6.863J Natural Language Processing Lecture 7: parsing with hierarchical structures – context-free parsing

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The Menu Bar

- Administrivia:
  - Schedule alert: Lab2 due Weds; Lab 3 out – Monday (chunk parsing to ‘real’ parsing)
  - Lab time today, tomorrow
  - Please read notes3.pdf, englishgrammar.pdf (on web)
- *Agenda:*
- Marxist analysis – simple & post-modern
- <u>What:</u> hierarchical representations; constituents, representation
- <u>How:</u> constituent or ‘context-free’ parsing (next time – how to do it *fast*)
- <u>Why:</u> to extract ‘meaning’

Motivation

- What, How, and Why
- <u>What:</u> word *chunks* behave as units, like words or endings (morphemes), like *ing*
- <u>How:</u> we have to recover these from input
- <u>Why:</u> chunks used to discover *meaning*
- Parsing: mapping from *strings* to *structured representation*

Programming languages

```
printf ("/charset [%s",
        (re_opcode_t) *(p - 1) == charset_not ? "^" : "");

assert (p + *p < pend);

for (c = 0; c < 256; c++)
  if (c / 8 < *p && (p[1 + (c/8)] & (1 << (c % 8)))) {
     /* Are we starting a range?  */
     if (last + 1 == c && ! inrange) {
        putchar ('-');
        inrange = 1;
     }
     /* Have we broken a range?  */
     else if (last + 1 != c && inrange) {
        putchar (last);
        inrange = 0;
     }

     if (! inrange)
        putchar (c);

     last = c;
  }
```

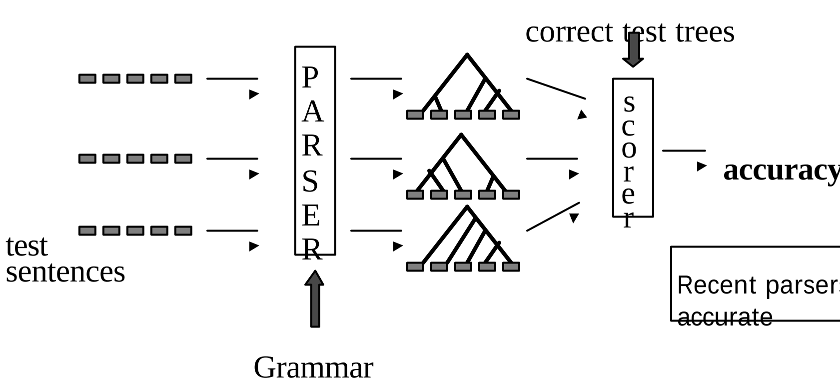
- Easy to parse.
- Designed that way!

Natural languages

```
printf "/charset %s", re_opcode_t *p - 1 == charset_not ? "^"
: ""; assert p + *p < pend; for c = 0; c < 256; c++ if c / 8 <
*p && p1 + c/8 & 1 << c % 8 Are we starting a range? if last +
1 == c && !  inrange putchar '-'; inrange = 1; Have we broken
a range? else if last + 1 != c && inrange putchar  last;
inrange = 0; if !  inrange putchar c; last = c;
```

- No {} () [] to indicate scope & precedence
- Lots of overloading (arity varies)
- Grammar isn’t known in advance!
- Context-free grammar not best formalism

How: The parsing problem



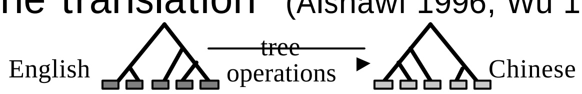
Recent parsers quite accurate

Syntactic Parsing

- Declarative formalisms like CFGs define the legal strings of a language but don't specify how to recognize or assign structure to them
- Parsing algorithms specify how to recognize the strings of a language and assign each string one or more syntactic structures
- Parse trees useful for grammar checking, semantic analysis, MT, QA, information extraction, speech recognition...and almost every task in NLP

Applications of parsing (1/2)

- Machine translation (Alshawi 1996, Wu 1997, ...)



- Speech synthesis from parses (Prevost 1996)

  The government plans to raise income tax.

  The government plans to raise income tax the imagination.

- Speech recognition using parsing (Chelba et al 1998)

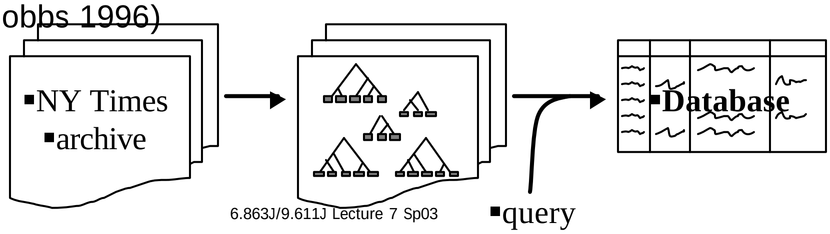
  Put the file in the folder.

  Put the file and the folder.

Applications of parsing

- Grammar checking (Microsoft)
- Indexing for information retrieval (Woods 72-1997)

  ... washing a car with a hose ... → vehicle maintenance
- Information extraction (Keyser, Chomsky '62 to Hobbs 1996)

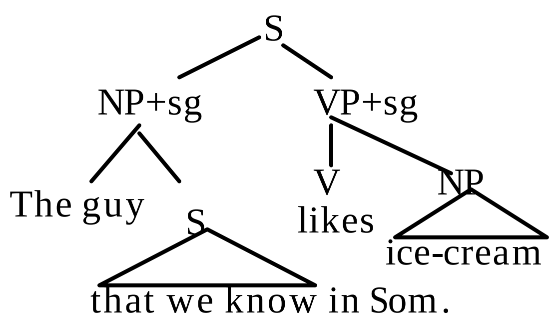


Why: Q&A systems (lab 4)

```
(top-level)
Shall I clear the database? (y or n) y
>John saw Mary in the park
OK.
>Where did John see Mary
IN THE PARK.
>John gave Fido to Mary
OK.
>Who gave John Fido
I DON'T KNOW
>Who gave Mary Fido
JOHN
>John saw Fido
OK.
>Who did John see
FIDO AND MARY
```

Why: express 'long distance' relationships via *adjacency*

- The guy that we know in Somerville likes ice-cream
- Who did the guy who lives in Somerville see __?

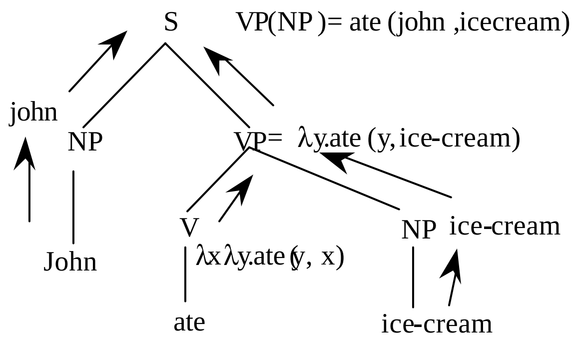


Why: recover meaning from structure

John ate ice-cream $\rightarrow$ ate(John, ice-cream)

-This must be done from *structure*
-Actually want something like $\lambda x \lambda y$ ate(x,y)
How?

Why: recover meaning from structure



Why: Parsing for the Turing Test

- Most linguistic properties are defined over hierarchical structure
- One needs to parse to see subtle distinctions

Sara likes her. *(her ¹ Sara)*

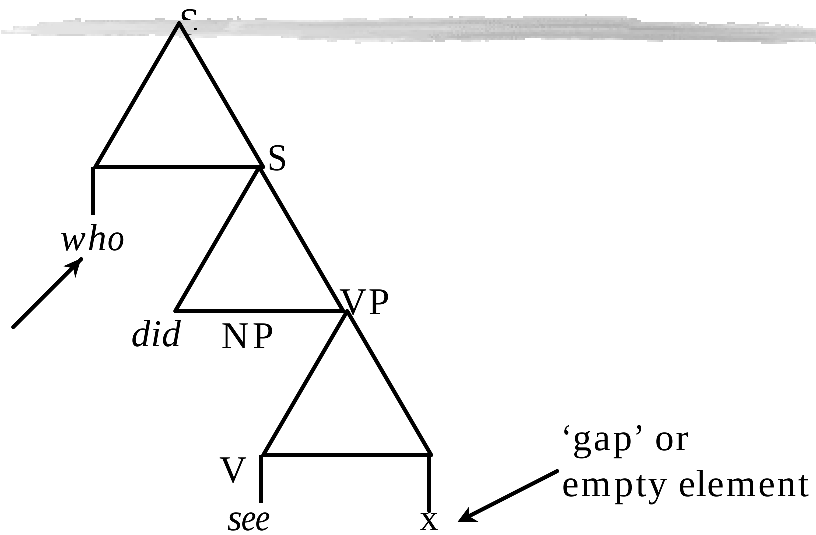
Sara thinks that someone likes her. *(her = or ¹ Sara)*

Sara dislikes anyone's criticism of her. *(her = Sara* or *her ¹ Sara)*

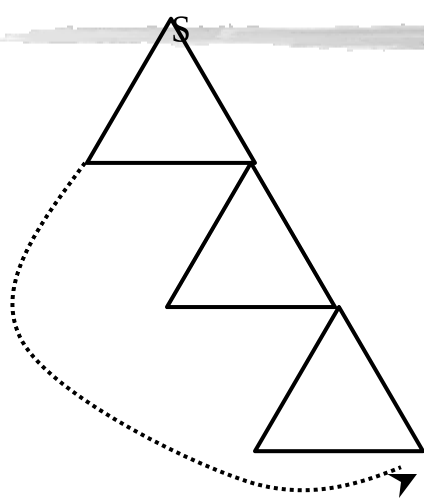
Who did John see? → For which x, x a person, likes(Bill, x)

Distinction here is based on *hierarchical structure* = <u>scope</u> in natural language

Structure *must* be recovered



What is the structure that matters?



Turns out to be SCOPE for natural languages!

The elements

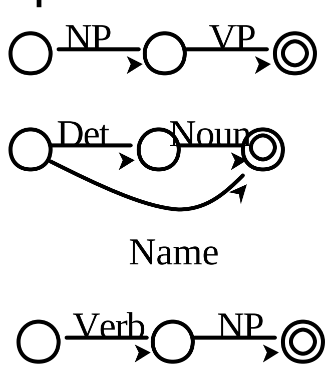
1. What: hierarchical representations (anything with recursion) using *phrases* AKA “constituents”
2. How: context-free parsing (plus...)
3. Why: (meaning)

Networks to context-free grammars (CFGs) and back: 1-1 correspondence

Sentence:

NP:

VP:



S→NP VP

NP→Name
NP→Det Noun

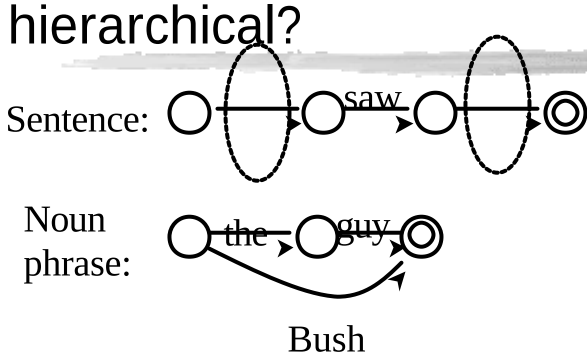
VP→Verb NP

+ *terminal expansion rules*

Added information

- FSA represents pure *linear* relation: what can *precede* or (*follow)* what
- CFG/RTN adds a new predicate: *dominate*
- Claim: The dominance and precedence relations amongst the words exhaustively describe its *syntactic* structure
- When we parse, we are recovering these predicates

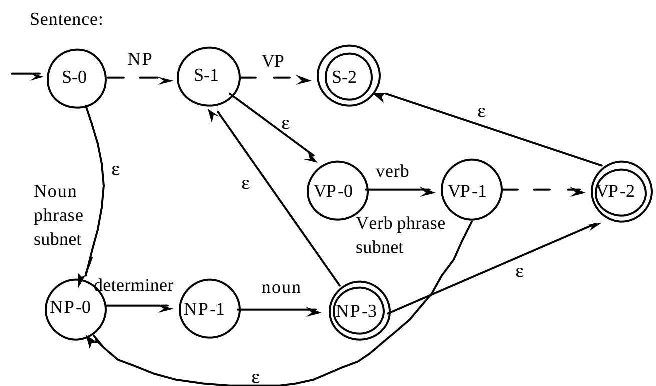
How do we move from linear to hierarchical?



"splice out" common subnets

We already have the machinery for this…

Use of epsilon transitions ('jump' arcs) – they consume <u>no</u> input



…note that *no* input is consumed during jump

This will work... with one catch

- Consider tracing through "the guy ate the ice-cream"
- What happens when we get to the second noun phrase????
- Where do we *return* to?
- Epsilon transition takes us back to <u>different</u> points

What: Context-free grammars (CFG)

S(entence)→NP VP
VP→V NP
NP→Det N
N → *pizza,* N → *guy,* Det → *the* } pre-terminals, lexical entries
V → *ate*

A context-free grammar (CFG):
Sets of terminals (either lexical items or parts of speech)
Sets of nonterminals (the constituents of the language)
Sets of rules of the form *A* → α where α is a string of zero or more terminals and nonterminals

Derivation by a context-free grammar:rewrite line by line

generation ↓

1. S	
2. NP VP	(via S→NP VP)
3. NP V NP	(via VP→V NP)
4. NP V Det N	(via NP→Det N)
5. NP V Det *pizza*	(via N → *pizza*)
6. NP V *the pizza*	(via Det → *the*)
7. NP *ate the pizza*	(via V → *ate*)
8. Det N *ate the pizza*	(via NP→Det N)
9. Det *guy ate the pizza*	(via N → *guy*)
10. *the guy ate the pizza*	(via Det → *the*)

Context-free representation

- Is this representation adequate – Not really...why?
- We'll start here, though & illustrate parsing methods – how to make parsing efficient (in length of sentence, size of grammar)
- Obvious methods are exponential; we want polynomial time (or, even linear time, or, even, real time...)
- Challenges: recursion, ambiguity, nondeterminism

How: context-free parsing

- Parsing: assigning a correct hierarchical structure (or its derivation) to a string, given some grammar
  - The leaves of the hierarchical structure cover all and only the input;
  - The hierarchical structure ('tree') corresponds to a valid derivation wrt the grammar
- Note: 'correct' here means consistent w/ the input & grammar – NOT the "right" tree or "proper" way to represent (English) in any more global sense

Parsing

- What kinds of constraints can be used to connect the grammar and the example sentence when searching for the parse tree?
- Top-down (goal-directed) strategy
  - Tree should have one rot (grammar constraint)
- Bottom-up (data-driven) strategy
  - Tree should have, e.g., 3 leaves (input sentence constraint)

The input

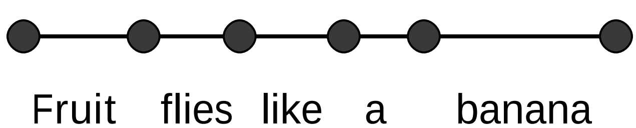
- For now, assume:
  - Input is not tagged (we can do this...)
  - The input consists of unanalyzed word tokens
  - All the words are known
  - All the words in the input are available simultaneously (ie, buffered)

How do we do this?

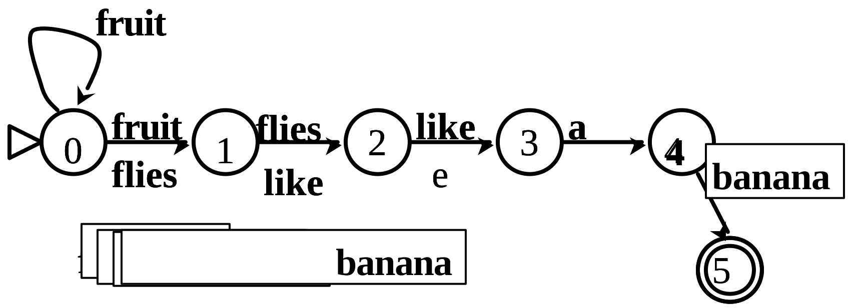
- Searching FSAs
  - Finding the right path through the automaton
  - Search space defined by structure of FSA
- Searching CFGs
  - Finding the right parse tree among all possible parse trees
  - Search space defined by the grammar
- Constraints provided by the input sentence and the automaton or grammar

Marxist analysis: simple version

- Suppose just *linear* relations to recover
- Still can be ambiguity – multiple paths
- Consider:



FSA, or linear Example



State-set parsing for fsa

Initialize: Compute initial state set, S_0

1. $S_0 \leftarrow q_0$
2. $S_0 \leftarrow \varepsilon$–closure($S_0$)

Loop: Compute S_i from S_{i-1}

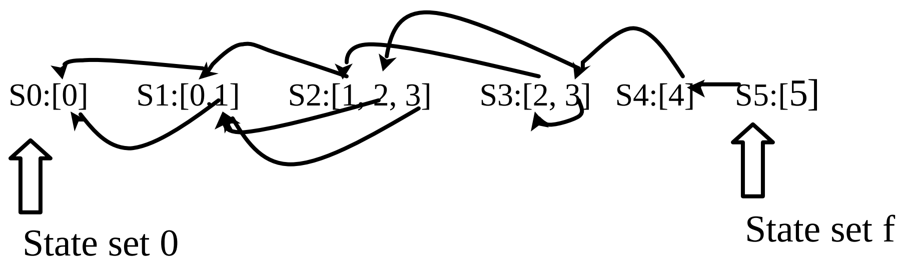
1. For each word w_i , i=1,2,...,n
2. $S_i \leftarrow \bigcup_{q \in S_{i-1}} d\,(q, w_i)$
3. $S_i \leftarrow \varepsilon$–closure($S_i$)
4. if $S_i = \emptyset$ then halt & reject else continue

Final: Accept/reject

1. If $q_f \in S_n$ then accept else reject

States in sequence dictate parse path:

States: {0} →{0,1} →{1,2,3} →{2,3} →{4} →{5} (final)



State to state jumps...

- Progress (& ultimately parse) recorded by what state machine is in
- Consider each transition as rule:

  $q_0 \rightarrow$ fruit q_1 , also loop: $q_0 \rightarrow$ fruit q_0

  $q_1 \rightarrow$ flies q_2

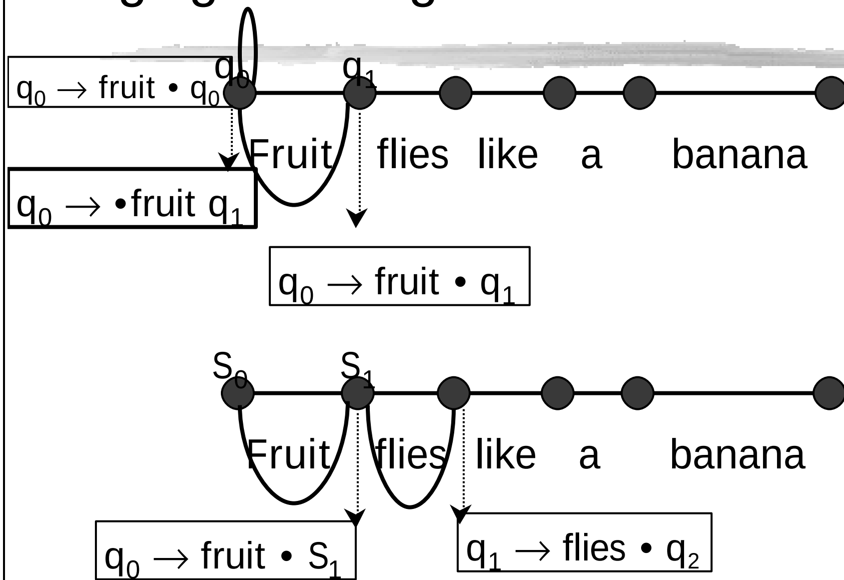
  $q_2 \rightarrow$ like q_3 also epsilon transition: $q_2 \rightarrow q_3$

  $q_3 \rightarrow$ a q_4

  $q_4 \rightarrow$ banana q_5

- We can record progress path via ‘bouncing ball’ telling us how to sing the song...

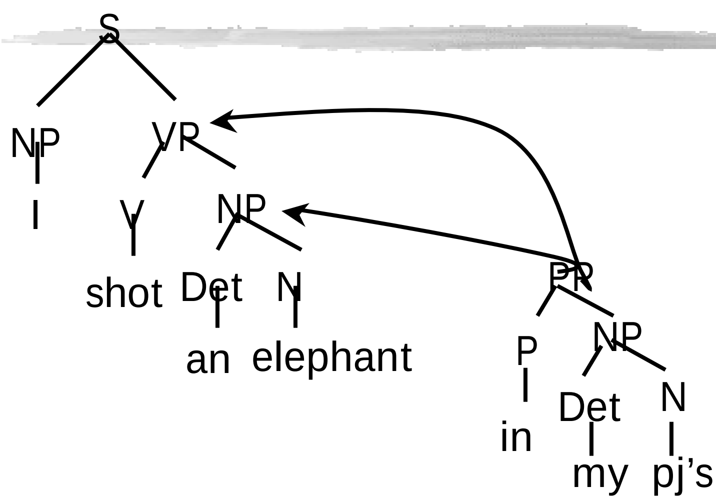
Singing the song...



But now we have a more complex Marxist analysis

- I shot an elephant in my pajamas
- This is *hierarchically* ambiguous – not just linear! (each possible hierarchical structure corresponds to a *distinct* meaning)

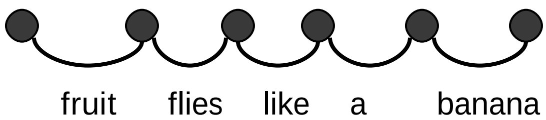
Marxist analysis



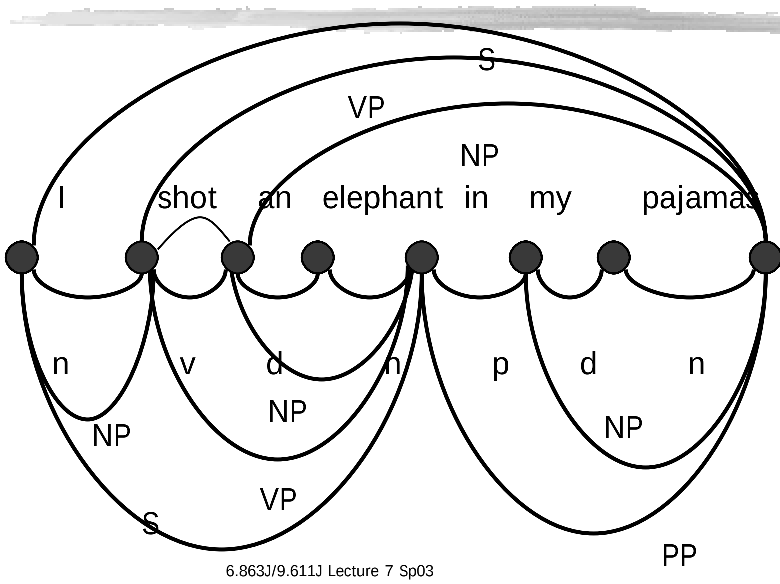
How can we extend this bouncing ball?

- Can't just be linear...
- How do we *pack* these possibilities together?
- We will augment... let's see how

From this...



To this... what is called a Chart



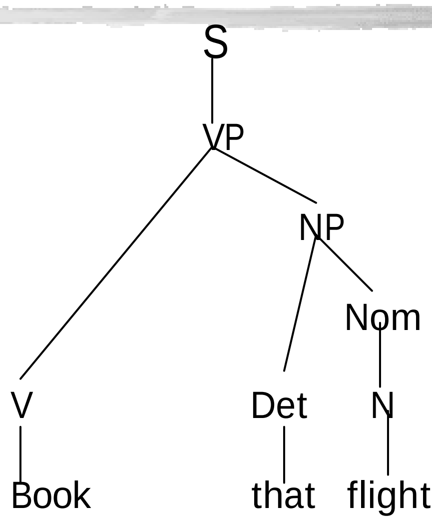
Three senses of rules

- generation (production): $S \rightarrow NP\ VP$
- parsing (comprehension): $S \leftarrow NP\ VP$
- verification (checking): $S = NP\ VP$
- CFGs are declarative – tell us *what* the well-formed structures & strings are
- Parsers are procedural – tell us *how* to compute the structure(s) for a given string

CFG minigrammar

S → NP VP	VP → V
S → Aux NP VP	Det → that | this | a
S → VP	N → book | flight | meal | money
NP → Det Nom	V → book | include | prefer
NP →PropN	Aux → does
Nom → N Nom	Prep →from | to | on
Nom → N	PropN → Boston | United
Nom → Nom PP	
VP → V NP	

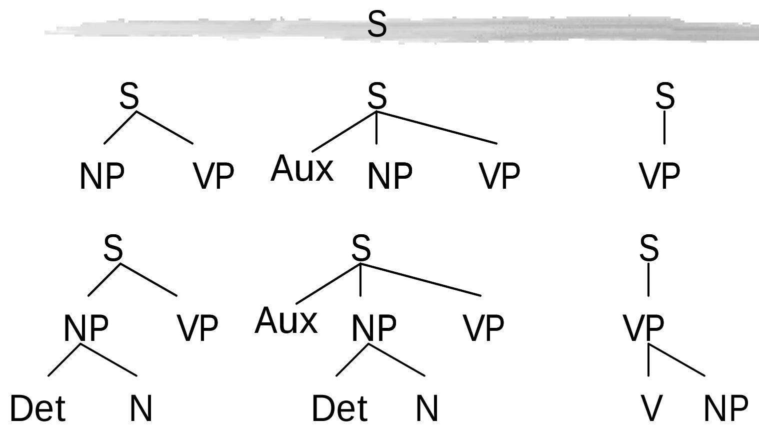
Parse Tree for 'Book that flight'



Strategy 1: Top-down parsing

- Goal or expectation driven – find tree rooted at *S* that derives input
- Trees built from root to leaves
- Assuming we build all trees in parallel:
  - Find all trees with root S (or all rules w/lhs S)
  - Next expand all constituents in these trees/rules
  - Continue until leaves are parts of speech (pos)
  - Candidate trees failing to match pos of input string are rejected (e.g. Book that flight can only match subtree 5)

Example: *book the flight*



Top-down strategy

- Depth-first search:
  - Agenda of search states: expand search space <u>incrementally</u>, exploring most recently generated state (tree) each time
  - When you reach a state (tree) inconsistent with input, backtrack to most recent unexplored state (tree)
- Which node to expand?
  - **Leftmost** or rightmost
- Which grammar rule to use?
  - Order in the grammar

Top-down, left-to-right, depth-first

- Initialize agenda with 'S' tree and ptr to first word and make this current search state (cur)
- Loop until successful parse or empty agenda
  - Apply all applicable grammar rules to leftmost unexpanded node of cur
    - If this node is a POS category and matches that of the current input, push this onto agenda
    - O.w. push new trees onto agenda
  - Pop new cur from agenda
- Does this flight include a meal?

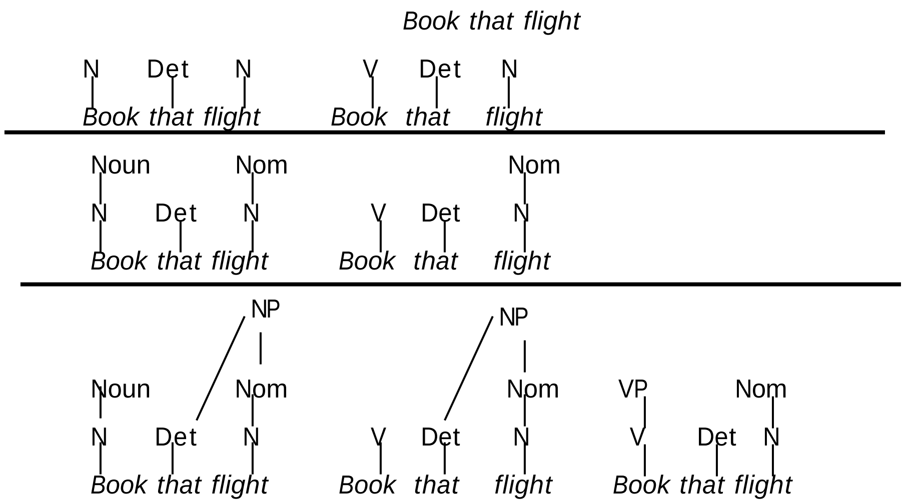
Strategy 2: Bottom-up

- Parser begins with words of input and builds up trees, applying grammar rules w/rhs that match
  - Book that flight

N	Det	N	V	Det	N
Book	that	flight	Book	that	flight

  - 'Book' ambiguous
  - Parse continues until an S root node reached or no further node expansion possible

Bottom-up search space



Comparing t-d vs. b-u

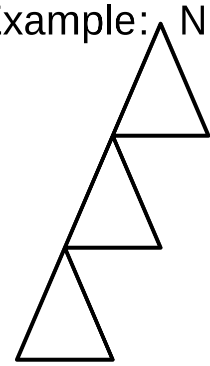
- Top-Down parsers never explore illegal parses (e.g. can't form an S) -- but waste time on trees that can never match the input
- Bottom-Up parsers never explore trees inconsistent with input -- but waste time exploring illegal parses (no S root)
- For both: how to explore the search space?
  - Pursuing all parses in parallel or ...?
  - Which rule to apply next?
  - Which node to expand next?

Problems...

- Left-recursion
- Ambiguity: multiple parses
- Principle AWP

Left-recursion

- Rules of form: X→ X α
- Example: NP → NP 's NP | Name



John's brother's book

Structural ambiguity

- Multiple legal structures
  - Attachment (e.g. I saw a man on a hill with a telescope)
  - Coordination (e.g. younger cats and dogs)
  - NP bracketing (e.g. Spanish language teachers)

How to fix?

- Principle AWP! Dynamic programming...
- Create table of solutions to sub-problems (e.g. subtrees) as parse proceeds
- Look up subtrees for each constituent rather than re-parsing
- Since all parses implicitly stored, all available for later disambiguation
- Examples: Cocke-Younger-Kasami (CYK) (1960), Graham-Harrison-Ruzzo (GHR) (1980) and Earley (1970) algorithms

General method: Chart Parsing

- Note: parses *share* common constituents
- Build chart = graph data structure for storing partial & complete parses (AKA well-formed substring table)
- Graph:
  - Vertices: used to delimit subsequences of the input
  - Edges (active, inactive)
    - Active = denote incompletely parsed (or found) phrase
    - Inactive = completely found phrase
    - Labels = name of phrase
- Note: chart *sufficient* to attain polynomial time parsability = $O(n^3 |G|)$, $|G|$ = 'size' of grammar, *no matter what strategy we use*

How do we build the chart?

- Idea: as parts of the input are successfully parsed, they are entered into chart
- Like memoization
- Can use any combo strategy of t-d, b-u, or in between to build the edges
- Annotate edges as they are built w/ the corresponding dotted rule
- Parser is a combination of chart + strategy

Chart parsing

- Example of chart

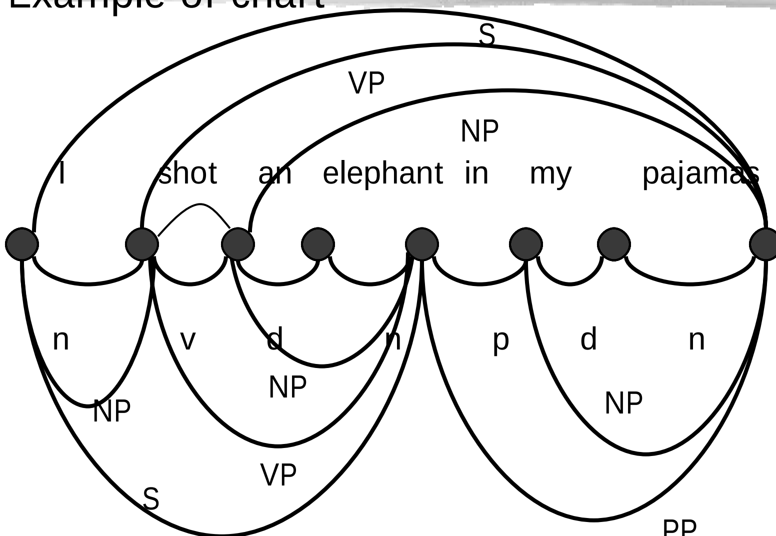


Chart parsing

- Think of chart entries as sitting between words in the input string keeping track of states of the parse at these positions
- For each word position, chart contains the <u>set of states</u> representing all partial parse trees generated to date

Chart parsing

- Chart entries represent three type of constituents (phrases):
  - predicted constituents
  - in-progress constituents
  - completed constituents

Representing complete (inactive) vs. incomplete (active) edges

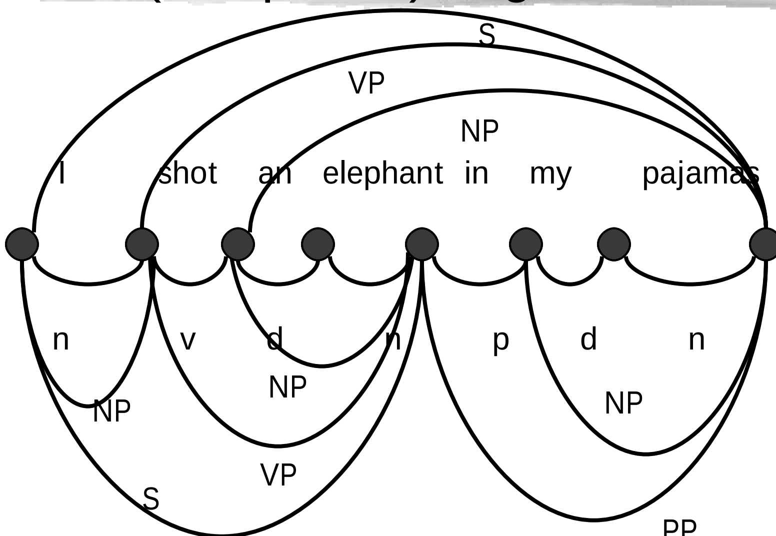
- Complete: full phrase found, e.g., NP, VP
- So: corresponding rule something like
  - NP→NP PP (“an elephant in my pajamas”)
  - S → NP VP (“I saw an elephant”)
  - NP → Det N (“an elephant”)
- Representation: use “dot” in rule to denote *progress* in discovering LHS of the rule:

NP→• Det NP = I’ve just started to find an NP (“predict”)

NP → Det • NP = Found a Det in input, now find NP

NP → Det NP • = Completed phrase (dot at end)

Chart we displayed has only *inactive* (completed) edges

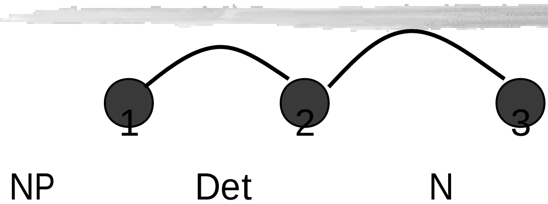


Complete (Inactive) vs. In-progress (active) edges

- Completed edges correspond to "having found a phrase" so really should be labeled with info like NP $\rightarrow$ Det NP •
- We should go back & annotate our chart like this
- These edges are "inactive" because there is no more processing to be done to them
- Incomplete or "active" edges: work in progress, i.e., NP$\rightarrow$• Det NP or NP $\rightarrow$ Det • NP
- We build up the chart by extending active edges, gluing them together – let's see how

Note correspondence between "dotted rules" & states in corresponding fsa - isomorphic

Dotted rule – fsa correspondence

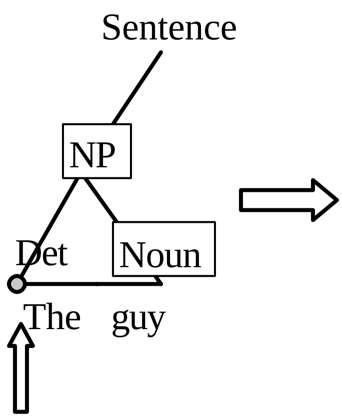


NP → •Det N = being in State 1

NP → Det • N = being in State 2

NP → Det N • = being in State 3

Correspondence

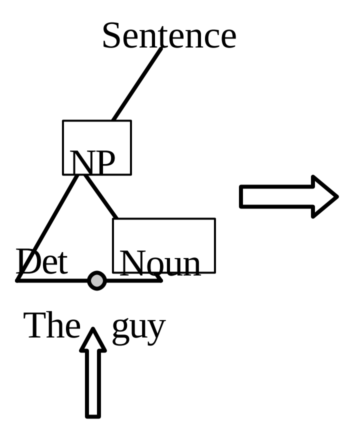


Dotted rule form

NP→ •Det Noun

Dot at beginning=
just started building a
phrase of this type

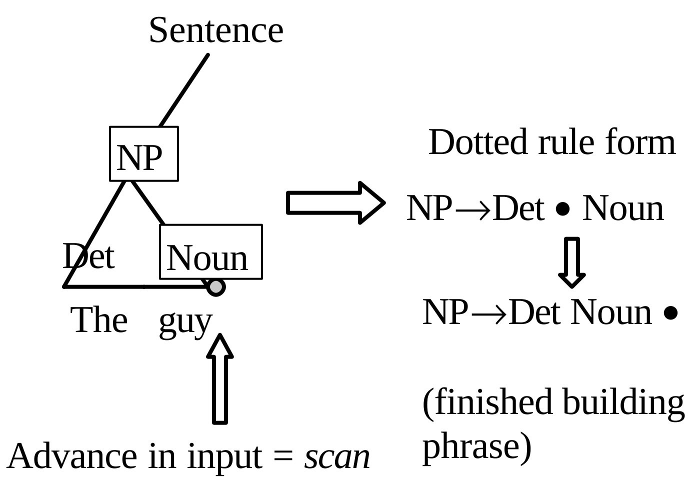
Correspondence



Dotted rule form

NP→Det • Noun

Correspondence



Representing the edges

- $_0$ Book $_1$ that $_2$ flight $_3$
  - S → • VP, [0,0] (predicting VP)
  - NP → Det • Nom, [1,2] (finding NP)
  - VP → V NP •, [0,3] (found VP)
- [x,y] tells us where a phrase begins (x) and where the dot lies (y) wrt the input – how much of the phrase is built *so far*
- So, a FULL description of a chart edge is:

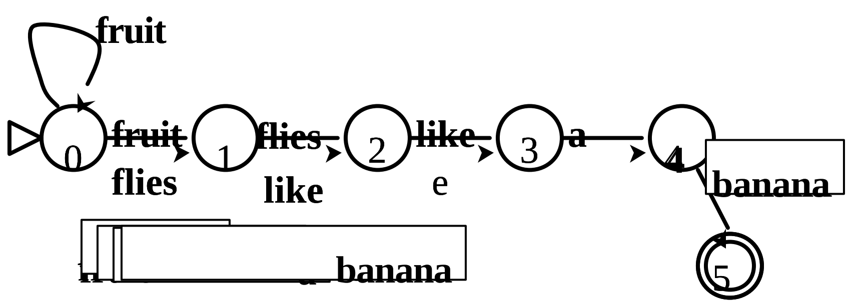
Edge Label, [start node, current progress dot pos] .e.g.,

NP → Det • Nom, [1,2]

Set of dotted rules encodes state of parse

- = all states parser could be in after processing *i* tokens
- We now have almost all the ingredients...

FSA, or linear Example



State-set parsing for fsa

Initialize: Compute initial state set, S_0

1. $S_0 \leftarrow q_0$
2. $S_0 \leftarrow \varepsilon\text{–closure}(S_0)$

Loop: Compute S_i from S_{i-1}

1. For each word w_i, i=1,2,...,n
2. $S_i \leftarrow \bigcup_{q \in S_{i-1}} d(q, w_i)$
3. $S_i \leftarrow \varepsilon\text{–closure}(S_i)$
4. if $S_i = \varnothing$ then halt & reject else continue

Final: Accept/reject

1. If $q_f \in S_n$ then accept else reject

Use backpointers to keep track of the different paths (parses):

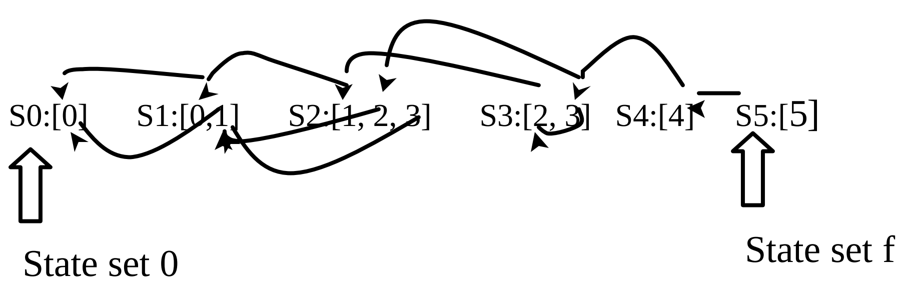


Chart parsing is the same, except

- Notion of 'state set' is just more complicated – not just the state #, but also the # of the state we started building the phrase at = the return ptr

- Note this is what the chart graph structure encodes

State set = chart after i words

- Given grammar G, input string $w=w_1\ w_2 \ldots w_n$

  Note: we mark interword positions $_0w_1\ w_2 \ldots w_n$
- Initialize: write down what can be in "start state set" S_0
- Loop: for each word w_i , compute S_i from S_{i-1}
- Final: see if final state is in last state set S_n

	FTN Parser	CFG Parser
Initialize:	Compute initial state set S_0 1. $S_0 \leftarrow q_0$ 2. $S_0 \leftarrow$ eta-closure (S_0) q_0= [Start→•S, 0] eta-closure= transitive closure of jump arcs	Compute initial state set S_0 1. $S_0 \leftarrow q_0$ 2. $S_0 \leftarrow$ eta-closure (S_0) q_0= [Start→•S, 0, 0] eta-closure= transitive closure of Predict and Complete
Loop:	Compute S_i from S_{i-1} For each word, wi, 1=1,...,n $S_i \leftarrow \bigcup_{q \in S_{i-1}} \delta(q, w_i)$ $S_i \leftarrow$ e-closure(S_i)	Compute S_i from S_{i-1} For each word, w_i, 1=1,...,n $Si \leftarrow \bigcup_{q \in S_{i-1}} \delta(q, w_i)$ = Scan(S_{i-1}) q=item $S_i \leftarrow$ e-closure(S_i) e-closure= closure(Predict, Complete)
Final:	Accept/reject: If $q_f \in S_n$ then accept; else reject q_f= [Start→S•, 0]	Accept/reject: If $q_f \in S_n$ then accept; else reject q_f= [Start→S•, 0, n]

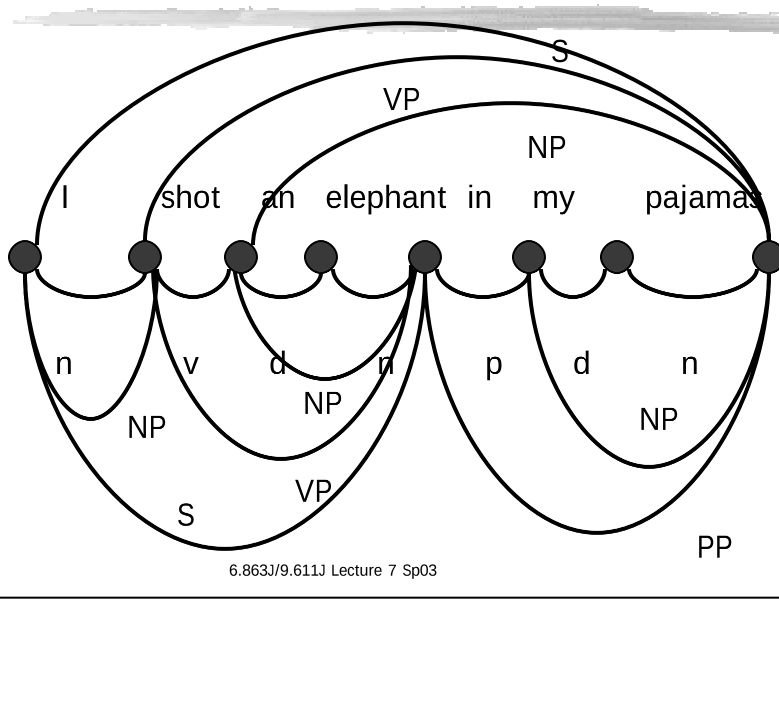
Parsing procedure w/ chart

- Move through each <u>set of states</u> in order, applying one of three operators to each state:
  - predictor: add new active edges, *predictions*, to the chart
  - scanner: read input and advance dot, add corresponding active edge to chart
  - completer: if dot at the right end of a rule, then see if we can glue two edges together to form a larger one

Note:

- Results (new edges) added to current or next set of states in chart
- No backtracking and no edges removed: keep complete history of parse
- When we get to the end, there ought to be an edge labeled S, extending from 0 to n (n= length of sentence)

As in



Predictor ('wishor')

- Intuition: new states represent top-down expectations
- Applied when non part-of-speech non-terminals are to the right of a dot – until closure

  S → • VP [i,i]
- Adds new states to *current* chart
  - One new state for each expansion of the non-terminal in the grammar

    VP → • V [i,i]

    VP → • V NP [i,i]

Scanner (as in fsa)

- New states for predicted part of speech
- Applicable when part of speech is to the right of a dot

  VP → • V NP [0,0] 'Book...'
- Looks at current word in input
- If match, adds dotted rule edge starting at next point over, e.g.,

  VP → V • NP [0,1]

Just as with fsa's – jump to next point

Completer

- Intuition: parser has discovered a complete constituent, so must see if this completed edge can be pasted together with any preceding active edge to make a bigger one...
- E.g., NP[0, 2] & VP[2, 7] yields S[0,7]
- "Glue together" two edges
- Must do this until closure...

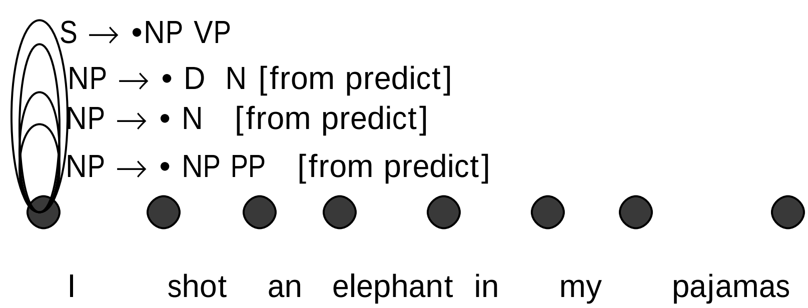
Examples – will use v, v simple G

- S $\rightarrow$ NP VP
- VP $\rightarrow$ V NP
- VP $\rightarrow$ V NP PP
- NP $\rightarrow$ D N
- NP $\rightarrow$ N
- NP $\rightarrow$ NP PP
- PP $\rightarrow$ P NP

Strategies w/ Chart

- Top-down
- Bottom-up
- Left-corner (what's that??)

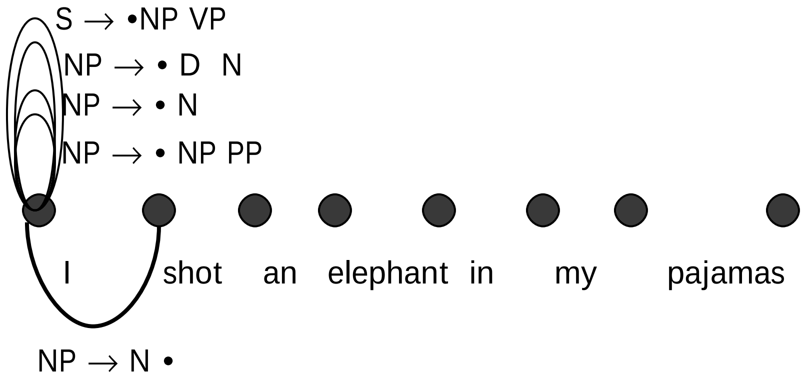
Example: Top-down w/ chart



State set S_0 - nothing more can be added, so *scan* next word

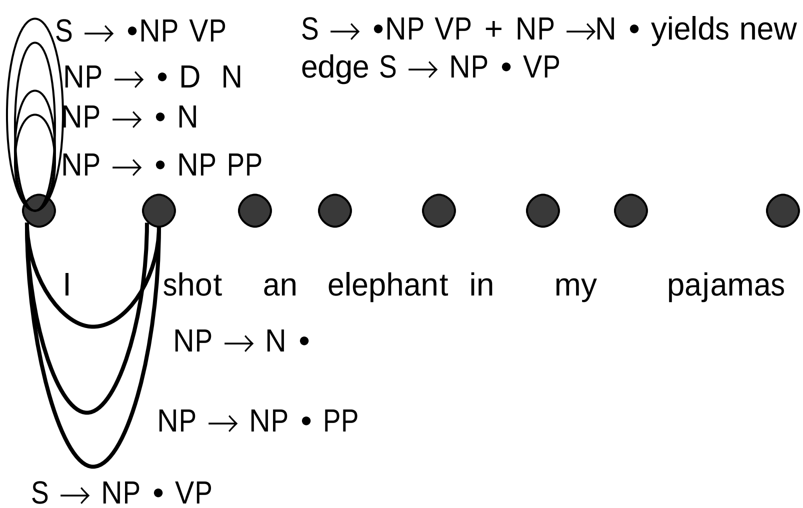
Note how top-down strategy can introduce rules unconnected to the input..

Scan to next word...follow the bouncing dot...

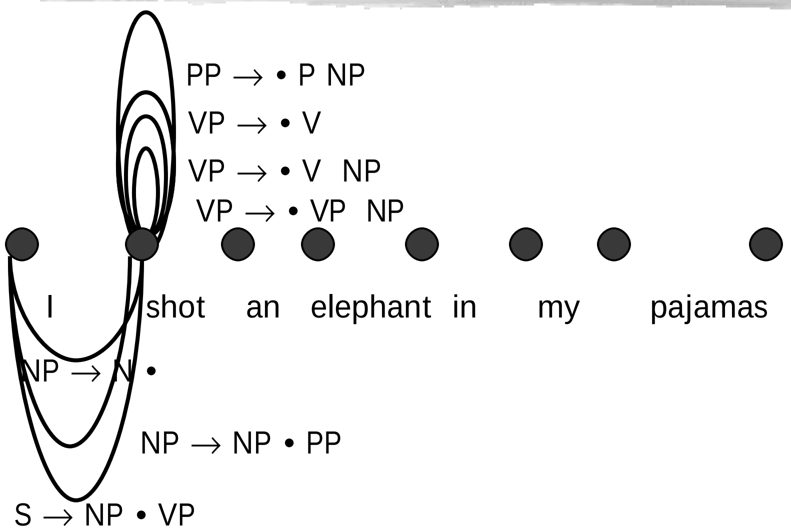


Dot at end...so we ‘complete’ NP

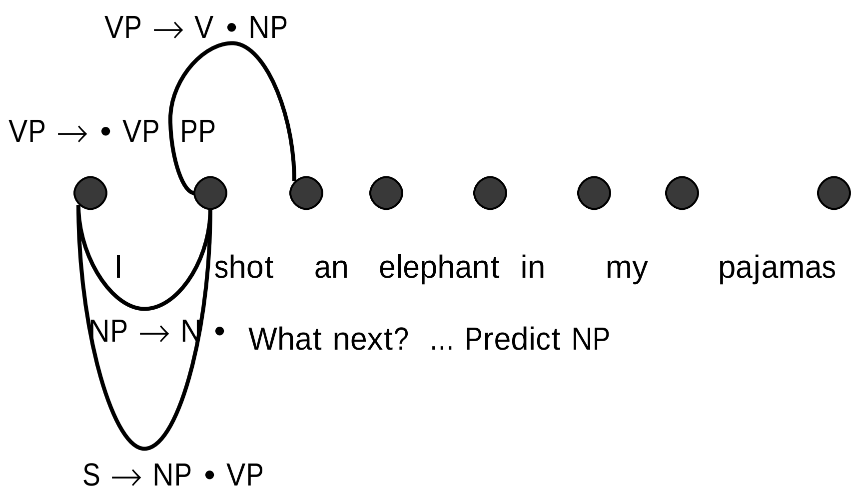
S → •NP VP + NP →N • yields new edge S → NP • VP



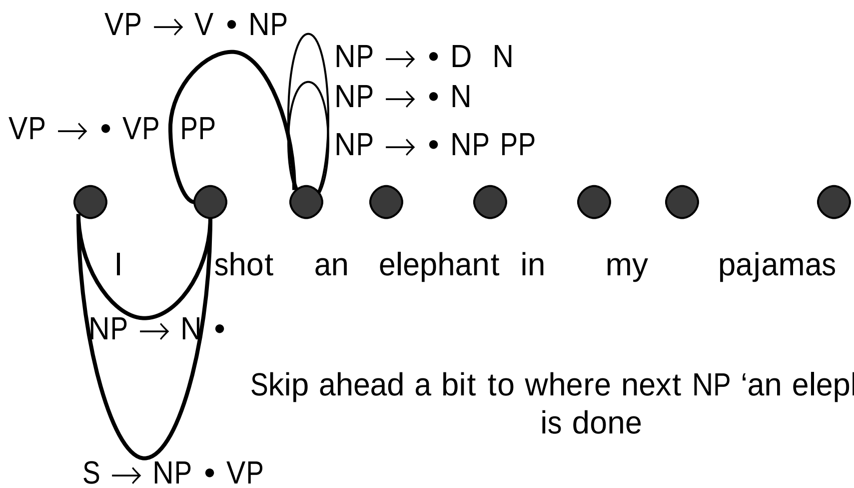
And now predict...expand VP (t-d)



Scan Verb

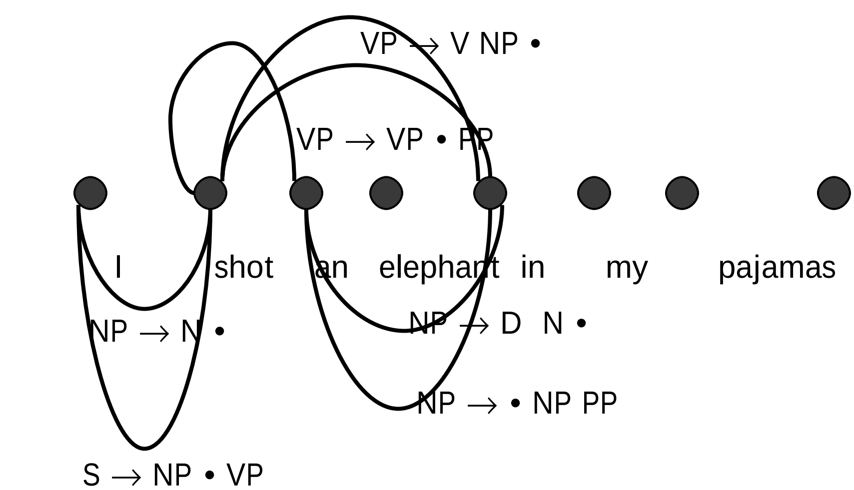


NP Predictions added



Skip ahead a bit to where next NP ‘an elephant’ is done

Process NP object



Enough...no more! Demo easier!