( p(H) = .5 \)). What’s the probability that exactly 2 of them will be H?

\[
L(p; x) = \frac{n!}{x!(n-x)!} p^x (1 - p)^{n-x}
\]

\[
L(.5; 2) = \frac{6!}{2!4!} \times .5^2 \times .5^4
\]

\[
L(.5; 2) = 15 \times .15625
\]

\[
\propto .15625
\]

A not so fair coin (p(H) = .3)

\[
L(.4; 2) = \frac{6!}{2!4!} \times .42 \times .6^4
\]

\[
L(.4; 2) = 15 \times .0576
\]

\[
\propto .0576
\]
Maximum Likelihood Estimate (MLE)

We might consider a number of different values for the probability of heads with that coin, and ask for each, what is the likelihood of getting exactly 45 heads.

Using the formula for a binomial distribution, we can plot a graph whose x-axis is the probability of a head in each model, and whose y axis is that is the probability of getting 45 heads with that coin.
Likelihood Graph

Likelihood: $p(s \mid m)$ (prob of sample given model)
MLE Drawbacks

- The probability of 45 heads in 100 throws is .08!
- 0.08 is not that high. The probability that a fair coin would produce this sample (that \( p = 0.5 \)) is about 0.047, which is not that much lower.
- Try the experiment with a fair coin. Very rarely will you get 50 heads. The probability of getting exactly 50 heads with a fair coin is also about 0.08.
- The MLE may be the **best** guess of the true model, but it is still not all that likely to be right.
- Bigger sample size helps discriminate models better.
- Rare events are still hard to model well.
The Bayesian estimate balances the likelihood of a sample given a model, $p(s \mid m)$, against some prior probability distribution over models, $\mu(m)$. If we have a prior belief that coins are fair, we choose a prior distribution favoring the fair coin model, with model probability dropping off rapidly as it moves away from fair:

$$\mu(m) = \arg \max_m \mu(m) \times p(s \mid m)$$
Joint Distributions

Joint distributions can be defined in terms of two random variables $\chi$ and $\gamma$:

$$p(x, y) = P(\chi = x, \gamma = y)$$

So now we have probabilities for paired outcomes.

The marginal probability of outcome $x$ is the sum of the probabilities of outcomes in which $x$ is involved, which means summing over all the $y$'s $x$ is paired with; and similarly for $y$:

$$p_\chi(x) = \sum_\gamma p(x, y) \quad p_\gamma(y) = \sum_\chi p(x, y)$$
Conditional Probabilities

Conditional Probabilities are defined by the **Chain Rule**:

(a) \( p_{X|Y}(x \mid y) = \frac{p(x, y)}{p(y)} \)

(b) \( p(x, y) = p_{X|Y}(x \mid y) \times P(y) \)
Conditional Prob Distributions

Each way of fixing $y$ defines a probability distribution:

$$\sum_{x} p(x \mid \gamma = y) = \sum_{x} \frac{p(x, y)}{p(y)}$$

$$= \frac{\sum_{x} p(x, y)}{p_\gamma(y)} = \frac{p(y)}{p(y)}$$

$$= 1$$

So $p(x \mid \gamma = y)$ is a probability distribution.
Chain Rule: review

\[
(1) \quad P(x_1, x_2) = P(x_1) \ast P(x_2 \mid x_1)
\]

\[
\vdots
\]

\[
(n-1) \quad P(x_1, x_2, \ldots, x_n) = P(x_1) \ast P(x_2 \mid x_1) \ast \cdots \ast P(x_n \mid x_1, \ldots, x_{n-1})
\]
Chain Rule: review

(1) \( P(x_1, x_2) = P(x_1) \times P(x_2 \mid x_1) \)

(2) \( P(x_1, x_2, x_3) = P(x_1, x_2) \times P(x_3 \mid x_1, x_2) \)

\[ \vdots \]

(n-1) \( P(x_1, x_2, \ldots, x_n) = P(x_1) \times P(x_2 \mid x_1) \cdots P(x_n \mid x_1, \ldots, x_{n-1}) \)
Chain Rule: review

(1) $P(x_1, x_2) = P(x_1) \cdot P(x_2 | x_1)$

(2) $P(x_1, x_2, x_3) = P(x_1) \cdot P(x_2 | x_1) \cdot P(x_3 | x_1, x_2)$

\[ \vdots \]

(n-1) $P(x_1, x_2, \ldots, x_n) = P(x_1) \cdot P(x_2 | x_1) \cdot \ldots \cdot P(x_n | x_1, \ldots, x_{n-1})$
Chain Rule: review

1. \( P(x_1, x_2) = P(x_1) \cdot P(x_2 | x_1) \)

2. \( P(x_1, x_2, x_3) = P(x_1) \cdot P(x_2 | x_1) \cdot P(x_3 | x_1, x_2) \)

3. \( P(x_1, x_2, x_3, x_4) = P(x_1, x_2, x_3) \cdot P(x_4 | x_1, x_2, x_3) \)

\[ \vdots \]

\( n-1 \) \( P(x_1, x_2, \ldots, x_n) = P(x_1) \cdot P(x_2 | x_1) \cdot \ldots \cdot P(x_n | x_1, \ldots, x_{n-1}) \)
Chain Rule: review

(1) \( P(x_1, x_2) = P(x_1) \times P(x_2 | x_1) \)

(2) \[ P\left( x_1, x_2, x_3 \right) = P(x_1) \times P(x_2 | x_1) \times P(x_3 | x_1, x_2) \]

(3) \[ P\left( x_1, x_2, x_3, x_4 \right) = P(x_1) \times P(x_2 | x_1) \times P(x_3 | x_1, x_2) \times P(x_4 | x_1, x_2, x_3) \]

\[ \vdots \]

(n-1) \[ P(x_1, x_2, \ldots, x_n) = P(x_1) \times P(x_2 | x_1) \times \cdots \times P(x_n | x_1, \ldots, x_{n-1}) \]
Conditional Probs and Relative frequencies

The chain rule tells us how to estimate conditional probabilities using relative frequencies:

\[
P(a \mid b) = \frac{P(a, b)}{P(b)} = \frac{|a, b|}{|S|} \frac{|S|}{|a, b|} \frac{|b|}{|S|}
\]

Instead of dividing the frequency by the size of the entire sample as we do for \( P(a,b) \), we divide by the size of the sample restricted to \( b \).
Predicting words

We are interested in predicting the nth word given some history of \( n - 1 \) words:

Consider a history of 6 words:

I want to make a long-distance _____
Motivations

Jurasky & Martin (pp. 83,84)

Apps

Speech and handwriting recognition:
- how do you wreck a nice beach?
- **how do you recognize speech?**

Choosing among the outputs of a Chinese statistical MT system:
- he briefed to reporters on the chief contents of of the statement.
- he briefed reporters on the chief contents of of the statement.
- **he briefed reporters on the main contents of of the statement.**

Spelling correction: errors that are valid words:
- They are leaving in about 15 **minuets** to go to her house.
- The design an construction of the system will take more than a year.
More subfields/apps

1. augmentative communication
2. authorship identification
3. predictive text input (cell phone texting)
4. part-of-speech tagging
5. language generation
6. word similarity
The problem

We start with the problem: How do we formulate the probability of a *string of words of length* \( n \)?

We use the chain rule for the joint probability of \( n \) events:

\[
P(x_1, x_2, \ldots, x_n) = P(x_1) \cdot P(x_2 | x_1) \cdot \cdots \cdot P(x_n | x_1, \ldots, x_{n-1})
\]

We abbreviate word sequences \( w_1, w_2, \ldots, w_n \) as \( w_1^n \).

We think of \( n \)-word word sequence \( w_1^n \) as a joint event consisting of word 1 occurring in the first position, word 2 occurring in the second position, and so on. So the Chain rule applies!
Word sequences

It follows immediately that:

\[ P(w_1^n) = P(w_1) \times P(w_2 \mid w_1) \times \ldots \times P(w_n \mid w_1^{n-1}) \]

The problem with this formulation of the probability can be seen by looking at the last term:

\[ \text{Prob}(w_n \mid w_1^{n-1}) \]

This is the probability of the last word given the entire sequence of words before it.

How would we compute such a thing?
How to compute: \( \text{Prob}(w_n | w_1^{n-1}) \)?

It’s easy!

\[
\frac{|w_1^n|}{|w_1^{n-1}|}
\]

For instance:

\[
| I \text{ want to make a long-distance call} |
\]

| I want to make a long-distance |

To do this right we need some corpus large enough to give us a representative sampling of the 5-word string *I want to make a long-distance* in which there is hopefully a representative sample of the 6-word string *I want to make a long-distance call*.
Not enough data

The problem is that there isn’t enough data in the world to get such representative samples in most cases for even moderately small $n$.

Consider a very small $n$. Consider Shakespeare.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word token Count</td>
<td>884,647</td>
</tr>
<tr>
<td>Word form Types</td>
<td>29,066</td>
</tr>
<tr>
<td>Number of bigram types</td>
<td>$29,066^2 = 844$ million</td>
</tr>
<tr>
<td>Number of bigram tokens</td>
<td>884,647</td>
</tr>
</tbody>
</table>

In any corpus of this size, we’re very unlikely to see most of the rarer bigrams.
Shakespeare’s trigrams

Word token Count       884, 647  
Word form Types        29, 066   
Number of trigram types \(29, 066^3 = 25, 636, 000, 000, 000\)  
Number of trigram tokens 884, 647  

We get only a vanishing small sample of the entire space of trigrams. We’re likely to encounter only the most common ones.
After training on 1.5 million words from IBM Laser Patent Text Corpus, Bahl, et al (1983) reported that 23% of the trigrams in unseen data were new!

Uggh! This is “the long tail of language”

Still worse, we need samples build out of independent events; In fact trigrams in a text aren’t independent:

Each partially overlaps (and partly helps determine) the next one:

I want to
want to make
make a
make a long

Content words tend to clump (a word's appearance in a document is one of the best predictors of its later appearance).

Auctorial tendencies (the Shakespeare corpus).
Zipf’s Law

“The long tail of language”

1. Frequency of a word: How many times it occurs in a sample of a certain size
2. Rank: Most frequent word has rank 1; least frequent in a vocab of 20K has rank 20K.
3. Zipf’s Law:

\[ f \cdot r = k \]
Almost all words are rare.
— Manning and Schuetze (1999)

Frequency of Frequencies in *Tom Sawyer*
(Manning & Schuetze, Table 1.2, p. 22)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Frequency of Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3993</td>
</tr>
<tr>
<td>2</td>
<td>1292</td>
</tr>
<tr>
<td>3</td>
<td>664</td>
</tr>
<tr>
<td>4</td>
<td>410</td>
</tr>
<tr>
<td>5</td>
<td>243</td>
</tr>
<tr>
<td>6</td>
<td>199</td>
</tr>
<tr>
<td>7</td>
<td>172</td>
</tr>
<tr>
<td>8-10</td>
<td>304</td>
</tr>
<tr>
<td>11-50</td>
<td>540</td>
</tr>
<tr>
<td>51-100</td>
<td>99</td>
</tr>
<tr>
<td>101-100</td>
<td>102</td>
</tr>
<tr>
<td>&gt;100</td>
<td>8018</td>
</tr>
</tbody>
</table>
### Zipf’s Law III

<table>
<thead>
<tr>
<th>Rank</th>
<th>Word</th>
<th>Frequency</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>the</td>
<td>3332</td>
<td>determiner (article)</td>
</tr>
<tr>
<td>2</td>
<td>and</td>
<td>2972</td>
<td>conjunction</td>
</tr>
<tr>
<td>3</td>
<td>a</td>
<td>1775</td>
<td>determiner</td>
</tr>
<tr>
<td>4</td>
<td>to</td>
<td>1725</td>
<td>preposition, infinitive marker</td>
</tr>
<tr>
<td>5</td>
<td>of</td>
<td>1440</td>
<td>preposition</td>
</tr>
<tr>
<td>6</td>
<td>was</td>
<td>1161</td>
<td>auxiliary verb</td>
</tr>
<tr>
<td>7</td>
<td>it</td>
<td>1027</td>
<td>personal/expletive pronoun</td>
</tr>
<tr>
<td>8</td>
<td>in</td>
<td>906</td>
<td>preposition</td>
</tr>
<tr>
<td>9</td>
<td>that</td>
<td>877</td>
<td>complementizer, demonstrative</td>
</tr>
<tr>
<td>10</td>
<td>he</td>
<td>877</td>
<td>personal pronoun</td>
</tr>
<tr>
<td>11</td>
<td>I</td>
<td>783</td>
<td>personal pronoun</td>
</tr>
<tr>
<td>12</td>
<td>his</td>
<td>772</td>
<td>possessive pronoun</td>
</tr>
<tr>
<td>13</td>
<td>you</td>
<td>686</td>
<td>personal pronoun</td>
</tr>
<tr>
<td>14</td>
<td>Tom</td>
<td>679</td>
<td>proper noun</td>
</tr>
<tr>
<td>18229</td>
<td></td>
<td>out of 71,370 (25.6%)</td>
<td>Common words in <em>Tom Sawyer</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Manning &amp; Schuetze, Table 1.1, p. 21)</td>
</tr>
</tbody>
</table>
A simplifying Assumption

Reduce the amount of history looked at (a Markov assumption)

\[ P(w_n | w_1, \ldots, w_{n-1}) = P(w_n | w_{n-1}) \]

The chain rule calculation goes from:

\[ P(w_1^n) = P(w_1) \times P(w_2 | w_1) \times P(w_3 | w_1, w_2) \cdots P(w_n | w_{n-1}) \]

to

\[ P(w_1^n) = P(w_1) \times P(w_2 | w_1) \times P(w_3 | w_2) \cdots P(w_n | w_{n-1}) \]
The assumption that the probability of an event is determined by some finite amount of history is called a **Markov Assumption**.

A consequence of the Markov assumption is that a Probability model can be completely described by a very simple kind of probabilistic finite-state automaton called a **Markov Chain**.
A Simple bigram Markov chain

Bigram for a simple language with a vocabulary of three words: a, b, and c.
String probability

String probabilities for abc and cba.

\[
P(abc) = P(a \mid S) \times P(b \mid c) \times P(c \mid b) \\
P(cba) = P(c \mid S) \times P(b \mid c) \times P(a \mid b)
\]
Markov Properties

- Markov models can encode dependencies on histories of any finite length – at the cost of more states. Consider a vocab of size 3:

1. bigram: 3 words = 3 possible histories = 3 states
2. trigram 3 * 3 histories = 9 states

- In a trigram model, where should we go if we’re in state “ab” and we see a “b”?

- Markov Chains: For any given emission, there is exactly one path through the network
- Hidden Markov Models: For any given emission there are an arbitrary number of paths through the network
- Ngram models are Markov chains.
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- In a trigram model, where should we go if we’re in state “ab” and we see a “b”? And what is the probability? $P(b \mid b)$? $P(b \mid a)$? $P(b \mid ab)$?

![Diagram showing states ab and bb connected by an arrow]

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- Hidden Markov Models: For any given emission there are an arbitrary number of paths through the network.
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Markov Properties

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In a trigram model, where should we go if we’re in state “ab” and we see a “b”? And what is the probability? $P(b | b)$? $P(b | a)$? $P(b | ab)$? $P(b | ab)$

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