Carnegie Mellon University
Language
Technologies
Institute

11-411/11-611 Natural Language Processing

Constituency Grammar

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Language Technologies Institute

Learning Objectives

- Define syntax and identify one respect in which it is useful to NLP.
- Distinguish the two major approaches to syntax
- Identify syntactic constituents using TESTS FOR CONSTITUENCY
- Indentify a few kinds of constituents in English.
- Define context free grammars (CFGs)
- Derive sentences, given a CFG
- Reproduce the CYK or CKY algorithm

What is Syntax and Why Is It Useful?

Syntax is Sentence and Phrase Structure

- Syntax concerns the patterns according to which words are combined to form phrases and sentences.
- It is distinct from morphology (how morphemes combine to form words) and semantics (what sentences mean) but is related to both.
- *Colorless green ideas sleep furiously.*

Syntax is the Door to Semantics

- To arrive at a semantic interpretation of a sentence, you have to know its syntax
- Parallel with programming languages
  - Semantics different from syntax (form versus function)
  - But semantics follows from syntax

Who Did What to Whom?

If you want to know who did what to whom with what thing having what properties, you must have access to syntax in some form.

Different perspectives on syntax

There are Two Major Approaches to Syntax in NLP

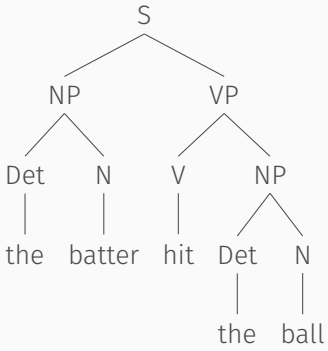
Two approaches:

- Syntax means taking sentences, dividing them into phrases and dividing those phrases into smaller phases until you arrive at individual words, yielding a tree of “constitutents”
- Syntax means taking sentences and characterizing the relationships between pairs of words in the sentence, yielding a tree or graph of “heads” and “dependents”

Phrase Structure Grammar is also Called Constituency Grammar

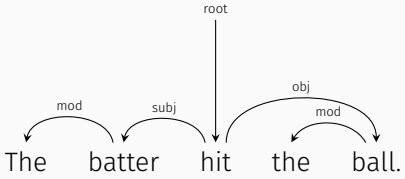
- The first approach is called PHRASE STRUCTURE GRAMMAR or CONSTITUENCY GRAMMAR.
- Basic unit — constituent
- Used by the parsers in the interpreters/compilers of most programming languages

S	sentence
NP	noun phrase
VP	verb phrase
Det	determiner
N	noun
V	verb



Dependency Grammar Is Based On Bilexical Dependencies

- The second approach is called DEPENDENCY GRAMMAR.
- Basic element — BILEXICAL DEPENDENCY
- Especially useful for many contemporary NLP tasks



The Notion of Constituency

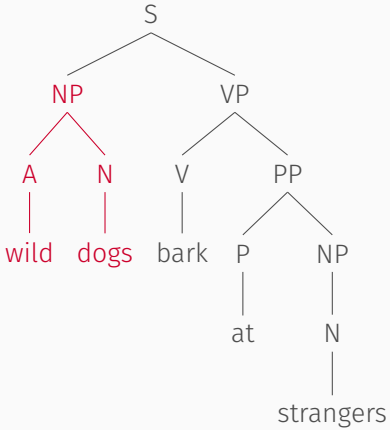
Constituents Are “Clumps” of Words

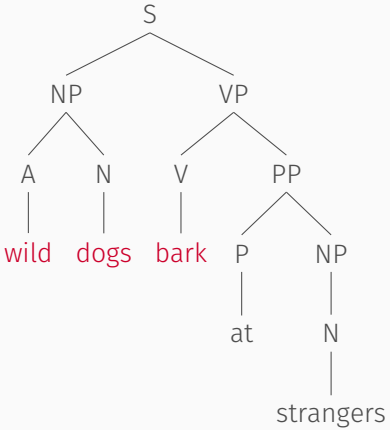
- Constituents: sequences of one or more words that “go together” (form a unit of which the preceding and following words are not a part)
- Constituents larger than a word are called “phrases”
- Phrases can contain other phrases

Constituents are not arbitrary

- **Criteria** exist for diagnosing whether a sequence of words forms a constituent
- These are called "**tests for constituency**"
- These include coordination, substitution, and movement.
- We will illustrate only substitution in this lecture.

Pro-form substitution trees



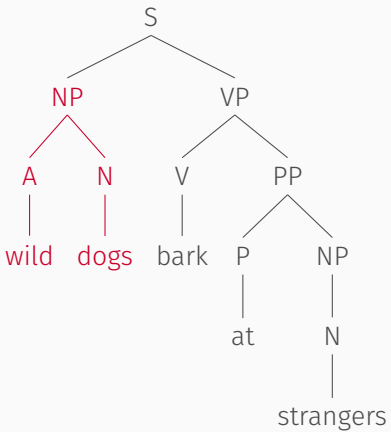


PP prepositional phrase
P preposition

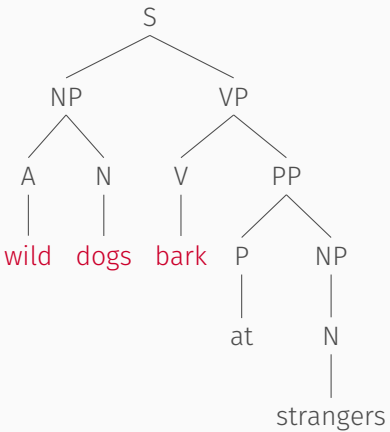
Pro-form substitution tests

Dogs bark at strangers	↔	**They** bark at strangers
Wild dogs bark at strangers	↔	**They** bark at strangers
The big dogs we saw by the house bark at strangers	↔	**They** bark at strangers
Dogs bark at strangers	↔	*__They__ at strangers

Grammatical and Ungrammatical

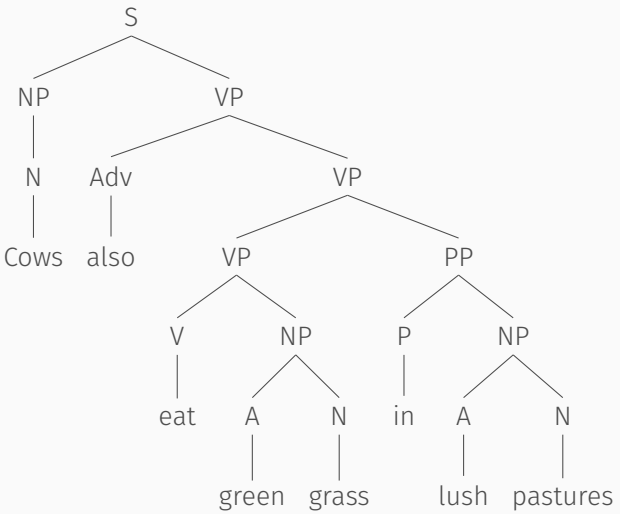


They bark at strangers. (grammatical)



*They at strangers. (ungrammatical)

Do-so substitution trees



Do-so substitution test

Horses eat green grass in lush pastures and

Cows also **eat green grass in lush pastures**.	↔	Cows also **do so**.
Cows also **eat green grass** in lush pastures.	↔	Cows also **do so** in green pastures.
Cows also **eat green** grass in lush pastures.	↔	*Cows also **do so** grass in lush pastures.

Types of constituents in English

Types of Constituents in English

There are several types of constituents in English

- Words: Noun, verb, preposition, adjective, etc
- Phrases: S, NP, VP, PP, AP, etc.

Following are some of the most important phrasal constituents.

Examples of Noun Phrases

Noun phrases typically, though not always, contain nouns (which form the center or "head" of the phrase). The subjects and objects of verbs and the objects of prepositions are noun phrases.

- The elephant arrived.
- It arrived.
- Elephants arrived.
- The big ugly elephant arrived.
- The elephant I love to hate arrived.
- The elephant who ate **my Cheetos** arrived.

Prepositional Phrases (PPs)

Every prepositional phrase contains a preposition (sometimes more than one) and a noun phrase:

- I arrived on **Tuesday**.
- I arrived in **March**.
- I arrived under **the leaking roof**.

Verb Phrases (VPs)

- Alan awoke.
- Alan scheduled frantically.
- Alan scheduled a meeting.
- Alan scheduled a meeting with a scientist from Punjab.
- Alan thought that **you thought that winter was here**.

Sentences or Clauses (Ss)

- John loves Mary.
- John loves the woman **he thinks is Mary**.
- Sometimes, John thinks **he is Mary**.
- It is patently false that **sometimes John thinks he is Mary**.

Context-Free Grammars (CFGs)

Context-Free Grammars Define Sets of Trees

S → NP VP

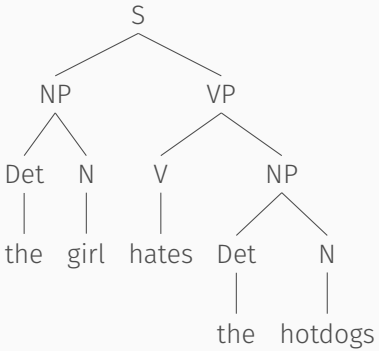
NP → Det Noun

VP → Verb NP

Det → the | a

Noun → boy | girl | hotdogs

Verb → likes | hates | eats



Context-Free Grammars

S → NP VP
NP → Det Noun
VP → Verb NP
Det → the | a
Noun → boy | girl | hotdogs
Verb → likes | hates | eats

- **Non-Terminal Symbols:** S, NP, VP, N, V, Det
- **Terminal Symbols:** the, a, boy, girl, hotdogs, likes, hates, eats
- **Rules:** One non-terminal symbol on the left of an arrow. Any number of terminal and non-terminal symbols on the right.

Non-Terminal Symbols Form Parent Nodes

A non-terminal symbol is one like S that can (and must!) be rewritten as either

- Other non-terminal symbols
- Terminal symbols

Non-terminals can be phrasal or pre-terminal (in which case they look like part of speech tags—Noun, Verb, etc.)

In natural language syntax, terminals are usually words They cannot be rewritten; they mean that you're done

Context-Free Grammars are 4-Tuples

Context-free grammars are a tuple $\langle N, \Sigma, R, S \rangle$

- N, a finite set of non-terminal symbols
- Σ, a finite set of terminal symbols
- S, a special start symbol $S \in N$
- R, a finite relation in $N \times (N \cup \Sigma)^*$.

Members of R are typically represented as rewrite rules of the form $X \to \alpha$ where

$$X \in N$$
$$\alpha \in (N \cup \Sigma)^*$$

In Chomsky Normal Form (about which, more later):

$$\alpha \in (N^2 \cup \Sigma)$$

CFGs Have no Context on the Left-Hand Side

The grammars are called “context-free” because there is no context in the LHS of rules—there is just one symbol.

NP $\rightarrow$ Det N

The rule lets NP expand into Det and N regardless of where it is in the tree. With a CFG, there is no way to say that NP expands to Det and N when it is in some contexts (e.g., inside a VP) but not others.

A Context-Free Grammar

S → NP VP
NP → Det Noun
VP → Verb NP
Det → the | a
Noun → boy | girl | hotdogs
Verb → likes | hates | eats

The same context free grammar can be used to parse sentences and to generate sentences.

Derivations and Parse Trees

Some Definitions

Grammatical said of a sentence in the language

Ungrammatical said of a sentence not in the language

Derivation sequence of top-down production steps

Parse tree graphical representation of the derivation

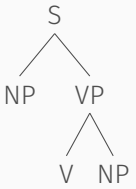
A string is grammatical iff there exists a derivation for it.

A Grammar Generates a Language

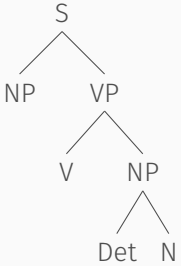
S → NP VP
NP → Det N
VP → V NP
Det → your, my, the, a
N → computer, sentence
V → parsed, misunderstood

S → NP VP

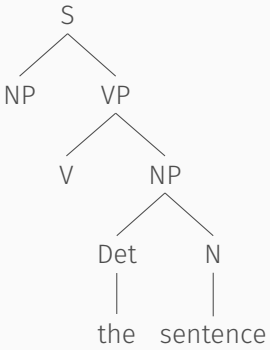
VP → V NP



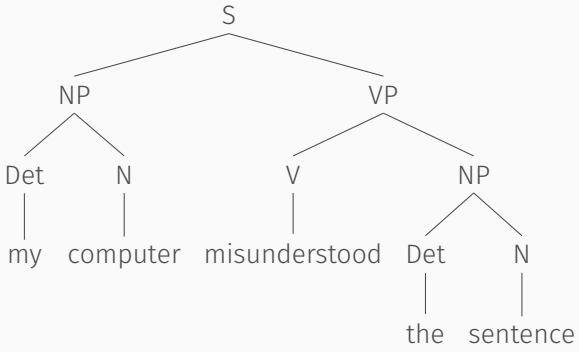
NP → Det N



Det → the
N → sentence



S → NP VP
NP → Det N
VP → V NP
Det → my
Det → the
N → computer
N → sentence
V → misunderstood



Recognition and Parsing

What is a Recognizer?

Input
- A sentence
- A grammar

Output Is the sentence a member of the set of sentences defined by the grammar?

An Example of Recognition

S → NP VP
NP → Det N
VP → V NP
Det → your, my, the, a
N → computer, sentence
V → parsed, misunderstood

Yes	Your computer parsed my sentence.
Yes	Your sentence parsed my computer.
No	The the my parsed computer.
No	Your computer misunderstood.
No	Your computer misunderstood that sentence.
No	Parsed parsed parsed.

What is a Parser?

Input
- Sentence
- Grammar

Output
- A parse tree (a tree data structure representing the syntactic structure of the sentence)
- Nothing if the sentence is not recognized by the grammar

Parsing is a Search Problem

In order to parse a sentence, a parser must find all the possible ways that that sentence could be derived in a grammar. It is searching through a large (potentially infinite space).

- Naïve approaches to this problem are intractable
- Recursive grammars allow for an unbounded number of derivations
- Fortunately, mathematicians and computer scientists have developed a wide range of algorithms for addressing the problems of context free recognition and parsing
- We will look at one of these—the Cocke-Younger-Kasami Algorithm (first published by Itiroo Sakai in 1961).

Search: rules that make contiguous, non-overlapping, connected sub-trees

$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$

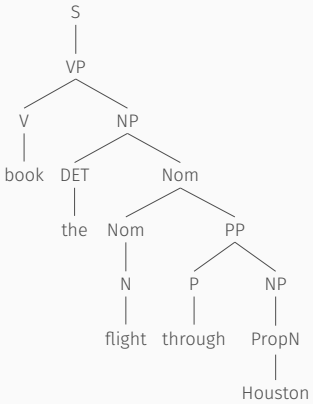
$S \rightarrow VP$

$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$

$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

Book the flight through Houston

S → VP
NP → Det Nom
NP → PropN
Nom → Nom PP
Nom → N
PP → P NP
VP → V NP



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$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$

$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

Book the flight through Houston

S → VP

NP → Det Nom

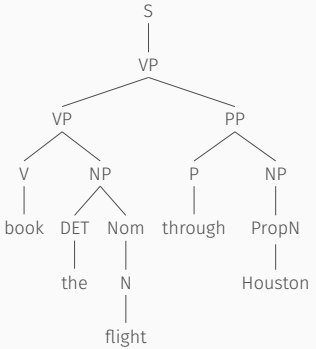
NP → PropN

Nom → N

PP → P NP

VP → V PP

VP → V NP



Search: rules that make contiguous, non-overlapping, connected sub-trees

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$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$

$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

Book the flight through Houston

S → VP

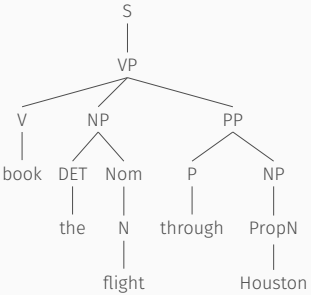
NP → Det Nom

NP → PropN

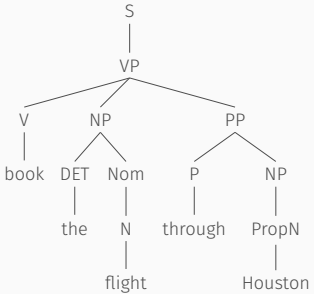
Nom → N

PP → P NP

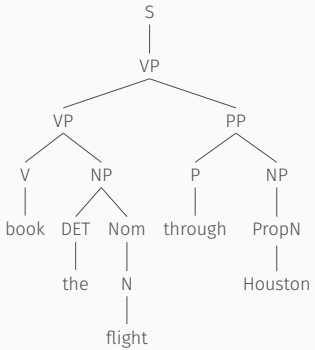
VP → V NP PP



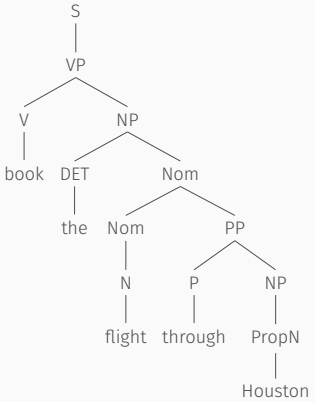
Trees Represent Ambiguity



Call Houston to book the flight.



Call Houston to book the flight.



The flight goes through Houston.

Constituency Parsing with CYK/CKY

Chomsky Normal Form is a Form in which All CFGs Can Be Represented

The general rule schema for CFGs is:

$NT \rightarrow (NT \cup T)^*$

Where NT means “non-terminal” (parts of speech and phrases) and T means “terminal” (words). All grammars made of rules of this kind can be represented in Chomsky Normal Form with rules only of these kinds:

$NT \rightarrow NT\ NT$

$NT \rightarrow T$

This usually involves creating many more rules and creating spurious constituents.

CFGs Can Be Converted to CNF

$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$

$S \rightarrow VP$

$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$

$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

$S \rightarrow NP\ VP$
$S \rightarrow X1\ VP$
$X1 \rightarrow Aux\ NP$
$S \rightarrow book \mid include \mid prefer$
$S \rightarrow Verb\ NP$
$S \rightarrow X2\ PP$
$S \rightarrow Verb\ PP$
$S \rightarrow VP\ PP$
$NP \rightarrow I \mid she \mid me$
$NP \rightarrow TWA \mid Houston$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow book \mid flight \mid meal \mid money$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow book \mid include \mid prefer$
$VP \rightarrow Verb\ NP$
$VP \rightarrow X2\ PP$
$X2 \rightarrow Verb\ NP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

The Cocke-Younger-Kasami Algorithm

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

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

The CYK or CKY Algorithm requires that grammars in by CNF.

CYK/CKY in Python 3.10 (Part 1)

```
def cyk(words: list[str], grammar: list[tuple[str]]) -> \
        tuple[defaultdict, defaultdict]:
    # Initialize data structures
    table = defaultdict(lambda: defaultdict(set))
    back = defaultdict(lambda: defaultdict(lambda: defaultdict(set)))
    n = len(words)

    # Iterate over columns
    for j in range(1, n + 1):

        # Find preterminals corresponding to the jth word
        preterms = set()
        # Accumulate preterminals in preterms based on matching rules
        for rule in grammar:
            match rule:
                case (a, b) if b == words[j - 1]:
                    preterms.add(a)
        table[j-1][j] = preterms
```

CYK/CKY in Python 3.10 (Part 2)

```
# Iterate over rows
for i in range(j - 2, -1, -1):

    # Iterate over spans
    for k in range(i + 1, j):
        # Determine whether there is a rule such that the symbols on the
        # right-hand side correspond to symbols at the "ends" of the
        # span
        for rule in grammar:
            match rule:
                case (a, b, c) if b in table[i][k] and c in table[k][j]:
                    # Add the left-hand side to the current position in
                    # the parse chart
                    table[i][j].add(a)
                    # Add a back-reference
                    back[i][j][a].add((k, b, c))
```

CYK/CKY in Python 3.10 (Part 3)

```
# Return the parse table and back-references if the whole sequence was parsed
if table[0][n]:
    return table, back
# Otherwise, return None (redundant)
else:
    return None
```

Stepping Through CYK

Grammar and Lexicon

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

$S \rightarrow NP\ VP$
$S \rightarrow X1\ VP$
$X1 \rightarrow Aux\ NP$
$S \rightarrow book \mid include \mid prefer$
$S \rightarrow Verb\ NP$
$S \rightarrow X2\ PP$
$S \rightarrow Verb\ PP$
$S \rightarrow VP\ PP$
$NP \rightarrow I \mid she \mid me$
$NP \rightarrow TWA \mid Houston$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow book \mid flight \mid meal \mid money$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow book \mid include \mid prefer$
$VP \rightarrow Verb\ NP$
$VP \rightarrow X2\ PP$
$X2 \rightarrow Verb\ NP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

This lexicon and grammar are taken from SLP3 and will be used as the basis for the examples that follow.

Noun	⇒	N
Proper-Noun	⇒	PN
PRO	⇒	Pronoun
Nominal	⇒	Nom
Preposition	⇒	P

Alphabetized Grammar

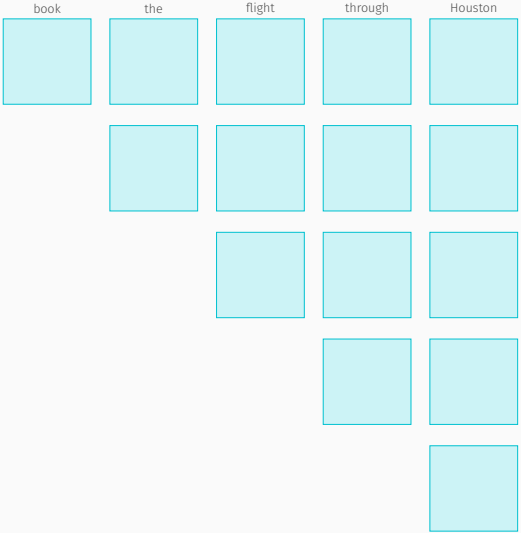
Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← Nom
book ← S
book ← VP
I ← NP
flight ← Nom
include ← S
include ← VP
me ← NP
meal ← Nom
money ← Nom
prefer ← S
prefer ← S
she ← NP
TWA ← NP
Houston ← NP

Overview

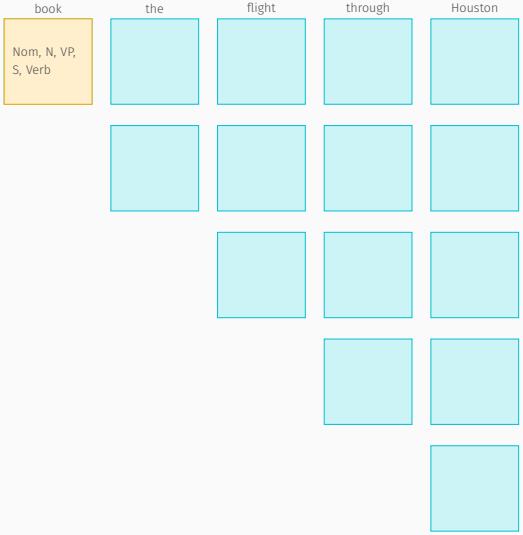
The parse chart will be shown as the northeast half of a square, with a word in each column.

- The cursor will move left to right (one column at a time, low indices to high indices)
- The cursor will move from bottom to top (one row at a time, high indices to low indices)
- As each new column is reached, the bottom square will turn gold and be populated with one or more preterminals (parts of speech).
- Red arrows pointing from the cursor to the west and south indicate which cells are being probed for a match to one of the rules
- These act like a rope stretched over the cursor—as the rope pointing west gets shorter, that pointing downward gets longer
- As matches are found, they will be added to the cell the cursor is on



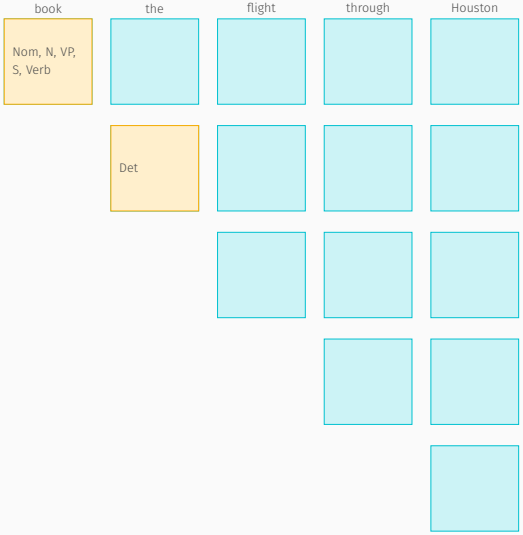
Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
book ← Nom
book ← S
book ← V
book ← VP
I ← NP
I ← Pro
flight ← Nom
flight ← N
include ← S
include ← VP
me ← NP
meal ← Nom
money ← Nom
prefer ← S
prefer ← S
she ← NP
to ← P
the ← Det
TWA ← NP
Houston ← NP
Houston ← PropN



Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
book ← Nom
book ← S
book ← V
book ← VP
I ← NP
I ← Pro
flight ← Nom
flight ← N
include ← S
include ← VP
me ← NP
meal ← Nom
money ← Nom
prefer ← S
prefer ← S
she ← NP
to ← P
the ← Det
TWA ← NP
Houston ← NP
Houston ← PropN



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VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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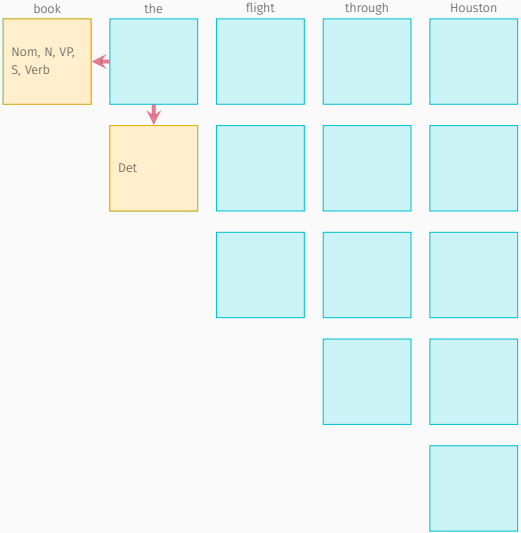

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VP PP ← VP
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X2 PP ← VP

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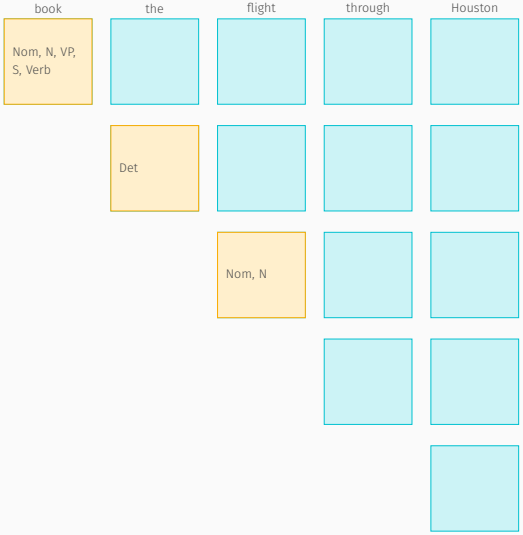

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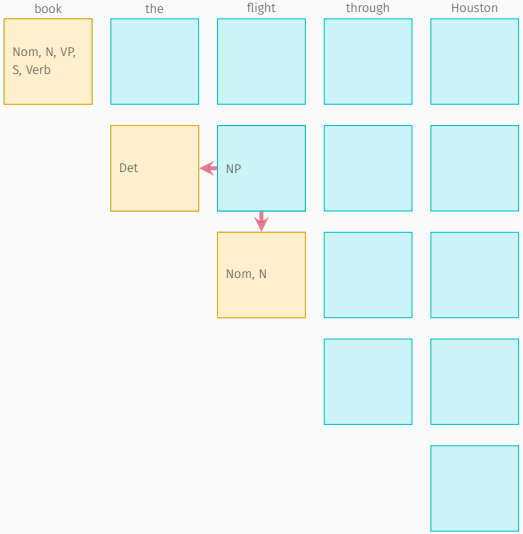

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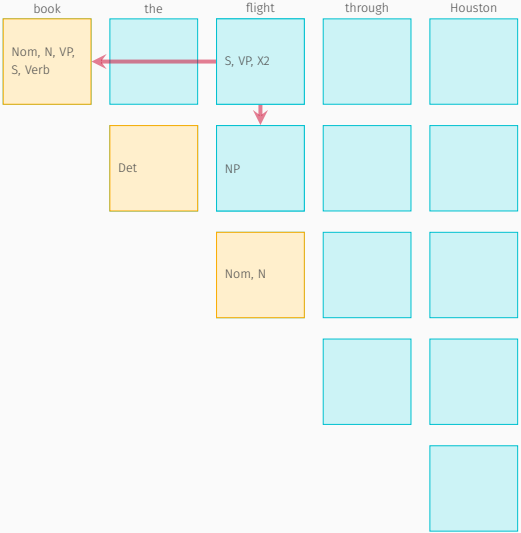

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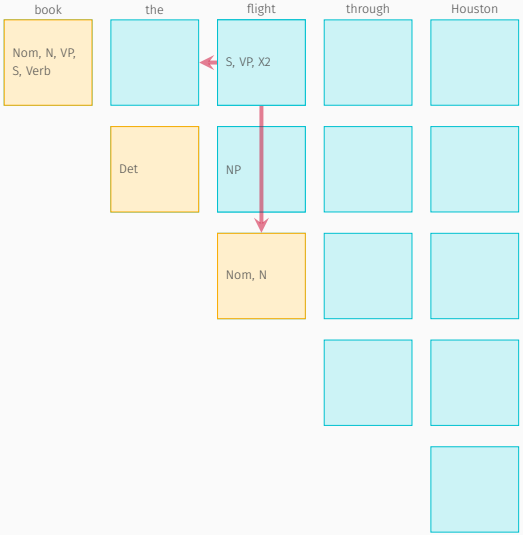

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Verb PP ← VP
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VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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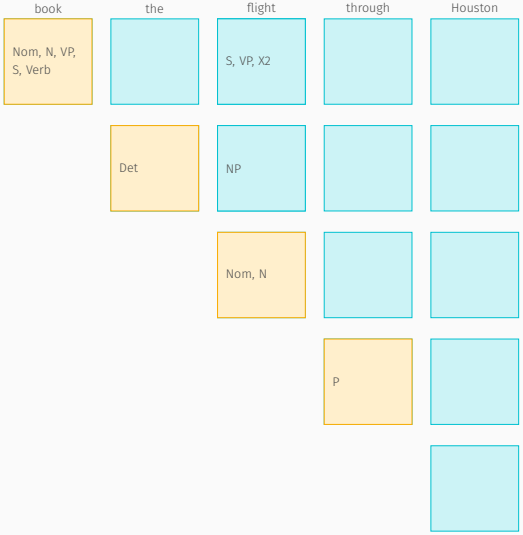

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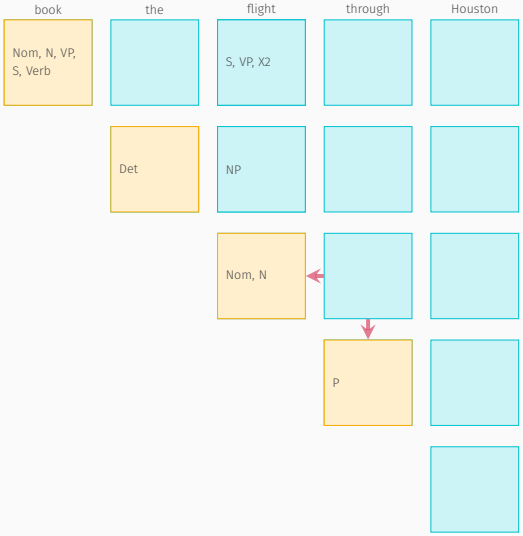

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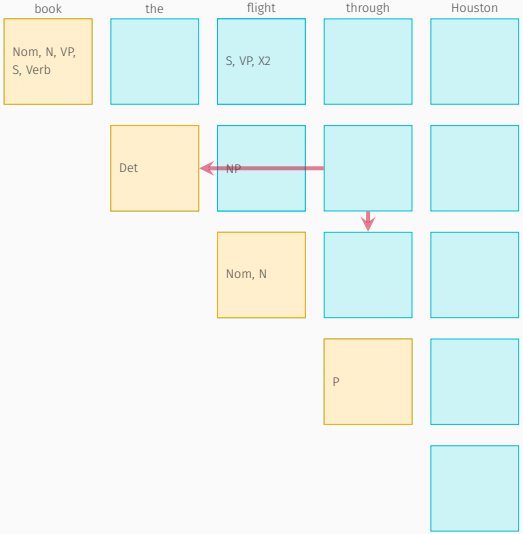

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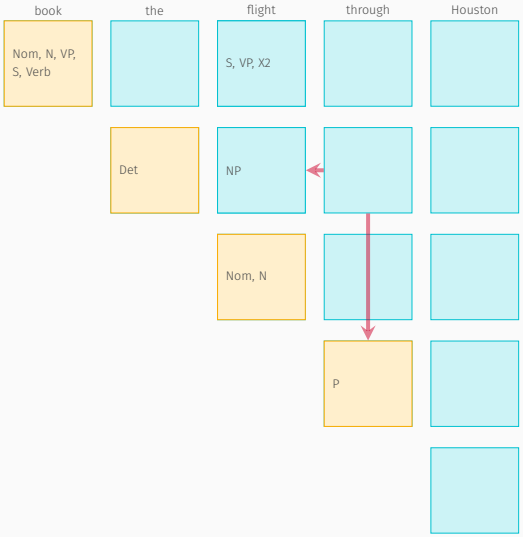

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Verb PP ← VP
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VP PP ← VP
X1 VP ← S
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X2 PP ← VP

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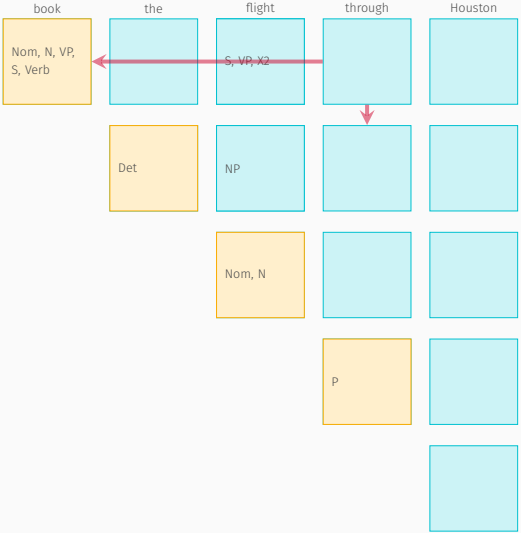

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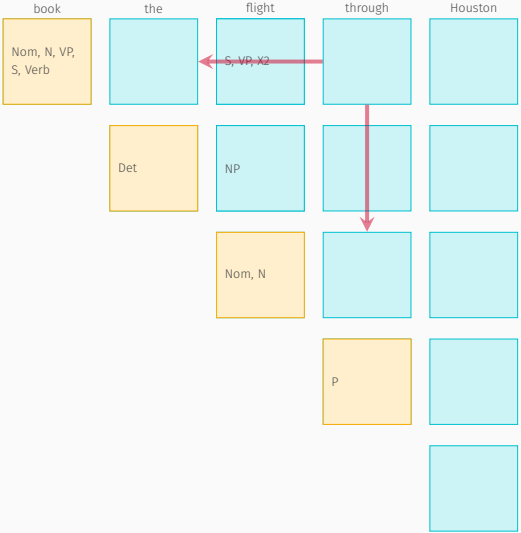

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Verb PP ← S
Verb PP ← VP
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VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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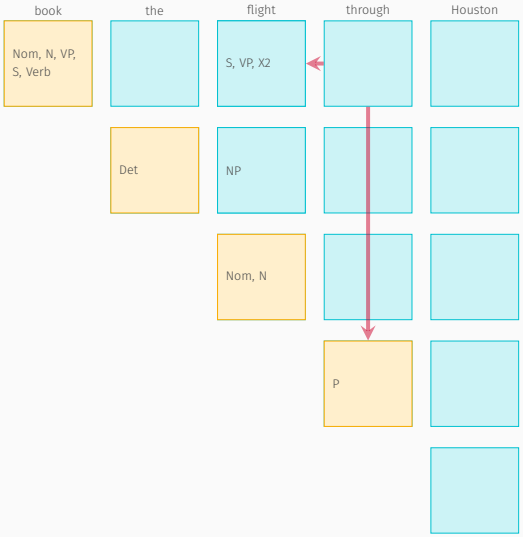

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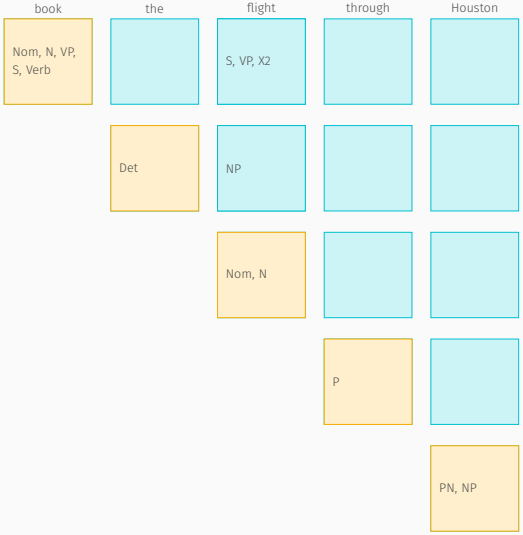

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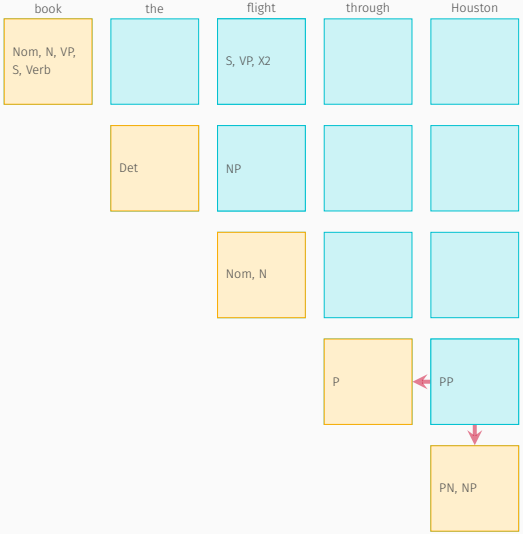

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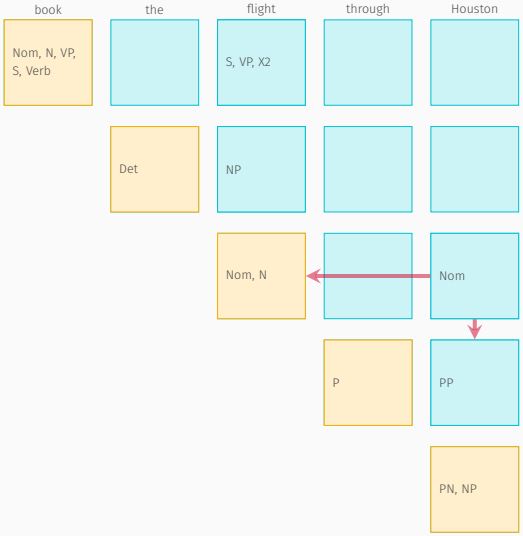

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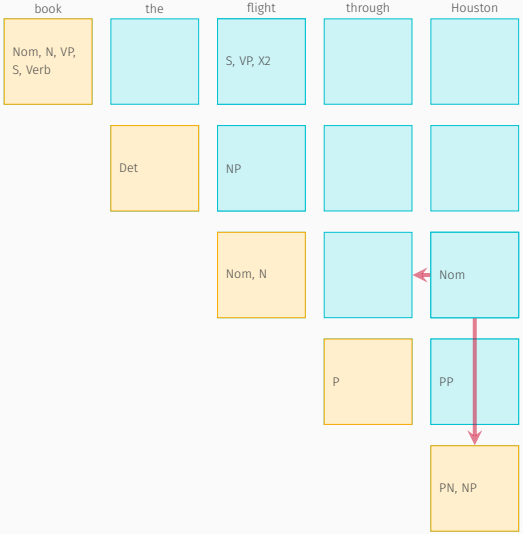

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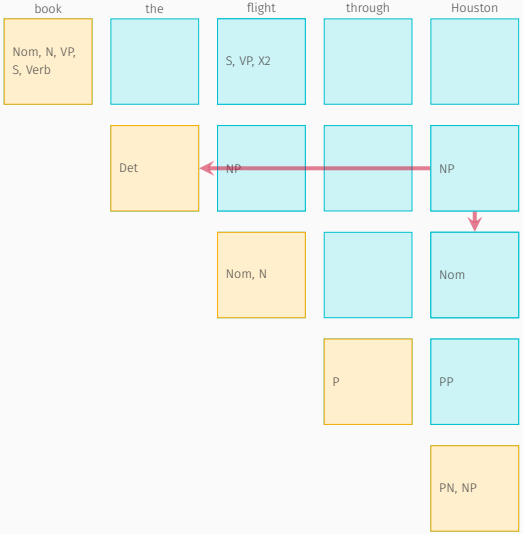

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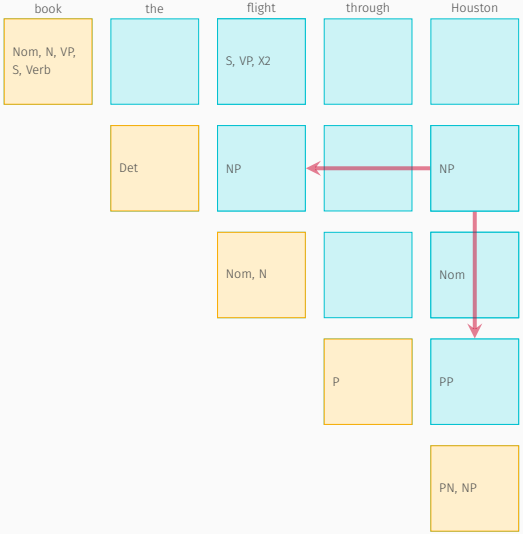

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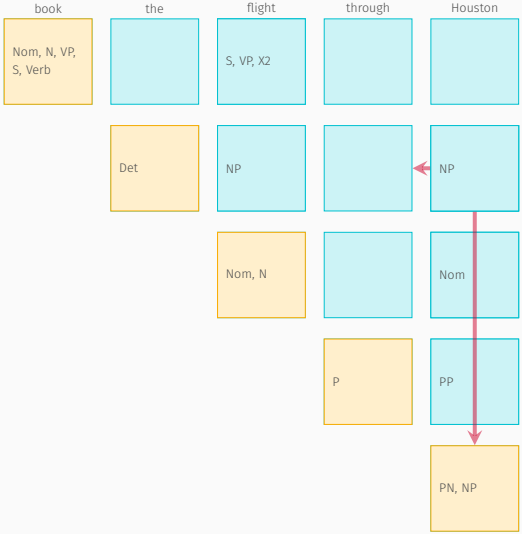

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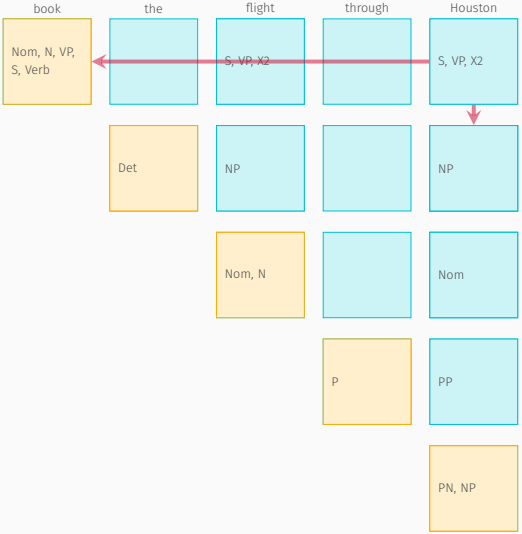
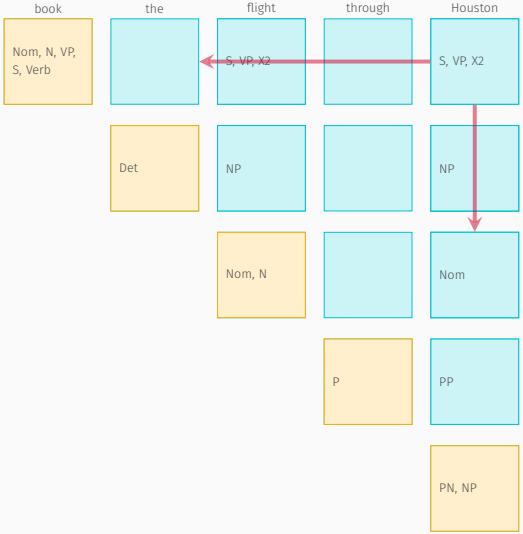
Houston ← PropN



Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
book ← Nom
book ← S
book ← V
book ← VP
I ← NP
I ← Pro
flight ← Nom
flight ← N
include ← S
include ← VP
me ← NP
meal ← Nom
money ← Nom
prefer ← S
prefer ← S
she ← NP
to ← P
the ← Det
TWA ← NP
Houston ← NP
Houston ← PropN



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VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
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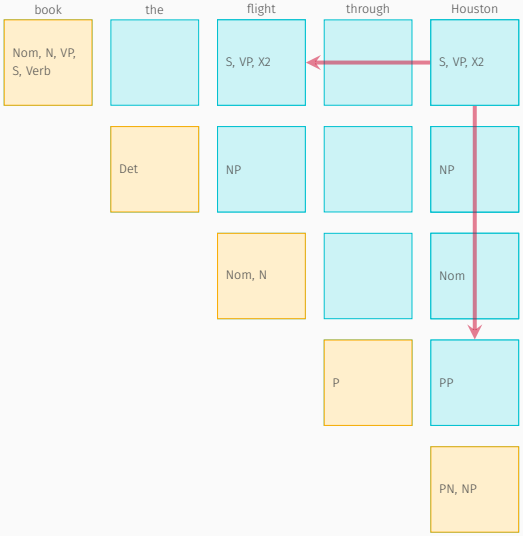

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VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
book ← Nom
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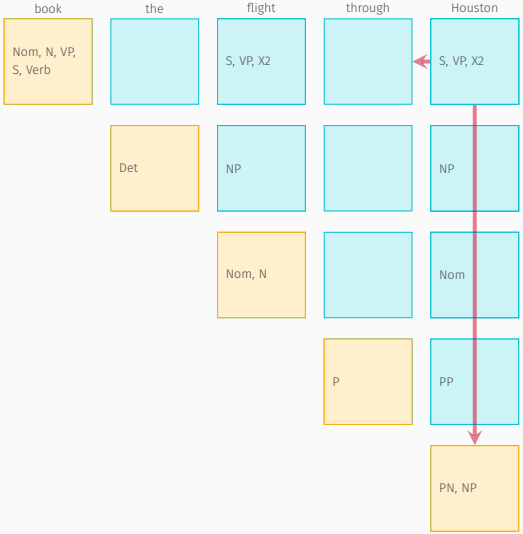

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VP PP ← VP
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X2 PP ← S
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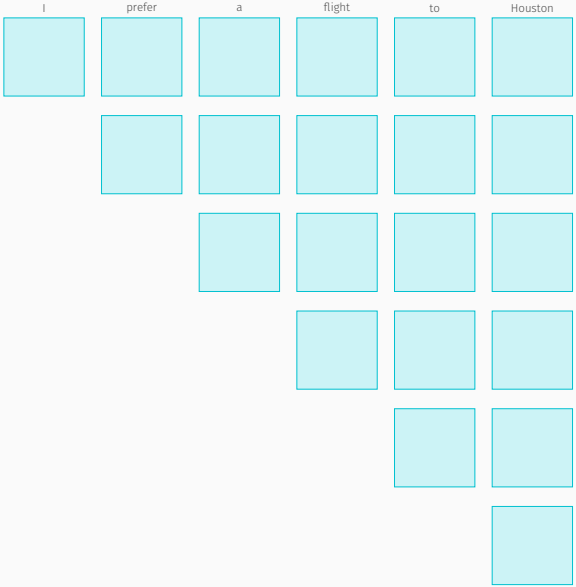
Now It’s Your Turn



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Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
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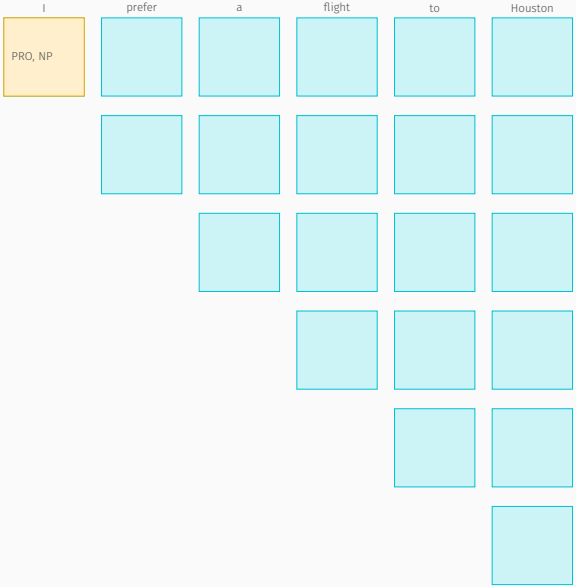

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Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
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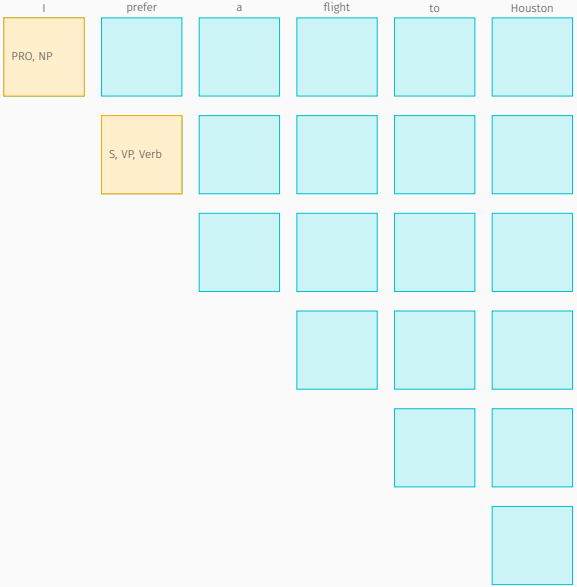

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Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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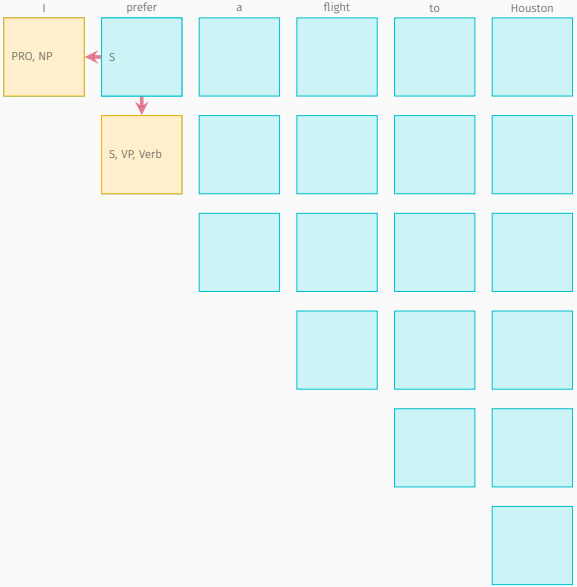

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Verb NP ← VP
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Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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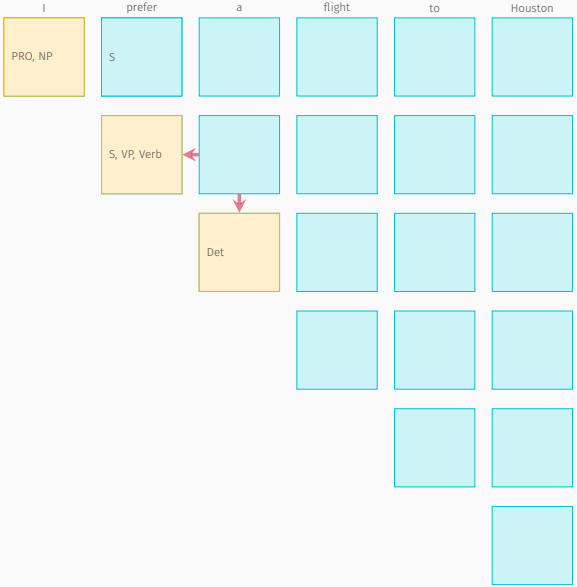

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Verb PP ← VP
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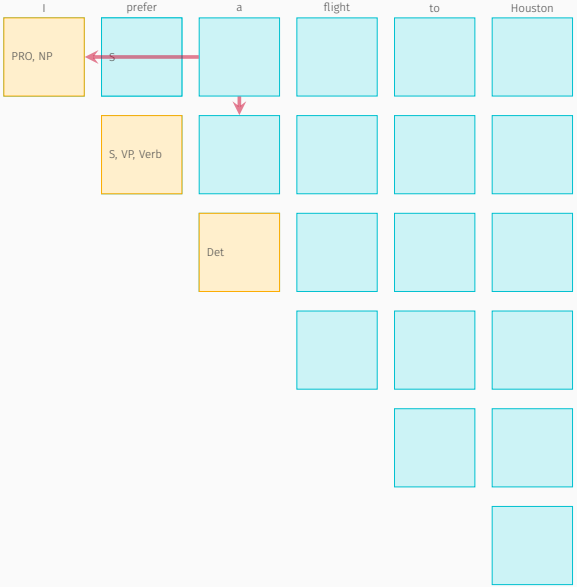

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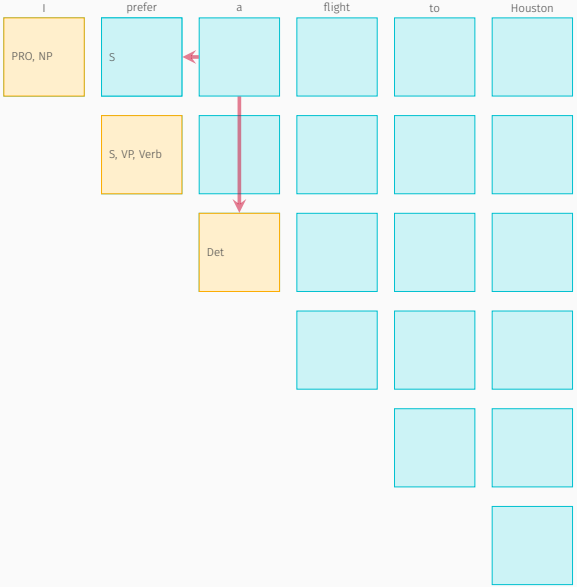

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Verb PP ← VP
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X1 VP ← S
X2 PP ← S
X2 PP ← VP

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Aux NP ← X1
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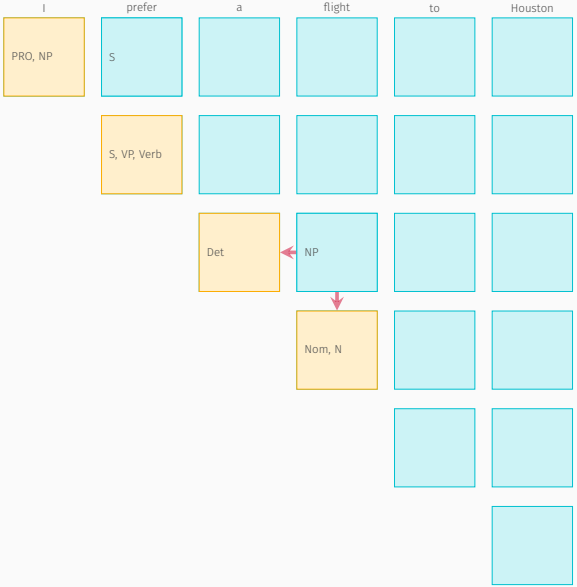

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Verb PP ← S
Verb PP ← VP
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X1 VP ← S
X2 PP ← S
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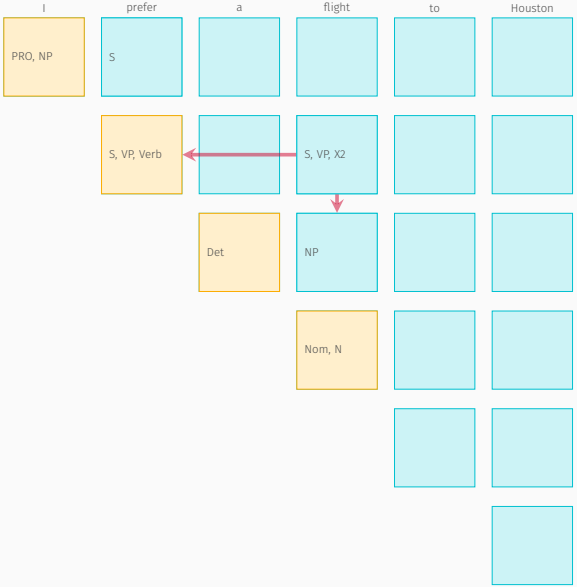

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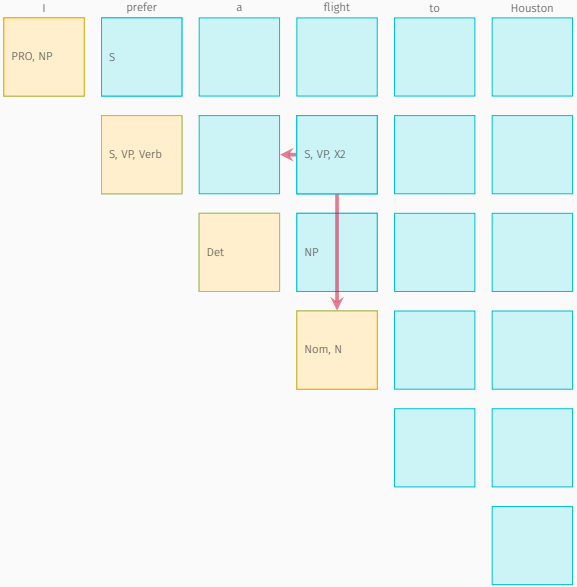

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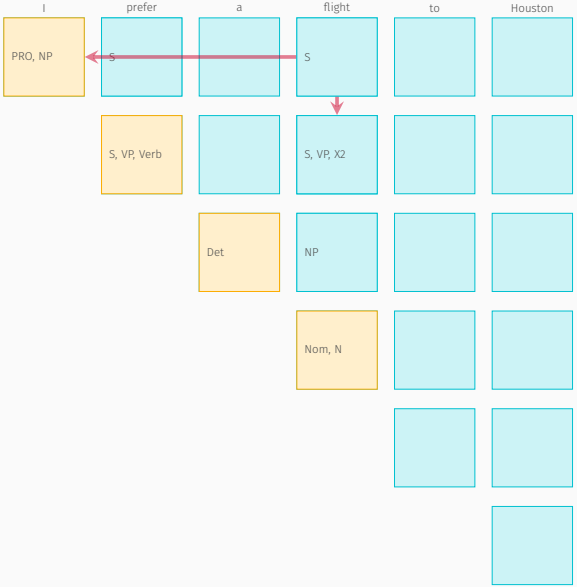

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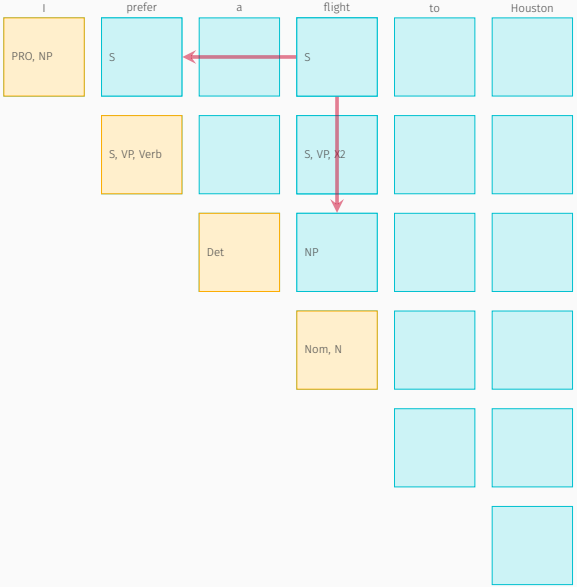

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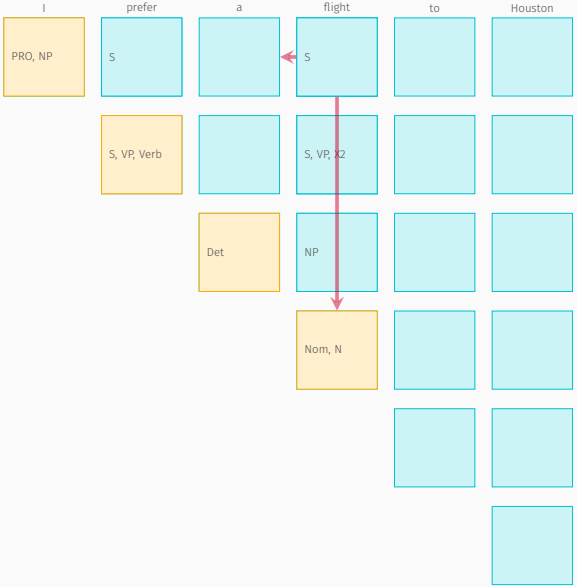

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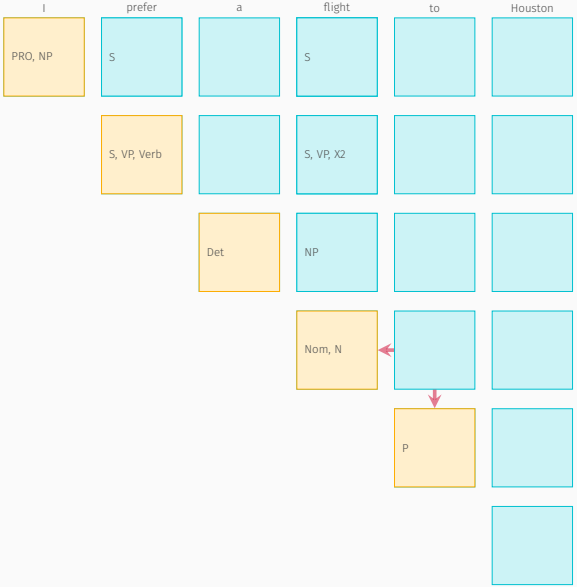

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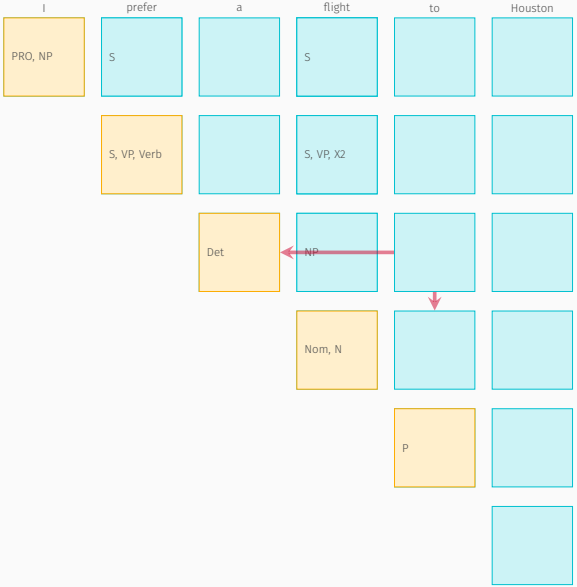

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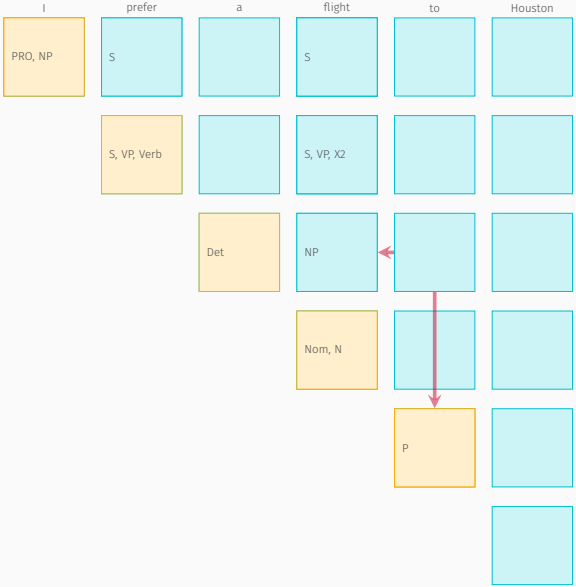
Houston ← NP
Houston ← PropN



Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
book ← Nom
book ← S
book ← V
book ← VP
I ← NP
I ← Pro
flight ← Nom
flight ← N
include ← S
include ← VP
me ← NP
meal ← Nom
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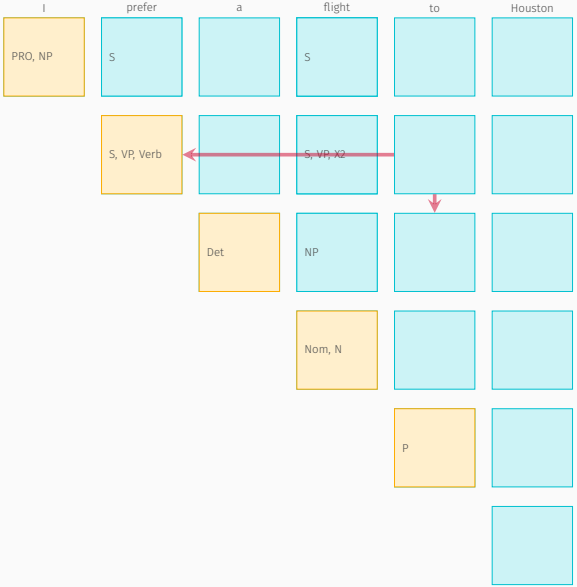
prefer ← S
prefer ← S
she ← NP
to ← P
the ← Det
TWA ← NP
Houston ← NP
Houston ← PropN



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X2 PP ← VP

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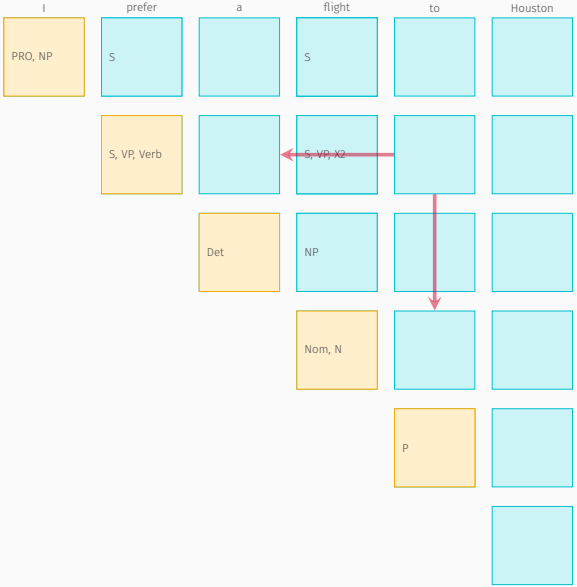

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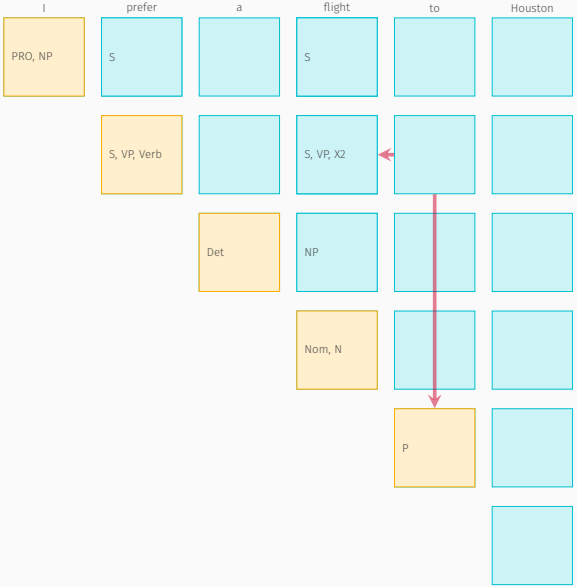

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VP PP ← VP
X1 VP ← S
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X2 PP ← VP

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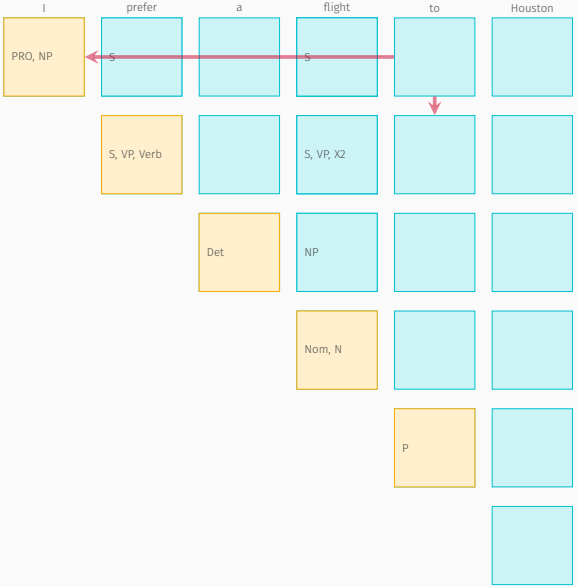

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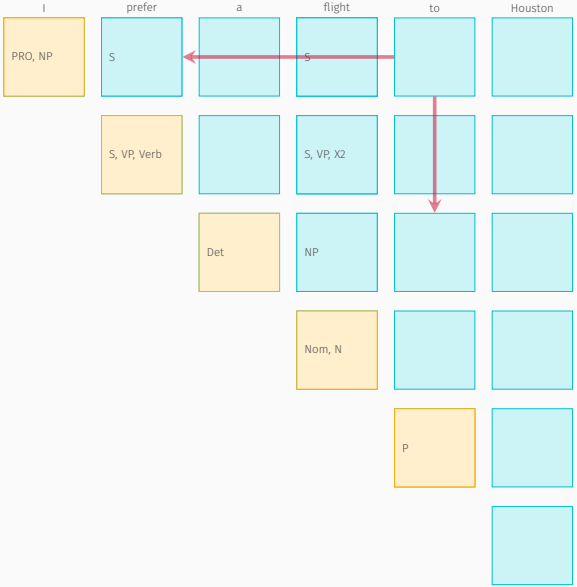

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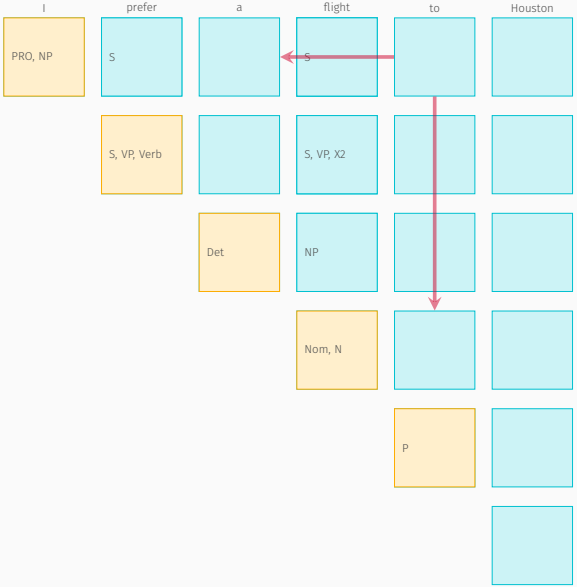

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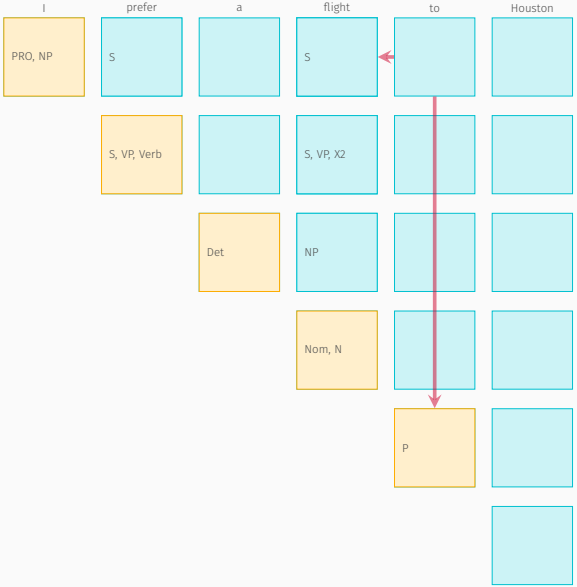

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VP PP ← VP
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Verb NP ← VP
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Verb PP ← S
Verb PP ← VP
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X2 PP ← S
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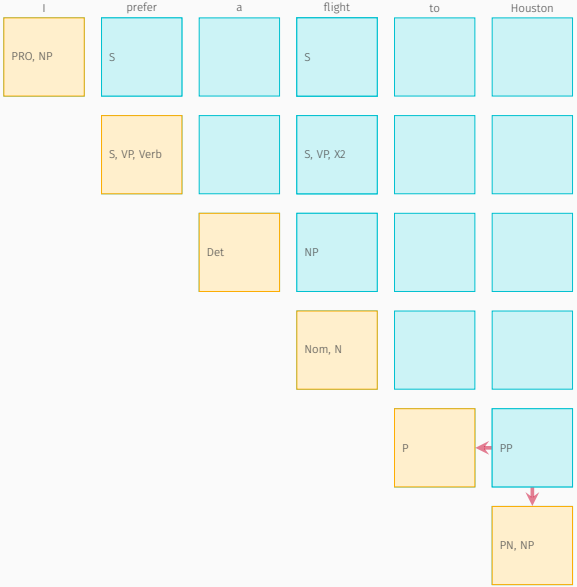

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Verb PP ← VP
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X1 VP ← S
X2 PP ← S
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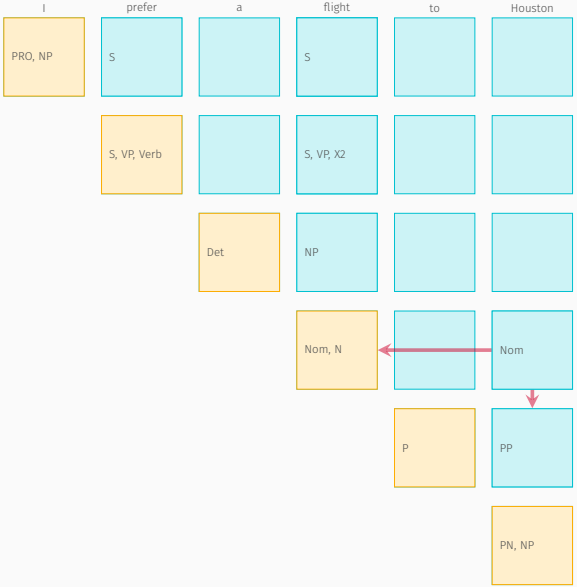

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VP PP ← VP
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X2 PP ← S
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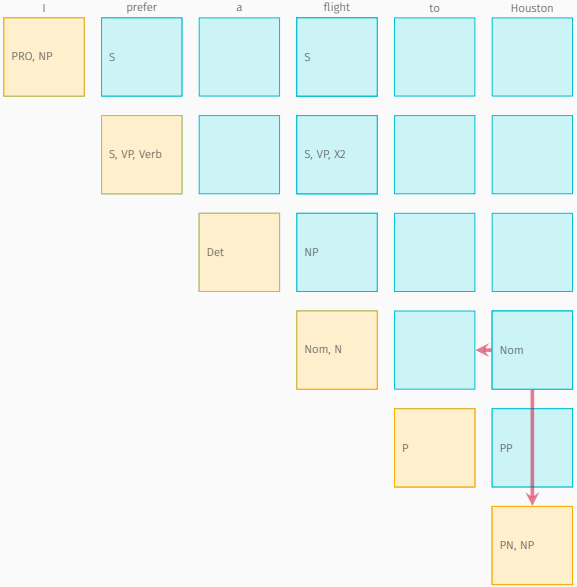

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Verb PP ← VP
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VP PP ← VP
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X2 PP ← S
X2 PP ← VP

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flight ← N
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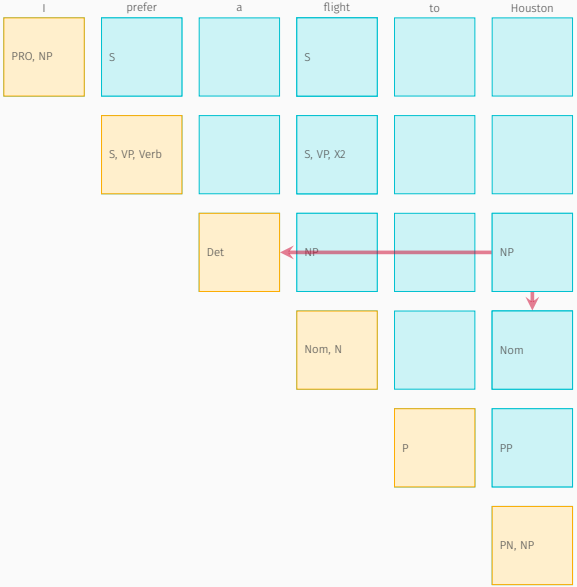

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Verb PP ← VP
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X2 PP ← S
X2 PP ← VP

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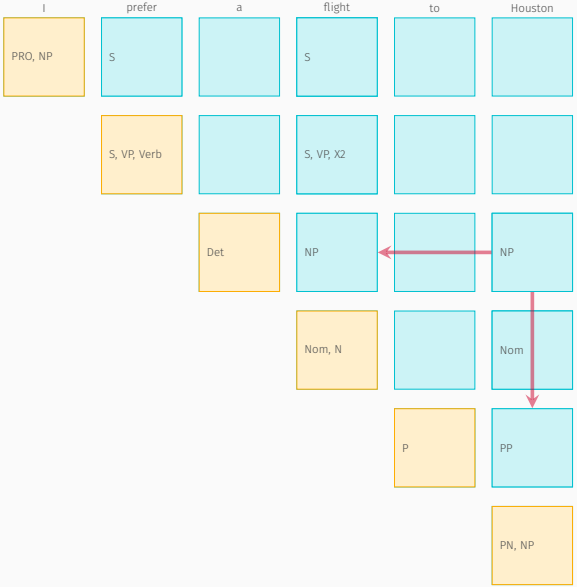

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X2 PP ← S
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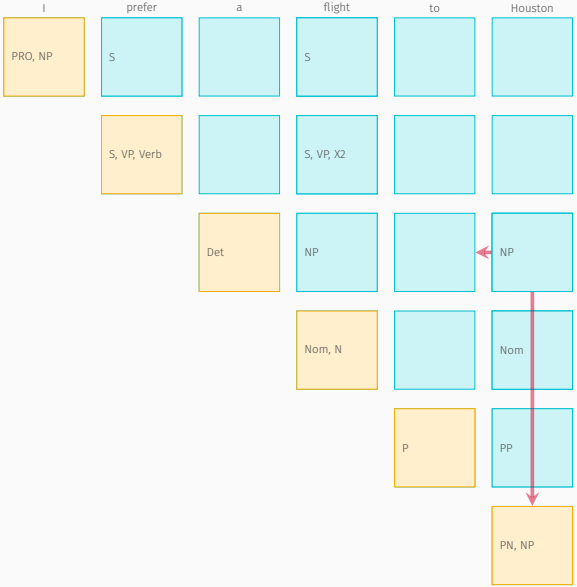

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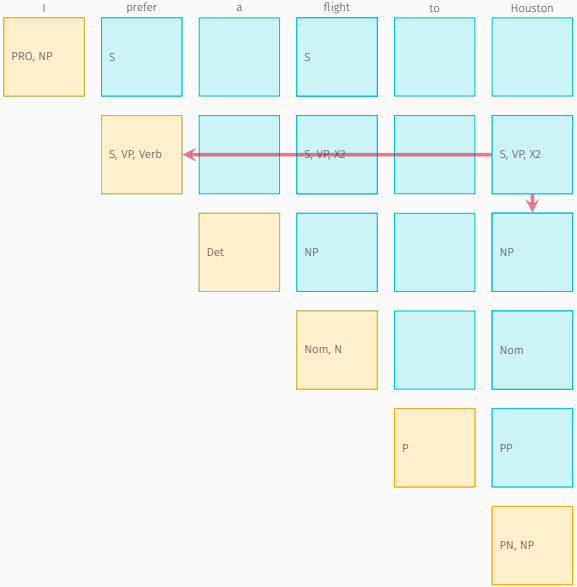

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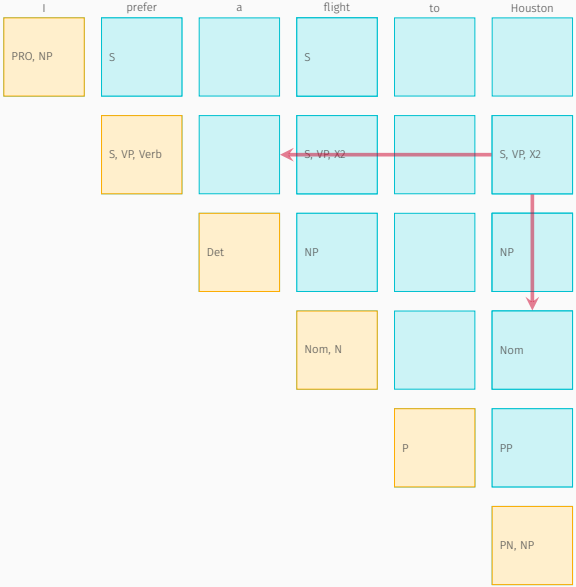

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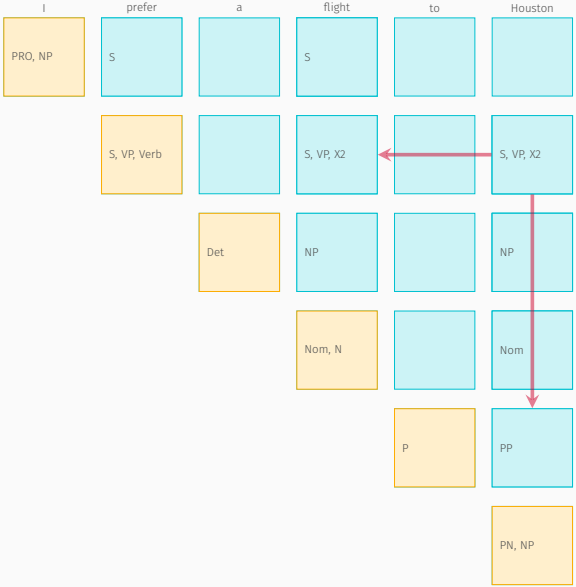

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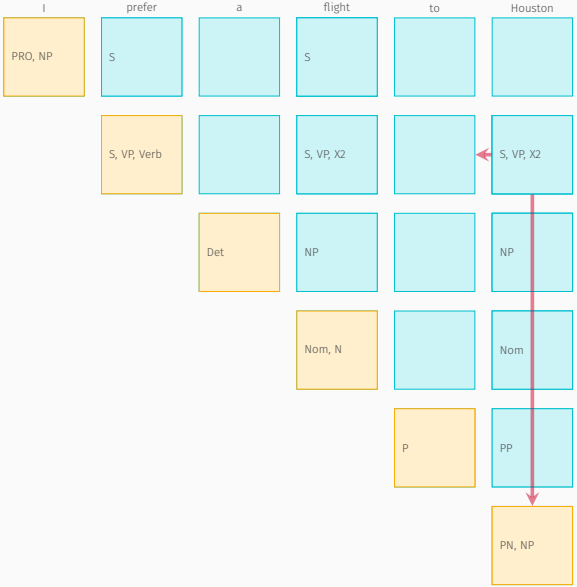

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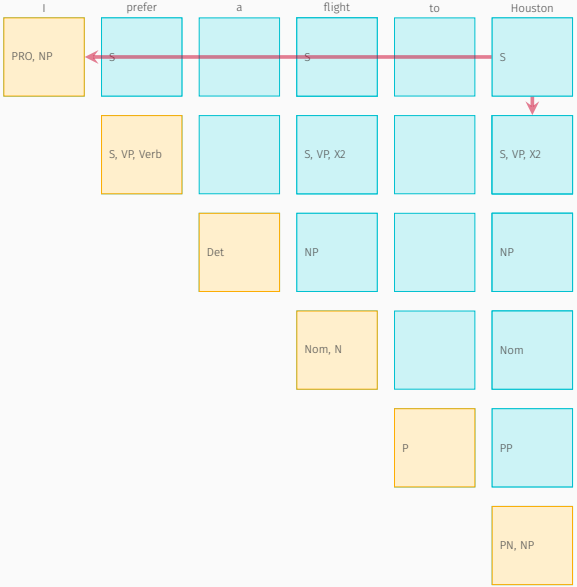

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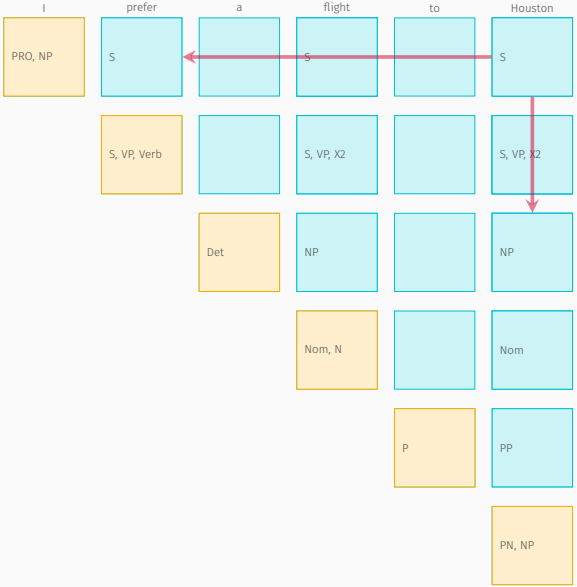

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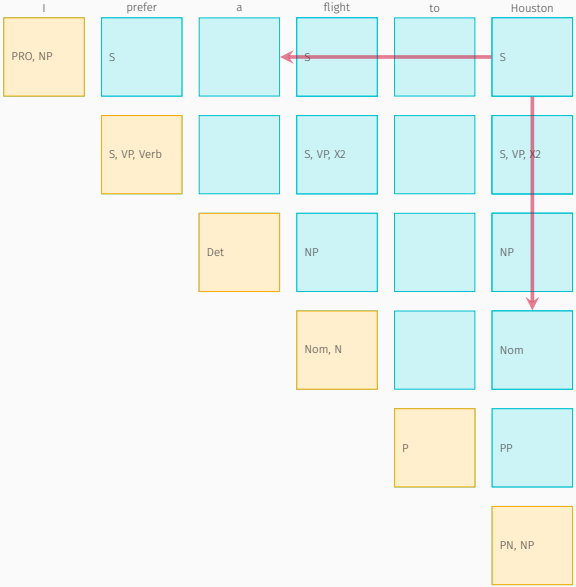

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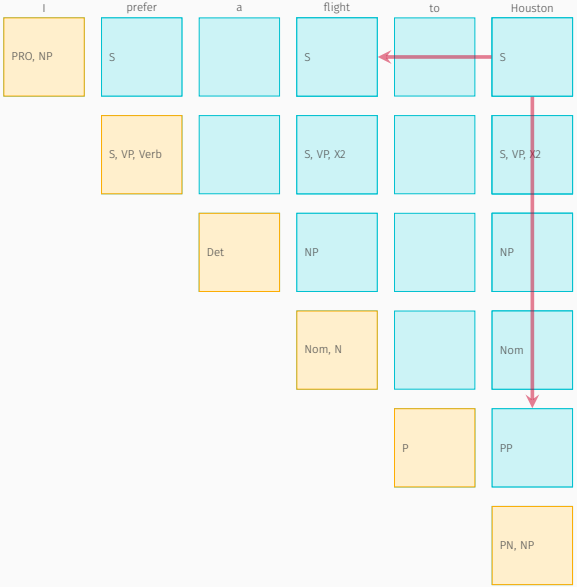
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

book ← N
book ← Nom
book ← S
book ← V
book ← VP
I ← NP
I ← Pro
flight ← Nom
flight ← N
include ← S
include ← VP
me ← NP
meal ← Nom
money ← Nom
prefer ← S
prefer ← S
she ← NP
to ← P
the ← Det
TWA ← NP
Houston ← NP
Houston ← PropN



Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
Verb NP ← S
Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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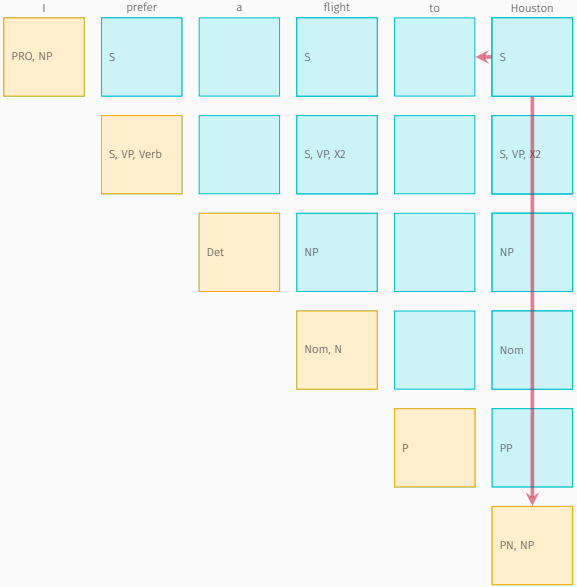

Aux NP ← X1
Det Nom ← NP
Nom N ← Nom
Nom PP ← Nom
NP VP ← S
P NP ← PP
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Verb NP ← VP
Verb NP ← X2
Verb PP ← S
Verb PP ← VP
VP PP ← S
VP PP ← VP
X1 VP ← S
X2 PP ← S
X2 PP ← VP

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prefer ← S
prefer ← S
she ← NP
to ← P
the ← Det
TWA ← NP
Houston ← NP
Houston ← PropN

Questions?