CPSC 540: Machine Learning

Markov Chains

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Last Time: Beyond Parametric/Discrete Mixture Models

- We discussed kernel density estimation (mixture centered on each $x^i$),
  \[ p(x^i) = \frac{1}{n} \sum_{j=1}^{n} k_A(x^i - x^j). \]

- We discussed probabilistic PCA,
  \[ p(x^i) = \int_{z^i} p(z^i)p(x^i | z^i)dz^i, \]
  where $z^i \sim \mathcal{N}(0, I)$ and $x^i | z^i \sim \mathcal{N}(W^T z^i, \sigma^2 I)$ (a Gaussian with restricted $\Sigma$).
A related method for discovering latent factors is **factor analysis** (FA).

- A standard tool and widely-used across science and engineering.

<table>
<thead>
<tr>
<th>Trait</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Openness</td>
<td>Being curious, original, intellectual, creative, and open to new ideas.</td>
</tr>
<tr>
<td>Conscientiousness</td>
<td>Being organized, systematic, punctual, achievement-oriented, and dependable.</td>
</tr>
<tr>
<td>Extraversion</td>
<td>Being outgoing, talkative, sociable, and enjoying social situations.</td>
</tr>
<tr>
<td>Agreeableness</td>
<td>Being affable, tolerant, sensitive, trusting, kind, and warm.</td>
</tr>
<tr>
<td>Neuroticism</td>
<td>Being anxious, irritable, temperamental, and moody.</td>
</tr>
</tbody>
</table>

Historical applications are measures of intelligence and personality traits.

- Some controversy, like trying to find factors of intelligence due to race.
  (without normalizing for socioeconomic factors)
Factor Analysis

- FA approximates (centered) $x^i$ by

$$x^i \approx W^T z^i,$$

and assumes $z^i$ and $x^i \mid z^i$ are Gaussian.

- Which should sound familiar...

- Are PCA and FA the same?
  - Both are more than 100 years old.
  - There are many online discussions about whether they are the same.
    - Some software packages run PCA when you call their FA method.
    - Some online discussions claiming they are completely different.
PCA vs. Factor Analysis

- In probabilistic PCA we assume
  \[ x^i \mid z^i \sim \mathcal{N}(W^T z^i, \sigma^2 I), \quad z^i \sim \mathcal{N}(0, I), \]
  and we obtain PCA as \( \sigma \rightarrow 0 \).

- In FA we assume
  \[ x^i \mid z^i \sim \mathcal{N}(W^T z^i, D), \quad z^i \sim \mathcal{N}(0, I), \]
  where \( D \) is a diagonal matrix.

- The difference is that you can have a noise variance for each dimension.
  - So FA has extra degrees of freedom in variance of original variables.
  - In practice there often isn’t a huge difference.
Motivation for Independent Component Analysis (ICA)

- Factor analysis has found an enormous number of applications.
  - People really want to find the “factors” that make up their data.

- But even in ideal settings factor analysis can’t uniquely identify the true factors.
  - We can rotate $W$ and obtain the same model.

- Independent component analysis (ICA) is a more recent approach.
  - Around 30 years old instead of > 100.
  - Under certain assumptions, it can identify factors.

- The canonical application of ICA is blind source separation.
Blind Source Separation

- **Input to blind source separation:**
  - Multiple microphones recording multiple sources.

- Each microphone gets different mixture of the sources.
  - Goal is to reconstruct sources (factors) from the measurements.

http://music.eecs.northwestern.edu/research.php
Independent Component Analysis Applications

- In some cases, ICA can identify true factors.
  - It's replacing PCA/FA in many applications.

- Key idea: if the $z^i$ are independent and non-Gaussian, we can identify them.
  - Optimize a measure of non-Gaussianity (maximize kurtosis, minimize entropy).

- It’s the only algorithm we didn’t cover in 340 from the list of “The 10 Algorithms Machine Learning Engineers Need to Know”.

- I put last year’s material on probabilistic PCA, factor analysis, and ICA here:
  - https://www.cs.ubc.ca/~schmidtm/Courses/540-W18/L18.5.pdf
We defined the problem of density estimation
- Computing probability of new examples $\tilde{x}^i$.

We discussed basic distributions for 1D-case:
- Bernoulli, categorical, Gaussian.

We discussed product of independent distributions:
- Just model each feature individually.

We discussed multivariate Gaussian:
- Joint Gaussian model of multiple variables.
End of Part 2: Basic Density Estimation and Mixture Models

- We discussed mixture models:
  - Write density as a convex combination of densities.
  - Examples include mixture of Gaussians and mixture of Bernoullis.
  - Can model multi-modal densities.

- Commonly-fit using expectation maximization.
  - Generic method for dealing with missing at random data.
  - Can be viewed as a “minimize upper bound” method.

- Kernel density estimation is a non-parametric mixture model.
  - Place on mixture component on each data point.
  - Nice for visualizing low-dimensional densities.

- Probabilistic PCA and factor analysis are continuous Gaussian mixture models.
  - ICA is a non-Gaussian variant that identifies true factors under certain conditions.
Outline

1. Mixture Model Wrap-Up
2. Markov Chains
Example: Vancouver Rain Data

- Consider density estimation on the “Vancouver Rain” dataset:

<table>
<thead>
<tr>
<th>Month</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
<th>Day 5</th>
<th>Day 6</th>
<th>Day 7</th>
<th>Day 8</th>
<th>Day 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Month 2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Month 3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Month 4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Month 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Month 6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

- Variable $x_j^i = 1$ if it rained on day $j$ in month $i$.
  - Each row is a month, each column is a day of the month.
  - Data ranges from 1896-2004.

- The strongest signal in the data is the simple relationship:
  - If it rained yesterday, it’s likely to rain today ($> 50\%$ chance of $(x_j^i = x_{j-1}^i)$).
Example: Vancouver Rain Data

- With independent Bernoullis, we get \( p(x_j^i = \text{“rain”}) \approx 0.41 \) (sadly).
- Real data vs. product of Bernoullis model (red means “rain”):

- Making days independent misses correlations.
A better density model for this data is a Markov chain.

- Models $p(x_j^i \mid x_{j-1}^i)$: probability of rain today given yesterday’s value.
- Captures dependency between adjacent days.

Mixture of Bernoullis can also model correlations, but it’s inefficient:

- Doesn’t account for “position independence” of correlation.
- Need clusters that correlate day 1 and 2, that correlate day 2 and 3, and so on.
Markov Chain Ingredients

- **Markov chain ingredients:**
  - **State space:**
    - Set of **possible states** (indexed by $c$) we can be in at time $j$ (“rain” or “not rain”).
  - **Initial probabilities:**
    - $p(x_1 = c)$: probability that we **start in state $c$** at time $j = 1$ (p(“rain”) on day 1).
  - **Transition probabilities:**
    - $p(x_j = c \mid x_{j-1} = c')$: probability that we **move from state $c'$ to state $c$** at time $j$.
    - Probability that it rains today, given what happened yesterday.

- **Notation alert:** I’m going to start using “$x_j$” as short for “$x^i_j$” for a generic $i$.

- We’re assuming a **meaningful ordering of features.**
  - We’re modeling dependency of each feature on the previous feature.
By using the **product rule**, \( p(a, b) = p(a)p(b \mid a) \), we can write any density as

\[
p(x_1, x_2, \ldots, x_d) = p(x_1)p(x_2, x_3, \ldots, x_d \mid x_1) \\
= p(x_1)p(x_2 \mid x_1)p(x_3, x_4, \ldots, x_d \mid x_1, x_2) \\
= p(x_1)p(x_2 \mid x_1)p(x_3 \mid x_2, x_1)p(x_4, x_5, \ldots, x_d \mid x_1, x_2, x_3),
\]

and so on until we get

\[
p(x_1, x_2, \ldots, x_d) = p(x_1)p(x_2 \mid x_1)p(x_3 \mid x_2, x_1) \cdots p(x_d \mid x_{d-1}, x_{d-2}, \ldots, x_1).
\]

This factorization of a density is called the **chain rule** of probability.

But it leads to **complicated conditionals**:

- **For binary** \( x_j \), **we need** \( 2^d \) **parameters** for \( p(x_d \mid x_1, x_2, \ldots, x_{d-1}) \) alone.
Markov Chains

- Markov chains simplify the distribution by assuming the **Markov property**:

\[ p(x_j \mid x_{j-1}, x_{j-2}, \ldots, x_1) = p(x_j \mid x_{j-1}), \]

that \( x_j \) is independent of the past given \( x_{j-1} \).

- To predict “rain”, the only relevant past information is whether it rained yesterday.

- The probability for a sequence \( x_1, x_2, \ldots, x_d \) in a Markov chain simplifies to

\[
p(x_1, x_2, \ldots, x_d) = p(x_1)p(x_2 \mid x_1)p(x_3 \mid x_2, x_1) \cdots p(x_d \mid x_{d-1}, x_{d-2}, \ldots, x_1)
\]

\[ = p(x_1)p(x_2 \mid x_1)p(x_3 \mid x_2) \cdots p(x_d \mid x_{d-1}) \]

- Another way to write the joint probability is

\[
p(x_1, x_2, \ldots, x_d) = p(x_1) \prod_{j=2}^{d} p(x_j \mid x_{j-1}).
\]

\text{initial prob.} \quad \text{transition prob.}
Markov Chains

- Markov chains are ubiquitous in sequence/time-series models:

  9 Applications
  9.1 Physics
  9.2 Chemistry
  9.3 Testing
  9.4 Speech Recognition
  9.5 Information sciences
  9.6 Queueing theory
  9.7 Internet applications
  9.8 Statistics
  9.9 Economics and finance
  9.10 Social sciences
  9.11 Mathematical biology
  9.12 Genetics
  9.13 Games
  9.14 Music
  9.15 Baseball
  9.16 Markov text generators
Homogenous Markov Chains

- For rain data it makes sense to use a **homogeneous Markov chain**: Transition probabilities $p(x_j \mid x_{j-1})$ are the same for all $j$.

- With discrete states, we could parameterize transition probabilities by

  $$p(x_j = c \mid x_{j-1} = c') = \theta_{c,c'}$$

  where $\theta_{c,c'} \geq 0$ and $\sum_{c=1}^{k} \theta_{c,c'} = 1$ (and we use the same $\theta_{c,c'}$ for all $j$).

  - So we have a categorical distribution over $c$ values for each $c'$ value.

- **MLE for homogeneous** Markov chain with discrete $x_j$ is:

  $$\theta_{c,c'} = \frac{\text{(number of transitions from } c' \text{ to } c)}{\text{(number of times we went from } c' \text{ to anything)}}.$$
Parameter Tieing

- Using same parameters $\theta_{c,c'}$ for different $j$ is called parameter tieing.
  - "Making different parts of the model use the same parameters."

**Key advantages to parameter tieing:**

1. You have more data available to estimate each parameter.
   - Don’t need to independently learn $p(x_j \mid x_{j-1})$ for days 3 and 24.
2. You can have models of different sizes.
   - Same model can be used for any number of days.
   - We could even treat the data as one long Markov chain ($n = 1$).

**We’ve seen parameter tieing before:**

- In 340 we discussed convolutaional neural networks, which repeat filters.
- Throughout 340/540, we’ve assumed tied parameters across training examples.
  - That you use the same parameter for $x^i$ and $x^j$. 
We’ve previously considered density estimation for MNIST images of digits. We saw that independent Bernoullis do terrible
Density Estimation for MNIST Digits

- We can do a bit better with mixture of 10 Bernoullis:

- The shape is looking better, but it’s missing correlation between adjacent pixels.
  - Could we capture this with a Markov chain?
Density Estimation for MNIST Digits

- Samples from a **homogeneous Markov chain** (putting rows into one long vector):

  ![Images of homogeneous Markov chain samples]

  - Captures correlations between adjacent pixels in the same row.
  - But misses **long-range dependencies in row and dependencies between rows**.
  - Also, “position independence” of homogeneity means it **loses position information**.
Inhomogeneous Markov Chains

- **Markov chains** could allow a different $p(x_j \mid x_{j-1})$ for each $j$.

- For discrete $x_j$ we could use

  $$p(x_j = c \mid x_{j-1} = c') = \theta_{c,c'}^j.$$  

- MLE for discrete $x_j$ values is given by

  $$\theta_{c,c'}^j = \frac{(\text{number of transitions from } c' \text{ to } c \text{ starting at } (j-1))}{(\text{number of times we saw } c' \text{ at position } (j-1))},$$

- Such inhomogeneous Markov chains include independent models as special case:
  - We could set $p(x_j \mid x_{j-1}) = p(x_j)$. 

Density Estimation for MNIST Digits

- Samples from an inhomogeneous Markov chain:

![Sample Images]

- We have correlations between adjacent pixels in rows and position information.
  - But isn't capturing long-range dependencies or dependency between rows.
  - Later we'll discuss graphical models which address this.
  - You could alternately consider a mixture of Markov chains.
Computation with Markov Chains

- **Common things we do with Markov chains:**
  1. **Sampling:** generate sequences that follow the probability.
  2. **Inference:** compute probability of being in state $c$ at time $j$.
  3. **Decoding:** compute most likely sequence of states.
    - Decoding and inference will be important when we return to supervised learning.
  4. **Conditioning:** do any of the above, assuming $x_j = c$ for some $j$ and $c$.
    - For example, “filling in” missing parts of the image.
  5. **Stationary distribution:** probability of being in state $c$ as $j$ goes to $\infty$.
    - Usually for homogeneous Markov chains.
Fun with Markov Chains

- Snakes and Ladders: http://datagenetics.com/blog/november12011/index.html
- Candyland: http://www.datagenetics.com/blog/december12011/index.html
- Yahtzee: http://www.datagenetics.com/blog/january42012/
- Chess pieces returning home and K-pop vs. ska: https://www.youtube.com/watch?v=63HHmjhlh794
Summary

- **Factor analysis** extends probabilistic PCA with different noise in each dimension.
  - Very similar but not identical to PCA.
  - **Independent component analysis**: allows identifying non-Gaussian latent factors.

- **Markov chains** model dependencies between adjacent features.

- **Parameter tying** uses same parameters in different parts of a model.
  - Example of “homogeneous” Markov chain.
  - Allows models of different sizes and more data per parameter.

- **Markov chain tasks**:
  - Sampling, inference, decoding, conditioning, stationary distributions.

- Next time: reading week.
Another weird mixture model is a **scale mixture of Gaussians**, 

\[ p(x^i) = \int_{\sigma^2} p(\sigma^2) \mathcal{N}(x^i | \mu, \sigma^2) d\sigma^2. \]

- Common choice for \( p(\sigma^2) \) is a gamma distribution (which makes integral work):
  - Many distributions are special cases, like Laplace and student \( t \).

- Leads to **EM algorithms for fitting Laplace and student \( t \)**.