Decoding for SMT

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Content

Model of translational equivalences

Describes the process of generating translations of a given input

- constrains and characterises
  the set of possible translation derivations

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we observe an input, segment it into phrases, permute the phrases into target language word-order, and finally, translate segments independently

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Hierarchical MT

we parse the input with a CFG, then translate (using synchronous rules) each and every edge independently

CFGs and FSAs

Compactly represent the set of translations

- keep the representation cost a tractable (polynomial) function of the input length

Phrase-based MT $O(n^2 2^d)$

Hierarchical MT $O(n^3)$

Independence assumptions

Translation rules (flat or CFG) are applied independently

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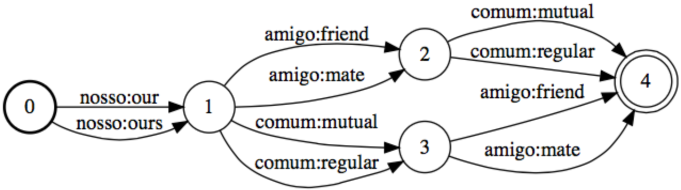

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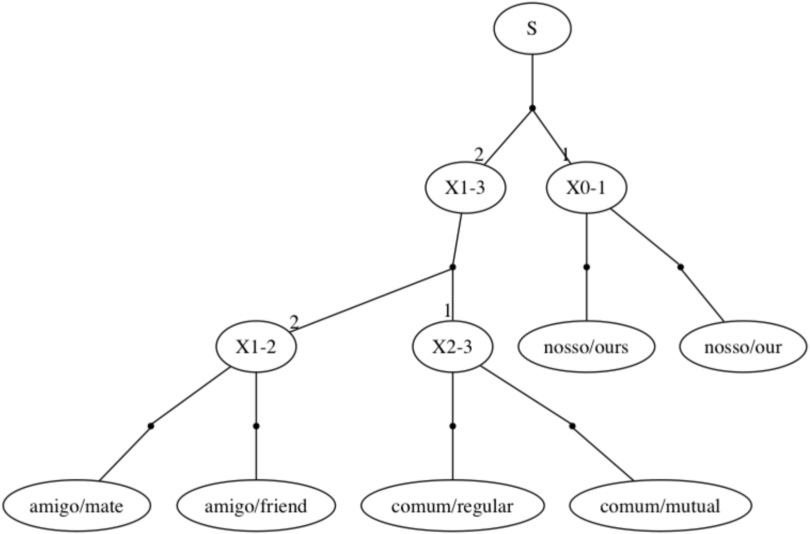

Directed B-hypergraphs

A hypergraph $\langle V, E \rangle$ consists of

- a set of nodes V
- a set of edges E
- an edge e has
  - a head node $\mathrm{head}(e) \in V$
  - a tail $\mathrm{tail}(e) \in V^*$ (sequence of nodes)

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CFGs

- nonterminal $\rightarrow$ node
- terminal $\rightarrow$ terminal node
- rule $\rightarrow$ edge
- LHS $\rightarrow$ head
- RHS $\rightarrow$ tail

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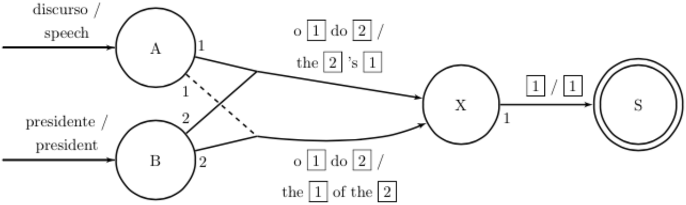
FSAs

- state $\rightarrow$ node
- symbol $\rightarrow$ terminal node
- transition $\rightarrow$ edge
- origin $\rightarrow$ tail node
- destination $\rightarrow$ head

A forest as a hypergraph



(a) Hypergraph

LHS	RHS_i	RHS_o
S →	X	$\boxed{1}$
X →	o A do B	the $\boxed{2}$'s $\boxed{1}$
X →	o A do B	the $\boxed{1}$ of the $\boxed{2}$
A →	discurso	speech
B →	presidente	president

(b) Synchronous rules

Weighted sets

A weighted set $\langle \mathcal{D}, \omega \rangle$ consists of

- a set of structures (e.g. hyperpaths/derivations)
- a function $w : \mathcal{D} \to \mathcal{K}$

Let us focus on weighted sets whose weight functions factorise

$$w(\mathbf{d}) = \bigotimes_{e \in \mathbf{d}} w(e)$$

Often the structure is just a means to an end (the yield)

$$w(\mathbf{y}) = \bigoplus_{\mathbf{d} \in \mathcal{D}_{\mathbf{y}}} w(\mathbf{d})$$

Semirings

An algebraic structure $\mathcal{K} = \langle \mathbb{K}, \oplus, \otimes, \bar{0}, \bar{1} \rangle$

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- $\otimes$ left distributes over $\oplus$
  $a \otimes (b \oplus c) = (a \otimes b) \oplus (a \otimes c)$
- $\bar{0}$ is the $\otimes$-annihilator
  $\bar{0} \otimes a = a \otimes \bar{0} = \bar{0}$

Examples of semirings

Name	$\mathbb{K}$	$\oplus$	$\otimes$	$\bar{0}$	$\bar{1}$
Binary	$\{0, 1\}$	$\vee$	$\wedge$	0	1
Counting	$\mathbb{N}$	$+$	$\times$	0	1
Prob	$[0, 1] \subset \mathbb{R}$	$+$	$\times$	0	1
LogProb	$\mathbb{R} \cup \{-\infty\}$	$\oplus_{\log}$	$+$	$-\infty$	0
Viterbi	$\mathbb{R} \cup \{-\infty\}$	$\max$	$+$	$-\infty$	0

where $a \oplus_{\log} b = \log(\exp(a) + \exp(b))$

Linear models

$$f(\mathbf{d}) = \mathbf{w}^\top \mathbf{\Phi}(\mathbf{d})$$

where

- $\mathbf{w} \in \mathbb{R}^m$
- $\mathbf{\Phi}(\mathbf{d}) = \langle \Phi_1(\mathbf{d}), \ldots, \Phi_m(\mathbf{d}) \rangle$
- $\Phi_i(\mathbf{d}) \in \mathbb{R}$ is a feature function
- w_i is the relative contribution of the ith feature

Linear models and independence assumptions

$$f(\mathbf{d}) = \mathbf{w}^\top \mathbf{\Phi}(\mathbf{d}) \quad (1)$$

$$= \sum_{i=1}^{m} w_i \Phi_i(\mathbf{d}) \quad (2)$$

$$= \sum_{i=1}^{m} w_i \prod_{e \in \mathbf{d}} \phi_i(e) \quad (3)$$

$$= \prod_{e \in \mathbf{d}} \sum_{i=1}^{m} w_i \phi_i(e) \quad (4)$$

$$= \prod_{e \in \mathbf{d}} \mathbf{w}^\top \boldsymbol{\phi}(e) \quad (5)$$

Assumption

- $\Phi_i(\mathbf{d})$ factorises over edges
  $\phi_i(e)$ is a local feature function

Linear models and CFGs

Linear models can be expressed through hypergraphs using an appropriate semiring

Decision rules

Best translation (MAP)

$$\mathbf{y}^* = \arg\max_{\mathbf{y}} \sum_{d \in \mathcal{D}_{\mathbf{y}}} f(\mathbf{d})$$

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Best derivation (Viterbi)

$$\mathbf{y}^* \approx \text{yield}\left\{\arg\max_{\mathbf{d}} f(\mathbf{d})\right\}$$

- less disambiguation power
- VITERBI semiring

Other decision rules?

Minimum Bayes risk (MBR)

$$\mathbf{y}^* = \arg\min_{\mathbf{y}'} \langle L(\mathbf{y}', \mathbf{y}) \rangle_{p(\mathbf{y})}$$

- requires the underlying model to have a probabilistic interpretation
- can be estimated through sampling

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Log-linear models

$$p(\mathbf{d}) = \frac{\exp(f(\mathbf{d}))}{\sum_{\mathbf{d}'} \exp(f(\mathbf{d}'))} \propto \exp\left(\sum_{e \in \mathbf{d}} \mathbf{w}^\top \boldsymbol{\phi}(e)\right) = \prod_{e \in \mathbf{d}} \exp(\mathbf{w}^\top \boldsymbol{\phi}(e))$$

LogProb semiring

Decoding

In SMT, decoding typically means the Viterbi approximation

$$\mathbf{d}^* = \arg\max_{\mathbf{d}} f(\mathbf{d})$$

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If the statistical model $f(\mathbf{d})$ does not violate the independence assumptions of the model of translational equivalences

- steps in a derivation are weighted independently

Decoding

In SMT, decoding typically means the Viterbi approximation

$$\mathbf{d}^* = \arg\max_{\mathbf{d}} f(\mathbf{d})$$

If the statistical model $f(\mathbf{d})$ does not violate the independence assumptions of the model of translational equivalences

- steps in a derivation are weighted independently

there is a straightforward (tractable) decomposition of $f(\mathbf{d})$

- wFSA (phrase-based MT)
- wCFG (hierarchical MT)

Inside

The INSIDE recursion can be generalised to an arbitrary semiring

$$\beta(v) = \begin{cases} \bar{1} & \text{if } BS(v) = \emptyset \\ \displaystyle\bigoplus_{e \in BS(v)} w(e) \bigotimes_{u \in \text{tail}(e)} \beta(u) & \text{otherwise} \end{cases}$$

Inside

The Inside recursion can be generalised to an arbitrary semiring

$$\beta(v) = \begin{cases} \bar{1} & \text{if } BS(v) = \emptyset \\ \bigoplus_{e \in BS(v)} w(e) \bigotimes_{u \in \text{tail}(e)} \beta(u) & \text{otherwise} \end{cases}$$

- efficient bottom-up dynamic program $O(|G|)$
  $|G|$ is the size of the graphical representation of $f(\mathbf{d})$
  - a lattice (phrase-based MT)
  - a forest (hierarchical MT)

Inference

Viterbi derivation

1. start from the goal (root)
2. recursively rewrite every symbol v by solving

$$e = \arg\max_{e \in BS(v)} w(e) \bigotimes_{u \in \mathrm{tail}(e)} \beta(u)$$

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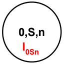
Sampling

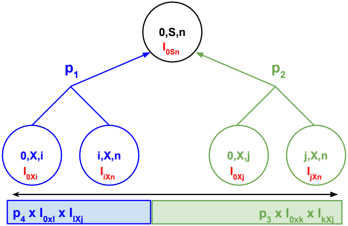
1. start from the goal (root)
2. recursively rewrite every symbol v by solving

$$e \sim p(e \in BS(v)|v) = \frac{w(e) \bigotimes_{u \in \text{tail}(e)} \beta(u)}{\beta(v)}$$

Viterbi



Viterbi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I0Sn
p1
p2
0,X,i
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IiXn
0,X,j
I0Xj
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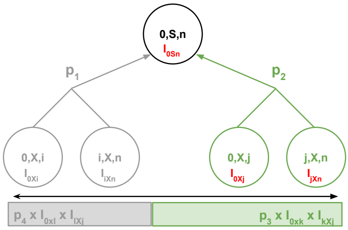
IjXn
p4 x I0xl x IlXj
p3 x I0xk x IkXj

Viterbi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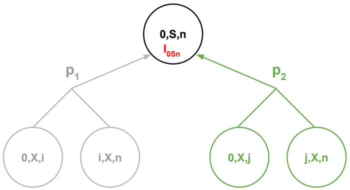

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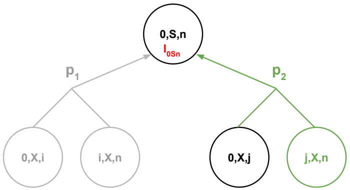

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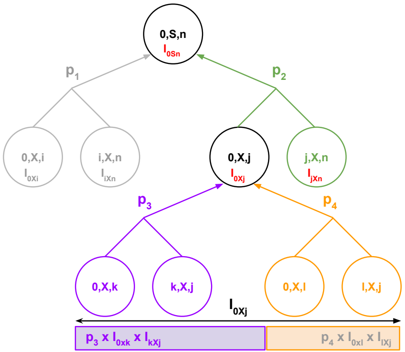
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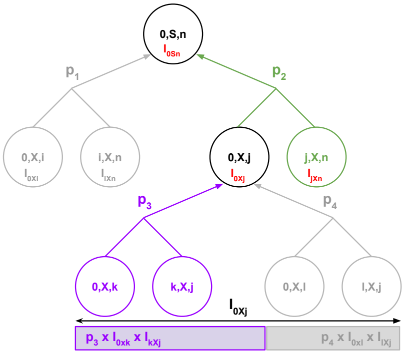
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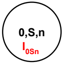
Sampling



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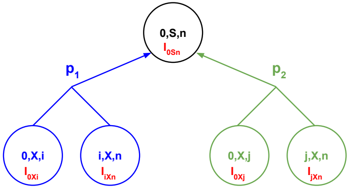

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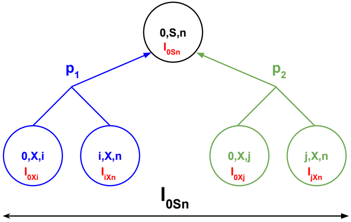

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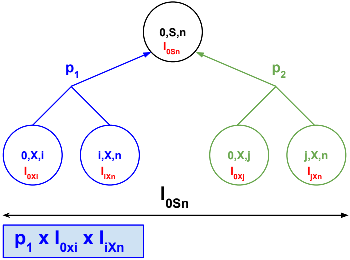
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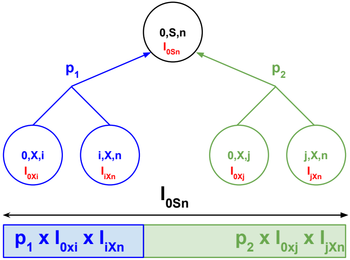
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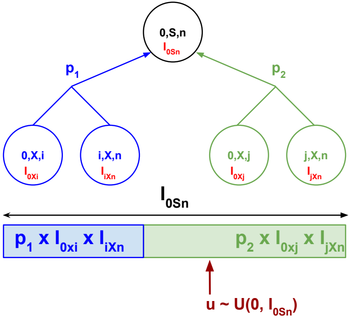
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u ~ U(0, I0Sn)

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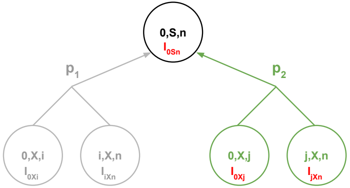

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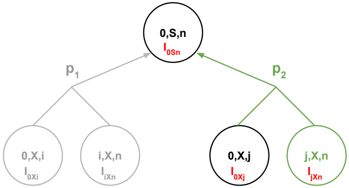

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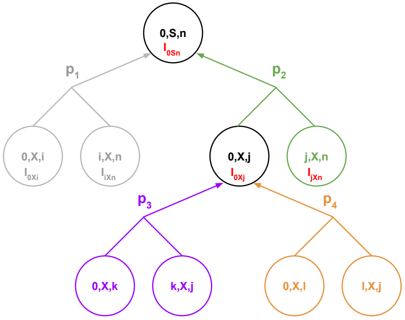
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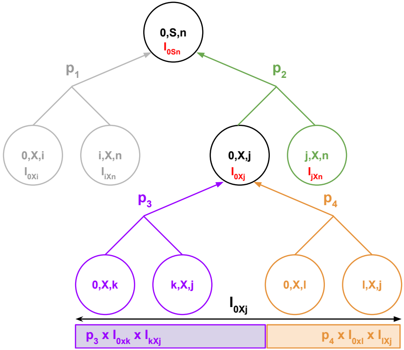
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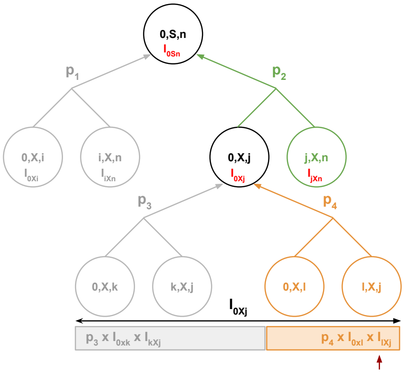
$p_4 \times I_{0xl} \times I_{lXj}$

Sampling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An example for hierarchical models

Model $f(\mathbf{d}) = \sum_i \varphi(e_i)$
where $\varphi(e_i)$ is a weighted combination of local features

Grammar

$X \rightarrow \langle \text{a}, \text{the} \rangle$
$X \rightarrow \langle \text{luz}, \text{light} \rangle$
$X \rightarrow \langle \text{apague } X_1, \text{switch } X_1 \text{ off} \rangle$
$X \rightarrow \langle X_1 \text{ por favor}, \text{please , } X_1 \rangle$
$X \rightarrow \langle X_1 X_2, X_1, X_2 \rangle$
$S \rightarrow \langle \vdash X_1 \dashv, \vdash X_1 \dashv \rangle$

Input: apague a luz por favor
Reference: please, switch the light off

Decoding with local features

Node	apague	a	luz	por	favor	Inside

Decoding with local features

NODE	apague	a	luz	por	favor	INSIDE
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				

Decoding with local features

NODE	apague	a	luz	por	favor	INSIDE
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			

Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$		$e_3 : \frac{X_{1,2}X_{2,3}}{X_{1,2}X_{2,3}}$				

Decoding with local features

Node	apague	a	luz	por	favor	Inside
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$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$					

Decoding with local features

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$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{off}}$					
$X_{2,5}$				$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$		

Decoding with local features

NODE	apague	a	luz	por	favor	INSIDE
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$					
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{ off}}$					

Decoding with local features

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<tr><td>$X_{1,2}$</td><td></td><td>$e_1 : \frac{\text{a}}{\text{the}}$</td><td></td><td></td><td></td><td></td></tr>
<tr><td>$X_{2,3}$</td><td></td><td></td><td>$e_2 : \frac{\text{luz}}{\text{light}}$</td><td></td><td></td><td></td></tr>
<tr><td>$X_{1,3}$</td><td></td><td colspan="2">$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$</td><td></td><td></td><td></td></tr>
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<tr><td>$X_{2,5}$</td><td></td><td></td><td colspan="3">$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$</td><td></td></tr>
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Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$					
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{ off}}$ $e_7 : \frac{X_{0,2} X_{2,3}}{X_{0,2} X_{2,3}}$					
$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$				

Decoding with local features

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<tr><td colspan="4">$e_9 : \frac{X_{1,2} X_{2,5}}{X_{1,2} X_{2,5}}$</td></tr>
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Decoding with local features

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<tr><td>$X_{2,3}$</td><td></td><td></td><td>$e_2 : \frac{\text{luz}}{\text{light}}$</td><td></td><td></td><td></td></tr>
<tr><td>$X_{1,3}$</td><td></td><td colspan="2">$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$</td><td></td><td></td><td></td></tr>
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Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$					
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{ off}}$ $e_7 : \frac{X_{0,2} X_{2,3}}{X_{0,2} X_{2,3}}$					
$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$ $e_9 : \frac{X_{1,2} X_{2,5}}{X_{1,2} X_{2,5}}$				
$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$ $e_{11} : \frac{\text{apague } X_{1,5}}{\text{switch } X_{1,5} \text{ off}}$					

Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{off}}$					
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{off}}$ $e_7 : \frac{X_{0,2} X_{2,3}}{X_{0,2} X_{2,3}}$					
$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$ $e_9 : \frac{X_{1,2} X_{2,5}}{X_{1,2} X_{2,5}}$				
$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$ $e_{11} : \frac{\text{apague } X_{1,5}}{\text{switch } X_{1,5} \text{ off}}$ $e_{12} : \frac{X_{0,3} \text{ por favor}}{\text{please, } X_{0,3}}$					

Decoding with local features

NODE	apague	a	luz	por	favor	INSIDE
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$					
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{ off}}$					
	$e_7 : \frac{X_{0,2} X_{2,3}}{X_{0,2} X_{2,3}}$					
$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$				
		$e_9 : \frac{X_{1,2} X_{2,5}}{X_{1,2} X_{2,5}}$				
$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$					
	$e_{11} : \frac{\text{apague } X_{1,5}}{\text{switch } X_{1,5} \text{ off}}$					
	$e_{12} : \frac{X_{0,3} \text{ por favor}}{\text{please, } X_{0,3}}$					
$S_{0,5}$	$e_{13} : \frac{\vdash X_{0,5} \dashv}{\vdash X_{0,5} \dashv}$					

Decoding with local features

NODE	apague a luz por favor	INSIDE
$X_{1,2}$	$e_1 : \frac{\text{a}}{\text{the}}$	$w(e_1)$
$X_{2,3}$	$e_2 : \frac{\text{luz}}{\text{light}}$	
$X_{1,3}$	$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$	
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$	
$X_{2,5}$	$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$	
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{ off}}$ $e_7 : \frac{X_{0,2} X_{2,3}}{X_{0,2} X_{2,3}}$	
$X_{1,5}$	$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$ $e_9 : \frac{X_{1,2} X_{2,5}}{X_{1,2} X_{2,5}}$	
$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$ $e_{11} : \frac{\text{apague } X_{1,5}}{\text{switch } X_{1,5} \text{ off}}$ $e_{12} : \frac{X_{0,3} \text{ por favor}}{\text{please, } X_{0,3}}$	
$S_{0,5}$	$e_{13} : \frac{\vdash X_{0,5} \dashv}{\vdash X_{0,5} \dashv}$	

Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				$w(e_1)$
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			$w(e_2)$
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{ off}}$					
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
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$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$				
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$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$					
	$e_{11} : \frac{\text{apague } X_{1,5}}{\text{switch } X_{1,5} \text{ off}}$					
	$e_{12} : \frac{X_{0,3} \text{ por favor}}{\text{please, } X_{0,3}}$					
$S_{0,5}$	$e_{13} : \frac{\vdash X_{0,5} \dashv}{\vdash X_{0,5} \dashv}$					

Decoding with local features

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Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				$w(e_1)$
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			$w(e_2)$
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				$w(e_3)\beta(X_{1,2})\beta(X_{2,3})$
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{off}}$					$w(e_4)\beta(X_{1,2})$
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{off}}$					
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$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$					
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<tr><td>$X_{1,3}$</td><td></td><td colspan="2">$e_3 : \frac{X_{1,2}X_{2,3}}{X_{1,2}X_{2,3}}$</td><td></td><td></td><td>$w(e_3)\beta(X_{1,2})\beta(X_{2,3})$</td></tr>
<tr><td>$X_{0,2}$</td><td colspan="2">$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2}\text{off}}$</td><td></td><td></td><td></td><td>$w(e_4)\beta(X_{1,2})$</td></tr>
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<tr><td>$S_{0,5}$</td><td colspan="5">$e_{13} : \frac{\vdash X_{0,5} \dashv}{\vdash X_{0,5} \dashv}$</td><td></td></tr>
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Decoding with local features

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<tr><td>$X_{1,3}$</td><td></td><td colspan="2">$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$</td><td></td><td></td><td>$w(e_3)\beta(X_{1,2})\beta(X_{2,3})$</td></tr>
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</table>

Decoding with local features

Node	apague	a	luz	por	favor	Inside
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				$w(e_1)$
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			$w(e_2)$
$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$				$w(e_3)\beta(X_{1,2})\beta(X_{2,3})$
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{off}}$					$w(e_4)\beta(X_{1,2})$
$X_{2,5}$			$e_5 : \frac{X_{2,3} \text{ por favor}}{\text{please, } X_{2,3}}$			$w(e_5)\beta(X_{2,3})$
$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } X_{1,3} \text{off}}$					$w(e_6)\beta(X_{1,3}) \oplus$
	$e_7 : \frac{X_{0,2} X_{2,3}}{X_{0,2} X_{2,3}}$					$w(e_7)\beta(X_{0,2})\beta(X_{2,3})$
$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } X_{1,3}}$				$w(e_8)\beta(X_{1,3}) \oplus$
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$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{X_{0,2} X_{2,5}}$					
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$X_{1,3}$	$e_3 : \frac{X_{1,2} X_{2,3}}{X_{1,2} X_{2,3}}$	$w(e_3)\beta(X_{1,2})\beta(X_{2,3})$
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2} \text{off}}$	$w(e_4)\beta(X_{1,2})$
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$S_{0,5}$	$e_{13} : \frac{\vdash X_{0,5} \dashv}{\vdash X_{0,5} \dashv}$	

Decoding with local features

<table>
<tr><th>NODE</th><th>apague</th><th>a</th><th>luz</th><th>por</th><th>favor</th><th>INSIDE</th></tr>
<tr><td>$X_{1,2}$</td><td></td><td>$e_1 : \frac{\text{a}}{\text{the}}$</td><td></td><td></td><td></td><td>$w(e_1)$</td></tr>
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The problem

Most interesting models employ nonlocal features!

- reordering model: previously translated span
- language model: generated strings

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Example

$$f(\mathbf{d}) = \psi(\text{yield}(\mathbf{d})) + \sum_i \varphi(e_i)$$

where $\psi(\mathbf{y}) = w_\psi \log p_{\text{LM}}(\mathbf{y})$
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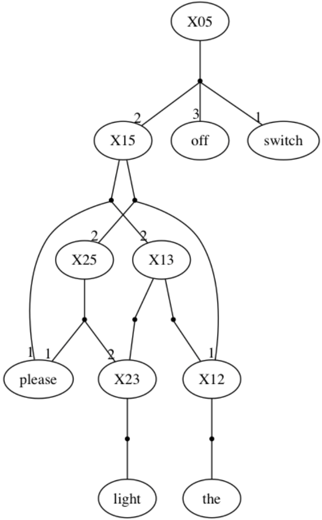
- p_{LM} violates independence assumptions

Illustration of the problem



How do we score the top edge?

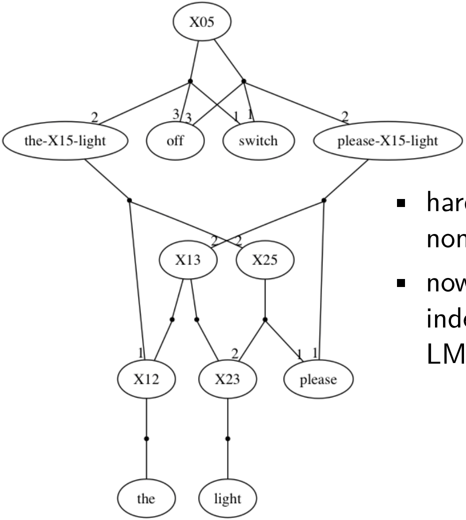
- [switch [please [[the][light]]] off]
- [switch [[the][please [light]]] off]

The solution

"Hard-code" structural dependencies

- disambiguate nodes w.r.t. the context they offer to feature functions
- intuition: we will be "splitting" nodes
- more intuition: nodes must memorise how to complete boundary n-grams

The intuition



- hard-code dependencies through nonterminals
- now we can weight edges independently even with a bigram LM

An example for hierarchical models

Model $f(\mathbf{d}) = \psi(\text{yield}(\mathbf{d})) \sum_i \varphi(e_i)$

where $\varphi(e_i)$ is a weighted combination of local features

$\psi(\text{yield}(\mathbf{d}))$ contains a 3-gram LM

i.e, $p_{\text{LM}_3}(\mathbf{y}) = \prod_i p(y_i | y_{i-2} y_{i-1})$

Grammar

$X \rightarrow \langle \text{a}, \text{the} \rangle$
$X \rightarrow \langle \text{luz}, \text{light} \rangle$
$X \rightarrow \langle \text{apague } X_1, \text{switch } X_1 \text{ off} \rangle$
$X \rightarrow \langle X_1 \text{ por favor}, \text{please , } X_1 \rangle$
$X \rightarrow \langle X_1 X_2, X_1, X_2 \rangle$
$S \rightarrow \langle \vdash X_1 \dashv, \vdash X_1 \dashv \rangle$

Input: apague a luz por favor

Reference: please, switch the light off

	apague a luz por favor	Left	Right	Node
				1
				2
				3
				4
				5
				6
				7
				8
				9
				10
				11
				12
				13
				14
				15
				16
				17
				18

	apague	a	luz	por	favor	LEFT	RIGHT	NODE
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				the	the	1
								2
								3
								4
								5
								6
								7
								8
								9
								10
								11
								12
								13
								14
								15
								16
								17
								18

	apague	a	luz	por	favor	Left	Right	Node
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				the	the	1
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			light	light	2
								3
								4
								5
								6
								7
								8
								9
								10
								11
								12
								13
								14
								15
								16
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	apague	a	luz	por	favor	Left	Right	Node
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				the	the	1
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$X_{1,3}$		$e_3 : \frac{X_{1,2} X_{2,3}}{(1)\ \ (2)}$				the light	the light	3
								4
								5
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$X_{0,2}$	$e_4 : \frac{\text{apague}\ X_{1,2}}{\text{switch}\ (1)\ \text{off}}$					switch the	the off	4
								5
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$X_{2,5}$			$e_5 : \frac{X_{2,3}\ \text{por favor}}{\text{please,}\ (2)}$			please ,	, light	5
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$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } (3) \text{ off}}$					switch the	light off	6
								7
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$X_{1,5}$		$e_8 : \frac{X_{1,3} \text{ por favor}}{\text{please, } (3)}$				please ,	the light	8
								9
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$X_{0,3}$	$e_6 : \frac{\text{apague } X_{1,3}}{\text{switch } (3) \text{ off}}$	switch the	light off	6
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	$e_9 : \frac{X_{1,2} X_{2,5}}{(1)\ (5)}$	the please	, light	9
$X_{0,5}$	$e_{10} : \frac{X_{0,2} X_{2,5}}{(4)\ (5)}$	switch the	, light	10
	$e_{11} : \frac{\text{apague } X_{1,5}}{\text{switch } (8) \text{ off}}$	switch please	light off	11
				12
				13
				14
				15
				16
				17
				18

	apague a luz por favor	Left	Right	Node
$X_{1,2}$	$e_1 : \frac{\text{a}}{\text{the}}$	the	the	1
$X_{2,3}$	$e_2 : \frac{\text{luz}}{\text{light}}$	light	light	2
$X_{1,3}$	$e_3 : \frac{X_{1,2}\,X_{2,3}}{(1)\ (2)}$	the light	the light	3
$X_{0,2}$	$e_4 : \frac{\text{apague}\ X_{1,2}}{\text{switch}\ (1)\ \text{off}}$	switch the	the off	4
$X_{2,5}$	$e_5 : \frac{X_{2,3}\ \text{por favor}}{\text{please,}\ (2)}$	please ,	, light	5
$X_{0,3}$	$e_6 : \frac{\text{apague}\ X_{1,3}}{\text{switch}\ (3)\ \text{off}}$	switch the	light off	6
	$e_7 : \frac{X_{0,2}\,X_{2,3}}{(4)\ (2)}$	switch the	off light	7
$X_{1,5}$	$e_8 : \frac{X_{1,3}\ \text{por favor}}{\text{please,}\ (3)}$	please ,	the light	8
	$e_9 : \frac{X_{1,2}\,X_{2,5}}{(1)\ (5)}$	the please	, light	9
$X_{0,5}$	$e_{10} : \frac{X_{0,2}\,X_{2,5}}{(4)\ (5)}$	switch the	, light	10
	$e_{11} : \frac{\text{apague}\ X_{1,5}}{\text{switch}\ (8)\ \text{off}}$	switch please	light off	11
	$e_{12} : \frac{\text{apague}\ X_{1,5}}{\text{switch}\ (9)\ \text{off}}$	switch the	light off	12
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	$e_{13} : \frac{X_{0,3}\ \text{por favor}}{\text{please,}\ (6)}$	please ,	light off	13
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	$e_{13} : \frac{X_{0,3} \text{ por favor}}{\text{please, } (6)}$	please ,	light off	13
	$e_{14} : \frac{X_{0,3} \text{ por favor}}{\text{please, } (7)}$	please ,	off light	14
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	$e_{18} : \frac{\vdash X_{0,5} \dashv}{\vdash (13) \dashv}$	$\vdash$ please	off $\dashv$	17
	$e_{19} : \frac{\vdash X_{0,5} \dashv}{\vdash (14) \dashv}$	$\vdash$ please	light $\dashv$	18

The problem with the solution

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Computational complexity!

The problem with the solution

Computational complexity!

1. it seems like the underlying grammar is growing
2. there are way too many n-grams leading to way too many nonterminals
3. the graphical representation (forest) is growing

What is really going on?

We are transferring memory from an automaton to the forest

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A nonterminal in the forest yields a set of strings

- strings project onto paths in the LM automaton
- paths are weighted

Nonterminals must be aware of (parts of) the strings they yield

- they must be annotated with states of the automaton

How hard is it?

Weighted intersection between a wCFG and a wFSA

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- input: $X_0 \rightarrow X_1 X_2 \dots X_a$ where $X_i \in N$

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Complexity

- input: $X_0 \rightarrow X_1 X_2 \ldots X_a$ where $X_i \in N$
- output: $X_0^{(q_1,q_a)} \rightarrow X_1^{(q_1,q_2)} X_2^{(q_2,q_3)} \ldots X_a^{(q_{a-1},q_a)}$ where $q_j \in Q$

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  where $q_j \in Q$
- complexity: $O(|N||Q|^{a+1})$

Solution

The usual suspect

- pruning

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- pruning

Alternatives

- local search (greedy methods)
- relaxation techniques
- sampling

Pruning: beam search

Approximate intersection by budgeting the combination of "comparable" nodes

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    - phrase-based: coverage vector
    - hierarchical: input spans

Pruning: beam search

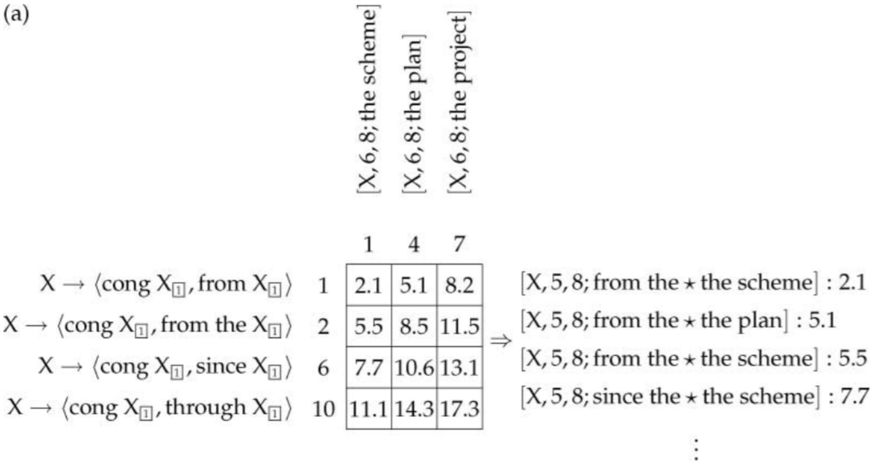
Approximate intersection by budgeting the combination of "comparable" nodes

- nodes that share structure
  - phrase-based: coverage vector
  - hierarchical: input spans
- heuristic view of interaction with LM
  - phrase-based: approximate future cost
  - local approximation based on limited context

Naive beam search

1. enumerate combinations
2. sort and prune all but the k best

Naive beam search

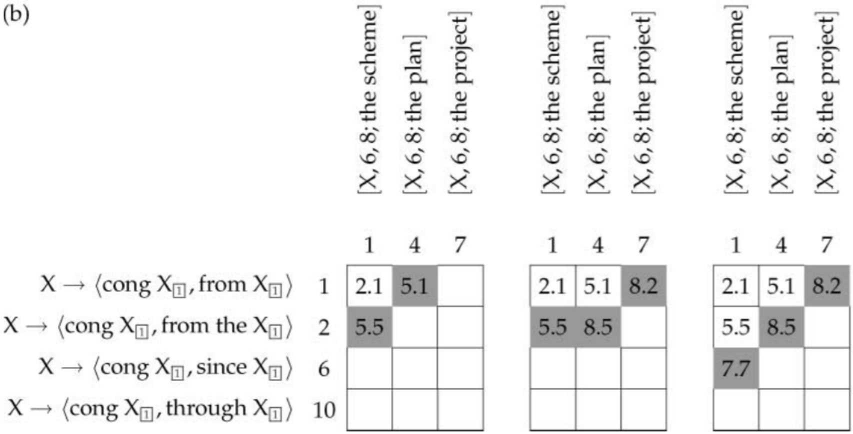


Cube pruning

An agenda for pruning [Chiang, 2007]

- tries to enumerate combinations in best-first order
- stops after k items have been enumerated
- inspiration: product of sorted lists
- heuristic: assumes the LM a monotone function over edges

Cube pruning



Problem with pruning

1. unbounded approximation
2. approximating the Viterbi solution
3. incompatible with models which have a probabilistic interpretation
4. cannot handle arbitrarily nonlocal dependencies

Beyond beam search

Local search [Hardmeier et al., 2012]

- computationally cheap
- unbounded approximation
- approximate Viterbi
- can handle arbitrarily nonlocal dependencies
- too local view of the distribution (bad for tuning)

Beyond beam search

Relaxation methods
[Chang and Collins, 2011, Rush and Collins, 2011]

- computationally expensive
- bounded approximation
- (approximate) Viterbi
- may handle arbitrarily nonlocal dependencies

Beyond beam search

Sampling [Arun et al., 2009, Aziz et al., 2013, Aziz, 2014]

- (bounded) approximation
- (approximate) Viterbi, expectations
- handle arbitrarily nonlocal dependencies
- in principle ideal for tuning (global view of distribution)
- potentially computationally expensive

Questions?

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