Introducing Bayesian Language models

Unigram, Bigram, Hidden Markov, & Topic models

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Language data

- A *minimal* description of observed language data is as follows:

  $$\mathcal{D} = \{w_1, w_2 \dots w_j \dots w_J\},$$

  with

  $$w_j = w_{ji}, w_{j2} \dots w_{jn_j},$$

  and

  $$w_{ji} \in \mathcal{V},$$

  where $\mathcal{V}$ is a finite vocabulary, which can be represented for simplicity by integers

  $$\mathcal{V} = \{1, 2 \dots V\}.$$

- In other words, we can describe language data as a set of sequences of symbols.
- Each w_{ji} usually represents a word (but could represent e.g. phonemes, instead) and each w_j represents a text or sentence.

Unigram probabilistic language model

- A *probailistic language model* is any probailistic generative model of the language data $\mathcal{D}$.
- One of the simplest possible probabilistic language models is

$$w_{ji} \sim \text{dcat}(\pi), \quad \text{for } i \in 1, 2 \ldots n_j, j \in 1, 2 \ldots J$$

  where dcat( ) represents a categorical distribution (probability mass function) over $1 \ldots V$ with

$$\text{Pr}(w_{ji} = k) = \pi_k.$$

- In other words, we model each word w_{ji} as drawn independently from a single categorical distribution with parameters π.

Bayesian unigram models

- In any Bayesian model, we provide a full probabilistic account of all variables, including observed variables, parameters, etc.
- For the case of a probabilistic unigram model, a common Bayesian unigram model would be

$$\begin{aligned} \pi &\sim \mathrm{ddirichlet}(\alpha), \\ w_{ji} &\sim \mathrm{dcat}(\pi), \quad \text{for } i \in 1, 2 \ldots n_j, j \in 1, 2 \ldots J. \end{aligned}$$

- Here, ddirichlet( ) denotes a V-dimensional Dirichlet distribution, which is a probability distribution over V-dimensional probability mass functions. It has hyperparameters $\alpha = \alpha_1, \alpha_2 \ldots \alpha_v \ldots \alpha_V$, where each $\alpha_v > 0.0$.
- The Dirichlet distribution is commonly chosen in this context because it is a conjugate prior of the categorical distribution.

Dirichlet Distribution

- The Dirichlet distribution is

$$\mathrm{ddirichlet}(\alpha) = \frac{\Gamma(\sum_v \alpha_v)}{\prod_v \Gamma(\alpha_v)} \prod_{v=1}^{V} \pi_v^{\alpha_v - 1}$$

where

$$\frac{\Gamma(\sum_v \alpha_v)}{\prod_v \Gamma(\alpha_v)}$$

is the normalizing constant, i.e.,

$$\frac{\prod_v \Gamma(\alpha_v)}{\Gamma(\sum_v \alpha_v)} = \int \prod_{v=1}^{V} \pi_v^{\alpha_v - 1} \mathrm{d}\pi$$

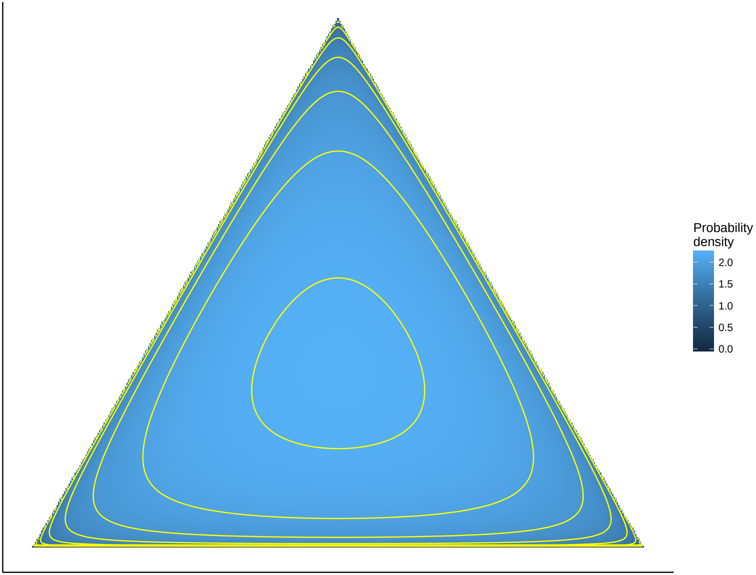
Dirichlet distribution hyperparameters

- As mentioned, the hyperparameters of a V-dimensional Dirichlet distribution is a V-dimensional vector α of positive values.
- It is convenient to sometimes represent α as follows:

  $$\alpha = a \cdot m$$

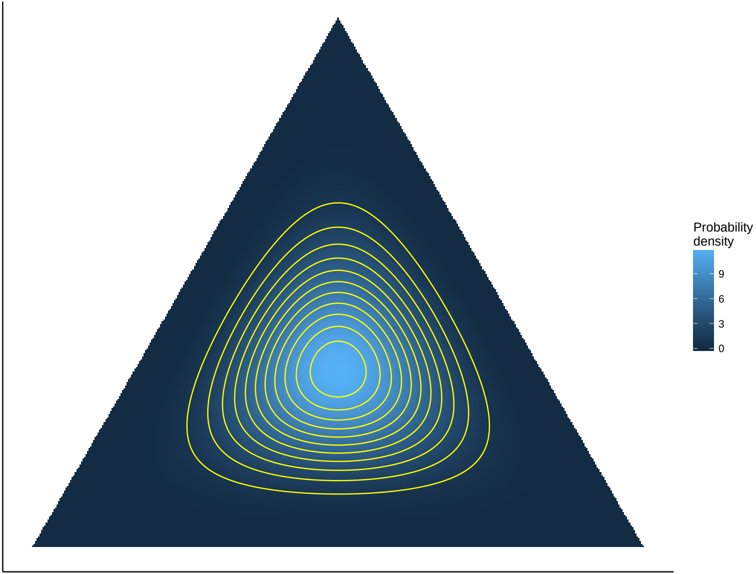
  where $a > 0$ is a scalar and m is V-dimensional probability mass function, i.e $0 \leqslant m_v \leqslant 1$ and $\sum_v m_v = 1$.
- In this reparameterization, m is a *location* vector and a is a *scale* vector. In other words, m is the centre of the distribution, and a indicates how spread out around the centre the distribution is. Also, m is exactly the average, or expected value of the distribution.
- Note $a = \sum_v \alpha_v$, $m = \alpha/a$.

3d Dirichlet distribution: Example 1



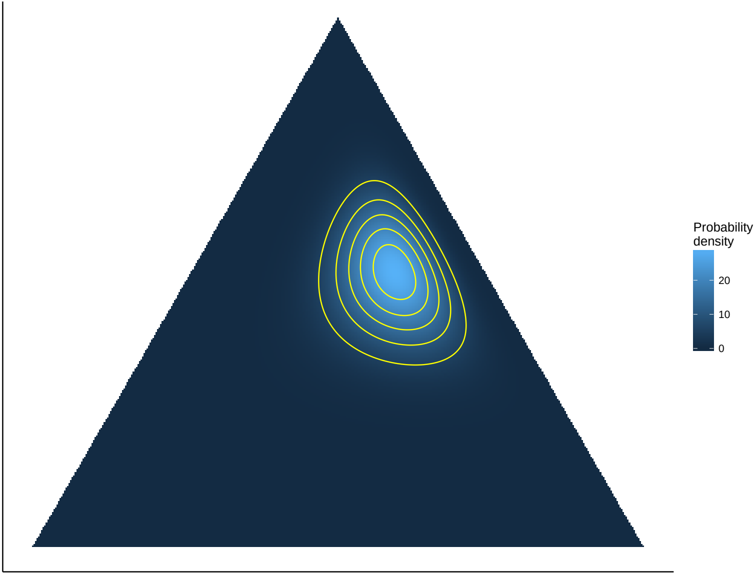
Here, $\alpha = 1.1, 1.1, 1.1$, or $a = 3.3$, $m = [\frac{1}{3}, \frac{1}{3}, \frac{1}{3}]$

3d Dirichlet distribution: Example 2



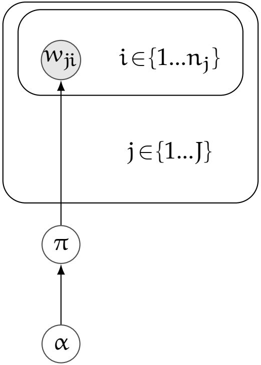
Here, $\alpha = 5, 5, 5$, or $a = 15$, $m = [\frac{1}{3}, \frac{1}{3}, \frac{1}{3}]$

3d Dirichlet distribution: Example 3



Here, $\alpha = 5, 10, 15$, or $a = 30$, $m = [\frac{1}{6}, \frac{1}{3}, \frac{1}{2}]$

Unigram model: Bayesian network



This is a *graphical model* or *Bayesian network*. It shows the conditional independence structure of the variables in the probabilistic model.

Posterior inference

- Because the Dirichlet distribution is a conjugate prior to the categorical distribution, calculating the posterior distribution over π is possible algebraically:

$$
\begin{aligned}
P(\pi|\mathcal{D},\alpha) = \frac{P(D|\pi)P(\pi|\alpha)}{\int P(D|\pi)P(\pi|\alpha)d\pi}, &\propto \prod_{\{ji\}} P(w_{ji}|\pi)P(\pi|\alpha), \\
&\propto \prod_{v=1}^{V} \pi_v^{n_v} \prod_{v=1}^{V} \pi_v^{\alpha_v - 1}, \\
&\propto \prod_{v=1}^{V} \pi_v^{n_v + \alpha_v - 1}, \\
&\text{ddirichlet}(n+\alpha).
\end{aligned}
$$

- In other words, given the prior ddirichlet(α) and observed counts of $n = n_1, n_2 \dots n_v$ (i.e., n_v is the number of observations of word v), the posterior distribution is always ddirichlet$(n+\alpha)$.

Unigram model of Moby Dick

```r
data("stop_words")
moby_dick <- gutenberg_download(2701)
```

```r
word_counts <- moby_dick %>%
  unnest_tokens(word, text, token = 'words') %>%
  anti_join(stop_words) %>%
  count(word, sort=TRUE)

# Make a (named) vector of counts
counts <- word_counts$n
words <- word_counts$word
```

Unigram model of Moby Dick

- As a starting point, choose uniform prior

```
alpha <- rep(1, length(counts))
```

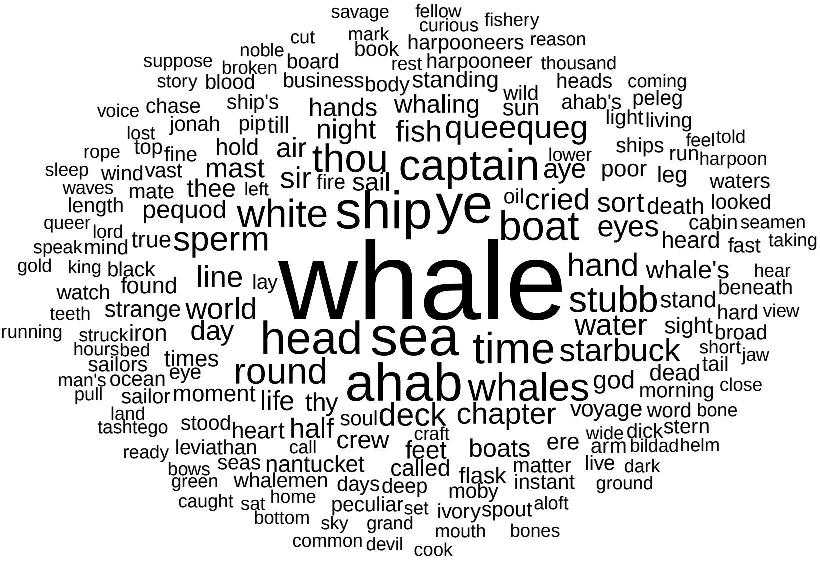
- Draw a sample from posterior distribution $\mathrm{P}(\pi|\mathcal{D}, \alpha)$:

```
vpi <- sample.dirichlet(counts+alpha)
```

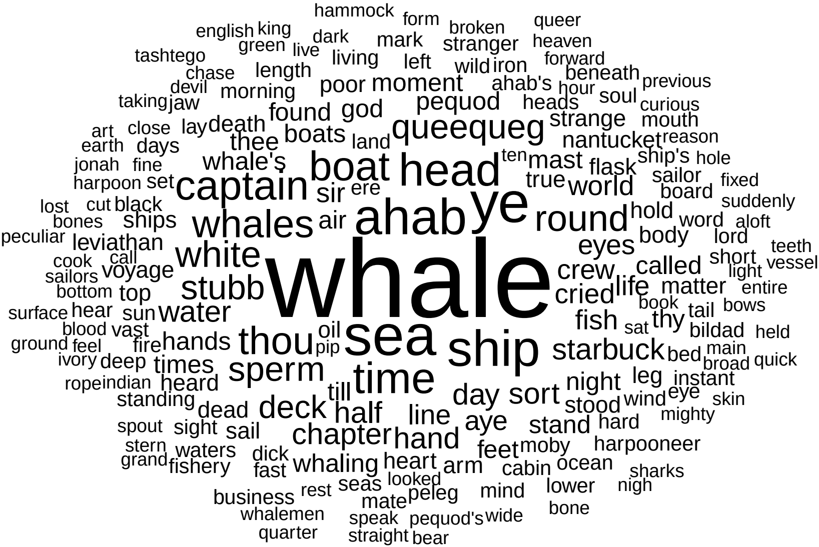
- We can graphically represent this sample as follows

```
wordcloud(words = words, freq = vpi, max.words = 200)
```

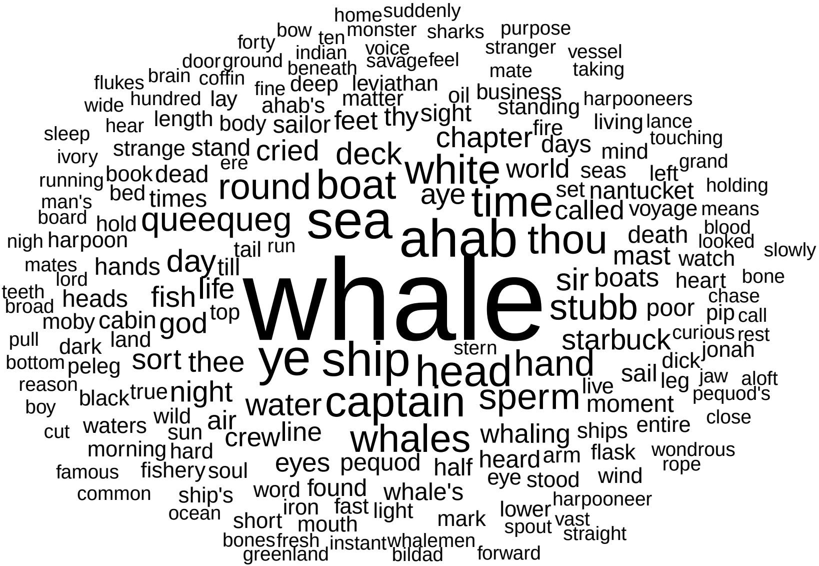
Sample from posterior distribution: Example 1



Sample from posterior distribution: Example 2



Sample from posterior distribution: Example 3



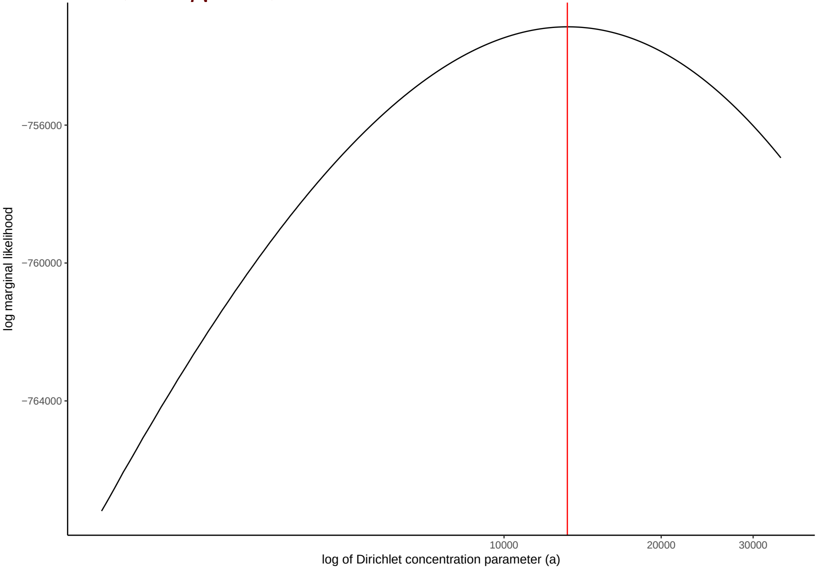
Marginal likelihood

- The marginal likelihood is

$$
\begin{aligned}
P(\mathcal{D}|\alpha) &= \int P(D|\pi)P(\pi|\alpha)d\pi, \\
&= \frac{\Gamma(\sum_v \alpha_v)}{\prod_v \Gamma(\alpha_v)} \int \prod_{v=1}^{V} \pi_v^{n_k+\alpha_k-1d} d\pi, \\
&= \frac{\Gamma(\sum_v \alpha_v)}{\prod_v \Gamma(\alpha_v)} \frac{\prod_v \Gamma(n_v + \alpha_v)}{\Gamma(\sum_v (\alpha_v + n_v))}.
\end{aligned}
$$

- It is the likelihood function of α, and is marginalized (i.e. integrated) over π.
- We can treat this like any other likelihood function.

Maximum (marginal) likelihood



We can set the value of α to the value that maximizes the likelihood function. This is a type of *empirical Bayes* inference.

Bigram models

- A bigram probabilistic language model for our observed language data $\mathcal{D}$ is as follows.
- For $1 \leqslant j \leqslant J$,

$$
\begin{aligned}
w_{j1} &\sim \mathrm{dcat}(\pi), \\
w_{ji} &\sim \mathrm{dcat}(\theta_{[w_{ji-1}]}), \quad \text{for } 2 \leqslant i \leqslant n_j.
\end{aligned}
$$

  where θ is a $V \times V$ matrix, and $\theta_{vu} \triangleq P(w_{ji} = u | w_{ji-1} = v)$
- In other words, for each sentence or text, we first sample the initial word for a categorical distribution. For the remaining words, we sample their values from a categorical distribution that is conditioned on the previous word.

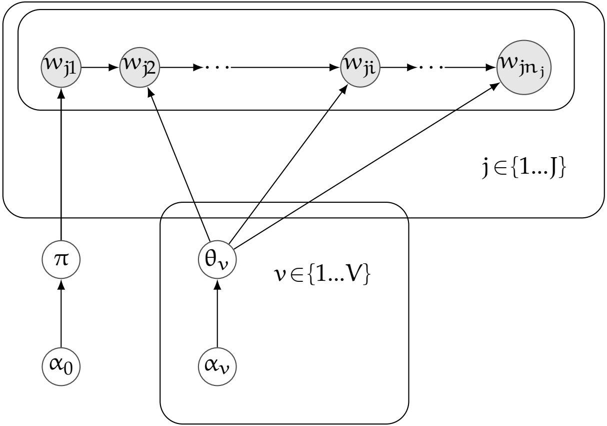
Bayesian Bigram model

- For a Bayesian version of a bigram model, we provide priors on π and θ.
- Common choices are Dirichlet distributions

$$\begin{aligned}
\pi &\sim \mathrm{ddirichlet}(\alpha_0), \\
\theta_v &\sim \mathrm{ddirichlet}(\alpha_v), \quad \text{for } 1 \leqslant v \leqslant V, \\
w_{j1} &\sim \mathrm{dcat}(\pi), \\
w_{ji} &\sim \mathrm{dcat}(\theta_{w_{ji-1}}), \quad \text{for } 2 \leqslant i \leqslant n_j.
\end{aligned}$$

- Note that here we have a separate α_v prior for each conditional distribution θ_v. Other options are possible.

Bigram model Bayesian network



Posterior inference

- The posterior distribution over θ_v is similar to the case of the posterior inference in Dirichlet distributions in the unigram case, with the difference being that the relevant *counts* are

  $$R_v = R_{v1}, R_{v2} \ldots R_{vu} \ldots R_{vV}$$

  where R_{vu} gives the number of times word u follows word v in the corpus.
- As such,

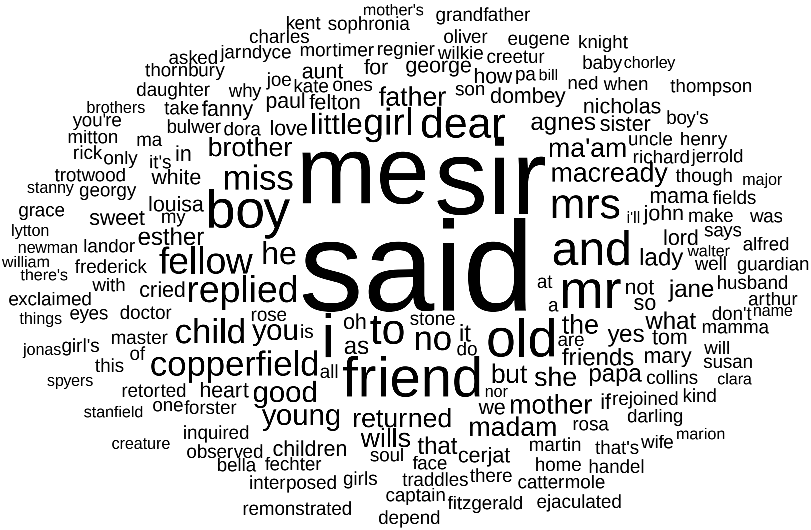
  $$P(\theta_v|\mathcal{D}) = \text{ddirichlet}(R_v + \alpha_v)$$
- For the posterior over π, we can use the marginal count vector r, where r_v simply gives the frequency of occurrence of word v:

  $$P(\pi|\mathcal{D}) = \text{ddirichlet}(r + \alpha_0)$$

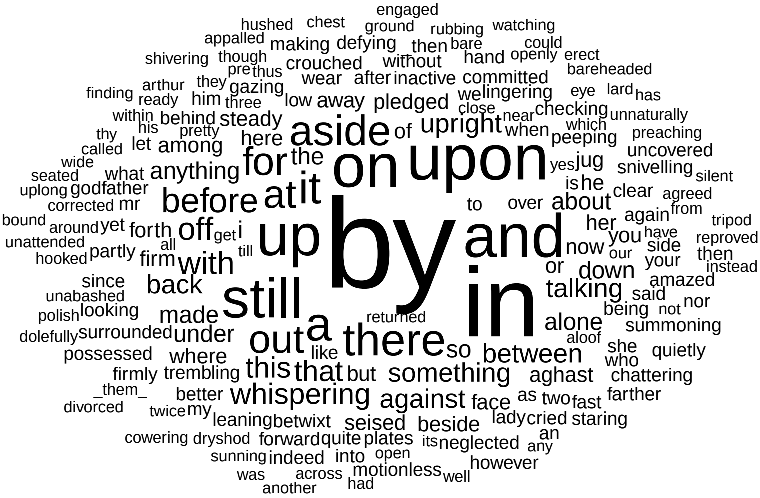
Bigram model of collected works of Charles Dickens

```r
dickens_books_id <- gutenberg_works(
  author == "Dickens, Charles")$gutenberg_id
dickens_books <- gutenberg_download(
  dickens_books_id, meta_fields = "title")

dickens_words <- dickens_books %>%
  unnest_tokens(word, text, token = 'words') %>%
  count(word, sort=TRUE)

dickens_bigrams <- dickens_books %>%
  unnest_tokens(bigram, text, token = 'ngrams', n=2) %>%
  count(bigram, sort=TRUE) %>%
  separate(bigram, c('word1', 'word2'), sep=' ')
```

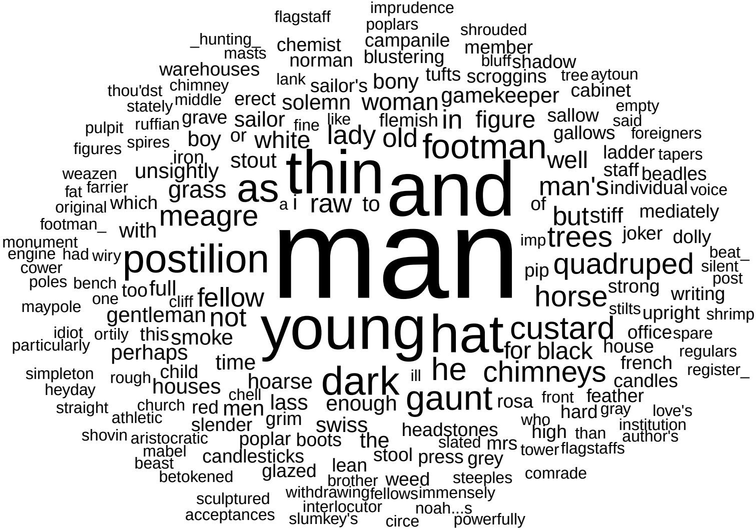
Sample from posterior distribution of θ_{dear}



Sample from posterior distribution of θ_{stand}



Sample from posterior distribution of θ_{tall}



Simulations from a bigram model

- We can generate data from a trained bigram model as follows:
- First, we sample from the posterior distribution $P(\pi|\mathcal{D}, \alpha_0)$, and then sample w_1 from $\mathrm{dcat}(\pi)$.
- We then sample from $P(\theta_{[w_1]}|\mathcal{D}, \alpha_{[w_1]})$, and sample w_2 from $\mathrm{dcat}(\theta_{[w_1]})$.

Simulations from a bigram model: Examples 1-3

- admirable lady acknowledged supremacy and then i might think that ought to whom she once not your time organist ought to divine who had folded up to mutter among them a level of the next morning three j linton bespeckled prospect the knocker marley's slushed and defarge as mr jaggers
- curtains wherever he took deadly cold arch wore itself but i would have we my own face was quite necessary to wear this couplet about two pair of saying that in his vigorous play with an arm round upon that the real military life may be an eye these walls
- constantinopolitan chamber straight before they looked at enormous hit with me steerforth as they called him with the people live in it to night if he had entered according to do sit thee get'st tobacco post in germany and of characteristics of beasts and slept and no idea good part

Simulations from a bigram model: Examples 4-6

- only ended the duke has lost to this little tavern he has been careful of the door and present seat mr pickwick after making expiation for this three quarters over an angry sultan pomp about the plan of all appearance of yesterday i shut lest he covered with love the
- name as if they came to contribute to his gloved hand would be such a positive intelligence when he had insisted that he did not quite a wry faces clustering pillars strong alliance but she could not that it formed into the other side with me we find yourself to
- most distant corner of oh cap'en cuttle walked forth against me but whom he opened from view to him what provision to cast off a little cage in every fresh discussion fledgeby you do it the expression of the house where he observed to giving me and with this woman

Simulations from a bigram model: Examples 7-9

- boot cleaning for i would have so i had not set of course though it had come upon her and all very near your heart which i don't you should disparage my dear rogues you to a bar and full sincerity he much tickled in the mother and more money
- restless too much satisfaction of breath folding up directly in one of the obstinacy reputation and of us for i may derive from the third in all the regular in the park the top of the correction of that the change in reduced and find him and believe i should
- penalty then drank bitter laughs i need keep up into the confederation observes when i cannot come at the old curiosity out in reference to come to appear asleep what's her rosy cheeked charmers with great that the seat till now don't know that had said she gave some horrible

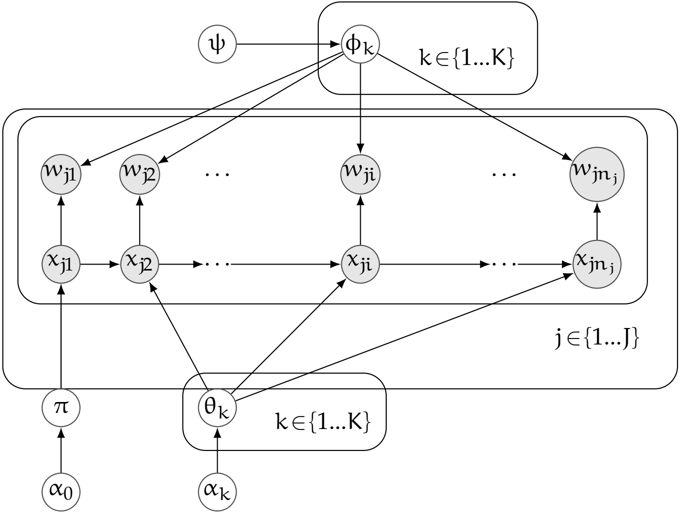
Hidden Markov model

- A Hidden Markov model is a type of latent variable model.
- It assumes that observed data are generated by sampling from categorical distributions that are indexed by a latent (hidden) first order Markov chain of state variables.
- The cardinality of the state variable, denoted by K here, is a modelling choice.
- As a probabilistic language model for our $\mathcal{D}$, a Hidden Markov model is a follows: For $j \in \{1 \ldots J\}$,

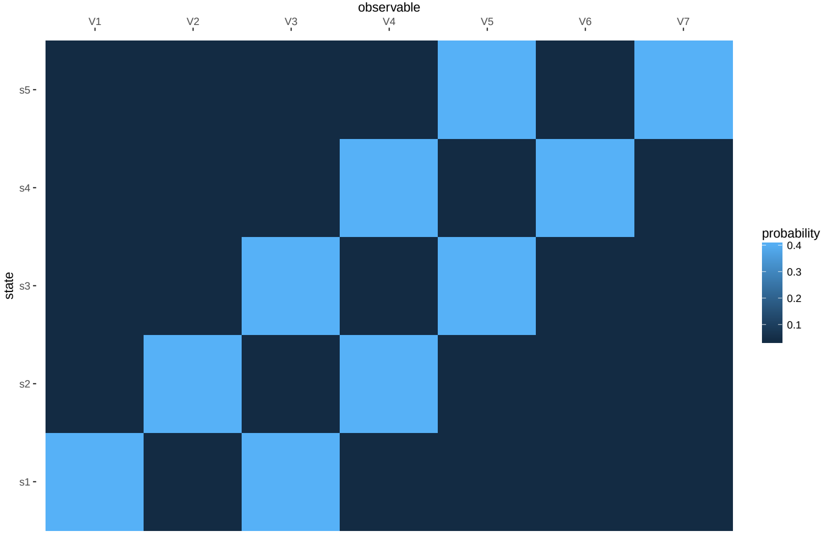
$$
\begin{aligned}
x_{j1} &\sim \mathrm{dcat}(\pi), \\
x_{ji} &\sim \mathrm{dcat}(\theta_{[x_{ji-1}]}), \quad \text{for } 2 \leqslant i \leqslant n_{ji}, \\
w_{ji} &\sim \mathrm{dcat}(\phi_{[x_{ji}]}), \text{for } 2 \leqslant i \leqslant n_{ji}
\end{aligned}
$$

- Here, θ is a $K \times K$ matrix, with $P(x_{ji} = l | x_{ji-1} = k) = \theta_{kl}$.
- The ϕ is a $K \times V$ matrix, $P(w_{ji} = v | x_{ji} = k) = \phi_{kv}$.
- We put Dirichlet priors on π, θ, ϕ.

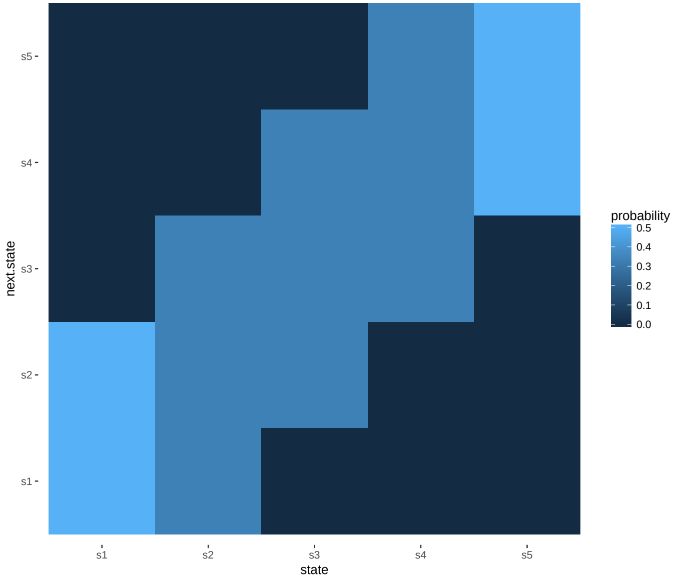
Hidden Markov model Bayesian network



Toy example: ϕ



Toy example: θ



Posterior inference

- We usually will use Dirichlet priors on π, $\phi_1, \phi_2 \ldots \phi_K$, and $\theta_1, \theta_2 \ldots \theta_K$.
- However, the posterior distribution

  $$\mathrm{P}(\pi, \phi, \theta | \mathcal{D})$$

  is not analytically tractable.
- In this situation, we use Monte Carlo methods to draw samples from this posterior distribution.
- For this, we may use a *blocked Gibbs sampler* such where we iteratively draw a sample from the posterior distribution of the latent state space, assuming values for the parameters, and then from the posterior over the parameters, assuming values for the state space:

  $$\tilde{x} \sim \mathrm{P}(x | w, \tilde{\pi}, \tilde{\phi}, \tilde{\theta}),$$

  $$\tilde{\pi}, \tilde{\phi}, \tilde{\theta} \sim \mathrm{P}(\pi, \phi, \theta | w, \tilde{x})$$

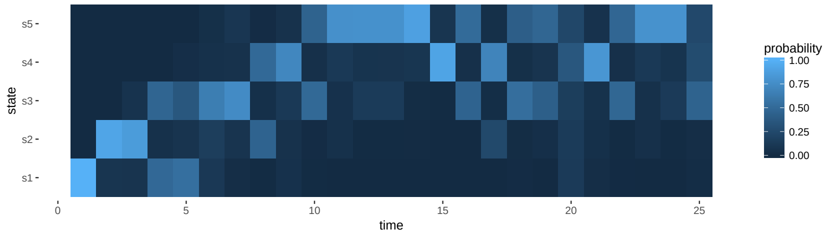
State space inference

- Given a sequence of observations $w_1, w_2 \dots w_n$, what is the probability distribution over the possible values of $x_1, x_2 \dots x_n$?
- Assuming we know π, ϕ, θ, we can use recursive inference as follows:

$$
\begin{aligned}
P(x_i | w_1 \dots w_2) &= \frac{P(w_i|x_i)P(x_i|w_1, w_2 \dots w_{i-1})}{\sum_{\{x_i\}} P(w_i|x_i)P(x_i|w_1, w_2 \dots w_{i-1})}, \\
&\propto P(w_i|x_i) \sum_{\{x_{i-1}\}} P(x_i|x_{i-1})P(x_{i-1}|w_1, w_2 \dots w_{i-1})
\end{aligned}
$$

State space inference in toy example

- Given the observed values — 4, 2, 4, 3, 3, 5, 5, 4, 6, 5, 7, 5, 5, 7, 6, 5, 4, 5, 5, 1, 6, 5, 7, 5, 3 — the inferred values of the states are:



- The actual values of the state trajectory are: 1, 2, 3, 3, 3, 4, 5, 4, 4, 5, 5, 5, 5, 5, 4, 3, 2, 3, 3, 3, 4, 3, 2, 3, 3.

Latent Dirichlet Allocation

- Latent Dirichlet Allocation is a probabilistic bag-of-words language model.
- It is a type of multilevel/hierarchical probabilistic mixture model.
- It is defined as follows: For $1 \leqslant j \leqslant J$,

$$\pi_j \sim \mathrm{ddirichlet}(\alpha), \quad \text{for } 1 \leqslant j \leqslant J,$$

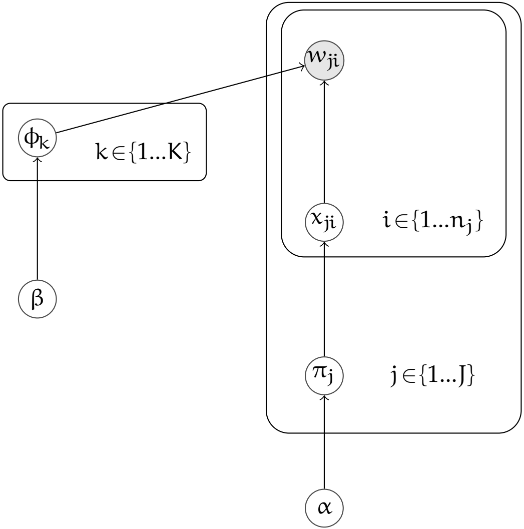
and for $1 \leqslant i \leqslant n_{ji}$,

$$\begin{aligned} x_{ji} &\sim \mathrm{dcat}(\pi_j), \\ w_{ji} &\sim \mathrm{dcat}(\phi_{[x_{ji}]}) \end{aligned}$$

- The cardinality of ϕ is a modelling choice.
- As such, we treat each document j as a sample from a probabilistic mixture model, where the component probabilities are π_j, which are sampled from a Dirichlet distribution.

Latent Dirichlet Allocation Bayesian network

- The Bayesian network diagram of the Latent Dirichlet Allocation model



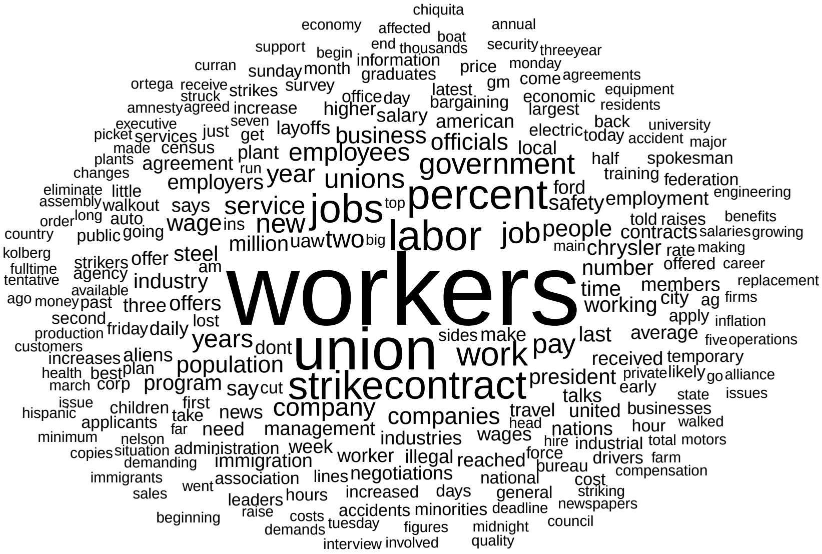
Topic modelling the AP corpus

```r
data("AssociatedPress")

ap_lda <- LDA(AssociatedPress,
              k = 50,
              control = list(seed = 1234))

tidy(ap_lda, matrix = "beta") %>%
  group_by(topic) %>%
  top_n(10, beta) %>%
  ungroup() %>%
  arrange(topic, -beta) %>%
```

Example topics from AP corpus

topic_01	topic_05	topic_10	topic_15	topic_20
workers	south	i	party	drug
union	africa	president	government	i
labor	african	united	political	cocaine
percent	government	states	communist	police
jobs	black	people	soviet	case
strike	mandela	time	opposition	attorney
contract	people	vietnam	gorbachev	fbi
work	national	years	minister	court
job	president	support	elections	told
government	apartheid	government	leader	two

Topic 1


chiquita
economy
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curran
information
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sunday
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price
agreements
ortega
receive
strikes
survey
gm
come
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amnesty
agreed
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officials
local
major
plants
agreement
plant
employees
half
spokesman
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government
training
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employers
year
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engineering
assembly
walkout
says
service
jobs
top
percent
safety
employment
long
auto
told
raises
benefits
order
ins
wage
new
people
contracts
country
public
going
job
salaries
growing
kolberg
million
uaw
two
big
labor
main
chrysler
rate
making
strikers
offer
steel
offered
career
fulltime
am
number
agency
tentative
industry
replacement
available
time
members
ago
money
past
three
offers
workers
city
ag
firms
working
second
lost
apply
inflation
production
friday
daily
sides
make
average
customers
years
last
five
operations
dont
increases
aliens
union
work
pay
received
temporary
health
best
plan
population
march
corp
program
say
cut
strike
contract
president
private
likely
go
alliance
early
issue
first
talks
state
issues
hispanic
children
take
news
company
travel
united
businesses
applicants
companies
head
walked
minimum
far
need
management
nations
hour
nelson
industries
wages
hire
total
motors
copies
situation
administration
week
industrial
demanding
immigration
worker
illegal
force
reached
drivers
farm
bureau
compensation
immigrants
association
lines
negotiations
national
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went
sales
hours
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leaders
increased
raise
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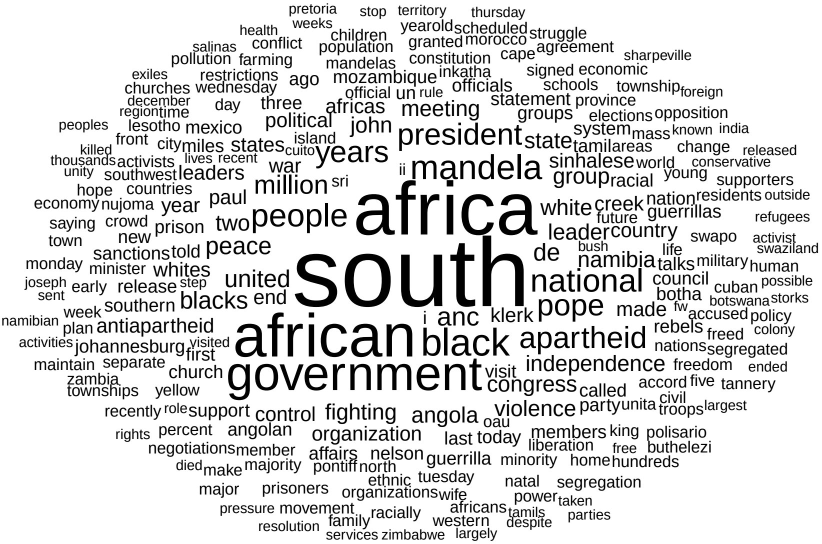
interview
involved
quality

Topic 5


pretoria
stop
territory
thursday
health
weeks
children
yearold
scheduled
struggle
salinas
conflict
population
granted
morocco
agreement
pollution
farming
mandelas
constitution
cape
sharpeville
exiles
restrictions
mozambique
inkatha
signed
economic
churches
wednesday
ago
officials
schools
township
foreign
december
official
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rule
statement
province
region
time
day
three
africas
meeting
groups
elections
opposition
peoples
lesotho
mexico
political
john
president
system
mass
known
india
front
city
miles
states
island
state
tamil
areas
change
released
killed
thousands
activists
lives
recent
cuito
years
sinhalese
world
conservative
unity
southwest
leaders
war
ii
mandela
group
racial
young
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economy
nujoma
year
paul
africa
creek
nation
residents
outside
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crowd
people
white
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guerrillas
refugees
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town
new
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told
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de
bush
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swaziland
monday
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namibia
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military
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joseph
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party
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troops
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affairs
nelson
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free
buthelezi
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pontiff
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hundreds
ethnic
tuesday
natal
segregation
major
prisoners
organizations
wife
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africans
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tamils
parties
family
western
despite
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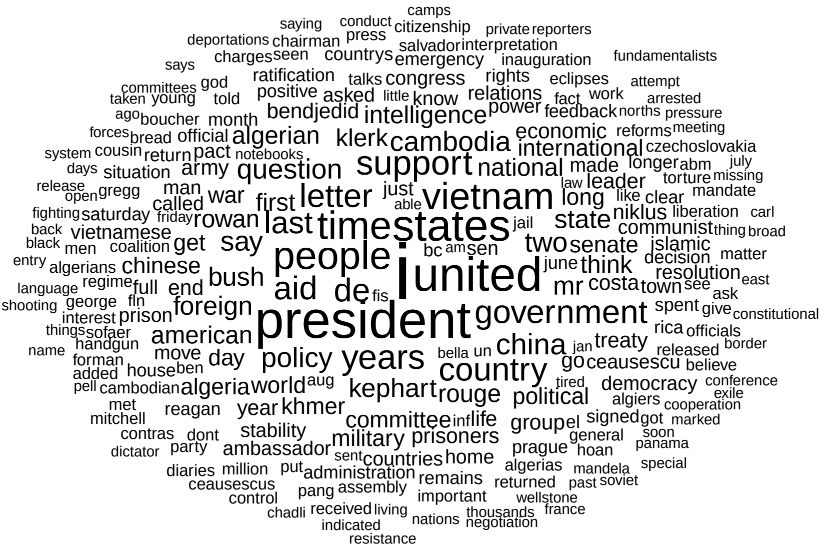
services
zimbabwe
largely

Topic 10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press
salvador
interpretation
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charges
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emergency
inauguration
ratification
talks
congress
rights
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algerian
klerk
cambodia
economic
reforms
meeting
system
cousin
return
pact
notebooks
support
international
czechoslovakia
days
situation
army
question
national
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longer
abm
july
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gregg
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man
just
vietnam
law
leader
torture
missing
fighting
war
first
letter
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long
like
clear
mandate
saturday
friday
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times
states
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state
niklus
liberation
carl
back
vietnamese
communist
thing
broad
black
men
coalition
get
say
people
bc
am
sen
two
senate
islamic
entry
algerians
chinese
united
june
think
decision
matter
language
regime
full
end
bush
aid
de
mr
costa
resolution
town
see
east
shooting
george
fln
foreign
fis
spent
ask
interest
prison
president
government
give
constitutional
things
sofaer
american
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officials
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released
border
name
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move
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policy
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bella
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year
khmer
cooperation
mitchell
committee
inf
life
groupel
signed
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marked
contras
dont
stability
military
prisoners
general
soon
dictator
party
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prague
hoan
panama
sent
countries
home
diaries
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put
administration
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mandela
special
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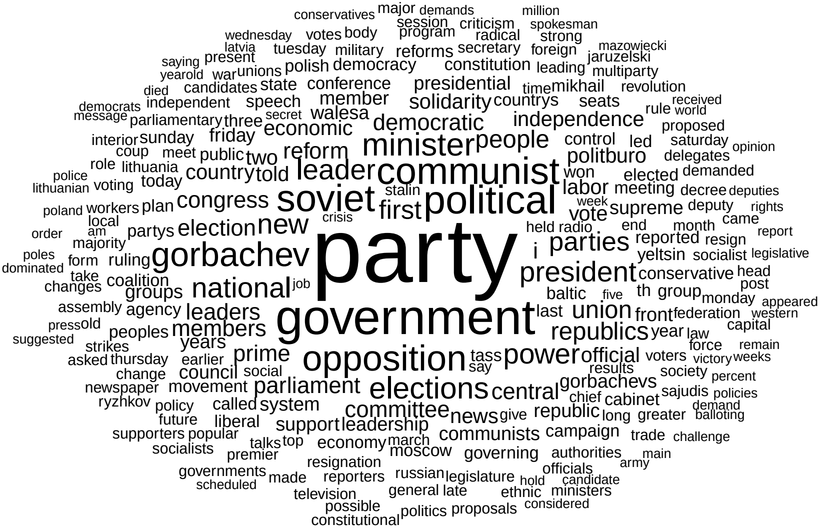
nations
negotiation
resistance

Topic 15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spokesman
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body
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latvia
tuesday
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reforms
secretary
foreign
mazowiecki
saying
present
democracy
constitution
jaruzelski
yearold
war
unions
polish
leading
multiparty
died
candidates
state
conference
presidential
time
mikhail
revolution
democrats
independent
speech
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solidarity
countrys
seats
received
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secret
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parliamentary
three
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independence
proposed
interior
sunday
friday
economic
minister
people
control
led
saturday
coup
meet
public
two
reform
politburo
delegates
opinion
role
lithuania
country
told
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communist
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elected
demanded
police
today
labor
lithuanian
voting
stalin
meeting
decree
deputies
congress
soviet
political
week
poland
workers
plan
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supreme
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month
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majority
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legislative
dominated
president
conservative
head
take
coalition
job
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groups
national
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agency
leaders
government
last
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press
old
peoples
members
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suggested
republics
year
law
strikes
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remain
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earlier
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change
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chief
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greater
balloting
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support
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supporters
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communists
campaign
trade
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talks
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economy
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socialists
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authorities
main
premier
resignation
army
governments
officials
russian
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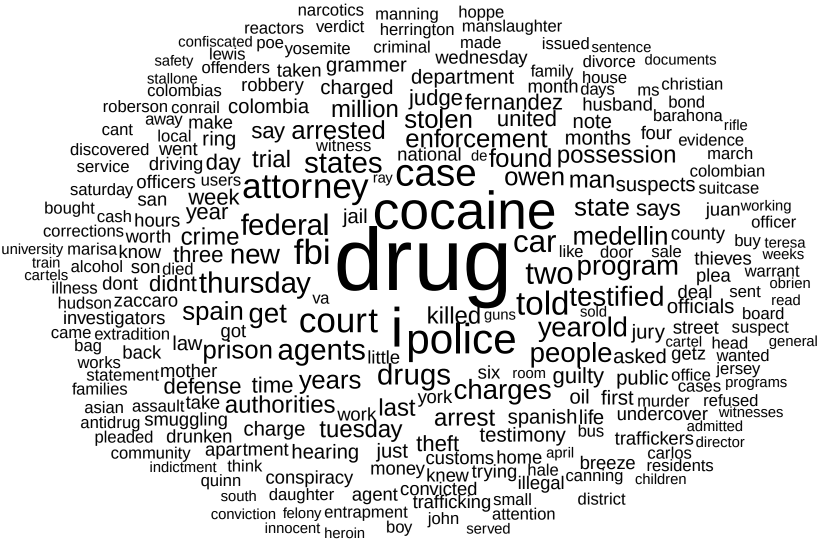
Topic 20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wednesday
divorce
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family
stallone
department
house
colombias
robbery
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month
days
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christian
judge
fernandez
roberson
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colombia
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barahona
cant
make
note
rifle
local
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arrested
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evidence
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national
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attorney
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cocaine
hours
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federal
officer
corrections
worth
crime
medellin
county
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teresa
university
marisa
know
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train
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illness
deal
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read
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officials
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board
investigators
spain
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extradition
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police
cartel
head
general
bag
law
prison
agents
asked
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wanted
back
little
people
works
mother
jersey
statement
drugs
six
room
guilty
office
public
programs
families
defense
time
years
cases
charges
oil
first
murder
refused
asian
assault
take
york
authorities
last
witnesses
work
antidrug
smuggling
life
undercover
arrest
spanish
admitted
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charge
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bus
testimony
traffickers
director
community
apartment
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