Speech Recognition

- a practical guide

Lecture 4

Decoding

Step covered in this lecture

```
$ cd ~/kaldi-trunk/egs/rm/s3/
$
$ # Decode first triphone system
$ local/decode.sh steps/decode_deltas.sh exp/tri1/decode
$
```

- "Decoding" means: given a model and an utterance, give me the most likely word-sequence.
- Difficult to do efficiently.

Viterbi algorithm

- Given a HMM and a sequence of output symbols (or vectors, in our case)...
- Give me the state-sequence through the HMM that contributes the most to the likelihood.
- Algorithm takes time O(N T), where N is #arcs in HMM, T is #observations.
- Simple dynamic programming: for each (state, time t), keep record of best state at t-1

Viterbi algorithm-- application

- We're actually searching a very large "HMM" that contains the information in:
  - The lexicon (pronouncing dictionary)
  - The language model
  - The phonetic decision tree
  - The topologies of the phone HMMs
- We'll use the Weighted Finite State Transducer (WFST) framework to combine them...

Viterbi with beam-pruning

- The graph we need to search is too big--would be very slow with standard Viterbi
- Beam-pruning means we access the frames (feature vectors) one by one, and on each frame, prune away states with score worse than (best-score minus beam)
- For reasonable beam values, we won't lose too much accuracy by doing this.
- This is the most basic component of a speech-recognition decoder.

Top-level decoding script

```
$ less scripts/decode.sh
#!/bin/bash
# This is somewhat simplified:
script=$1
decode_dir=$2

# (1) Make the decoding graph
scripts/mkgraph.sh data/lang_test $dir $dir/graph

# (2) Decode the various different test sets (of Resource Management)
for test in mar87 oct87 feb89 oct89 feb91 sep92; do
  $script $dir data/test_$test data/lang $decode_dir_1/$test &
done
```

- This script calls scripts/mkgraph.sh to make the "decoding graph"
- Then it decodes the different test sets that Resource Management comes with.

Language models

- "Prior" probability of sentences are often given by N-gram language model (for large vocabulary tasks).
- Read "A Bit of Progress in Language Modeling" (Joshua Goodman) for intro.
- Can represent this in a graph structure using the Weighted Finite State Transducer (WFST) framework.
- Gives a very large graph!

Language models

- A "backoff language model" is the standard type of LM.
- Typically represented in the "ARPA" or equivalently "arpabo" format (look it up).
- In the bigram case (one word of history):
  - If last word was "b", we'll have a number of successor-words with explicit probabilities given (e.g. b->c, b->d)...
  - We'll also "back off" with some weight, to the unigram distribution-- so all successor-words have a nonzero probability.

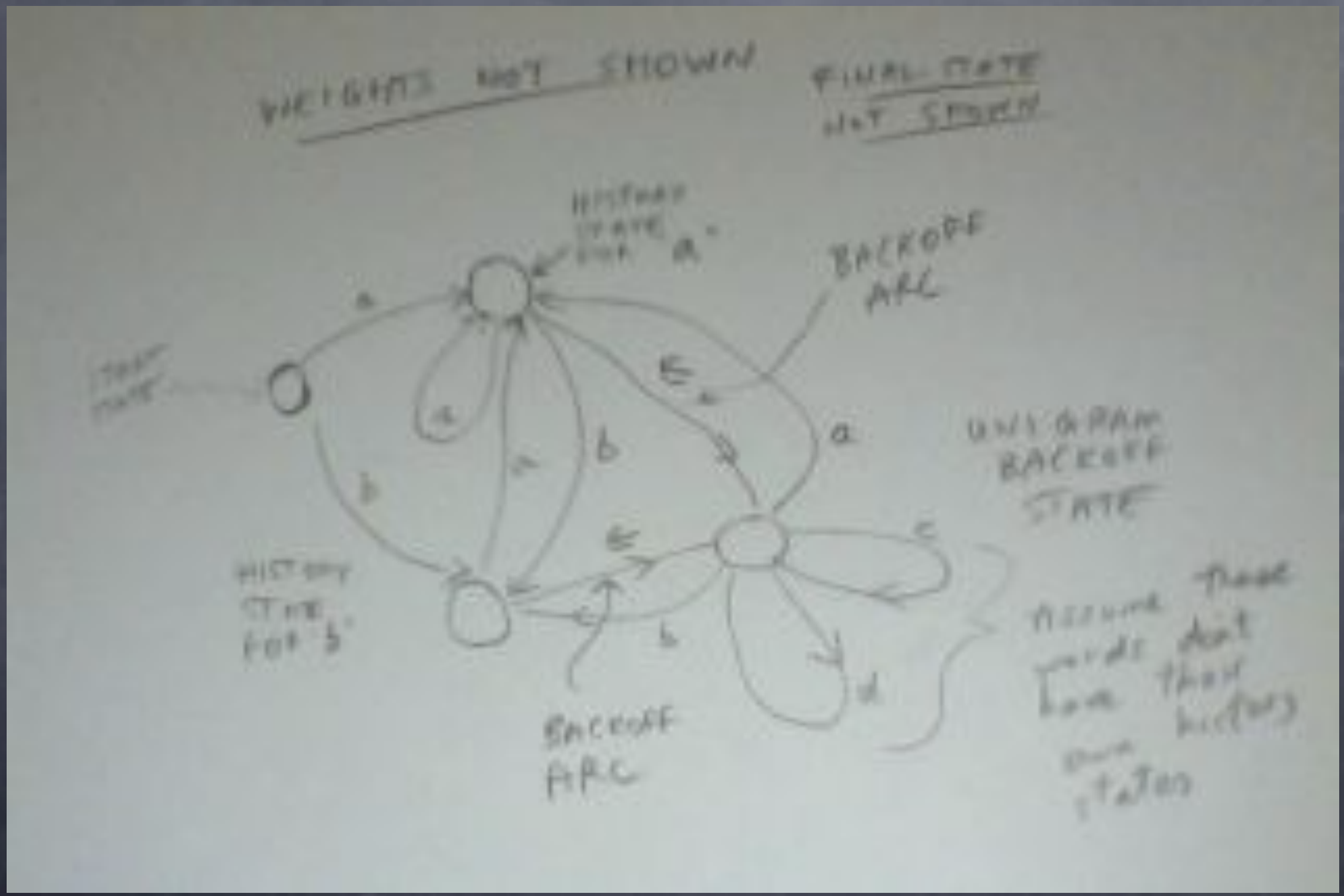
Language models: ARPA

```
$ cd ~/kaldi-trunk/egs/wsj/s3
$ less data/local/lm_bg.arpa.gz
\data\
ngram 1=19982
ngram 2=1460564

\1-grams:
-1.7282 <UNK>   -0.7021
-1.3780 </s>    0.0000
-99.999 <s> -1.5255
-5.2162 'EM -0.3535
-5.0255 'N  -1.1501
-1.6566 A   -1.8164
-5.5854 A'S -0.1161
-2.8439 A.  -0.9302
<snip>
\2-grams:
-1.3457 <UNK> <UNK>
-1.1291 <UNK> </s>
-4.5784 <UNK> 'EM
-4.2774 <UNK> 'N
```

- Has log-probabilities in log-base 10 (backoff weights at end of line, in log-base-10).
- This example from WSJ (no ARPA in RM)

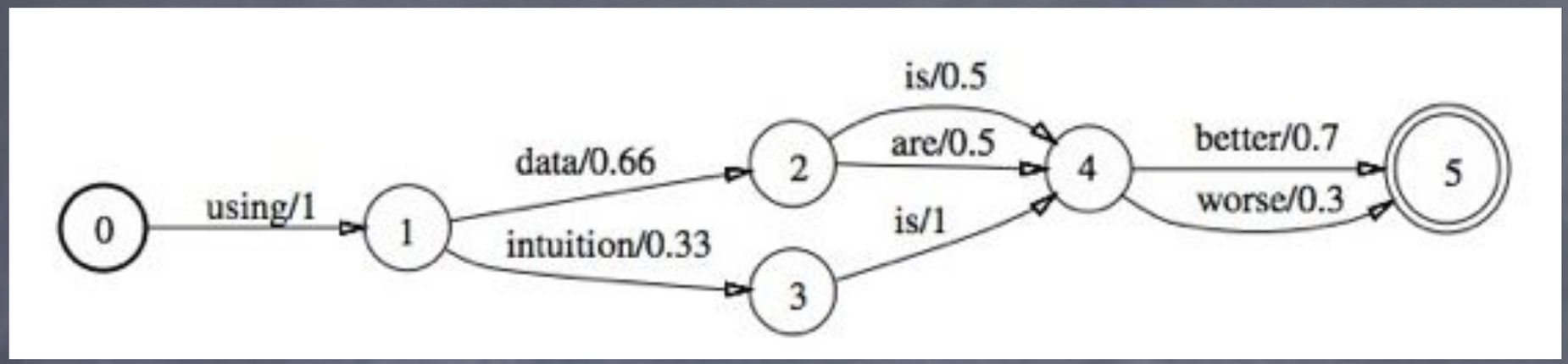
Language models, graph



Language models, graph

- Graph for LM has separate state for each seen history-state
  - For trigram LM, a history state would correspond to a pair of words
- Also has states for less-specific history states (corresponding to single words), and unigram-backoff state (the "empty history")
- Each state (except unigram state) has "backoff arc" to less specific history state
  - Backoff-arc has epsilon on it.

Language models, graph



- This is a more "grammar-like" example (not a backoff LM)
- Taken from Mohri's "Springer Handbook" article (search for hbka.pdf)

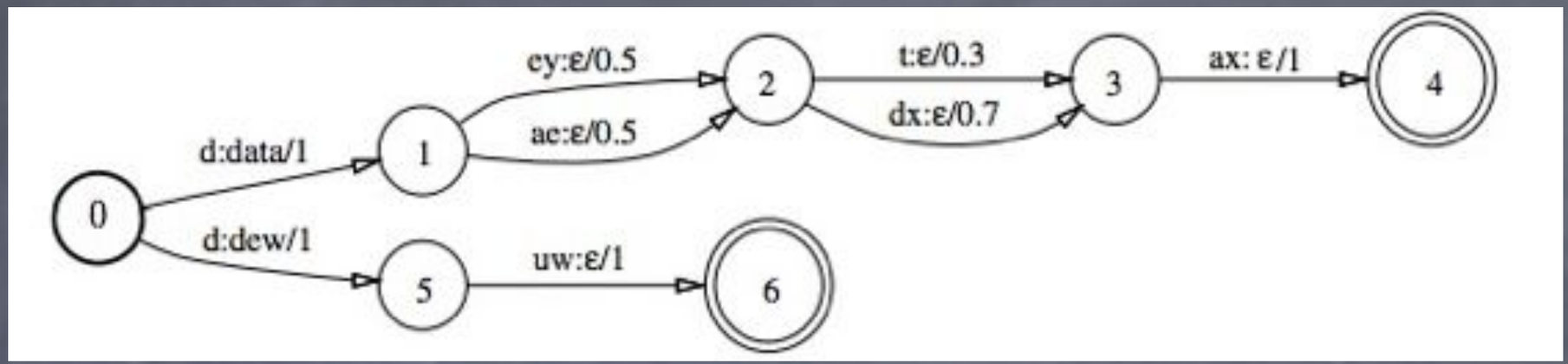
Language models: RM

```
$ cd ~/kaldi-trunk/egs/rm/s3
$ less local/rm_data_prep.sh
<snip>
scripts/make_rm_lm.pl $RMROOT/rm1_audio1/rm1/doc/wp_gram.txt  > data/local/G.txt
<snip>

$ less data/local/G.txt
0    1    ADD    ADD    5.19849703126583
0    2    AJAX+S    AJAX+S    5.19849703126583
0    3    APALACHICOLA+S    APALACHICOLA+S    5.19849703126583
0    4    ARE    ARE    5.19849703126583
0    5    AREN+T    AREN+T    5.19849703126583
0    6    ARKANSAS+S    ARKANSAS+S    5.19849703126583
0    7    BADGER+S    BADGER+S    5.19849703126583
0    8    BAINBRIDGE+S    BAINBRIDGE+S    5.19849703126583
0    9    BIDDLE+S    BIDDLE+S    5.19849703126583
0    10    BROOKE+S    BROOKE+S    5.19849703126583
0    11    BRUNSWICK+S    BRUNSWICK+S    5.19849703126583
0    12    CAMDEN+S    CAMDEN+S    5.19849703126583
0    13    CAMPBELL+S    CAMPBELL+S    5.19849703126583
0    14    CAN    CAN    5.19849703126583
```

- RM has a simple word-pair grammar instead of a "proper" language model (it comes with this; it's conventional to use this in testing).

Lexicon



- Gives for each word, a set of alternative pronunciations (possibly with weights)
- This example is also from Mohri's article
- In Kaldi, the lexicon also encodes optional silences between words.

Lexicon: raw data

```
$ cd ~/kaldi-trunk/egs/rm/s3
$ less data/local/lexicon.txt
A               ax
A42128          ey f ao r t uw w ah n t uw ey td
AAW             ey ey d ah b y uw
ABERDEEN        ae b er d iy n
ABOARD          ax b ao r dd
ABOVE           ax b ah v
ADD             ae dd
ADDED           ae dx ax dd
ADDING          ae dx ih ng
AFFECT          ax f eh kd
AFTER           ae f t er
AGAIN           ax g eh n
AJAX            ey dd jh ae k s
AJAX+S          ey dd jh ae k s ax z
ALASKA          ax l ae s k ax
```

- This is the original file from which we create the lexicon (it's created by a human).

Lexicon: disambiguation symbols

```
$ cd ~/kaldi-trunk/egs/rm/s3
$ less data/local/lexicon_disambig.txt
A          ax #1
A42128     ey f ao r t uw w ah n t uw ey td
AAW        ey ey d ah b y uw
ABERDEEN           ae b er d iy n
ABOARD     ax b ao r dd
ABOVE      ax b ah v
ADD        ae dd
ADDED      ae dx ax dd
ADDING     ae dx ih ng
AFFECT     ax f eh kd
AFTER      ae f t er
AGAIN      ax g eh n
```

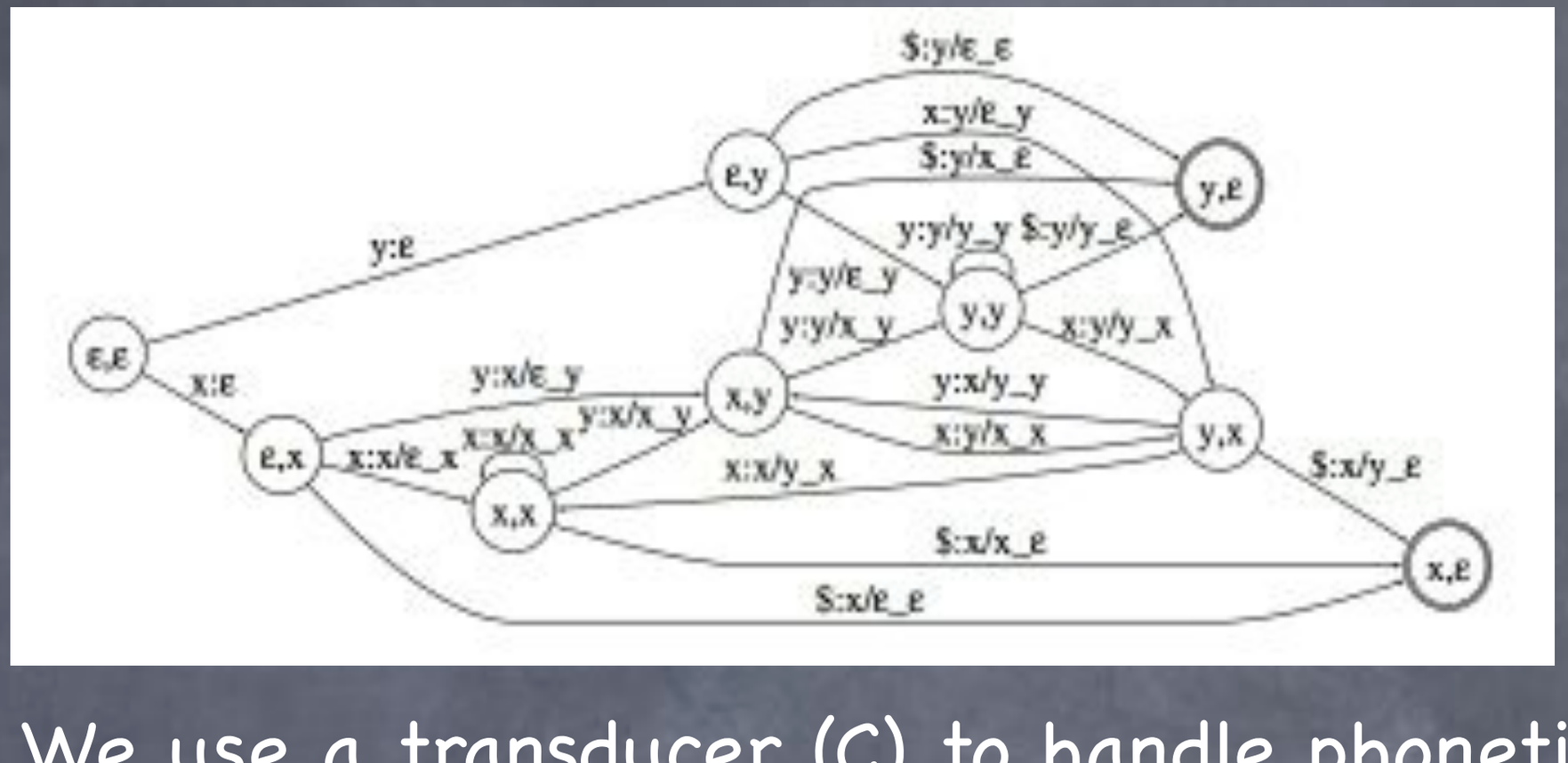
- We require each pronunciation to be unique
- This relates to issues of WFSTs (determinizability).
- Add "fake phones" #1, #2, ... to pronunciations.

Lexicon: preparing as WFST

```
$ cd ~/kaldi-trunk/egs/rm/s3
$ less local/rm_format_data.sh
<snip>
silprob=0.5
scripts/make_lexicon_fst.pl data/local/lexicon_disambig.txt $silprob sil '#'$ndisambig | \
   fstcompile --isymbols=data/lang_test/phones_disambig.txt --osymbols=data/lang_test/words.txt \
   --keep_isymbols=false --keep_osymbols=false | fstarcsort --sort_type=olabel \
    > data/lang_test/L_disambig.fst
<snip>
```

- This script takes the lexicon in text form and outputs as a WFST (in text format)
- Handles adding optional silences (a bit like alternative pronunciations)

Context-dependency



- We use a transducer (C) to handle phonetic context dependency.
- It expands phones into context-dependent phones (i.e. triphones, in the normal case)
- In our case the phones are on the right (output symbols), context-dep. on left (input)

Context-dependency

- A few extra details to be aware of:
  - The symbol $ is the "end-of-sentence symbol"-- needed to handle issues relating to determinizability.
  - We need self-loops on all states in C, with the disambiguation symbols #0, #1, ... on.
  - Want it deterministic on phones for fast composition... as a result, input and output are not "synced up": there is a delay of 1 (for triphone case)

Overall recipe

- Standard WFST recipe is "HCLG"
- Composition of:
  - H = HMM structure
  - C = phonetic context dependency
  - L = lexicon
  - G = grammar (or LM).
- Optimizations such as determinization, minimization, weight-pushing done to improve beam-pruning performance.

Making the graph

```
$ less scripts/mkgraph.sh
#!/bin/bash
# Takes 3 arguments
lang=$1
tree=$2/tree
model=$2/final.mdl
dir=$3

tscale=1.0
loopscale=0.1
```

- First set up some variables relating to probability scales
  - Relates to scaling the transition probabilities.
  - We treat self-loops differently

Making the graph: LG

```
$ less scripts/mkgraph.sh
<snip>
fsttablecompose $lang/L_disambig.fst $lang/G.fst | fstdeterminizestar --use-log=true | \
  fstminimizeencoded  > $lang/tmp/LG.fst || exit 1;
fstisstochastic $lang/tmp/LG.fst || echo "warning: LG not stochastic."
```

- Compose L and G, then determinize and minimize.
- Then check result is stochastic (probabilities out of each state sum to one)
  - actually it won't be, quite.
- These programs are similar to OpenFst programs, but are all Kaldi programs.

Purpose of each stage

- "compose" (of L and G) expands each word into phones.
- "determinize" is like making a tree-structured lexicon (in each language-model state)
- "minimize" is like suffix-sharing

Kaldi FST tools

- We use a combination of OpenFst's native command-line tools, and Kaldi versions of them
- fsttablecompose like fstcompose but faster (uses heuristics that OpenFst authors would find ugly)
- fstminimizeencoded is a convenience mechanism (would require several native OpenFst commands)
- fstdeterminizestar is like fstdeterminize but does epsilon-removal as part of determinization.
  - Both for mathematical and practical reasons.

Making the graph: CLG

```
$ less scripts/mkgraph.sh
<snip>
grep '#' $lang/phones_disambig.txt | awk '{print $2}' > $lang/tmp/disambig_phones.list
clg=$lang/tmp/CLG_${N}_${P}.fst

fstcomposecontext --context-size=$N --central-position=$P \
  --read-disambig-syms=$lang/tmp/disambig_phones.list \
  --write-disambig-syms=$lang/tmp/disambig_ilabels_${N}_${P}.list \
   $lang/tmp/ilabels_${N}_${P} < $lang/tmp/LG.fst >$clg

fstisstochastic $clg  || echo "warning: CLG not stochastic."
```

- Compose C with LG to make CLG
- C is created "on the fly" in memory (we only expand the parts we need).
- Also outputs file "ilabels_3_1", which maps the (integer) input symbols of CLG to triphones.

Making the graph: H

```
$ less scripts/mkgraph.sh
<snip>
make-h-transducer --disambig-syms-out=$dir/disambig_tid.list \
  --transition-scale=$tscale $lang/tmp/ilabels_${N}_${P} $tree $model \
   > $dir/Ha.fst
```

- H is the "HMM-structure" transducer (info from HMM topologies, transition-probs, decision-tree
- Ha.fst is as H.fst, but no self-loops (more compact)
- Input symbols are "transition-ids" which encode the "pdf-id" (id of the mixture of Gaussians) and also a bit more information (e.g. the phone)
- Only includes triphones listed in ilabels_3_1

Making the graph: HCLG

```
$ less scripts/mkgraph.sh
<snip>
fsttablecompose $dir/Ha.fst $clg | fstdeterminizestar --use-log=true \
  | fstrmsymbols $dir/disambig_tid.list | fstrmepslocal | \
   fstminimizeencoded > $dir/HCLGa.fst
```

- Compose Ha.fst with CLG.fst
- Remove epsilons and determinize [fstdeterminizestar]...
  - Do this in log semiring, which keeps the weights suitably "sum-to-one".
- Remove disambiguation symbols #0, #1, ...
- Remove any resulting epsilons and minimize.

Weight-pushing

- This was part of the originally published recipe (search for "hbka.pdf")
- Gives better pruning behavior... make graph like properly normalized HMM.
- Can fail (crash, or give weird results) for ARPA-type LMs.
- We ensure this property "stochasticity" differently in our recipe...
- Idea is to ensure no stage will destroy stochasticity. Robust to not-quite-stochastic LMs.

Adding self-loops

```
$ less scripts/mkgraph.sh
<snip>
 add-self-loops --self-loop-scale=$loopscale --reorder=true \
    $model < $dir/HCLGa.fst > $dir/HCLG.fst || exit 1;
```

- This stage adds the self-loops to the final graph
- Corresponds to the self-loops of the HMM states.
- Doing this as a separate stage allows us to build larger graphs.
- Note: the --reorder option puts the self-loop after the transition out of the state
  - Leads to faster-to-search graph.

Running the decoding

```
$ local/decode.sh steps/decode_deltas.sh exp/tri1/decode &
```

- Run the decoding in the background.
- Note: it uses about 6 cpus, for about 2 minutes
  - the 6 test sets are decoded in parallel

The decoding command

```
$ head exp/tri1/decode/feb89/decode.log
gmm-latgen-simple --beam=20.0 --acoustic-scale=0.1 --word-symbol-
table=data/lang/words.txt exp/tri1/final.mdl exp/tri1/graph/HCLG.fst
'ark:compute-cmvn-stats --spk2utt=ark:data/test_feb89/spk2utt scp:data/
test_feb89/feats.scp ark:- | apply-cmvn --norm-vars=false --
utt2spk=ark:data/test_feb89/utt2spk ark:- scp:data/test_feb89/feats.scp
ark:- | add-deltas ark:- ark:- |' 'ark:|gzip -c > exp/tri1/decode/feb89/
lat.gz'
```

- Look at the decoding command in a log file
- Try running it from the command line (copy and paste)
  - You'll have to source "path.sh" (type ". path.sh")
  - Change the name of the "lat.gz" output or you'll interfere with the decoding that's running.

Lattices

```
$ head exp/tri1/decode/feb89/decode.log
gmm-latgen-simple --beam=20.0 --acoustic-scale=0.1 --word-symbol-
table=data/lang/words.txt exp/tri1/final.mdl exp/tri1/graph/HCLG.fst
'ark:compute-cmvn-stats --spk2utt=ark:data/test_feb89/spk2utt scp:data/
test_feb89/feats.scp ark:- | apply-cmvn --norm-vars=false --
utt2spk=ark:data/test_feb89/utt2spk ark:- scp:data/test_feb89/feats.scp
ark:- | add-deltas ark:- ark:- |' 'ark:|gzip -c > exp/tri1/decode/feb89/
lat.gz'
```

- We actually don't do Viterbi, we generate "lattices" (a graph-based record of the most likely utterances)
- These are later rescored at various acoustic weights, and we pick the best.
- The option for the acoustic scale during lattice generation only affects pruning behavior.

Changing the beam

```
$ head exp/tri1/decode/feb89/decode.log
gmm-latgen-simple --beam=10.0 --acoustic-scale=0.1 --word-symbol-
table=data/lang/words.txt exp/tri1/final.mdl exp/tri1/graph/HCLG.fst
'ark:compute-cmvn-stats --spk2utt=ark:data/test_feb89/spk2utt scp:data/
test_feb89/feats.scp ark:- | apply-cmvn --norm-vars=false --
utt2spk=ark:data/test_feb89/utt2spk ark:- scp:data/test_feb89/feats.scp
ark:- | add-deltas ark:- ark:- |' 'ark:|gzip -c > exp/tri1/decode/feb89/
lat.gz'
```

- Change the beam width in the command from 20 to 10 and run again
- Notice the change in speed.
- When the decoding finishes, change the beam width in the script to 10 and rerun (change exp/tri/decode to exp/tri/decode_10)
  - Check the effect on speed and accuracy.

The decoder code

```
$ cd ~/kaldi-trunk/src
$ less gmmbin/gmm-decode-simple.cc
<snip>

      DecodableAmDiagGmmScaled gmm_decodable(am_gmm, trans_model,
                                             features, acoustic_scale);
      decoder.Decode(&gmm_decodable);
```

- gmm-decode-simple just does beam-pruned Viterbi
- The "gmm_decodable" object is a simple interface to the acoustic model and features.
- It has a function that returns the log-likelihood for a given (frame, pdf-id)

Decoder code (internal)

```
$ cd ~/kaldi-trunk/src
$ less decoder/simple-decoder.h
<snip>
class SimpleDecoder {
  <snip>
  bool Decode(DecodableInterface *decodable) {
    // clean up from last time:
    ClearToks(cur_toks_);
    ClearToks(prev_toks_);
    StateId start_state = fst_.Start();
    KALDI_ASSERT(start_state != fst::kNoStateId);
    Arc dummy_arc(0, 0, Weight::One(), start_state);
    cur_toks_[start_state] = new Token(dummy_arc, NULL);
    ProcessNonemitting();
    for (int32 frame = 0; !decodable->IsLastFrame(frame-1); frame++) {
      ClearToks(prev_toks_);
      cur_toks_.swap(prev_toks_);
      ProcessEmitting(decodable, frame);
      ProcessNonemitting();
      PruneToks(beam_, &cur_toks_);
    }
```

Other decoders

- Apart from simple-decoder.h ("internal" decoder code), there are:
  - faster-decoder.h [a bit more optimized]
  - lattice-faster-decoder.h [that also generates lattices]
- A couple more that are less important.
- Each model-type has a command-line wrapper for each decoder (e.g. gmm-latgen-faster)

End of this lecture