Speech and Language Processing

SLP Chapter 13

Parsing

Today

- Parsing with CFGs
  - Bottom-up, top-down
  - Ambiguity
  - CKY parsing

Parsing

- Parsing with CFGs refers to the task of assigning proper trees to input strings
- Proper here means a tree that covers all and only the elements of the input and has an S at the top
- It doesn't actually mean that the system can select the correct tree from among all the possible trees

Parsing

- As with everything of interest, parsing involves a search which involves the making of choices
- We'll start with some basic (meaning bad) methods before moving on to the one or two that you need to know

For Now

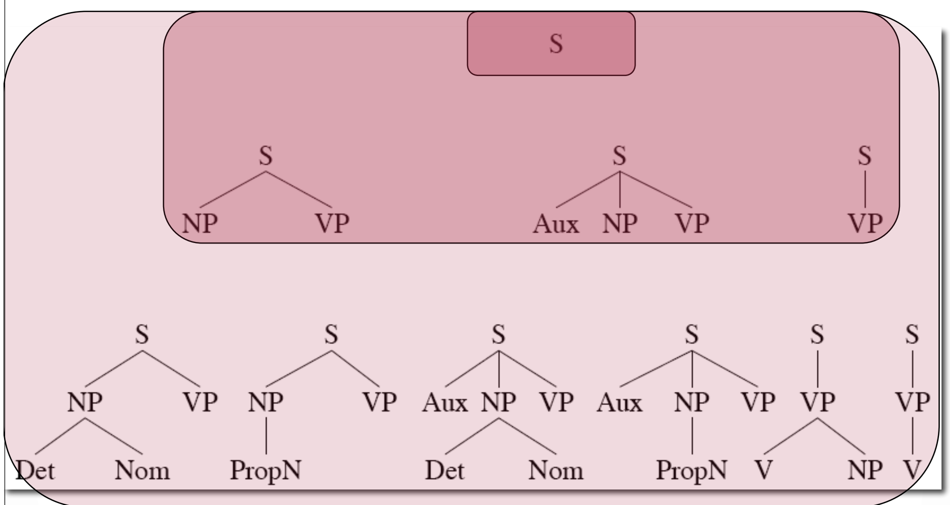
- Assume…
  - You have all the words already in some buffer
  - The input isn't POS tagged
  - We won't worry about morphological analysis
  - All the words are known

  - These are all problematic in various ways, and would have to be addressed in real applications.

Top-Down Search

- Since we're trying to find trees rooted with an *S* (Sentences), why not start with the rules that give us an *S*.
- Then we can work our way down from there to the words.

Top Down Space



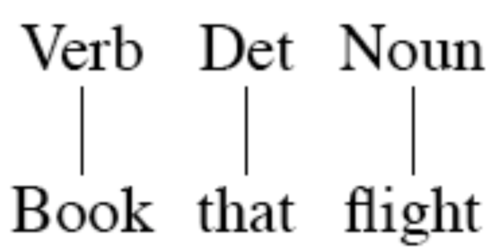
Bottom-Up Parsing

- Of course, we also want trees that cover the input words. So we might also start with trees that link up with the words in the right way.
- Then work your way up from there to larger and larger trees.

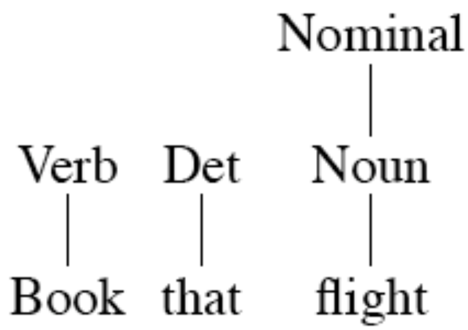
Bottom-Up Search

Book that flight

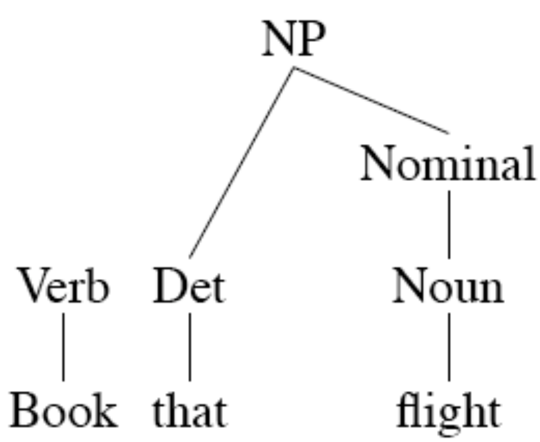
Bottom-Up Search



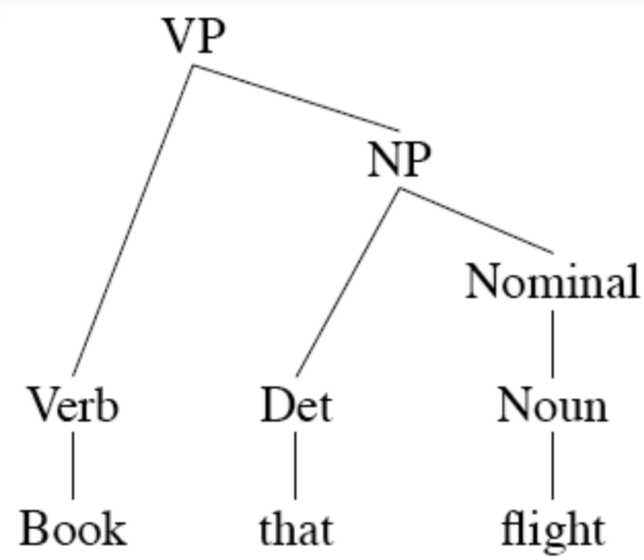
Bottom-Up Search



Bottom-Up Search



Bottom-Up Search



Top-Down and Bottom-Up

- Top-down
  - Only searches for trees that can be answers (i.e. S's)
  - But also suggests trees that are not consistent with any of the words
- Bottom-up
  - Only forms trees consistent with the words
  - But suggests trees that make no sense globally

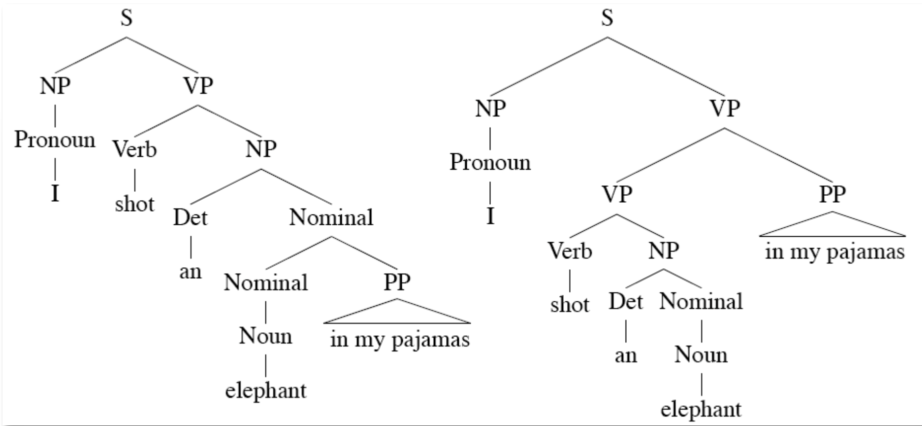
Control

- Of course, in both cases we left out how to keep track of the search space and how to make choices
  - Which node to try to expand next
  - Which grammar rule to use to expand a node
- One approach is called backtracking.
  - Make a choice, if it works out then fine
  - If not then back up and make a different choice

Problems

- Even with the best filtering, backtracking methods are doomed because of two inter-related problems
  - Ambiguity
  - Shared subproblems

Ambiguity

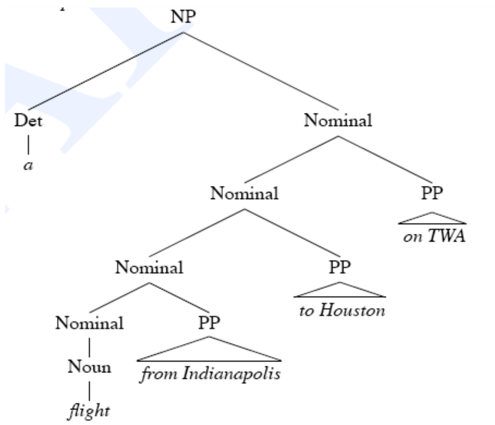


Shared Sub-Problems

- No matter what kind of search (top-down or bottom-up or mixed) that we choose.
  - We don't want to redo work we've already done.
  - Unfortunately, naïve backtracking will lead to duplicated work.

Shared Sub-Problems

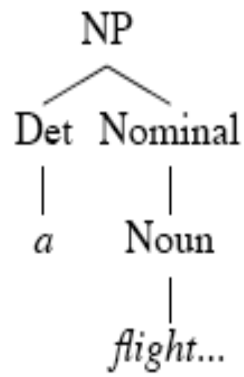
- Consider
  - A flight from Indianapolis to Houston on TWA



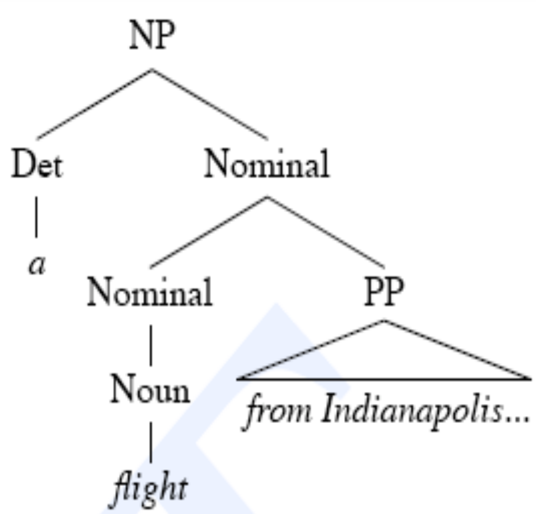
Shared Sub-Problems

- Assume a top-down parse making choices among the various Nominal rules.
- In particular, between these two
  - Nominal -> Noun
  - Nominal -> Nominal PP
- Statically choosing the rules in this order leads to the following bad results...

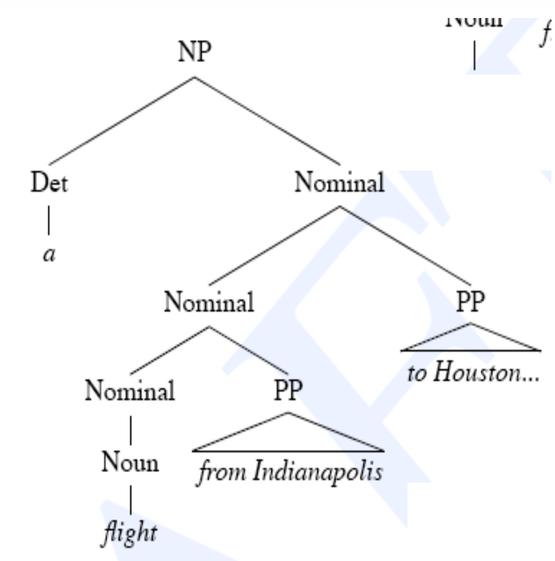
Shared Sub-Problems



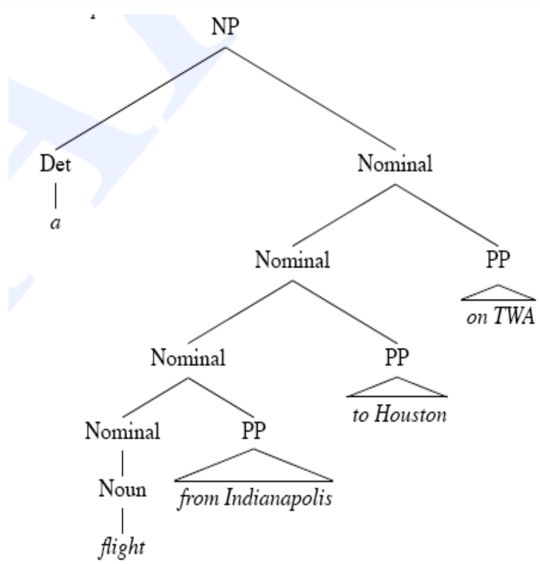
Shared Sub-Problems



Shared Sub-Problems



Shared Sub-Problems



Dynamic Programming

- DP search methods fill tables with partial results and thereby
  - Avoid doing avoidable repeated work
  - Solve exponential problems in polynomial time (well, no not really)
  - Efficiently store ambiguous structures with shared sub-parts.
- We'll cover two approaches that roughly correspond to top-down and bottom-up approaches.
  - CKY
  - Earley

CKY Parsing

- First we'll limit our grammar to epsilon-free, binary rules (more later)
- Consider the rule $A \rightarrow BC$
  - If there is an A somewhere in the input then there must be a B followed by a C in the input.
  - If the A spans from i to j in the input then there must be some k st. i<k<j
    - Ie. The B splits from the C someplace.

Problem

- What if your grammar isn't binary?
  - As in the case of the TreeBank grammar?
- Convert it to binary… any arbitrary CFG can be rewritten into Chomsky-Normal Form automatically.
- What does this mean?
  - The resulting grammar accepts (and rejects) the same set of strings as the original grammar.
  - But the resulting derivations (trees) are different.

Problem

- More specifically, we want our rules to be of the form

  A → B C

  Or

  A → *w*

  That is, rules can expand to either 2 non-terminals or to a single terminal.

Binarization Intuition

- Eliminate chains of unit productions.
- Introduce new intermediate non-terminals into the grammar that distribute rules with length > 2 over several rules.
  - So… *S → A B C turns into*

S → X C and

X → A B

Where X is a symbol that doesn't occur anywhere else in the the grammar.

Sample L1 Grammar

Grammar	Lexicon
S → NP VP	*Det → that | this | a*
S → Aux NP VP	*Noun → book | flight | meal | money*
S → VP	*Verb → book | include | prefer*
NP → Pronoun	*Pronoun → I | she | me*
NP → Proper-Noun	*Proper-Noun → Houston | NWA*
NP → Det Nominal	*Aux → does*
Nominal → Noun	*Preposition → from | to | on | near | through*
Nominal → Nominal Noun	
Nominal → Nominal PP	
VP → Verb	
VP → Verb NP	
VP → Verb NP PP	
VP → Verb PP	
VP → VP PP	
PP → Preposition NP	

CNF Conversion

$\mathscr{L}_1$ Grammar	$\mathscr{L}_1$ in CNF
S → NP VP	S → NP VP
S → Aux NP VP	S → X1 VP
	X1 → Aux NP
S → VP	S → book | include | prefer
	S → Verb NP
	S → X2 PP
	S → Verb PP
	S → VP PP
NP → Pronoun	NP → I | she | me
NP → Proper-Noun	NP → TWA | Houston
NP → Det Nominal	NP → Det Nominal
Nominal → Noun	Nominal → book | flight | meal | money
Nominal → Nominal Noun	Nominal → Nominal Noun
Nominal → Nominal PP	Nominal → Nominal PP
VP → Verb	VP → book | include | prefer
VP → Verb NP	VP → Verb NP
VP → Verb NP PP	VP → X2 PP
	X2 → Verb NP
VP → Verb PP	VP → Verb PP
VP → VP PP	VP → VP PP
PP → Preposition NP	PP → Preposition NP

CKY

- So let's build a table so that an A spanning from i to j in the input is placed in cell [i,j] in the table.
- So a non-terminal spanning an entire string will sit in cell [0, n]
  - Hopefully an *S*
- If we build the table bottom-up, we'll know that the parts of the A must go from i to k and from k to j, for some k.

CKY

- Meaning that for a rule like A → B C we should look for a B in [i,k] and a C in [k,j].
- In other words, if we think there might be an A spanning i,j in the input… AND

  A → B C is a rule in the grammar THEN
- There must be a B in [i,k] and a C in [k,j] for some i<k<j

CKY

- So to fill the table loop over the cell[i,j] values in some systematic way
  - What constraint should we put on that systematic search?
  - For each cell, loop over the appropriate k values to search for things to add.

CKY Algorithm

function CKY-PARSE(*words, grammar*) **returns** *table*

for $j \leftarrow$ **from** 1 **to** LENGTH(*words*) **do**
  $table[j-1, j] \leftarrow \{A \mid A \rightarrow words[j] \in grammar\}$
  for $i \leftarrow$ **from** $j-2$ **downto** 0 **do**
    for $k \leftarrow i+1$ **to** $j-1$ **do**
      $table[i,j] \leftarrow table[i,j] \cup \{A \mid A \rightarrow BC \in grammar, B \in table[i,k], C \in table[k,j]\}$

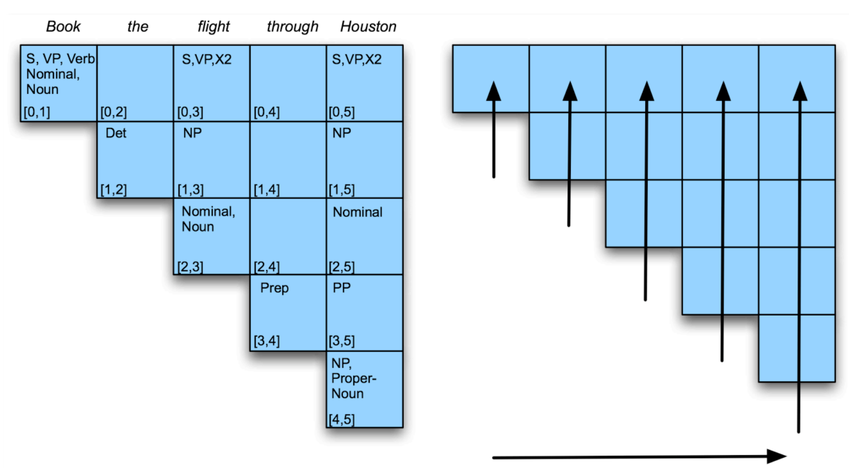
CKY Parsing

- Is that really a parser?

Note

- We arranged the loops to fill the table a column at a time, from left to right, bottom to top.
  - This assures us that whenever we're filling a cell, the parts needed to fill it are already in the table (to the left and below)
  - It's somewhat natural in that it processes the input a left to right a word at a time
    - Known as online

Example



Example

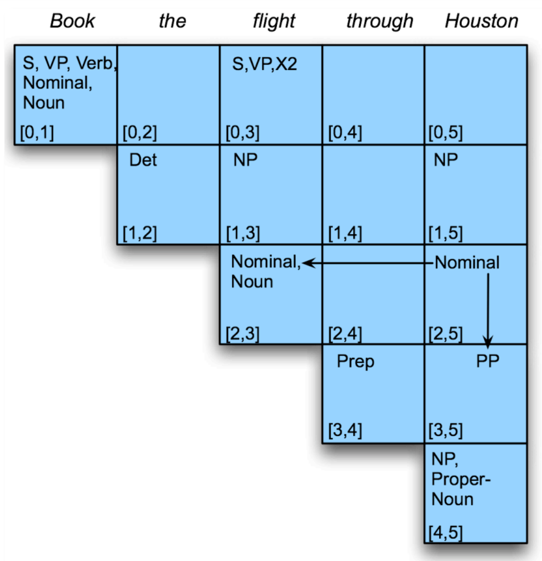
Book	the	flight	through	Houston
S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	[0,5]
	Det [1,2]	NP [1,3]	[1,4]	[1,5]
		Nominal, Noun [2,3]	[2,4]	Nominal [2,5]
			Prep [3,4]	[3,5]
				NP, Proper-Noun [4,5]

Filling column 5

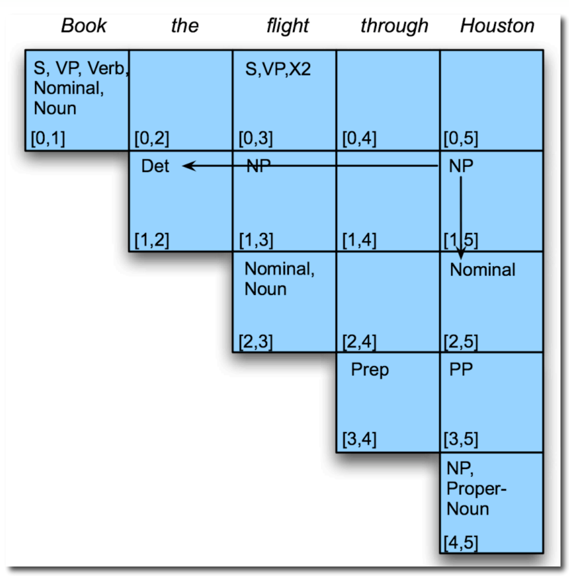
Example

Book	the	flight	through	Houston
S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	[0,5]
	Det [1,2]	NP [1,3]	[1,4]	NP [1,5]
		Nominal, Noun [2,3]	[2,4]	[2,5]
			Prep [3,4]	PP [3,5]
				NP, Proper-Noun [4,5]

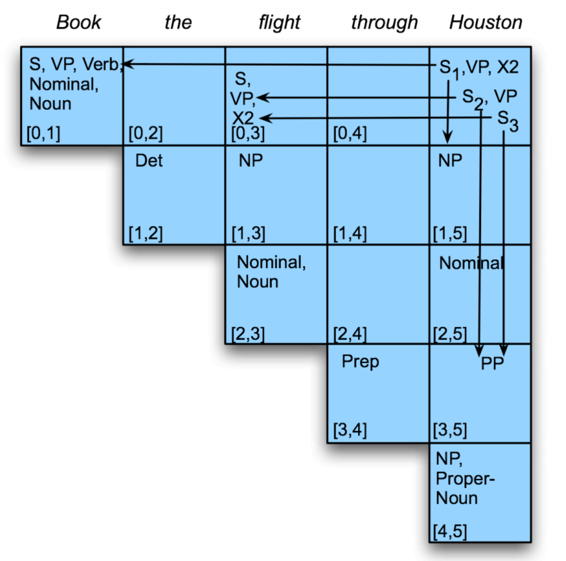
Example



Example



Example



CKY Notes

- Since it's bottom up, CKY populates the table with a lot of phantom constituents.
  - Segments that by themselves are constituents but cannot really occur in the context in which they are being suggested.
  - To avoid this we can switch to a top-down control strategy
  - Or we can add some kind of filtering that blocks constituents where they can not happen in a final analysis.

Earley Parsing

- Allows arbitrary CFGs
- Top-down control
- Fills a table in a single sweep over the input
  - Table is length N+1; N is number of words
  - Table entries represent
    - Completed constituents and their locations
    - In-progress constituents
    - Predicted constituents

States

- The table-entries are called states and are represented with dotted-rules.

S → · VP	A VP is predicted
NP → Det · Nominal	An NP is in progress
VP → V NP ·	A VP has been found

States/Locations

- S → ● VP [0,0]
  - A VP is predicted at the start of the sentence
- NP → Det ● Nominal [1,2]
  - An NP is in progress; the Det goes from 1 to 2
- VP → V NP ● [0,3]
  - A VP has been found starting at 0 and ending at 3

Earley

- As with most dynamic programming approaches, the answer is found by looking in the table in the right place.
- In this case, there should be an S state in the final column that spans from 0 to N and is complete. That is,
  - S → α ● [0,N]
- If that's the case you're done.

Earley

- So sweep through the table from 0 to N…
  - New predicted states are created by starting top-down from S
  - New incomplete states are created by advancing existing states as new constituents are discovered
  - New complete states are created in the same way.

Earley

- More specifically…
  1. *Predict* all the states you can upfront
  2. Read a word
     1. Extend states based on matches
     2. Generate new predictions
     3. Go to step 2
  3. When you're out of words, look at the chart to see if you have a winner

Core Earley Code

```
function EARLEY-PARSE(words, grammar) returns chart

  ENQUEUE((γ → • S, [0,0]), chart[0])
  for i ← from 0 to LENGTH(words) do
   for each state in chart[i] do
     if INCOMPLETE?(state) and
              NEXT-CAT(state) is not a part of speech then
        PREDICTOR(state)
     elseif INCOMPLETE?(state) and
              NEXT-CAT(state) is a part of speech then
         SCANNER(state)
     else
        COMPLETER(state)
   end
  end
  return(chart)
```

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Earley Code

```
procedure PREDICTOR((A → α • B β, [i, j]))
   for each (B → γ) in GRAMMAR-RULES-FOR(B, grammar) do
        ENQUEUE((B → • γ, [j, j]), chart[j])
   end

procedure SCANNER((A → α • B β, [i, j]))
   if B ⊂ PARTS-OF-SPEECH(word[j]) then
       ENQUEUE((B → word[j], [j, j+1]), chart[j+1])

procedure COMPLETER((B → γ •, [j,k]))
   for each (A → α • B β, [i, j]) in chart[j] do
        ENQUEUE((A → α B • β, [i,k]), chart[k])
   end
```

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Example

- Book that flight
- We should find… an S from 0 to 3 that is a completed state…

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Chart[0]

S0	$\gamma \rightarrow \bullet S$	[0,0]	Dummy start state
S1	$S \rightarrow \bullet NP\ VP$	[0,0]	Predictor
S2	$S \rightarrow \bullet Aux\ NP\ VP$	[0,0]	Predictor
S3	$S \rightarrow \bullet VP$	[0,0]	Predictor
S4	$NP \rightarrow \bullet Pronoun$	[0,0]	Predictor
S5	$NP \rightarrow \bullet Proper\text{-}Noun$	[0,0]	Predictor
S6	$NP \rightarrow \bullet Det\ Nominal$	[0,0]	Predictor
S7	$VP \rightarrow \bullet Verb$	[0,0]	Predictor
S8	$VP \rightarrow \bullet Verb\ NP$	[0,0]	Predictor
S9	$VP \rightarrow \bullet Verb\ NP\ PP$	[0,0]	Predictor
S10	$VP \rightarrow \bullet Verb\ PP$	[0,0]	Predictor
S11	$VP \rightarrow \bullet VP\ PP$	[0,0]	Predictor

Note that given a grammar, these entries are the same for all inputs; they can be pre-loaded.

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Chart[1]

S12	$Verb \rightarrow book \bullet$	[0,1]	Scanner
S13	$VP \rightarrow Verb \bullet$	[0,1]	Completer
S14	$VP \rightarrow Verb \bullet NP$	[0,1]	Completer
S15	$VP \rightarrow Verb \bullet NP\ PP$	[0,1]	Completer
S16	$VP \rightarrow Verb \bullet PP$	[0,1]	Completer
S17	$S \rightarrow VP \bullet$	[0,1]	Completer
S18	$VP \rightarrow VP \bullet PP$	[0,1]	Completer
S19	$NP \rightarrow \bullet Pronoun$	[1,1]	Predictor
S20	$NP \rightarrow \bullet Proper\text{-}Noun$	[1,1]	Predictor
S21	$NP \rightarrow \bullet Det\ Nominal$	[1,1]	Predictor
S22	$PP \rightarrow \bullet Prep\ NP$	[1,1]	Predictor

Charts[2] and [3]

S23	$Det \rightarrow that \bullet$	[1,2]	Scanner
S24	$NP \rightarrow Det \bullet Nominal$	[1,2]	Completer
S25	$Nominal \rightarrow \bullet Noun$	[2,2]	Predictor
S26	$Nominal \rightarrow \bullet Nominal\ Noun$	[2,2]	Predictor
S27	$Nominal \rightarrow \bullet Nominal\ PP$	[2,2]	Predictor
S28	$Noun \rightarrow flight \bullet$	[2,3]	Scanner
S29	$Nominal \rightarrow Noun \bullet$	[2,3]	Completer
S30	$NP \rightarrow Det\ Nominal \bullet$	[1,3]	Completer
S31	$Nominal \rightarrow Nominal \bullet Noun$	[2,3]	Completer
S32	$Nominal \rightarrow Nominal \bullet PP$	[2,3]	Completer
S33	$VP \rightarrow Verb\ NP \bullet$	[0,3]	Completer
S34	$VP \rightarrow Verb\ NP \bullet PP$	[0,3]	Completer
S35	$PP \rightarrow \bullet Prep\ NP$	[3,3]	Predictor
S36	$S \rightarrow VP \bullet$	[0,3]	Completer
S37	$VP \rightarrow VP \bullet PP$	[0,3]	Completer

Efficiency

- For such a simple example, there seems to be a lot of useless stuff in there.
- Why?

• It's predicting things that aren't consistent with the input
• That's the flipside to the CKY problem.

Details

- As with CKY that isn't a parser until we add the backpointers so that each state knows where it came from.

Back to Ambiguity

- Did we solve it?

Ambiguity

- No…
  - Both CKY and Earley will result in multiple S structures for the [0,N] table entry.
  - They both efficiently store the sub-parts that are shared between multiple parses.
  - And they obviously avoid re-deriving those sub-parts.
  - But neither can tell us which one is right.

Ambiguity

- In most cases, humans don't notice incidental ambiguity (lexical or syntactic). It is resolved on the fly and never noticed.
- We'll try to model that with probabilities.
- But note something odd and important about the Groucho Marx example…