Hierarchical Phrase-based Translation Representations

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Hierarchical Phrase-Based Decoding I

Given:

- A source sentence s
- A Synchronous Context Free Grammar (SCFG) G
- An n-gram Language Model M

Exact decoding is done in three general steps:

1. *Apply the grammar to the sentence:* $\mathcal{T} = \{s\} \circ G$
2. *Intersect the Search Space* $\mathcal{T}$ *with the language model :* $\mathcal{L} = \mathcal{T} \cap M$,
3. *Search for the highest-probablity path:* $\mathrm{argmax}\ \mathcal{L}$

Hierarchical Phrase-Based Decoding II

- Different **hierarchical phrase-based translation representations** of the space of translation hypotheses $\mathcal{T}$:
  - Hypergraphs: Cube Pruning Decoder[1]
  - Finite-State Automata(FSA): **HiFST**, a weighted finite-state hiero decoder[2].
    - Exact Search for carefully designed hiero grammars
- This paper: We propose to use Push-Down Automata (PDA) in the decoder (**HiPDT**) for exact decoding of larger grammars.

[1] David Chiang. **Hierarchical phrase-based translation.** Computational Linguistics, 2007. 33(2), pp201-228.

[2] G. Iglesias et al.**Hierarchical phrase-based translation with weighted finite state transducers.** In Proceedings of NAACL 2009, pp433-441.

Push-Down Automata I

- Informally: PDA augment FSA with a stack
- PDT extension[3] implemented in OpenFST[4].
  - We restrict a transition to be labeled by a stack operation or a regular input symbol but not both.
  - Stack operations are **implicitly** represented by pairs of open and close ”parentheses”
  - This representation is identical to the finite automaton representation except that certain symbols
    (the parentheses) have special semantics.
  - Advantage: many FSA operations still work or do so with minor changes

[3] Cyril Allauzen and Michael Riley. **Pushdown Transducers**.http://pdt.openfst.org,2011.

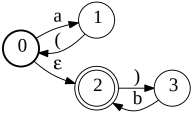
[4] Cyril Allauzen et al.**OpenFst: A General and Efficient Weighted Finite-State Transducer Library.** In Proceedings of CIAA, 2007.

Push-Down Automata II

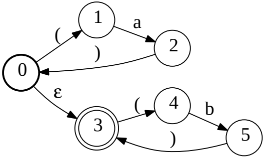
- A *weighted pushdown automaton* (PDA) T over the tropical semiring $(\mathbb{R} \cup \{\infty\}, \min, +, \infty, 0)$ is a 9-tuple $(\Sigma, \Pi, \overline{\Pi}, Q, E, I, F, \rho)$ where Σ is the finite input alphabet, Π **and** $\overline{\Pi}$ **are the finite open and close parenthesis alphabets,** Q is a finite set of states, $I \in Q$ the initial state, $F \subseteq Q$ the set of final states, $E \subseteq Q \times (\Sigma \cup \widehat{\Pi} \cup \{\epsilon\}) \times (\mathbb{R} \cup \{\infty\}) \times Q$ a finite set of transitions, and $\rho : F \to \mathbb{R} \cup \{\infty\}$ the final weight function.

- A *weighted finite state automaton* (FSA) is a particular case of a PDA where the open and close parentheses alphabets are empty.

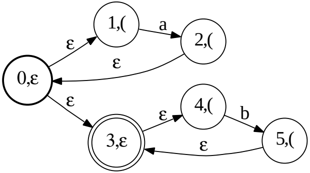
Push-Down Automata III



PDA accepting $a^n b^n$



PDA accepting $a^* b^*$.



Equivalent FSA

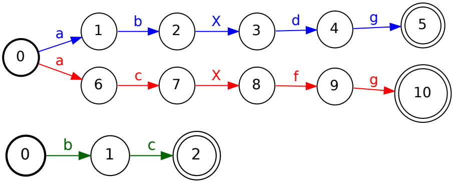
- An accepting path π is **balanced** if its sequence of open/close parentheses is in a Dyck Language ([( ) ( )] { } [ ]) ( )
- Accepts paths with finite number of unmatched open parentheses – bounded stack
- There exists an equivalent FSA.

Replacement

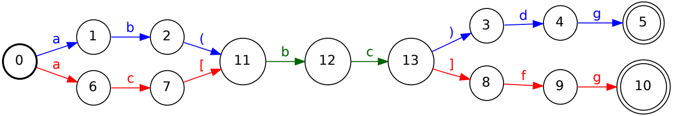
The replacement algorithm transforms a Recursive Transition Network (RTN) into an equivalent PDA

- RTN:

$S \rightarrow a\ b\ X\ d\ g$
$S \rightarrow a\ c\ X\ f\ g$
$X \rightarrow b\ c$



- PDA:



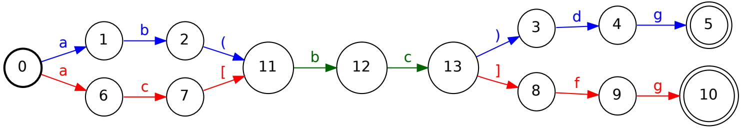
- The replacement algorithm transforms an RTN into an equivalent PDA.
- The RTN has finite recursion level → PDA guaranteed to have a bounded stack.

Intersection

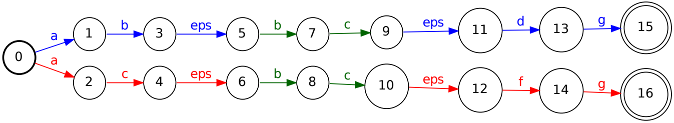
- PDA T intersection with FSA M is closed (Bar-Hillel intersection)
- Almost identical to FSA intersection
  - parentheses treated as epsilons but retained as parentheses in the result
- Time/Space complexity: $O(|T||M|)$

Expansion

- If the PDA is stack-bounded, it represents a regular language $\rightarrow$ The PDA can be expanded into an equivalent FSA.
- PDA:



- FSA:



Shortest Distance

SHORTESTDISTANCE(T)

for each $q \in Q$ and $a \in \Pi$ **do**
  $B[q,a] \leftarrow \emptyset$
GETDISTANCE(T, I)
return $d[f, I]$

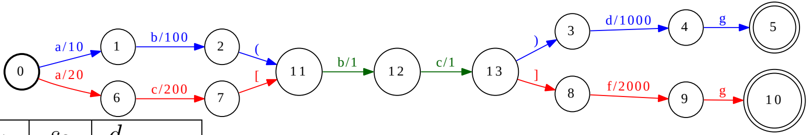
RELAX$(q, s, w, \mathcal{S})$

if $d[q,s] > w$ **then**
  $d[q,s] \leftarrow w$
  if $q \notin \mathcal{S}$ **then**
    ENQUEUE$(\mathcal{S}, q)$

GETDISTANCE(T, s)

for each $q \in Q$ **do**
  $d[q,s] \leftarrow \infty$
$d[s,s] \leftarrow 0$
$\mathcal{S}_s \leftarrow s$
while $\mathcal{S}_s \neq \emptyset$ **do**
  $q \leftarrow$ HEAD$(\mathcal{S}_s)$
  DEQUEUE$(\mathcal{S}_s)$
  for each $e \in E[q]$ **do**
    if $i[e] \in \Sigma \cup \{\epsilon\}$ **then**
      RELAX$(n[e], s, d[q,s] + w[e], \mathcal{S}_s)$
    elseif $i[e] \in \overline{\Pi}$ **then**
      $B[s, \overline{i[e]}] \leftarrow B[s, \overline{i[e]}] \cup \{e\}$
    elseif $i[e] \in \Pi$ **then**
      if $d[n[e], n[e]]$ is undefined **then**
        GETDISTANCE$(T, n[e])$
      for each $e' \in B[n[e], i[e]]$ **do**
        $w \leftarrow d[q,s] + w[e] + d[p[e'], n[e]]$ -
        RELAX$(n[e'], s, w, \mathcal{S}_s)$

Shortest Distance



s_1	s_2	$d_{s_1 \to s_2}$
0	0	0
0	1	10
0	2	110
11	11	0
11	12	1
11	13	2
0	3	112
...		
0	6	20
0	7	220
0	8	222
...		

- Memoization of shortest distance for local sub-lattices
- For a general PDA, complexity $O(|T|^3)$
- If PDA derived from acyclic RTN $\rightarrow$ complexity $O(|T|)$
- But if PDA intersected with M this introduces $|M|^3$ in time complexity

Hiero with RTN/FSA

- **HiFST decoder**[5]: $\longrightarrow$ $\boxed{\text{Time/Space: } O(e^{|s|^3|G|}\,|M|)}$
  1. CYK Parse sentence s with Grammar G. **(finite)**
  2. Build RTN **(no cyclic references)**
  3. Expand RTN to FSA
  4. Intersect FSA with Language Model **M**
  5. Shortest Path / prune for lattice rescoring

[5] Adrià de Gispert et al. **Hierarchical Phrase-based Translation with Weighted Finite State Transducers and Shallow-N Grammars.** Computational Linguistics,2010.

Hiero with PDA

- **HiPDT decoder**: $\longrightarrow$ $\boxed{\text{Time: } O(|s|^3|G|\,|M|^3)\text{; Space: } O(|s|^3|G|\,|M|^2)}$
  1. CYK Parse sentence s with Grammar G. **(finite)**
  2. Build RTN **(no cyclic references)**
  3. Convert RTN into PDA (Replacement algorithm) **(stack-bounded)**
  4. Intersect PDA with **M**
  5. PDA-Shortest Path / (Pruned) Expansion of PDA for lattice rescoring
- **CFG/Hypergraph decoder**: $\longrightarrow$ $\boxed{\text{Time,Space: } O(|s|^3|G|\,|M|^3)}$
- **HiFST decoder**: $\longrightarrow$ $\boxed{\text{Time,Space: } O(e^{|s|^3|G|}\,|M|)}$

- In practice, HiFST and HiPDT faster due to **optimizations** over RTN
- HiPDT will be more efficient than HiFST for bigger grammars, if language model is small enough.
- HiFST more efficient with bigger language models and smaller grammar

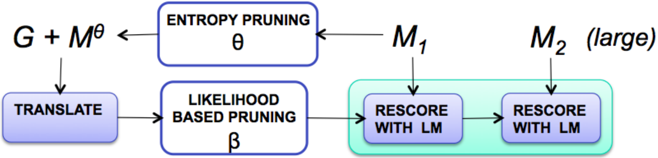
Decoding Pipeline with Entropy-Pruned LMs I

- Given:
  1. Hierarchical Grammar G
  2. Language Model M_1 for decoding
  3. Large 5-gram Language Model M_2 for rescoring
- We entropy-prune[6] M_1 under relative perplexity θ to obtain M^θ for direct translation + rescoring with M_1
- Successful in Speech Recognition systems[7]

[6] Andreas Stolcke. **Entropy-based Pruning of Backoff Language Models.** Proceedings of DARPA Broadcast News Transcription and Understanding Workshop, 1998.

[7] Andrej Ljolje et al. **Efficient general lattice generation and rescoring.** In Proceedings of Eurospeech, 1999.

Decoding Pipeline with Entropy-Pruned LMs II

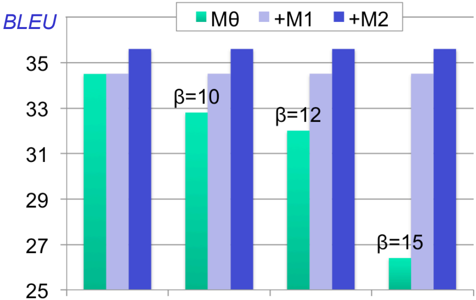


1. Fast translation under M^θ
2. Likelihood based pruning of output lattice, beam width β
3. Take out M^θ scores from lattice
4. Rescore lattice with M_1
5. Additionally, rescore with large 5-gram model M_2

Zh→En Translation with Compact Grammars

- Compact Grammar G_1
  - Only rules with translation probability > 0.01 are used
  - Entire lattice can be expanded and intersected with M_1
  - FSA (HiFST) and PDA (HiPDT) representations equally good
  - Exact decoding – we can analyse impact of different entropy pruned language models

- Full performance recovered after rescoring with LM
- Critical beam width β required
- Decoding speed-up



Entropy threshold θ	-	1.0E-09	1.0E-08	1.0E-07
Number of N-grams:	200M	20M	4M	1M
Time (sec/w):	0.68	0.38	0.28	0.20

Zh→En Translation with Large Grammars

- Large Grammar G_2
  - All observed rules are considered (+alternatives per rule)
  - HiFST representation cannot decode under 10GB
    - RTN expansion is critical (pruning in search would alleviate)
  - HiPDT achieves exact decoding under small M_θ

	HiFST			HiPDT		
entropy pruning θ	Success	Expand Fails	Intersect Fails	Success	Intersect Fails	Expand Fails
10^{-9}	12%	51%	37%	40%	8%	52%
10^{-8}	16%	53%	31%	76%	1%	23%
10^{-7}	18%	53%	29%	**99.8%**	0%	0.2%

- Improved results with HiPDT (+0.5 BLEU) due to exact decoding with larger grammar G_2.

Conclusions

- HiPDT allows exact decoding of larger hierarchical grammars than HiFST, but with smaller language models – Improves translation performance
- Expensive PDA shortest path algorithm after PDA intersection with LM
- Entropy-pruned LMs allow *faster decoding times*, less memory requirements. Same performance after LM rescoring.
- Translation search space is finite – RTN/PDA/FSA efficient representations
- HiPDT (and HiFST) implemented with general purpose library OpenFST[8] – complexity is hidden to the user

- Hybrid FSA/PDA approach for improved robustness (exact decoding under M when feasible)
- Other LM smoothing strategies[9]

[8] See www.openfst.org

[9] Chelba et al. **Study on Interaction between Entropy Pruning and Kneser-Ney Smoothing.** In Proceedings of Interspeech 2010.

Thank you!

Questions?