Syntax-based decoding

JHU Machine Translation class
April 1, 2014

Administrative

- Homework 4 out, due April 14
- Final project proposals due today

Where do grammars come from?

- We left off on Thursday with
  - a formalism for describing the relationship between two languages,
  - an loosely-sketched algorithm for producing translations
- Questions for today:
  - Where do synchronous grammars come from?
  - How do we decode with an ngram language model?

Data-driven grammar extraction

- Grammar rules are not written by hand, they are extracted from bilingual parallel corpora

Arabic	English
فالتعذيب لا يزال يمارس على نطاق واسع	Torture is still being practised on a wide scale.
وتتم عمليات الاعتقال والاحتجاز دون سبب بصورة روتينية	Arrest and detention without cause take place routinely.
وحان وقت التحلى بالبصيرة والشجاعة السياسية .	This is a time for vision and political courage
. . .	. . .

Chinese	English
我国 能源 原材料 工业 生产 大幅度 增长 .	China's energy and raw materials production up.
非国大 要求 阻止 更 多 被 拘留 人员 死亡 .	ANC calls for steps to prevent deaths in police custody .
. . .	. . .

Hiero

- Consider the redundancy in this phrase table

Spanish	English
la bruja verde	the green witch
la bruja roja	the red witch
la bruja azúl	the blue witch

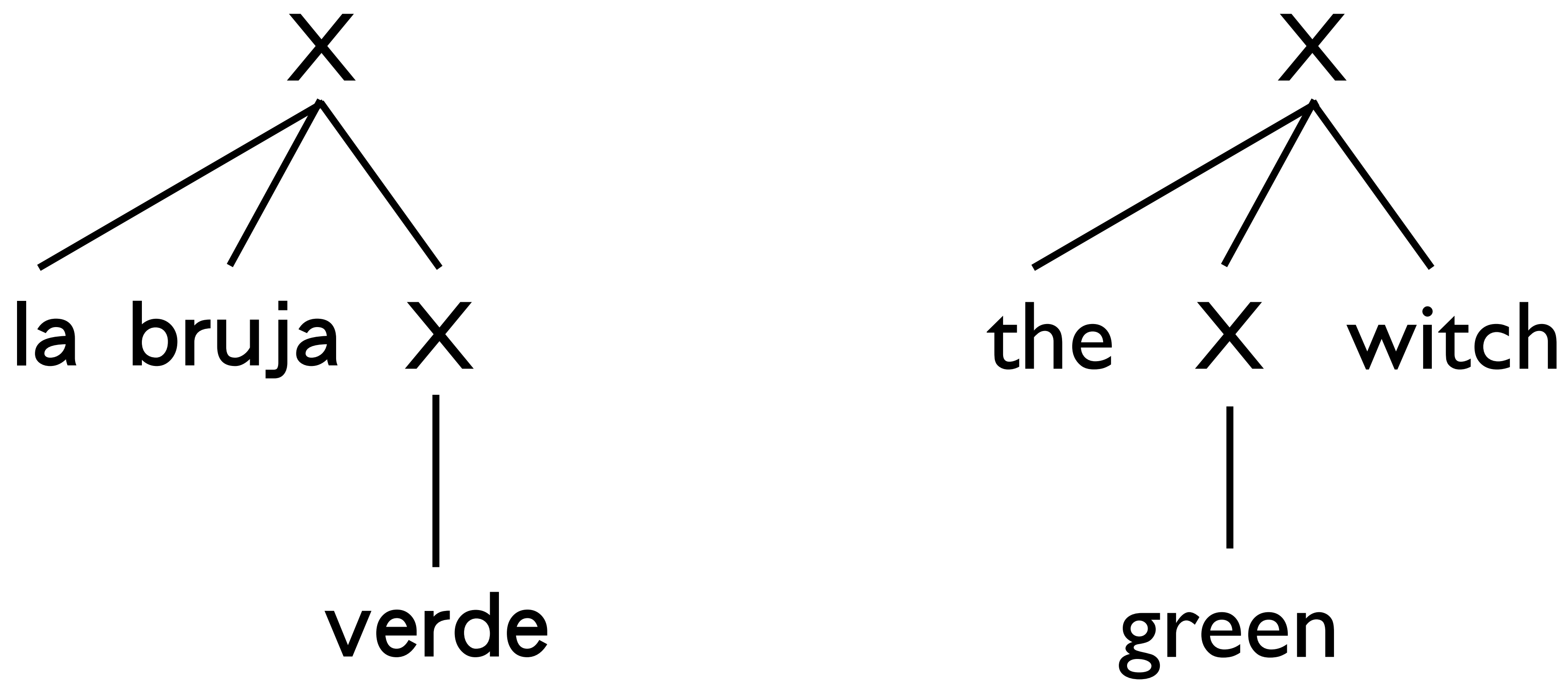
- What generalization is missing?

Hiero

- Synchronous grammar rules

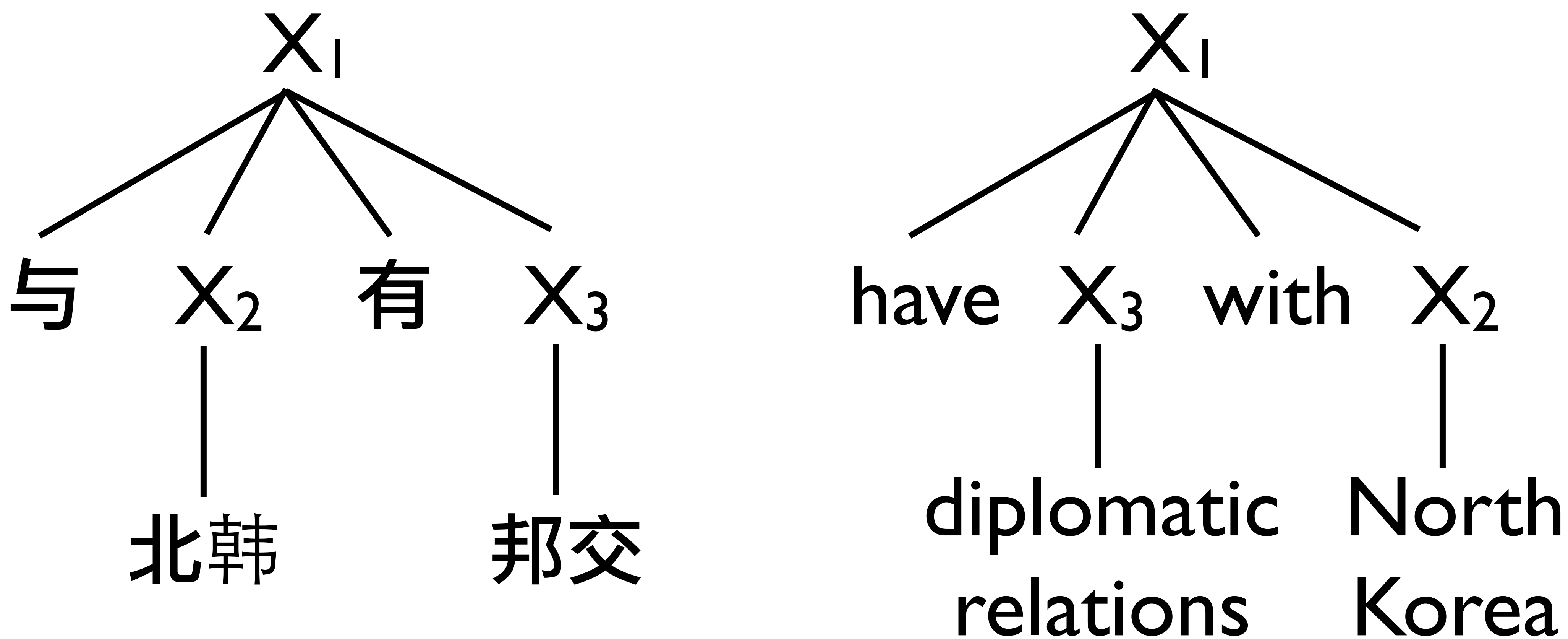
  $X \rightarrow$ la bruja $X_{(1)}$ ||| the $X_{(1)}$ witch
  $X \rightarrow$ verde ||| green

- As a tree



Hiero-style SCFG rules

- Most common type of SCFG in SMT is Hiero which has rules w/one non-terminal symbol
- Not as nice as linguistically motivated rules, does not capture the reordering in Urdu



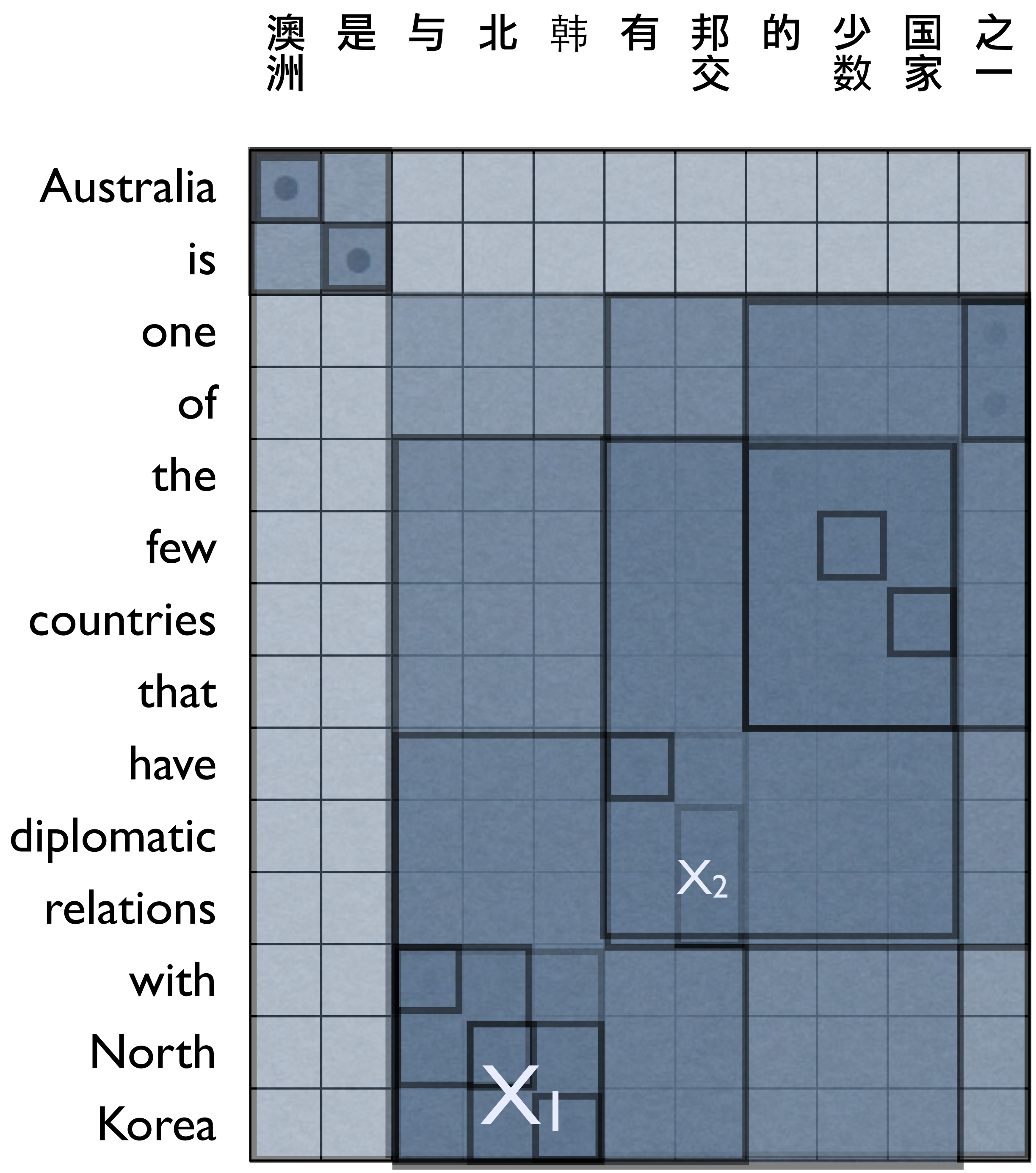
Hiero

- Consider the redundancy in this phrase table

Spanish	English
la bruja verde	the green witch
la bruja roja	the red witch
la bruja azúl	the blue witch

- What generalization is missing?
- Hiero abandons conventional English syntax
- Relies instead on evidence-based phrasal "subtractions"

Extracting Hiero rules



$X \rightarrow$ 与 北 韩 有 邦交,
have diplomatic relations
with North Korea

$X \rightarrow$ 邦交,
diplomatic relations

$X \rightarrow$ 北 韩,
North Korea

$X \rightarrow$ 与 X_1 有 X_2,
have X_2 with X_1

Decoding

- We now have a way to obtain a synchronous grammar
- Last week, we sketched the decoding algorithm, which was based on parsing
- Today, we'll cover it in more detail, and correct a crucial omission (ngram language models)

Review (1)

- We've discussed how syntactic differences between languages motivated reordering as a preprocessing step

Ich werde Ihnen den Report aushaendigen, damit Sie den eventuell uebernehmen koennen.

↓

Ich werde aushaendigen Ihnen den Report, damit Sie koennen uebernehmen den eventuell.

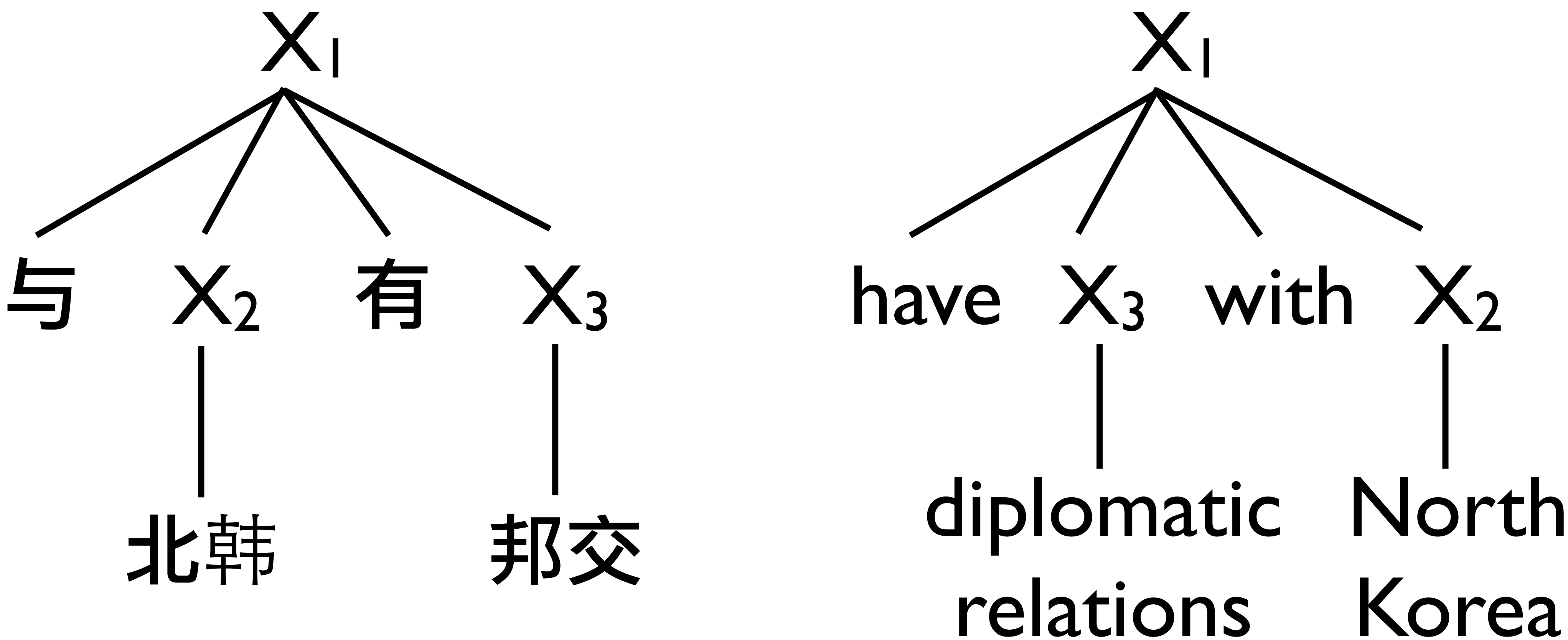
Review (2)

- We've also discussed synchronous grammar rules, which describe the generation of sentences in pairs

	Urdu	English
S →	NP① VP②	NP① VP②
VP→	PP① VP②	VP② PP①
VP→	V① AUX②	AUX② V①
PP →	NP① P②	P② NP①
NP →	*hamd ansary*	*Hamid Ansari*
NP →	*na}b sdr*	*Vice President*
V →	*namzd*	*nominated*
P →	*kylye*	*for*
AUX →	*taa*	*was*

Review (3)

- ...and how we could extract those rules automatically from text



Today

- How do we actually *decode* with these grammars?
- The solution is the CKY / CYK algorithm

{CKY algorithm}	{CYK algorithm}
6,090	~ 13,700

Google

- Outline
  - Parsing in one language
  - Parsing in two languages *with inversion transduction grammar (ITG)*
  - Decoding as parsing *with synchronous context-free grammars (SCFG) and integrated language models*
  - Time-permitting: advanced topics

Review: monolingual parsing

Using the CKY algorithm to find (the best) structure for a sentence given a grammar

Formal definitions

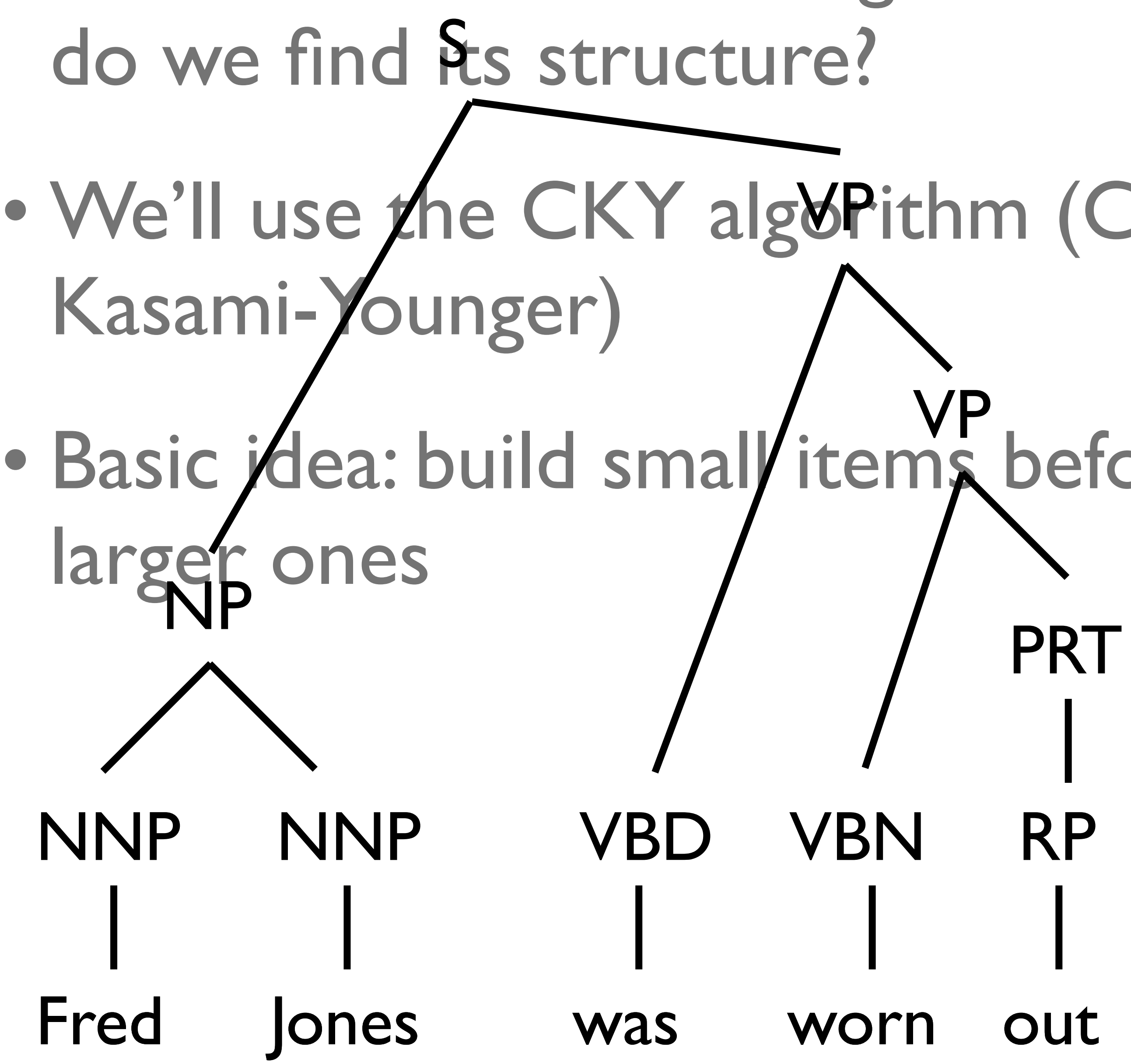
- Formal languages are (possibly infinite) sets of strings that are generated by a grammar
  - e.g., {a+} is a language of all strings with one or more *as*
  - Its grammar could be written as

    A → Aa

    A → a
- We can view natural languages in this manner, too
  - e.g., the English language is the set of word sequences that constitute valid English sentences
  - We believe there to be a grammar that generates those sentences
  - We don't know what it is, but we have some guesses and approximations

Parsing

- Given a sentence and a grammar, how do we find its structure?
- We'll use the CKY algorithm (Cocke-Kasami-Younger)
- Basic idea: build small items before larger ones

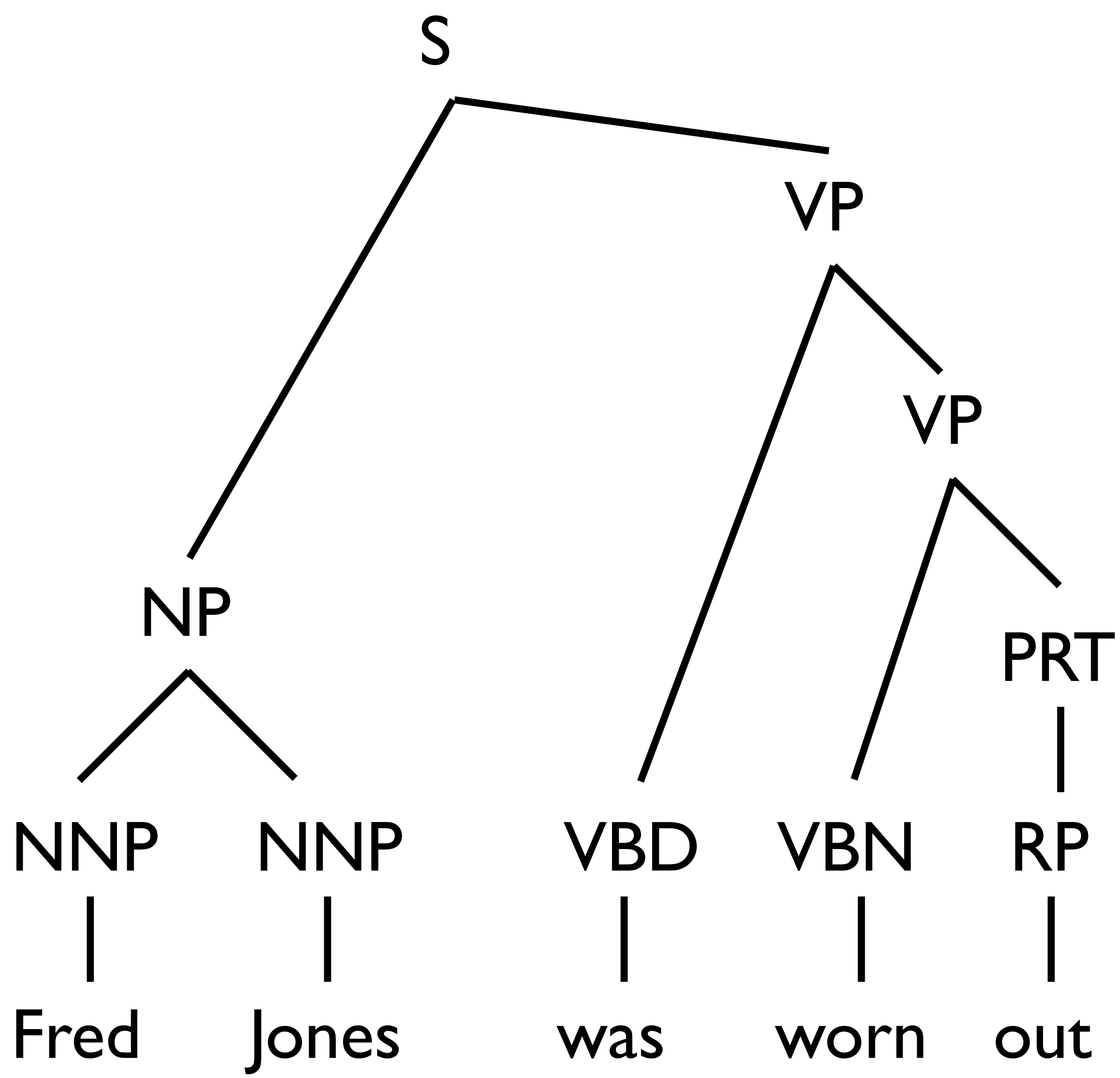


sentence

S	→	NP VP
VP	→	VBN PRT
PRT	→	RP
VP	→	VBD VP
NP	→	NNP NNP
NNP	→	Fred | Jones
VBD	→	was
VBN	→	worn
RP	→	out

grammar

Parsing with CKY



sentence

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grammar

Implementation details

- Dynamic programming maintains a **chart** of **items**
  - Each cell item represents the **dynamic programming state**
    - (NNP,1,1), (S,1,5)
  - The **chart** is the collection of all items

```
struct item {
  // d.p. state
  string nt;
  int i, j;
  // backpointer
  float score;
  Rule* rule;
  item* rhs1,
      rhs2;
}
```

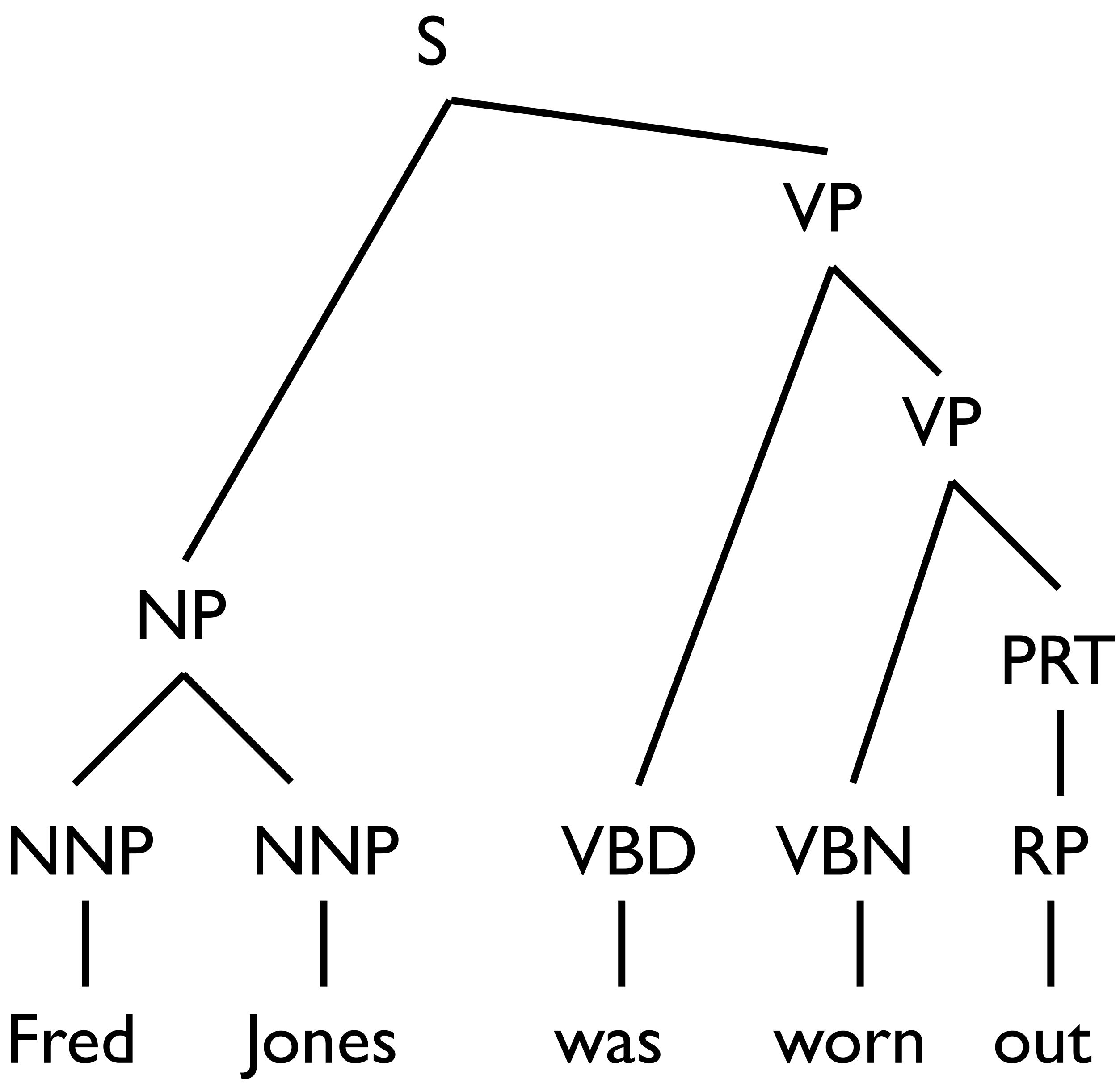
- The **score** resolves alternate ways of constructing an item
- We also store **backpointers**: the items and rule used to construct each item

a.k.a. "predecessor"

CKY algorithm

```
input: words[1..N]
for i in 1..N
  for each unary rule X → words[i]
    add (X,i,i) to the chart
for span in 1..N
  for i in 1..(N-span)
    j = i + span
    for k in i..j
      for rule X → Y Z
        if (Y,i,k) and (Z,k,j)
          add (X,i,j) to the chart
output: (S,1,N)
```

Parsing with CKY



	1	2	3	4	5	
Fred	NNP					1
Jones	NP	NNP				2
was			VBD			3
worn				VBN		4
out	S		VP	VP	RP PRT	5
	Fred	Jones	was	worn	out	

```
item
  nt = "S";
  i = 1, j = 5;
  score = -42.5;
  Rule = &rule("S → NP VP")
  rhs1 = &item(NP,1,2);
  rhs2 = &item(VP,3,5);
```

Reconstructing the best parse

- We can reconstruct the best parse by following backpointers

```
nodes.append(item(S,1,N))
while nodes.size() > 0:
  item = nodes.pop()
  print item
  nodes.append(item.rhsr)
  nodes.append(item.rhsl)
```

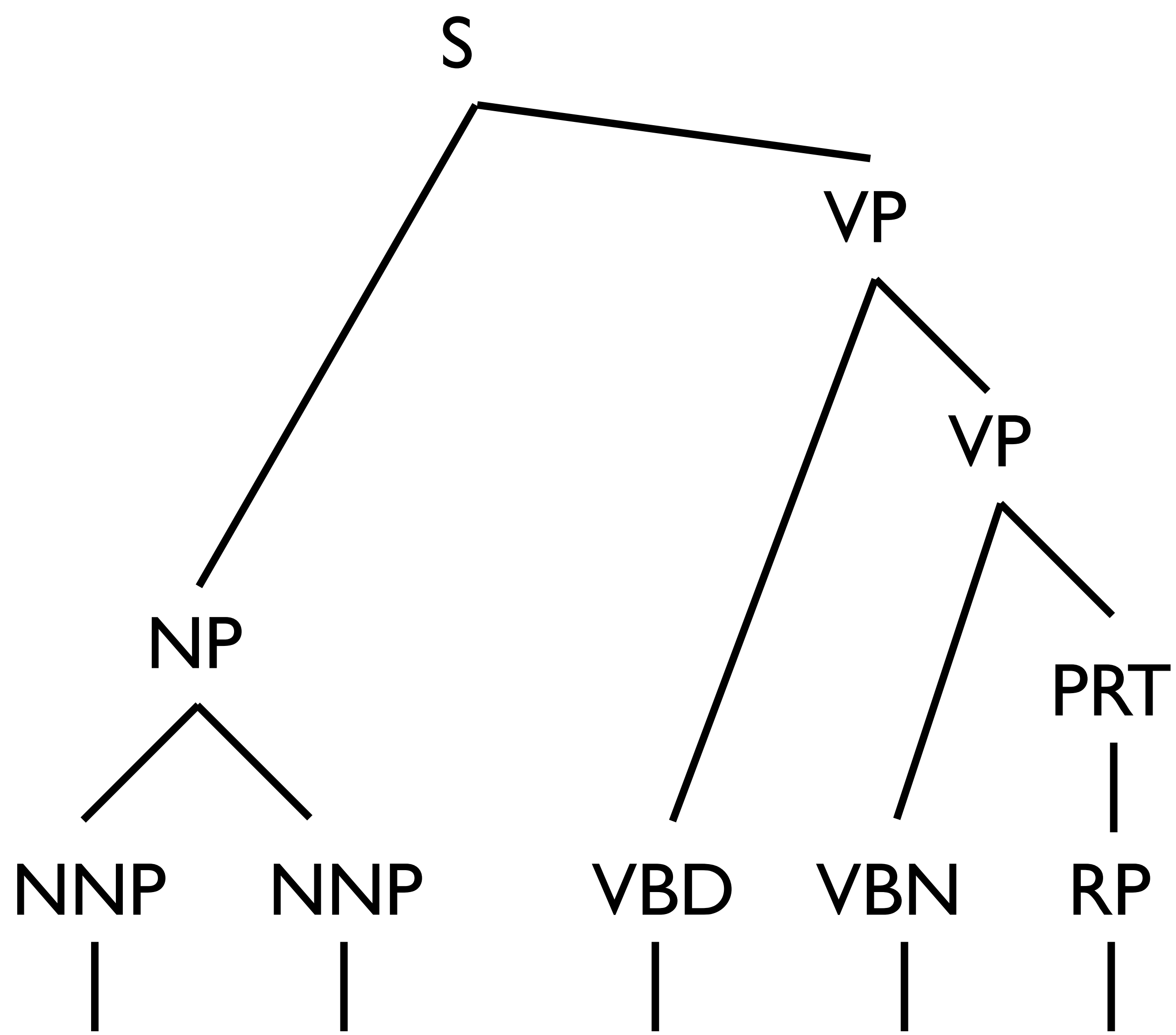
nodes

[illegible] (NNP,1,1)

Fred	NNP				
Jones	NP	NNP			
was			VBD		
worn				VBN	
out	S		VP	VP	RP PRT
	Fred	Jones	was	worn	out

S → NP VP (1,5)
NP → NNP NNP (1,2)
NNP → Fred (1,1)
NNP → Jones (2,2)
VP → VBD VP (3,5)
VBD → was (3,3)
VP → VBN PRT (4,5)
VBN → worn (4,4)
PRT → RP (5,5)
RP → out (5,5)

Parsing with CKY

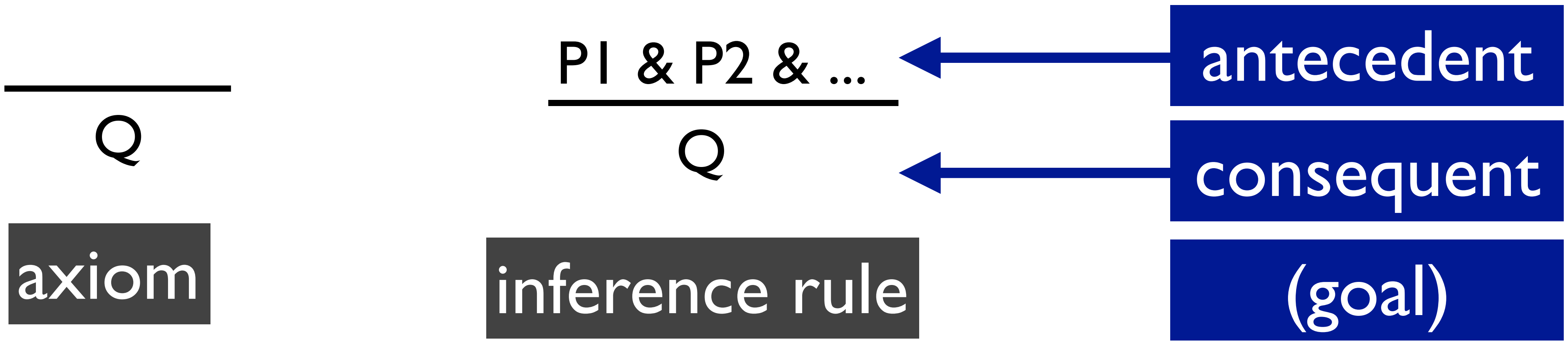


	1	2	3	4	5	
Fred	NNP					1
Jones	NP	NNP				2
was			VBD			3
worn				VBN		4
out	S		VP	VP	RP PRT	5
	Fred	Jones	was	worn	out	

Fred Jones was worn out *from caring for his often screaming and crying wife during the day but he couldn't sleep at night for she in a stupor from the drugs that didn't ease the pain would set the house ablaze with a cigarette*

Parsing as (weighted) deduction

- Deductive reasoning:
  - axioms: statements that are true or false (“it is raining”)
  - inference rules: statements that are conditionally true (“If it is raining and I am outside, I’ll get wet”)
  - goals: statements that are licensed by combinations of axioms, inference rules, and other conclusions (“I am wet”)



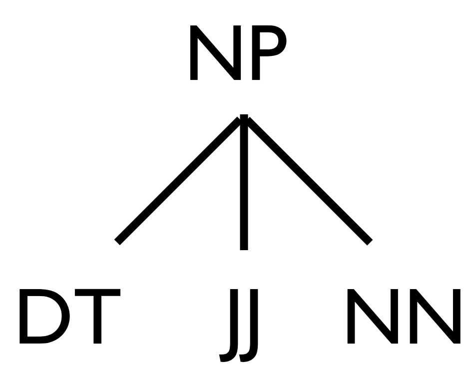
Parsing as (weighted) deduction

- input: words w[1..N]

Axioms	$$\frac{}{X \rightarrow w[i]}$$	for all (X → w[i])
Inference rules	$$\frac{X \rightarrow w[i]}{(X, i, i)}$$ $$\frac{(B, i, j) \quad (C, j, k) \quad A \rightarrow BC}{(A, i, k)}$$	in bottom-up order (smaller spans first)
Goal	(S, 1, n)	

Complexity

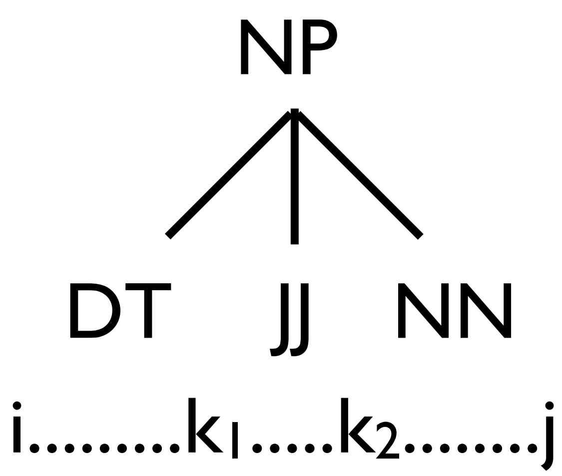
- Complexity of parsing is $O(Gn^3)$
    - G - number of (binarized) rules in the grammar
    - n - length of the sentence
- All those rules were binary; what about longer rules?
    - e.g.,



    - We have to enumerate every split point!

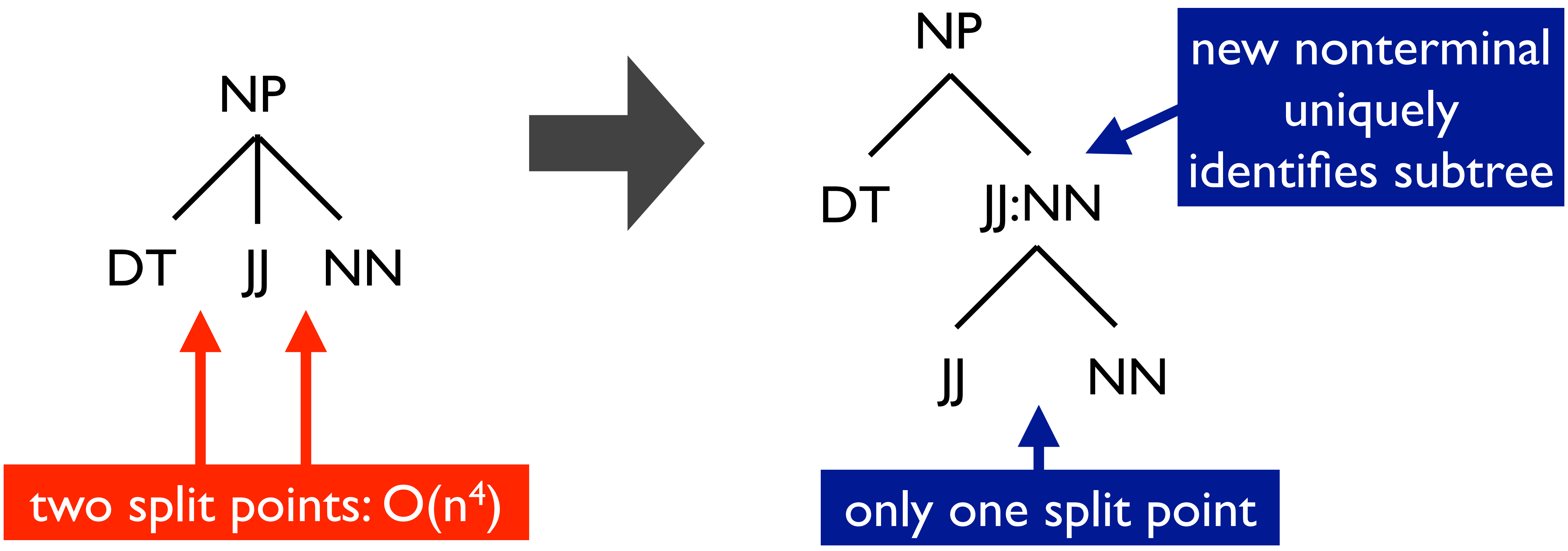
CKY algorithm

```
input: words[1..N]
for i in 1..N
  for each unary rule X → words[i]
    add (X,i,i) to the chart
for span in 1..N
  for i in 1..(N-span)
    j = i + span
    for k1 in i..j-1
      for k2 in k1..j
        for rule X → W Y Z
          if (W,i,k1) and (Y,k1,k2) and (Z,k2,j)
            add (X,i,j) to the chart
output: (S,1,N)
```



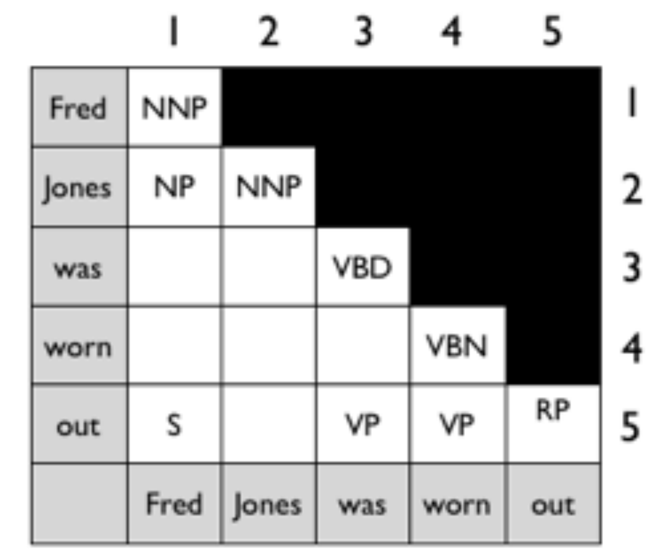
Binarization into Chomsky Normal Form

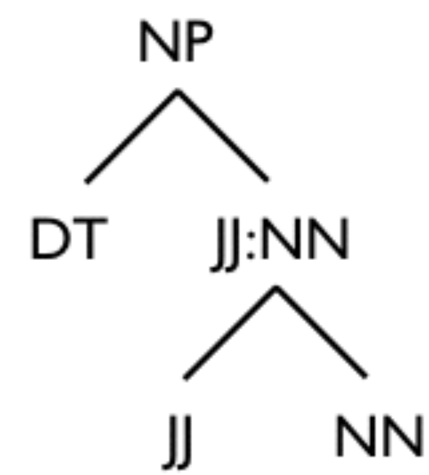
- In general, for a rule with k RHS items, complexity is $O(n^{k+1})$ (and cumbersome, since you have to explicitly add inner loops to enumerate them)
- Fortunately, we can **binarize** rules to make them all have a rank of 2



CKY algorithm

- In summary, monolingual parsing:
  - finds the best structure
  - works bottom-up, enumerating all spans, from small to large, building searching for applicable rules and building new chart items
  - works with the binarized form of a grammars (easily unbinarized afterward) for a complexity of $O(Gn^3)$
  - all grammars are binarizable





Synchronous parsing

Synchronous parsing

- We can extend CKY to parse two languages at once!
- Consider the following grammar:

A → fat, gordos	(lexical)
A → thin, delgados	
N → cats, gatos	
VP → eat, comen	
NP → $A^{(1)}$ $N^{(2)}$, $N^{(2)}$ $A^{(1)}$	(inverted)
S → $NP^{(1)}$ $VP^{(2)}$, $NP^{(1)}$ $VP^{(2)}$	(straight)

- and the following sentence pair:

fat cats eat / gatos gordos comen

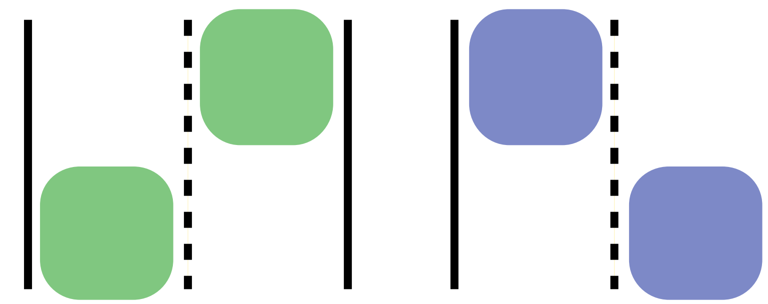
Synchronous parsing

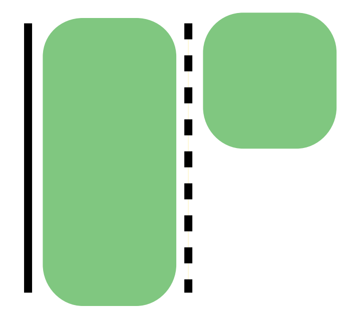
- We now have to enumerate *pairs* of spans
  - instead of (i,j)...
  - ...we have (i,j) and (s,t)
- For each of the bilingual blocks, we attempt to match both straight and inverted rules

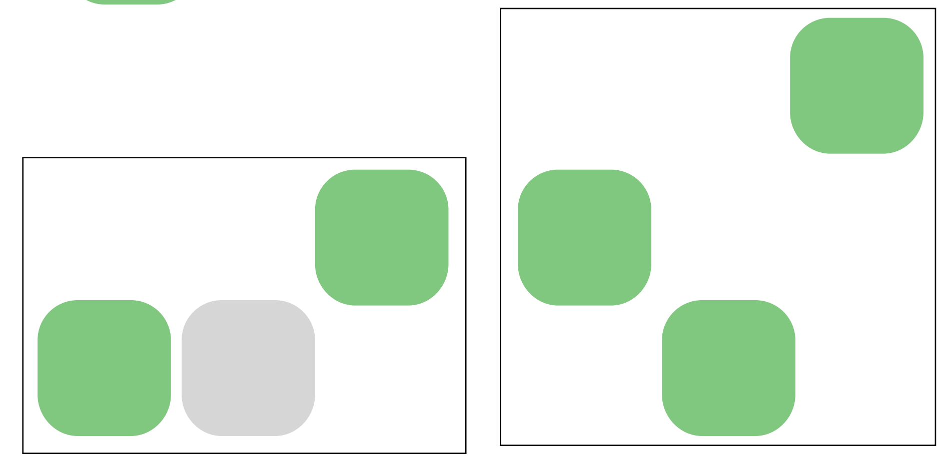
A → fat, gordos
N → cats, gatos
VP → eat, comen
VP → eat, como
NP → $A^{(1)}$ $N^{(2)}$, $N^{(2)}$ $A^{(1)}$
S → $NP^{(1)}$ $VP^{(2)}$, $NP^{(1)}$ $VP^{(2)}$

Relation to monolingual parsing

- Why do we combine like this?
  - Think about monolingual CKY: combine adjacent spans
  - These pieces are adjacent in both languages; it's only when we consider them *together* that reordering comes into play
- Why can't we do this?
  - It doesn't make sense!
- What about these?
  - Possible, but complex



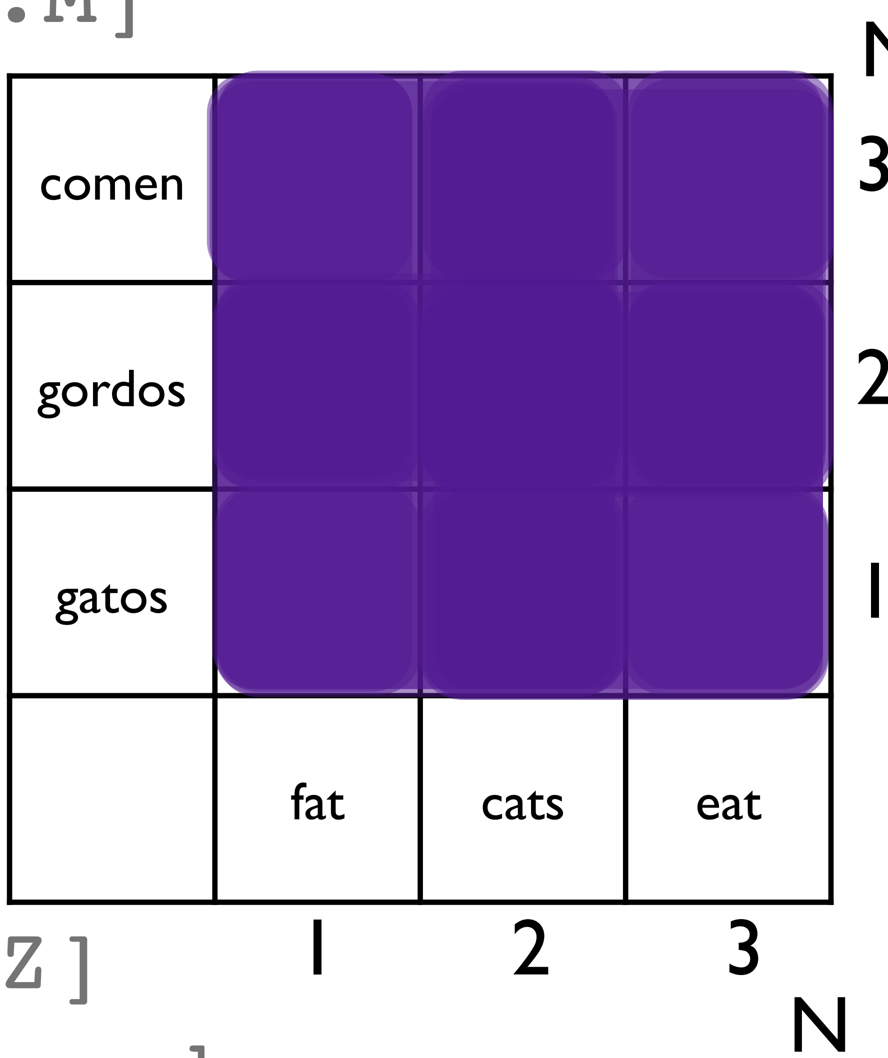




gap rank > 2

CKY for synchronous parsing

```
input: source[1..N], target[1..M]
for span₁ in 1..N
  for i in 1..(N-span₁)
    j = i + span₁
      for k in i..j
        for span₂ in 1..M
          for s in 1..(M-span₂)
            t = s + span₂
              for u in s..t
                for rule X → [Y Z]
                  if (Y,i,k,s,u) and
                     (Z,k,j,u,v) then
                    add (X,i,j,s,t) to chart
output: (S,1,N,1,M)
```



Synchronous parsing

- Complexity:
  $O(GN^3M^3) \approx O(GN^6)$
- Why?
  - We have to enumerate all valid combinations of six variables
  - This can be seen in the six nested loops of the algorithm

$A \rightarrow$ fat, gordos

$N \rightarrow$ cats, gatos

$VP \rightarrow$ eat, comen

$VP \rightarrow$ eat, como

$NP \rightarrow A^{(1)}\ N^{(2)},\ N^{(2)}\ A^{(1)}$

$S \rightarrow NP^{(1)}\ VP^{(2)},\ NP^{(1)}\ VP^{(2)}$

Visualization of O(GN⁶) complexity

```
  input: source[1..N], target[1..M]
1 for span1 in 1..N
2   for i in 1..(N-span1)
      j = i + span1
3       for k in i..j
4         for span2 in 1..M
5           for s in 1..(M-span2)
              t = s + span2
6               for u in s..t
  times all rules...  for rule X → [Y Z]
                        if (Y,i,k,s,u) and
                           (Z,k,j,u,v) then
                          add (X,i,j,s,t) to chart
output: (S,1,N,1,M)
```

Synchronous binarization

- In the above, we considered two nonterminals (per side)
- What if we want more (Zhang et al., 2006)?

$$\begin{array}{rl} \mathrm{S} \rightarrow & \mathrm{NP}^{(1)}\ \mathrm{VP}^{(2)}\ \mathrm{PP}^{(3)},\ \mathrm{NP}^{(1)}\ \mathrm{PP}^{(3)}\ \mathrm{VP}^{(2)} \\ \mathrm{NP} \rightarrow & \text{Powell, } \textit{Baoweier} \\ \mathrm{VP} \rightarrow & \text{held a meeting, } \textit{juxing le huitan} \\ \mathrm{PP} \rightarrow & \text{with Sharon, } \textit{yu Shalong} \end{array}$$

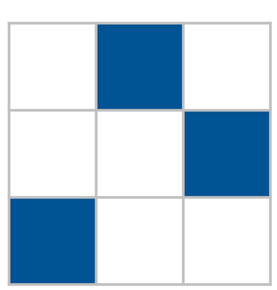
- Three nonterminals? No problem:

$$\begin{array}{rl} \mathrm{S} \rightarrow & V_{\text{NP-PP}}\ \mathrm{VP} \\ V_{\text{NP-PP}} \rightarrow & \mathrm{NP}\ \mathrm{PP} \end{array} \quad \text{or} \quad \begin{array}{rl} \mathrm{S} \rightarrow & \mathrm{NP}\ V_{\text{PP-VP}} \\ V_{\text{PP-VP}} \rightarrow & \mathrm{PP}\ \mathrm{VP} \end{array}$$

- More?

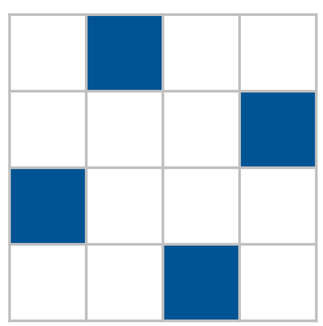
Permutations

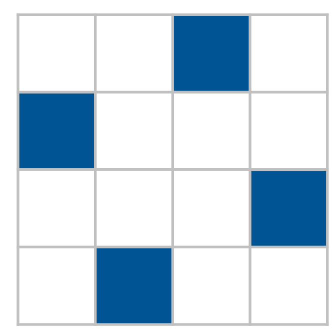
- The nonterminals in the right-hand side of a rule define a permutation between the languages
  - we assume the source language nonterminals are in order (wlog)
  - intermingled terminal symbols do not affect binarization ability
- Example: $S \rightarrow \quad NP^{(1)}\ VP^{(2)}\ PP^{(3)},\ NP^{(1)}\ PP^{(3)}\ VP^{(2)}$
  - permutation: 1 3 2



Synchronous binarization

- Bad news: synchronous grammars can't be binarized in the general case (Shapiro & Stephens, 1991; Wu, 1997) *
- Famous examples: the (2,4,1,3) and (3,1,4,2) permutations



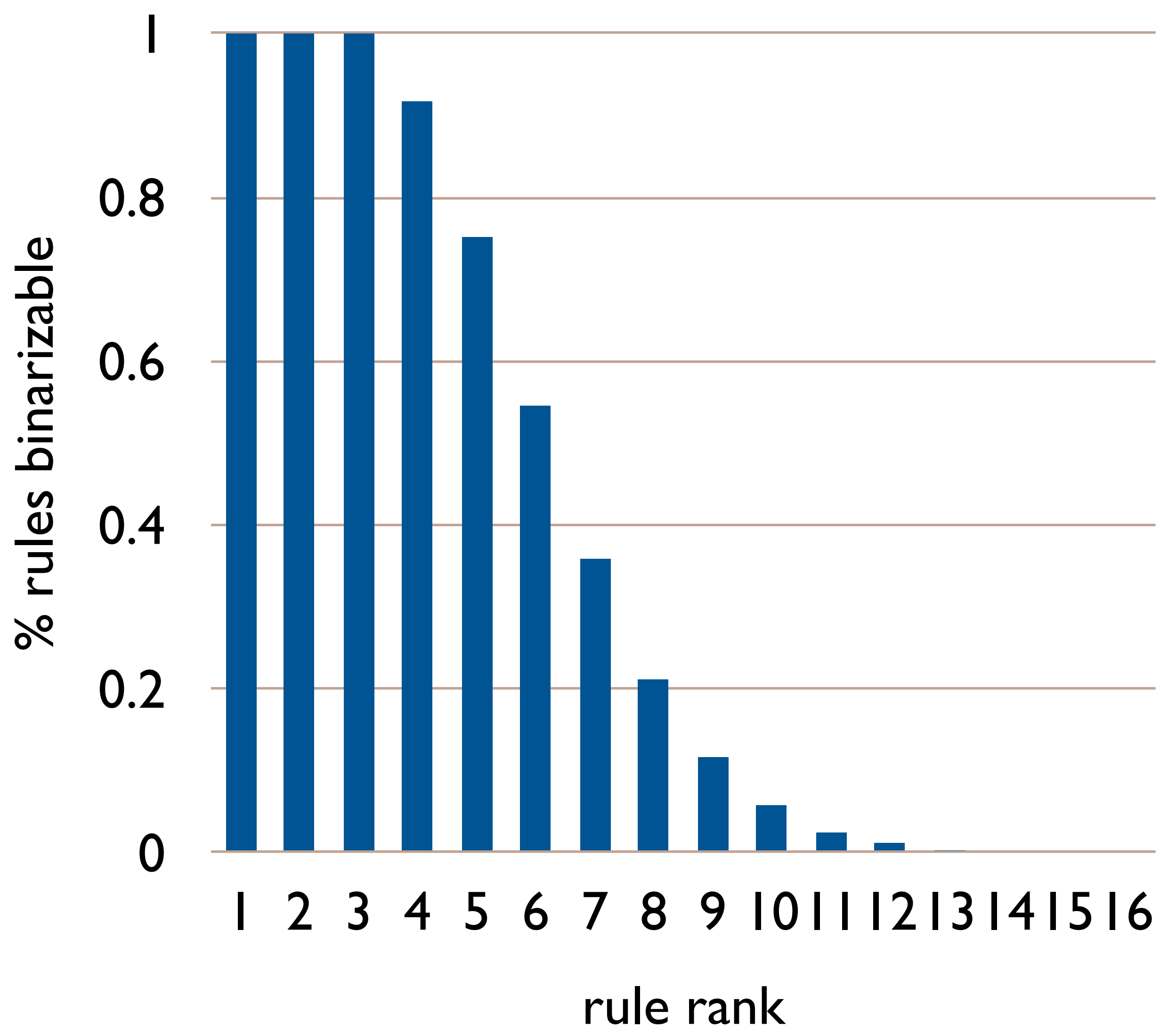


- What makes these unbinarizable?
  - Crucial: parsing works by combining *adjacent* elements
  - No pair of alignments here is adjacent in *both* languages simultaneously

(*) Technically, you can binarize any synchronous grammar, but you may increase the ***fan-out****, which mitigates the potential gains.*

Synchronous binarization

- As the rank of a rule grows, the percentage of binarizable rules approaches 0



- In summary:
  - We can't binarize all rules
  - The first unbinarizable rule has rank 4

Silver lining

- Empirically, we don't observe that many non-binarizable rules (Zhang et al., 2006):

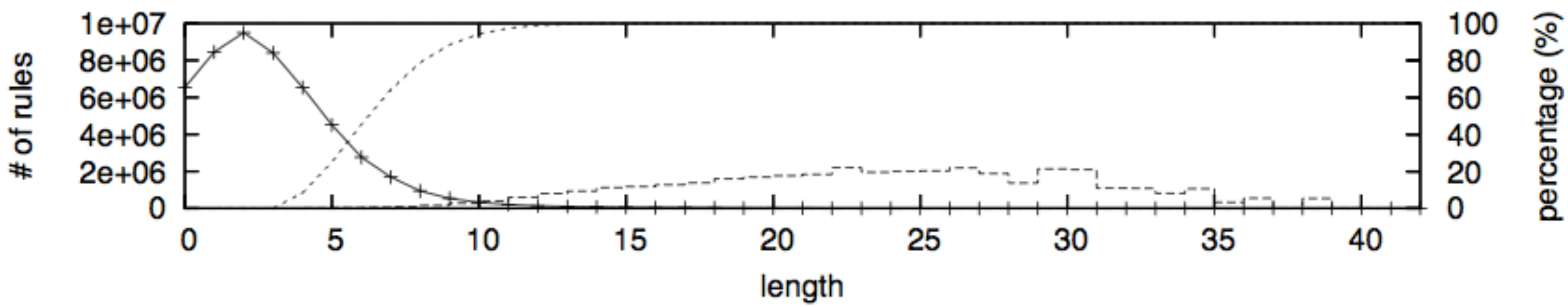


Figure 6: The solid-line curve represents the distribution of all rules against permutation lengths. The dashed-line stairs indicate the percentage of non-binarizable rules in our initial rule set while the dotted-line denotes that percentage among all permutations.

- ...and we can safely throw out the ones we do find
  - 99.7% of rules extracted were binarizable
  - many not were due to alignment errors

Decoding as parsing

Synchronous decoding

- Enough parsing; what we care about is decoding
- Parsing is relevant, though, because we can view decoding as a task where we are doing synchronous parsing but we don't happen to know the target side text
- This works by parsing with a source-side projection of the synchronous grammar rules
  - At the end, we can follow backpointers to discover the most probable target side

Updated data structure

- Just like regular parsing, we combine items in pairs to produce new items over larger spans:

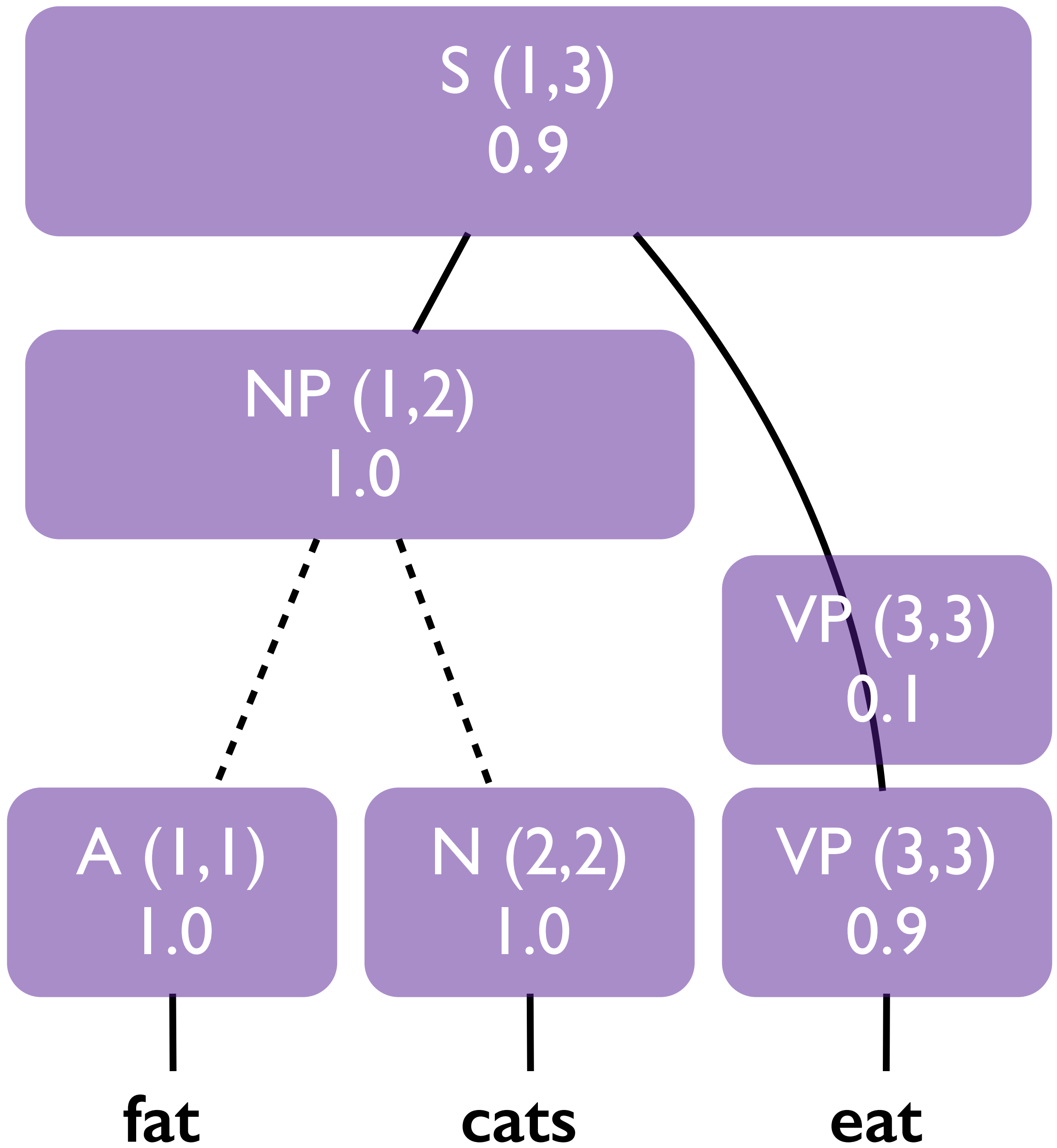
$$\frac{(A,1,1) \quad (N,2,2)}{(NP,1,2)}$$

- However, we also have to maintain our guess of the target side

A → fat, gordos
N → cats, gatos
VP → eat, comen
VP → eat, como
NP → $A^{(1)}\ N^{(2)},\ N^{(2)}\ A^{(1)}$
S → $NP^{(1)}\ VP^{(2)},\ NP^{(1)}\ VP^{(2)}$

Decoding

- Again, a bottom-up process



$A \rightarrow$ fat, gordos	1.0
$N \rightarrow$ cats, gatos	1.0
$VP \rightarrow$ eat, comen	0.1
$VP \rightarrow$ eat, como	0.9
$NP \rightarrow A^{(1)}\ N^{(2)},\ N^{(2)}\ A^{(1)}$	1.0
$S \rightarrow NP^{(1)}\ VP^{(2)},\ NP^{(1)}\ VP^{(2)}$	1.0

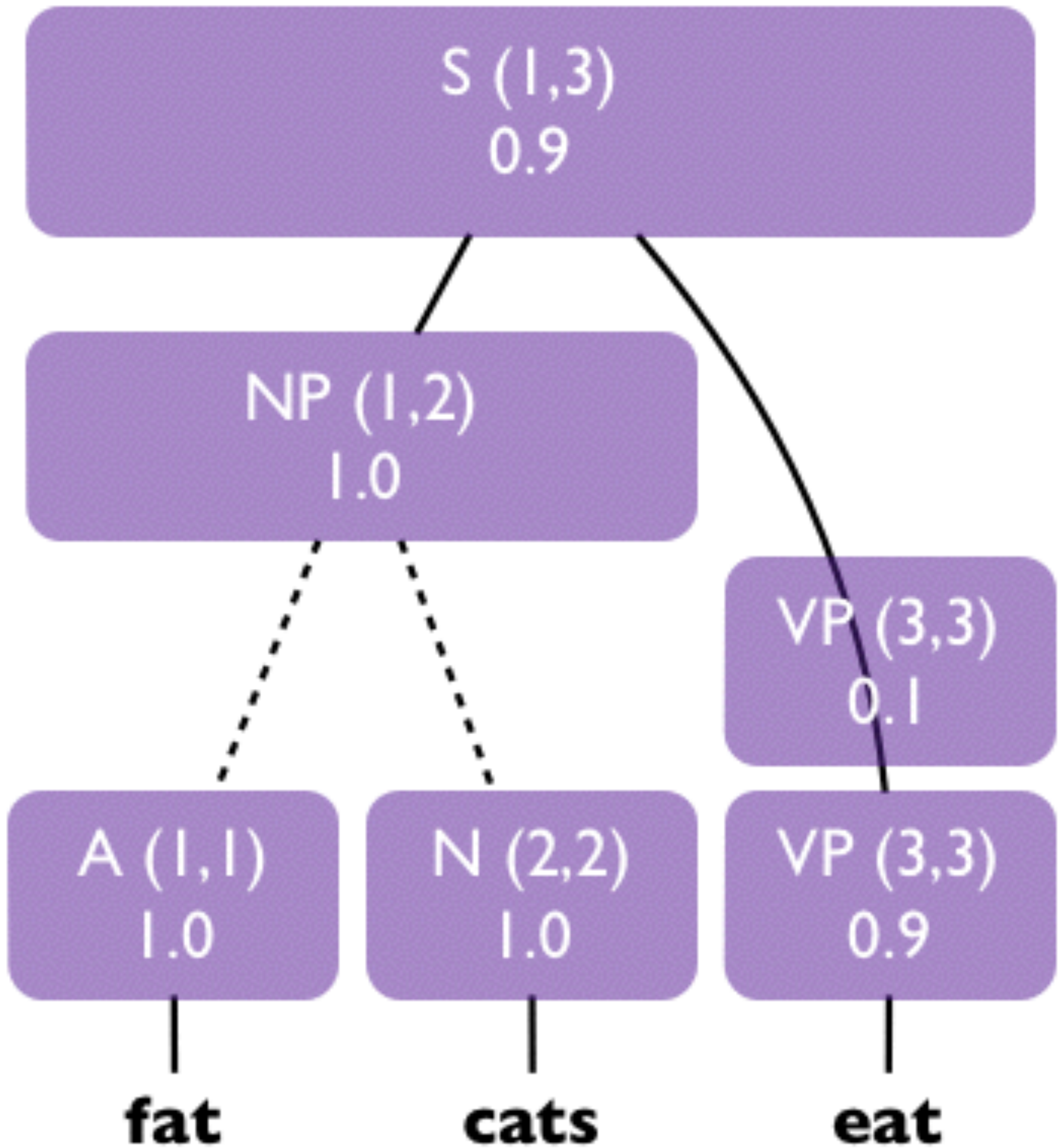
Legend

straight rule application (solid line)

inverted rule application (dashed line)

Getting the translation

- Follow the backpointers
  - (S,1,3)
    - (NP,1,2)
      - (N,2,2) → gatos
      - (A,1,1) → gordos
    - (VP,3,3) → como
- translation:
  gatos gordos como
  * *cats* *fat* *1ps-eat*



What happened?

- We forgot the language model
- We're inventing the target side (which is what decoding does), so we need to incorporate it
- How?
  - Stack-based decoding: we maintained the last word
  - Integration was easy because hypotheses always extended to the right
  - Here, hypotheses are *merged* either straight or inverted

Language model integration

phrase-based

+

tengo
→am

=

synchronous grammars

A (1,1)
1.0

+

N (2,2)
1.0

$NP \rightarrow A^{(1)}\ N^{(2)},\ N^{(2)}\ A^{(1)}$

=

N (1,2)
1.0
gatos gordos

A (1,1)
1.0

+

N (2,2)
1.0

$NP \rightarrow A^{(1)}\ N^{(2)},\ A^{(1)}\ N^{(2)}$

=

N (1,2)
1.0
gordos gatos

Language model integration

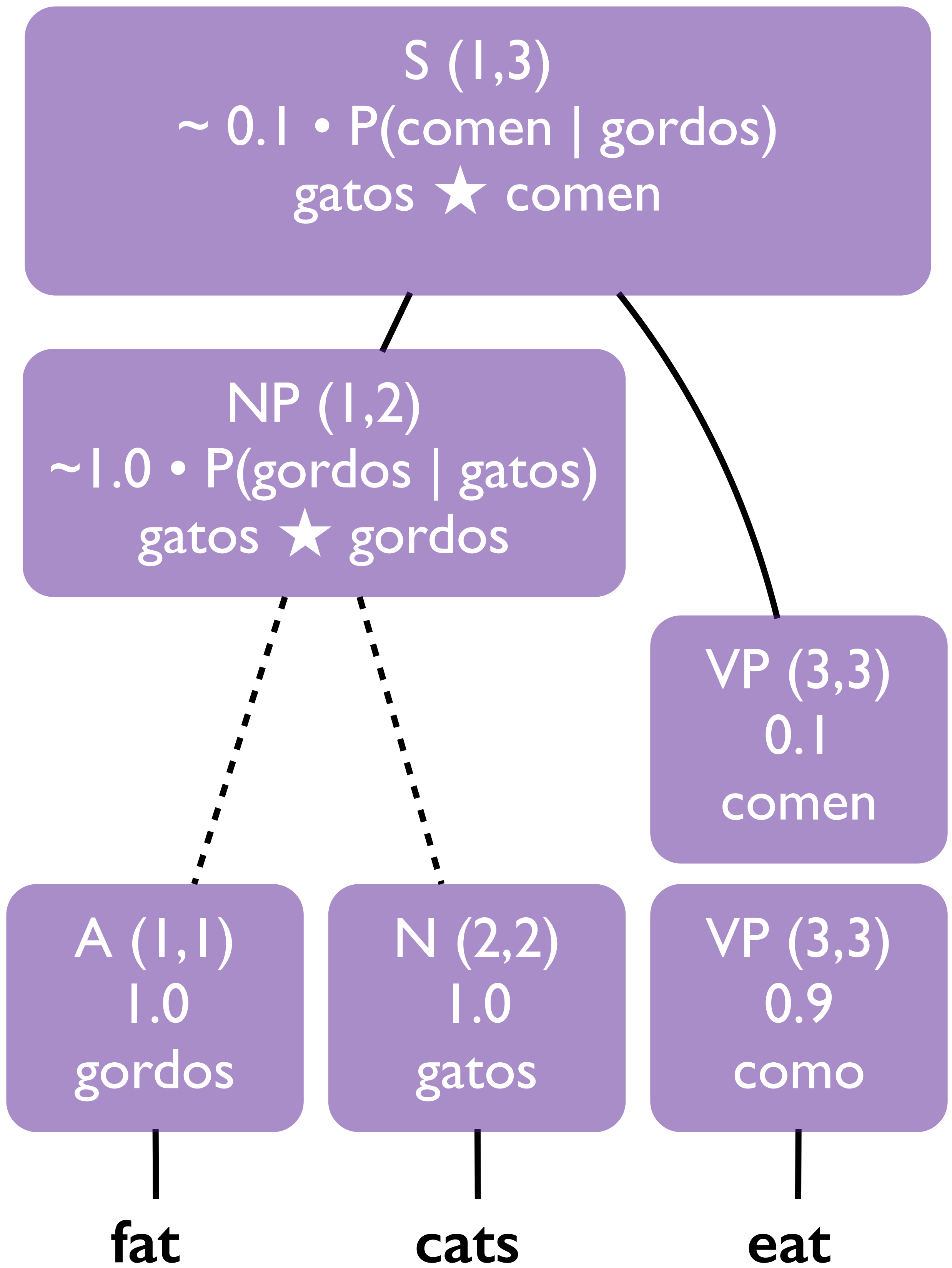
- We still maintain a chart of items, but now the items have to contain the target side words
- Just like regular parsing, we combine items in pairs to produce new items over larger spans
- When items are merged, we can use these words to compute a language model probability
- Formally, we are intersecting a *context-free grammar* (the translation model) with a *regular grammar* (Bar-Hillel et al., 1964; Wu, 1996)

Updated data structure

- With dynamic programming, we only need a word on either side
  - (for bigram LMs; for the general case, see Chiang (2007, §5.3.2))
  - Following Chiang, we represent the elided middle portion with a ★
  - The complete string can be reconstructed by following the backpointers

```
struct item {
  // d.p. state
  string nt;
  int i, j;
  string left_words;
  string right_words;
  // backpointer
  float score;
  Rule* rule;
  item* rhs1,
        rhs2;
}
```

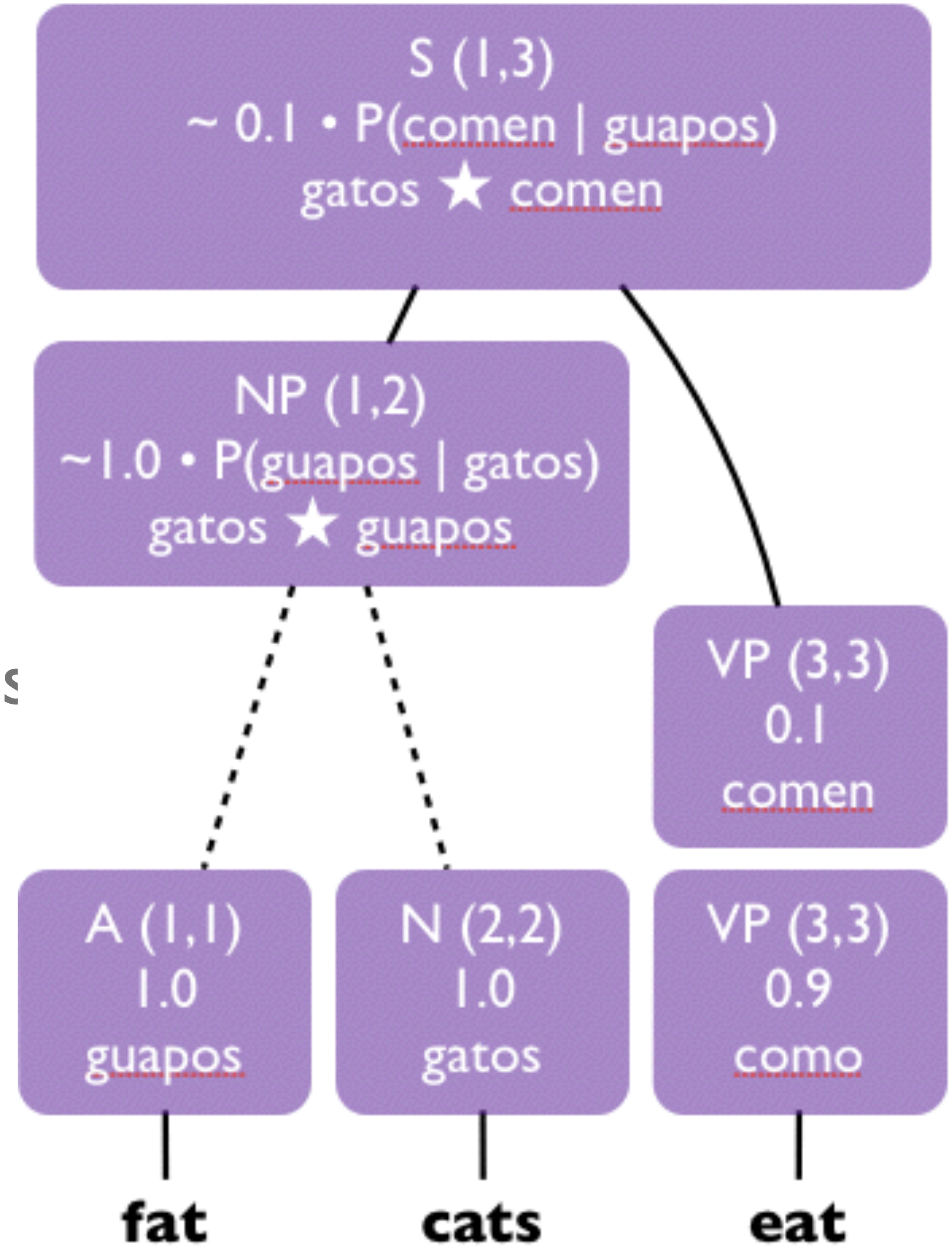
Decoding with an integrated LM



A → fat, gordos	1.0
N → cats, gatos	1.0
VP → eat, comen	0.1
VP → eat, como	0.9
NP → $A^{(1)}$ $N^{(2)}$, $N^{(2)}$ $A^{(1)}$	1.0
S → $NP^{(1)}$ $VP^{(2)}$, $NP^{(1)}$ $VP^{(2)}$	1.0

Getting the translation

- Follow the backpointers
  - (S,1,3,gatos★comen)
    - (NP,1,2,gatos★gordos)
      - (N,2,2,gatos) → gatos
      - (A,1,1,gordos) → gordos
    - (VP,3,3,comen) → comen
- translation:
  gatos gordos comen
  cats fat 3pp-eat



Pruning

- We have also not dealt much with ambiguity and competition amongst hypotheses
- In general, there are too many hypotheses to consider, so we keep only the top k of them (per input span (i,j))
- When considering a span (i,j) and a split point k, we have a large number of ways to combine items
    - there can be any number of applicable rules
    - there can be up to k items located at span (i,k)
    - there can be up to k items located at span (k,j)

Applying a unary rule

- The naive way is to consider the full cross product

		[X, 6, 8; the scheme] 1	[X, 6, 8; the plan] 4	[X, 6, 8; the project] 7
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from } X_{\boxed{1}} \rangle$	1	2.1	5.1	8.2
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from the } X_{\boxed{1}} \rangle$	2	5.5	8.5	11.5
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{since } X_{\boxed{1}} \rangle$	6	7.7	10.6	13.1
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{through } X_{\boxed{1}} \rangle$	10	11.1	14.3	17.3

$\Rightarrow$

[X, 5, 8; from the ⋆ the scheme] : 2.1
[X, 5, 8; from the ⋆ the plan] : 5.1
[X, 5, 8; from the ⋆ the scheme] : 5.5
[X, 5, 8; since the ⋆ the scheme] : 7.7
.

Cube pruning

- When considering a span (i,j) of a length-N sentence:
  - *unary rules:* there are rk items to compute (r the number of rules, k the number of child items)
  - *binary rules:* there are Nrk^2 items to compute (since there are O(N) split points)
- However, we're only going to be keeping the top k of them!
  - this problem gets worse as k gets larger
- We'd like to avoid computing all of these new items, which we accomplish with cube pruning

Cube pruning

- We start with sorted lists of rules and the items they applied to
- Observation:
  - the best item comes from the best rule and the best cell
  - the next-best item uses either the 2nd best rule *or* the 2nd-best cell

	rule	rhsl	rhsr
1	1	1	1
2	2	7	3
3	4	9	4
...			

best item

	rule	rhsl	rhsr
1	1	1	1
2	2	7	3
3	4	9	4
...			

2nd-best

	rule	rhsl	rhsr
1	1	1	1
2	2	7	3
3	4	9	4
...			

3rd-best

Applying a unary rule

- The Huang & Chiang (2005) way:

		[X, 6, 8; the scheme] 1	[X, 6, 8; the plan] 4	[X, 6, 8; the project] 7
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from } X_{\boxed{1}} \rangle$	1	2.1	5.1	
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from the } X_{\boxed{1}} \rangle$	2	5.5		
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{since } X_{\boxed{1}} \rangle$	6			
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{through } X_{\boxed{1}} \rangle$	10			

		[X, 6, 8; the scheme] 1	[X, 6, 8; the plan] 4	[X, 6, 8; the project] 7
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from } X_{\boxed{1}} \rangle$	1	2.1	5.1	8.2
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from the } X_{\boxed{1}} \rangle$	2	5.5	8.5	
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{since } X_{\boxed{1}} \rangle$	6			
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{through } X_{\boxed{1}} \rangle$	10			

		[X, 6, 8; the scheme] 1	[X, 6, 8; the plan] 4	[X, 6, 8; the project] 7
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from } X_{\boxed{1}} \rangle$	1	2.1	5.1	8.2
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{from the } X_{\boxed{1}} \rangle$	2	5.5	8.5	
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{since } X_{\boxed{1}} \rangle$	6	7.7		
$X \rightarrow \langle \text{cong } X_{\boxed{1}}, \text{through } X_{\boxed{1}} \rangle$	10			

Cube pruning

- We haven't discussed the language model, which complicates this procedure by making it *nonmonotonic*
- But that's the basic idea

Summary

- Today, we have reviewed
  - Monolingual parsing
  - Synchronous (bilingual) parsing
  - Decoding as parsing with an intersected bigram language model
- We have also briefly touched on efficiency considerations with cube pruning

Advanced topics

Advanced topics: implicit binarization

- We'd decoded in an ITG settings, where the rules all look like this:

$$X \rightarrow \text{boy, chico} \qquad \text{(lexical)}$$
$$X \rightarrow X^{(1)}\ X^{(2)},\ X^{(2)}\ X^{(1)} \qquad \text{(inverted)}$$
$$X \rightarrow X^{(1)}\ X^{(2)},\ X^{(1)}\ X^{(2)} \qquad \text{(straight)}$$

  - This is the closest thing to Chomsky Normal Form for synchronous grammars

- How do we decode with intermingled terminals and nonterminals?

$$X \rightarrow \text{the } X^{(1)} \text{ was } X^{(2)}, \text{ el } X^{(1)} \text{ era } X^{(2)}$$

Advanced topics: implicit binarization

- One answer: binarize (terminals can always be binarized):

$X \rightarrow$ the X was X, el X era X

$X \rightarrow$ the X_{174}, el X_{174}

$X_{174} \rightarrow X\ X_{295}$, $X\ X_{295}$

$X_{295} \rightarrow$ was X, era X

- However, this is inefficient:
  - it leads to a huge blowup in the number of nonterminals
  - it introduces a split point that has to be searched over (avoidable in this case, but not always)

Advanced topics: implicit binarization

- Instead, we'd like to do implicit, Earley-style binarization

Advanced topics: spurious ambiguity

- *Spurious ambiguity* - multiple structures leading to the same interpretation
- Especially problematic in ITG with its weak grammar
- This can be addressed in various ways
  - Grammar canonical forms