Computational Semantics

LING 571 — Deep Processing for NLP

October 27th, 2018

UNIVERSITY OF WASHINGTON

PROFESSIONAL MASTER'S IN COMPUTATIONAL LINGUISTICS

Recap:
Model Theoretic Semantics

The Model

- A "model" represents a particular state of the world
- Our language has **logical** and **non-logical** elements.
  - **Logical:** Symbols, operators, quantifiers, etc
  - **Non-Logical**: Names, properties, relations, etc

Denotation

- Every **non-logical** element points to a fixed part of the model
- **Objects** — elements in the domain
  - *John, Farah, fire engine, dog, stop sign*
- **Properties** — sets of elements
  - ***red**: {fire hydrant, apple,…}*
- **Relations** — *sets of tuples of elements*
  - ***CapitalCity**:* {(*Washington, Olympia*), (*Yamoussokro, Cote d'Ivoire*), (*Ulaanbaatar, Mongolia*),…}

Sample Domain $\mathcal{D}$

via J&M, p. 554

Objects

	Matthew, Franco, Katie, Caroline	a,b,c,d
	Frasca, Med, Rio	e,f,g
	Italian, Mexican, Eclectic	h,i,j

Properties

Noisy	Frasca, Med, and Rio are noisy	$\textit{Noisy}=\{e,f,g\}$

Relations

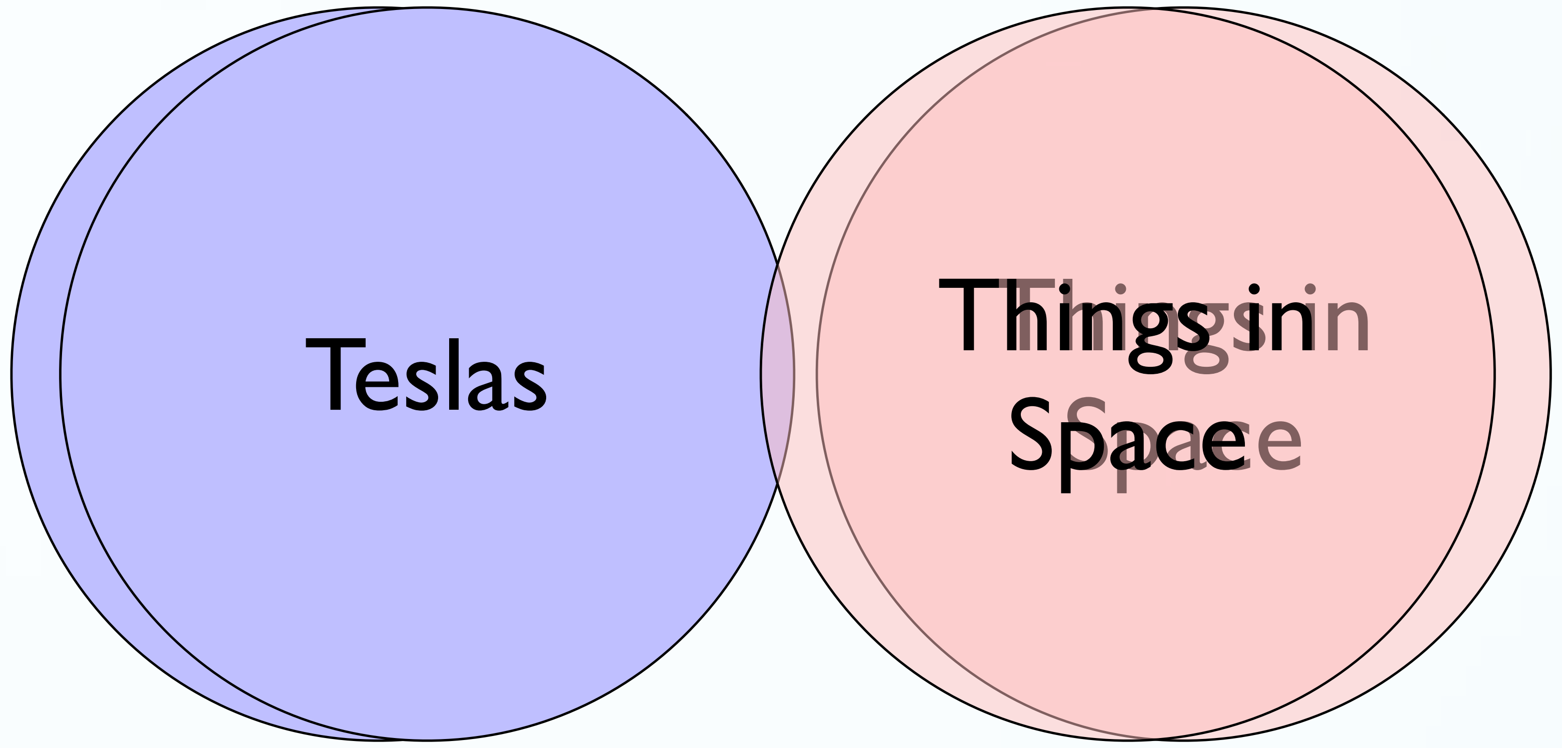
Likes	Matthew likes the Med Katie likes the Med and Rio Franco likes Frasca Caroline likes the Med and Rio	$\textit{Likes}=\{\langle a,f\rangle,\langle c,f\rangle, \langle c,g\rangle, \langle b,e\rangle, \langle d,f\rangle, \langle d,g\rangle\}$
Serves	Med serves eclectic Rio serves Mexican Frasca serves Italian	$\textit{Serves}=\{\langle c,f\rangle, \langle f,i\rangle, \langle e,h\rangle\}$

Today:

- More on the rule-to-rule hypothesis
  - More λ-calculus

State of known Universe: 2/6/2018

Ambiguity & Models



- *"Every Tesla is powered by a battery."* — Ambiguous!
  - $\forall x. Tesla(x) \Rightarrow (\exists(y). Battery(y) \wedge Powers(y, x))$
  - $\exists(y). Battery(y) \Rightarrow (\forall x. Tesla(x) \wedge Powers(y, x))$

- Every Tesla is not hurtling toward Mars.
  - ~~$\forall x. Tesla(x) \Rightarrow (HurtlingTowardMars(x))$~~
  - $\neg\forall \mathrm{x}.(Tesla(x) \Rightarrow (HurtlingTowardMars(x)))$

$\exists(\boldsymbol{x}). Tesla(\boldsymbol{x}) \wedge HurtlingTowardsMars(\boldsymbol{x}))$

Scope Ambiguity

- Potentially $O(n!)$ scope interpretations ("scopings")
  - Where n=number of quantifiers.
    - (*every*, *a*, *all*, *no*)

Chiasmus:
Syntax affects Semantics!

Bowie playing Tesla

The Prestige (2006)

Tesla playing Bowie

SpaceX Falcon Heavy Test Launch (2/6/2018)

Chiasmus: Syntax affects Semantics!

- "Never let a fool kiss you or a kiss fool you" (Grothe, 2002)

- *"Then you should say what you mean," the March Hare went on.*

  "I do," Alice hastily replied; "at least—at least I mean what I say—that's the same thing, you know."

  "Not the same thing a bit!" said the Hatter. "Why, you might just as well say that 'I see what I eat' is the same thing as 'I eat what I see'!"

  "You might just as well say," added the March Hare, "that 'I like what I get' is the same thing as 'I get what I like'!"

  "You might just as well say," added the Dormouse, which seemed to be talking in his sleep, "that 'I breathe when I sleep' is the same thing as 'I sleep when I breathe'!"

  —*Alice in Wonderland*, Lewis Carrol

Recap:
Rule-to-Rule Model

Recap

- **Meaning Representation**
  - Can represent meaning in natural language in many ways
  - We are focusing on First-Order Logic (FOL)
- **Principle of compositionality**
  - The meaning of a complex expression is a function of the meaning of its parts
- **Lambda Calculus** and the **Rule-to-Rule Hypothesis**
  - λ-expressions can be attached to grammar rules
  - used to compute meaning representations from syntactic trees based on the principle of compositionality

Integrating Semantics into Syntax

1. Pipeline System

- Feed parse tree and sentence to semantic analyzer
- How do we know which pieces of the semantics link to which part of the analysis?
- Need detailed information about sentence, parse tree
- Infinitely many sentences & parse trees
- Semantic mapping function per parse tree → intractable

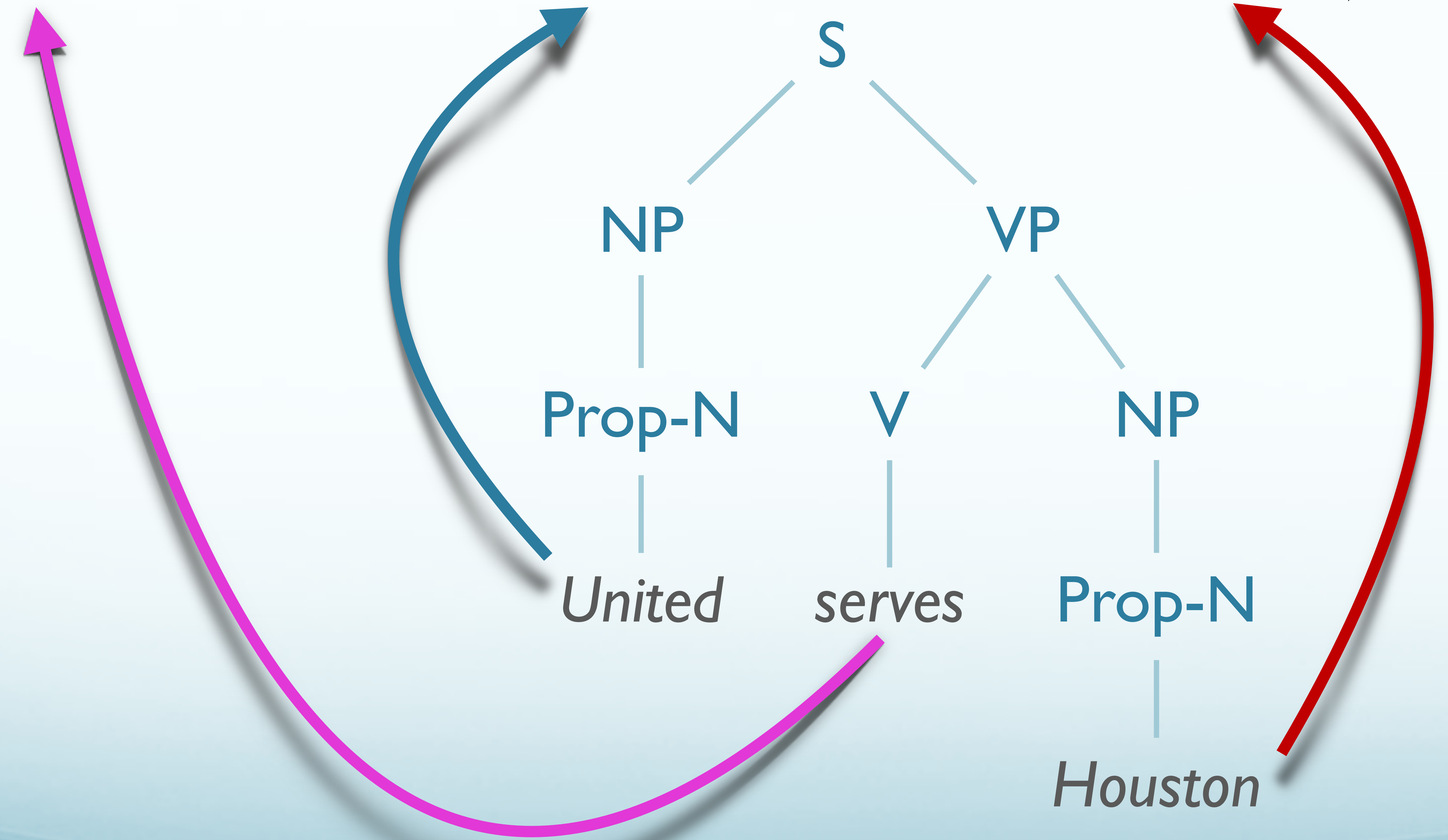
Integrating Semantics into Syntax

2. Integrate Directly into Grammar
   - This is the "rule-to-rule" approach we've been examining
   - Tie semantics to finite components of grammar (rules & lexicon)
   - Augment grammar rules with semantic info
     - a.k.a. "attachments" — specify how RHS elements compose to LHS

Simple Example

- *United serves Houston*

$$\exists e\big(Serving(e) \wedge Server(e, United) \wedge Served(e, Houston)\big)$$



Semantic Attachments

- Basic Structure:

$$A \rightarrow a_1, \; \ldots, \; a_n \; \{f(a_j.\text{sem}, \; \ldots \; a_k.\text{sem})\}$$

Semantic Function

- In NLTK syntax:

```
A → a₁ … aₙ[SEM=<f(?aⱼ.sem …)>]
```

Attachments as SQL!

[NLTK book, ch. 10]

```
>>> nltk.data.show_cfg('grammars/book_grammars/sql0.fcfg')
% start S
S[SEM=(?np + WHERE + ?vp)] -> NP[SEM=?np] VP[SEM=?vp]
VP[SEM=(?v + ?pp)] -> IV[SEM=?v] PP[SEM=?pp]
VP[SEM=(?v + ?ap)] -> IV[SEM=?v] AP[SEM=?ap]
NP[SEM=(?det + ?n)] -> Det[SEM=?det] N[SEM=?n]
PP[SEM=(?p + ?np)] -> P[SEM=?p] NP[SEM=?np]
AP[SEM=?pp] -> A[SEM=?a] PP[SEM=?pp]
NP[SEM='Country="greece"'] -> 'Greece'
NP[SEM='Country="china"'] -> 'China'
Det[SEM='SELECT'] -> 'Which' | 'What'
N[SEM='City FROM city_table'] -> 'cities'
IV[SEM=''] -> 'are'
A[SEM=''] -> 'located'
P[SEM=''] -> 'in'
```

'What cities are located in China'

```
parses[0]: SELECT City FROM city_table WHERE Country="china"
```

Semantic Attachments: Options

- Why not use SQL? Python?
  - Arbitrary power but hard to map to logical form
  - No obvious relation between syntactic, semantic elements

- Why Lambda Calculus?
  - First Order Predicate Calculus (FOPC) with function application is
  - Can extend our existing feature-based model, using unification

Semantic Analysis Approach

- Semantic attachments:
  - Each CFG production gets semantic attachment

- Semantics of a phrase is function of combining the children
  - Complex functions need to have parameters
  - $Verb \rightarrow \text{`arrived'}$
    - Intransitive verb, so has one argument: ***subject***
    - …but we don't have this available at the preterminal level of the tree!

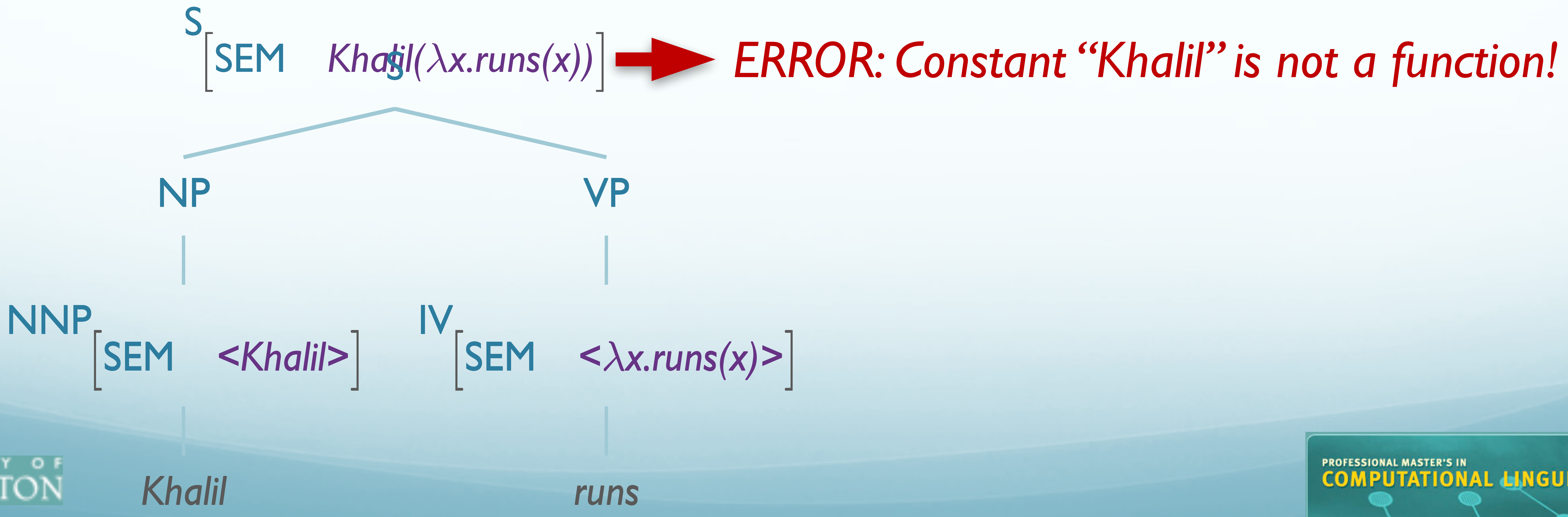
Defining Representations

- Proper Nouns
- Intransitive Verbs
- Transitive Verbs
- Quantifiers

Proper Nouns & Intransitive Verbs

- Our instinct for names is to just use the constant:
  - `NNP[SEM=<Khalil>] → 'Khalil'`
- However, we want to apply our λ-closures left-to-right consistently.

```
S[SEM=np?(vp?)] → NP[SEM=np?] VP[SEM=vp?]
```



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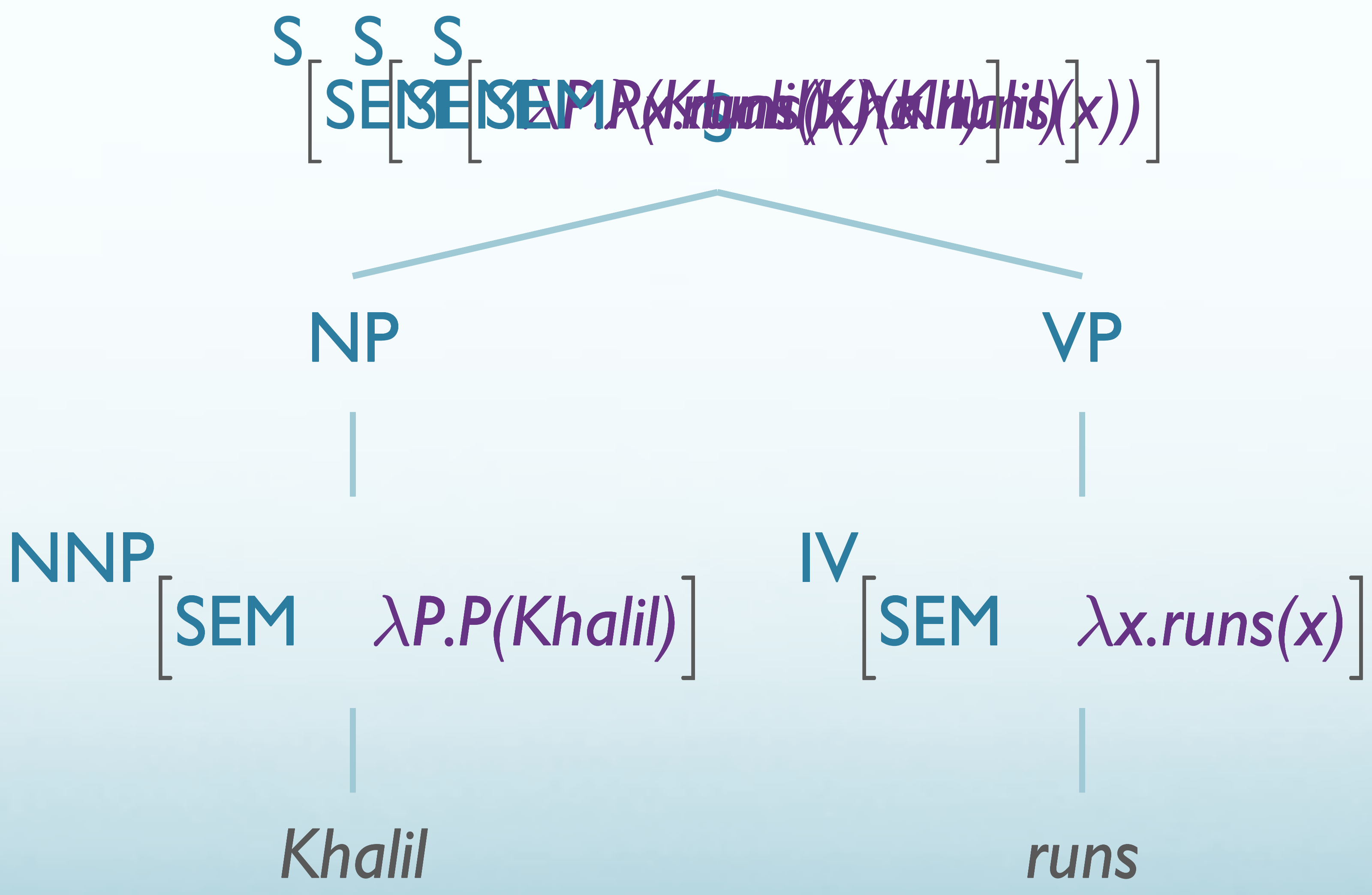
Proper Nouns & Intransitive Verbs

- Instead, we use a ***dummy predicate***:
  - $\lambda Q.Q(Khalil)$

Proper Nouns & Intransitive Verbs

- With the dummy predicate:
  - `NNP[SEM=<\P.P(Khalil)>] → 'Khalil'`

`S[SEM=np?(vp?)] → NP[SEM=np?] VP[SEM=vp?]`



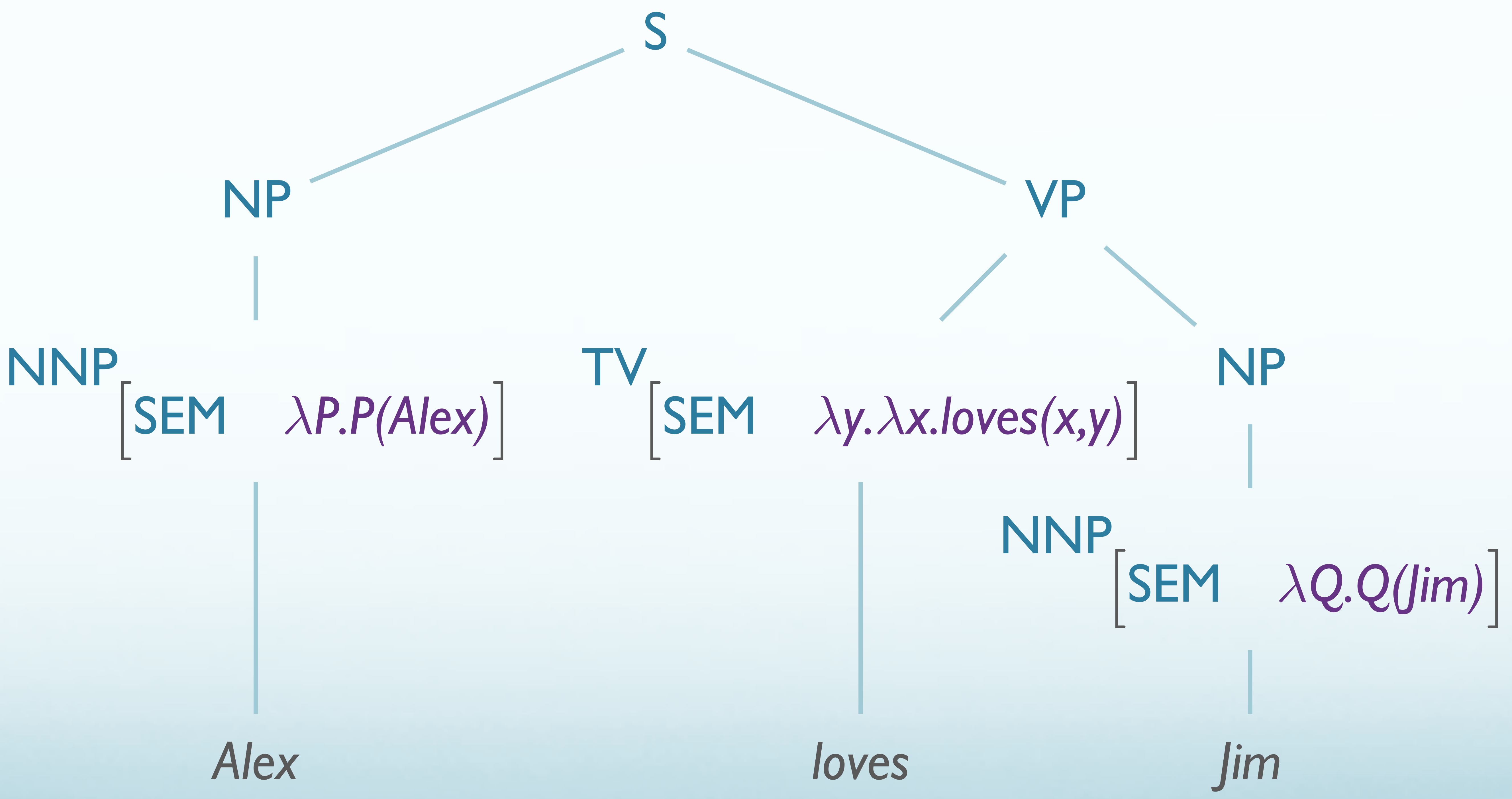
Transitive Verbs

Transitive Verbs

- So, if we want to say "*Alex loves Jim*" we would want `λy.λx.loves(x,y)`
- …but going in linear order, we have one arg to the left and one to the right.
- So, instead:
  - `λX y.X(λx.loves(x,y))`

Transitive Verbs

- So, if we want to say "*Alex loves Jim*" we would want `λy.λx.loves(x,y)`
- …but going in linear order, we have one arg to the left and one to the right.

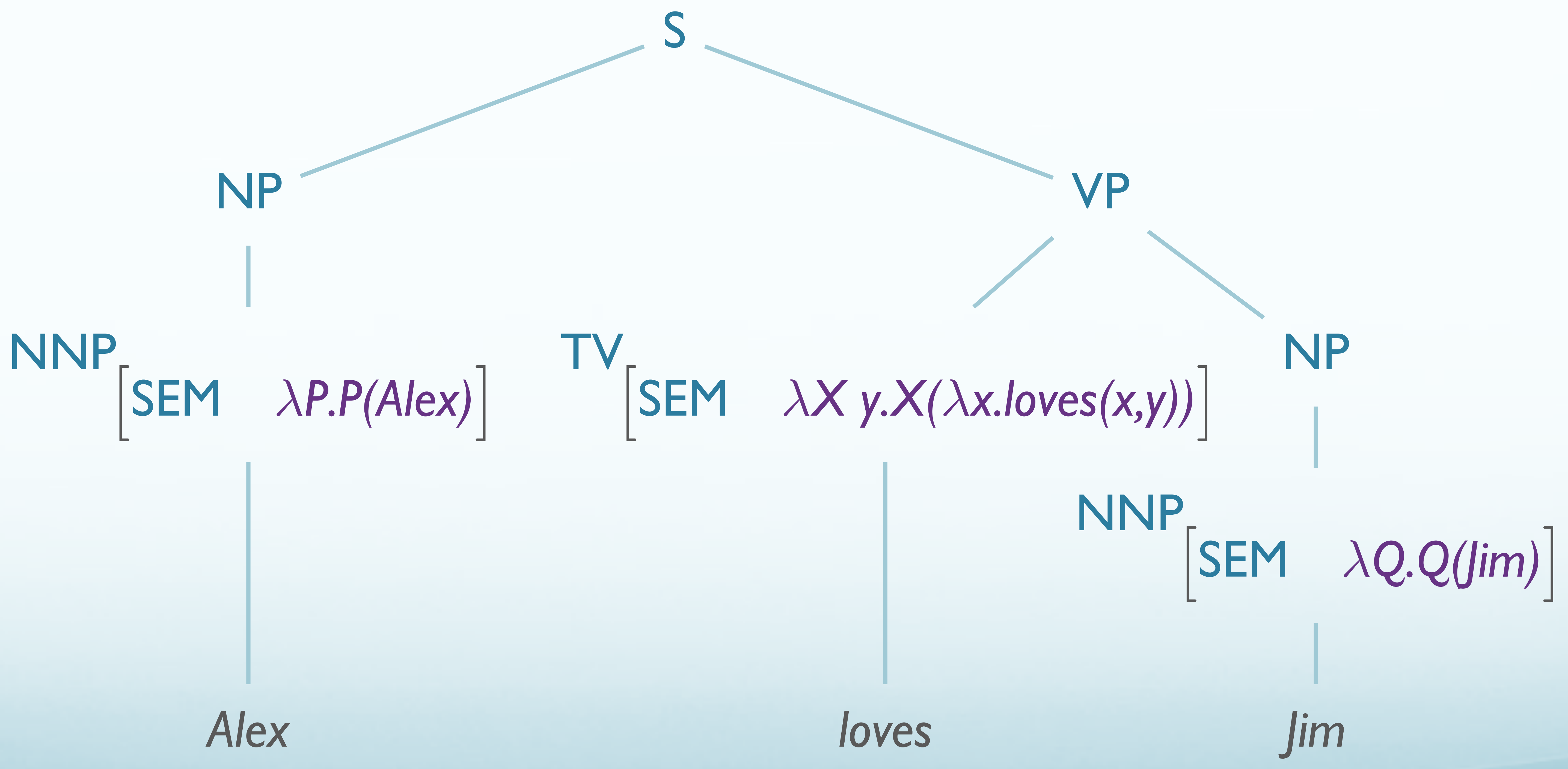


Transitive Verbs

- TV(NP):
  - `λy.λx.loves(x,y) (λQ.Q(Alex))`
  - `λx.loves(x,λQ.Q(Alex))`
    - ➜ ***Error!*** We can't reduce Alex.

Transitive Verbs

- Instead: $\lambda X\ y.X(\lambda x.\text{loves}(x,y))$



Transitive Verbs

- TV(NP):
  - λX y.X(λx.loves(x,y)) (λQ.Q(Jim))
  - λy.(λQ.Q(Jim)(λx.loves(x,y))
  - λy.(λx.loves(x,y)(Jim))
  - λy.(loves(Jim,y))

λX takes (λQ.Q(Jim))

λQ takes (λx.loves(x,y))

λx takes (Jim)

- NP(VP):
  - λP.P(Alex)(λy.(loves(Jim,y))
  - λy.(loves(Jim,y)(Alex)
  - loves(Jim,Alex)

λP takes (λy.(loves(Jim,y))

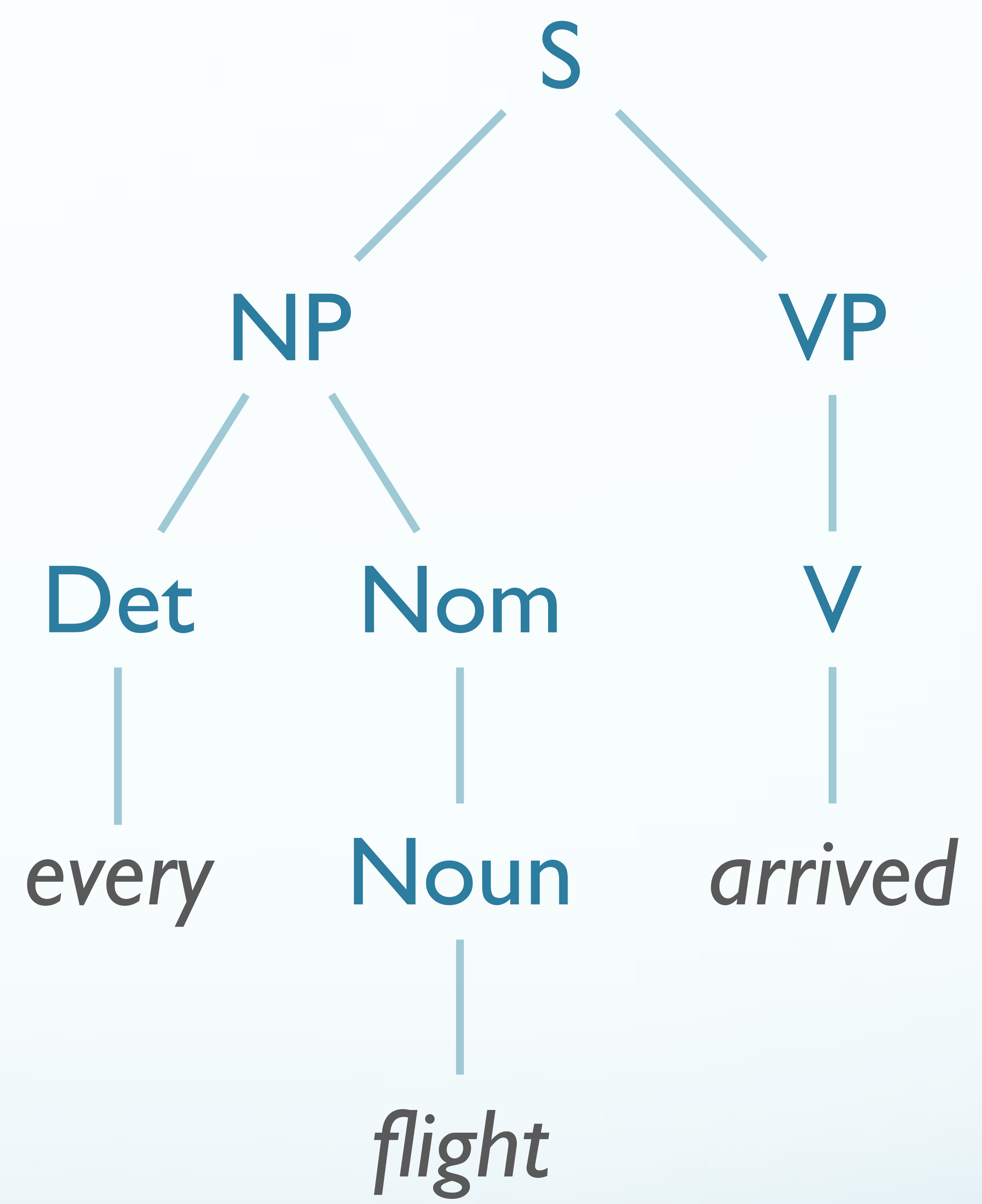
λy takes (Alex)

Converting to an Event

- "y loves x," Originally:
  - $\lambda X\ y.X(\lambda x.loves(x,y))$
- as a Neo-Davidsonian event:
  - $\lambda X\ y.X(\lambda x.\exists e\ love(e) \wedge lover(e,y) \wedge loved(e,x))$

Semantic Analysis Example

- Basic model
  - Neo-Davidsonian event-style model
  - Complex quantification
- Example: *Every flight arrived*



$$\forall x\ Flight(x) \Rightarrow \exists e\ Arrived(e) \wedge ArrivedThing(e,x)$$

Quantifiers & Scope

“Every flight arrived”

- First intuitive approach:
  - Every flight = $\forall x \; Flight(x)$ ✗
    - “Everything is a flight”
- Instead, we want:
  - $\forall x \; Flight(x) \Rightarrow Q(x)$
    - “if a thing is a flight, then *Q*”
  - Since Q isn't available yet… Dummy predicate!
    - $\lambda Q.\forall x \; Flight(x) \Rightarrow Q(x)$

"*Every flight arrived*"

- "*Every flight*" is:
  - $\lambda Q.\forall x\, Flight(x) \Rightarrow Q(x)$
- …so what is the representation for "*every*"?
  - $\lambda P.\lambda Q.\forall x\, P(x) \Rightarrow Q(x)$

"A flight arrived"

- We just need one item for truth value
  - So, start with ∃x…
  - $\lambda P.\lambda Q.\exists x\ P(x) \wedge Q(x)$

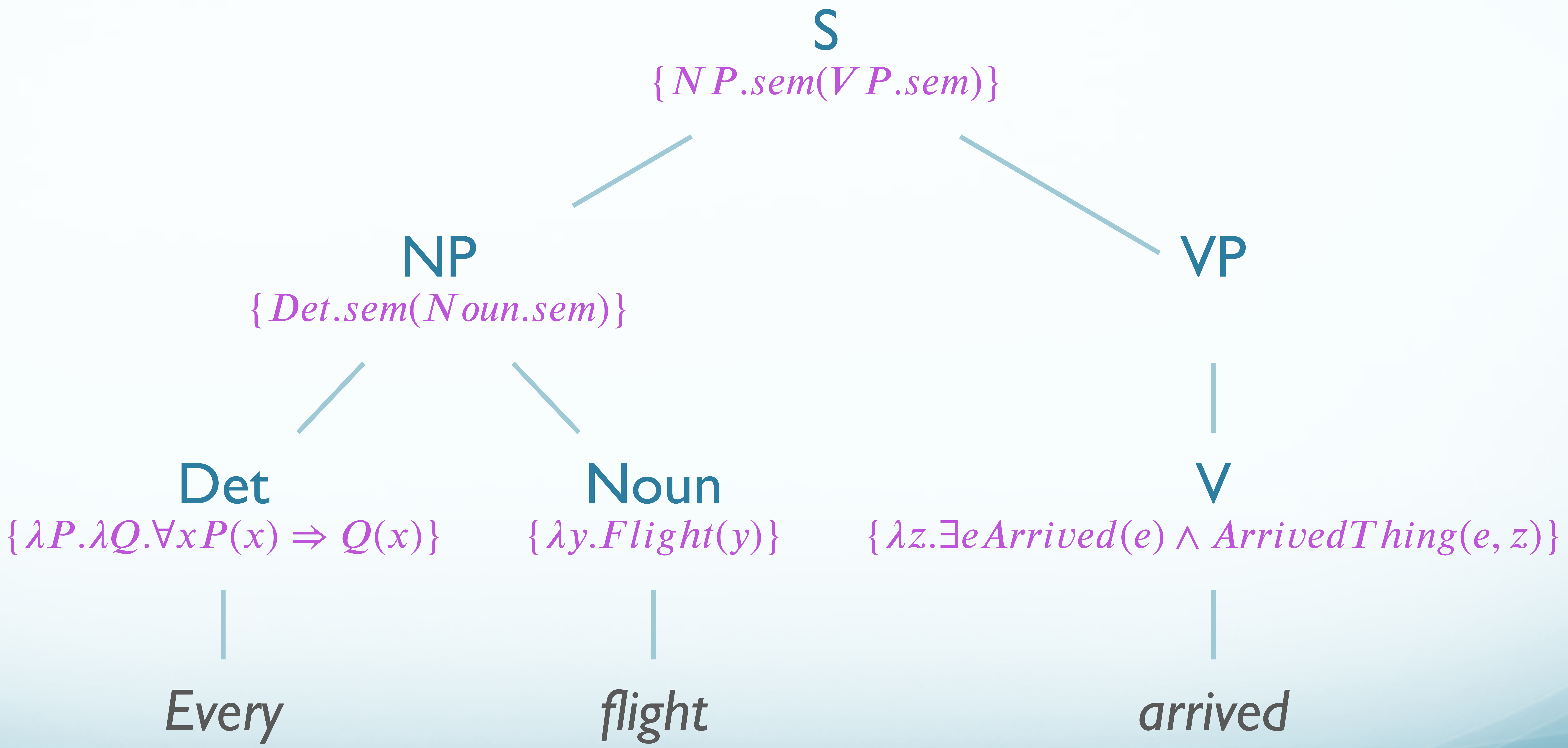
“The flight arrived”

- …yeah, this turns out to be tricky.
- We’ll save it for Wednesday.
- It’s not on the homework.

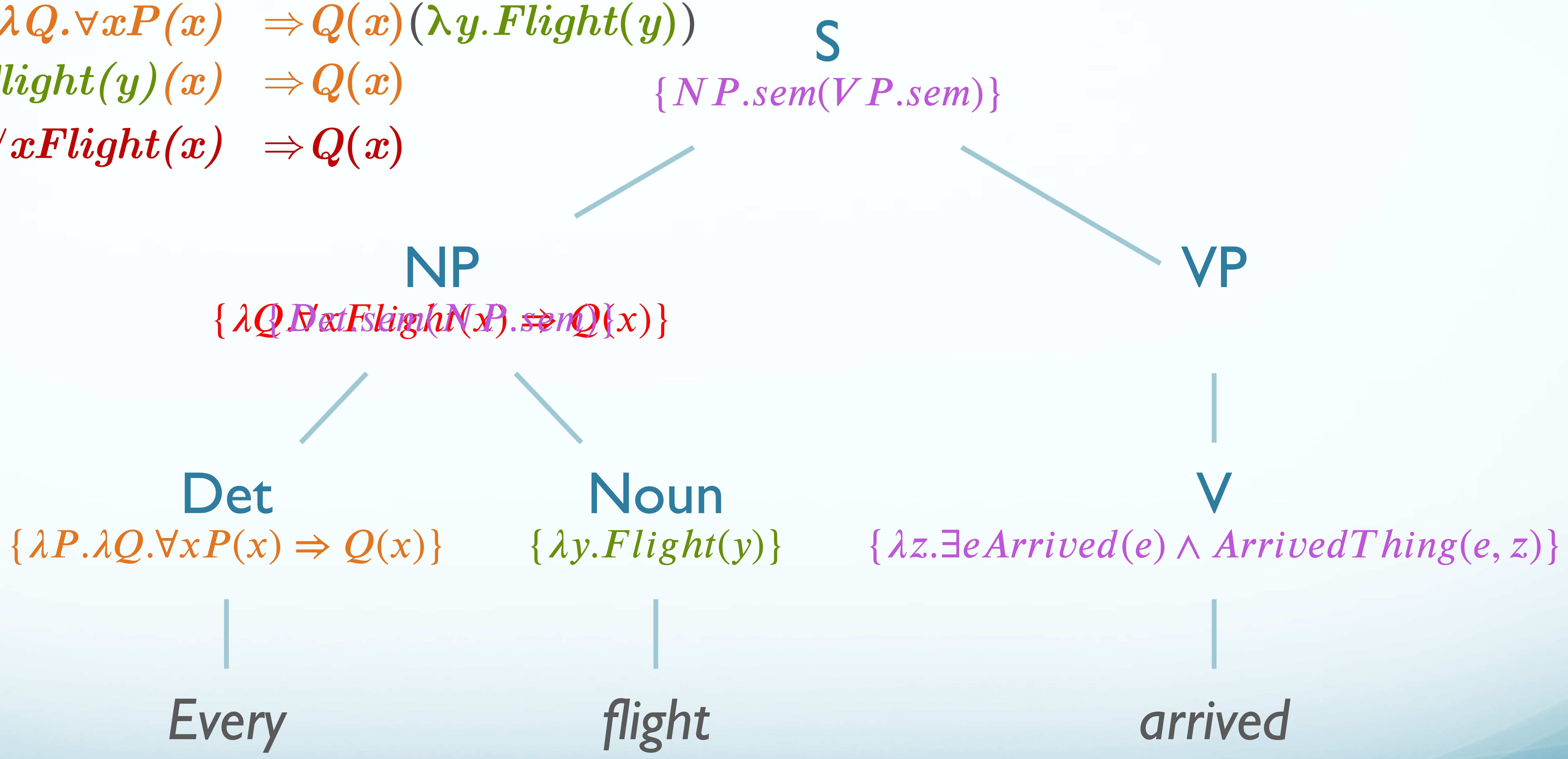
Creating Attachments

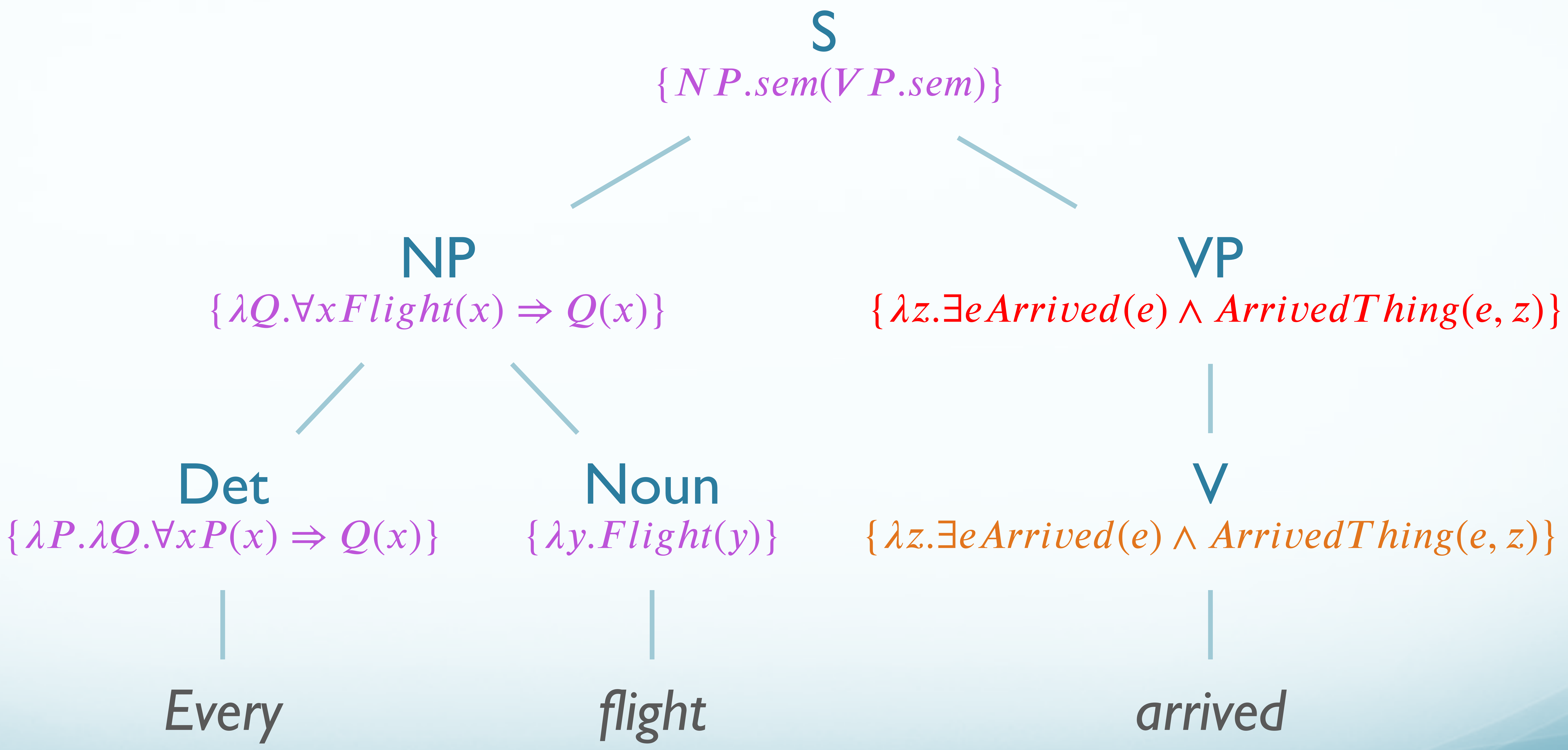
"Every flight arrived"

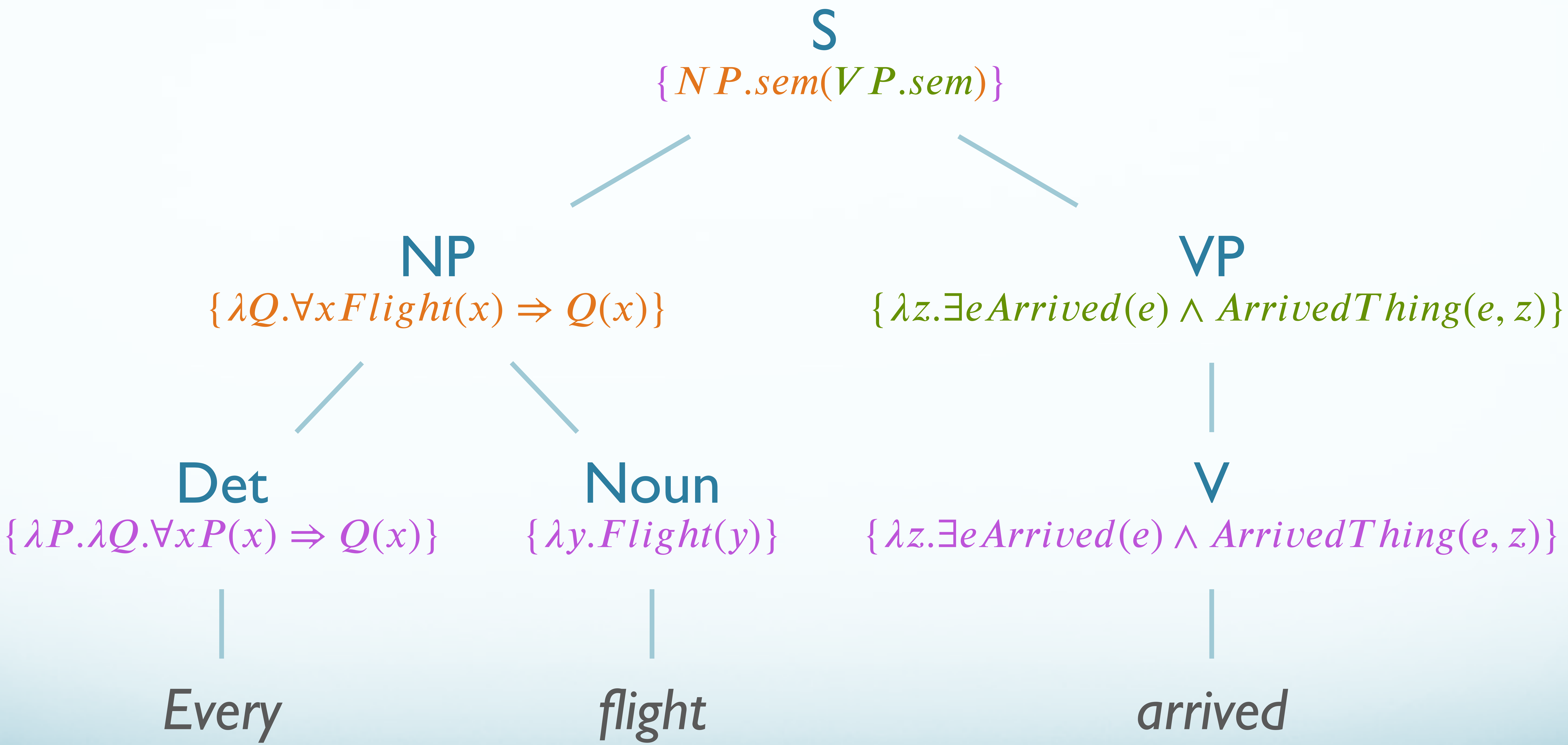
$$
\begin{array}{lll}
Det & \rightarrow \text{`}Every\text{'} & \{\ \lambda P.\lambda Q.\forall \boldsymbol{x}\ P(\boldsymbol{x}) \Rightarrow\ Q(\boldsymbol{x})\ \} \\
Noun & \rightarrow \text{`}flight\text{'} & \{\ \lambda \boldsymbol{x}.Flight(\boldsymbol{x})\ \} \\
Verb & \rightarrow \text{`}arrived\text{'} & \{\lambda \boldsymbol{y}.\exists \boldsymbol{e} Arrived(\boldsymbol{e}) \wedge ArrivedThing(\boldsymbol{e},\ \boldsymbol{y})\} \\
VP & \rightarrow\ Verb & \{\ Verb.sem\ \} \\
Nom & \rightarrow\ Noun & \{\ Noun.sem\ \} \\
S & \rightarrow\ NP\ VP & \{\ NP.sem(VP.sem)\ \} \\
NP & \rightarrow\ Det\ Nom & \{\ Det.sem(Nom.sem)\ \}
\end{array}
$$


S
$\{NP.sem(VP.sem)\}$
NP
$\{Det.sem(Noun.sem)\}$
VP
Det
$\{\lambda P.\lambda Q.\forall x P(x) \Rightarrow Q(x)\}$
Noun
$\{\lambda y.Flight(y)\}$
V
$\{\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e,z)\}$
Every
flight
arrived

$$
\begin{aligned}
NP &\rightarrow Det.sem(NP.sem) \\
\lambda P.\lambda Q.\forall x P(x) &\Rightarrow Q(x)(\lambda y.Flight(y)) \\
\lambda Q.\forall x \lambda y.Flight(y)(x) &\Rightarrow Q(x) \\
\lambda Q.\forall x Flight(x) &\Rightarrow Q(x)
\end{aligned}
$$




S
$\{NP.sem(VP.sem)\}$
NP
$\{\lambda Q.\forall x Flight(x) \Rightarrow Q(x)\}$
VP
$\{\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z)\}$
Det
$\{\lambda P.\lambda Q.\forall x P(x) \Rightarrow Q(x)\}$
Noun
$\{\lambda y.Flight(y)\}$
V
$\{\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z)\}$
Every
flight
arrived


S
$\{NP.sem(VP.sem)\}$
NP
$\{\lambda Q.\forall x Flight(x) \Rightarrow Q(x)\}$
VP
$\{\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z)\}$
Det
$\{\lambda P.\lambda Q.\forall x P(x) \Rightarrow Q(x)\}$
Noun
$\{\lambda y.Flight(y)\}$
V
$\{\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z)\}$
Every
flight
arrived

S

$\{\forall x Flight(x) \Rightarrow \exists e Arrived(e) \wedge ArrivedThing(e, x)\}$

NP

$\{\lambda Q.\forall x Flight(x) \Rightarrow Q(x)\}$

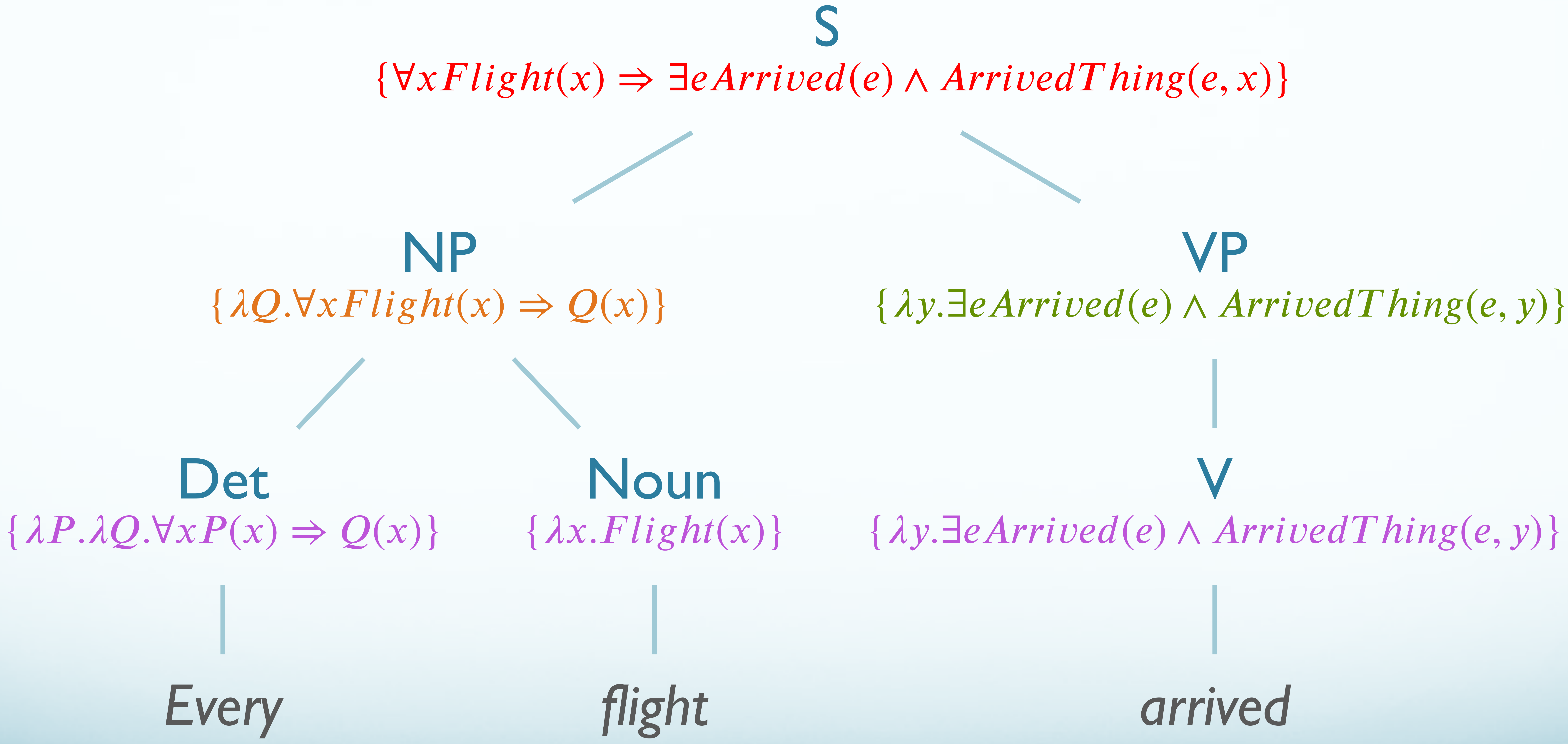
VP

$\{\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z)\}$

$$\lambda Q.\forall x Flight(x) \Rightarrow Q(x)(\lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z))$$

$$\forall x Flight(x) \Rightarrow \lambda z.\exists e Arrived(e) \wedge ArrivedThing(e, z)(x)$$

$$\forall x Flight(x) \Rightarrow \exists e Arrived(e) \wedge ArrivedThing(e, x)$$


S
$\{\forall x Flight(x) \Rightarrow \exists e Arrived(e) \land ArrivedThing(e,x)\}$
NP
$\{\lambda Q.\forall x Flight(x) \Rightarrow Q(x)\}$
VP
$\{\lambda y.\exists e Arrived(e) \land ArrivedThing(e,y)\}$
Det
$\{\lambda P.\lambda Q.\forall x P(x) \Rightarrow Q(x)\}$
Noun
$\{\lambda x.Flight(x)\}$
V
$\{\lambda y.\exists e Arrived(e) \land ArrivedThing(e,y)\}$
Every
flight
arrived

'John Booked A Flight'

$Det \rightarrow$ 'a'	$\{\ \lambda P.\lambda Q.\exists x\ P(x)\ \wedge\ Q(x)\ \}$
$Det \rightarrow$ 'every'	$\{\ \lambda P.\lambda Q.\forall x\ P(x)\ \Rightarrow\ Q(x)\ \}$
$NN \rightarrow$ 'flight'	$\{\lambda x.Flight(x)\}$
$NNP \rightarrow$ 'John'	$\{\lambda X.X(John)\}$
$NP \rightarrow NNP$	$\{NNP.sem\}$
$S \rightarrow NP\ VP$	$\{NP.sem(VP.sem)\}$
$VP \rightarrow Verb\ NP$	$\{Verb.sem(NP.sem)\}$
$Verb \rightarrow$ 'booked'	$\{\lambda W.\lambda z.W(\exists e Booked(e)\ \wedge\ Booker(e,z)\ \wedge\ BookedThing(e,y))\}$

…we'll step through this on Wednesday.

Strategy for Semantic Attachments

- General approach:
  - Create complex lambda expressions with lexical items
  - Introduce quantifiers, predicates, terms
  - Percolate up semantics from child if non-branching
  - Apply semantics of one child to other through lambda
    - Combine elements, don't introduce new ones

Semantics Learning

- Zettlemoyer & Collins (2005, 2007, etc); Kate & Mooney (2007)
- Given semantic representation and corpus of parsed sentences
  - Learn mapping from sentences to logical form
- Similar approaches to:
  - Learning instructions from computer manuals
  - Game play via walkthrough descriptions
  - Robocup/Soccer play from commentary

Parsing with Semantics

- Implement semantic analysis in parallel with syntactic parsing
  - Enabled by this rule-to-rule compositional approach
- Required modifications
  - Augment grammar rules with semantics field
  - Augment chart states with meaning expression
  - Incrementally compute semantics
  - Additional constraint of requiring logical blocks to compose
    - Invalid/incomplete compositions will cause a failure in parsing.
    - ‘*The restaurant serves*’ → unclosed lambda
    - ‘*Every Space Needle is in Seattle*’ → Quantifier conflict w/Every and NNP

Sidenote: Idioms

- Not purely compositional
  - *kick the bucket* → die
  - *tip of the iceberg* → small part of the entirety
- Handling
  - Mix lexical items with constituents
  - Create idiom-specific construct for productivity
  - Allow non-compositional semantic attachments
- Extremely complex, e.g. metaphor

HW #6

Goals

- Semantics
  - Gain better understanding of semantic representations
  - Develop experience with lambda calculus and FOL
  - Create semantic attachments
  - Understand semantic composition

Compositional Semantics

- **Part 1**:
  - ***Manually*** create target semantic representations
  - Use Neo-Davidsonian event representation
    - e.g. verb representation with event variable, argument conjuncts
  - Can use as test cases for part 2
- **Part 2**:
  - Create semantic attachments to reproduce (NLTK)
  - Add to grammatical rules to derive sentence representations
- Note: Lots of ambiguities (scope, etc)
  - Only need to produce one

Semantics in NLTK

- Grammar files:
  - .fcfg extension
  - Example format in NLTK Book Chapter 10
  - `/corpora/nltk/nltk-data/grammars/book_grammars/simple-sem.fcfg`
  - Note: Not "event-style"
- Parsing:
  - Use `nltk.parse.FeatureChartParser` (or similar)

Semantics in NLTK

- Printing semantic representations:

```
item.label()['SEM'].simplify()
    all x.(dog(x) -> exists e.(barking(e) & barker(e,x)))
```

- Also `nltk.sem.util.root_semrep(item)`

Semantic attachments in NLTK: Syntax

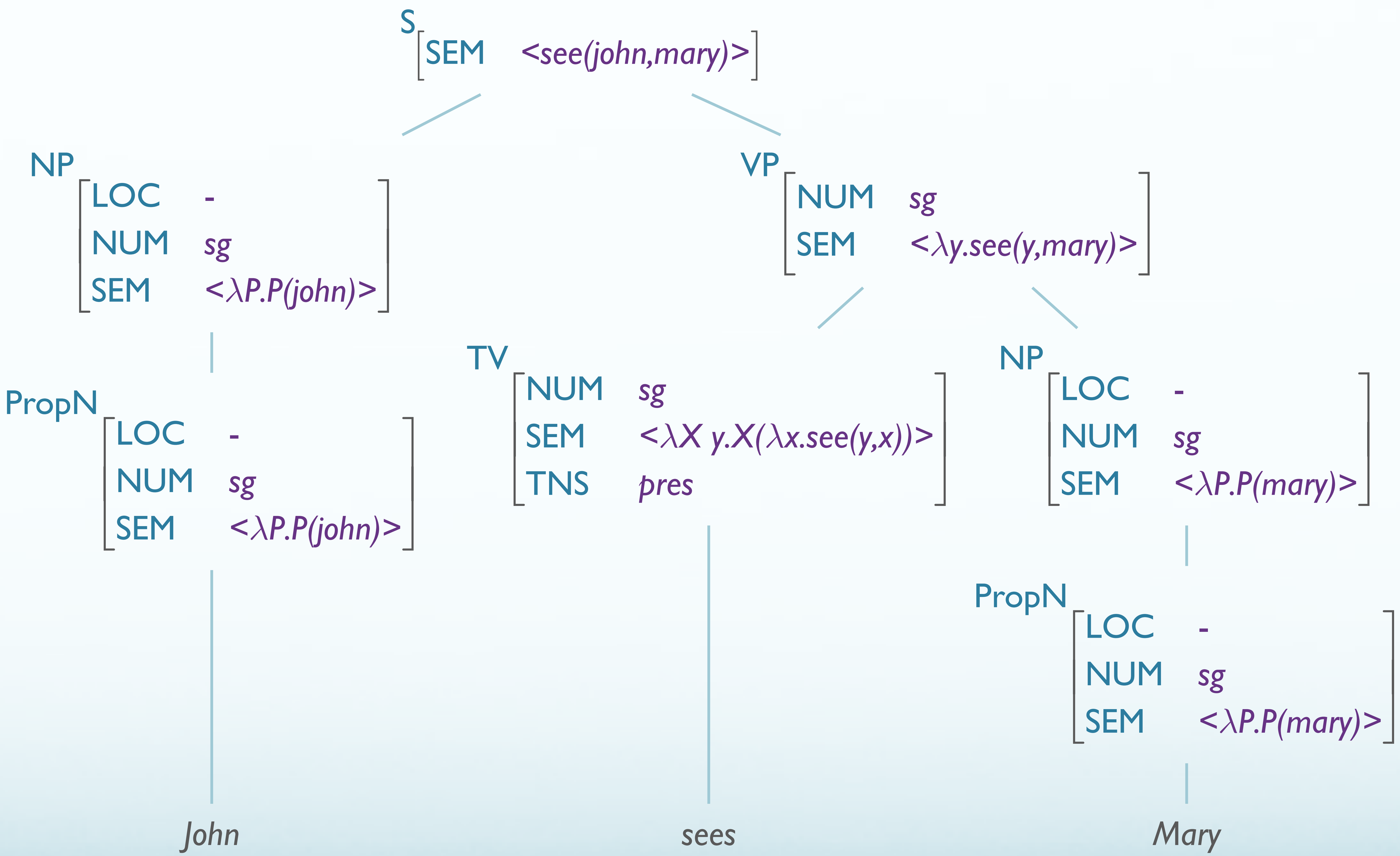
(The programming kind)

- `a,b,e,x`
  - lowercase variables can be arguments:
  - `\x.dog(x)`
- `P,Q,X`
  - uppercase lambda variables are functors
  - `\P.P(john)`

λ	=	`\`
$\exists$	=	`exists`
$\forall$	=	`all`
$\wedge$	=	`&`
$\vee$	=	`|`
$\Rightarrow$	=	`->`

More NLTK Logic Format

- Added to typical CFG rules
  - Basic approach similar to HW #5
  - Composing semantics:
    - S[SEM=<?np(?vp)>] -> NP[SEM=?np] VP[SEM=?vp]
- Creating lambdas:
  - IV[SEM=<\x.exists e.(barking(e) & barker(e,x))>] -> ‘barks’
- Nested lambdas:
  - \x.\y. Etc → \x y.
    Can remove ‘.’ between sequences of lambda elements
    Keep ‘.’ between sections: lambdas, quantifiers, body


S
SEM <see(john,mary)>
NP
LOC -
NUM sg
SEM <λP.P(john)>
VP
NUM sg
SEM <λy.see(y,mary)>
PropN
LOC -
NUM sg
SEM <λP.P(john)>
TV
NUM sg
SEM <λX y.X(λx.see(y,x))>
TNS pres
NP
LOC -
NUM sg
SEM <λP.P(mary)>
PropN
LOC -
NUM sg
SEM <λP.P(mary)>
John
sees
Mary