深蓝学院
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音频语音与语言处理研究组
SLP
Audio, Speech and Language Processing Group NPU

语音识别：从入门到精通

第八讲：基于WFST的解码器

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内容提要

- 解码
  - 公式
  - 框架
  - 孤立词与LM
  - 计算问题
- 解码器
  - 剪枝(Prunning)
  - Lattice和N-best List
  - A* decoder思想(简要)
  - 字典树(简要)
  - Language Look-ahead(简要)
- WFST介绍
- 识别中的WFST—基于kaldi

解码任务—解码公式

给定声学观测$O = o_1, o_2, \ldots, o_T$,找到最可能的词序列$W = w_1, w_2, \ldots, w_N$：

$$\hat{W} = argmax_w P(W|O)$$

$$= argmax_w \underbrace{P(O|W)}_{\text{Acoustic Model}} \underbrace{P(W)}_{\text{Language Model}}$$

$\hat{W} = argmax_w P(O|W)P(W)$
实际应用中对吗

其实你已经学过理论上该怎么做了！----Viterbi算法。

(顺便回忆一下Forward algorithm和Viterbi algorithm的关系)

找到了最可能的状态序列，我们就能恢复出最可能的词序列。

---解码范围，LM约束的图

解码任务—解码公式

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$$\hat{W} = argmax_w P(W|O)$$

$$= argmax_w \underbrace{P(O|W)}_{\text{Acoustic Model}} \underbrace{P(W)}_{\text{Language Model}}$$

$$= argmax_w P(O|W)P(W)^{LMWT}$$

语言模型缩放权重(LMWT):language model weight

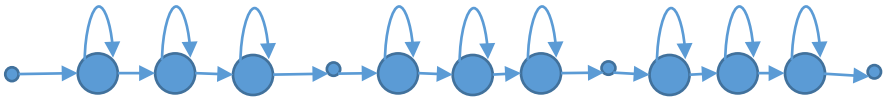
$$= argmax_w P(O|W)P(W)^{LMWT} WIP^N$$

插入词惩罚(WIP):word insertion penalty

解码任务—框架

特征提取

Acoustic Model
P(O|W)



HMM序列

简单解码器

AY1 AE1 M

Language Model
P(W)

字典

I am

词序列

解码任务—Token Passing Algorithm(令牌环传递算法)

Token Passing算法就是Viterbi算法的实现

Token的设计：存储经过某状态的最优路径的概率，存储与全局最优路径的距离，以及帮助寻找其它token或者回溯的指针。

Initialisation:

Each model initial state holds a token with value 0;
All other states hold a token with value ∞

Algorithm:

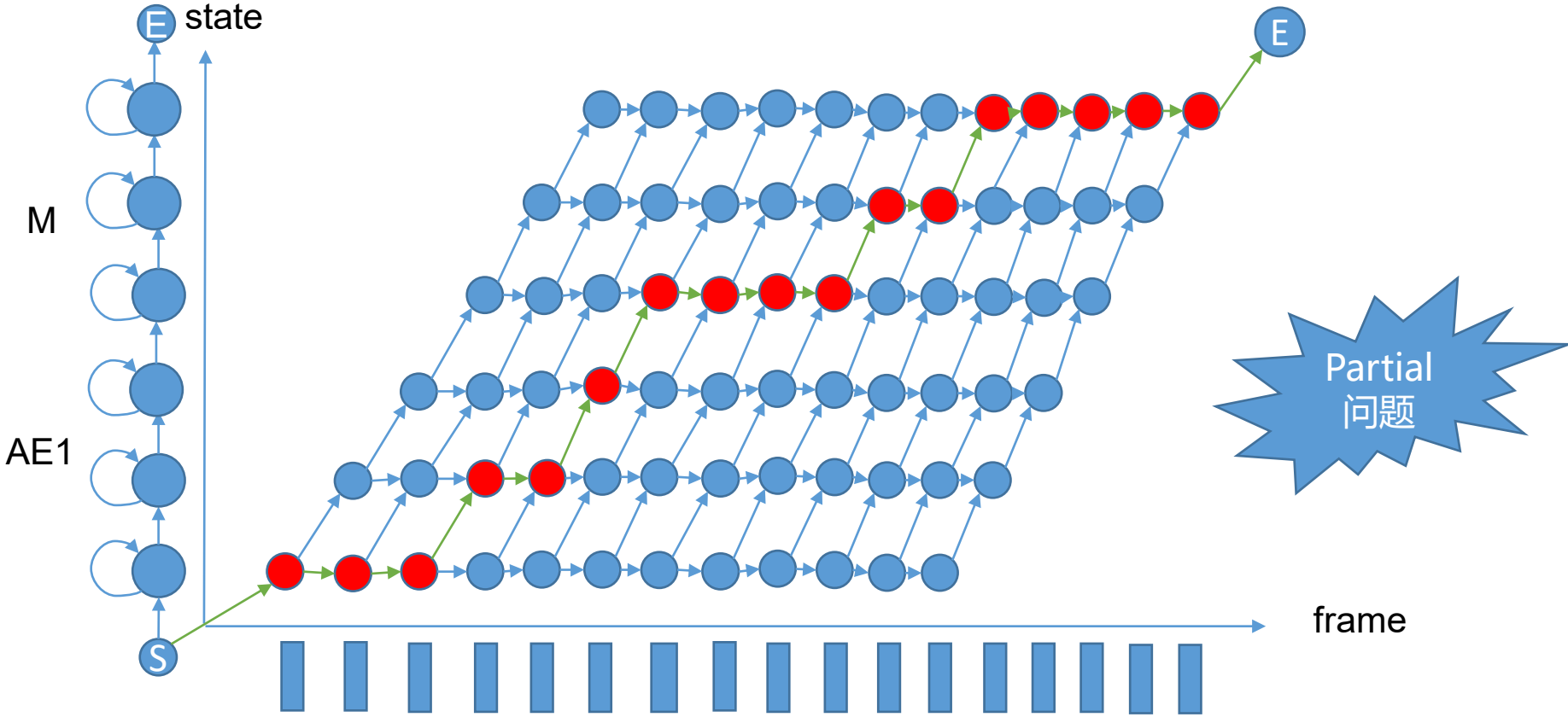
for t:= 1 **to** T **do**
  for each state i **do**
    Pass a copy of the token in state i to all connecting states j, incrementing its s value by $p_{ij} + d_j(t)$;
  end;
  Discard the original tokens;
  for each state i **do**
    find the token in state i with the smallest s value and discard the rest
  end;
end;

发射概率

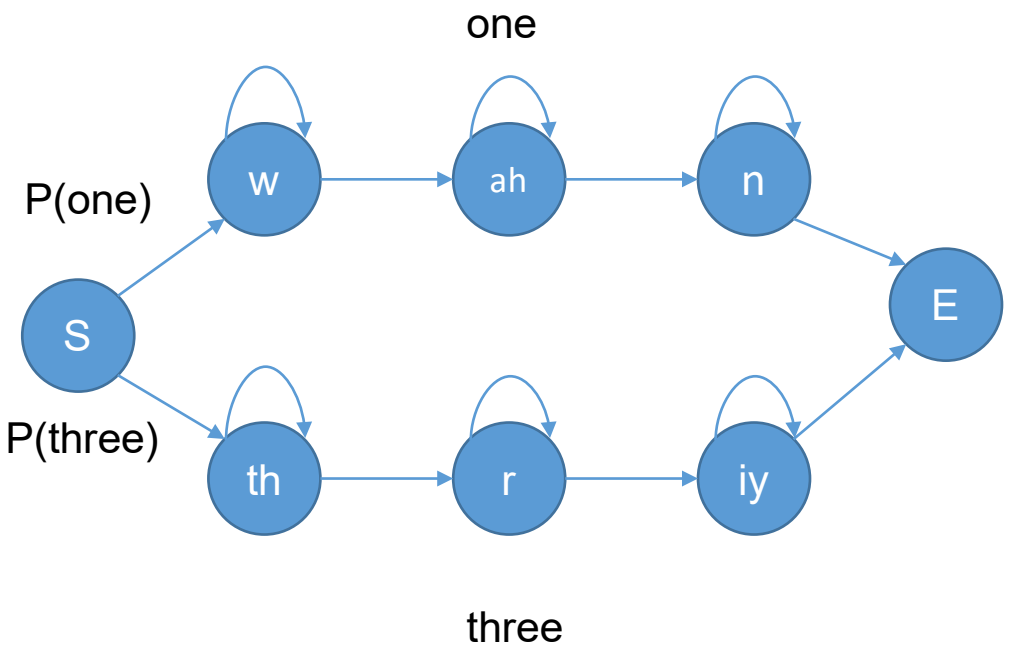
转移概率

From Wiki

解码任务—晶格网（trellis）

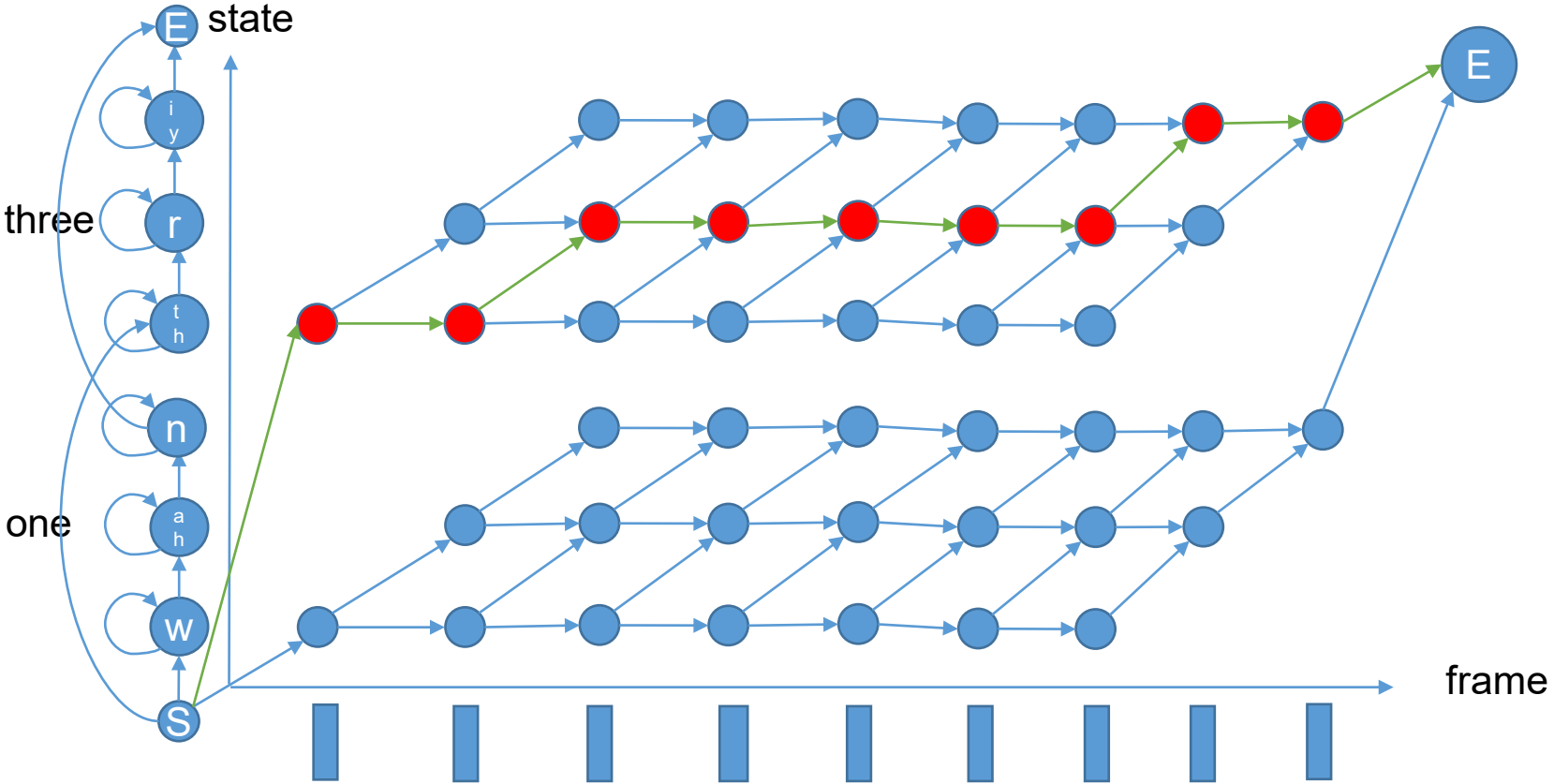


解码任务—孤立词



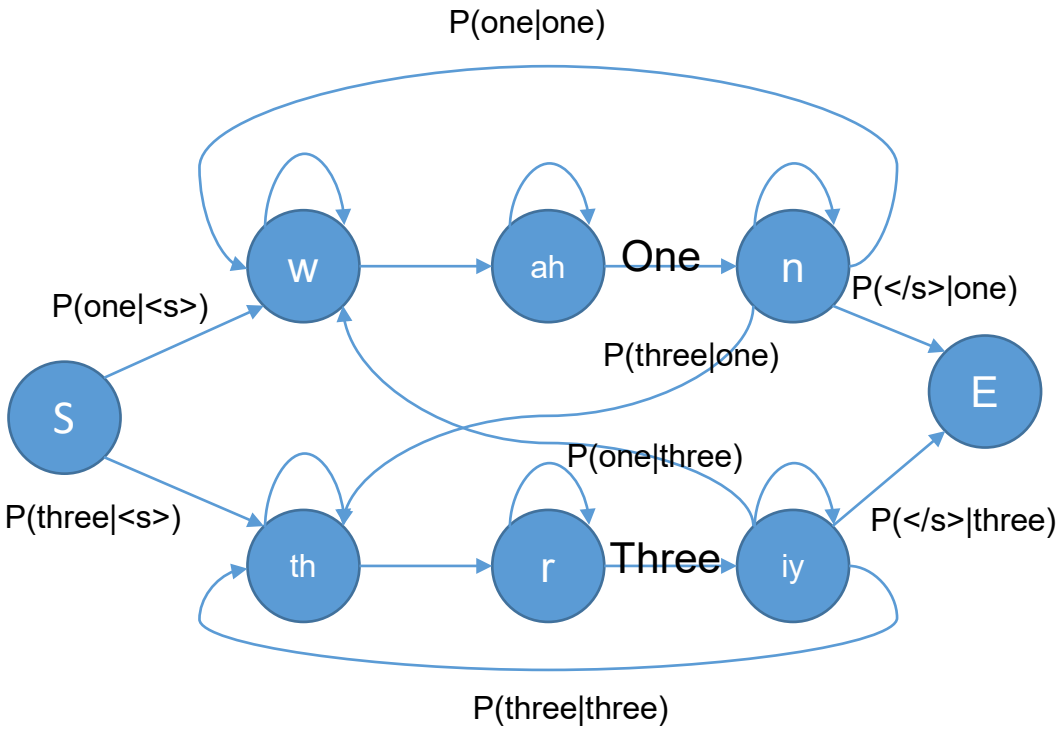
示意图：每个phone一个状态(for simple)

解码任务—孤立词



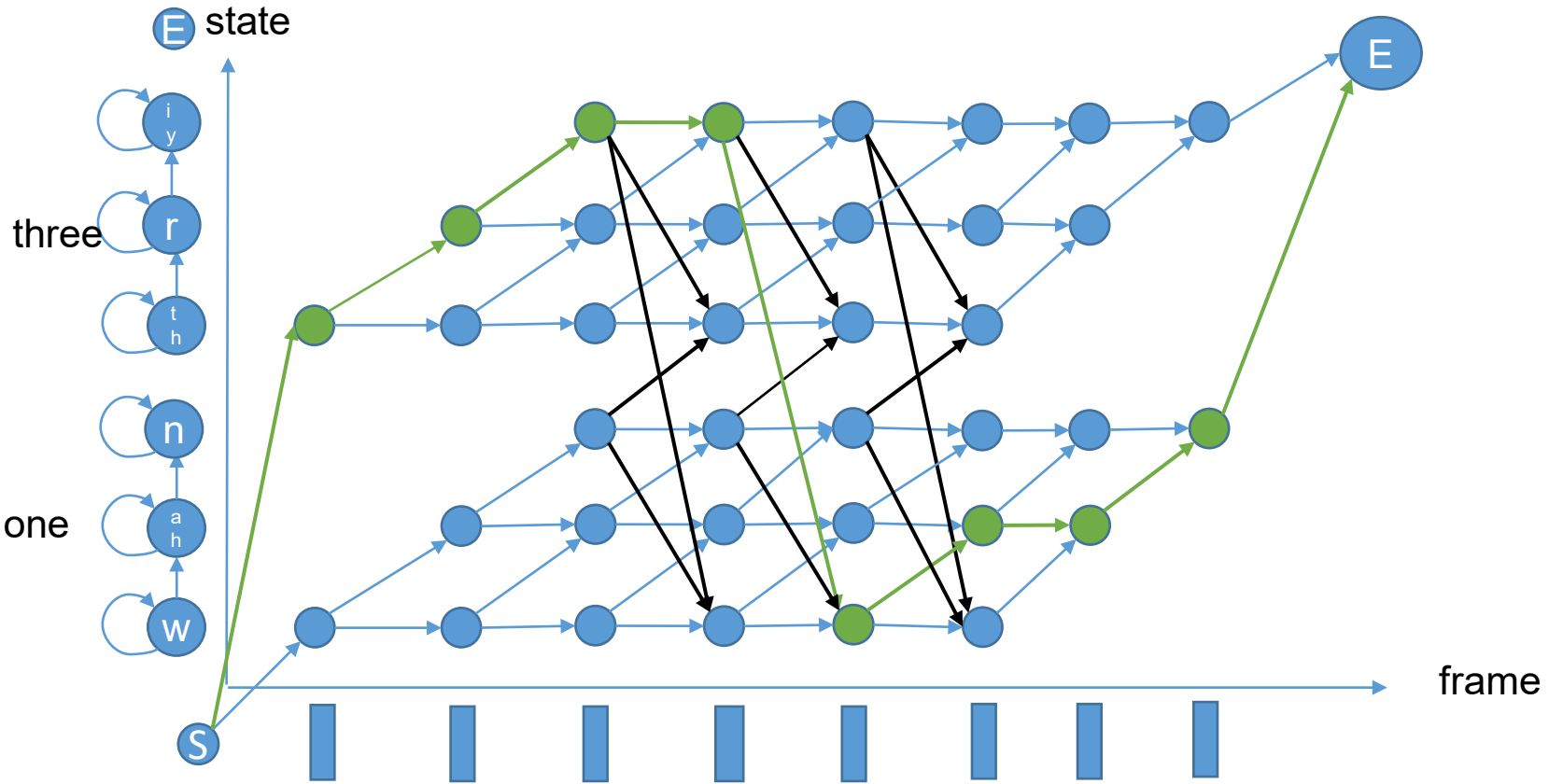
解码任务—LM

Bigram为例子



示意图：每个phone一个状态(for simple)

解码任务—LM



解码任务—计算问题

Viterbi算法理论上准确有效的完成了解码工作，实际上有什么问题？

你已经训练过LM了，它的wordlist是不是巨大？形成的N-gram是不是条数超多？

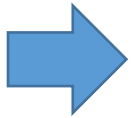
由于LVCSR实际任务中N-gram，Lexicon和triphone建模导致无法只简单的使用Viterbi算法，需要进行一些工程优化。

解码器

如何解决计算问题?

1. 剪枝(Pruning):beam search and histogram pruning
2. 多阶段解码(Multi-stage decoding)
3. A*解码(A* decoding)
4. 树状字典(Tree structured lexicons)
5. 语言模型超前使用(Language model Look-ahead)

……



解码器

解码器—Pruning

思想：去除没有竞争力的路径。

Beam Search: 每帧只保留Best Path以及与Best Path距离小于beam-threshold的tokens。

Histogram Pruning: 每帧只处理前Top N个tokens。

解码器—Lattice和N-best list

产生一条最优路径只是解码器的部分工作，对于解码器的研究，更重要的是生成一个准确的lattice，然后再进行后处理，如重打分(Re-scoring)[i.e. 多阶段解码]。

N-best List：解码获得最好的Top N条词序列。
Lattice: 他是一个有向图，有效的表示关于可能词序列的更多信息。[i.e. 把到达终点的tokens走过路径的信息绘制在一张图里。]

Rank	Path	AM logprob	LM logprob
1.	it's an area that's naturally sort of mysterious	-7193.53	-20.25
2.	that's an area that's naturally sort of mysterious	-7192.28	-21.11
3.	it's an area that's not really sort of mysterious	-7221.68	-18.91
4.	that scenario that's naturally sort of mysterious	-7189.19	-22.08
5.	there's an area that's naturally sort of mysterious	-7198.35	-21.34
6.	that's an area that's not really sort of mysterious	-7220.44	-19.77
7.	the scenario that's naturally sort of mysterious	-7205.42	-21.50
8.	so it's an area that's naturally sort of mysterious	-7195.92	-21.71
9.	that scenario that's not really sort of mysterious	-7217.34	-20.70
10.	there's an area that's not really sort of mysterious	-7226.51	-20.01

Figure 10.2 An example 10-Best list from the Broadcast News corpus, produced by the CU-HTK BN system (thanks to Phil Woodland). Logprobs use $\log_{10}$; the language model scale factor (LMSF) is 15.

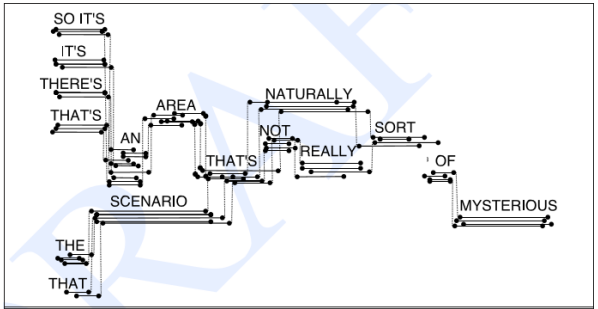


Figure 10.3 Word lattice corresponding to the *N*-best list in Fig. 10.2. The arcs beneath each word show the different start and end times for each word hypothesis in the lattice; for some of these we've shown schematically how each word hypothesis must start at the end of a previous hypothesis. Not shown in this figure are the acoustic and language model probabilities that decorate each arc.

From Dan Jurafsky, Speechh and Language Processing

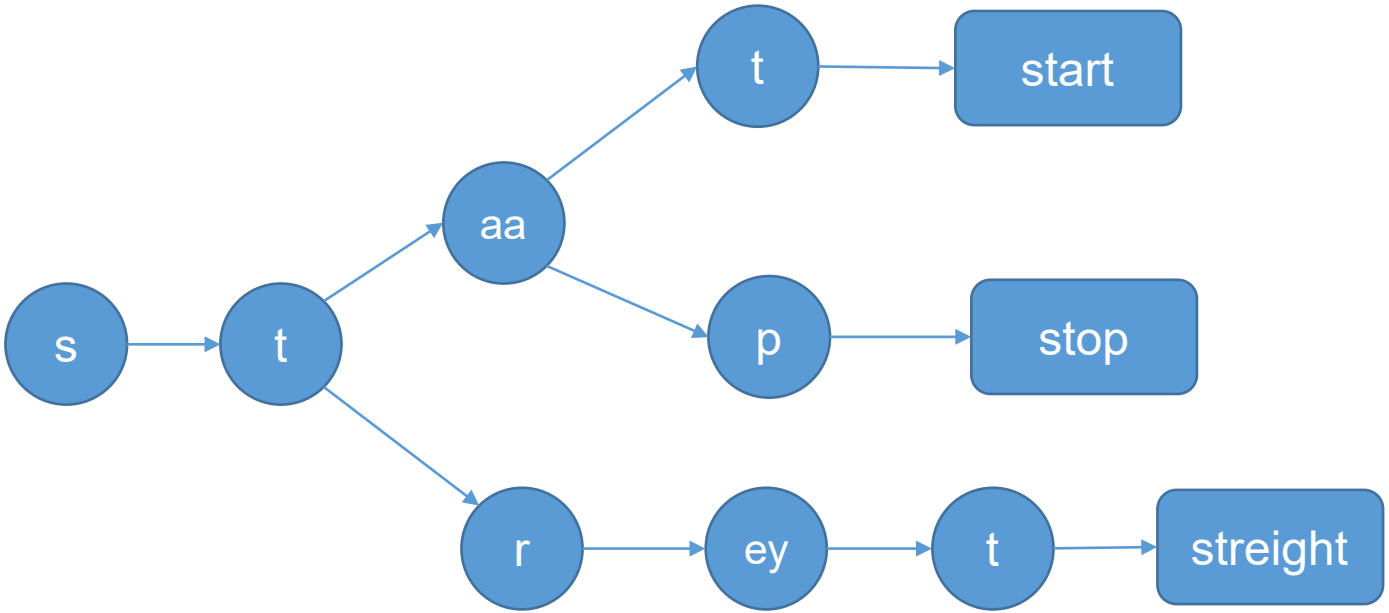
解码器—A* decoder

$$H^*(s) = f(s) + g^*(s)$$

$H^*(s)$是经过状态s，最好的完整路径分数。
$f(s)$是从初始到状态s的部分路径分数(真实)。
$g^*(s)$是估计的从状态s到结束这个部分路径的最优分数(估计)。

如何能提出好的$g^*(s)$估计至今是研究者们探究的问题。

解码器—树状字典



解码器—Language model Look-ahead

在Tree Structured decoder中，把LM概率分配到结点上，而不是走到叶子结点才累积LM概率，从而更早的剪枝。

$$P(j|i,h) = \frac{\max_{w \epsilon \sigma(j)} P(w|h)}{\max_{v \epsilon \sigma(i)} P(v|h)}$$

在一个字典树上，N-gram的history是h，i和j为树上两个结点，w为从j结点能到达的所有词，v为从i结点能到达的所有词。那么从i结点到j结点上的概率由上式计算。

WFST介绍

试想你用高阶N-gram语言模型，一个有数以百万词的字典，构建一个解码图。

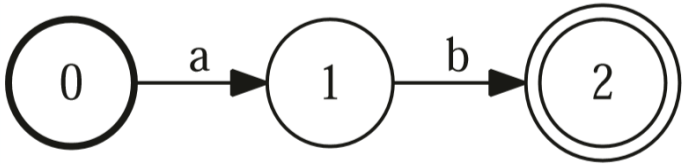
冗杂

高效，统一的解决办法：WFST构图

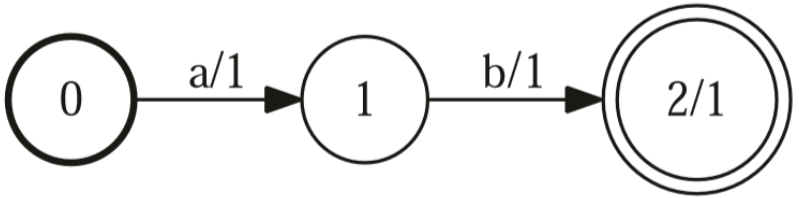
WFST介绍

epsilon

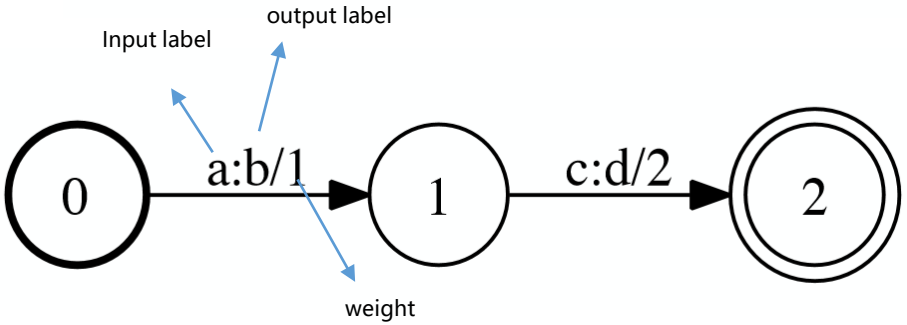
有限状态接收器(FSA): Finite-state Acceptor



加权有限状态接收器(WFSA):
Weighted Finite-state Acceptor



加权有限状态转换器(WFST):
Weighted Finite-state Transducer:



WFST介绍—半环

半环：

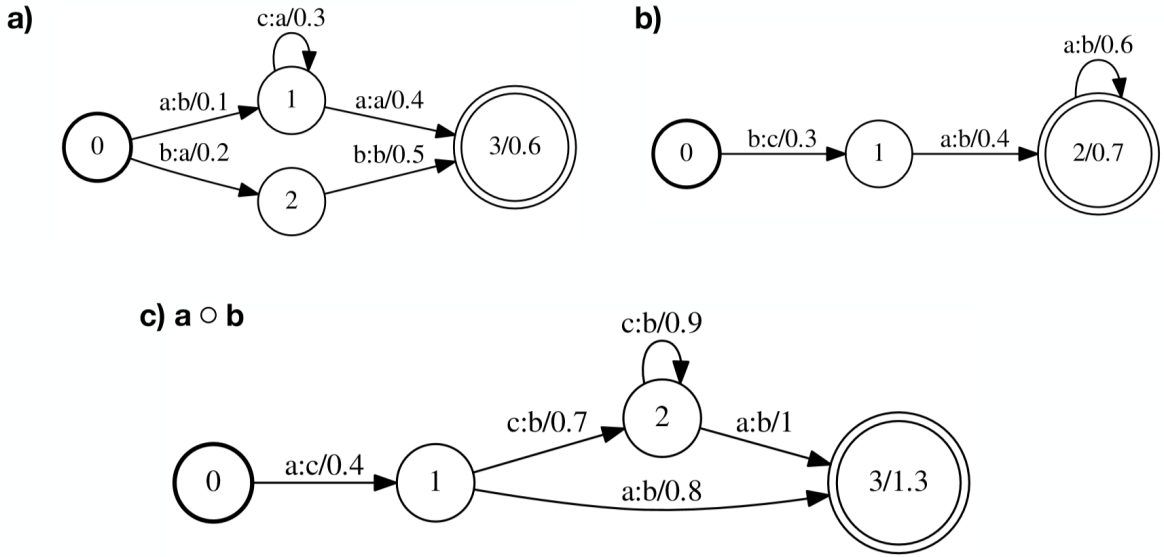
- 有一个元素集合(e.g. R)
- 有两个特殊元素$\bar{0}$(零元)和$\bar{1}$(幺元)
- 有两个操作$\oplus$(加操作)和$\otimes$(乘操作)。
  - 加操作有交换律，结合律，与零元相加为本身
  - 乘操作有结合律，于幺元乘为本身
  - 分配律：$w_1 \otimes (w_2 \oplus w_3) = (w_1 \otimes w_2) \oplus (w_1 \otimes w_3)$
  - 任意数与零元乘操作为零元。

SEMIRING	SET	$\oplus$	$\otimes$	$\bar{0}$	$\bar{1}$
Boolean	$\{0,1\}$	$\vee$	$\wedge$	0	1
Probability	$\mathbb{R}_+$	$+$	$\times$	0	1
Log	$\mathbb{R} \cup \{-\infty, +\infty\}$	$\oplus_{\log}$	$+$	$+\infty$	0
Tropical	$\mathbb{R} \cup \{-\infty, +\infty\}$	min	$+$	$+\infty$	0

From Mehryar Mohri, Speech Recognition with WFST

WFST介绍--Composition

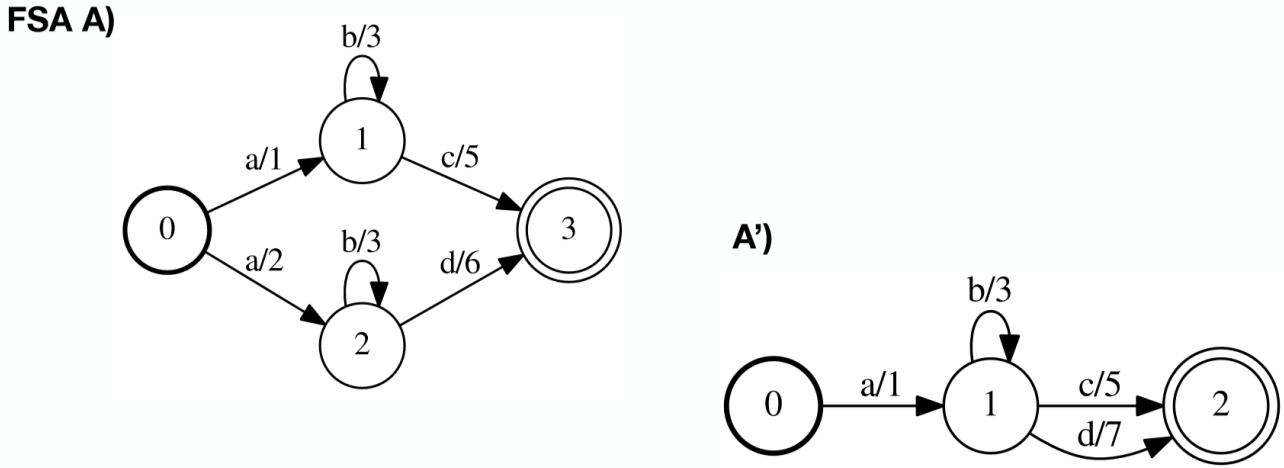
组合：如果一个转换器A将序列x映射到序列y伴随着权重a，并且转换器B将序列y映射到序列z伴随着权重b，那么组合的转换器将序列x映射到序列z，权重为a $\otimes b$。



假设Tropical半环

WFST介绍--Determinization

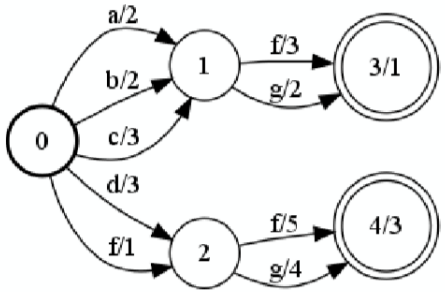
确定化：创建等价的FST，任意一个状态都没有两个相同input label的出弧(arc).
条件：这个FST是functional的，即每一个输入序列可以转换成独一无二的输出序列。

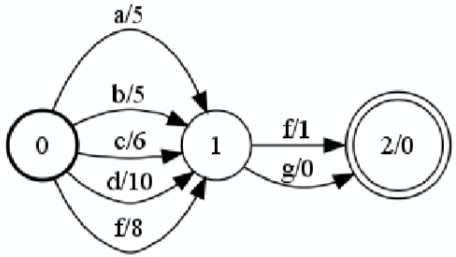


WFST介绍--Minimization

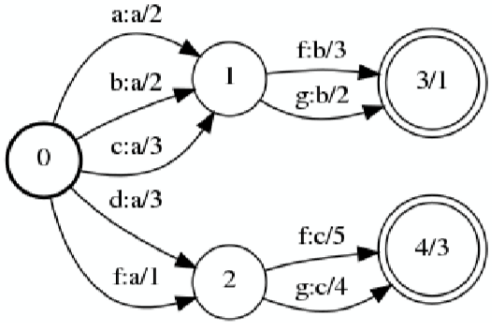
最小化：创建等价的FST，拥有最少的状态数和弧数。

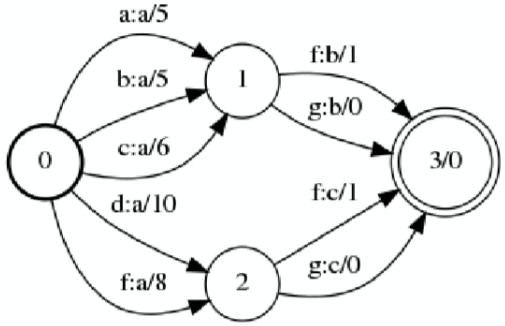
WFSA





WFST



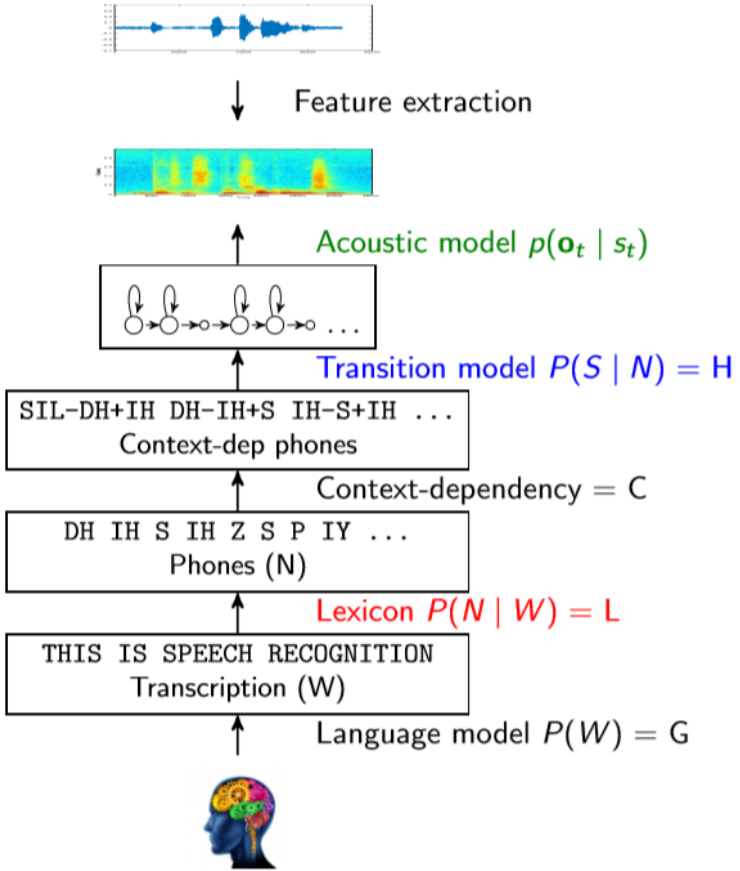


WFST介绍—其它操作

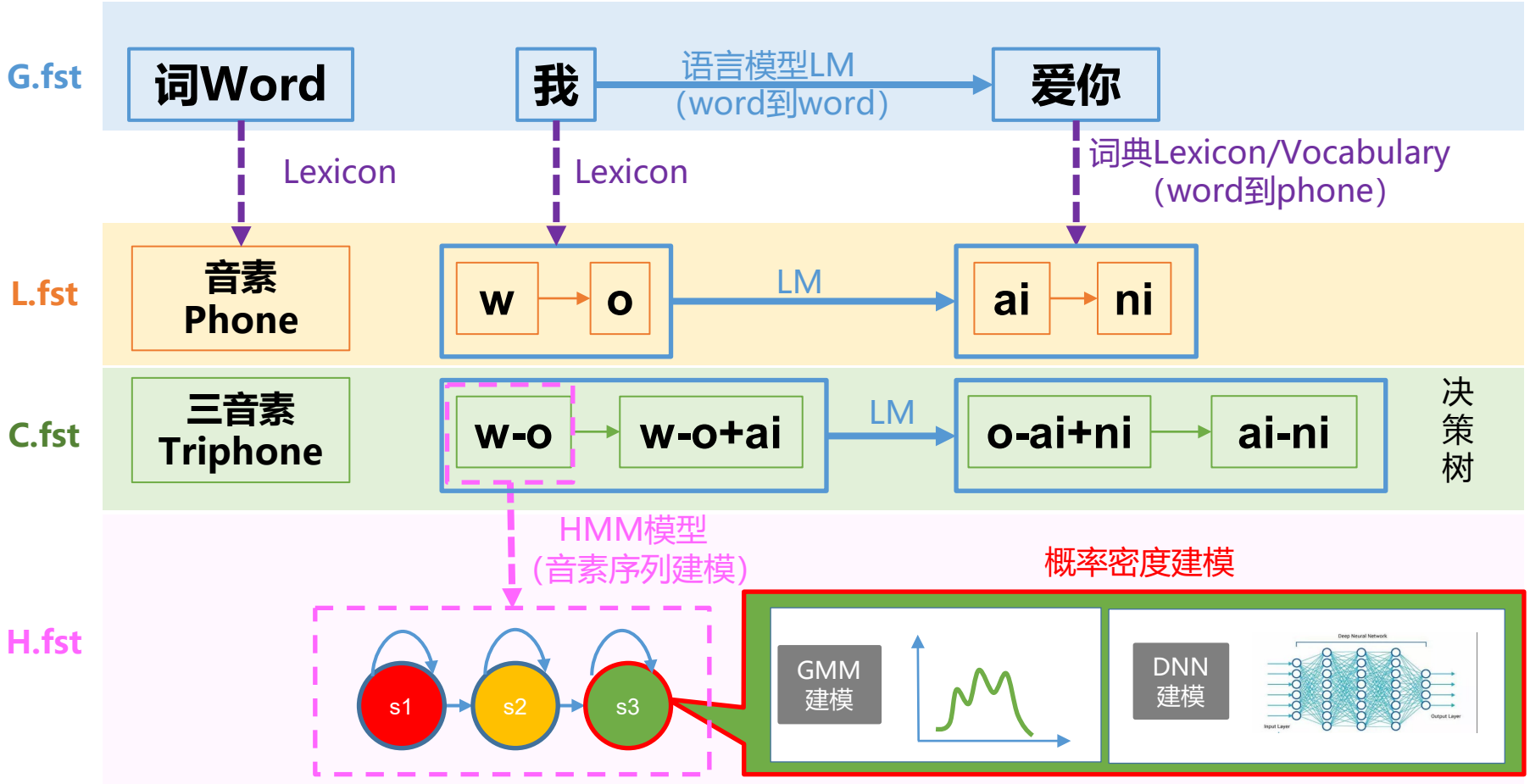
- 弧排序(ArcSort):根据input label或者output label排序每个state的arcs。
- 链接(Connect): 剪枝FST，去掉所有不在成功路径(从初始状态到终止状态）的state和arcs。
- 相等(Equal): 确定两个FST(A和B)有相同数量和顺序的state，arcs。
- 等价(Equivalent):确定两个不含epsilon的确定化状态机(A和B)等价，即对于相同的输入，有相同输出和权重。
- 推(Push)：将权重向初始状态或者终止状态推动。
- 。。。

小贴士：多看openfst官网

识别中的WFST


Feature extraction
Acoustic model $p(\mathbf{o}_t \mid s_t)$
Transition model $P(S \mid N) = \mathrm{H}$
SIL-DH+IH DH-IH+S IH-S+IH ...
Context-dep phones
Context-dependency = C
DH IH S IH Z S P IY ...
Phones (N)
Lexicon $P(N \mid W) = \mathrm{L}$
THIS IS SPEECH RECOGNITION
Transcription (W)
Language model $P(W) = \mathrm{G}$

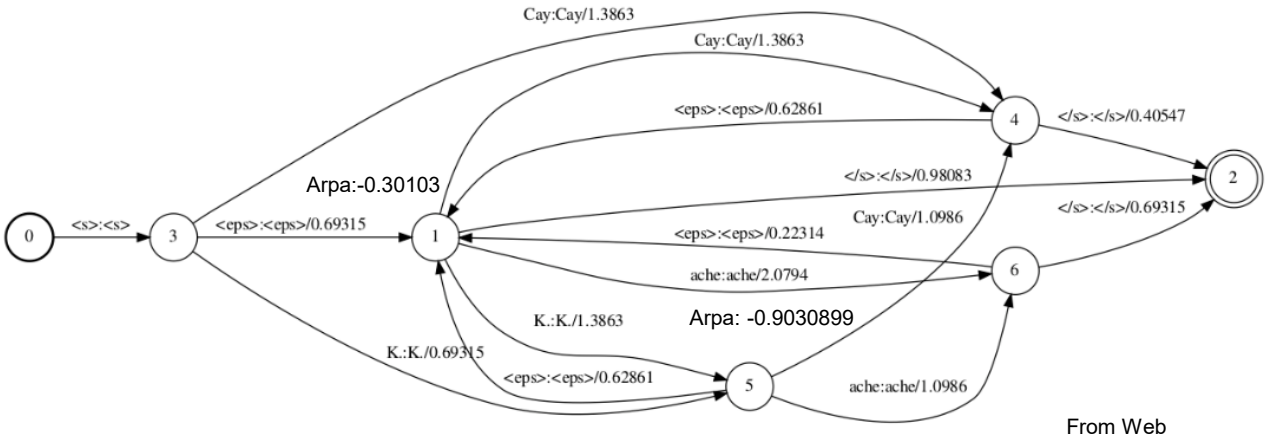
概念梳理图与HCLG


G.fst
词Word
我
语言模型LM
(word到word)
爱你
Lexicon
Lexicon
词典Lexicon/Vocabulary
(word到phone)
L.fst
音素
Phone
w
o
LM
ai
ni
C.fst
三音素
Triphone
w-o
w-o+ai
LM
o-ai+ni
ai-ni
决策树
HMM模型
(音素序列建模)
概率密度建模
H.fst
s1
s2
s3
GMM
建模
DNN
建模

识别中的WFST

G.Fst示例解析

State 0和1为history=空
State 2-6为history=</s>,<s>,<Cay>,<K>,<ache>

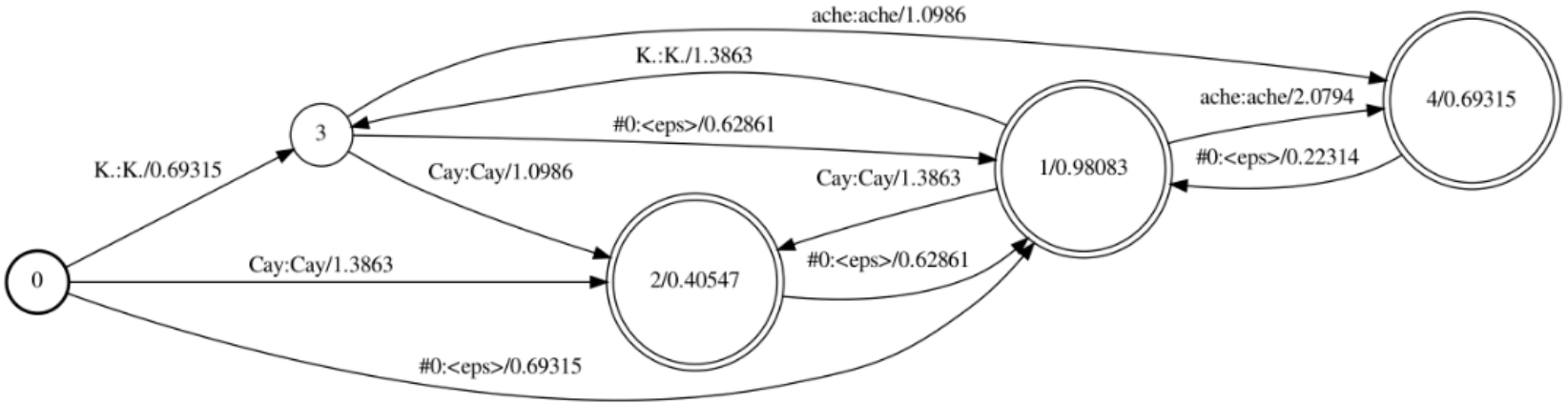


From Web

识别中的WFST

确定化的G.fst

a.用#0替换backoff边的input label
b.用epsilon替换<s>和</s>
c.确定化

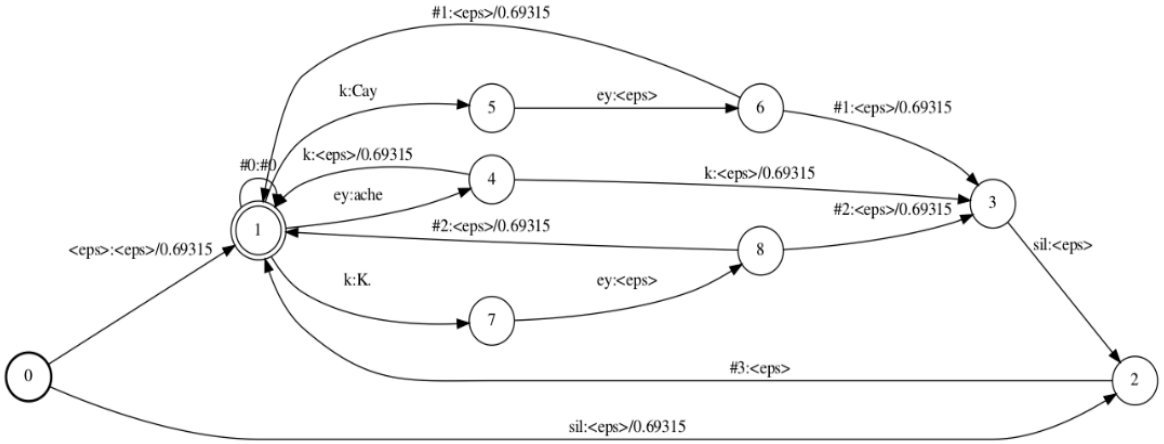


识别中的WFST

L.Fst介绍：

a. 消歧义符(disambiguation symbol,#1,#2…):解决发音前缀和同音异形字。
b. 为词前后添加silence。
c. Add-self-loop:为终止状态添加#0的自环，从而和G.fst合并。

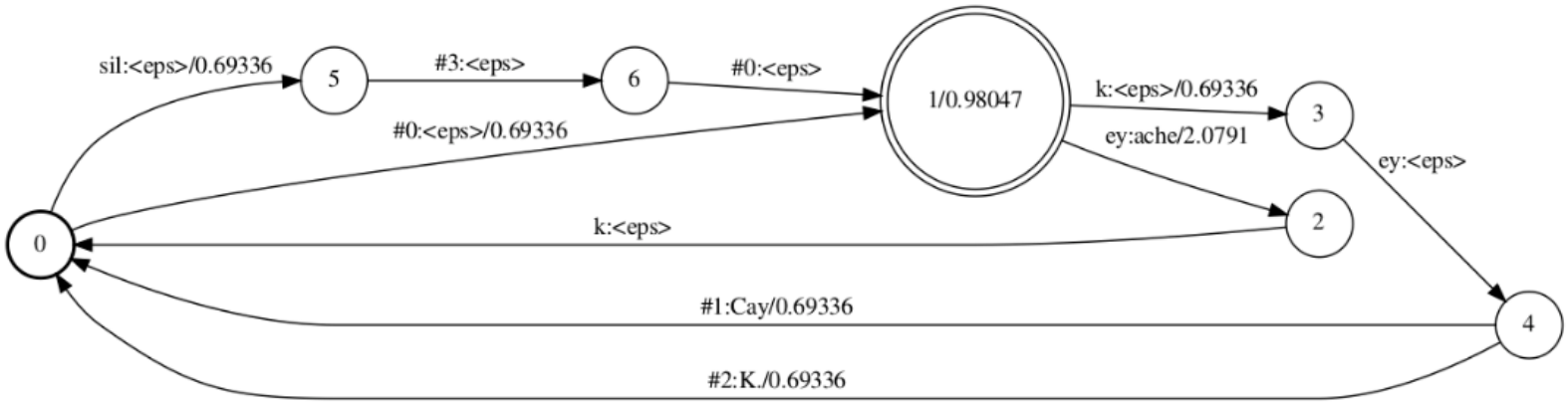
尝试自己写出字典：
Cay k ey
ache ey k
K. K ey



识别中的WFST

L compose G: [addsubsequentialloop由于C的尾处理]

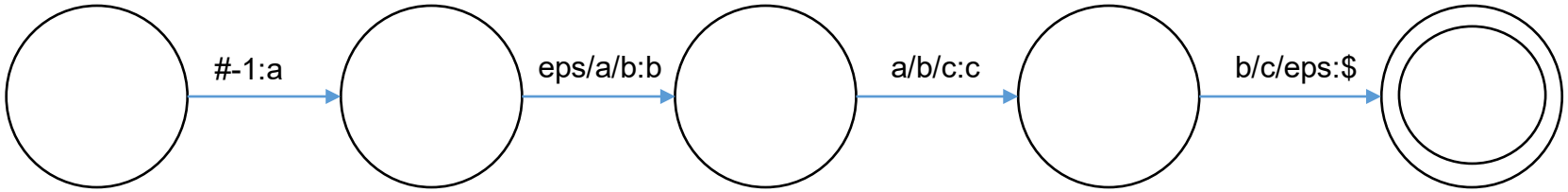
Kaldi有一些自己的fst command-line，略不同于Openfst，源于具体问题的处理。使用fst时善用openfst/bin, openfst/src, kaldi/src/fstbin, kaldi/src/fstext



识别中的WFST

a.通常Kaldi里不单独生成C，而是直接与LG进行compose，生成CLG [fstcomposecontext]。这样可以动态生成，避免穷举所有cd-phone.
b.Kaldi用N表示窗长，P表示中心音素位置。[left-context1/phone/right-context1]=[N=3,P=1]
c.(N=3,P=1为例):每个arc的格式为left/phone/right:right，如a/b/c:c，这里输出的不是中心音素。
d.用#-1和$处理开头结尾。
e.决策树会将你想的逻辑cd-phone变为绑定后的形式。[make-ilabel-transducer]

Logical cd-phone C的示意图：[Morhi的表示方法不同,格式为phone:phone/left_right]



识别中的WFST

H Fst:
理想化：我们只要把pdf-id到cd-phone就可以了。
但由于kaldi的决策树一个pdf-id可以对应若干cd-phone,所以引入了transition-id
= (transition-state, transition-index)
transition-state = (phone, hmm-state, forward pdf, self-loop pdf)—new
= (phone, hmm-state, pdf)—new

$$HCLG = asl(min(rds(det(H_a \circ min(det(C \circ min(det(L \circ G))))))))$$

加自环　去除消歧义符号

Kaldi

$$HCLG = rds(min(det(H \circ det(C \circ det(L \circ G)))))$$

Mohri.

识别中的WFST

	Input	output
H (HMM)	HMM状态 (transition-id kaldi)	上下文相关音素
C (Context-Dependency)	上下文相关音素	音素
L (Lexicon)	音素	词
G (grammar/language model,acceptor)	词	词

对于HCLG：每个arc的ilabel=transition-id, olabel=word-id, weight为transition概率,LM概率等, weight pushing后的值。

识别中的WFST—生成lattice—基于Viterbi的解码

WFST使得你的解码操作就是图上的搜索！

所以你的常用操作：

遍历state:

```
fst::StateIterator<FST> siter(*fst_); !siter.Done(); siter.Next() {
  const StateId &state_id = siter.Value();  ….
}
```

遍历arc:

```
fst::ArcIterator<FST> aiter(*fst_, state_id); !aiter.Done(); aiter.Next() {
  const Arc &arc = aiter.Value();
  BaseFloat graph_cost = arc.weight.Value();
}
```

你已经有了解码所需的WFST

Utterance对应的Lattice

识别中的WFST—生成lattice—所需数据结构

```
Token {
  BaseFloat tot_cost;      // 从句子其实到当前位置的cost
  BaseFloat extra_cost;  // 穿过该状态的best path与全局best path距离
  ForwardLinkT *links;  // 发出的所有arc
  Token *next;   // 当前帧的下一个token
}
```

```
ForwardLink {
  Token *next_token;  // 目标token
  Label ilabel;   // 输入标签
  Label olabel;  // 输出标签
  BaseFloat graph_cost;  // wfst图上的weight (LM等)
  BaseFloat acoustic_cost;  // 发射概率
  ForwardLink *next;  //下一个link
}
```

识别中的WFST—生成lattice—核心函数

ProcessEmitting():
处理那些需要发射概率的arc，即ilabel ！ = 0。

ProcessNonemitting():
处理那些不需要发射概率的arc，即ilabel == 0。

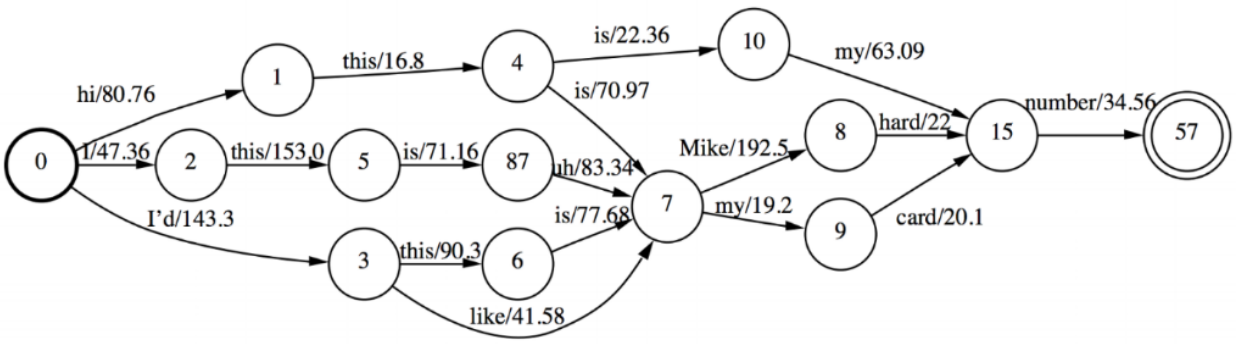
FindOrAddToken():
创立新Token或对同一时刻，到达同一状态的token合并。

识别中的WFST—再看lattice

对于HCLG：每个arc的ilabel=transition-id, olabel=word-id, weight。

在kaldi里有Lattice和CompactLattice，是一个事物的两种存储形式，可以相互转化，在外观上都和HCLG相似，由state和arc组成, 从中你可以知道概率分数和时间。

Lattice的arc：ilabel=transition-id, olabel=word-id, weight=(graph_cost, acoustic_cost)
CompactLattice的arc: ilabel=olabel=word-id, weight=(graph_cost, acoustic_cost, transition-id sequence).



识别中的WFST—从lattice转换了解基本操作

```
void Factor(const Fst<Arc> &fst, MutableFst<Arc> *ofst,
            std::vector<std::vector<I> > *symbols_out) {
  KALDI_ASSERT_IS_INTEGER_TYPE(I);
  typedef typename Arc::StateId StateId;
  typedef typename Arc::Label Label;
  typedef typename Arc::Weight Weight;
  assert(symbols_out != NULL);
  ofst->DeleteStates();
  if (fst.Start() < 0) return;  // empty FST.
  std::vector<StateId> order;
  DfsOrderVisitor<Arc> dfs_order_visitor(&order);
  DfsVisit(fst, &dfs_order_visitor);
  assert(order.size() > 0);
  StateId max_state = *(std::max_element(order.begin(), order.end()));
  std::vector<StatePropertiesType> state_properties;
  GetStateProperties(fst, max_state, &state_properties);

  std::vector<bool> remove(max_state+1);  // if true, will remove this state.

  // Now identify states that will be removed (made the middle of a chain).
  // The basic rule is that if the FstStateProperties equals
  // (kStateArcsIn|kStateArcsOut) or (kStateArcsIn|kStateArcsOut|kStateIlabelsOut),
  // then it is in the middle of a chain.  This eliminates state with
  // multiple input or output arcs, final states, and states with arcs out
  // that have olabels [we assume these are pushed to the left, so occur on the
  // 1st arc of a chain.

  for (StateId i = 0; i <= max_state; i++)
    remove[i] = (state_properties[i] == (kStateArcsIn|kStateArcsOut)
                 || state_properties[i] == (kStateArcsIn|kStateArcsOut|kStateIlabelsOut));
  std::vector<StateId> state_mapping(max_state+1, kNoStateId);

  typedef unordered_map<std::vector<I>, Label, kaldi::VectorHasher<I> > SymbolMapType;
  SymbolMapType symbol_mapping;
  Label symbol_counter = 0;
  {
    std::vector<I> eps;
    symbol_mapping[eps] = symbol_counter++;
  }
```

```
  std::vector<I> this_sym;  // a temporary used inside the loop.
  for (size_t i = 0; i < order.size(); i++) {
    StateId state = order[i];
    if (!remove[state]) {  // Process this state...
      StateId &new_state = state_mapping[state];
      if (new_state == kNoStateId) new_state = ofst->AddState();
      for (ArcIterator<Fst<Arc> > aiter(fst, state); !aiter.Done(); aiter.Next()) {
        Arc arc = aiter.Value();
        if (arc.ilabel == 0) this_sym.clear();
        else {
          this_sym.resize(1);
          this_sym[0] = arc.ilabel;
        }
        while (remove[arc.nextstate]) {
          ArcIterator<Fst<Arc> > aiter2(fst, arc.nextstate);
          assert(!aiter2.Done());
          const Arc &nextarc = aiter2.Value();
          arc.weight = Times(arc.weight, nextarc.weight);
          assert(nextarc.olabel == 0);
          if (nextarc.ilabel != 0) this_sym.push_back(nextarc.ilabel);
          assert(static_cast<Label>(static_cast<I>(nextarc.ilabel))
                 == nextarc.ilabel); // check within integer range.
          arc.nextstate = nextarc.nextstate;
        }
        StateId &new_nextstate = state_mapping[arc.nextstate];
        if (new_nextstate == kNoStateId) new_nextstate = ofst->AddState();
        arc.nextstate = new_nextstate;
        if (symbol_mapping.count(this_sym) != 0) arc.ilabel = symbol_mapping[this_sym];
        else arc.ilabel = symbol_mapping[this_sym] = symbol_counter++;
        ofst->AddArc(new_state, arc);
      }
      if (fst.Final(state) != Weight::Zero())
        ofst->SetFinal(new_state, fst.Final(state));
    }
  }
  ofst->SetStart(state_mapping[fst.Start()]);
  // Now output the symbol sequences.
  symbols_out->resize(symbol_counter);
  for (typename SymbolMapType::const_iterator iter = symbol_mapping.begin();
       iter != symbol_mapping.end(); ++iter)
    (*symbols_out)[iter->second] = iter->first;
```

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感谢聆听！

Thanks for Listening