Constituency Parsing

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Outline

A More Grounded Syntax Theory

- A central question in linguistics is **how do we know when a sentence is grammatical**?
- Chomsky's generative grammars attempted to mathematically formalize this question
- Linguistic phrases contained a universal, hierarchical structure formalized as parse trees

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- A central question in linguistics is **how do we know when a sentence is grammatical**?
- Chomsky's generative grammars attempted to mathematically formalize this question
- Linguistic phrases contained a universal, hierarchical structure formalized as parse trees
- Today
    - A formalization
    - Foundation of all computational syntax
    - Learnable from data

Outline

Context Free Grammars

Definition

- N: finite set of non-terminal symbols
- Σ: finite set of terminal symbols
- R: productions of the form $X \rightarrow Y_1 \dots Y_n$, where $X \in N$, $Y \in (N \cup \Sigma)$
- S: a start symbol within N

Examples of non-terminals:

- NP for "noun phrase"
- VP for "verb phrase"
- Often correspond to multiword syntactic abstractions

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Examples of terminals:

- "*dog*"
- "*play*"
- "*the*"

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Examples of productions:

- $\mathrm{N} \rightarrow$ "*dog*"
- $\mathrm{NP} \rightarrow \mathrm{N}$
- $\mathrm{NP} \rightarrow \mathrm{ADJ} \;\; \mathrm{N}$

Context Free Grammars

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- S: a start symbol within N

In NLP applications, by convention we use S as the start symbol

Flexibility of CFG Productions

- Unary rules: $\text{NN} \rightarrow$ "*man*"
- Mixing terminals and nonterminals on RHS:
  - $\text{NP} \rightarrow$ "*Congress*" Vt "*the*" "*pooch*"
  - $\text{NP} \rightarrow$ "*the*" NN
- Empty terminals
  - $\text{NP} \rightarrow \epsilon$
  - $\text{ADJ} \rightarrow \epsilon$

Derivations

- A derivation is a sequence of strings $s_1 \dots s_T$ where
- $s_1 \equiv S$, the start symbol
- $s_T \in \Sigma^*$: i.e., the final string is only terminals
- $s_i, \forall i > 1$, is derived from s_{i-1} by replacing some non-terminal X in s_{i-1} and replacing it by some β, where $x \rightarrow \beta \in R$.

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- Example: parse tree

Example Derivation

Productions

$\textsc{S} \rightarrow \textsc{NP} \;\; \textsc{VP}$

$\textsc{VP} \rightarrow \textsc{AdvP} \;\; \textsc{VZ}$

$\textsc{Det} \rightarrow$ "*the*"

$\textsc{NN} \rightarrow$ "*dot*"

$\textsc{VZ} \rightarrow$ "*barked*"

$\vdots$

$\textsc{NP} \rightarrow \textsc{Det} \;\; \textsc{NN}$

$\textsc{NP} \rightarrow \textsc{AdjP} \;\; \textsc{NN}$

$\textsc{Det} \rightarrow$ "*a*"

$\textsc{NN} \rightarrow$ "*cat*"

$\textsc{VZ} \rightarrow$ "*ran*"

$\vdots$

$\textsc{VP} \rightarrow \textsc{VZ}$

$\textsc{NP} \rightarrow \textsc{PRO}$

$\textsc{Det} \rightarrow$ "*an*"

$\textsc{NN} \rightarrow$ "*mouse*"

$\textsc{VZ} \rightarrow$ "*sat*"

$\vdots$

$s_1 =$

S

Example Derivation

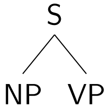
Productions

S → NP VP
VP →
AdvP VZ
Det → "*the*"
NN → "*dot*"
VZ → "*barked*"
⋮

NP → Det NN
NP →
AdjP NN
Det → "*a*"
NN → "*cat*"
VZ → "*ran*"
⋮

VP → VZ
NP → PRO
Det → "*an*"
NN → "*mouse*"
VZ → "*sat*"
⋮

$s_2 =$



Productions

S → NP VP
VP → AdvP VZ
Det → "*the*"
NN → "*dot*"
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⋮

NP → Det NN
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Det → "*a*"
NN → "*cat*"
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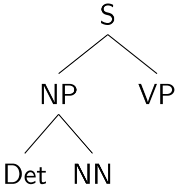
VP → VZ
NP → PRO
Det → "*an*"
NN → "*mouse*"
VZ → "*sat*"
⋮

$s_3 =$



Productions

S → NP VP
VP → AdvP VZ
Det → "*the*"
NN → "*dot*"
VZ → "*barked*"
⋮

NP → Det NN
NP → AdjP NN
Det → "*a*"
NN → "*cat*"
VZ → "*ran*"
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VP → VZ
NP → PRO
Det → "*an*"
NN → "*mouse*"
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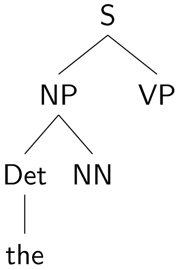
$s_4 =$



Productions

S → NP VP
VP → AdvP VZ
Det → "*the*"
NN → "*dot*"
VZ → "*barked*"
⋮

NP → Det NN
NP → AdjP NN
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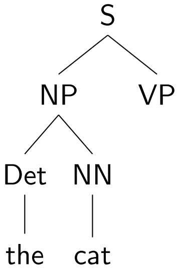
VZ → "*ran*"
⋮

VP → VZ
NP → PRO
Det → "*an*"
NN → "*mouse*"
VZ → "*sat*"
⋮

$s_5 =$



Productions

S → NP VP
VP → AdvP VZ
Det → "*the*"
NN → "*dot*"
VZ → "*barked*"
⋮

NP → Det NN
NP → AdjP NN
Det → "*a*"
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⋮

VP → VZ
NP → PRO
Det → "*an*"
NN → "*mouse*"
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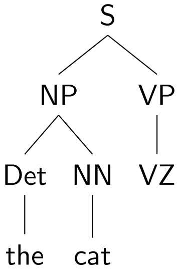
⋮

$s_6 =$



Productions

S → NP VP
VP → AdvP VZ
Det → "*the*"
NN → "*dot*"
VZ → "*barked*"
⋮

NP → Det NN
NP → AdjP NN
Det → "*a*"
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VP → VZ
NP → PRO
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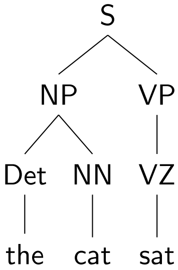
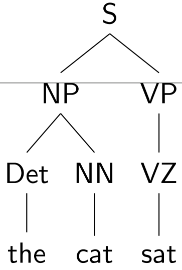
$s_7 =$



Example Derivation



Ambiguous Yields

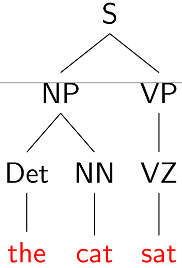
The **yield** of a parse tree is the collection of terminals produced by the parse tree. Given a yield s.

Parsing / Decoding

Given, a yield s and a grammar G, determine the set of parse trees that could have produced that sequence of terminals: $T_G(s)$.

$s_7 =$

Example Derivation



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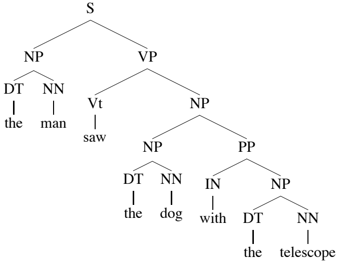
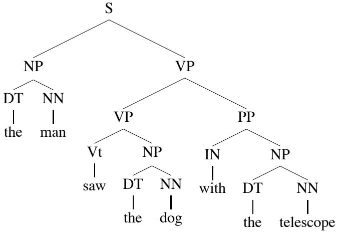
Ambiguity

Example sentence: "The man saw the dog with the telescope"

- Grammatical: $T_G(s) > 0$
- Ambiguous: $T_G(s) > 1$





- Which should we prefer?

Ambiguity

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- Grammatical: $T_G(s) > 0$
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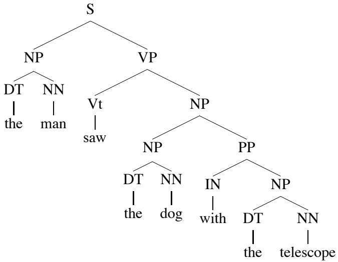

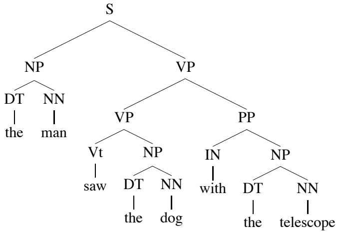

- Which should we prefer?
- One is more *probable* than the other
- Add probabilities!

Outline

Goals

- What we want is a probability distribution over possible parse trees $t \in T_G(s)$

$$\forall t, p(t) \geq 0 \qquad \sum_{t \in T_G(s)} p(t) = 1 \tag{1}$$

- Rest of this lecture:
  - How do we define the function $p(t)$ (paramterization)
  - How do we learn $p(t)$ from data (estimation)
  - Given a sentence, how do we find the possible parse trees (parsing / decoding)

Parametrization

- For every production $\alpha \rightarrow \beta$, we assume we have a function $q(\alpha \rightarrow \beta)$
- We consider it a **conditional probability** of β (LHS) being derived from α (RHS)

$$\sum_{\alpha \rightarrow \beta \in R : \alpha = X} q(\alpha \rightarrow \beta) = 1 \tag{2}$$

- The total probability of a tree $t \equiv \{\alpha_1 \rightarrow \beta_1 \dots \alpha_n \rightarrow \beta_n\}$ is

$$p(t) = \prod_{i=1}^{n} q(\alpha_i \rightarrow \beta_i) \tag{3}$$

Estimation

- Get a bunch of grad students to make parse trees for a million sentences
- Mitch Markus: Penn Treebank (Wall Street Journal)
- To compute the conditional probability of a rule,

$$q(\text{NP} \rightarrow \text{Det ADJ NN}) \approx \frac{\text{Count}(\text{NP} \rightarrow \text{Det ADJ NN})}{\text{Count}(\text{NP})}$$

- Where "Count" is the number of times that derivation appears in the sentences

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$$q(\textsc{np} \rightarrow \textsc{Det} \ \textsc{adj} \ \textsc{nn}) \approx \frac{\text{Count}(\textsc{np} \rightarrow \textsc{Det} \ \textsc{adj} \ \textsc{nn})}{\text{Count}(\textsc{np})}$$

- Where "Count" is the number of times that derivation appears in the sentences
- Why no smoothing?

Dynamic Programming

- Like for dependency parsing, we build a chart to consider all possible subtrees
- First, however, we'll just consider whether a sentence is grammatical or not
- Build up a chart with all possible derivations of spans
- Then see entry with start symbol over the entire sentence: those are all grammatical parses

CYK Algorithm (deterministic)

Assumptions

Assumes binary grammar (not too difficult to extend) and no recursive rules

Given sentence $\vec{w}$ of length N, grammar (N, Σ, R, S)
Initialize array $C[s, t, n]$ as array of booleans, all false ($\perp$)

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Initialize array $C[s, t, n]$ as array of booleans, all false ($\perp$)
for $i = 0 \ldots N$ **do**
  for For each production $r_j \equiv N_a \rightarrow w_i$ **do**
    set $C[i, i, a] \leftarrow \top$

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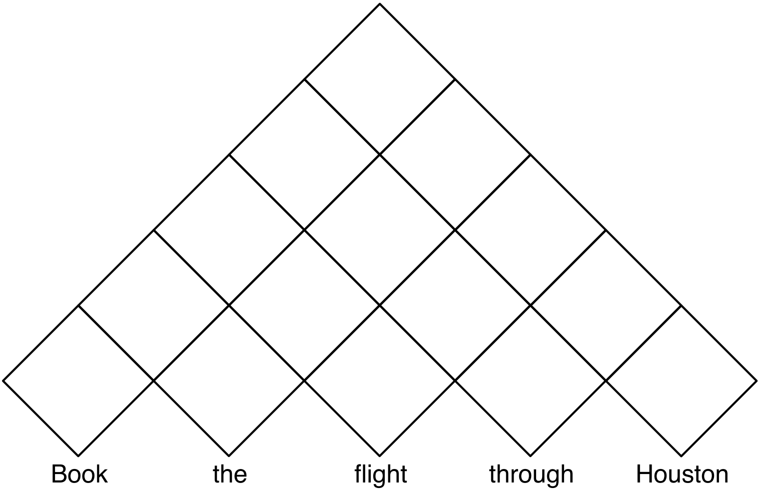
Initialize array $C[s, t, n]$ as array of booleans, all false $(\perp)$
for $i = 0 \dots N$ **do**
  for For each production $r_j \equiv N_a \rightarrow w_i$ **do**
    set $C[i, i, a] \leftarrow \top$
for $l = 2 \dots n$ (length of span) **do**
  for $s = 1 \dots N - l + 1$ (start of span) **do**
    for $k = 1 \dots l - 1$ (pivot within span) **do**
      for each production $r \equiv \alpha \rightarrow \beta\gamma$ **do**
        if $\neg C[s, s + l, \alpha]$ **then**
          $C[s, s + l, \alpha] \leftarrow C[s, s + k - 1, \beta] \wedge C[s + k, s + l, \gamma]$

Chart Parsing



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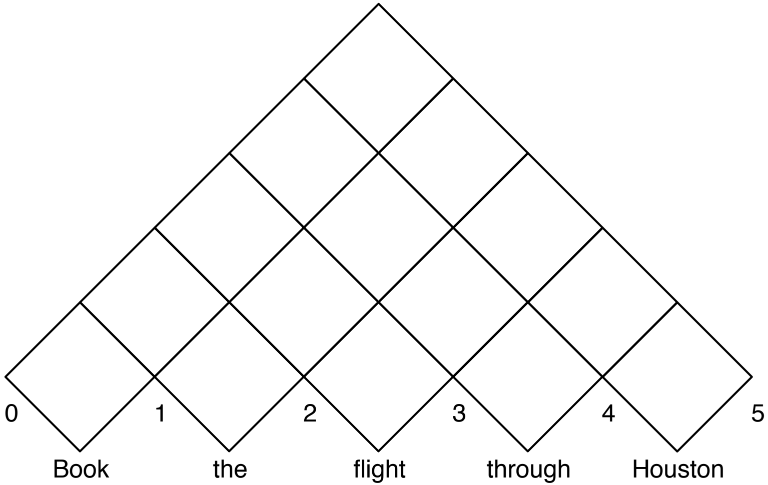

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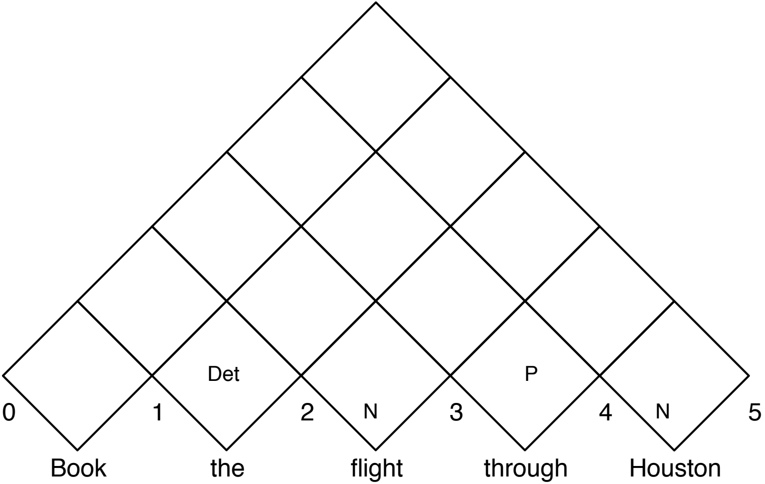

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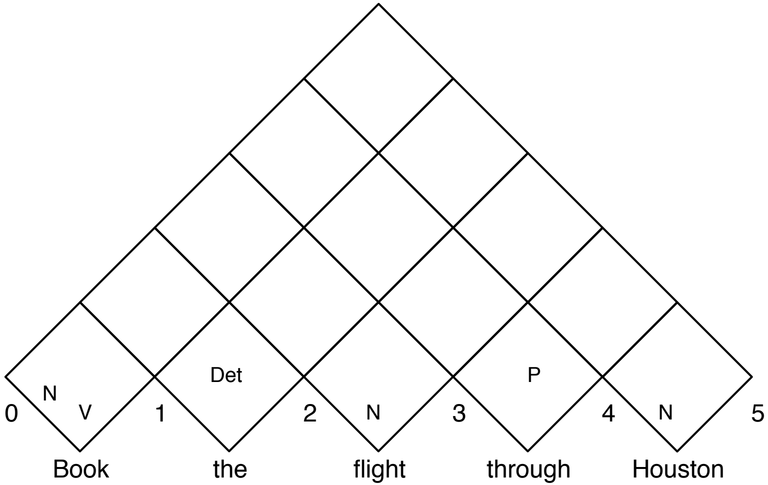

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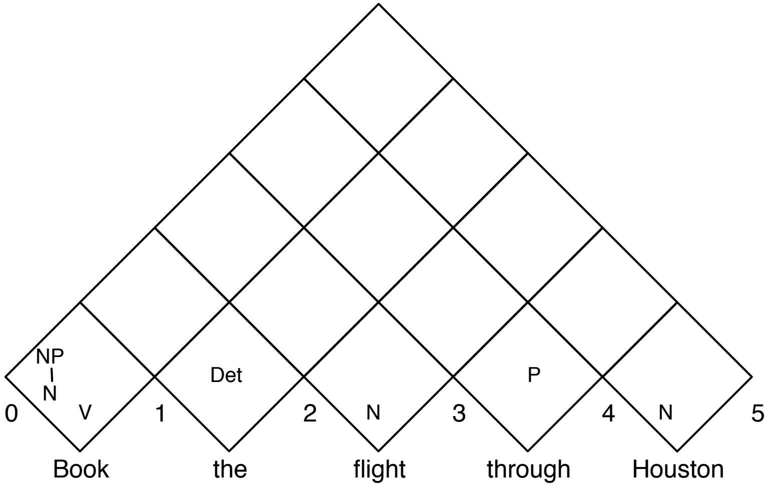

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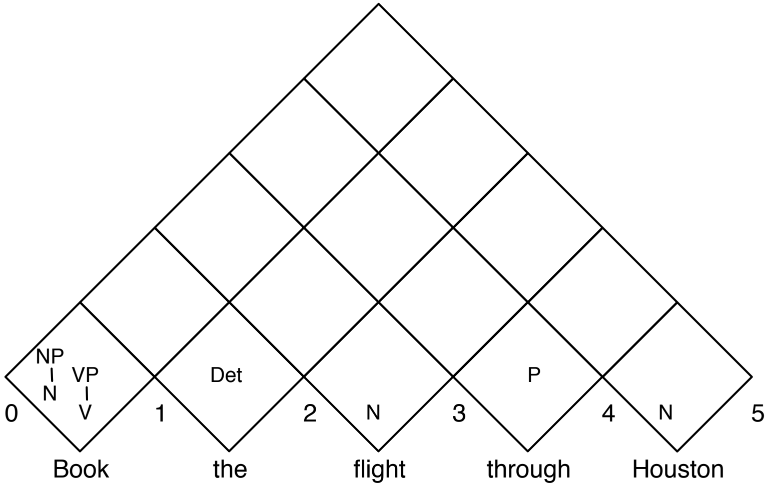

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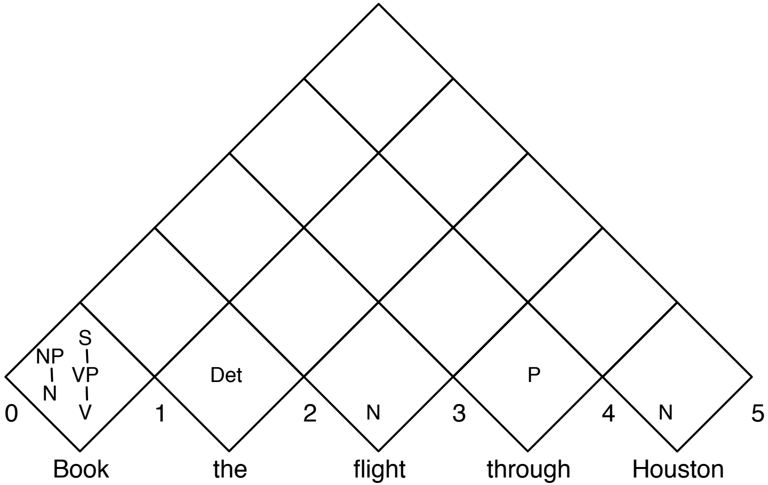

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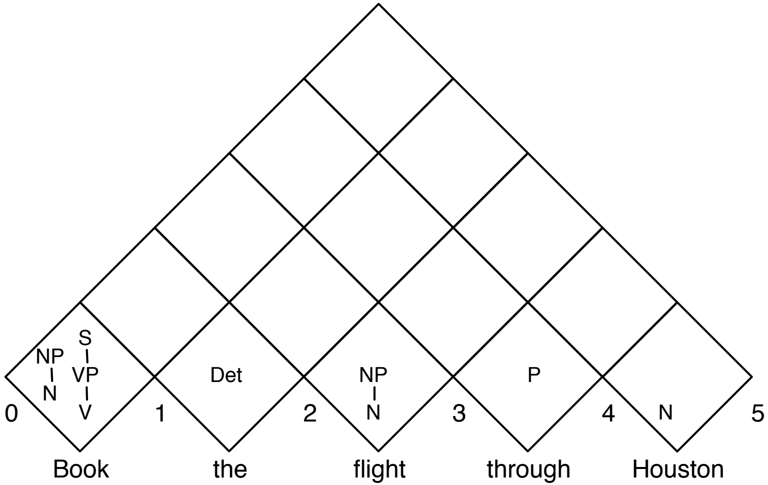

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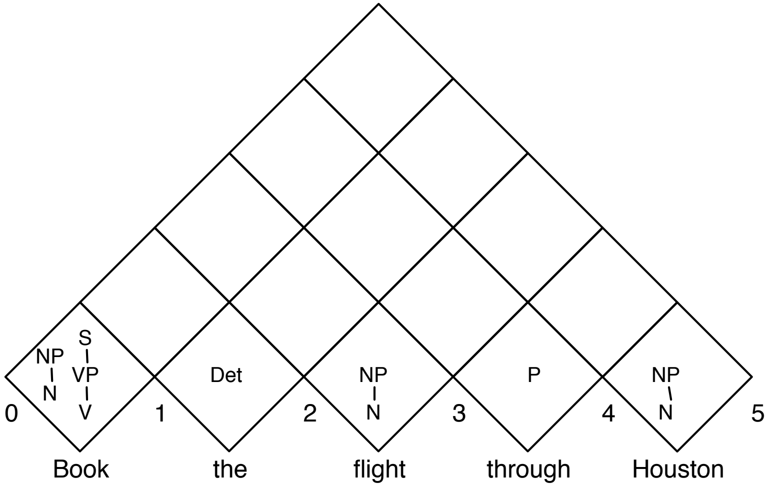

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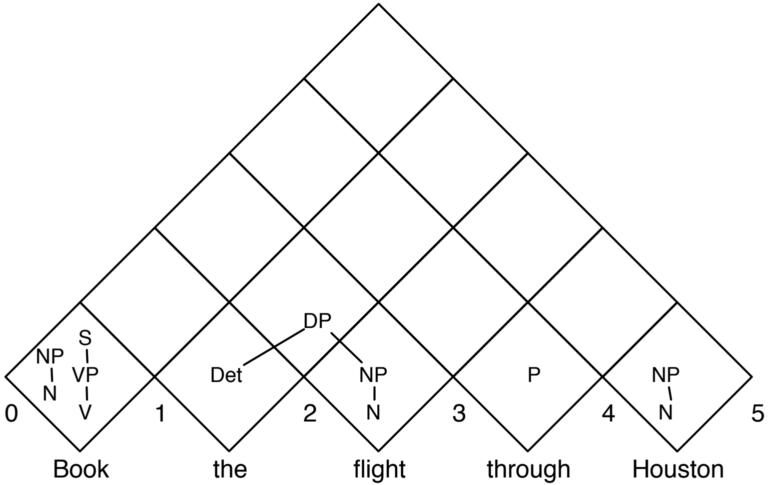

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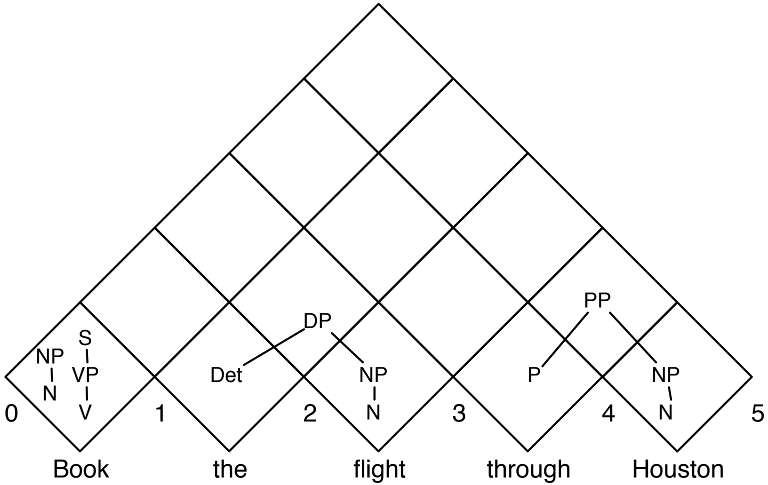

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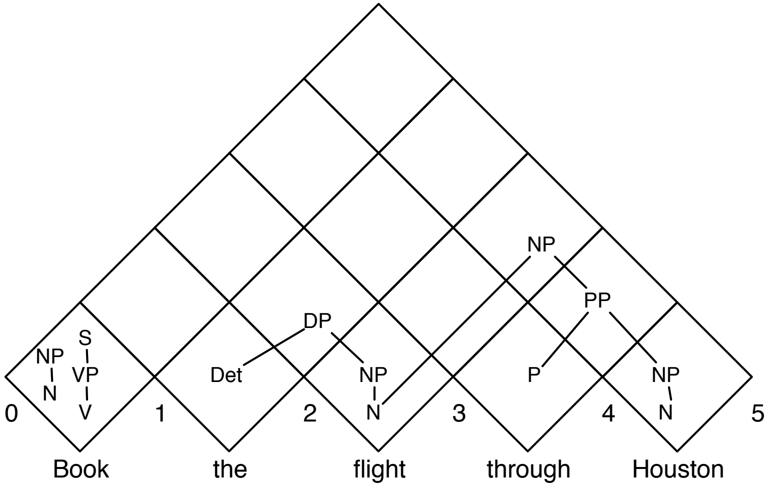

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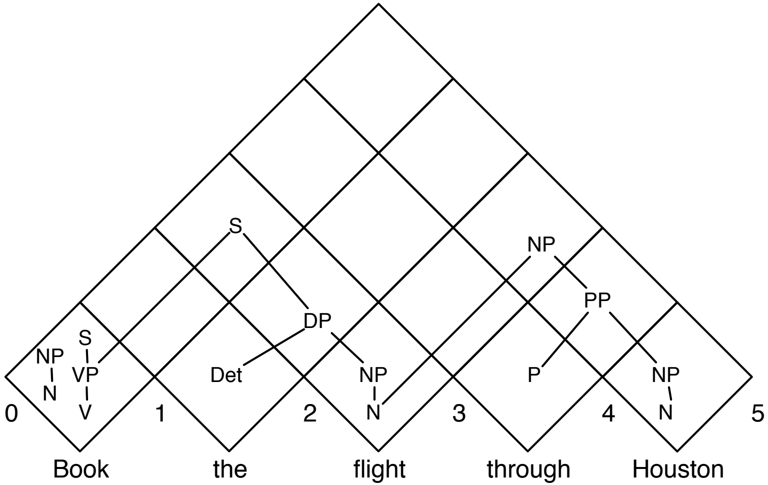

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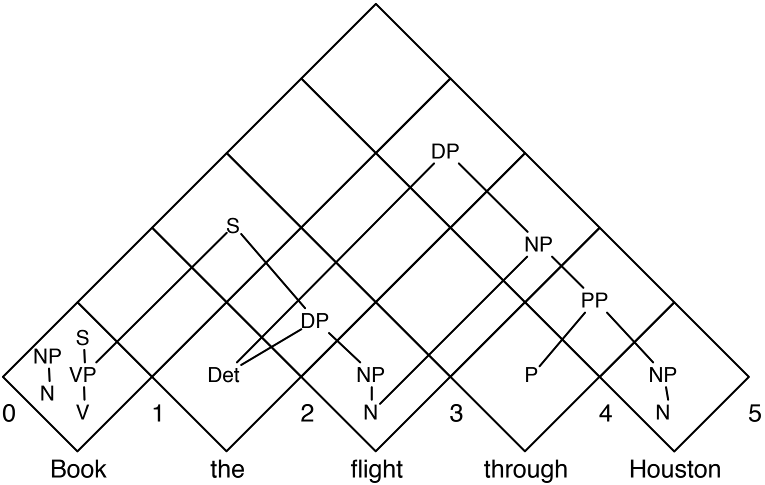

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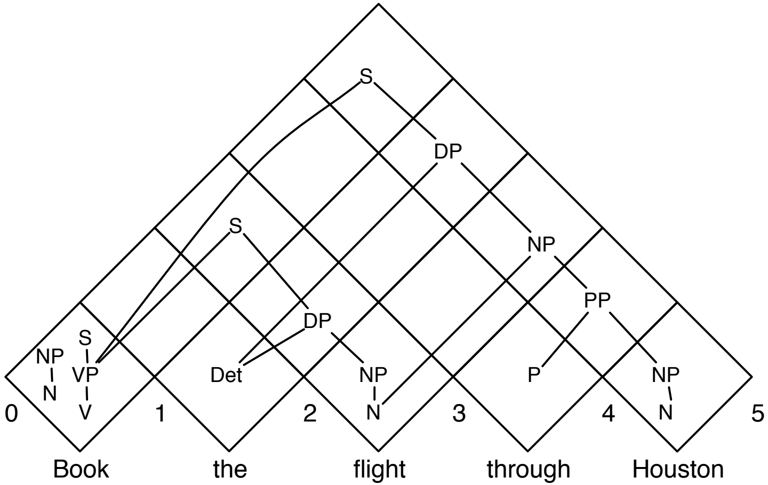

Complexity?

- Chart has n^2 cells

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- Each cell has n options

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- Times the number of productions $|G|$

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- Chart has n^2 cells
- Each cell has n options
- Times the number of productions $|G|$
- Thus, $O(n^3|G|)$

How to deal with PCFG ambiguity

- In addition to keeping track of non-terminals in cell, also include **max** probability of forming non-terminal from sub-trees

  $$C[s, s+k, \alpha] \leftarrow \max(C[s, s+k, \alpha], C[s, s+l-1, \beta] \cdot C[s+l, s+k, \gamma])$$

- The score associated with S in the top of the chart is the best overall parse-tree (**given the yield**)

Recap

- Hierarchical syntax model: context free grammar
- Probabilistic interpretation: learn from data to solve ambiguity
- In class (next time):
  - Work through example to resolve ambiguity
  - Scoring a sentence