Earley Parsing

Informatics 2A: Lecture 18

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27 October 2011

CYK Chart entries

The CYK algorithm avoids redundant work by storing in a chart all the constituents it finds.

- Populates the table with phantom constituents.
- These are constituents that cannot occur in the context they are being suggested.
- No justification for a chart entry – why it was built.

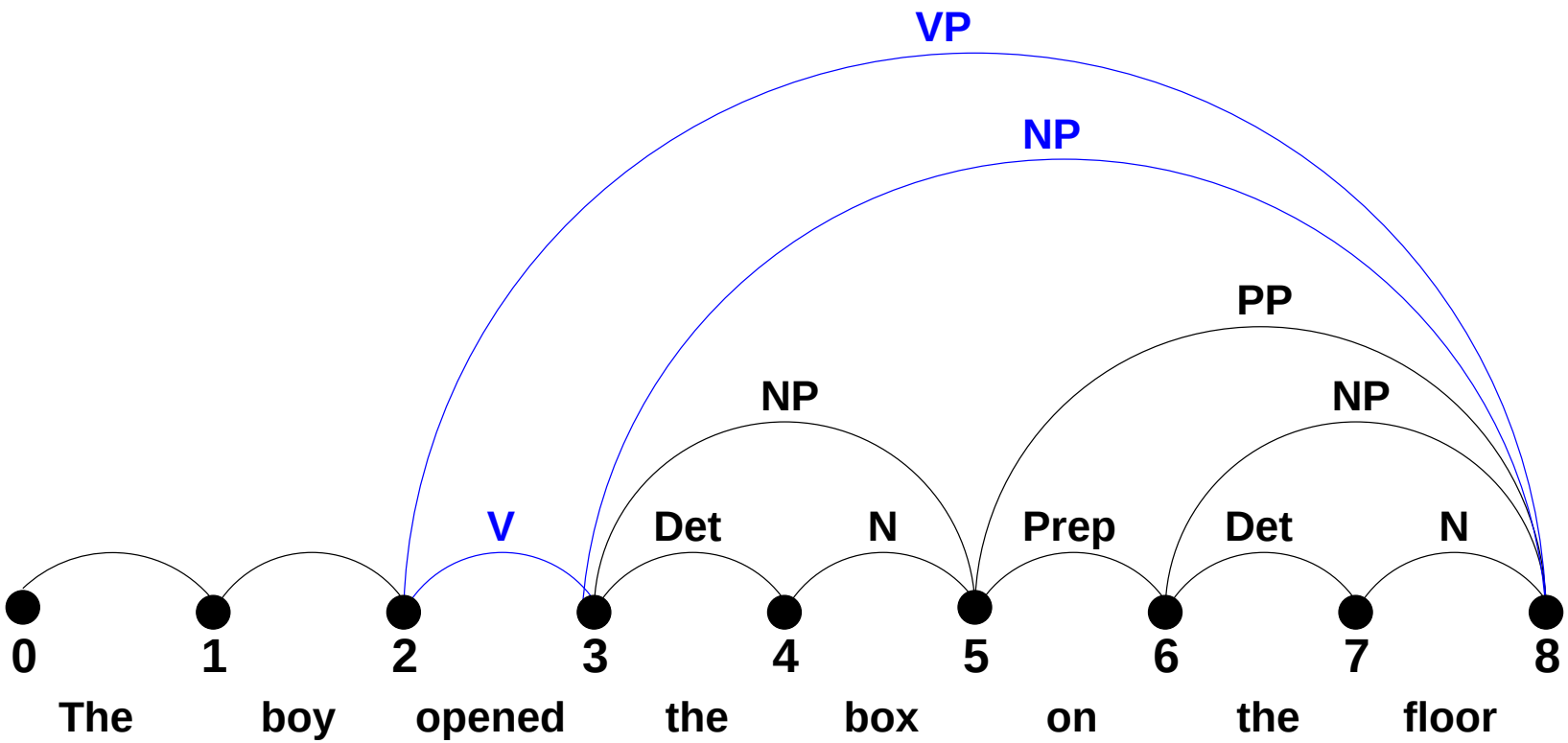
So if we have two VP rules:

$\text{VP} \rightarrow \text{V NP}$
$\text{VP} \rightarrow \text{VP PP}$

and the input string *The boy opened the box on the floor*

CYK Chart entries

We don't know which production the VP arc [2, 8] represents: $VP \rightarrow V\ NP$ or $VP \rightarrow VP\ PP$ (graph-based representation).



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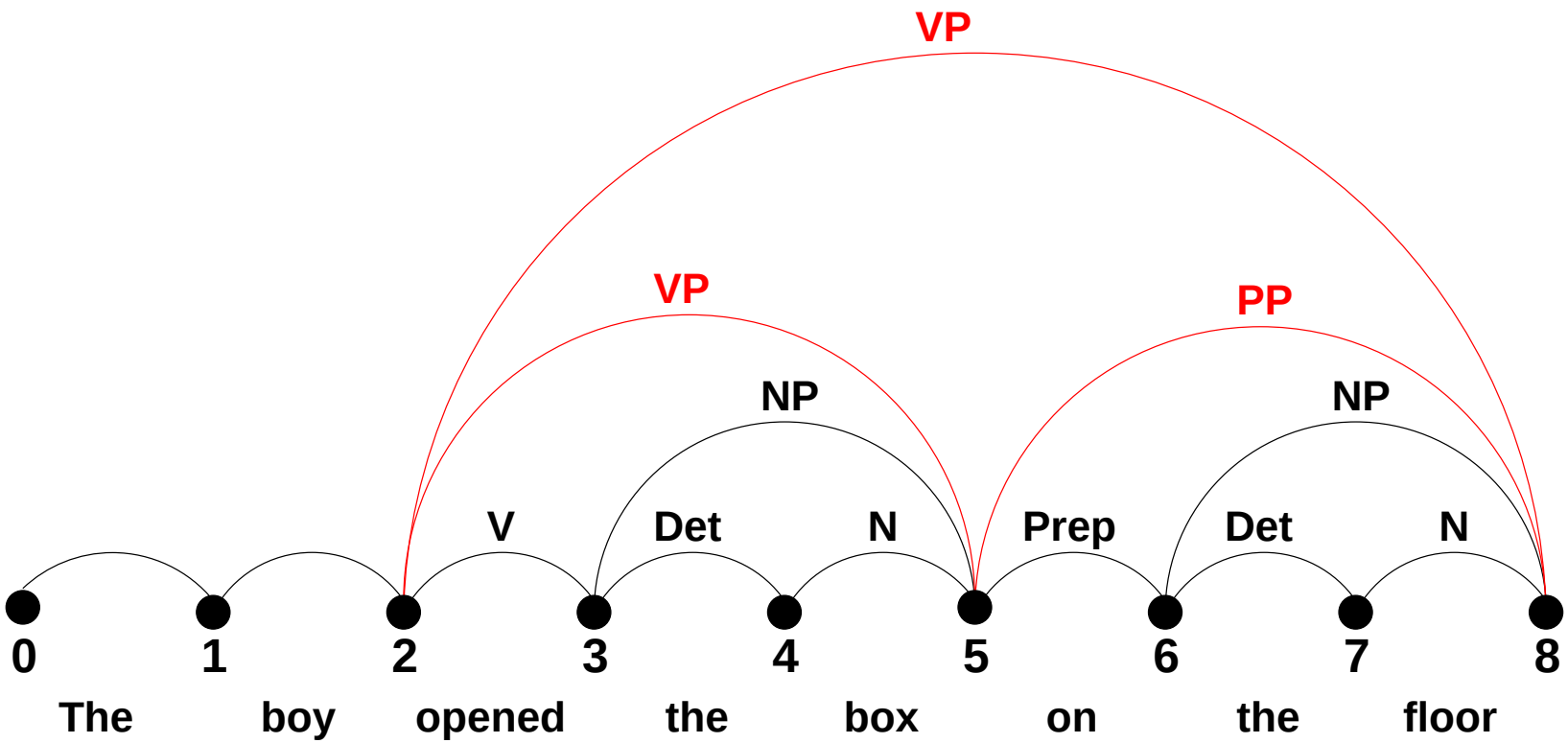
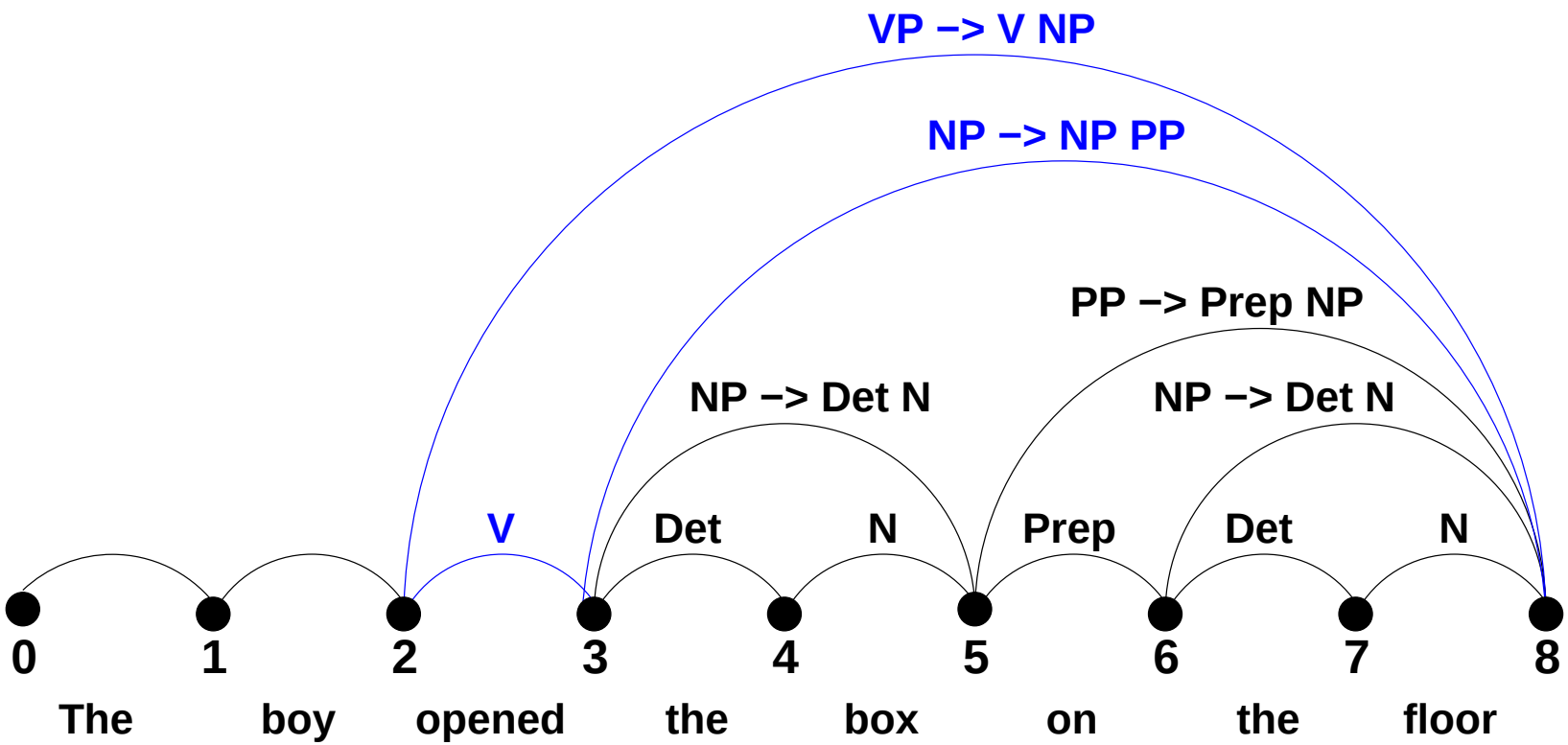


CYK Chart entries

If the entire production were recorded, rather than just its LHS (ie, the constituent that it analyses), then we'd know.



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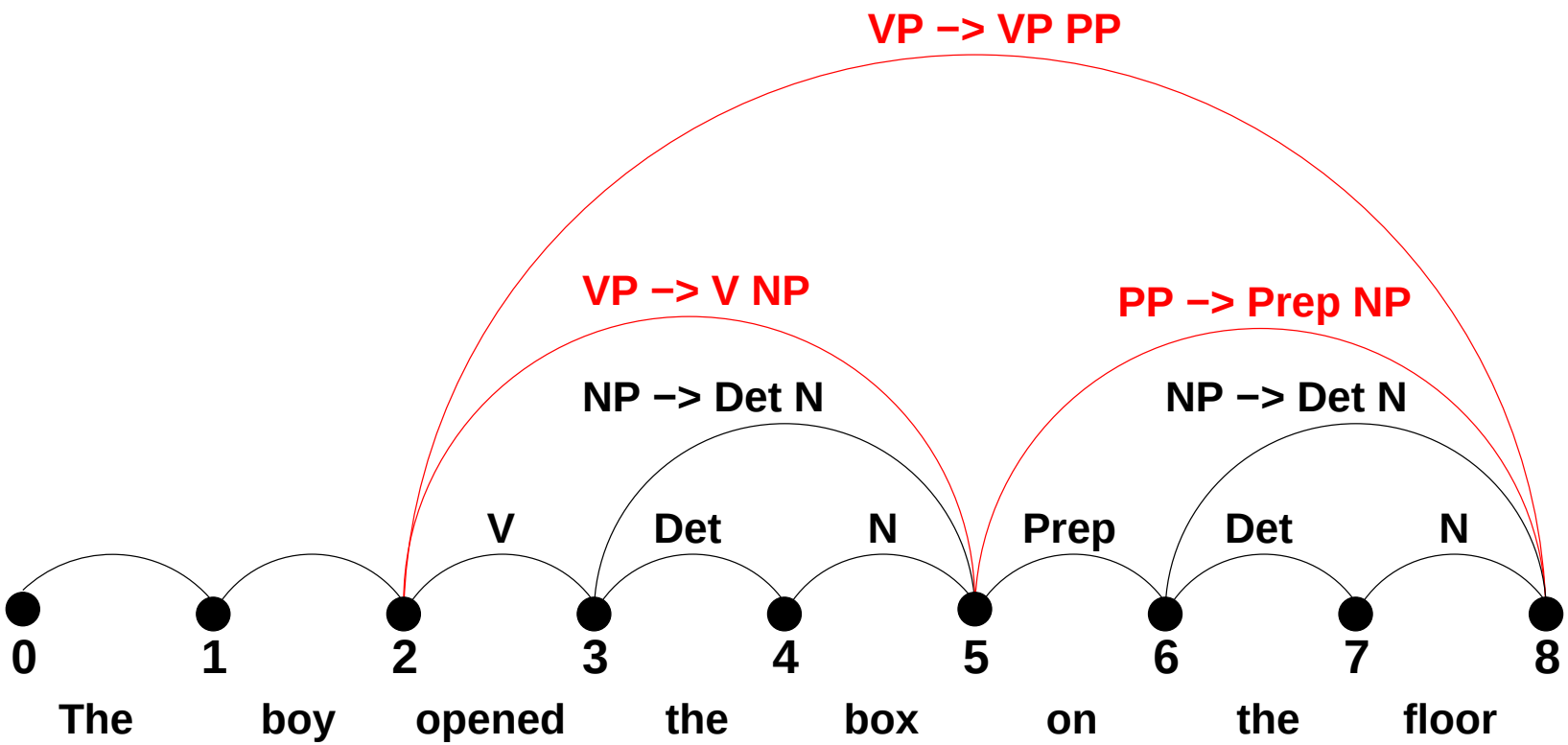
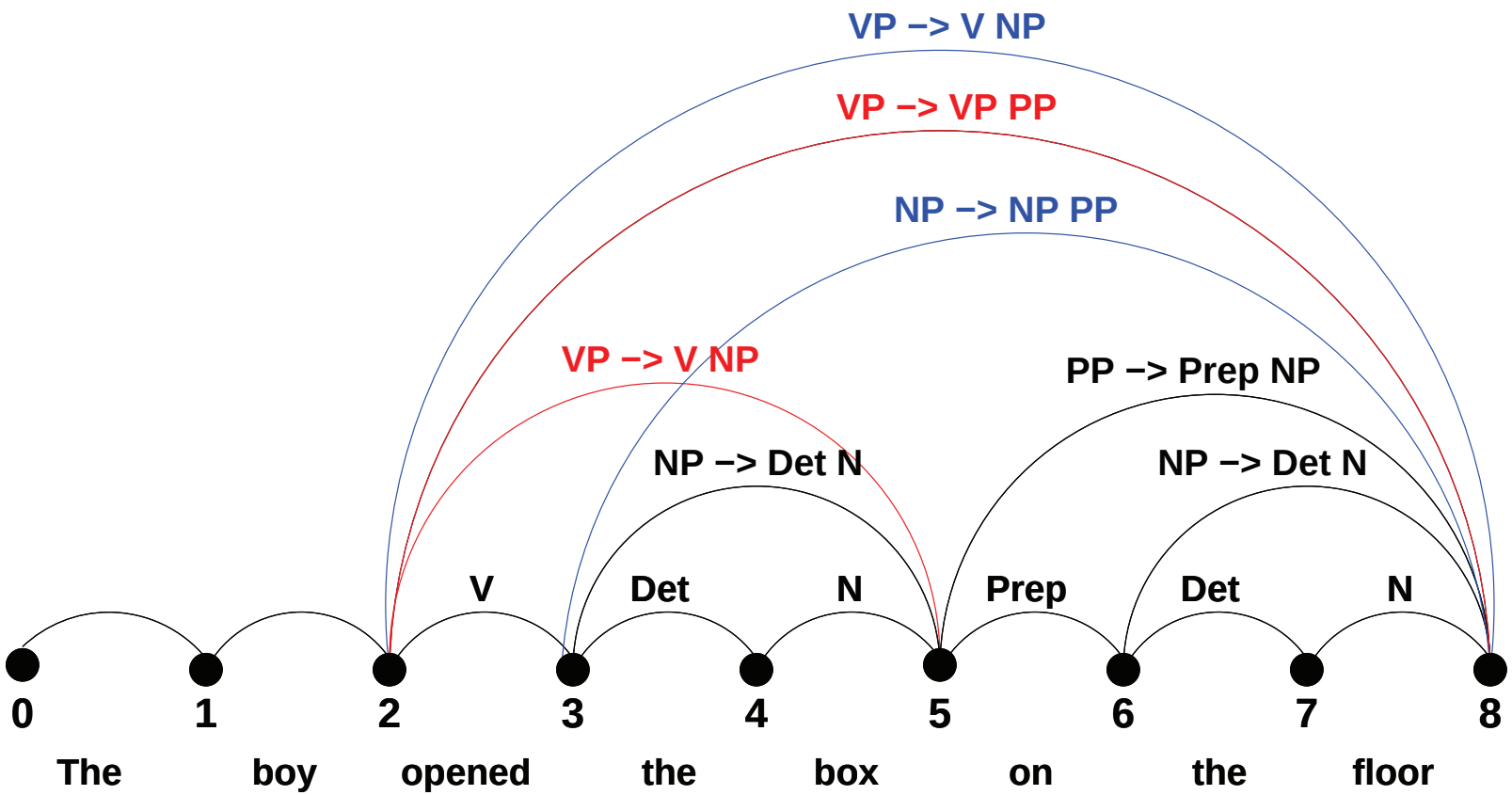


Chart entries: Both analyses



Earley Parsing

Key idea: if we record completed productions (ie, ones whose entire RHS have been recognized), we could also consider recording incomplete productions (ie, ones for which there may so far be only partial evidence).

- Incomplete productions (aka incomplete constituents) are effectively predictions about what might come next and what will be learned from finding it.
- Incomplete constituents can be represented using an extended form of production rule called a dotted rule.
- The dot indicates how much of the RHS has already been found. The rest is a prediction of what is to come.

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.

$S \rightarrow \bullet\ VP\ [0,0]$	A *VP* is predicted at the start of the sentence
$NP \rightarrow Det \bullet Nominal\ [1,2]$	An NP is in progress; seen *Det*, *Nominal* is expected
$VP \rightarrow V\ NP \bullet [0,3]$	A VP has been found starting at 0 and ending at 3

Once chart is populated there should be an S the final column that spans from 0 to N and is complete: $S \rightarrow \alpha \bullet [0, N]$. If that's the case you're done.

Sketch of Earley Algorithm

Sweep through the table from 0 to N:

1. Predict all the states you can upfront, start top-down from S
2. Read a word
   1. Extend states based on matches
   2. Generate new predictions
   3. Go to step 2
3. When you are out of words, look at the chart to see if you have a winner

The algorithm uses three basic operations to process states in the chart: Predictor and Completer add states to the chart entry being processed; Scanner adds a state to the next chart entry.

Predictor

- Creates new states representing top-down expectations
- Applied to any state that has a non-terminal immediately to its right other than a part-of-speech category
- Application results in creation of one new state for each alternative expansion of that non-terminal
- New states placed into same chart entry as generating state

$S \rightarrow \bullet VP$, [0,0]
$VP \rightarrow \bullet$ *Verb*, [0,0]
$VP \rightarrow \bullet$ *Verb NP*, [0,0]
$VP \rightarrow \bullet$ *Verb NP PP*, [0,0]
$VP \rightarrow \bullet$ *Verb PP*, [0,0]
$VP \rightarrow \bullet$ *VP PP*, [0,0]

Scanner

- Applies to states with a part-of-speech category to right of dot
- Incorportates into chart a state corresponding to prediction of a word with particular part-of-speech
- Creates new state from input state with dot advanced over predicted input category
- Unlike CYK, only parts-of-speech of a word that are predicted by some existing state will enter the chart (top-down input)

VP $\rightarrow \bullet$ *Verb NP*, [0,0]
VP $\rightarrow$ book $\bullet$, [0,1]

Completer

- Applied to state when its dot has reached right end of the rule
- This means that parser has successfully discovered a particular grammatical category over some span of the input
- Completer finds and advances all previously created states that were looking for this category at this position in input
- Creates states copying the older state, advancing dot over expected category, and installing new state in chart

$NP \rightarrow Det\ Nominal \bullet$, [1,3]			
finds state	VP	$\rightarrow$	$Verb \bullet NP$, [0,1]
finds state	VP	$\rightarrow$	$Verb \bullet NP\ PP$, [0,1]
adds complete state	VP	$\rightarrow$	$Verb\ NP \bullet$, [0,3]
adds incomplete state	VP	$\rightarrow$	$Verb\ NP \bullet PP$, [0,3]

The Earley Algorithm

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

ENQUEUE($(\gamma \rightarrow \bullet S, [0,0])$, *chart[0]*)
for $i \leftarrow$ **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*)

The Earley Algorithm

procedure PREDICTOR($(A \rightarrow \alpha \bullet B\ \beta,\ [i,j])$)
  for each $(B \rightarrow \gamma)$ **in** GRAMMAR-RULES-FOR($B, grammar$) **do**
    ENQUEUE($(B \rightarrow \bullet\ \gamma,\ [j,j]), chart[j]$)
  end

procedure SCANNER($(A \rightarrow \alpha \bullet B\ \beta,\ [i,j])$)
  if B $\subset$ PARTS-OF-SPEECH($word[j]$) **then**
    ENQUEUE($(B \rightarrow word[j],\ [j, j+1]), chart[j+1]$)

procedure COMPLETER($(B \rightarrow \gamma \bullet, [j,k])$)
  for each $(A \rightarrow \alpha \bullet B\ \beta,\ [i,j])$ **in** $chart[j]$ **do**
    ENQUEUE($(A \rightarrow \alpha\ B \bullet \beta,\ [i,k]), chart[k]$)
  end

Visualizing the Chart

We will use the grammar to parse the sentence "*Book that flight*".

Grammar Rules

$S \rightarrow NP\ VP$	$VP \rightarrow Verb$
$S \rightarrow Aux\ NP\ VP$	$VP \rightarrow Verb\ NP$
$S \rightarrow VP$	$VP \rightarrow Verb\ NP\ PP$
$NP \rightarrow Pronoun$	$VP \rightarrow Verb\ PP$
$NP \rightarrow Proper\text{-}Noun$	$VP \rightarrow VP\ PP$
$NP \rightarrow Det\ Nominal$	$PP \rightarrow Preposition\ NP$
$Nominal \rightarrow Noun$	$Verb \rightarrow book \mid include \mid prefer$
$Nominal \rightarrow Nominal\ Noun$	$Nominal \rightarrow book \mid flight \mid meal$
$Nominal \rightarrow Nominal\ PP$	$Det \rightarrow that \mid this \mid these$

Visualizing the Chart[0]

state	rule	start/end	reason
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

Visualizing the Chart[1]

state	rule	start/end	reason
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	$VP \rightarrow VP \bullet PP$	[1,1]	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

Visualizing the Chart[2]

state	rule	start/end	reason
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

Visualizing the Chart[3]

state	rule	start/end	reason
S28	$Noun \rightarrow \bullet\ flight$	[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	$PP \rightarrow Prep\ \bullet\ NP$	[3,3]	Predictor
S36	$S \rightarrow VP\ \bullet$	[0,3]	Completer
S37	$Nominal \rightarrow VP\ \bullet\ PP$	[0,3]	Completer

Parsing the Input

As with CKY we have formulated a recognizer. We can change it to a parser by adding backpointers so that each state knows where it came from.

Chart[1]	S12	*Verb* → *book* •	[0,1]	Scanner
Chart[2]	S23	*Det* → *that* •	[1,2]	Scanner
Chart[3]	S28	*Noun* → *flight* •	[2,3]	Scanner
	S29	*Nominal* → *Noun* •	[2,3]	(S28)
	S30	*NP* → *Det Nominal* •	[1,3]	(S23, S29)
	S33	*VP* → *Verb NP* •	[0,3]	(S12, S30)
	S36	*S* → *VP* •	[0,3]	(S33)

Comparing Earley and CYK

- For such a simple example, there seems to be a lot of useless stuff in the chart.
- We are predicting things inconsistent with the input!
- That's the flipside to the CKY problem.

Did we solve ambiguity? Both CKY and Earley will result in multiple S structures for the $[0, N]$ table entry. They efficiently store the sub-parts shared between multiple parses but neither can tell us which one is right.

Clicker Questions

1. The CYK parser processes the input string:
   (a) top-down (b) bottom-up (c) a bit of both
2. The Earley parser processes the input string:
   (a) top-down (b) bottom-up (c) neither, just left-to-right
3. A shift reduce parser processes the input string:
   (a) top-down (b) bottom-up (c) with a stack
4. A recursive decent parser process the input string:
   (a) top-down (b) bottom-up (c) using backtracking

Summary

- The Earley algorithm uses dynamic programming to implement a top-down search strategy.
- Single left to right pass that fills chart with $N + 1$ entries.
- Dotted rule represents progress in recognizing RHS of rule.
- Algorithm always moves forward, never backtracks to previous chart entry, once it has moved on.
- States are processed using Predictor, Completer, Scanner operations.

Reading: Same as for Lecture 17
Next lecture: statistical parsing or how to solve ambiguity.