Decoding for SMT

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We will be reasoning

Decoding for SMT

We will be reasoning

making decisions

Decoding for SMT

We will be reasoning

making decisions

about solutions

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structures (translations)

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We will be reasoning

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structures (translations)

under a statistical model

Decoding for SMT

We will be reasoning

making decisions

about solutions

structures (translations)

under a statistical model

a function / a partial ordering

Keywords

We need to better characterise

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1. space of solutions
   get to know the terrain

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1. space of solutions
   get to know the terrain
2. statistical model
   how to assess the importance of things

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We need to better characterise

1. space of solutions
   get to know the terrain
2. statistical model
   how to assess the importance of things
3. decision rules
   know what you want

Terrain

Terrain

not everywhere is a good place to stand

The importance (or cost) of things

German xmas market

The importance (or cost) of things

Brazilian street market

The importance (or cost) of things

German xmas market

Price of product depends on

The importance (or cost) of things

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Price of product depends on

- the product

The importance (or cost) of things

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Price of product depends on

- the product
- brand

The importance (or cost) of things

German xmas market

Price of product depends on

- the product
- brand
- quality of service

The importance (or cost) of things

Brazilian street market

Price of product depends on

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Price of product depends on

- the product
- brand
- quality of service
- seller's mood

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Price of product depends on

- the product
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- quality of service
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- your look

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Price of product depends on

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- products you acquired from other stalls

The importance (or cost) of things

Brazilian street market

Price of product depends on

- the product
- brand
- quality of service
- seller's mood
- your look
- products you acquired from other stalls
- from whom you bought those

Know what you want

what do you think when you see this picture?

Know what you want

make a selfie (and lose a couple of fingers in the process)?

Know what you want

French goodies in a cozy chalet?

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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Phrase-based MT

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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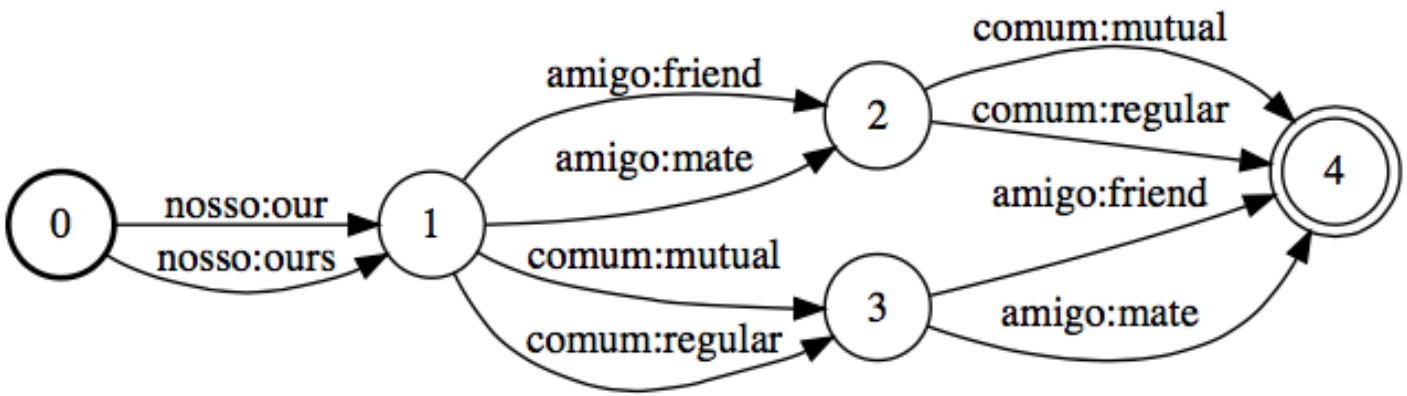

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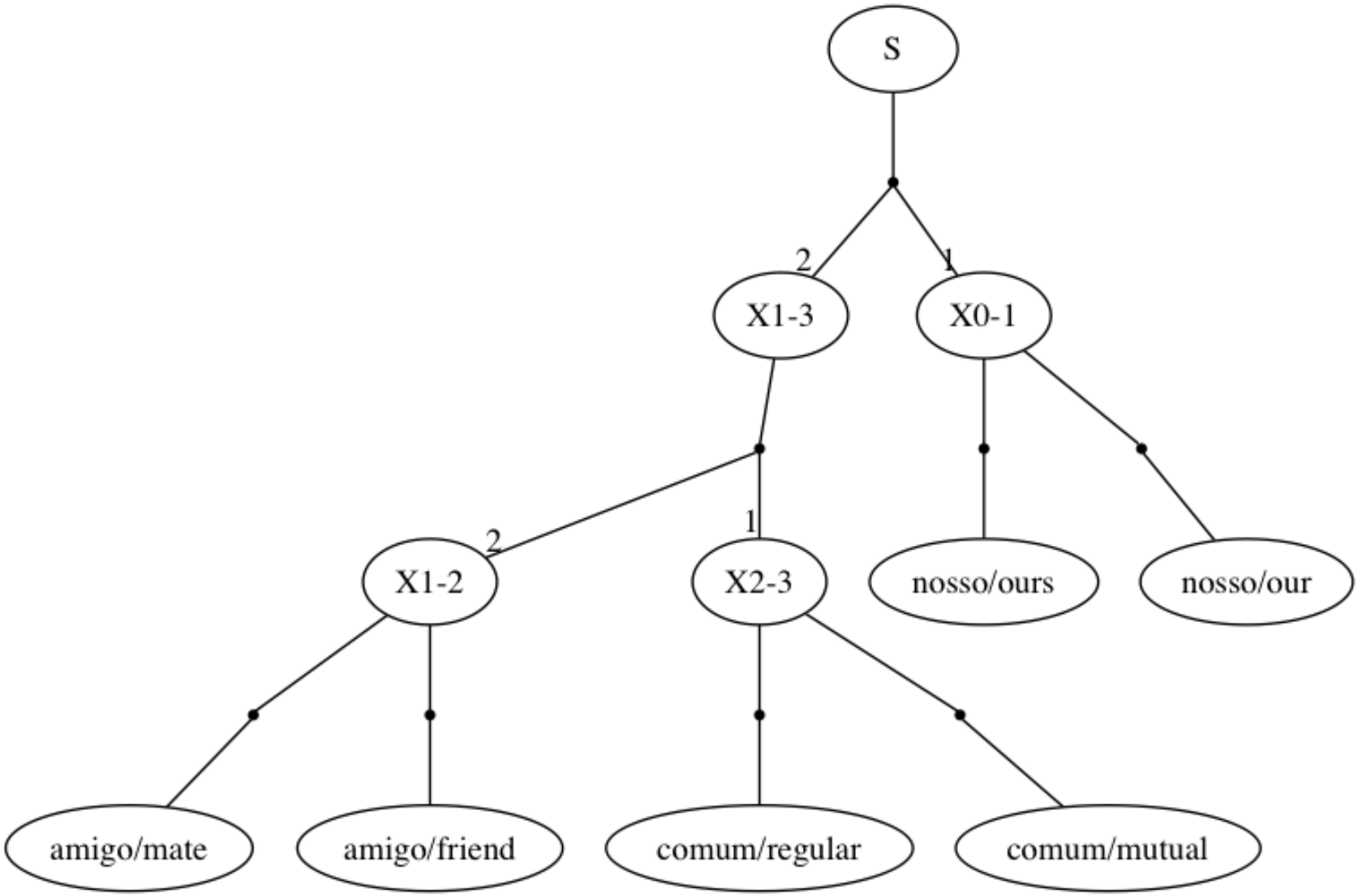

Directed B-hypergraphs

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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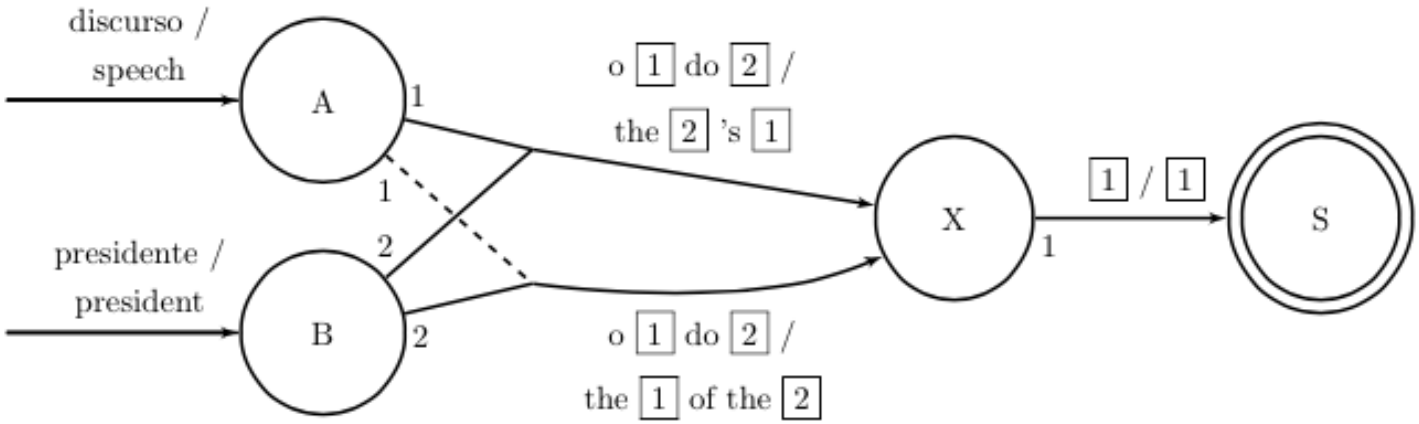
FSAs

- 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	1
X →	o A do B	the 2 's 1
X →	o A do B	the 1 of the 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

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

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

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

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

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

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)

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

- 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

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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

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

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- 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

$$e = \underset{e \in BS(v)}{\arg\max}\, w(e) \bigotimes_{u \in \text{tail}(e)} \beta(u)$$

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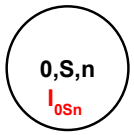
Sampling

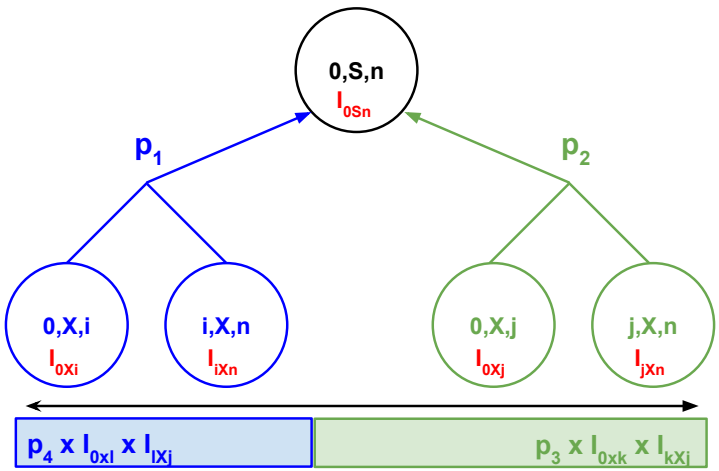
1. start from the goal (root)
2. recursively rewrite every symbol v by solving

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

Viterbi



Viterbi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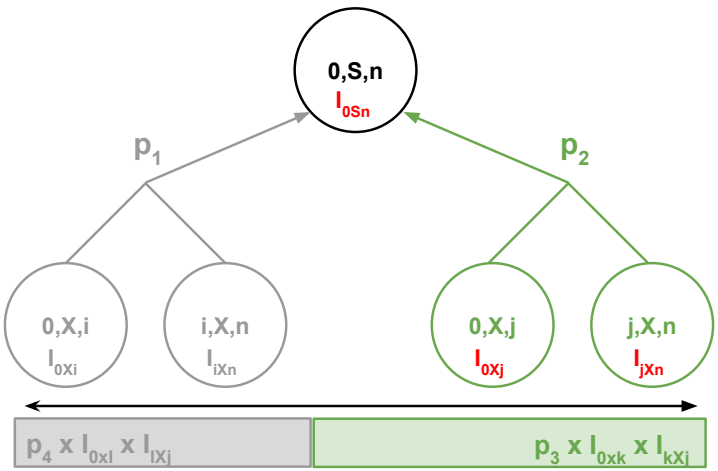
$p_4 \times l_{0xl} \times l_{lXj}$
$p_3 \times l_{0xk} \times l_{kXj}$

Viterbi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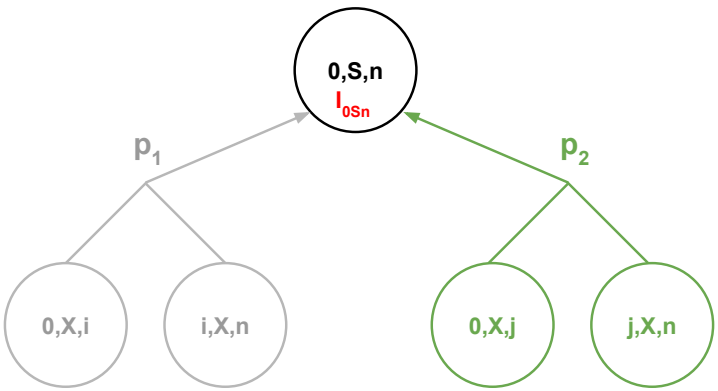

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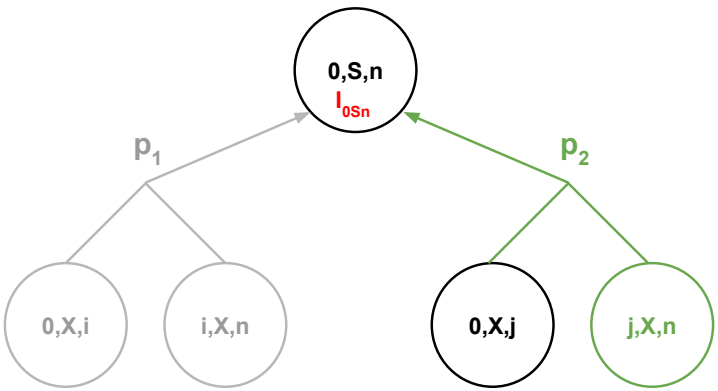

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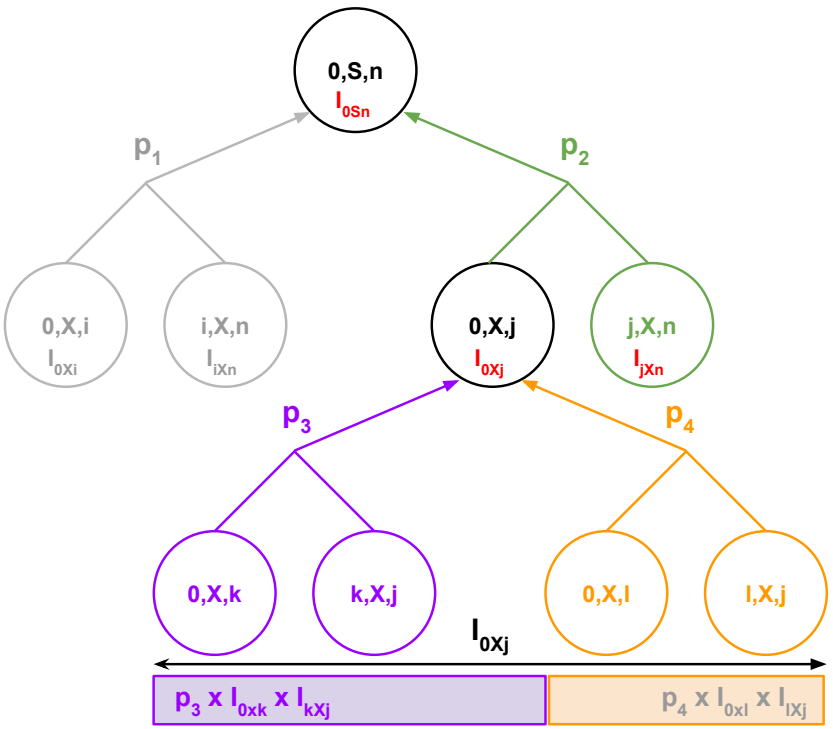
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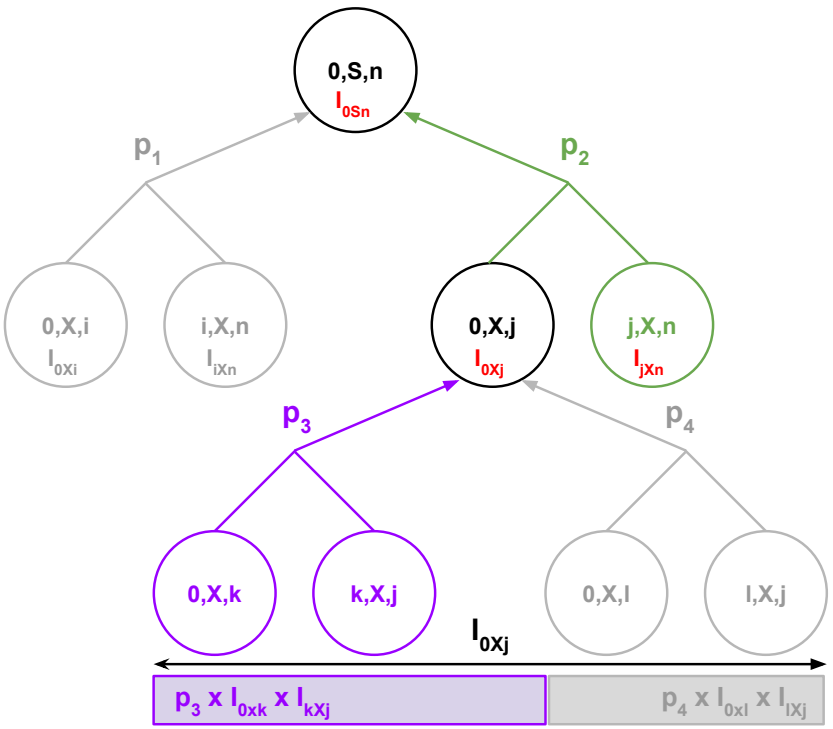
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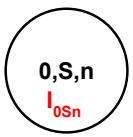

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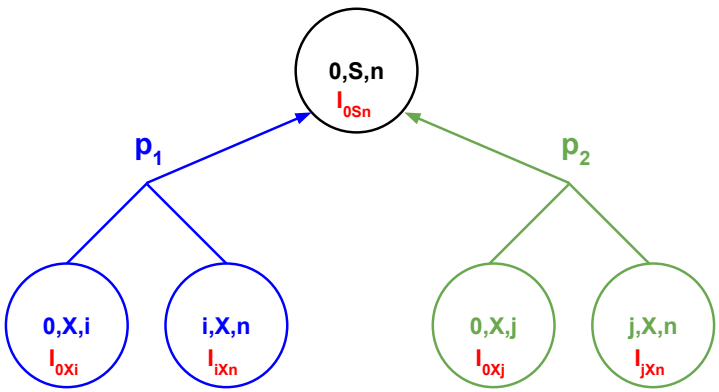

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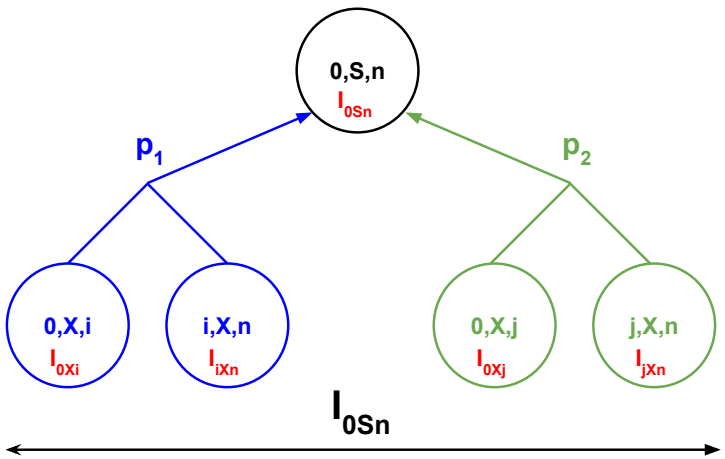

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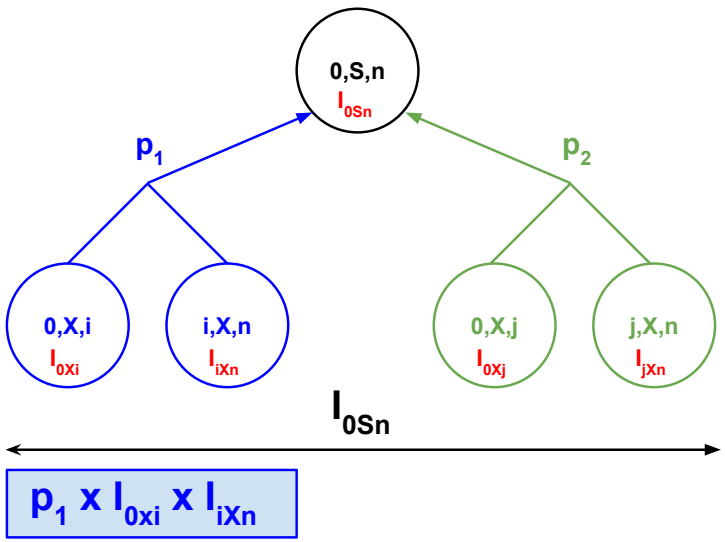
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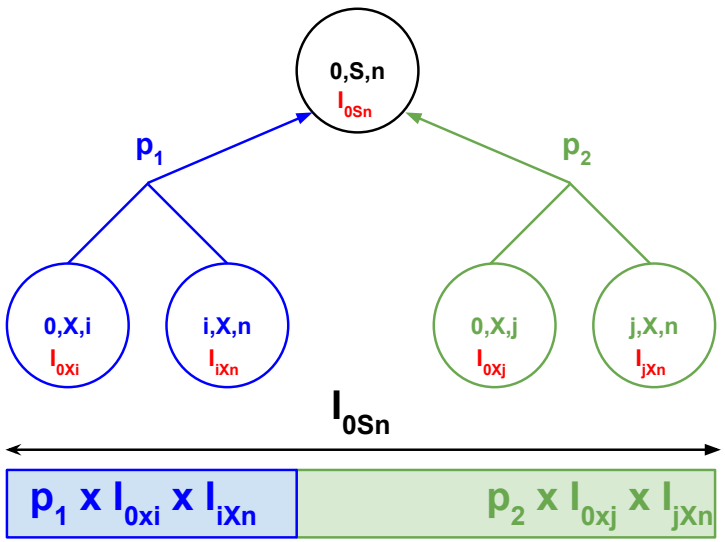
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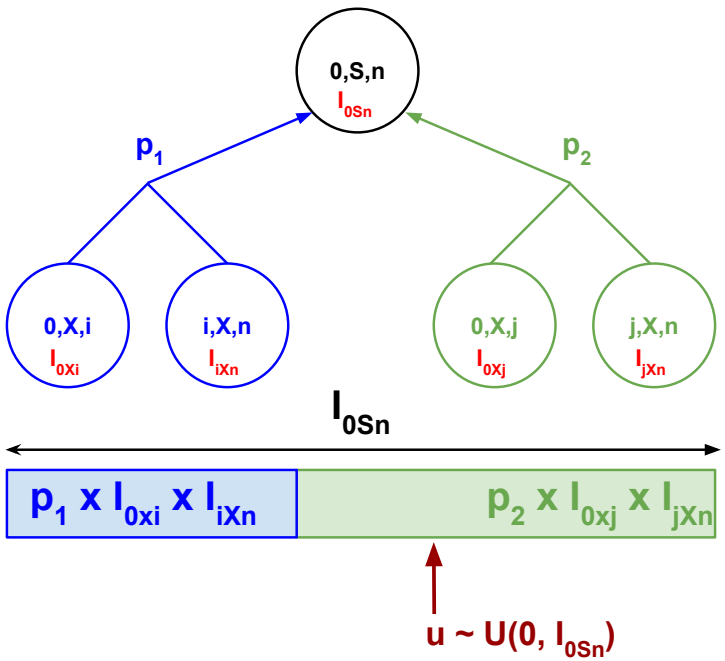
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$u \sim U(0, l_{0Sn})$

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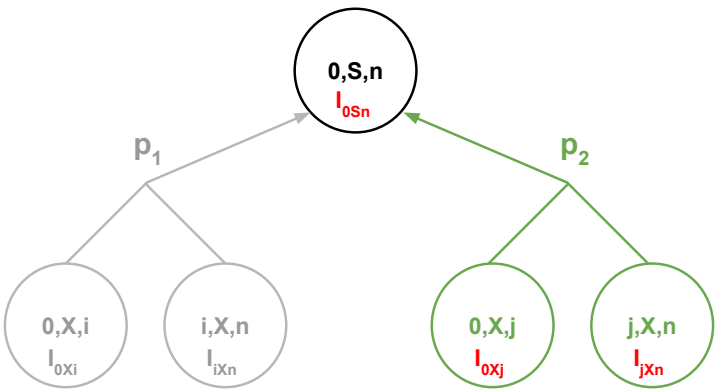

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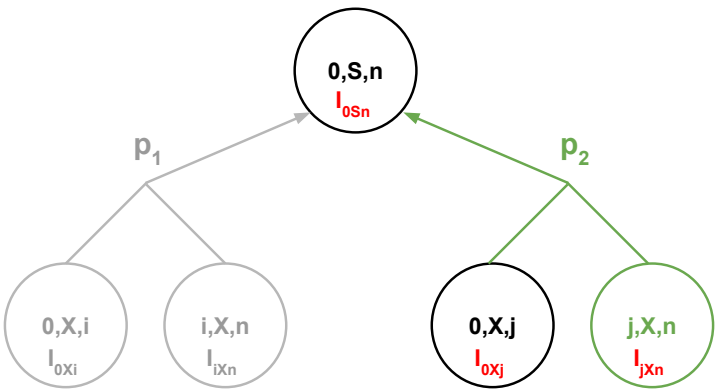

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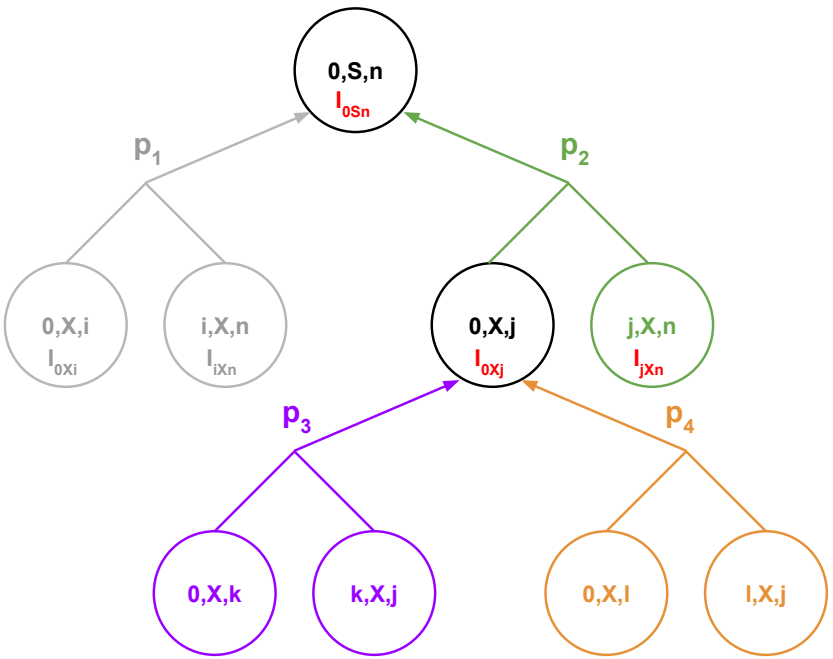
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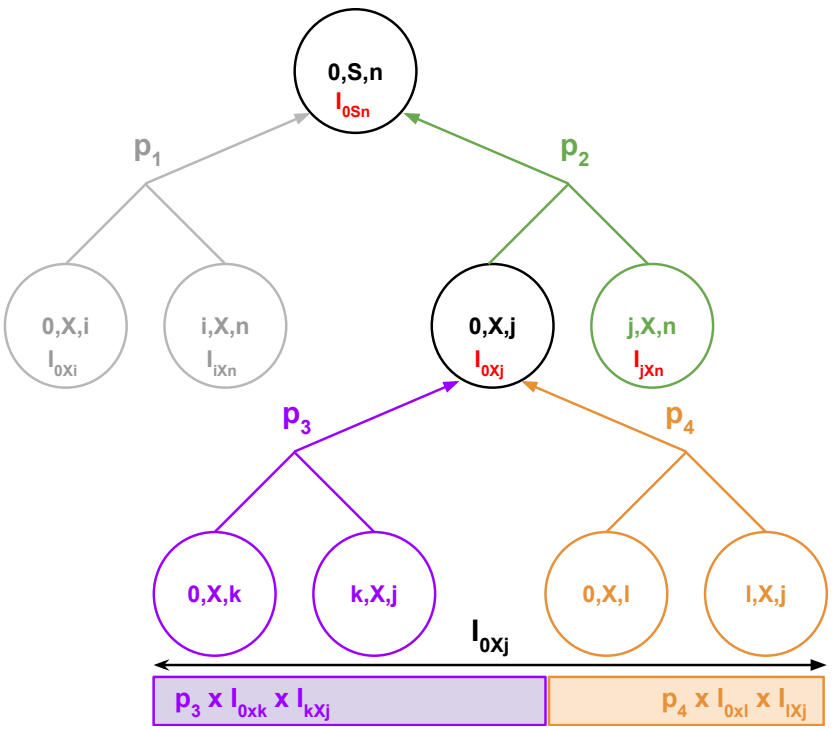
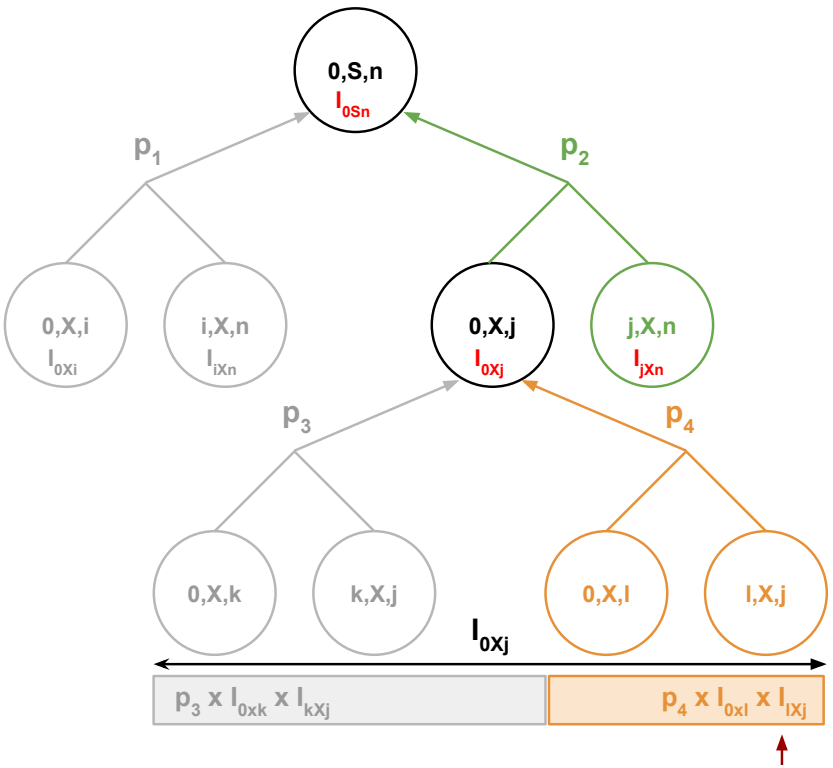
l,X,j

Sampling


0,S,n
l0Sn
p1
p2
0,X,i
l0Xi
i,X,n
liXn
0,X,j
l0Xj
j,X,n
ljXn
p3
p4
0,X,k
k,X,j
0,X,l
l,X,j
l0Xj
p3 x l0xk x lkXj
p4 x l0xl x llXj

Sampling


0,S,n
l_{0Sn}
p_1
p_2
0,X,i
l_{0Xi}
i,X,n
l_{iXn}
0,X,j
l_{0Xj}
j,X,n
l_{jXn}
p_3
p_4
0,X,k
k,X,j
0,X,l
l,X,j
l_{0Xj}
$p_3 \times l_{0xk} \times l_{kXj}$
$p_4 \times l_{0xl} \times l_{lXj}$

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
$X_{1,2}$		$e_1 : \frac{\text{a}}{\text{the}}$				
$X_{2,3}$			$e_2 : \frac{\text{luz}}{\text{light}}$			
$X_{1,3}$			$e_3 : \frac{X_{1,2}X_{2,3}}{X_{1,2}X_{2,3}}$			
$X_{0,2}$	$e_4 : \frac{\text{apague } X_{1,2}}{\text{switch } X_{1,2}\text{off}}$					

Decoding with local features

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

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

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

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

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

Decoding with local features

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

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

Decoding with local features

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

Decoding with local features

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

Decoding with local features

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

Decoding with local features

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

Decoding with local features

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

Decoding with local features

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

Decoding with local features

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

The problem

Most interesting models employ nonlocal features!

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

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- reordering model: previously translated span
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Example

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

where $\psi(\mathbf{y}) = w_\psi \log p_{\text{LM}}(\mathbf{y})$
and $p_{\text{LM}}(\mathbf{y}) = \prod_i p(y_i | y_{i-n+1}^{i-1})$ is an n-gram LM

The problem

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Example

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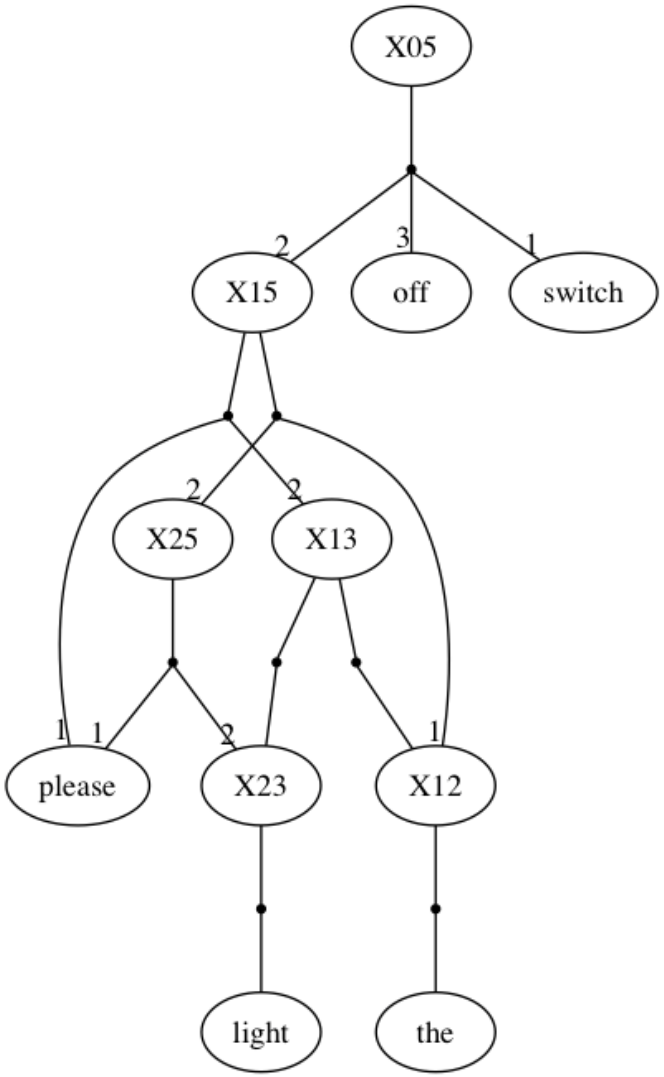
and $p_{\text{LM}}(\mathbf{y}) = \prod_i p(y_i | y_{i-n+1}^{i-1})$ is an n-gram LM

- p_{LM} violates independence assumptions

Illustration of the problem



How do we score the top edge?

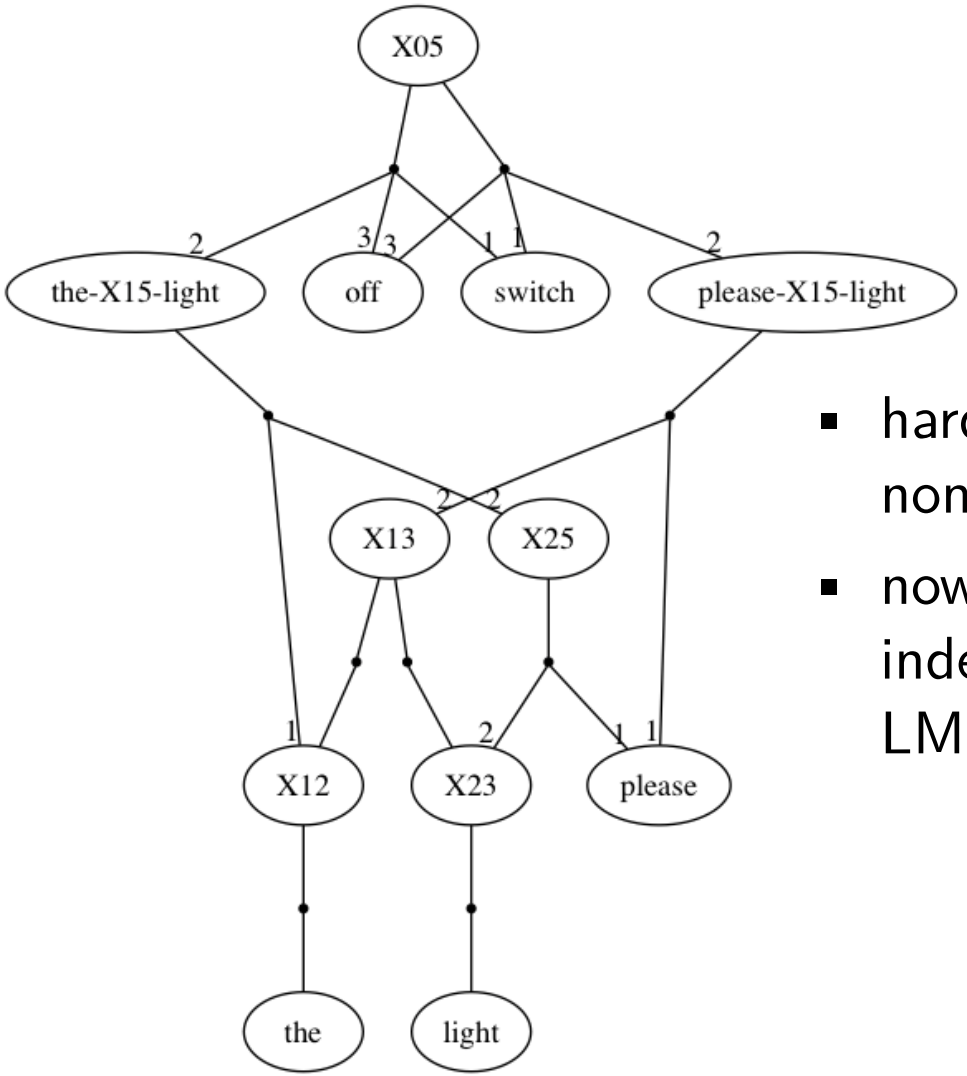
- [switch [please [[the][light]]] off]
- [switch [[the][please [light]]] off]

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 : a / the				the	the	1
$X_{2,3}$			e_2 : luz / light			light	light	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
$X_{1,3}$	$e_3 : \frac{X_{1,2}\,X_{2,3}}{(1)\ \ (2)}$	the light	the light	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
$X_{1,3}$	$e_3 : \frac{X_{1,2}\,X_{2,3}}{(1)\ \ (2)}$	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
				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 : a / the					the	the	1
$X_{2,3}$			e_2 : luz / light			light	light	2
$X_{1,3}$			e_3 : $X_{1,2}X_{2,3}$ / (1) (2)			the light	the light	3
$X_{0,2}$	e_4 : apague $X_{1,2}$ / switch (1) off					switch the	the off	4
$X_{2,5}$				e_5 : $X_{2,3}$ por favor / please, (2)		please ,	, light	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
$X_{1,3}$		$e_3 : \frac{X_{1,2}\,X_{2,3}}{(1)\ \ (2)}$				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
$X_{0,3}$								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
$X_{1,3}$		$e_3 : \frac{X_{1,2}X_{2,3}}{(1)\ (2)}$				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
								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
$X_{1,3}$		$e_3 : \frac{X_{1,2}\,X_{2,3}}{(1)\ (2)}$				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
								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
$X_{1,3}$		$e_3 : \frac{X_{1,2}\,X_{2,3}}{(1)\ (2)}$				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
								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
$X_{1,3}$			$e_3 : \frac{X_{1,2}X_{2,3}}{(1)\ (2)}$			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
								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
								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
								13
								14
								15
								16
								17
								18

	apague a luz por favor	Left	Right	Node
$X_{1,2}$	e_1 : a / the	the	the	1
$X_{2,3}$	e_2 : luz / 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 : apague $X_{1,2}$ / switch (1) 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 : apague $X_{1,3}$ / switch (3) 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} : apague $X_{1,5}$ / switch (8) off	switch please	light off	11
	e_{12} : apague $X_{1,5}$ / switch (9) off	switch the	light off	12
	$e_{13} : \frac{X_{0,3}\ \text{por favor}}{\text{please, } (6)}$	please ,	light off	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
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$X_{0,5}$	$e_{10} : \frac{X_{0,2}\,X_{2,5}}{(4)\ (5)}$	switch the	, light	10
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	$e_{13} : \frac{X_{0,3} \text{ por favor}}{\text{please, } (6)}$	please ,	light off	13
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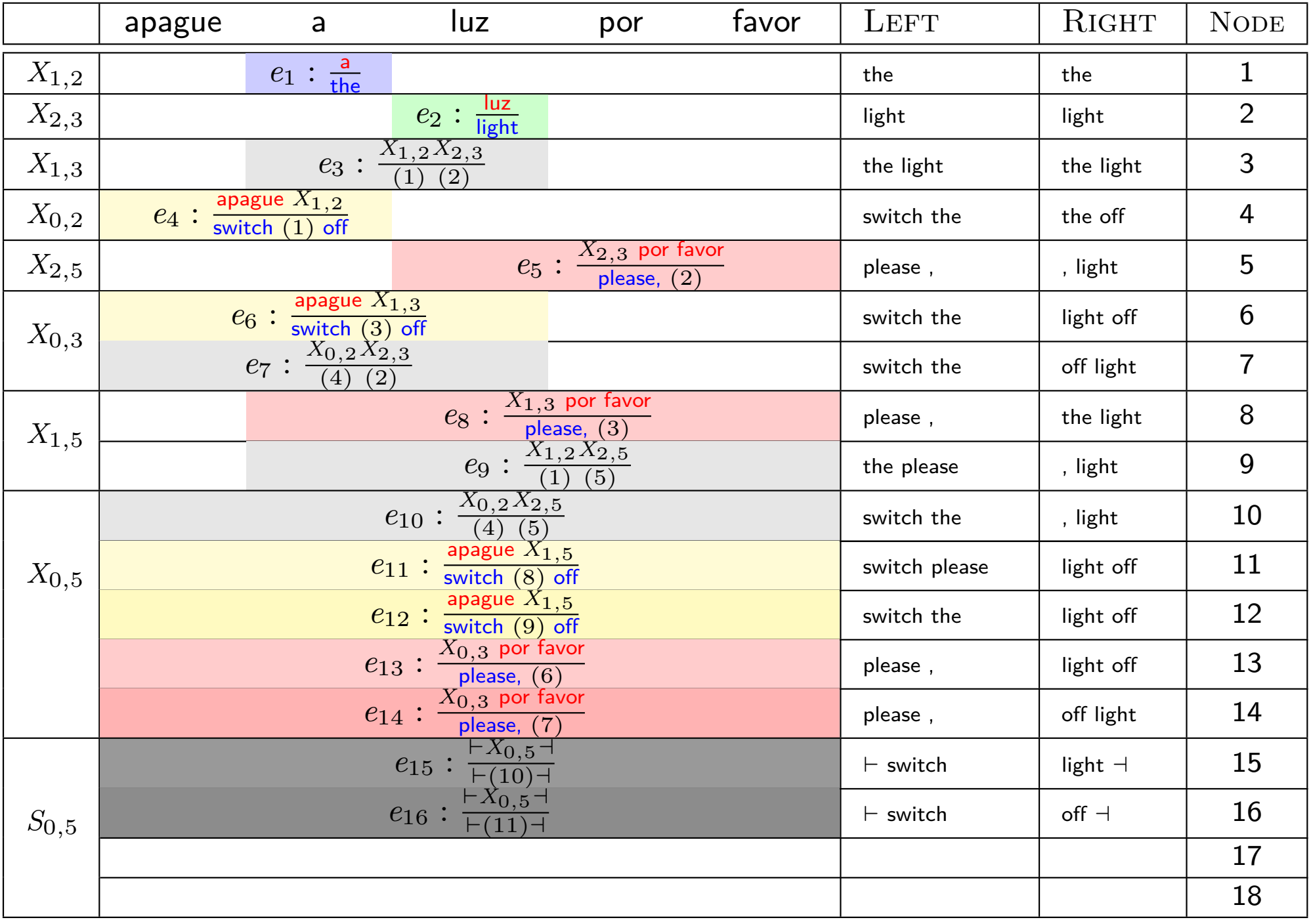
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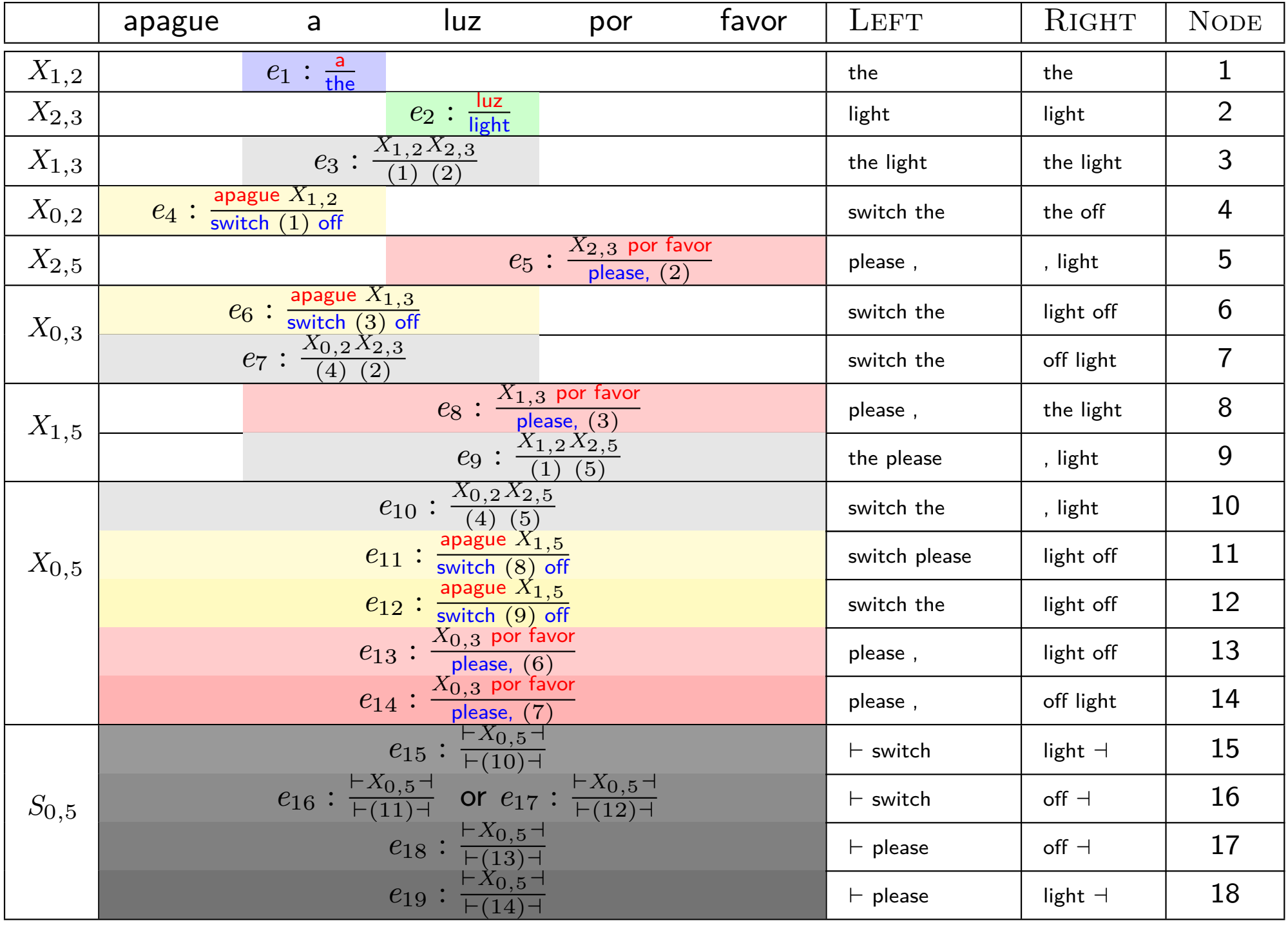
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The problem with the solution

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Computational complexity!

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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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- strings project onto paths in the LM automaton
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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: $X_0 \to X_1 X_2 \ldots X_a$ where $X_i \in N$

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

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- 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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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

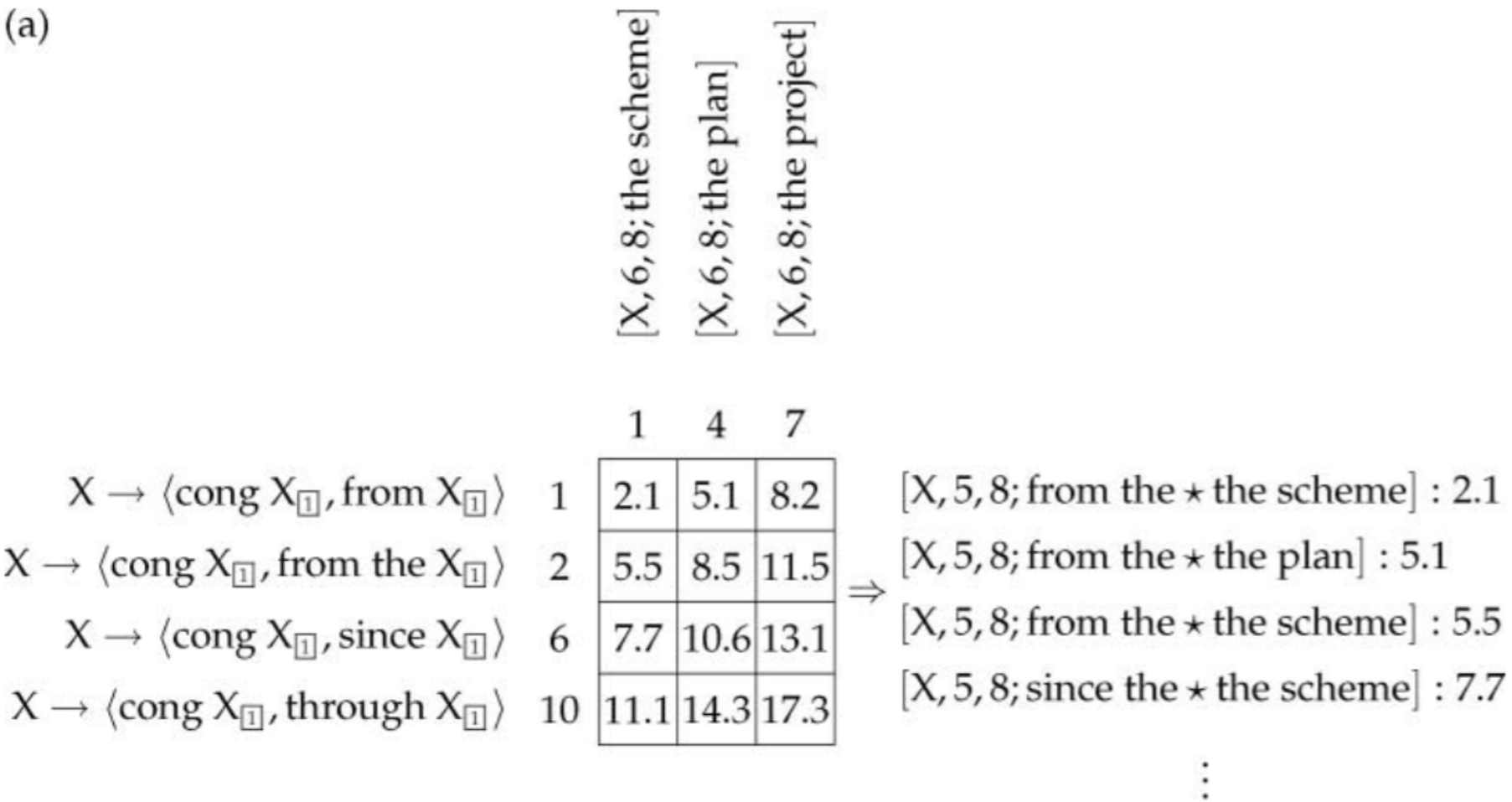
- nodes that share structure
  - phrase-based: coverage vector
  - hierarchical: input spans
- heuristic view of interaction with LM
  - phrase-based: approximate future cost
  - local approximation based on limited context

Naive beam search

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

Naive beam search

(a)

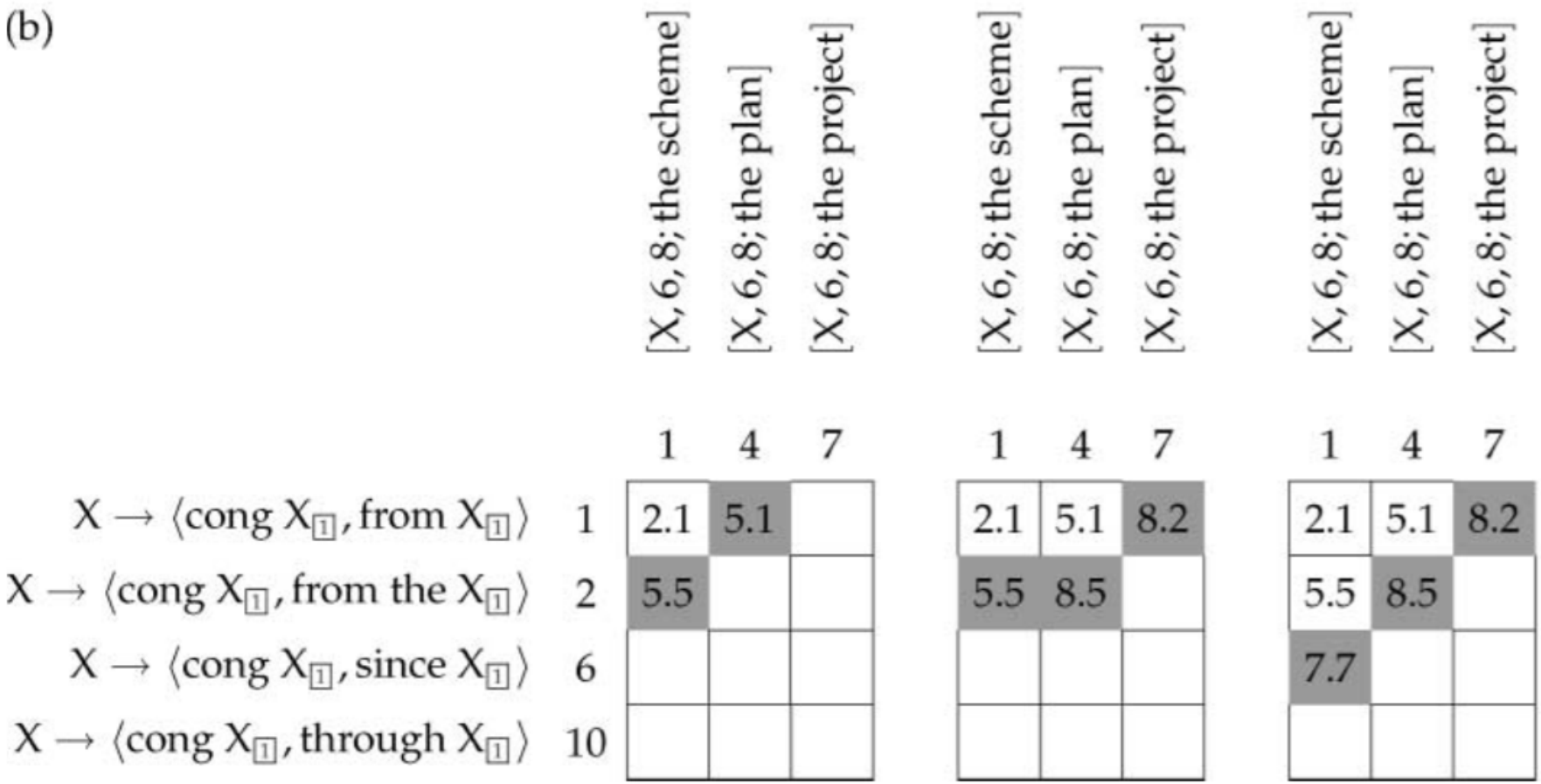


Cube pruning

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?

References I

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