This lecture

• An extractive summary of the course.
Exam

• 24 April from 9h00—12h00.

<table>
<thead>
<tr>
<th>A-Mah</th>
<th>Mai-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR 25</td>
<td>ST VLAD</td>
</tr>
<tr>
<td>New College III, 45 Willcocks St.</td>
<td>Auditorium B, St. Vladimir Institute, 620 Spadina Avenue (Students should enter via the south doors.)</td>
</tr>
</tbody>
</table>

• **No aids allowed** – your desk should have nothing but:
  • Your UofT ID,
  • The exam, and
  • A writing implement.
Structure

• Following the format of previous years:
  • 20 **multiple-choice** questions [40 marks]
    • 4 options each.
  • 10 **short-answer** questions [30 marks]
    • Some of these involve simply giving a definition. Others involve some calculation.
  • 3 **subject-specific** questions [30 marks]
    • These questions involve a small component of original thinking.
Hints for studying

• **Definitions**: *n.pl.* Terms that are useful to know.

• **Highlights are also useful to know.**

• Not all definitions/highlights are in the exam.
• Not all things on the exam have been highlighted.
  • This review lecture is likewise not a substitute for the rest of the material in this course.
Hints for studying

• Go through the exams on the website from previous years (and focus on those items related to topics we covered this year).

• Go through the quiz from this year.

• Work out worked-out examples for yourself, ideally more than once.

• I find it helpful to just relax before an exam.
Exam material

• The exam covers all material in the lectures and assignments **except**:
  • Material in the bonuses of assignments, and
  • Slides with ‘Aside’ in the title.

• The reading material (e.g., Manning & Schütze) provides background to concepts discussed in class.
  • If a concept appears in the textbook but not in the lectures/assignments, you don’t need to know it, even if it’s **very interesting**.
2014 Final exam distribution
Course outline (approximate)

• Introduction and linguistic data (2 lectures)
• \(N\)-gram models and features of data (2 lectures) *
• Entropy and information theory (2 lectures) *
• Hidden Markov models (3 lectures) *
• Statistical machine translation (3 lectures) **
• Articulatory and acoustic phonetics (2 lectures) *
• Automatic speech recognition (2 lectures) **
• Speech synthesis (1 lecture) **
• Information retrieval (2 lectures) **
• Text summarization (1 lecture) **
• Other classifiers and review (2 lectures)

* techniques  ** applications
Categories of linguistic knowledge

- **Phonology**: the study of patterns of speech sounds.
  - e.g., “read” → /r iy d/

- **Morphology**: how words can be changed by inflection or derivation.
  - e.g., “read”, “reads”, “reader”, “reading”, ...

- **Syntax**: the ordering and structure between words and phrases.
  - e.g., *NounPhrase* → *det. adj. n.*

- **Semantics**: the study of how meaning is created by words and phrases.
  - e.g., “book” →

- **Pragmatics**: the study of meaning in broad contexts.
NLC as Artificial Intelligence

• NLC involves resolving ambiguity at all levels.
  • Reasoning with world knowledge.
    • In the early days knowledge was explicitly encoded in artificial symbolic systems (e.g., context-free grammars) by experts.

• Now, algorithms learn using probabilities to distinguish subtly different competing hypotheses.
  • E.g., is Google a noun or a verb?
  • An example where Google ∈ Nouns ("Google makes Android"), does not mean that Google is never a verb ("Go Google yourself").

• $P(\text{Google} \in \text{Nouns}) > P(\text{Google} \in \text{Verbs}) > 0$
Corpora

• **Corpus**: *n.* A body of language data of a particular sort (*pl.* corpora).

• Most **valuable** corpora occur naturally
  • e.g., newspaper articles, telephone conversations, multilingual transcripts of the United Nations

• We use corpora to gather statistics; more is better (typically between $10^7$ and $10^{12}$ tokens).
Notable corpora

- **Penn treebank**: Syntactically annotated Brown, plus others incl. 1989 *Wall Street Journal*.
- **Switchboard corpus**: 120 hours ≈ 2.4M tokens. 2.4K telephone conversations between US English speakers.
- **Hansard corpus**: Canadian parliamentary proceedings, French/English bilingual.
Very simple predictions

• A model at the heart of SMT, ASR, and IR...
• We want to know the probability of the next word given the previous words in a sequence.

• We can approximate conditional probabilities by counting occurrences in large corpora of data.
  • E.g., \( P(\text{food} \mid I \text{ want Chinese}) = \frac{P(I \text{ want Chinese food})}{P(I \text{ want Chinese)}} \approx \frac{\text{Count}(I \text{ want Chinese food})}{\text{Count}(I \text{ want Chinese})} \)
Bayes’ theorem

\[ P(A, B) = P(A)P(B|A) \]
\[ P(A, B) = P(B)P(A|B) \]

Bayes theorem: 

\[ P(A|B) = \frac{P(B|A)P(A)}{P(B)} \]
Maximum likelihood estimate

• Maximum likelihood estimate (MLE) of parameters $\theta$ in a model $M$, given training data $T$ is

  the estimate that maximizes the likelihood of the training data using the model.

• e.g., $T$ is the Brown corpus, $M$ is the bigram and unigram tables $\theta_{(to|want)}$ is $P(to|want)$. 
### Sparsity of unigrams vs. bigrams

- E.g., we’ve seen lots of every unigram, but are missing many bigrams:

<table>
<thead>
<tr>
<th>Unigram counts:</th>
<th>l</th>
<th>want</th>
<th>to</th>
<th>eat</th>
<th>Chinese</th>
<th>food</th>
<th>lunch</th>
<th>spend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2533</td>
<td>927</td>
<td>2417</td>
<td>746</td>
<td>158</td>
<td>1093</td>
<td>341</td>
<td>278</td>
</tr>
</tbody>
</table>

#### Example Table

<table>
<thead>
<tr>
<th>Count($w_{t-1}$,$w_t$)</th>
<th>l</th>
<th>want</th>
<th>to</th>
<th>eat</th>
<th>Chinese</th>
<th>food</th>
<th>lunch</th>
<th>spend</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_t$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>5</td>
<td>827</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>want</td>
<td>2</td>
<td>0</td>
<td>608</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>to</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>686</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>211</td>
</tr>
<tr>
<td>eat</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>16</td>
<td>2</td>
<td>42</td>
<td>0</td>
</tr>
<tr>
<td>Chinese</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>82</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>food</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>lunch</td>
<td>2</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>spend</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Zipf’s law on the Brown corpus

\[ f \propto \frac{1}{r} \] i.e., for some \( k \)

\[ f \cdot r = k \]
Smoothing as redistribution

- Steal from the rich and give to the poor.
- E.g., $\text{Count}(I \text{ caught } \cdot)$
Add-1 smoothing (Laplace)

• Given a vocab size $||V||$ and corpus size $N$, just add 1 to all the counts! No more zeros!

• MLE
  \[ P(w_i) = \frac{C(w_i)}{N} \]

• Laplace estimate
  \[ P_{Lap}(w_i) = \frac{C(w_i)+1}{N+||V||} \]

• Does this give a proper probability distribution? Yes:

  \[
  \sum_w P_{Lap}(w) = \sum_w \frac{C(w) + 1}{N + ||V||} = \frac{\sum_w C(w) + \sum_w 1}{N + ||V||} = \frac{N + ||V||}{N + ||V||} = 1
  \]
Add-$\delta$ smoothing

• Laplace’s method generalizes to the add-$\delta$ estimate:

\[ P_\delta(w_i) = \frac{C(w_i) + \delta}{N + \delta||V||} \]

• Consider also:
  • Simple interpolation
  • Katz smoothing
  • Good-Turing smoothing
Feature vectors

- Values for several features of an observation can be put into a single vector.

<table>
<thead>
<tr>
<th></th>
<th># proper nouns</th>
<th># 1st person pronouns</th>
<th># commas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damien Fahey</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Faux John Madden</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jim Gaffigan</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Parts of speech (PoS)

• Linguists like to group words according to their **structural function** in building sentences.
  • This is similar to grouping Lego by their shapes.

• **Part-of-speech**: *n.* lexical category or morphological class.

Nouns collectively constitute a part of speech (called **Noun**).
Parts of speech (PoS)

• Things that are useful to know about PoS:
  • **Content words vs. function words**
  • **Properties** of content words (e.g., number).
  • **Agreement.** Verbs and nouns should match in number in English (e.g., “the dogs runs” is ‘wrong’.)
  • What **PoS Tagging** is, and perhaps some vague idea of how to do it.
mRMR feature selection

• Minimum-redundancy-maximum-relevance (mRMR) can use correlation, distance scores (e.g., $D_{KL}$) or mutual information to select features as in

• For feature set $S$ of features $f_i$, class $c$, $D(S, c)$: a measure of relevance of $S$ for $c$, and $R(S)$: a measure of the redundancy of $S$,

$$S_{mRMR} = \arg\max_S [D(S, c) - R(S)]$$
Information and entropy
Entropy

- **Entropy**: *n.* the **average** amount of information we get in observing the output of source $S$.

$$H(S) = \sum_i p_i I(w_i) = \sum_i p_i \log_2 \frac{1}{p_i}$$

Note that this is **very** similar to how we define the expected value (i.e., ‘average’) of something:

$$E[X] = \sum_{x \in X} p(x) x$$
Joint entropy

- **Joint Entropy**: *n.* the **average** amount of information needed to specify multiple variables simultaneously.

\[ H(X, Y) = \sum_{x} \sum_{y} p(x, y) \log_2 \frac{1}{p(x, y)} \]

Same general form as entropy, except you sum over each variable, and probabilities are joint.
Conditional entropy

- **Conditional entropy**: \( n. \) the average amount of information needed to specify one variable given that you know another.

\[
H(Y|X) = \sum_{x \in X} p(x)H(Y|X = x)
\]

It’s an average of entropies over all possible conditioning values.
Relations between entropies

\[ H(X, Y) = H(X) + H(Y) - I(X; Y) \]
Mutual information

- **Mutual information**: the *average* amount of information shared between variables.

\[
I(X; Y) = H(X) - H(X|Y) = H(Y) - H(Y|X) \\
= \sum_{x,y} p(x, y) \log_2 \frac{p(x, y)}{p(x)p(y)}
\]

Again, a sum over each variable, but the log fraction is normalized by an assumption that they’re independent (\(p(x)p(y)\)).
Information theory

• In general, lecture 2-1 includes some walked-through examples of applying the preceding formula.
• It’s probably a good idea to walk through these examples yourself on paper.
Collocations

• **Collocation:** *n.* a ‘turn-of-phrase’ or usage where a sequence of words is *perceived* to have a meaning ‘*beyond*’ the sum of its parts.

• E.g., ‘disk drive’, ‘video recorder’, and ‘soft drink’ are collocations. ‘cylinder drive’, ‘video measurer’, ‘weak drink’ are not despite some near-synonymy between alternatives.

• Collocations are **not** just highly frequent bigrams, otherwise ‘of the’, and ‘and the’ would be collocations.

• **How can we test if a bigram is a collocation or not?**
Decision trees

• Consists of rules for classifying data that consists of many attributes/features.

• Walk through the Simpsons example from 3-2.
Markov models
Observable Markov model

- Probabilities on all outgoing arcs must sum to 1.

- \( P(ship|ship) + P(tops|ship) + P(pass|ship) = 1 \)

- \( P(ship|tops) + P(tops|tops) + P(mother|tops) = 1 \)

- ...
Multivariate systems

- What if a conditioning variable changes over time?
  - e.g., I’m happy one second and disgusted the next.
- Here, the state is the mood and the observation is the word.

<table>
<thead>
<tr>
<th>word</th>
<th>P(word)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ship</td>
<td>0.1</td>
</tr>
<tr>
<td>pass</td>
<td>0.05</td>
</tr>
<tr>
<td>camp</td>
<td>0.05</td>
</tr>
<tr>
<td>flock</td>
<td>0.6</td>
</tr>
<tr>
<td>soccer</td>
<td>0.05</td>
</tr>
<tr>
<td>mother</td>
<td>0.1</td>
</tr>
<tr>
<td>tops</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>word</th>
<th>P(word)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ship</td>
<td>0.3</td>
</tr>
<tr>
<td>pass</td>
<td>0.0</td>
</tr>
<tr>
<td>camp</td>
<td>0.0</td>
</tr>
<tr>
<td>flock</td>
<td>0.2</td>
</tr>
<tr>
<td>soccer</td>
<td>0.05</td>
</tr>
<tr>
<td>mother</td>
<td>0.05</td>
</tr>
<tr>
<td>tops</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Observable multivariate systems

Q: How do you learn these probabilities?
- $P(w_{0:t}, q_{0:t}) \approx \prod_{i=0}^{t} P(q_i|q_{i-1})P(w_i|q_i)$

A: Basically, the same as before.
- $P(q_i|q_{i-1}) = \frac{P(q_{i-1}q_i)}{P(q_{i-1})}$ is learned with MLE from training data.
- $P(w_i|q_i) = \frac{P(w_iq_i)}{P(q_i)}$ is also learned with MLE from training data.
Hidden variables

• Q: What if you don’t have access to the state during testing?
  • e.g., you’re asked to compute $P(⟨ship, ship⟩)$

• Q: What if you don’t have access to the state during training?
Questions for HMMs

1. Given a model with particular parameters \( \theta = \langle \Pi, A, B \rangle \), how do we efficiently compute the likelihood of a particular observation sequence, \( P(O; \theta) \)?

2. Given an observation sequence \( O \) and a model \( \theta \), how do we choose a state sequence \( Q = \{q_0, \ldots, q_T\} \) that best explains the observations?

3. Given a large observation sequence \( O \), how do we choose the best parameters \( \theta = \langle \Pi, A, B \rangle \) that explain the data \( O \)?
1. Trellis

Probability of being in state $s_3$ at time $t = 2$
2. Choosing the best state sequence

I want to guess which sequence of states generated an observation.

E.g., if states are **PoS** and observations are **words**
2. The Viterbi algorithm

- Also an inductive dynamic-programming algorithm that uses the trellis.

- Define the probability of the most probable path leading to the trellis node at \((\text{state } i, \text{time } t)\) as

  $$\delta_i(t) = \max_{q_0 \ldots q_{t-1}} P(q_0 \ldots q_{t-1}, \sigma_0 \ldots \sigma_{t-1}, q_t = s_i; \theta)$$

- And the incoming arc that led to this most probable path is defined as \(\psi_i(t)\)
3. Training HMMs

• We want to modify the parameters of our model $\theta = \langle \Pi, A, B \rangle$ so that $P(\mathcal{O}; \theta)$ is maximized for some training data $\mathcal{O}$:

$$\hat{\theta} = \arg\max_{\theta} P(\mathcal{O}; \theta)$$

• If we want to choose a best state sequence $Q^*$ on previously unseen test data, the parameters of the HMM should first be tuned to similar training data.
3. Expectation-maximization

• If we knew $\theta$, we could estimate **expectations** such as
  • Expected number of times in state $s_i$,
  • Expected number of transitions $s_i \rightarrow s_j$

• If we knew:
  • Expected number of times in state $s_i$,
  • Expected number of transitions $s_i \rightarrow s_j$
  then we could compute the **maximum likelihood estimate** of

$$\theta = \langle \pi_i, \{a_{ij}\}, \{b_i(w)\} \rangle$$
Statistical machine translation

STICK ONE IN YOUR EAR, YOU CAN INSTANTLY UNDERSTAND ANYTHING SAID TO YOU IN ANY FORM OF LANGUAGE: THE SPEECH YOU HEAR DECODES THE BRAIN WAVE MATRIX.
Challenges of SMT

- Lexical ambiguity (e.g., words are polysemous).
- Differing word orders.
- Syntactic ambiguity.
- Miscellaneous idiosyncracies.

- Sentence alignment.
  - Gale&Church: alignment by length (minimize costs).
  - Church: cognates approximated by 4-graphs.
  - Melamed: cognates approximated by longest common subsequence.
The noisy channel

\[
E^* = \arg\max_E P(F|E)P(E)
\]
Word alignment

• **Word alignments** can be 1:1, N:1, 1:N, 0:1, 1:0, ... E.g.,

> “zero fertility” word: not translated (1:0)

**Canada** → **‘s** **program** → **has** **been** **implemented**

> “spurious” words: generated from ‘nothing’ (0:1)

**Le** **programme** **du** **Canada** **a** **été** **mis** **en** **application**

> One word translated as several words (1:N)

**Note** that this is only one possible alignment.
IBM Model 1 assumption

\[ P(\text{Canada 's program has been implemented}) \]

\[ P(\text{Canada 's program has been implemented}) = \]

\[ P(\text{Canada 's program has been implemented}) \]
IBM Model 1: EM

1. Initialize translation parameters randomly (or uniformly).

2. **Expectation:** Compute expected value of $\text{Count}(e, f)$ for all words in training data $\mathcal{O}$, given your current translation parameters, $\theta_k$.

3. **Maximization:** Compute the maximum likelihood estimate of the parameters based on the expected counts, giving improved parameters, $\theta_{k+1}$. 
IBM Model 1: EM

1. Take the **product** of each $p(e)$ with each alignments and sentence pair.
2. **Normalize** by summing over all alignments for each sentence.
3. **Add** the appropriate normalized counts for each French/English word pair to find $t_{count}$ (and total).
4. Use $t_{count}$ and total to **re-estimate** $p(f|e)$.

(See lecture 6-1)

$$P(F|a, E) = P(maison|blue) \times 1 \cdot 1 = \frac{1}{9}$$

$$P(blue|house) = \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$$

$$P(F|a, E) = P(la|the) \times 1 \cdot 1 = \frac{1}{9}$$

$$P(la|house) = \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$$
Decoding IBM Model 1; phrases

• How does greedy decoding work at an abstract level?
  • Consider some of the transformation functions.

• How does phrase-based translation differ from word-based translation?
  • E.g., we learn alignments given fully observable models in which word alignments are given.
Bilingual evaluation: BLEU

• In lecture 6-2, \( ||\text{Ref1}|| = 16, ||\text{Ref2}|| = 17, ||\text{Ref3}|| = 16, \) and \( ||\text{Cn1}|| = 18 \) and \( ||\text{Cn2}|| = 14, \)

\[
\text{brevity}_1 = \frac{17}{18} \quad \text{BP}_1 = 1
\]

\[
\text{brevity}_2 = \frac{16}{14} \quad \text{BP}_2 = e^{1-\left(\frac{8}{7}\right)} = 0.8669
\]

• Final score of candidate \( C \):

\[
\text{BLEU} = \text{BP} \times (p_1 p_2 \ldots p_n)^{1/n}
\]

where

\[
p_n = \frac{\sum_{\text{ngram} \in C} \text{Count}_R(\text{ngram})}{\sum_{\text{ngram} \in C} \text{Count}_C(\text{ngram})}
\]
BLEU example

• Reference 1: I am afraid Dave
  Reference 2: I am scared Dave
  Reference 3: I have fear David
  Candidate: I fear David

- brevity = \( \frac{4}{3} \geq 1 \) so \( BP = e^{1 - \left( \frac{4}{3} \right)} \)

- \( p_1 = \frac{\sum_{1\text{gram} \in C} \text{Count}_R(1\text{gram})}{\sum_{1\text{gram} \in C} \text{Count}_C(1\text{gram})} = \frac{1+1+1}{1+1+1} = 1 \)

- \( p_2 = \frac{\sum_{2\text{gram} \in C} \text{Count}_R(2\text{gram})}{\sum_{2\text{gram} \in C} \text{Count}_C(2\text{gram})} = \frac{1}{2} \)

- \( \text{BLEU} = BP(p_1 p_2)^{\frac{1}{2}} = e^{1 - \left( \frac{4}{3} \right)} \left( \frac{1}{2} \right)^{\frac{1}{2}} \approx 0.5067 \)

Assume \( cap(n) = 2 \) for all \( n \)-grams
Automatic speech recognition
Manners of articulation

• **Phoneme**: *n.* a distinctive unit of speech sound.

• **English phonemes can be partitioned into groups**, e.g.,:
  - **Stops/plosives**: complete vocal tract constriction and burst of energy (e.g., ‘*papa*’).
  - **Fricatives**: noisy, with air passing through a tight constriction (e.g., ‘*shift*’).
  - **Nasals**: involve air passing through the nasal cavity (e.g., ‘*mama*’).
  - **Vowels**: open vocal tract, no nasal air.
  - **Glides/liquids**: similar to vowels, but typically with more constriction (e.g., ‘*wall*’).
What is sound?

- A single **tone** is a sinusoidal function of pressure and time.
  - **Amplitude**: \( n \). The degree of the displacement in the air. This is similar to ‘loudness’. Often measured in **Decibels (dB)**.
  - **Frequency**: \( n \). The number of cycles within a unit of time. e.g., 1 Hertz (Hz) = 1 vibration/second
Windowing and spectra
Spectrograms

• **Spectrogram**: *n.* a 3D plot of amplitude and frequency over time.
Formants and phonemes

- **Formant**: *n.* A large concentration of energy within a band of frequency (e.g., \(F_1\), \(F_2\), \(F_3\)).
The vowel trapezoid

If I asked you about phonemes, I’d probably give you example words.

e.g., *iy* as in *sheet*
Prosody

- **Sonorant**: *n.* Any **sustained** phoneme in which the **glottis** is vibrating (i.e., the phoneme is ‘voiced’).
  - Includes some consonants (e.g., /w/, /m/, /g/).

- **Prosody**: *n.* the **modification** of speech acoustics in order to convey some **extra-lexical** meaning:
  - **Pitch**: Changing of $F_0$ over time.
  - **Duration**: The length in time of sonorants.
  - **Loudness**: The amount of **energy** produced by the **lungs**.
Mel-frequency cepstral coefficients

- **Mel-frequency cepstral coefficients (MFCCs)** are the most popular representation of speech used in ASR.
  - They are the spectra of the logarithms of the mel-scaled filtered spectra of the windows of the waveform.

- Based on what we know about human perception of sound and the source-filter model.
Classifying speakers

- The speech produced by one speaker will cluster differently in MFCC space than speech from another speaker.
- We can decide if a given observation comes from one speaker or another.

Observation matrix

\[
P(\text{one speaker}) > P(\text{another speaker})
\]
Continuous distributions

- In the past, we used discrete probability functions.
- Since we are now operating with **continuous** variables, we need to **fit** continuous probability functions to a discrete number of observations.

- If we assume the 1-dimensional data in this histogram is Normally distributed, we can fit a continuous Gaussian function simply in terms of the mean $\mu$ and variance $\sigma^2$. 
Mixtures of Gaussians

- Gaussian mixture models (GMMs) are a weighted linear combination of $M$ component Gaussians, $\langle \Gamma_1, \Gamma_2, \ldots, \Gamma_M \rangle$ such that

$$P(\hat{x}) = \sum_{j=1}^{M} P(\Gamma_j) P(\hat{x} | \Gamma_j)$$
Continuous HMMs

• Previously we saw **discrete HMMs**: at each state we observed a discrete symbol from a finite set of discrete symbols.
• A **continuous HMM** has observations that are distributed over continuous variables.
  • Observation probabilities, $b_i$, are also continuous.

\[
\tilde{x} = \begin{array}{c}
\text{0} \\
\text{1} \\
\text{2}
\end{array}
\]

\[
\begin{array}{c}
b_0 \\
b_1 \\
b_2
\end{array}
\]

\[
\begin{array}{c}
4.32957 \\
2.48562 \\
1.08139 \\
\ldots \\
0.45628
\end{array}
\]
Levenshtein distance

<table>
<thead>
<tr>
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<th>how</th>
<th>to</th>
<th>wreck</th>
<th>a</th>
<th>nice</th>
<th>beach</th>
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<td>1</td>
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<td>3</td>
<td>2</td>
<td>2</td>
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<td>4</td>
</tr>
</tbody>
</table>

- See the example in lecture 9-1. **Work it out yourself.**
Speech synthesis
Speech synthesis

• **Text-to-speech**: *n.* the conversion of electronic text into equivalent, audible speech waveforms.

• Three **architectures** for performing speech synthesis:
  • Formant synthesis,
  • Concatenative synthesis,
  • Articulatory synthesis.

• How do they differ? What are their (dis)advantages?

• Common **components** of speech synthesis:
  • **Letter-to-sound rules** and dictionaries,
  • Acoustic prosody modification.
Information retrieval
Information retrieval (IR)

- Given queries in natural language, search for documents or information that answers those queries.
  - Returning documents vs. answering the questions directly.

- Evaluating multiple IR systems using precision and recall.

- The vector space model.

- High-level aspects of singular-value decomposition
The cosine measure

• The **cosine measure** (a.k.a., ‘normalized correlation coefficient’) is

$$\cos(\hat{q}, \hat{d}) = \frac{\sum_{i=1}^{n} q_i d_i}{\sqrt{\sum_{i=1}^{n} q_i^2} \sqrt{\sum_{i=1}^{n} d_i^2}}$$

where $\hat{q}$ and $\hat{d}$ are $n$-dimensional vectors for the query and document, respectively.

• **Larger** values of $\cos(\hat{q}, \hat{d})$ means **stronger** correlation, so $\hat{q}$ is ‘closer’ to $\hat{d}_1$ than $\hat{d}_2$ iff $\cos(\hat{q}, \hat{d}_1) > \cos(\hat{q}, \hat{d}_2)$. 
Summarization
Summarization

• Reducing a single document or multiple documents down to their most important or salient elements.

  • **Extractive** summarization vs. **synthetic** summaries.

  • What features are useful in identifying important phrases or sections? What are their properties?
Determining relevance

• The relevance of sentences and phrases within the text can be approximated by:

  • **Position:** The location of the phrase in the document.
  
  • **Cues:** The presence of certain words that indicate relevance (e.g., “crucially”, “in conclusion”).

  • **Cohesion:** The distribution of words and their co-occurrences across the document.
ROUGE-2 example

**Candidate:** An egg falls off a wall.

Don’t sit on a wall if you’re an egg.

Horses fail to perform surgery upon an egg.

Humpty Dumpty had a great fall.

\[
ROUGE2 = \frac{\sum_{S \in \{Ref\text{Summ}\}} \sum_{\text{bigram} \in S} \text{Count}_{\text{match}}(\text{bigram})}{\sum_{S \in \{Ref\text{Summ}\}} \sum_{\text{bigram} \in S} \text{Count}(\text{bigram})}
\]

\[
ROUGE2 = \frac{2 + 1 + 0}{8 + 7 + 5} = \frac{3}{20}
\]
Miscellaneous classification
Miscellaneous classification

• Walk through and understand the high-level aspects of these models:
  • Neural networks,
  • Support vector machines,
  • Transformation-based learning,
  • $K$ nearest neighbours.

• **Hint**: How do these models differ and how they are similar? What are their **strengths** and **weaknesses**? Are there any that are associated with a particular task?
Final thoughts

(not thoughts on the final)
NLC in industry
Final thoughts

• This course **barely** scratches the surface of **natural language computing**. Talk to these people:

  Graeme Hirst  
  Gerald Penn  
  Frank Rudzicz  
  Suzanne Stevenson

• Most of the techniques in this course are applicable **generally**.
  • Hidden Markov models, e.g., are used almost universally, including in finance, biology, medicine, and robotics.
My research
Aside – Knowledge

• **Anecdotes** are often useless except as proofs by contradiction.
  • E.g., “I saw Google used as a verb” does not mean that Google is always (or even likely to be) a verb, just that it is not always a noun.

• **Shallow statistics** are often not enough to be truly meaningful.
  • E.g., “My ASR system is 95% accurate on my test data. Yours is only 94.5% accurate, you horrible knuckle-dragging idiot.”
    • What if the test data was biased to favor my system?
    • What if we only used a very small amount of data?

• We need a test to see if our statistics actually mean something.

Find some way to be comfortable trying to prove yourself wrong
Thank you