Formal Semantics

Natural Language Processing
CS 6120—Spring 2014
Northeastern University

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some slides from Jason Eisner

Language as Structure

- So far, we've talked about **structure**
- What structures are **more probable**?
    - Language modeling: Good sequences of words/characters
    - Text classification: Good sequences in defined contexts
- How can we recover **hidden structure**?
    - Tagging: hidden word classes
    - Parsing: hidden word relations

What Does It All Mean?

- Studying phonology, morphology, syntax, etc. independent of meaning is methodologically very useful
- We can study the structure of languages we don't understand
- We can use HMMs and CFGs to study protein structure and music, which don't bear meaning in the same way as language

What Does It All Mean?

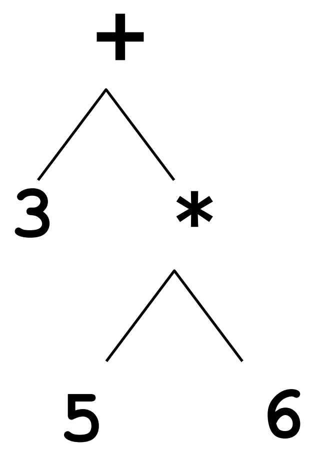
- How would you know if a computer “understood” the “meaning” of an (English) utterance (even in some weak “scare-quoted” way)?
- How would you know if a **person** understood the meaning of an utterance?

What Does It All Mean?

- Paraphrase, "state in your own words" (English to English translation)
- Translation into another language
- Reading comprehension questions
- Drawing appropriate inferences
- Carrying out appropriate actions
- Open-ended dialogue (Turing test)

Programming Language Interpreter

- What is meaning of `3+5*6`?
- First parse it into `3+(5*6)`



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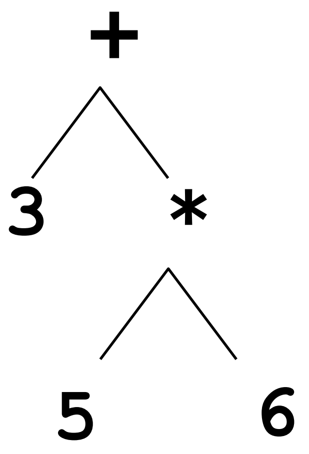

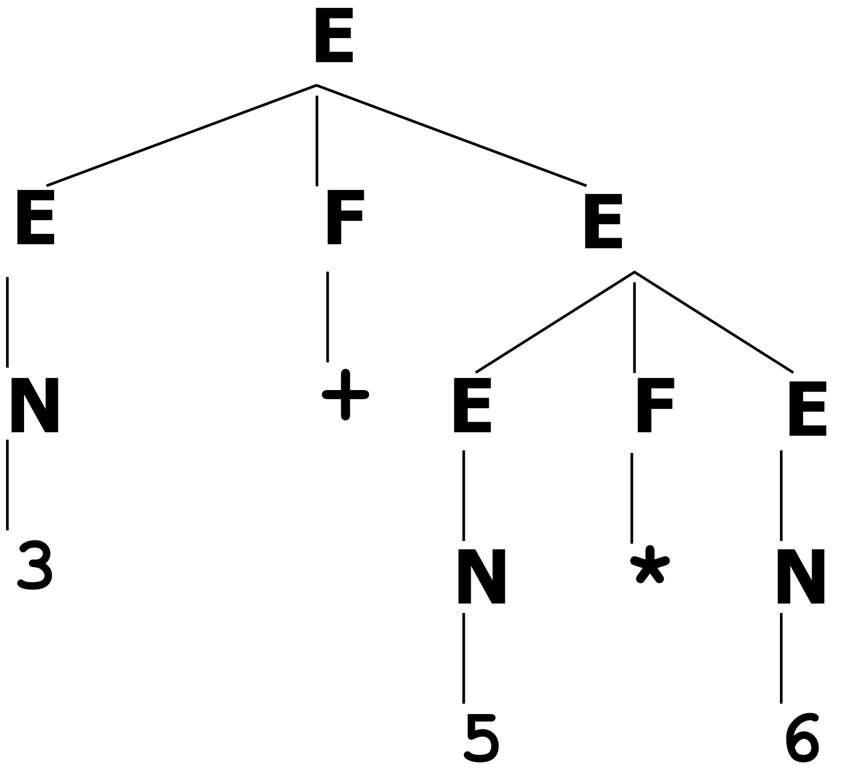

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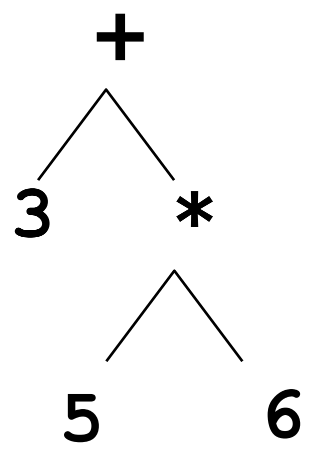

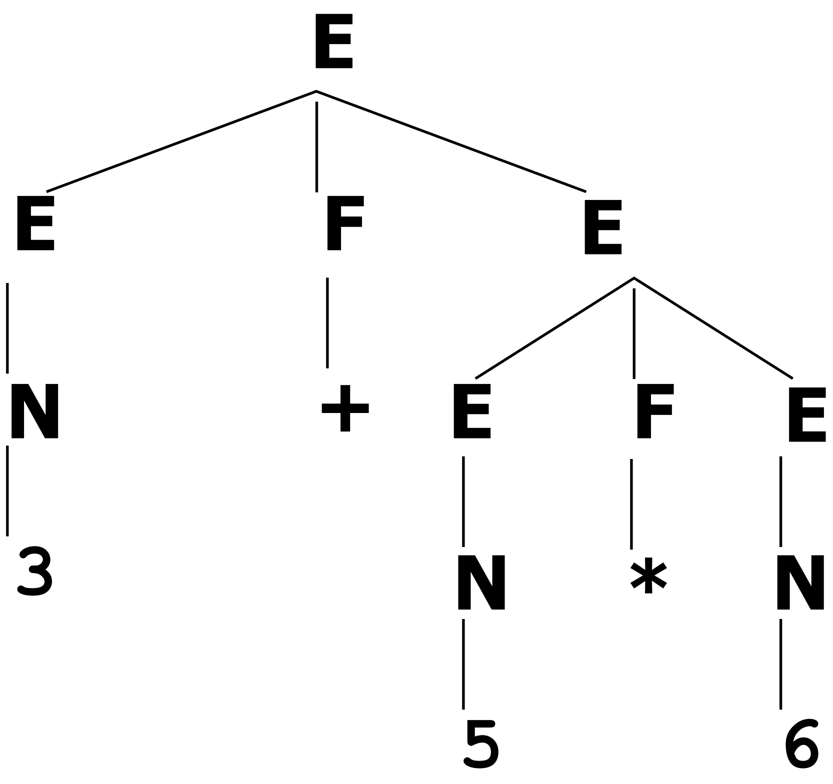

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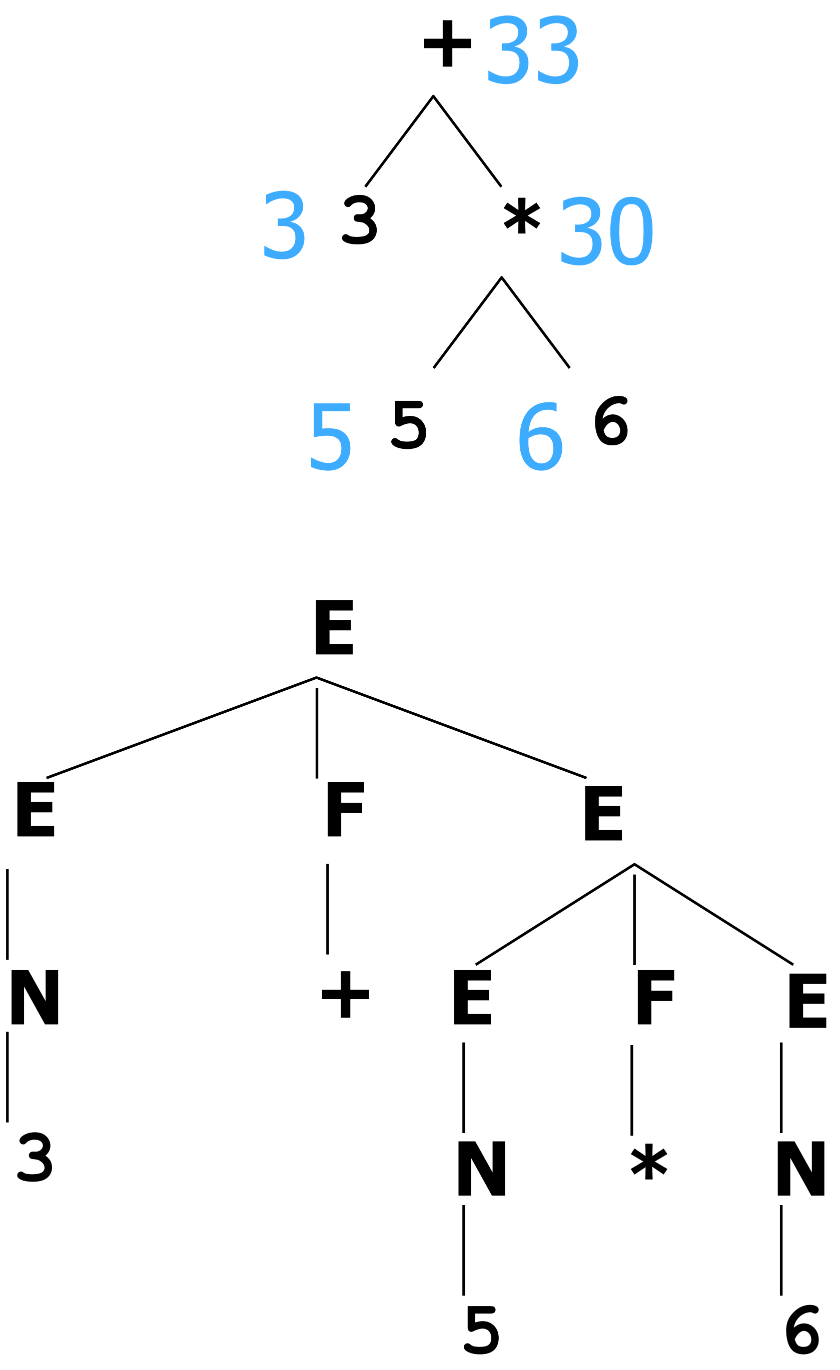

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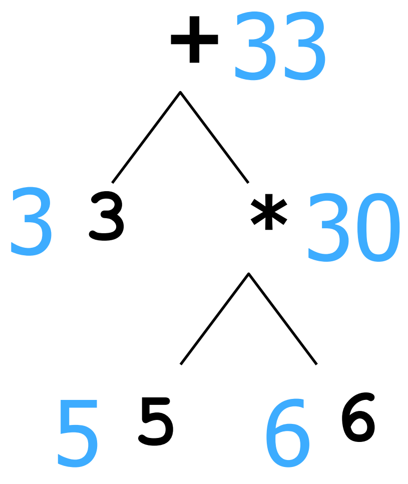

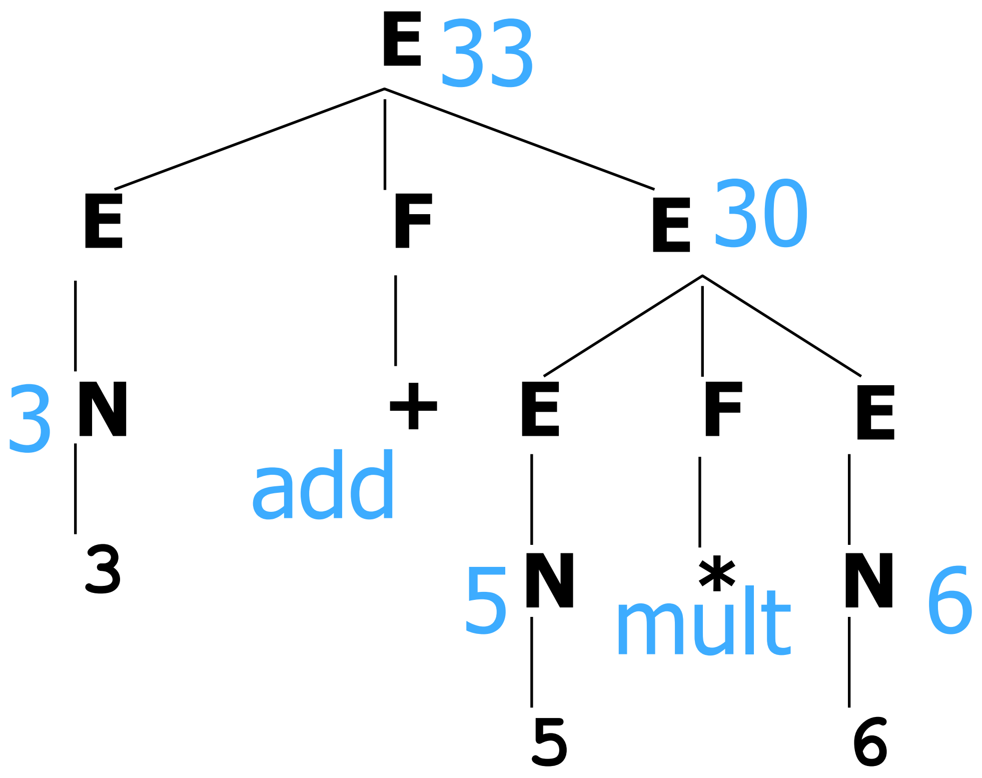

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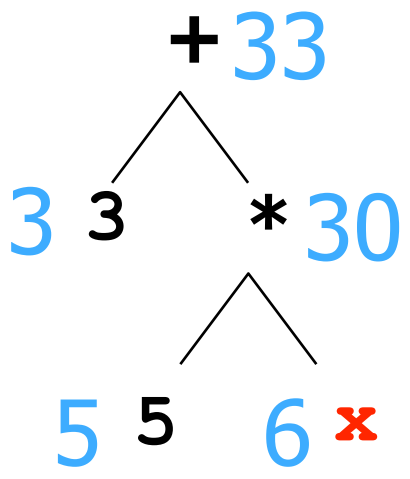

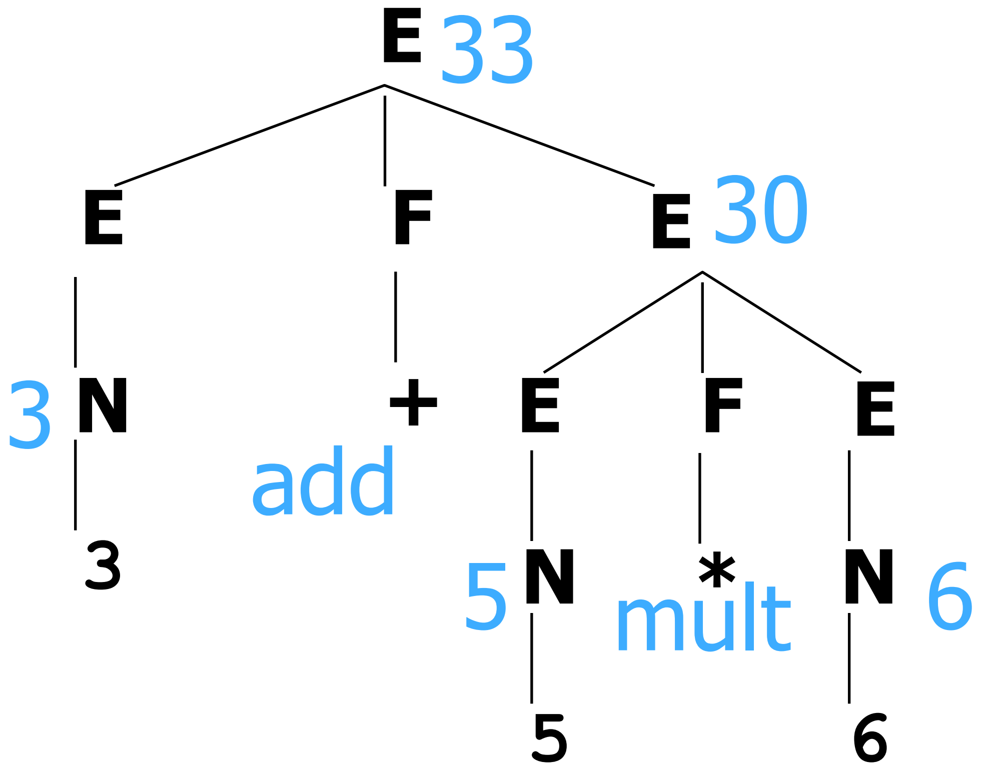

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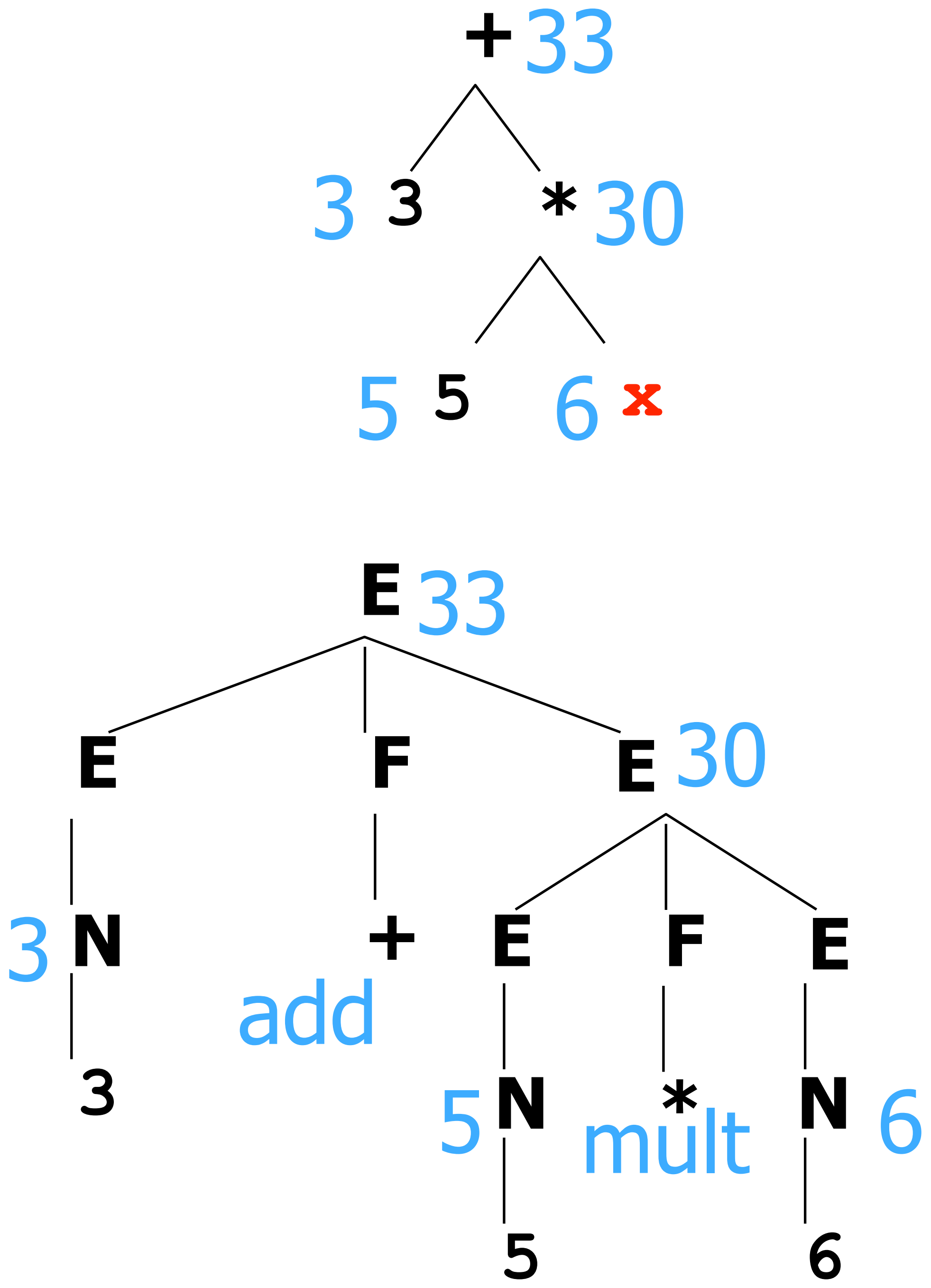

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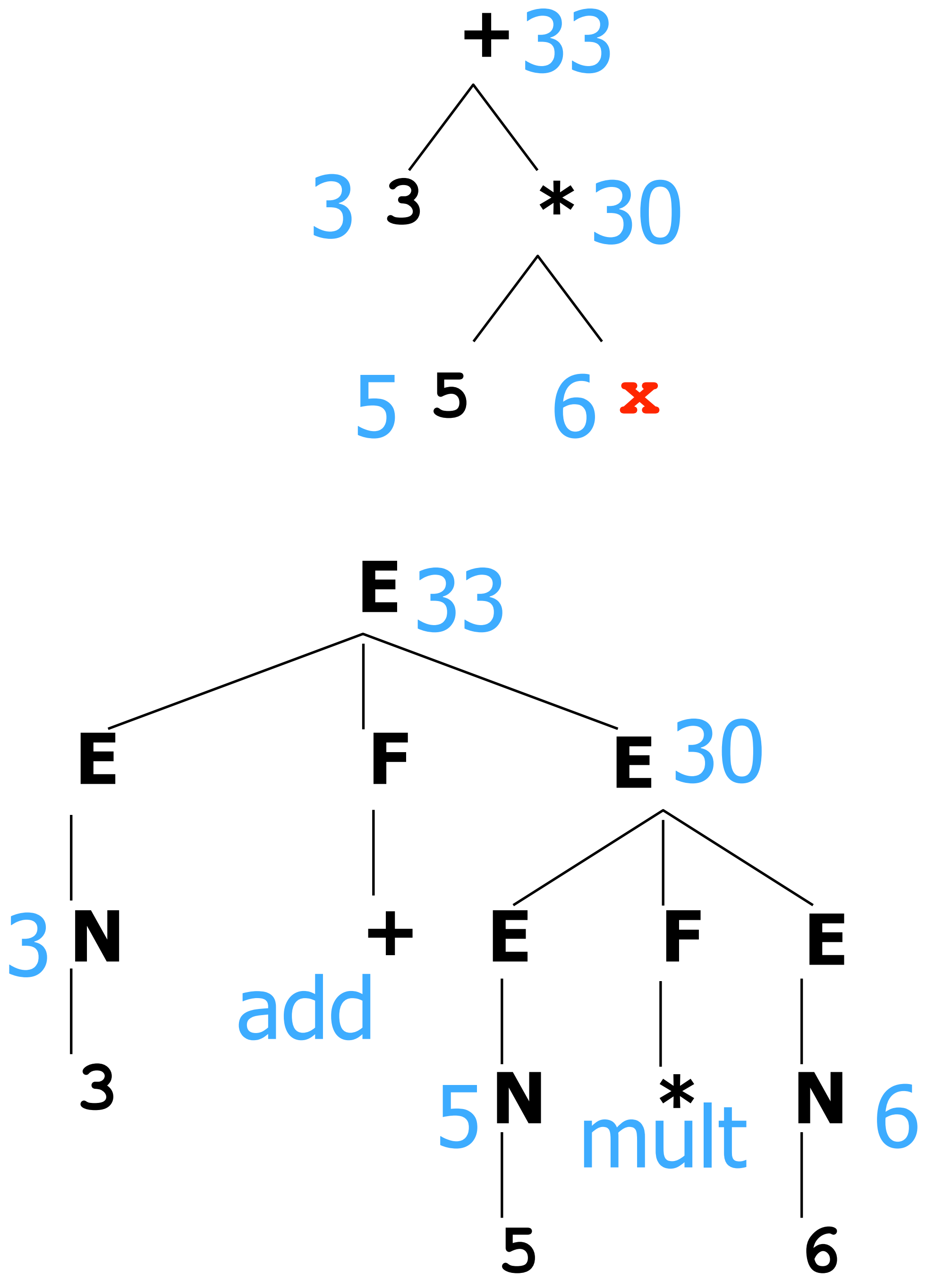

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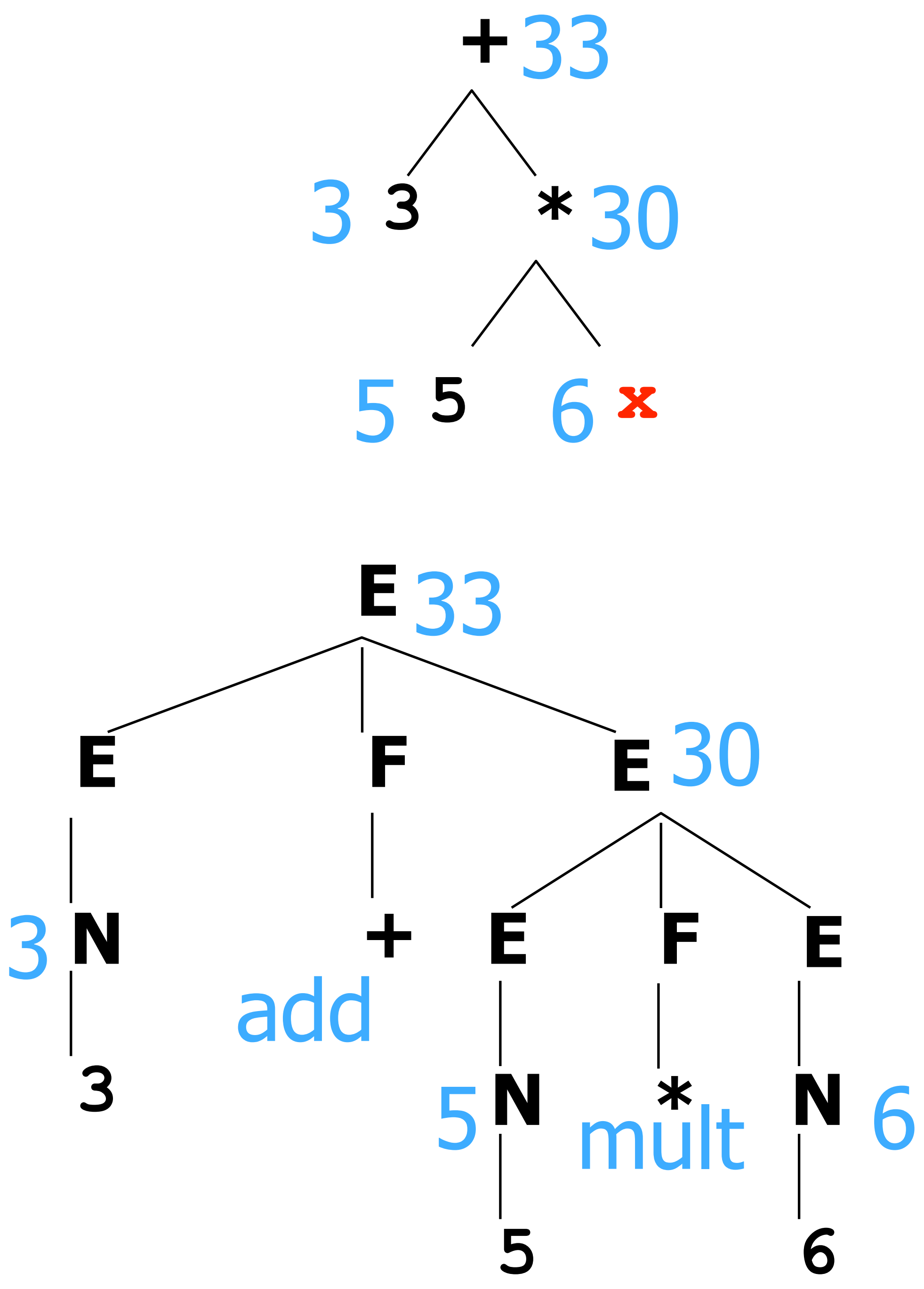

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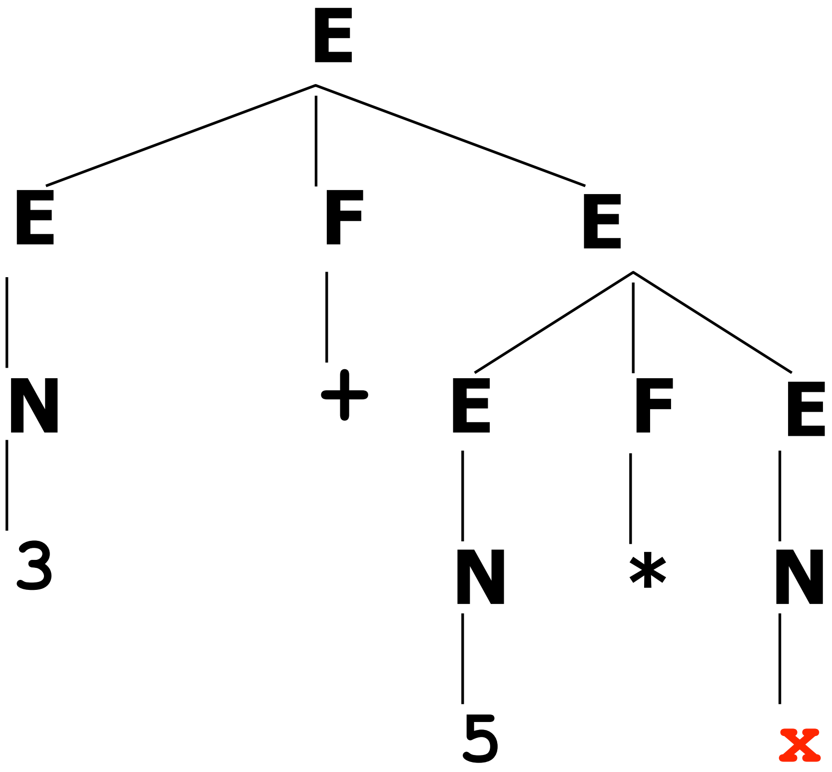

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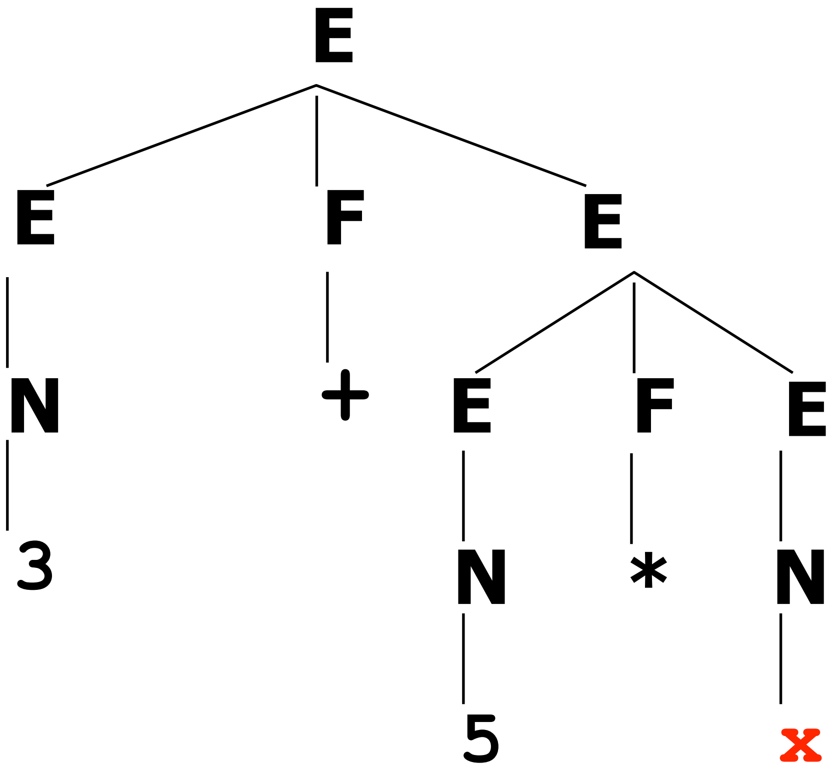

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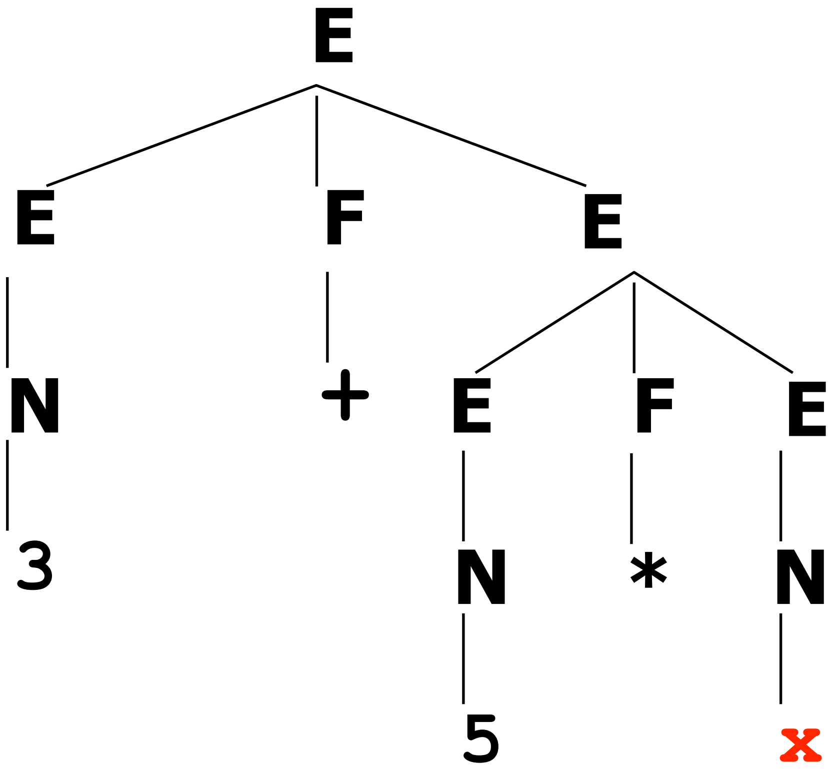

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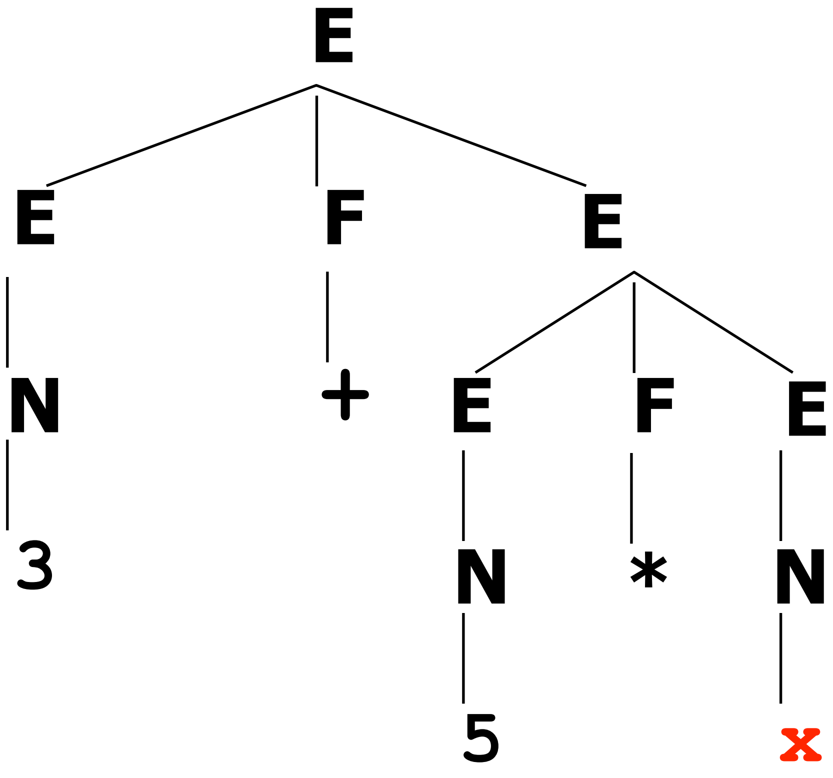

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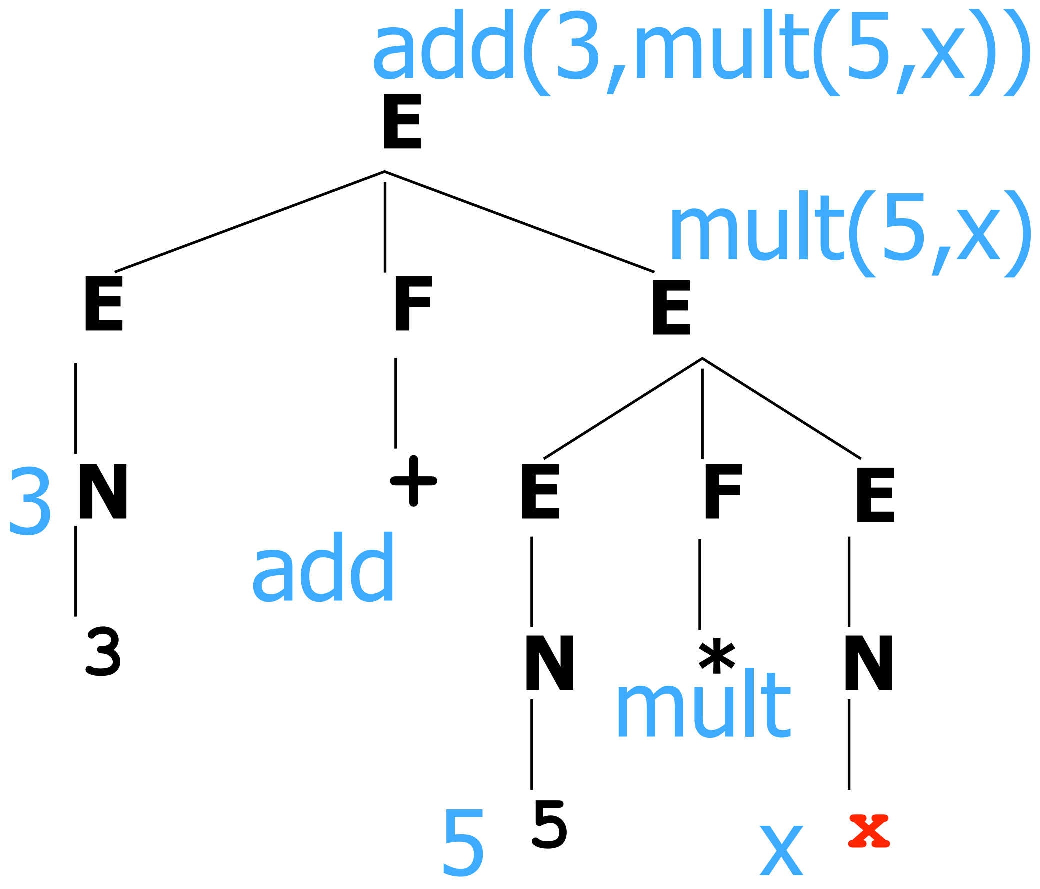

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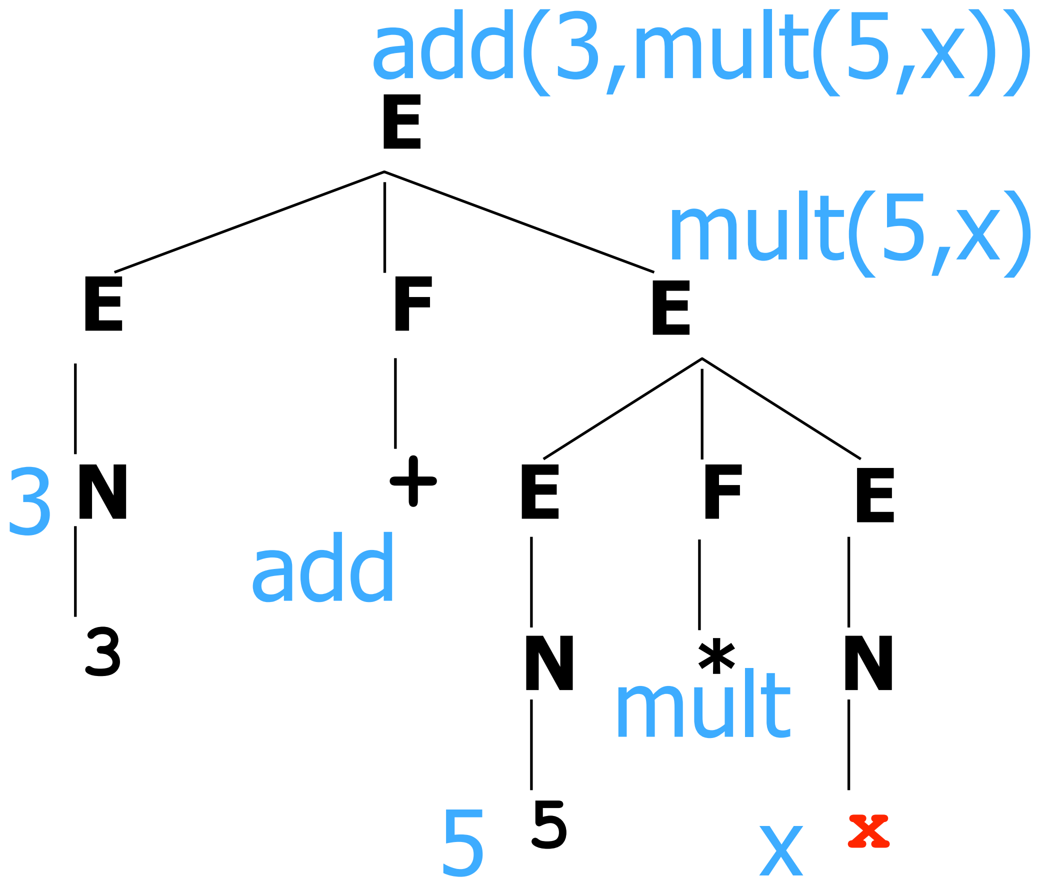

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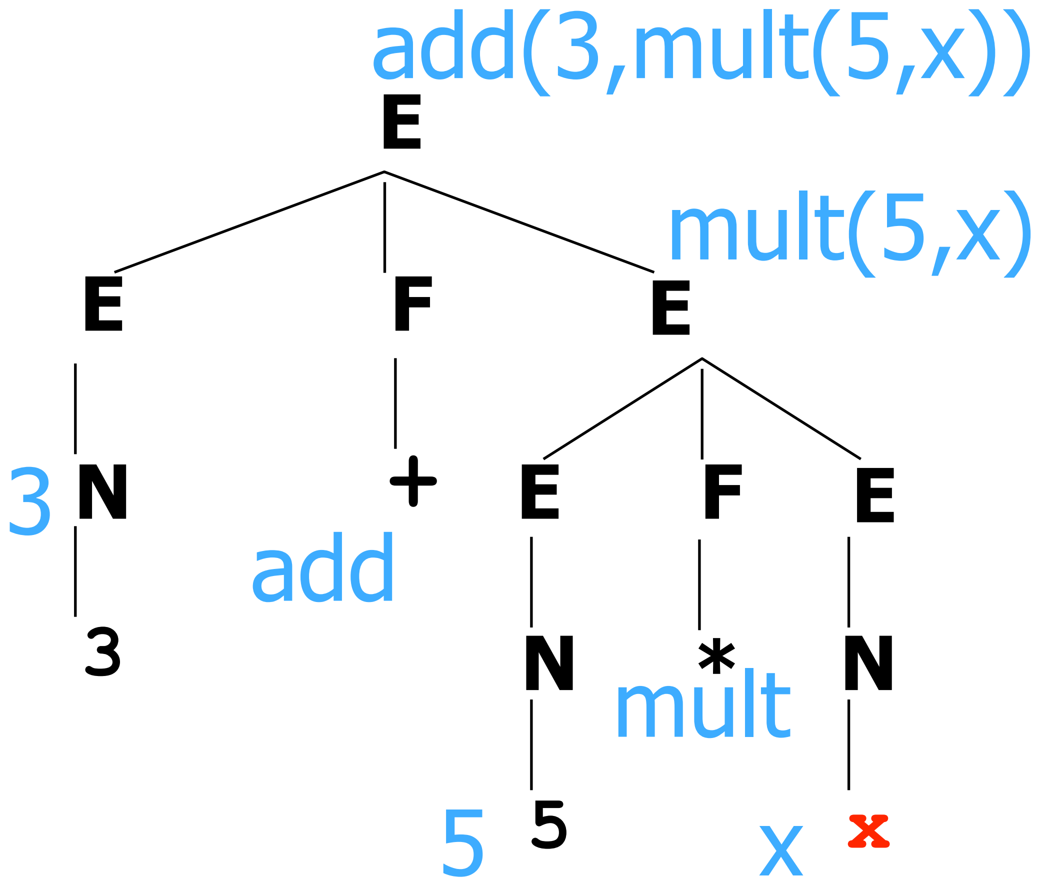

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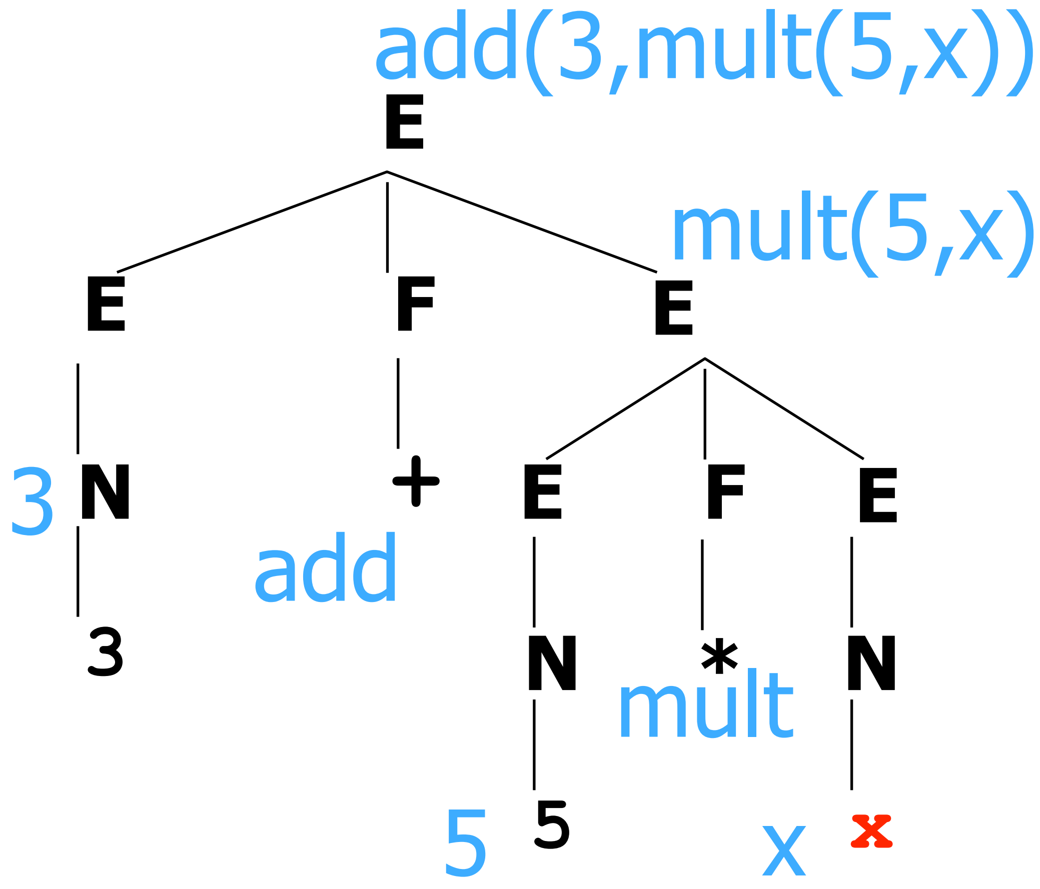

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Analogies in language?

What Counts as Understanding?

some notions

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- We understand if we can respond appropriately
  - ok for commands, questions (these demand response)
  - "Computer, warp speed 5"
  - "throw axe at dwarf"
  - "put all of my blocks in the red box"
  - imperative programming languages
  - SQL database queries and other questions

- We understand statement if we can determine its truth
  - ok, but if you knew whether it was true, why did anyone bother telling it to you?
  - comparable notion for understanding NP is to compute what the NP refers to, which might be useful

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- We understand statement if we know how one could (in principle) determine its truth
  - What are exact conditions under which it would be true?
    - necessary + sufficient
  - Equivalently, derive all its consequences
    - what else must be true if we accept the statement?
  - Match statements with a “domain theory”
  - Philosophers tend to use this definition

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  - Match statements with a "domain theory"
  - Philosophers tend to use this definition
- We understand statement if we can use it to answer questions [very similar to above – requires reasoning]
  - **Easy:** John ate pizza. What was eaten by John?
  - **Hard:** White's first move is P-Q4. Can Black checkmate?
  - Constructing a procedure to get the answer is enough

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- Open-ended dialogue (Turing test)
- Translation to **logical form** that we can reason about

(First Order) Logic
Some Preliminaries

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Three major kinds of objects

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    - Values of NPs, e.g., objects like this slide
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3. Functions of various types
   - Functions from booleans to booleans (and, or, not)
   - A function from entity to boolean is called a "predicate" – e.g., frog(x), green(x)
   - Functions might return other functions!

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   - Functions might return other functions!
   - Function might take other functions as arguments!

Logic: Lambda Terms

- Lambda terms:
  - A way of writing “anonymous functions”
    - No function header or function name
    - But defines the key thing: **behavior** of the function
    - Just as we can talk about 3 without naming it “x”
  - Let square = λp p*p
  - Equivalent to int square(p) { return p*p; }
  - But we can talk about λp p*p without naming it
  - Format of a lambda term: λ variable expression

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    (proving that these functions are equal – and indeed they are,
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    - This happens to denote the same predicate as even does

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- Suppose times is defined as λx λy (x*y)
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- Remember: square can be written as λx square(x)
  - And now times can be written as λx λy times(x,y)

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- Maybe *(5,6) just executes a multiplication function
- What is executed by loves(john, mary) ?

Logic: Interesting Constants

- Thus, have “constants” that name some of the entities and functions (e.g., *):
  - GeorgeWBush - an entity
  - red – a predicate on entities
    - holds of just the red entities: red(x) is true if x is red!
  - loves – a predicate on 2 entities
    - loves(GeorgeWBush, LauraBush)
    - Question: What does loves(LauraBush) denote?
- Constants used to define meanings of words
- Meanings of phrases will be built from the constants

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- most – a predicate on 2 predicates on entities
  - most(pig, big) = “most pigs are big”
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  - returns true if most of the things satisfying the first predicate also satisfy the second predicate
- similarly for other quantifiers
  - all(pig,big) (equivalent to $\forall$x pig(x) $\Rightarrow$ big(x))
  - exists(pig,big) (equivalent to $\exists$x pig(x) AND big(x))
  - can even build complex quantifiers from English phrases:
    - “between 12 and 75”; “a majority of”; “all but the smallest 2”

A reasonable representation?

- `Gilly swallowed a goldfish`
- First attempt: swallowed(Gilly, goldfish)

- Returns true or false. Analogous to
  - prime(17)
  - equal(4,2+2)
  - loves(GeorgeWBush, LauraBush)
  - swallowed(Gilly, Jilly)
- … or is it analogous?

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- But we’re not paying attention to `a`!

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- In particular, don't want `Gilly swallowed a goldfish and Milly swallowed a goldfish` to translate as swallowed(Gilly, goldfish) AND swallowed(Milly, goldfish) since probably not the same goldfish …

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  - Equivalently: exists(goldfish, swallowed(Gilly))
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- Here goldfish is a predicate on entities
  - This is the same semantic type as red
  - But `goldfish` is noun and `red` is adjective .. #@!?

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(Simplify Notation)

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- Replace time variable t with an event variable e
  - ∃e past(e), act(e,swallowing), swallower(e,Gilly), exists(goldfish, swallowee(e)), exists(booth, location(e)), …
    - As with probability notation, a comma represents AND
    - Could define past as λe ∃t before(t,now), ended-at(e,t)

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  - ∃e past(e), act(e,swallowing), swallower(e,Gilly), exists(goldfish, swallowee(e)), exists(booth, location(e)), …
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says that there's only one event
with a single goldfish getting swallowed
that took place in a lot of booths ...

Quantifier Order

- Groucho Marx celebrates quantifier order ambiguity:
  - **`In this country a woman gives birth every 15 min. Our job is to find that woman and stop her.`**
  - ∃woman (∀15min gives-birth-during(woman, 15min))
  - ∀15min (∃woman gives-birth-during(15min, woman))
  - Surprisingly, both are possible in natural language!
  - Which is the joke meaning (where it's always the same woman) and why?

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  - Probably false unless Gilly can be in every booth during her swallowing of a single goldfish

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    - all(booth, λb [∃e past(e), act(e,swallowing), swallower (e,Gilly), exists(goldfish, swallowee(e)), location(e,b)])
    - "for all booths b, there was such an event in b"

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- Intensional verbs besides `want`: `hope`, `doubt`, `believe`,…

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  - Can imagine other worlds where set of unicorn ≠ set of dodos
  - Other worlds also useful for: `You must pay the rent`

```
                                You can pay the rent
                      If you hadn't, you'd be homeless
```

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- `Willy wants Lilly to get married`

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  - The only trick is to construct the representation from the syntax. The empty subject position of "to get married" is said to be controlled by the subject of "wants."

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  - λg expert(g)

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    - Right: λg (bogus(expert))(g)   … `bogus` maps to new concept
- `Baltimore expert` (`white-collar expert, TV expert` …)
  - λg Related(Baltimore, g), expert(g) – expert from Baltimore
  - Or with different intonation:
    - λg (Modified-by(Baltimore, expert))(g) – expert on Baltimore
    - Can't use Related for this case: `law expert and dog catcher`
      = λg Related(law,g), expert(g), Related(dog, g), catcher(g)
      = `dog expert and law catcher`

Nouns and Their Modifiers

- `the goldfish that Gilly swallowed`
- `every goldfish that Gilly swallowed`
- `three goldfish that Gilly swallowed`

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$$\lambda g\ [\text{goldfish}(g),\ \text{swallowed}(\text{Gilly},\ g)]$$

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λg [goldfish(g), swallowed(Gilly, g)]

like an adjective!

- `three swallowed-by-Gilly goldfish`

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- `three goldfish that Gilly swallowed`

λg [goldfish(g), swallowed(Gilly, g)]

like an adjective!

- `three swallowed-by-Gilly goldfish`

Or for real: λg [goldfish(g), ∃e [past(e), act(e,swallowing), swallower(e,Gilly), swallowee(e,g)]]

Adverbs

Adverbs

- `Lili passionately wants Billy`
  - Wrong?: passionately(want(Lili,Billy)) = passionately(true)
  - Better: (passionately(want))(Lili,Billy)
  - Best: ∃e present(e), act(e,wanting), wanter(e,Lili), wantee(e, Billy), manner(e, passionate)

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- `Lili often stalks Billy`
  - (often(stalk))(Lili,Billy)
  - many(day, λd ∃e present(e), act(e,stalking), stalker(e,Lili), stalkee(e, Billy), during(e,d))

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  - many(day, λd ∃e present(e), act(e,stalking), stalker(e,Lili), stalkee(e, Billy), during(e,d))
- `Lili obviously likes Billy`
  - (obviously(like))(Lili,Billy) – one reading
  - obvious(like(Lili, Billy)) – another reading

Speech Acts

Speech Acts

- What is the meaning of a full sentence?
  - Depends on the punctuation mark at the end. ☺
  - Billy likes Lili. → **assert**(like(B,L))
  - Billy likes Lili? → **ask**(like(B,L))
    - or more formally, “Does Billy like Lili?”
  - Billy, like Lili! → **command**(like(B,L))
    - or more accurately, “Let Billy like Lili!”

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- Let's try to do this a little more precisely, using event variables etc.

Speech Acts

Speech Acts

- `What did Gilly swallow?`
  - **ask**(λx ∃e past(e), act(e,swallowing), swallower(e,Gilly), swallowee(e,x))
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  - Is there any common syntax?

Speech Acts

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- Eat your fish!
  - **command**(λf act(f,eating), eater(f,Hearer), eatee(…))

Speech Acts

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  - **ask**(λx ∃e past(e), act(e,swallowing),
    swallower(e,Gilly), swallowee(e,x))
  - Argument is identical to the modifier "that Gilly swallowed"
  - Is there any common syntax?
- `Eat your fish!`
  - **command**(λf act(f,eating), eater(f,Hearer), eatee(…))
- `I ate my fish.`
  - **assert**(∃e past(e), act(e,eating), eater(f,Speaker),
    eatee(…))

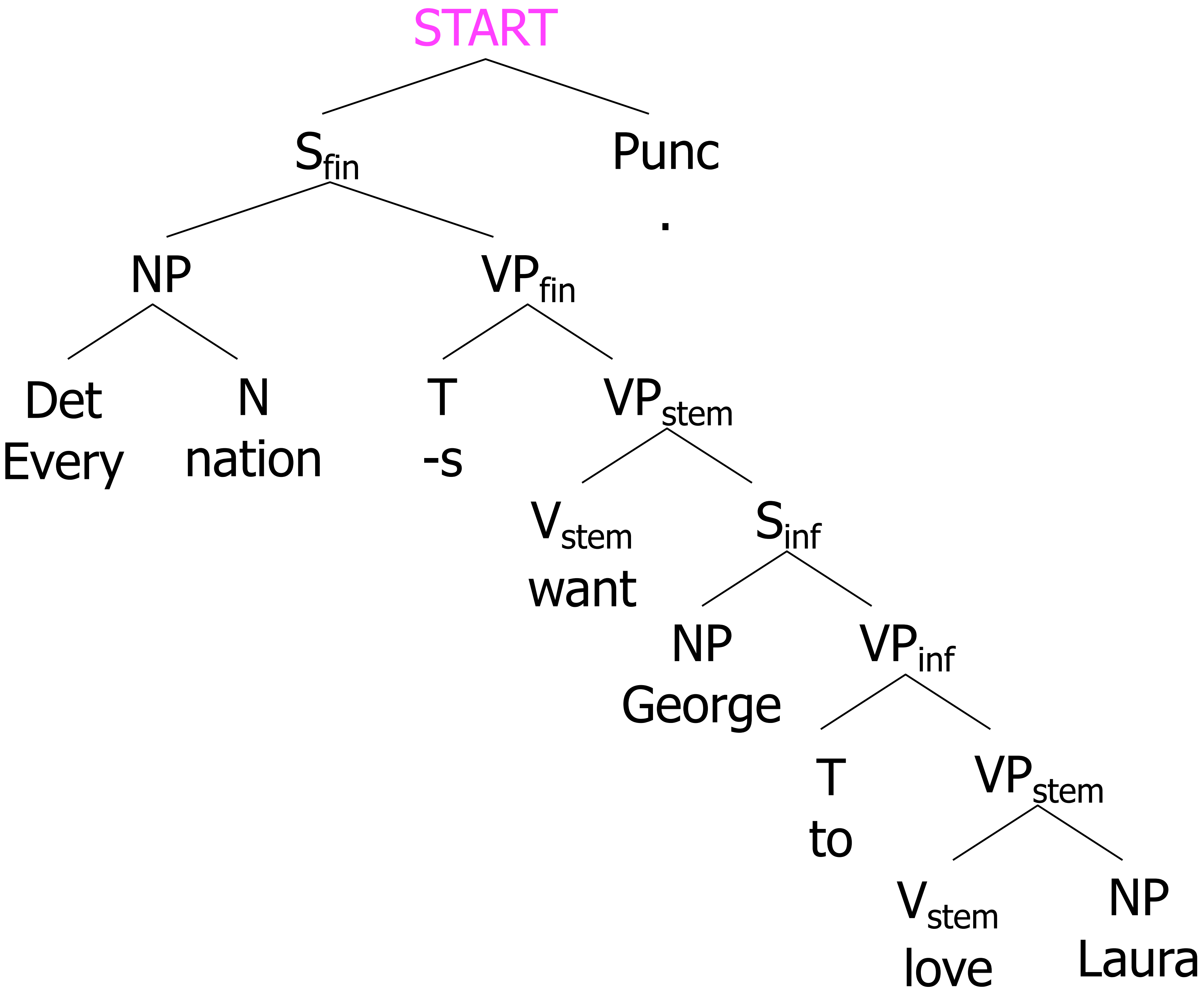
Compositional Semantics

- We've discussed what semantic representations should look like.

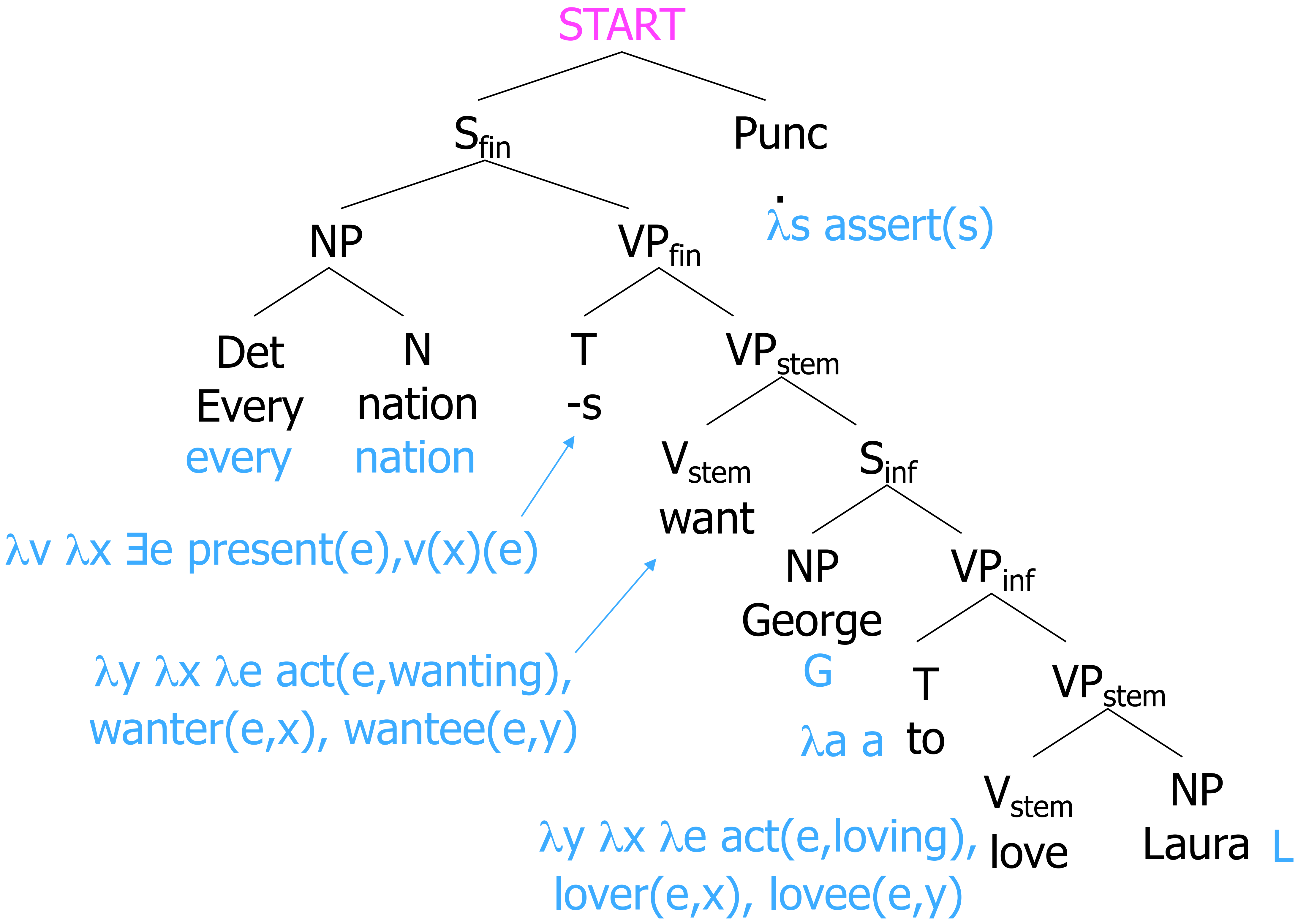
- **But how do we get them from sentences???**

- First - parse to get a syntax tree.
- Second - look up the semantics for each word.
- Third - build the semantics for each constituent
  - Work from the bottom up
  - The syntax tree is a "recipe" for how to do it

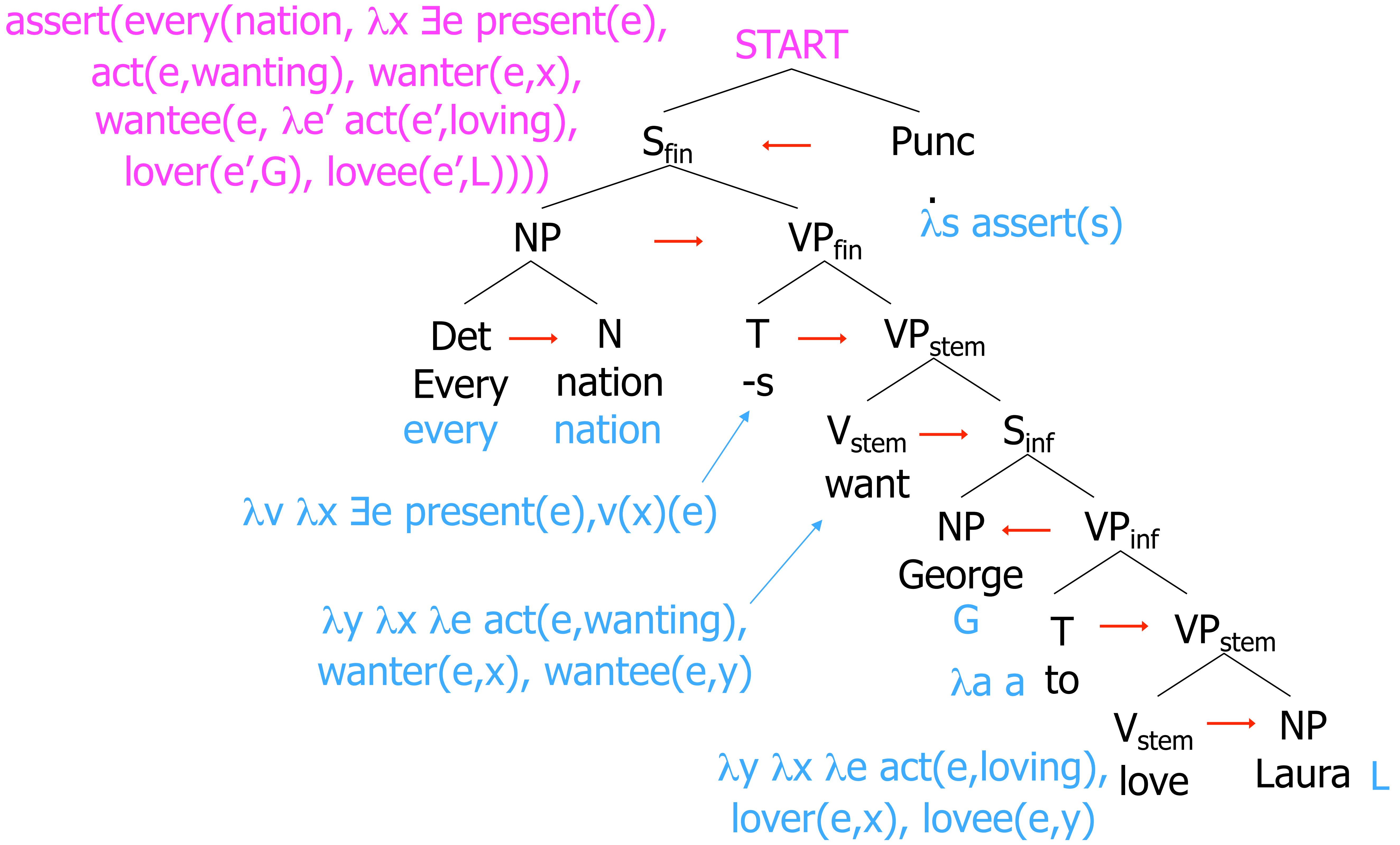
Compositional Semantics



Compositional Semantics



Compositional Semantics



assert(every(nation, λx ∃e present(e),
act(e,wanting), wanter(e,x),
wantee(e, λe′ act(e′,loving),
lover(e′,G), lovee(e′,L))))

START

S_{fin} ← Punc

.

λs assert(s)

NP → VP_{fin}

Det → N

Every nation

every nation

T → VP_{stem}

-s

λv λx ∃e present(e),v(x)(e)

V_{stem} → S_{inf}

want

λy λx λe act(e,wanting),
wanter(e,x), wantee(e,y)

NP ← VP_{inf}

George

G

T → VP_{stem}

λa a to

V_{stem} → NP

love Laura L

λy λx λe act(e,loving),
lover(e,x), lovee(e,y)

Compositional Semantics

Compositional Semantics

- Add a “sem” feature to each context-free rule
  - S → NP loves NP
  - S[sem=loves(x,y)] → NP[sem=x] loves NP[sem=y]
  - Meaning of S depends on meaning of NPs

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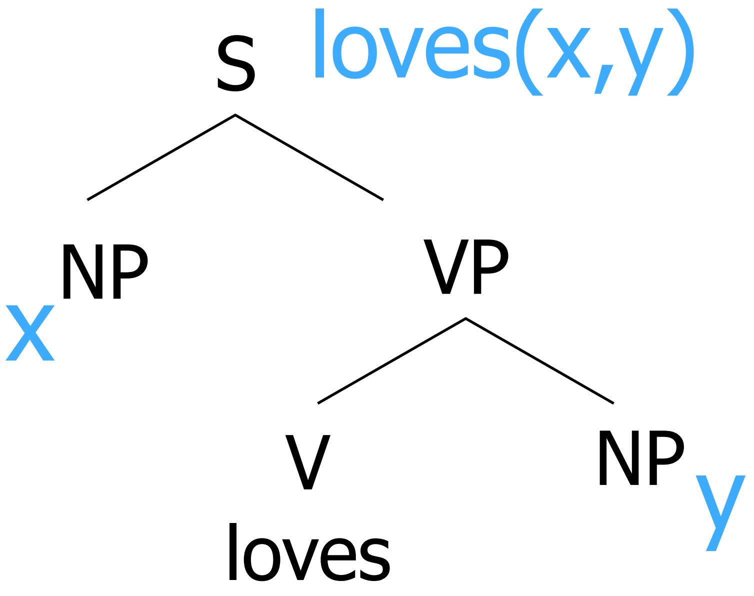

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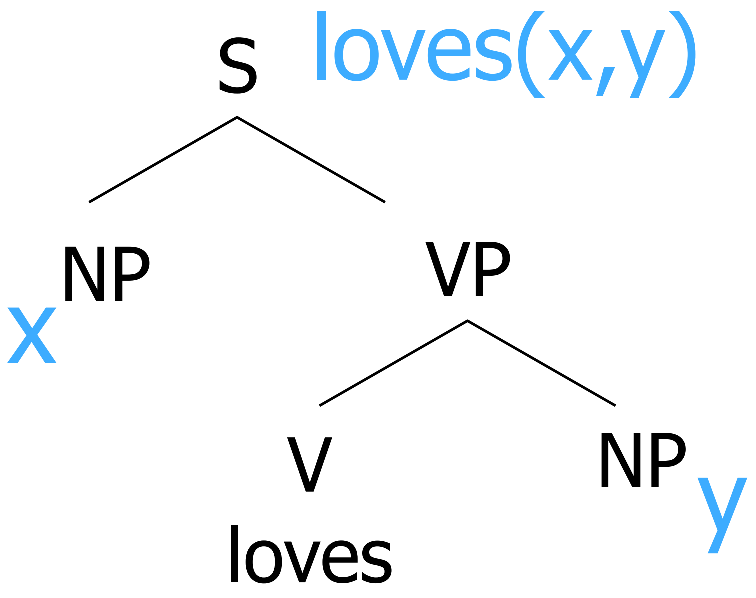

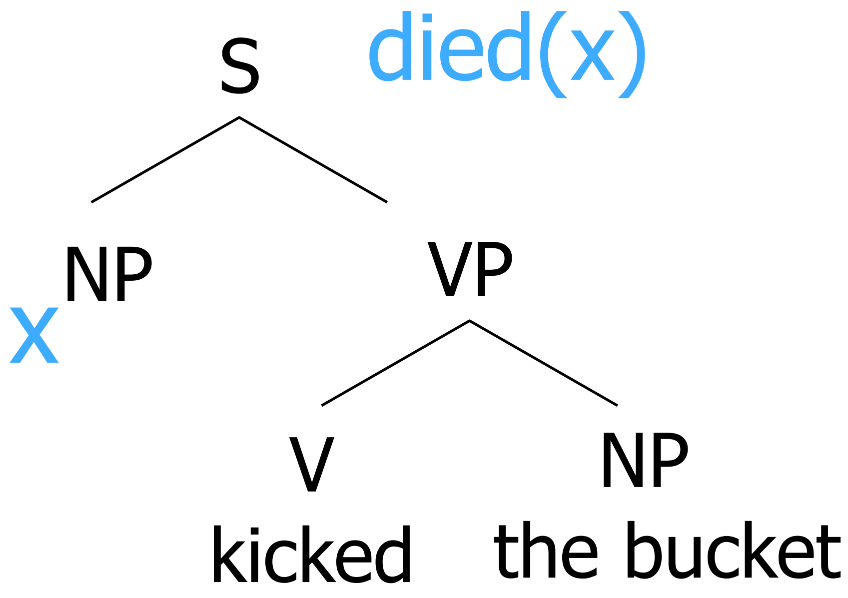

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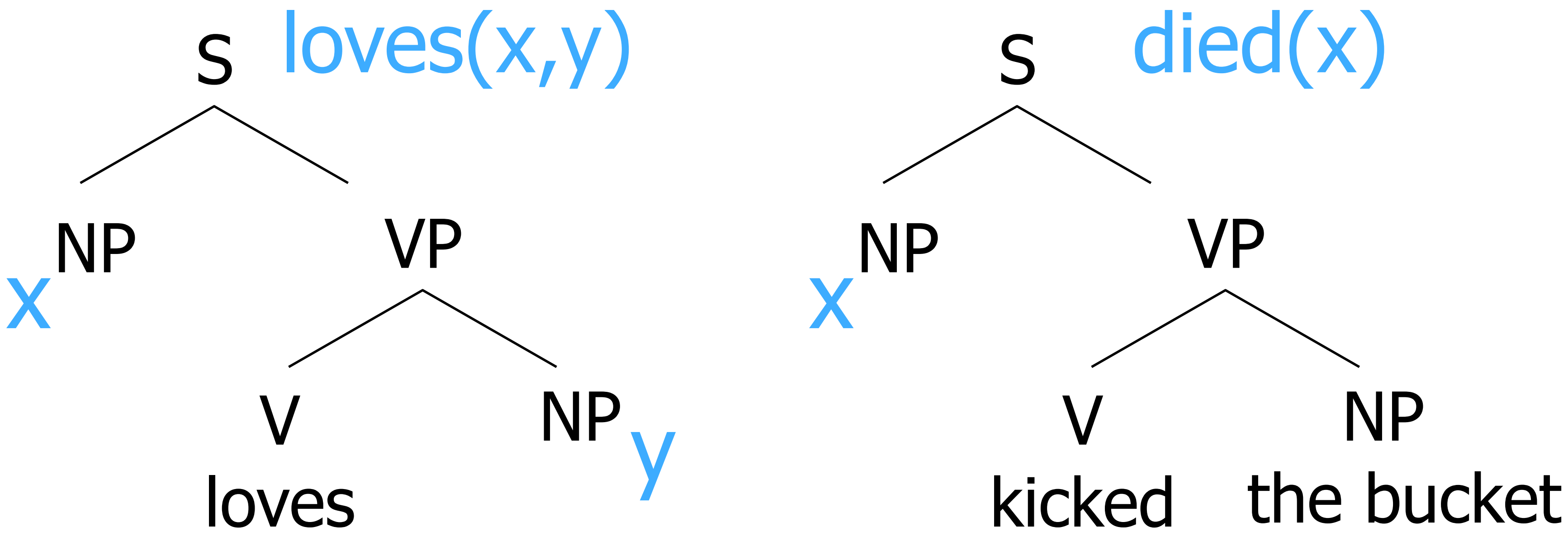

- Template filling: S[sem=showflights(x,y)] →
  I want a flight from NP[sem=x] to NP[sem=y]

Compositional Semantics

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- Instead of S → NP loves NP
  - S[sem=loves(x,y)] → NP[sem=x] loves NP[sem=y]

Compositional Semantics

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- might want general rules like S → NP VP:
  - V[sem=loves] → loves
  - VP[sem=v(obj)] → V[sem=v] NP[sem=obj]
  - S[sem=vp(subj)] → NP[sem=subj] VP[sem=vp]

Compositional Semantics

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- Now `George loves Laura` has sem=loves(Laura)(George)

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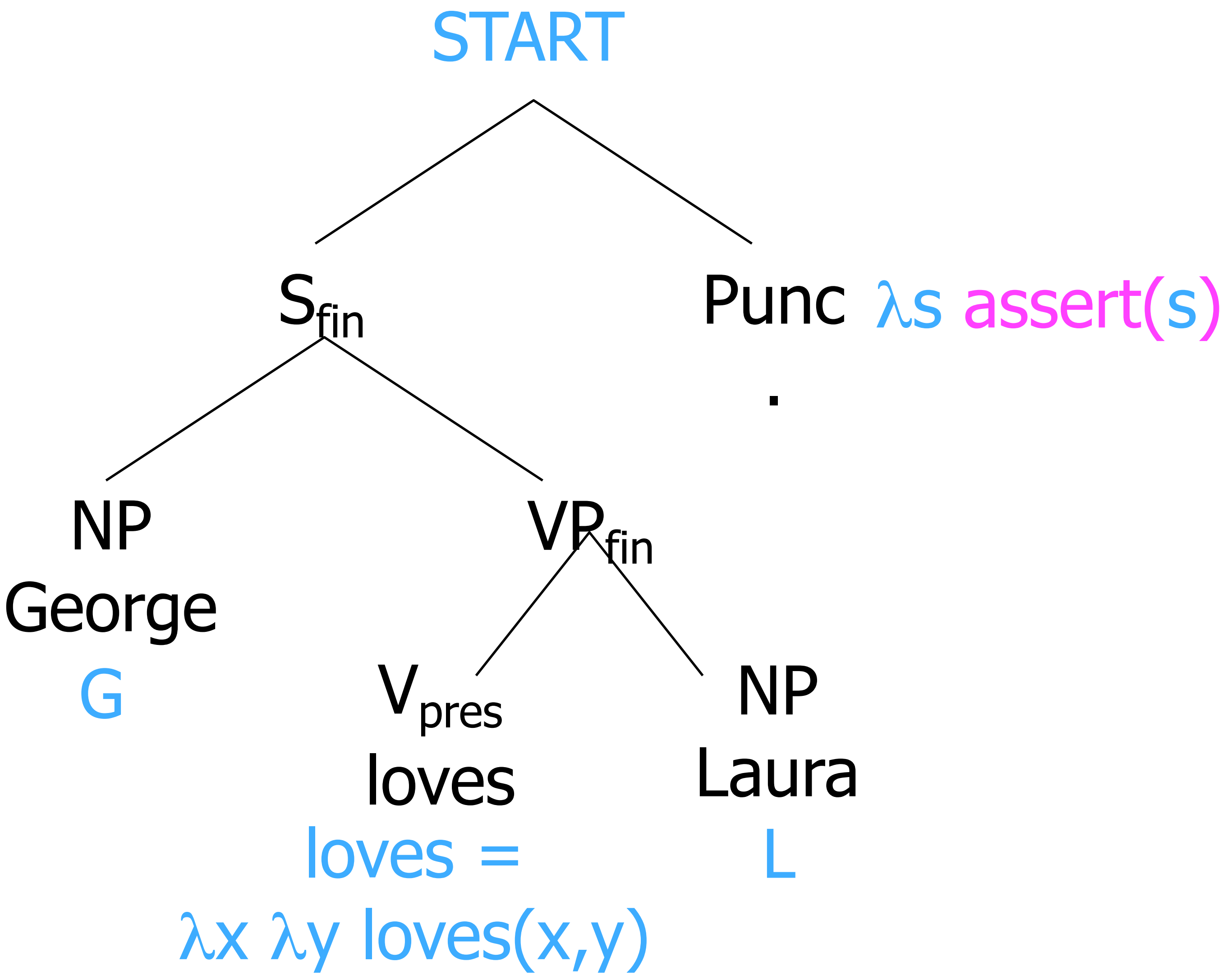
  - S[sem=vp(subj)] → NP[sem=subj] VP[sem=vp]
- Now `George loves Laura` has sem=loves(Laura)(George)
- In this manner we'll sketch a version where
  - Still compute semantics bottom-up
  - Grammar is in Chomsky Normal Form
  - So each node has 2 children: 1 function & 1 argument
  - To get its semantics, apply function to argument!

Compositional Semantics



START

S_{fin}

Punc λs assert(s)

.

NP

George

G

VP_{fin}

V_{pres}

loves

loves =

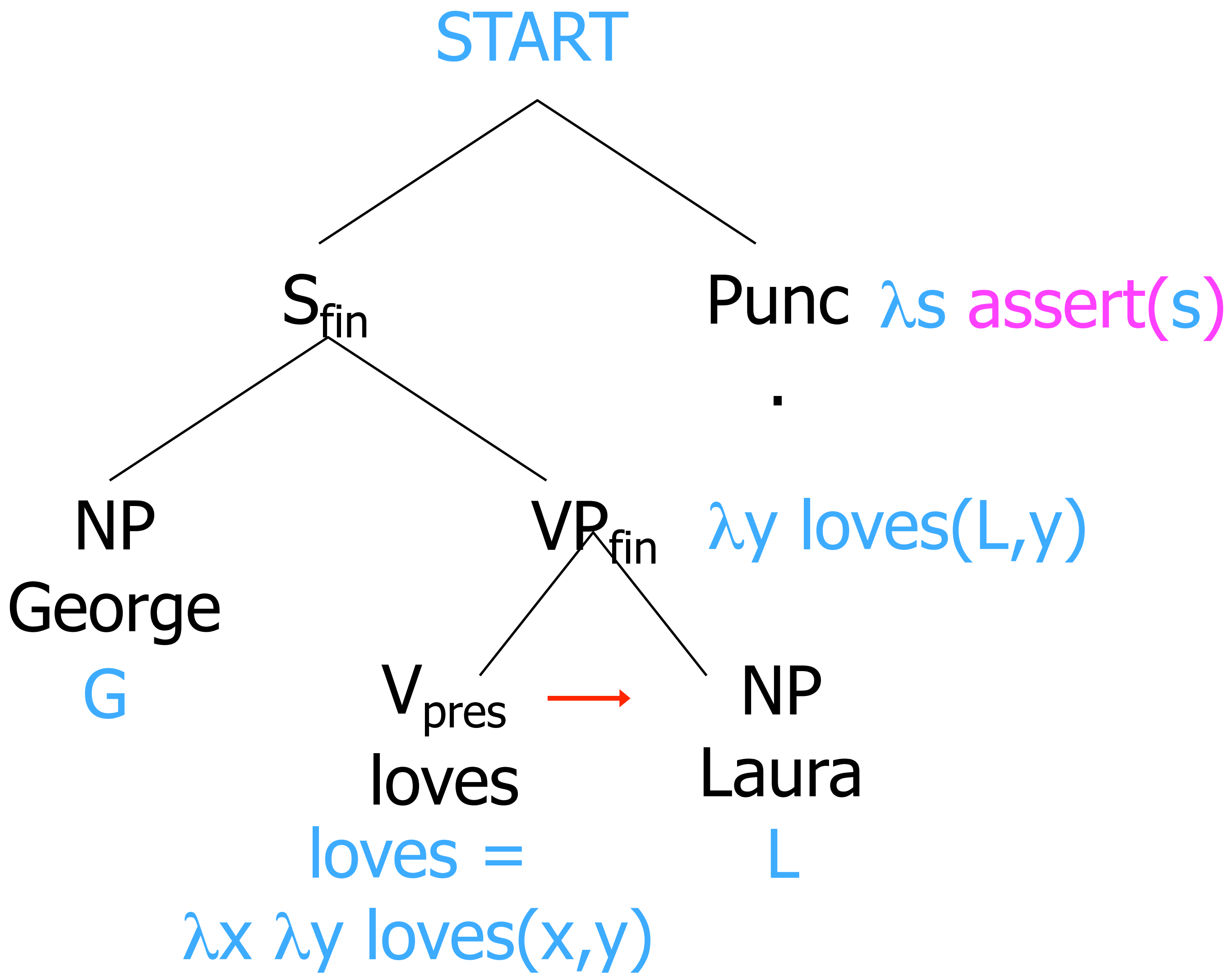
$\lambda x\ \lambda y$ loves(x,y)

NP

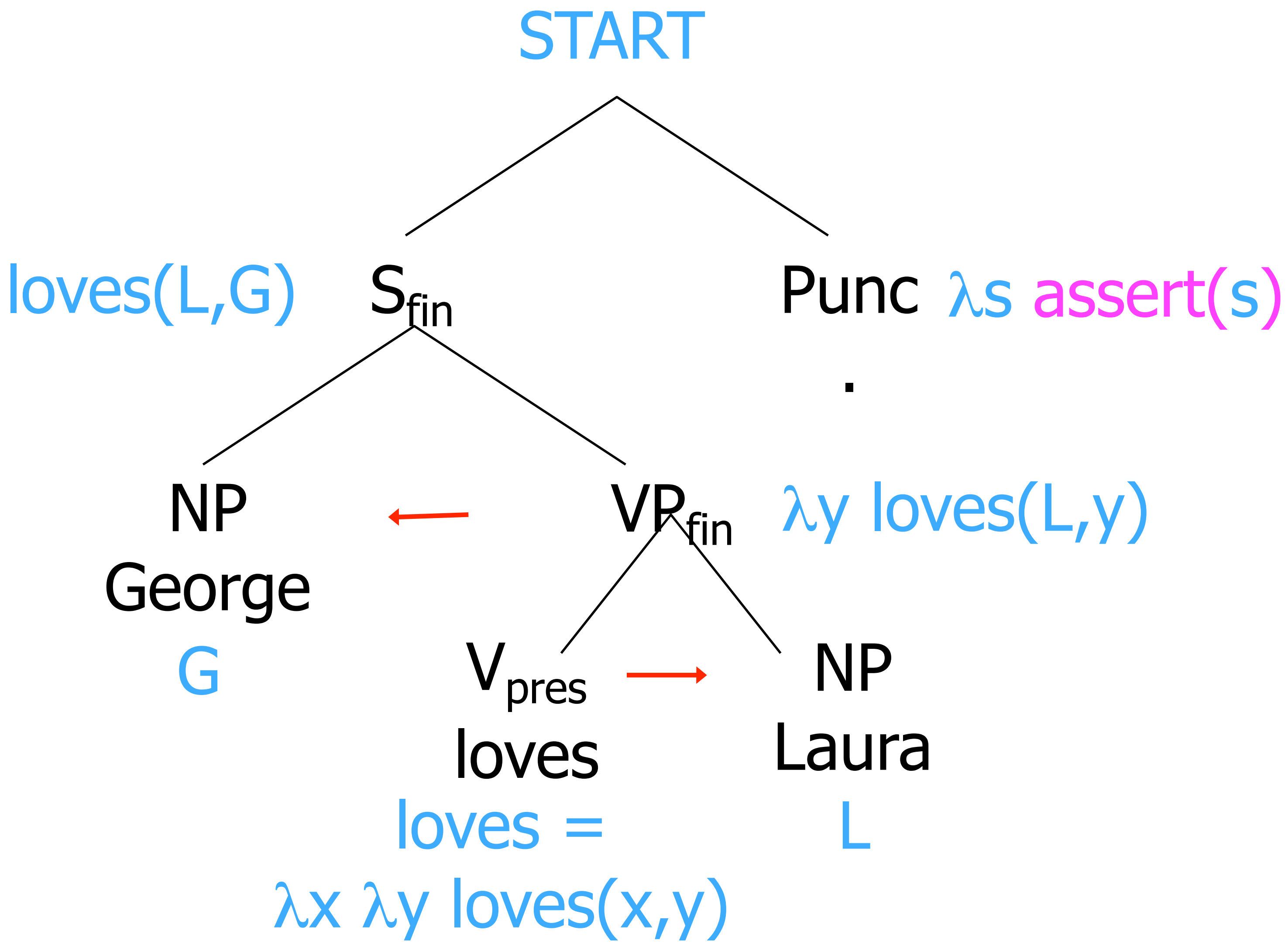
Laura

L

Compositional Semantics



Compositional Semantics



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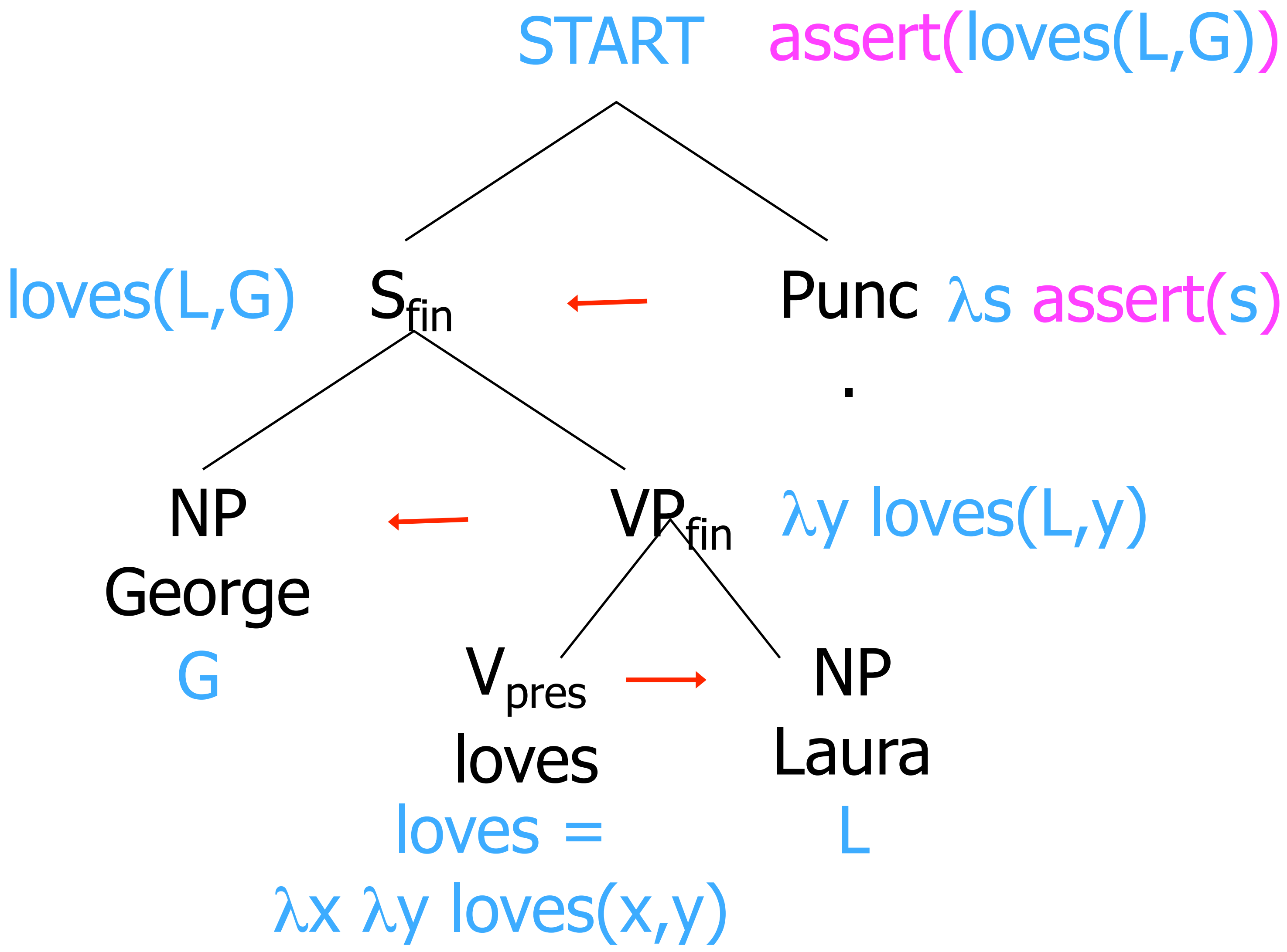


START assert(loves(L,G))

loves(L,G) S$_{fin}$ ← Punc λs assert(s)

.

NP ← VP$_{fin}$ λy loves(L,y)

George

G

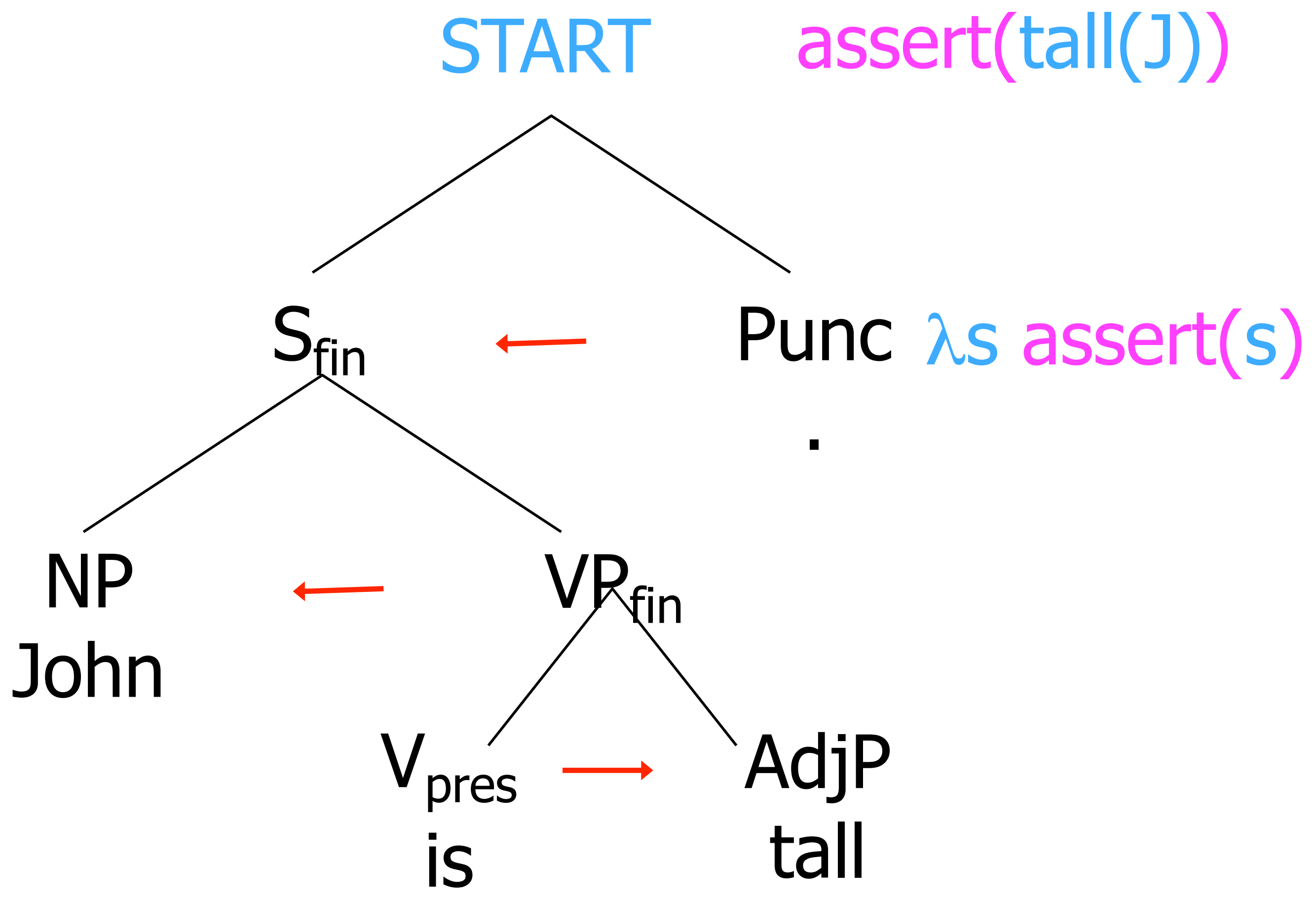
V$_{pres}$ → NP

loves Laura

loves = L

λx λy loves(x,y)

Compositional Semantics



START assert(tall(J))

S_{fin}

Punc λs assert(s)

.

NP

John

VP_{fin}

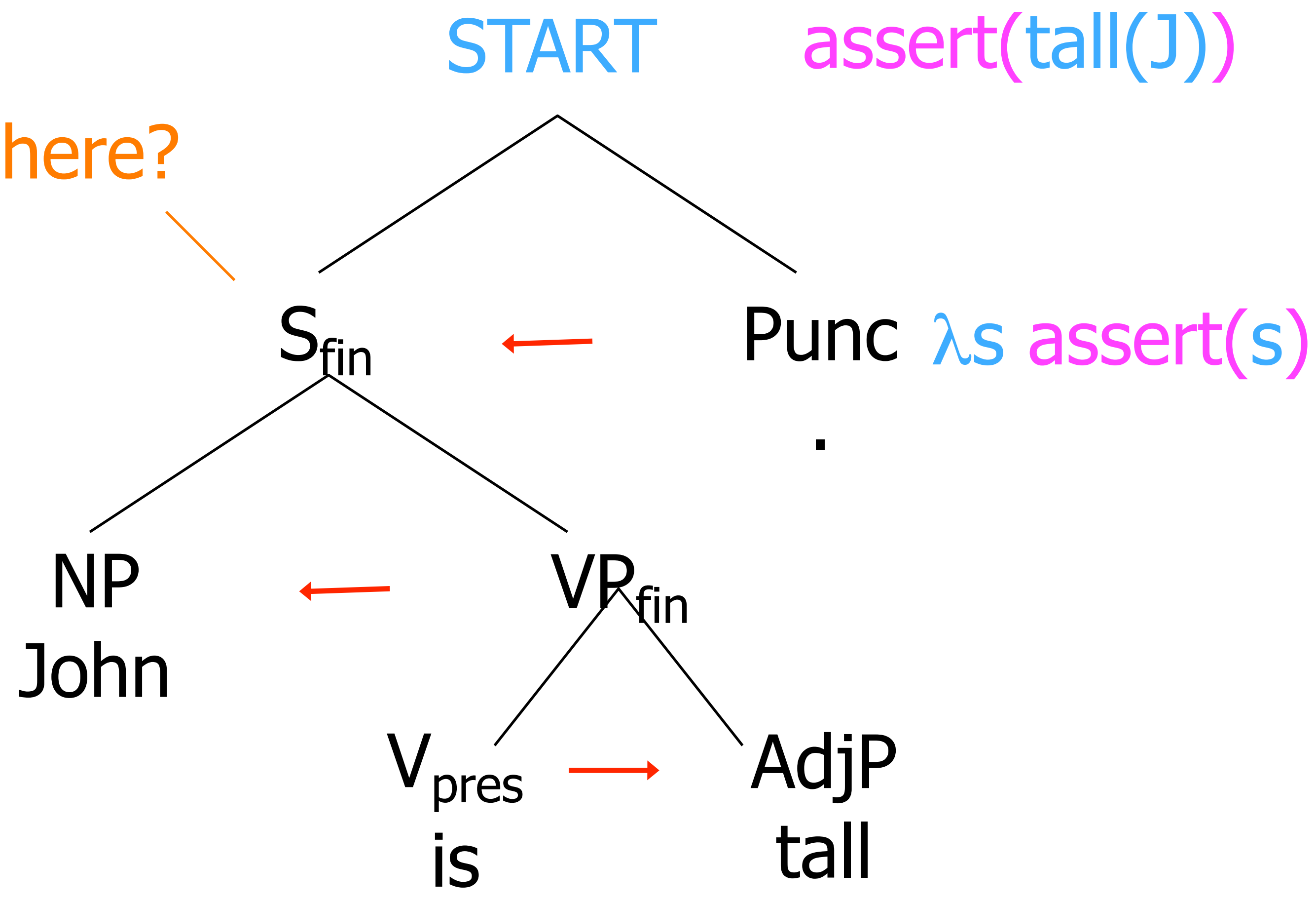
V_{pres}

is

AdjP

tall

Compositional Semantics



START assert(tall(J))

So what do we want here?

S_{fin}

Punc λs assert(s)

.

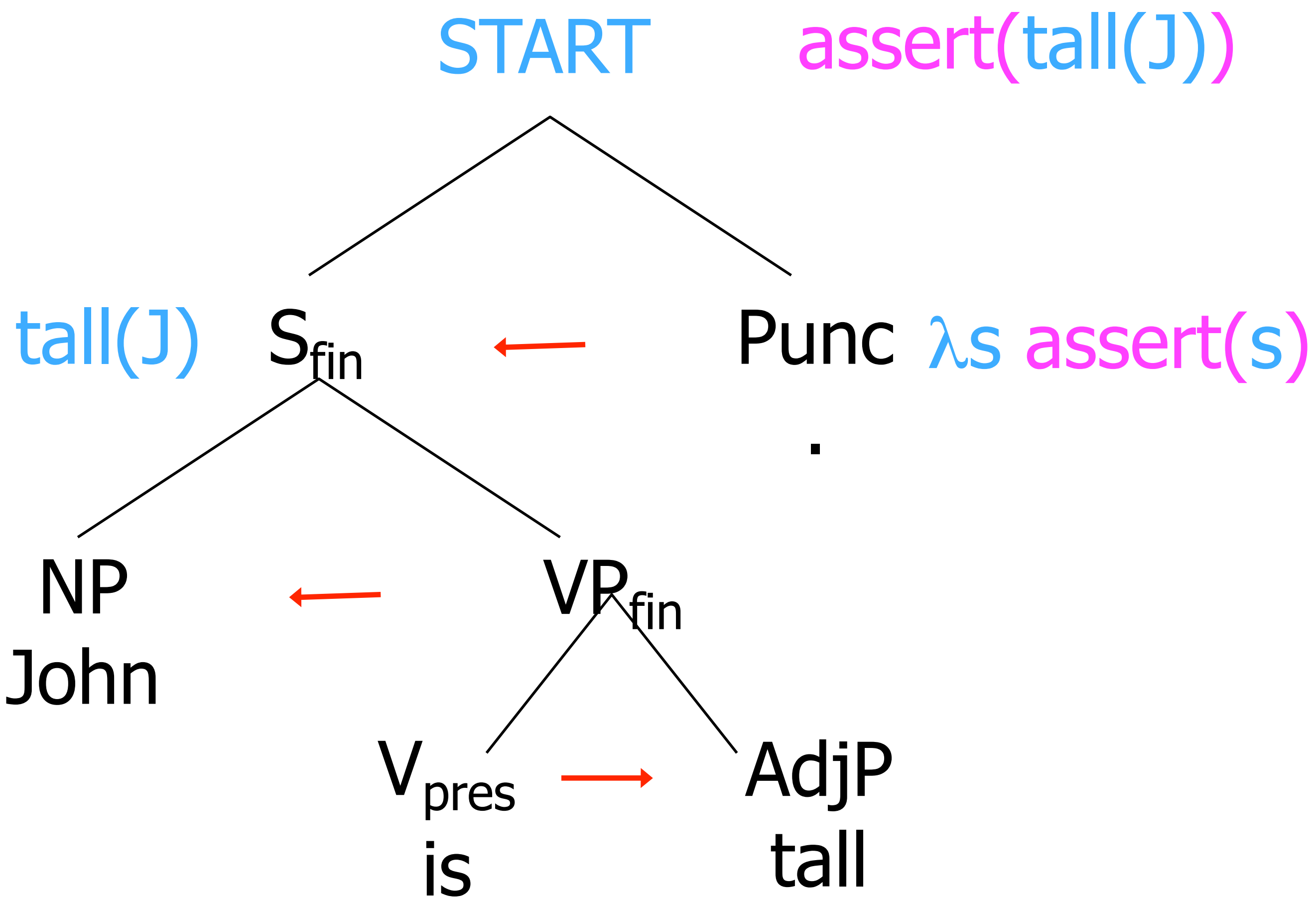
NP
John

VP_{fin}

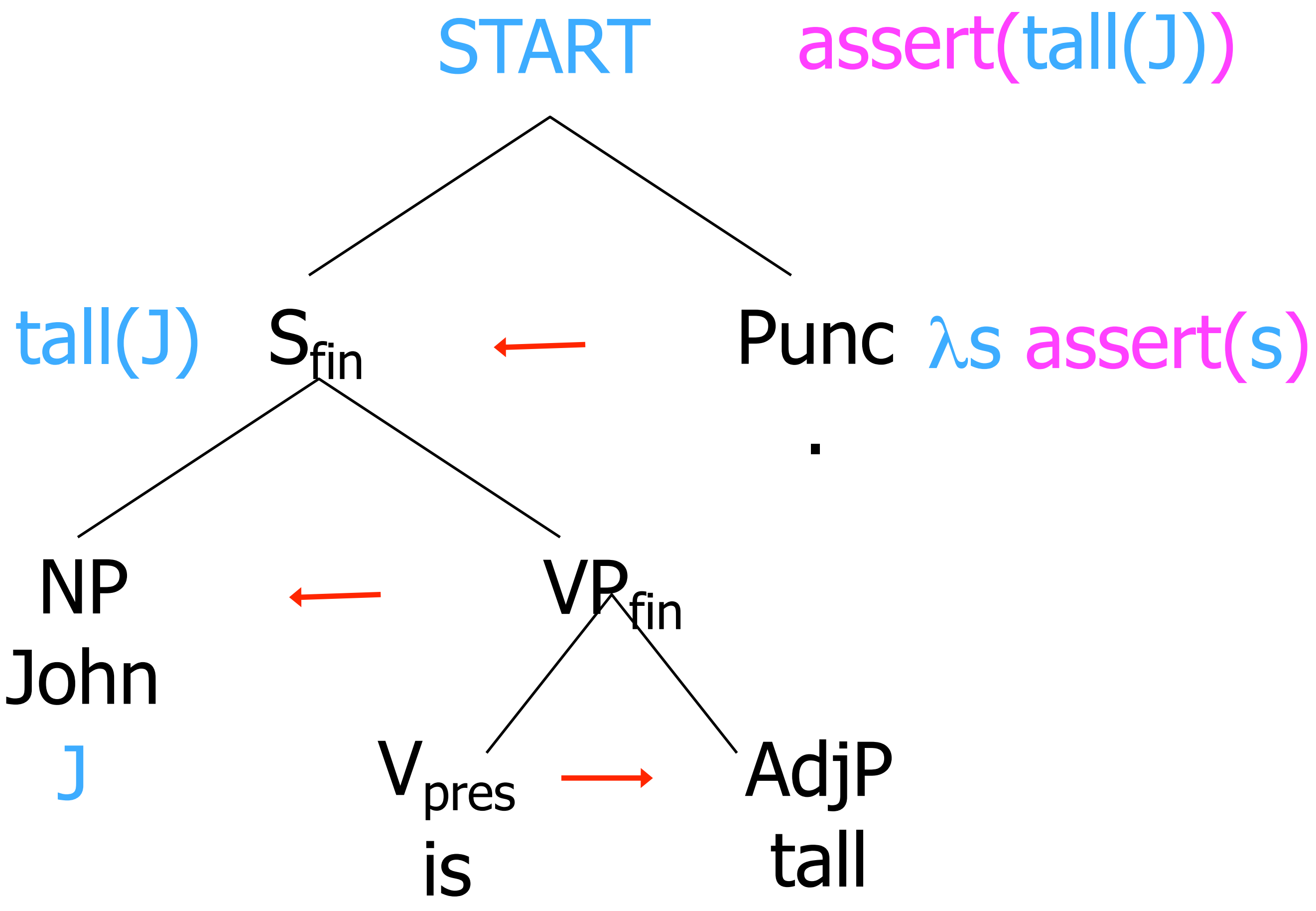
V_{pres}
is

AdjP
tall

Compositional Semantics



Compositional Semantics



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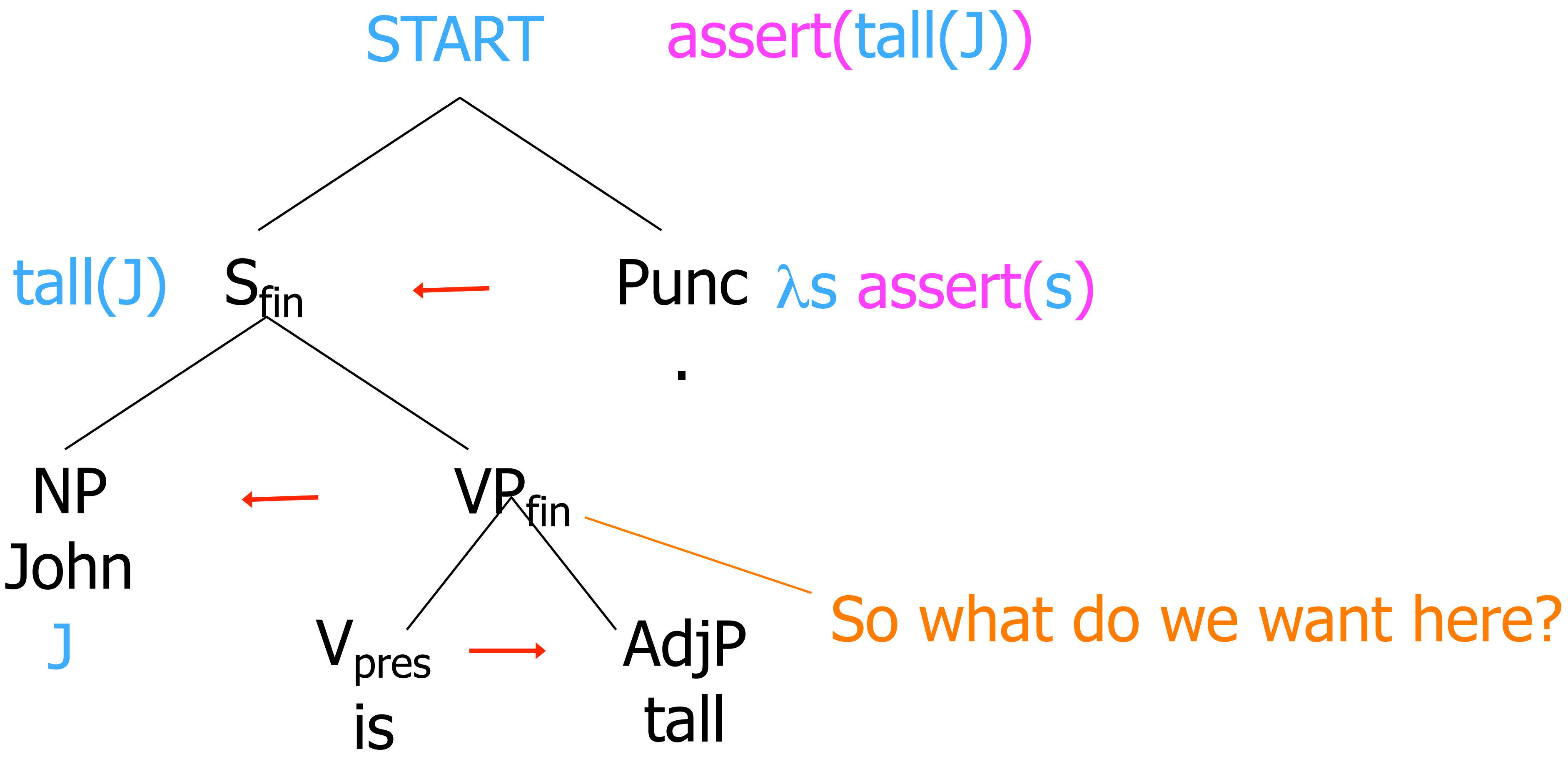

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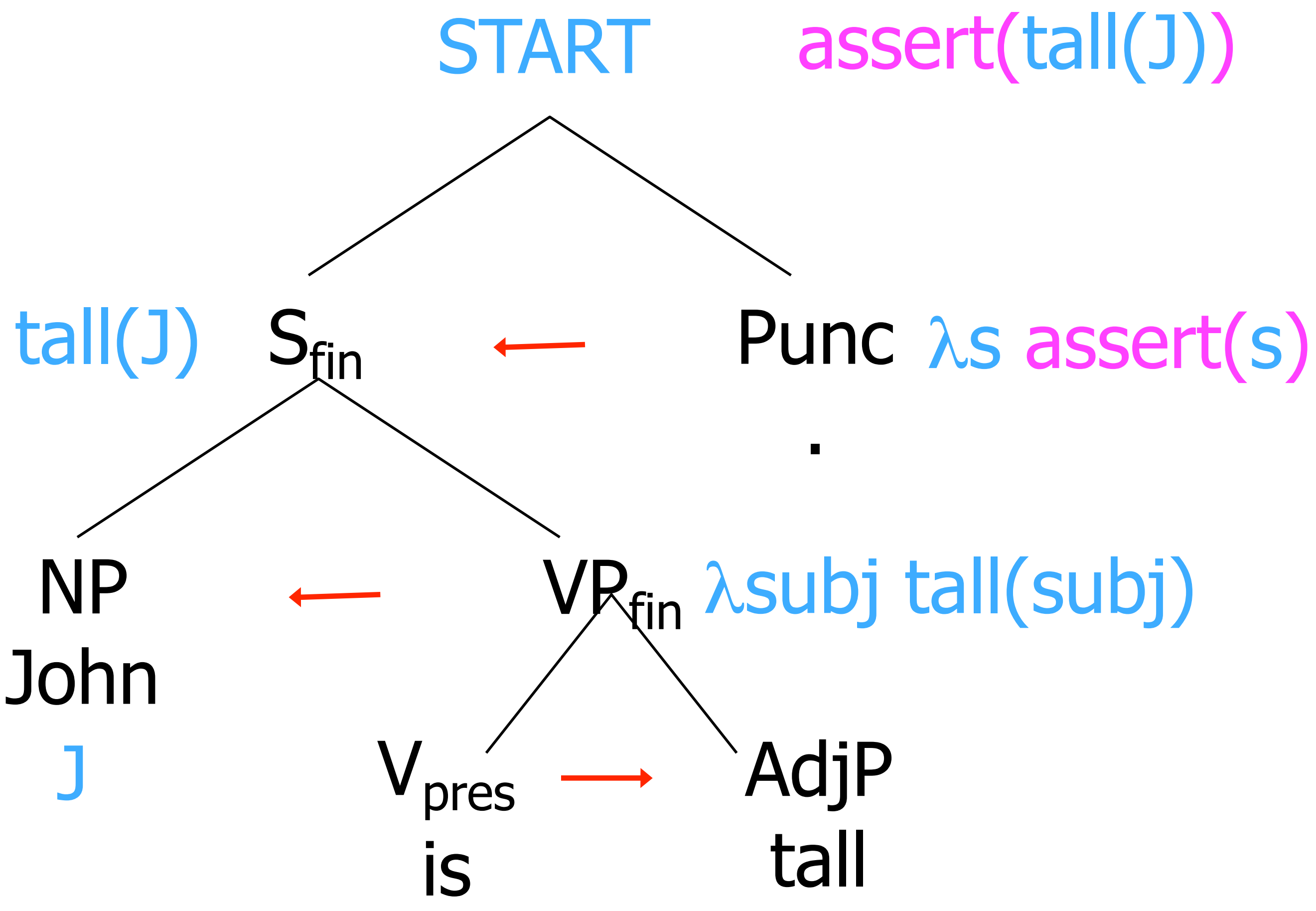


START assert(tall(J))

tall(J) S_{fin}

Punc λs assert(s)

.

NP

John

J

VP_{fin} λsubj tall(subj)

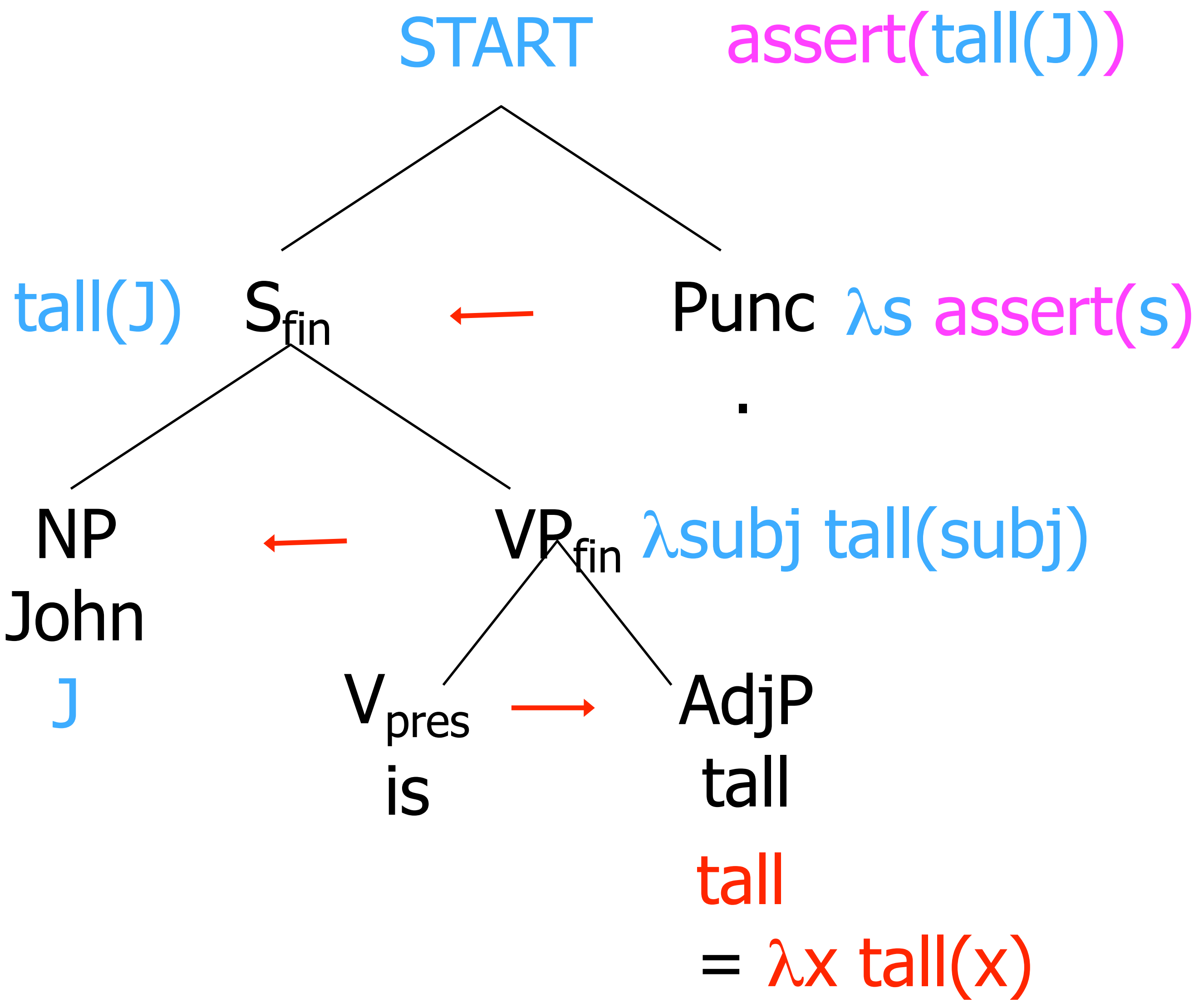
V_{pres}

is

AdjP

tall

Compositional Semantics



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NP

John

J

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V_{pres}

is

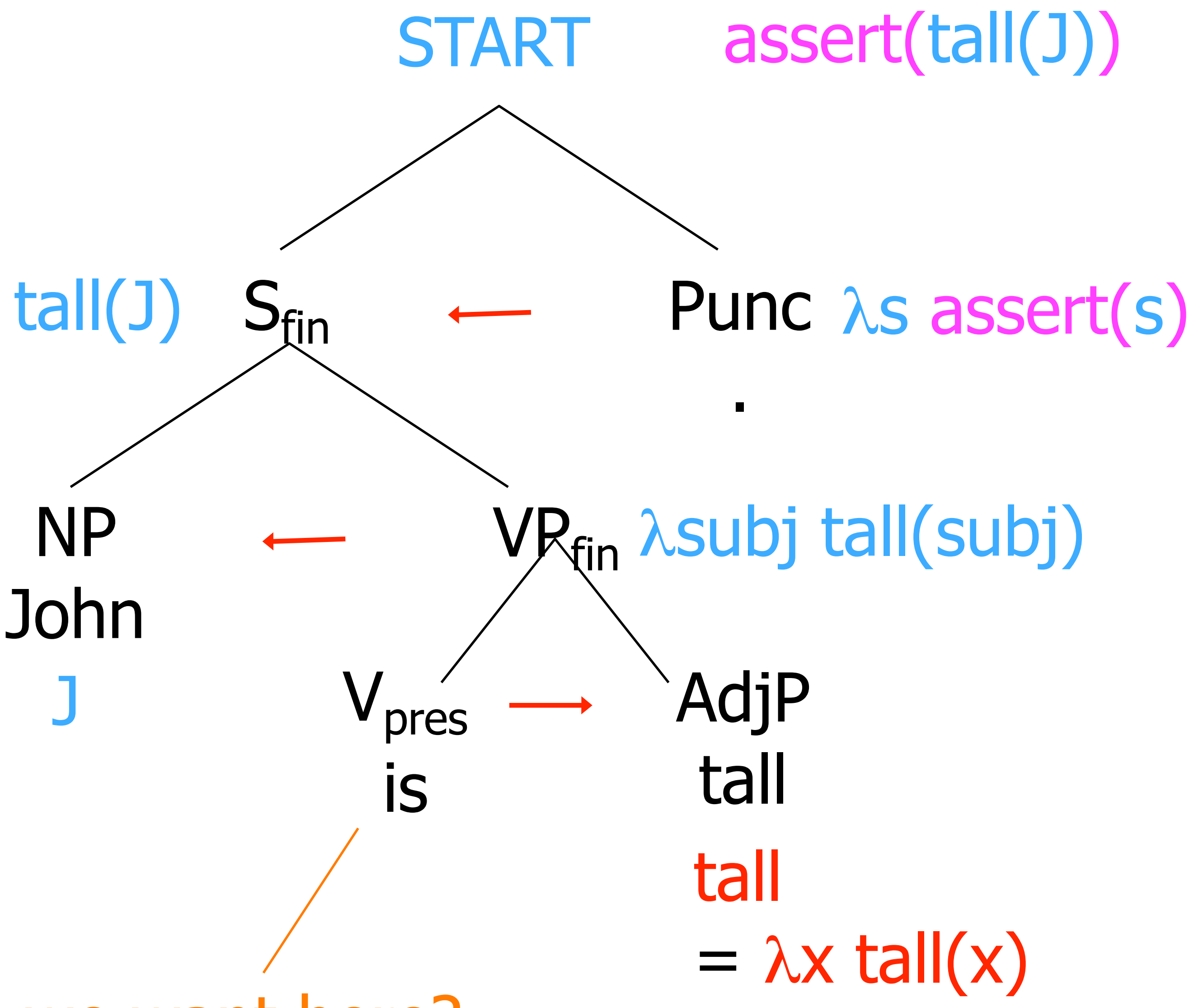
AdjP

tall

tall

= λx tall(x)

Compositional Semantics



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.

NP ← VP_{fin} λsubj tall(subj)

John

J

V_{pres} → AdjP

is

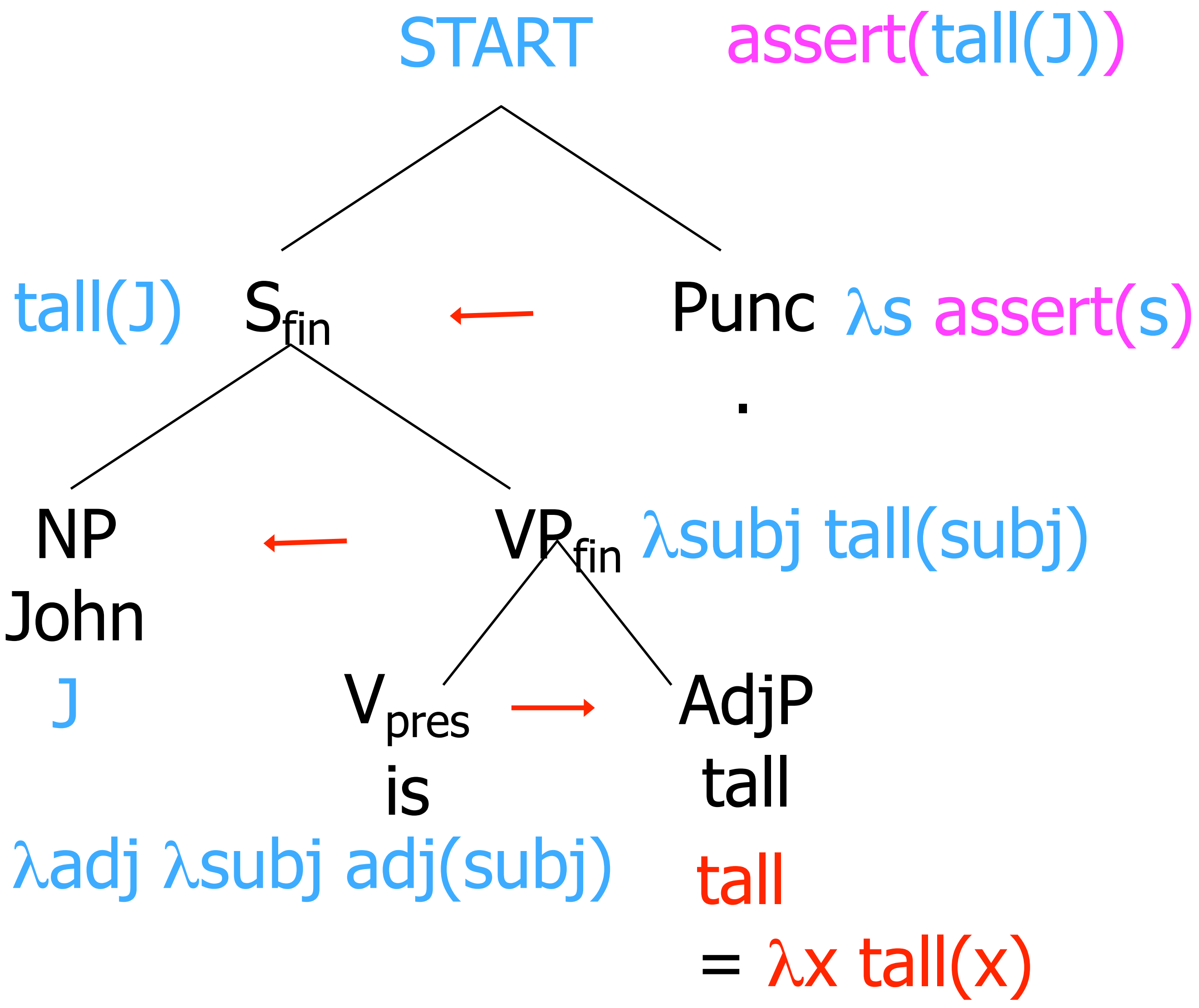
tall

tall

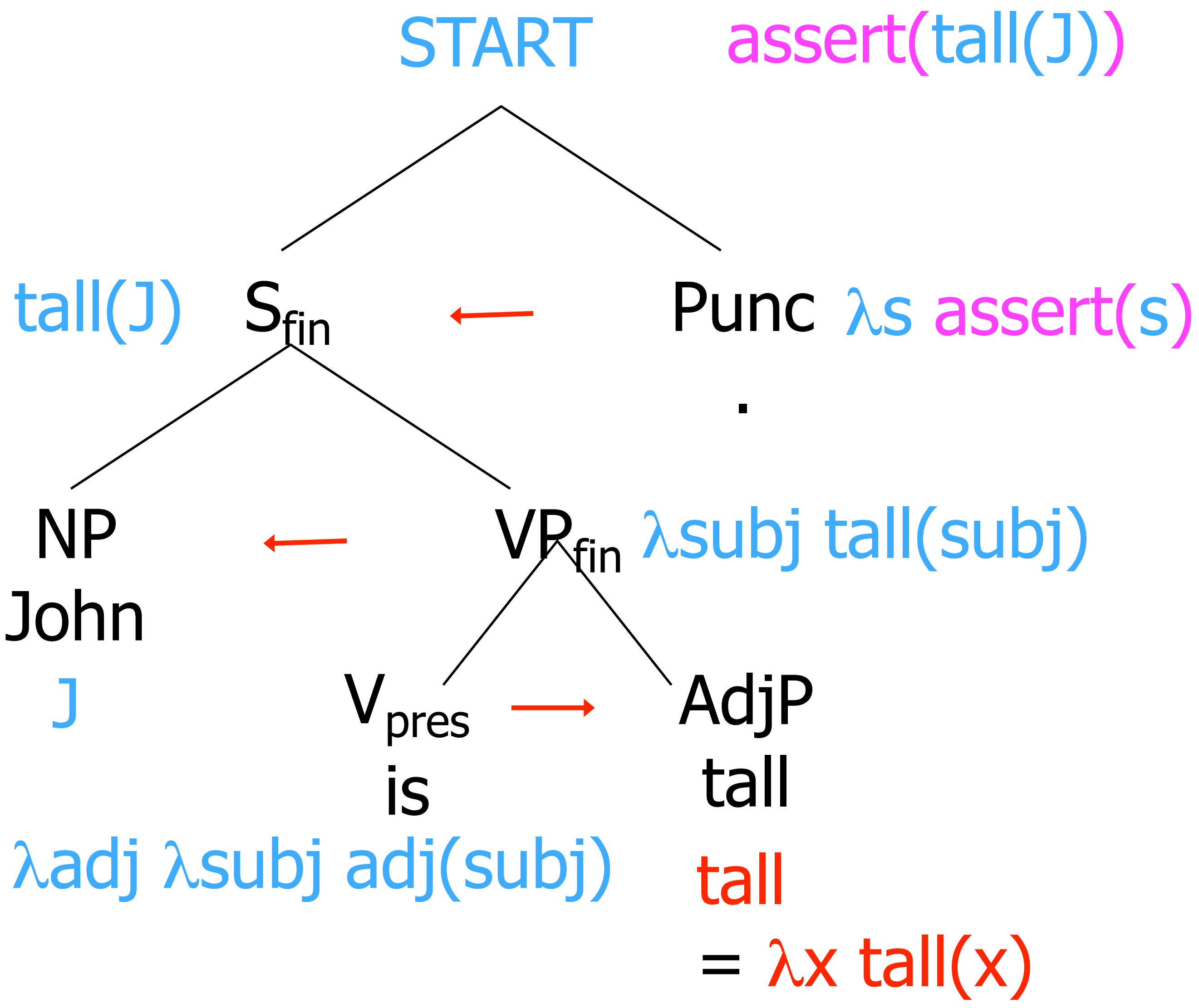
= λx tall(x)

So what do we want here?

Compositional Semantics



Compositional Semantics



START assert(tall(J))

tall(J) S_{fin} ← Punc λs assert(s)

.

NP ← VP_{fin} λsubj tall(subj)

John

J

V_{pres} → AdjP

is

tall

λadj λsubj adj(subj)

tall

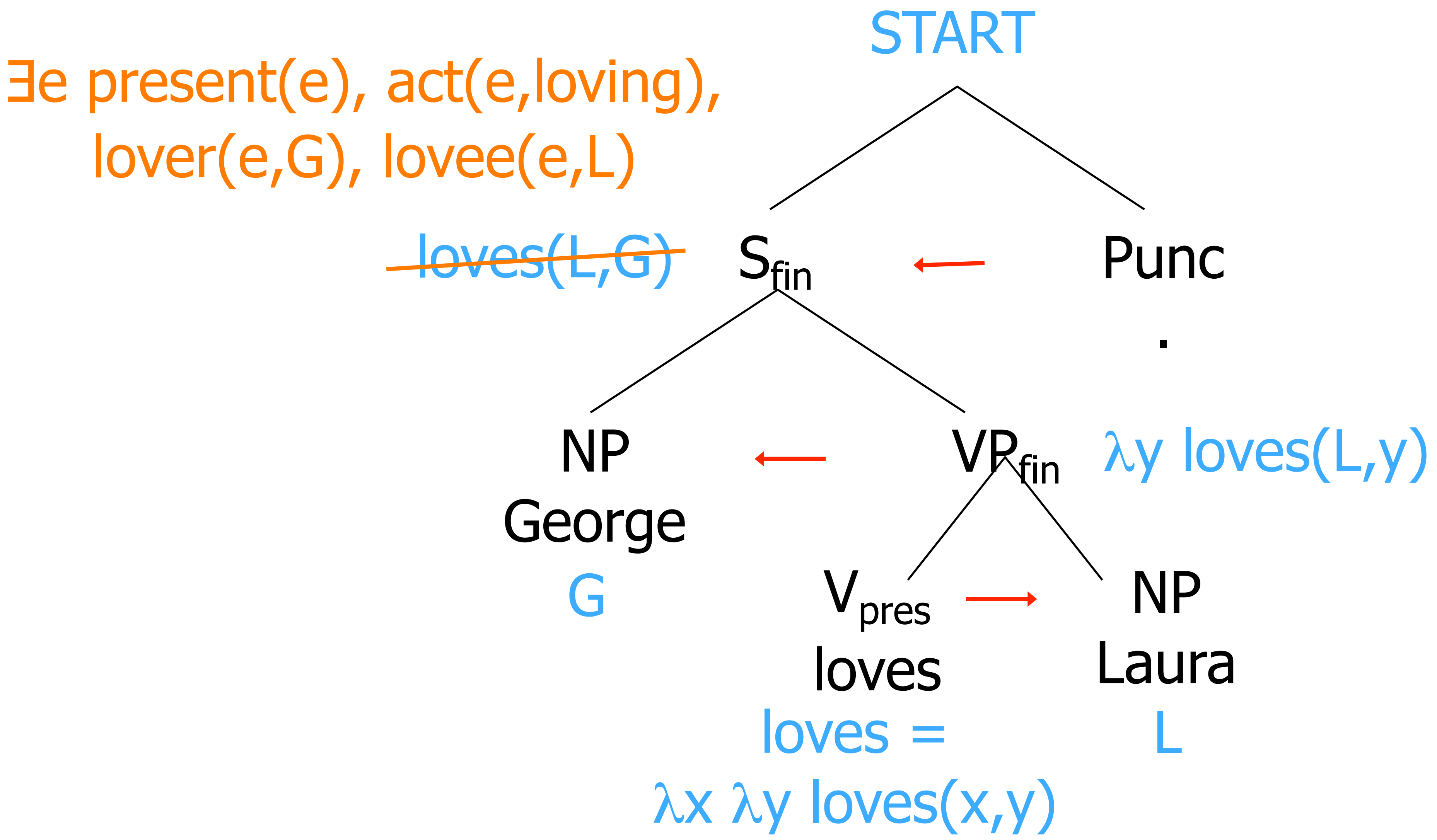
= λx tall(x)

(λadj λsubj adj(subj))(λx tall(x))

= λsubj (λx tall(x))(subj)

= λsubj tall(subj)

Compositional Semantics



START

∃e present(e), act(e,loving),
lover(e,G), lovee(e,L)

~~loves(L,G)~~ S_{fin}

Punc

.

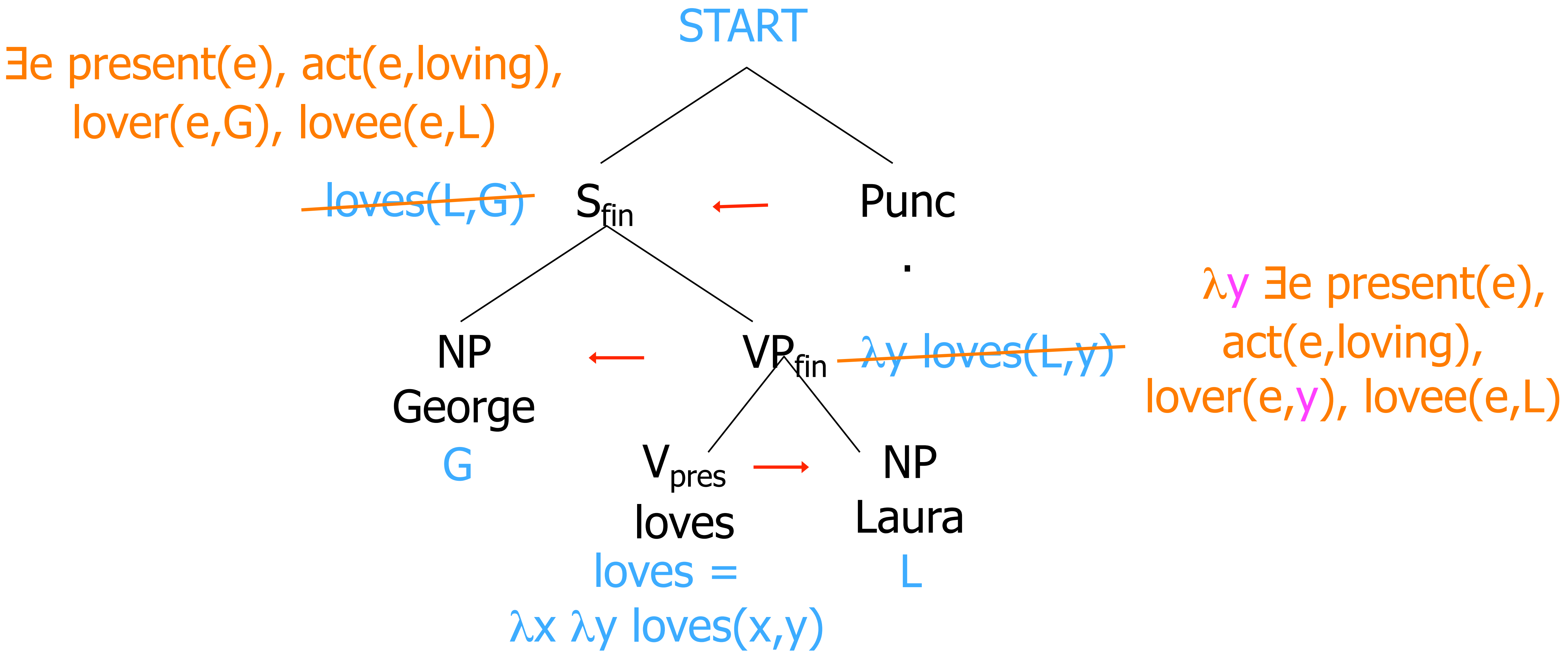
NP
George
G

VP_{fin} λy loves(L,y)

V_{pres}
loves
loves =
$\lambda x \lambda y$ loves(x,y)

NP
Laura
L

Compositional Semantics



START

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lover(e,G), lovee(e,L)

~~loves(L,G)~~ S_{fin}

Punc

.

NP
George
G

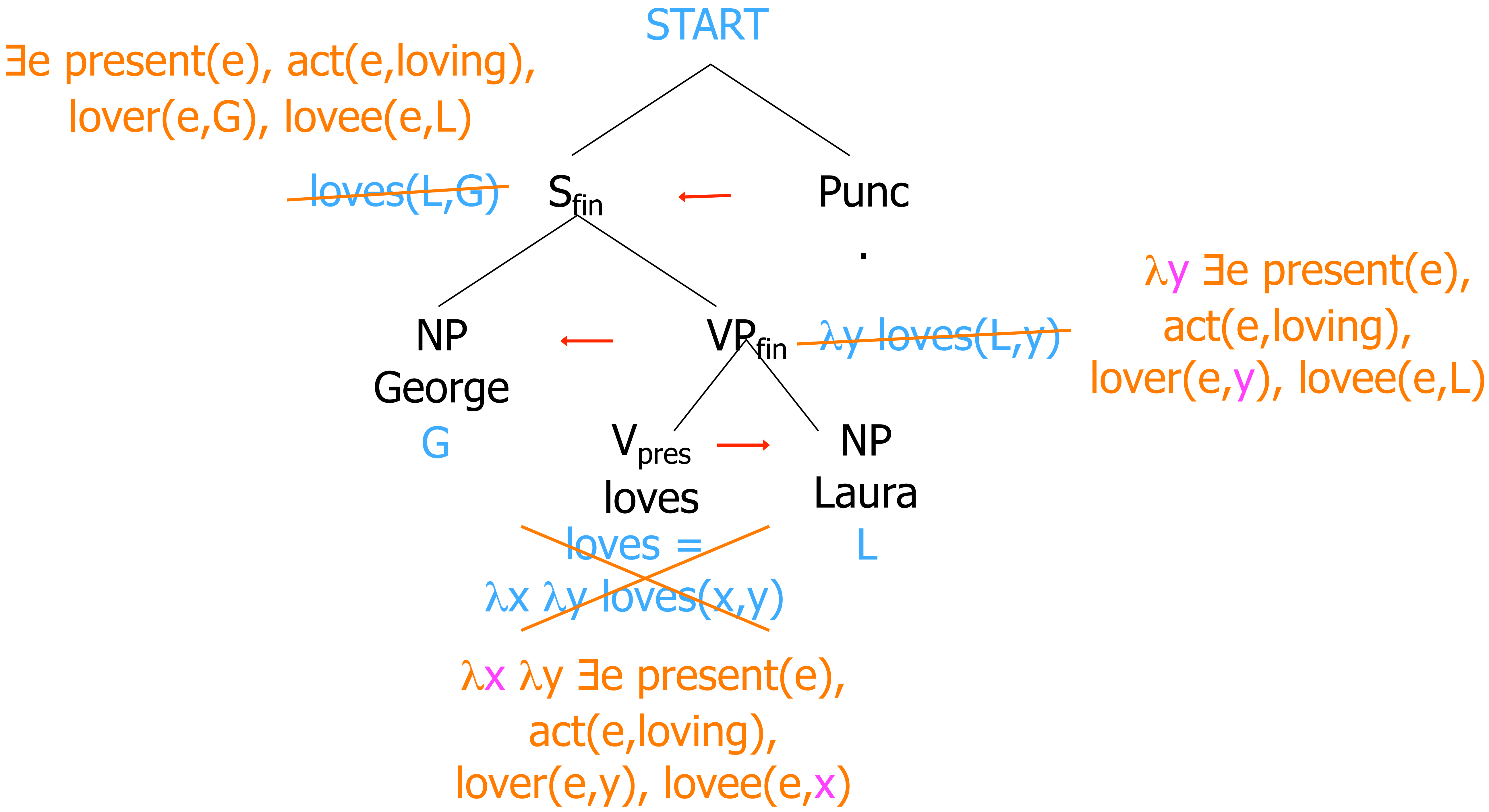
VP_{fin} ~~λy loves(L,y)~~

λy ∃e present(e),
act(e,loving),
lover(e,y), lovee(e,L)

V_{pres}
loves
loves =
λx λy loves(x,y)

NP
Laura
L

Compositional Semantics



START

∃e present(e), act(e,loving),
lover(e,G), lovee(e,L)

~~loves(L,G)~~ S_{fin} ← Punc

.

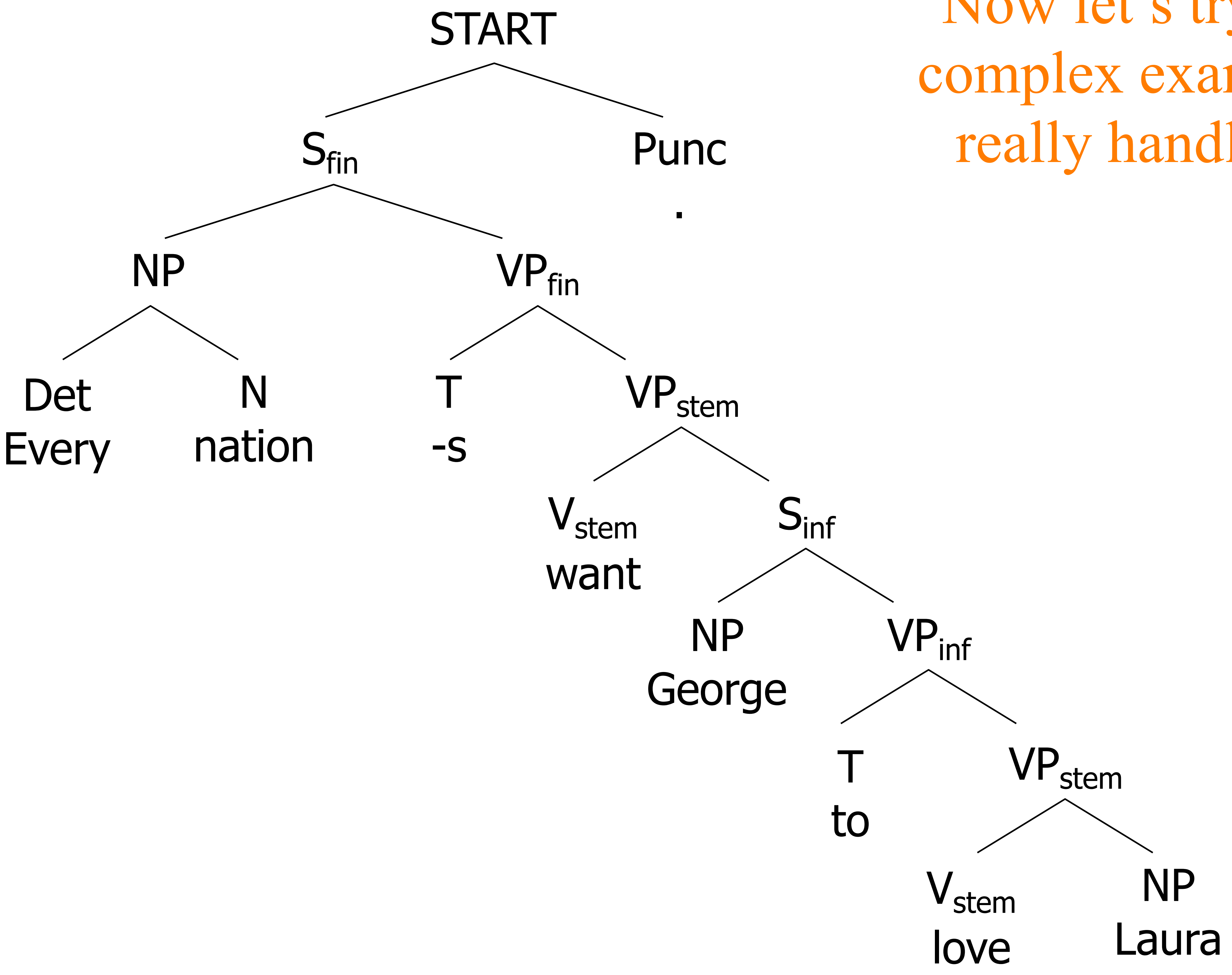
NP ← VP_{fin} ~~λy loves(L,y)~~
George
G

λy ∃e present(e),
act(e,loving),
lover(e,y), lovee(e,L)

V_{pres} → NP
loves Laura
L

~~loves =~~
~~λx λy loves(x,y)~~

λx λy ∃e present(e),
act(e,loving),
lover(e,y), lovee(e,x)



Now let's try a more complex example, and really handle tense.

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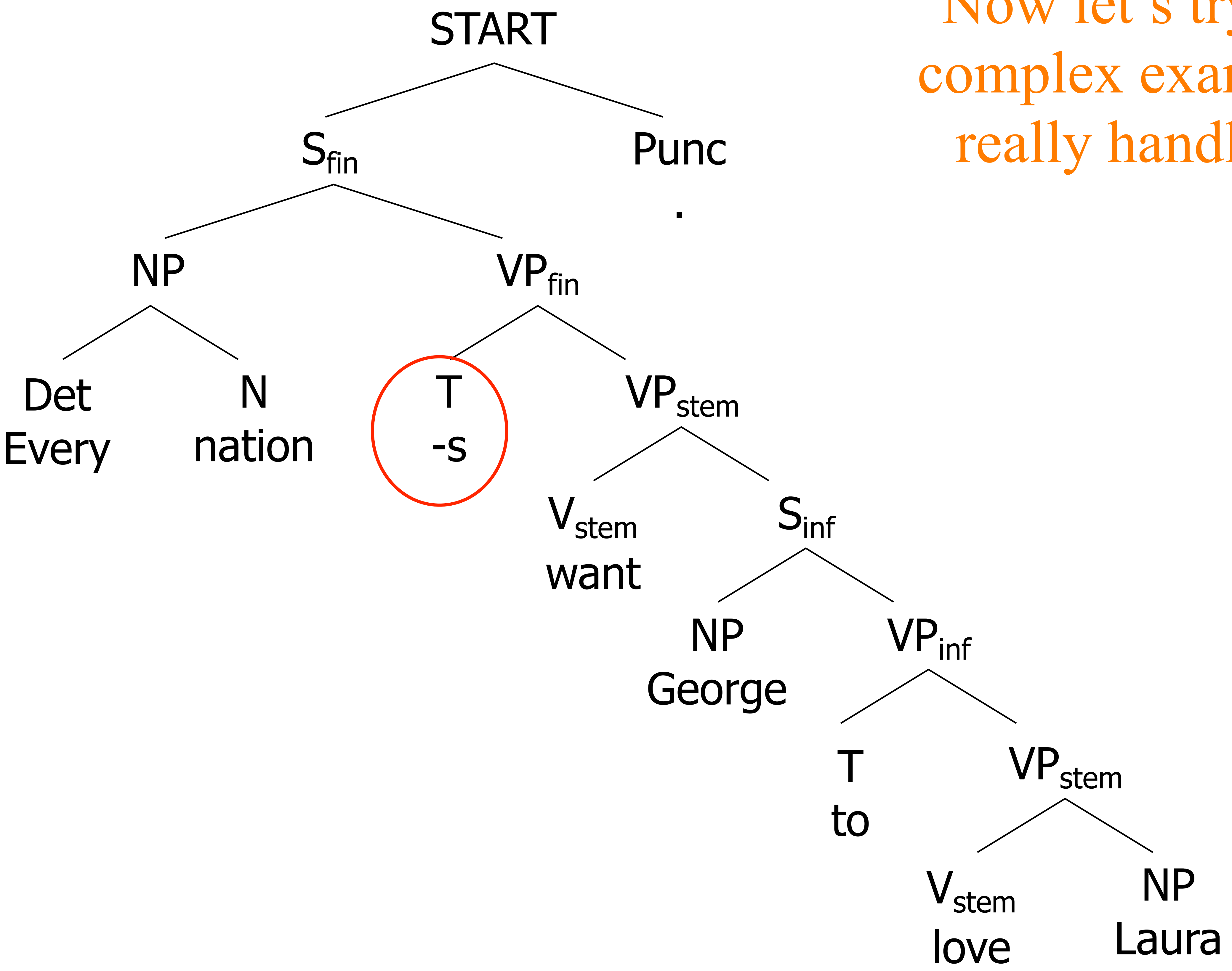

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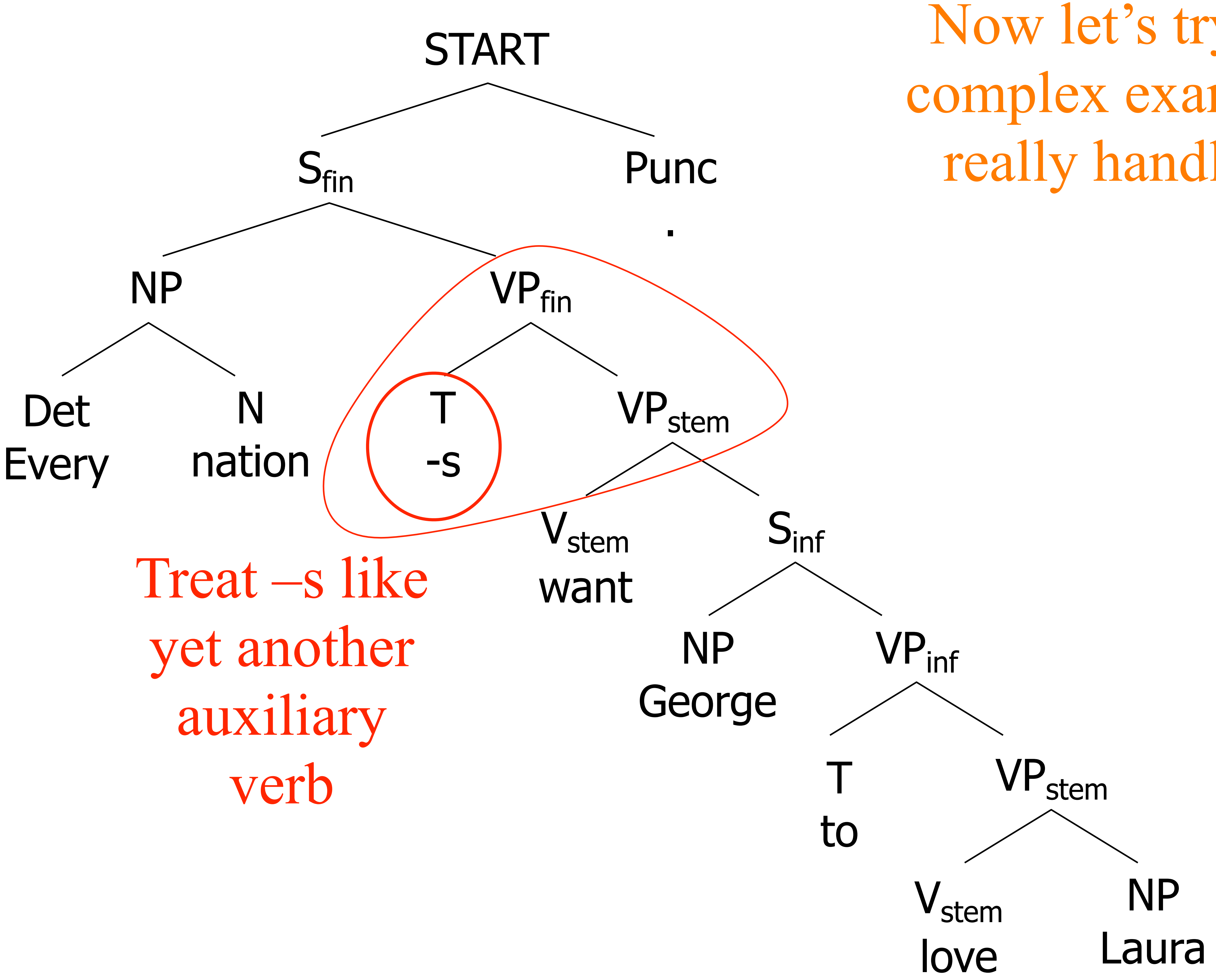
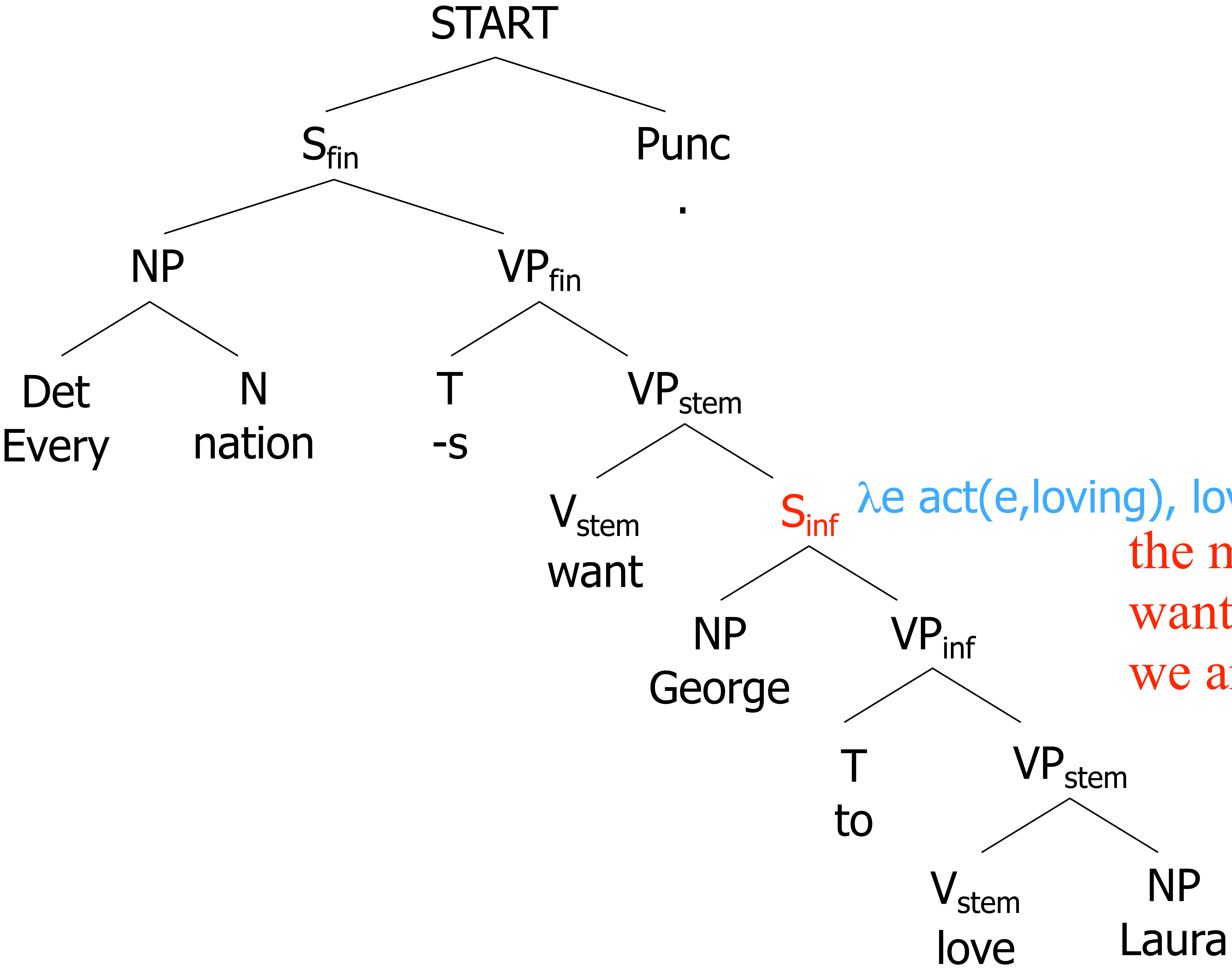
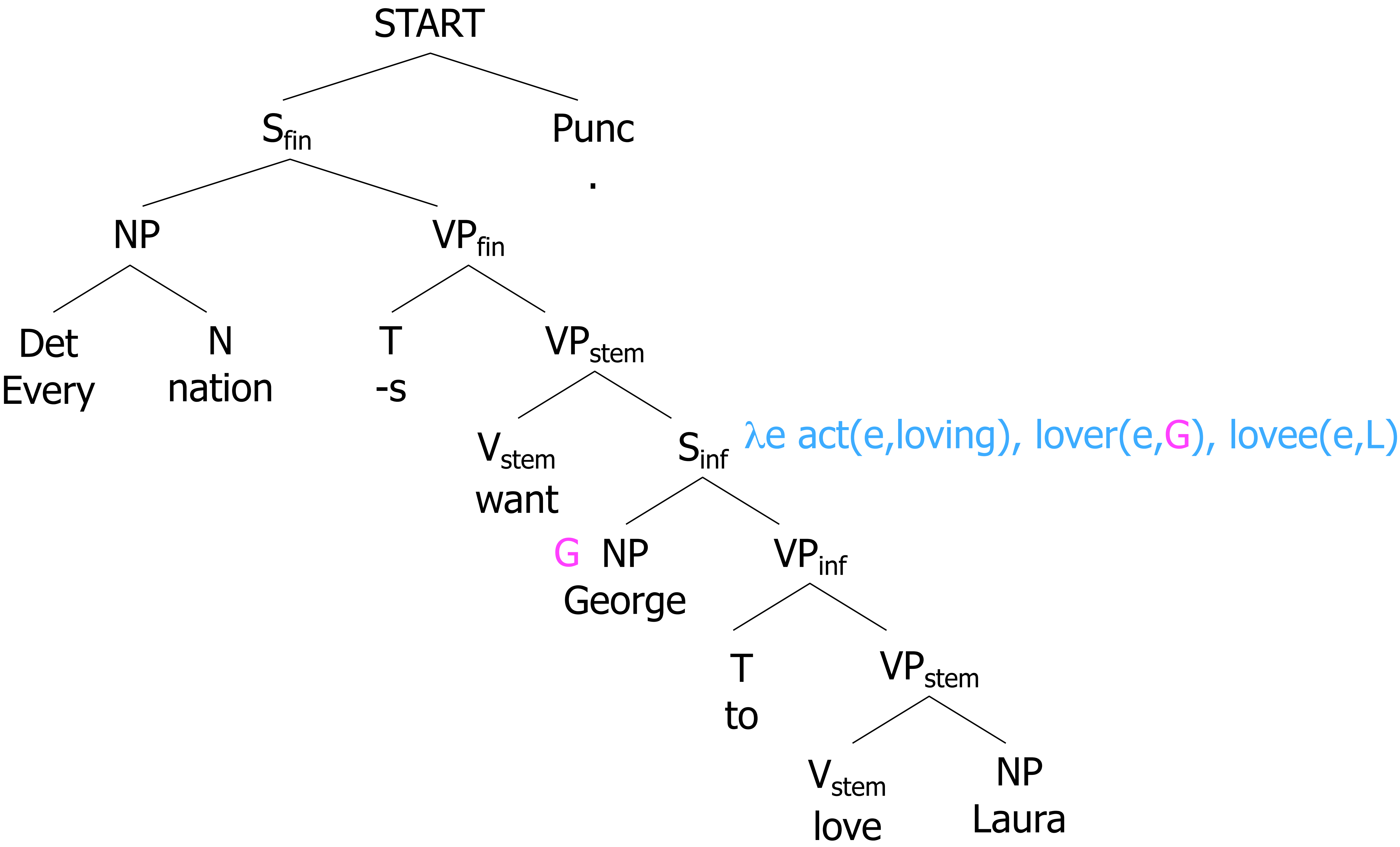


Treat –s like yet another auxiliary verb

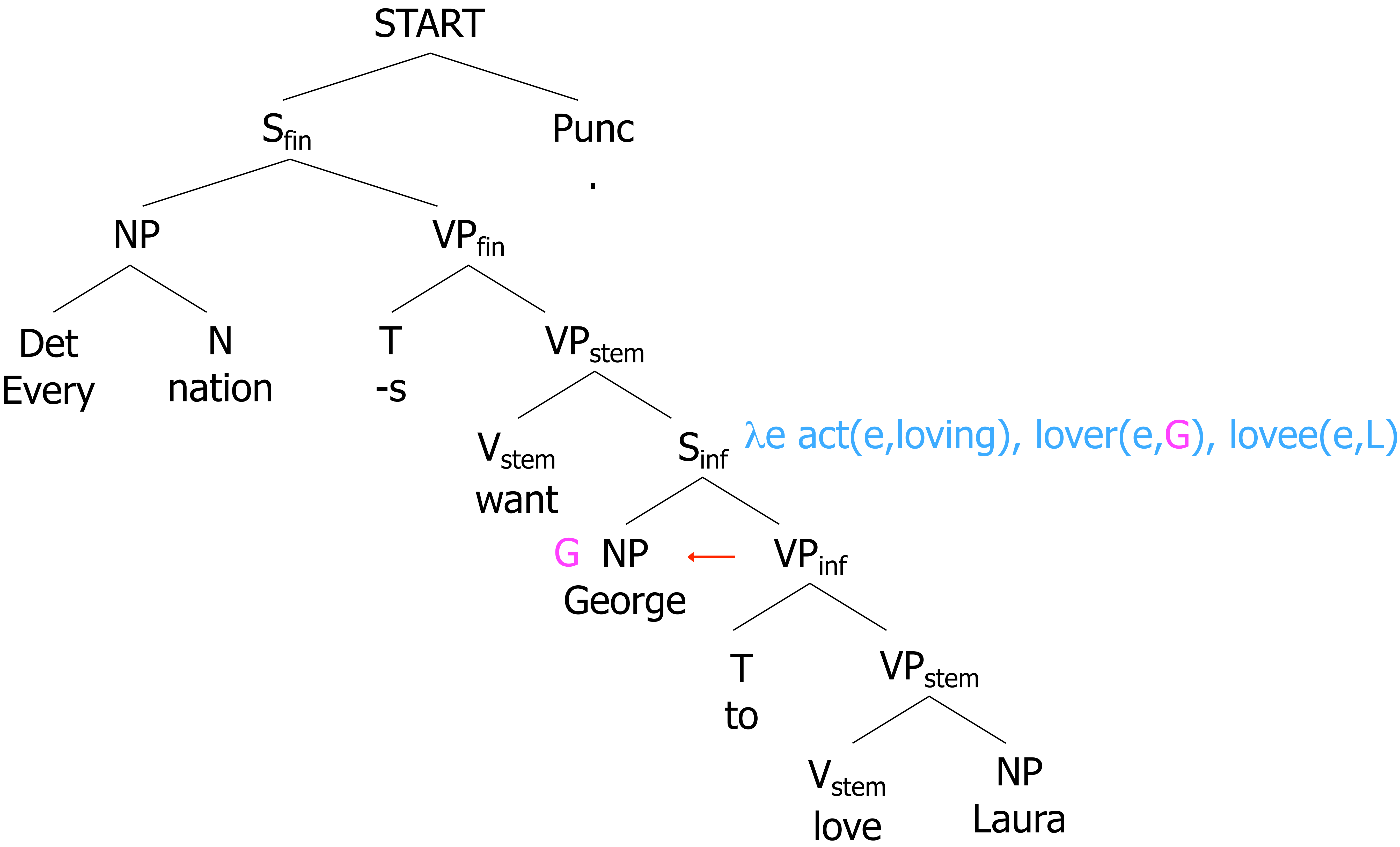


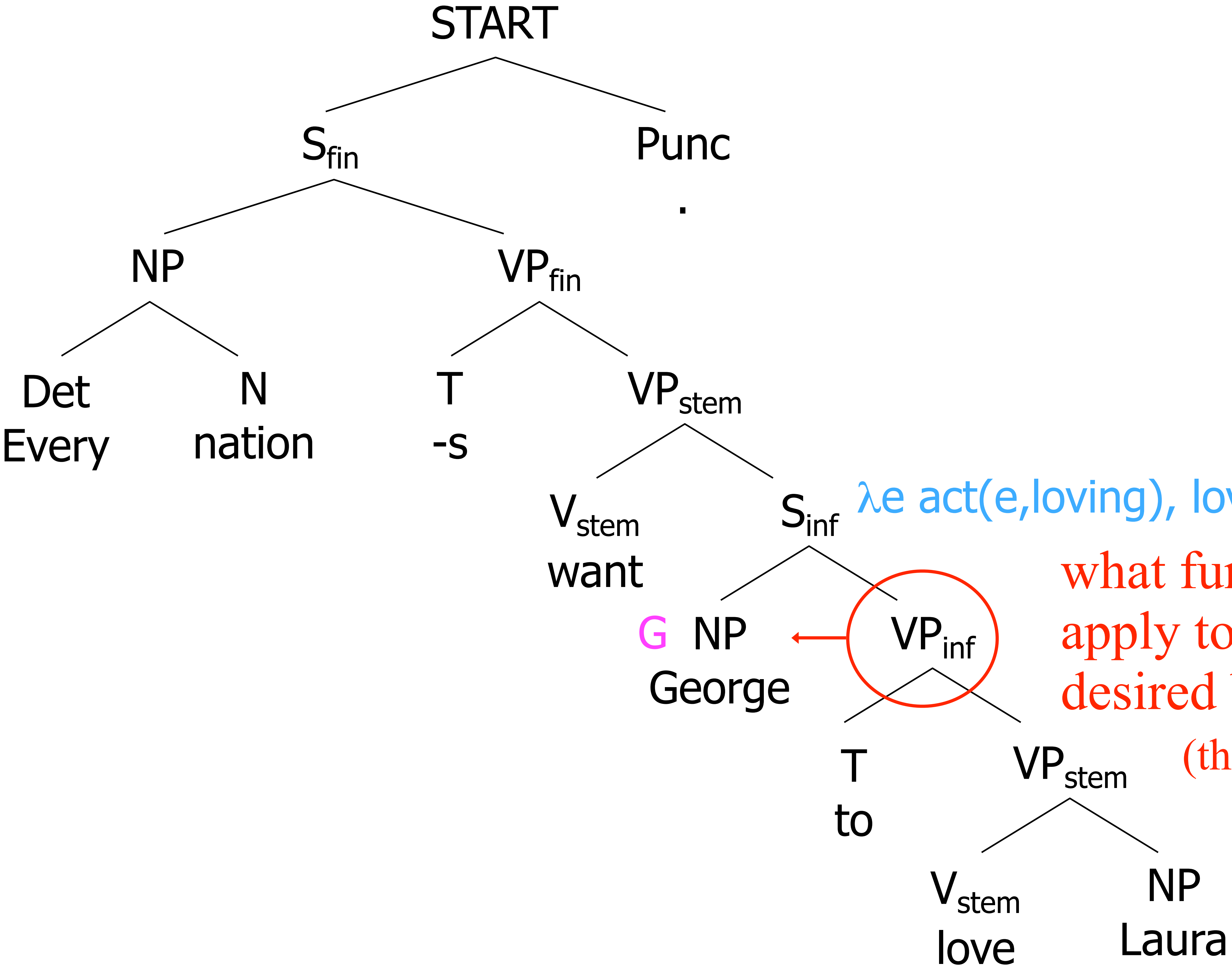
λe act(e,loving), lover(e,G), lovee(e,L)

the meaning that we want here: how can we arrange to get it?



λe act(e,loving), lover(e,G), lovee(e,L)

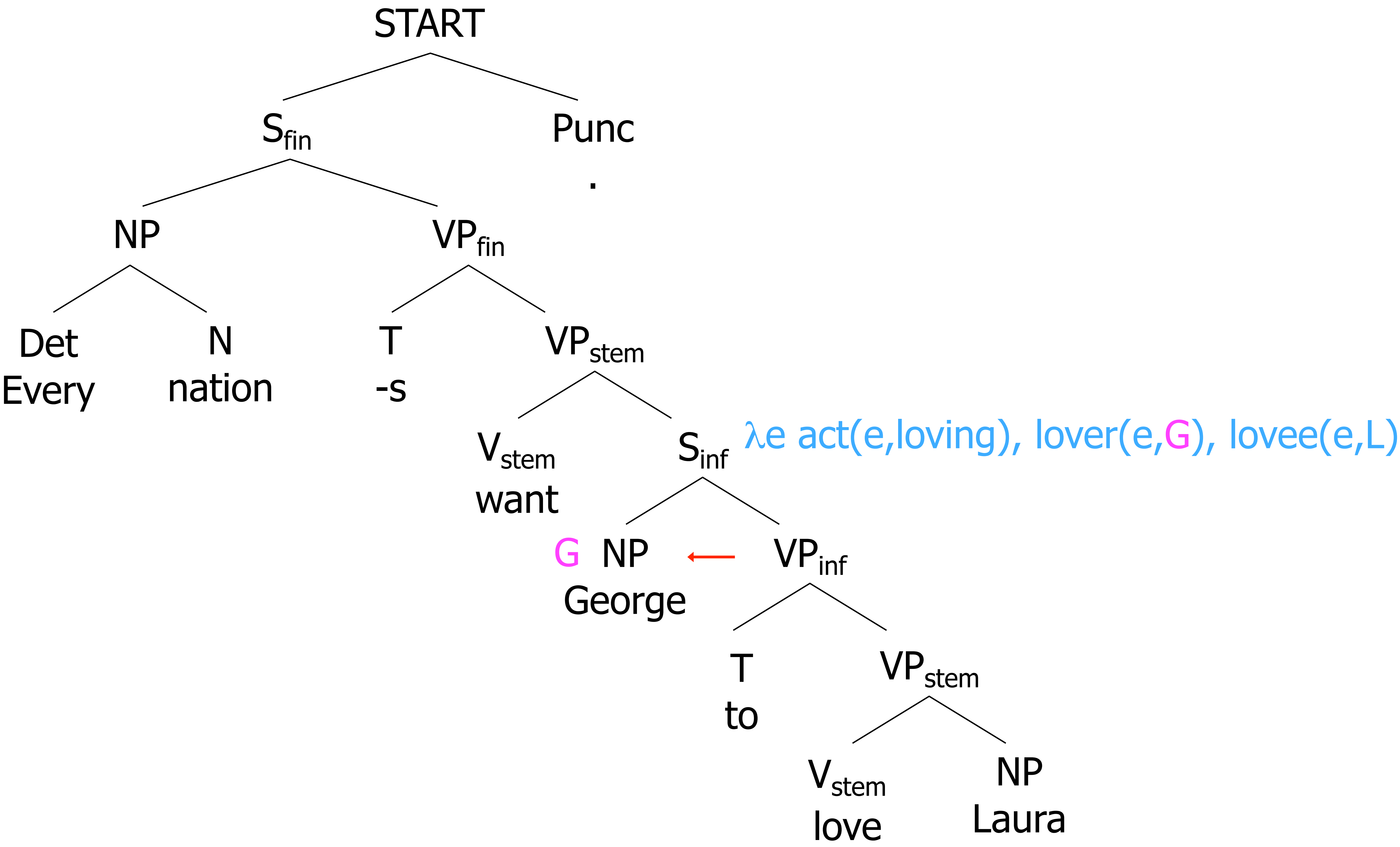

START
S fin
Punc
.
NP
VP fin
Det
Every
N
nation
T
-s
VP stem
V stem
want
S inf
λe act(e,loving), lover(e,G), lovee(e,L)
G NP
George
VP inf
T
to
VP stem
V stem
love
NP
Laura



$\lambda e\ act(e,loving), lover(e,G), lovee(e,L)$

what function should apply to G to yield the desired blue result?

(this is like division!)



START

S_{fin} Punc

.

NP VP_{fin}

Det N T VP_{stem}

Every nation -s

V_{stem} S_{inf} λe act(e,loving), lover(e,G), lovee(e,L)

want

G NP ← VP_{inf}

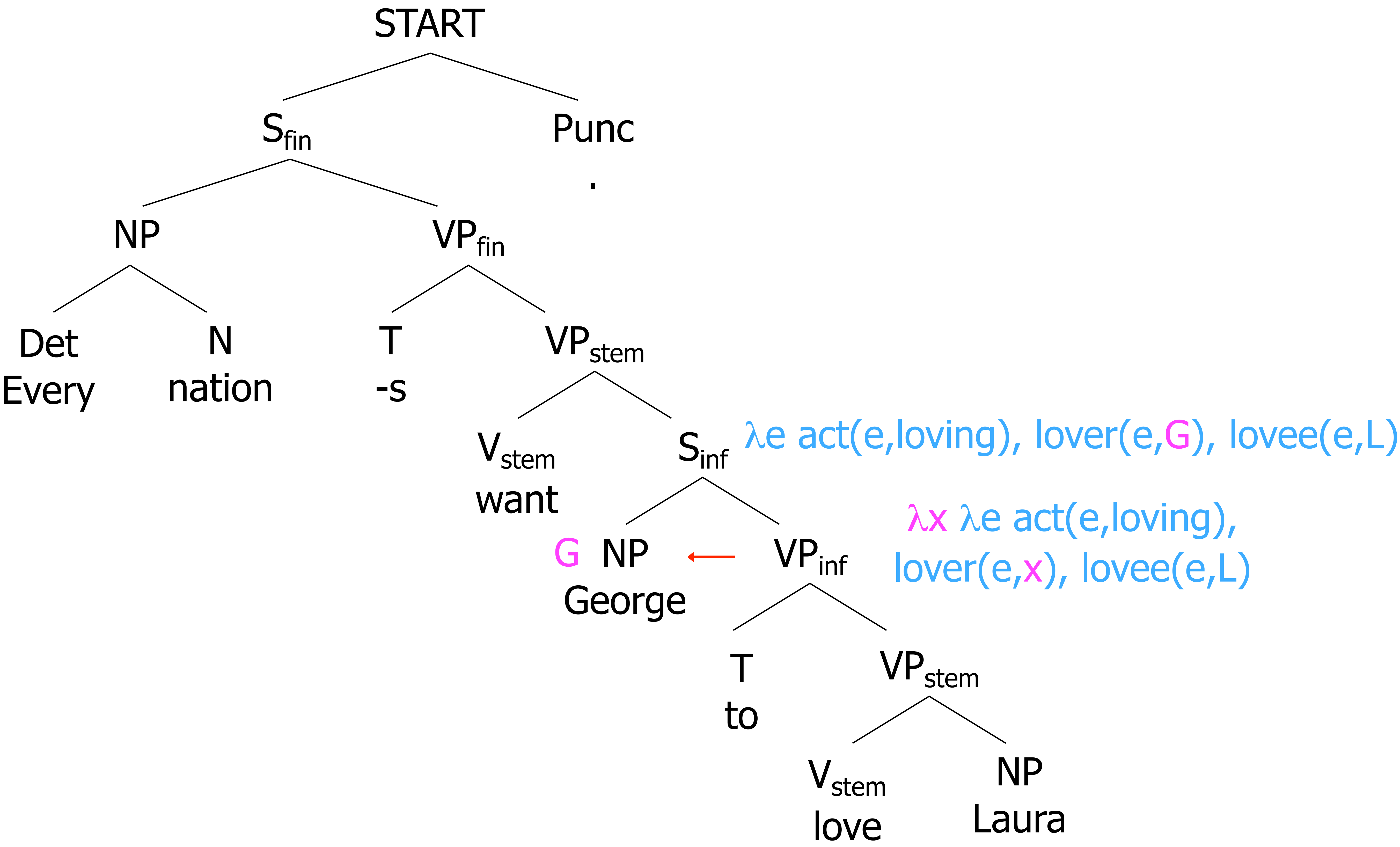
George

T VP_{stem}

to

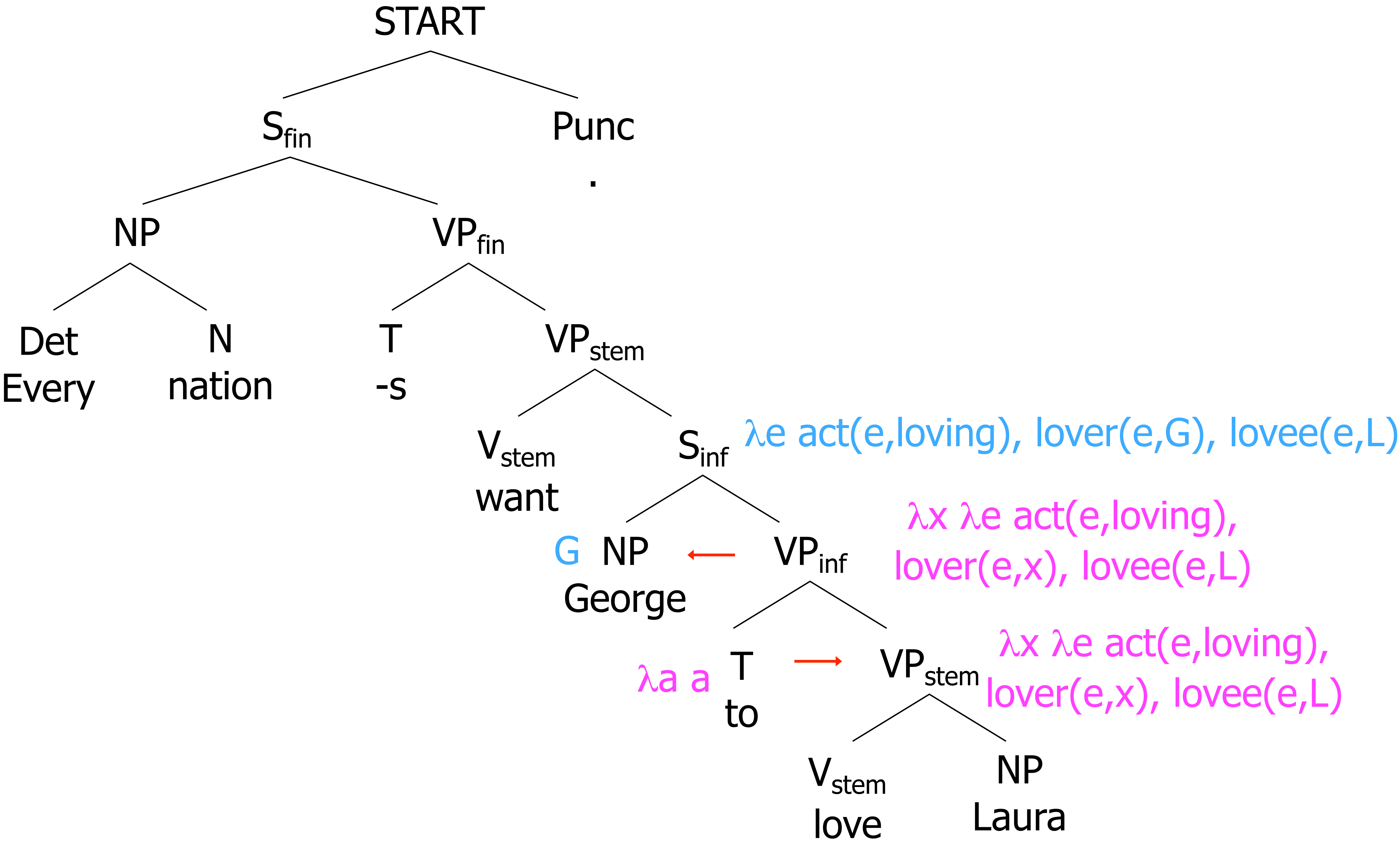
V_{stem} NP

love Laura



λe act(e,loving), lover(e,G), lovee(e,L)

λx λe act(e,loving), lover(e,x), lovee(e,L)



START

S_{fin} Punc

.

NP VP_{fin}

Det Every

N nation

T -s

VP_{stem}

V_{stem} want

S_{inf} λe act(e,loving), lover(e,G), lovee(e,L)

G NP George ⟵ VP_{inf}

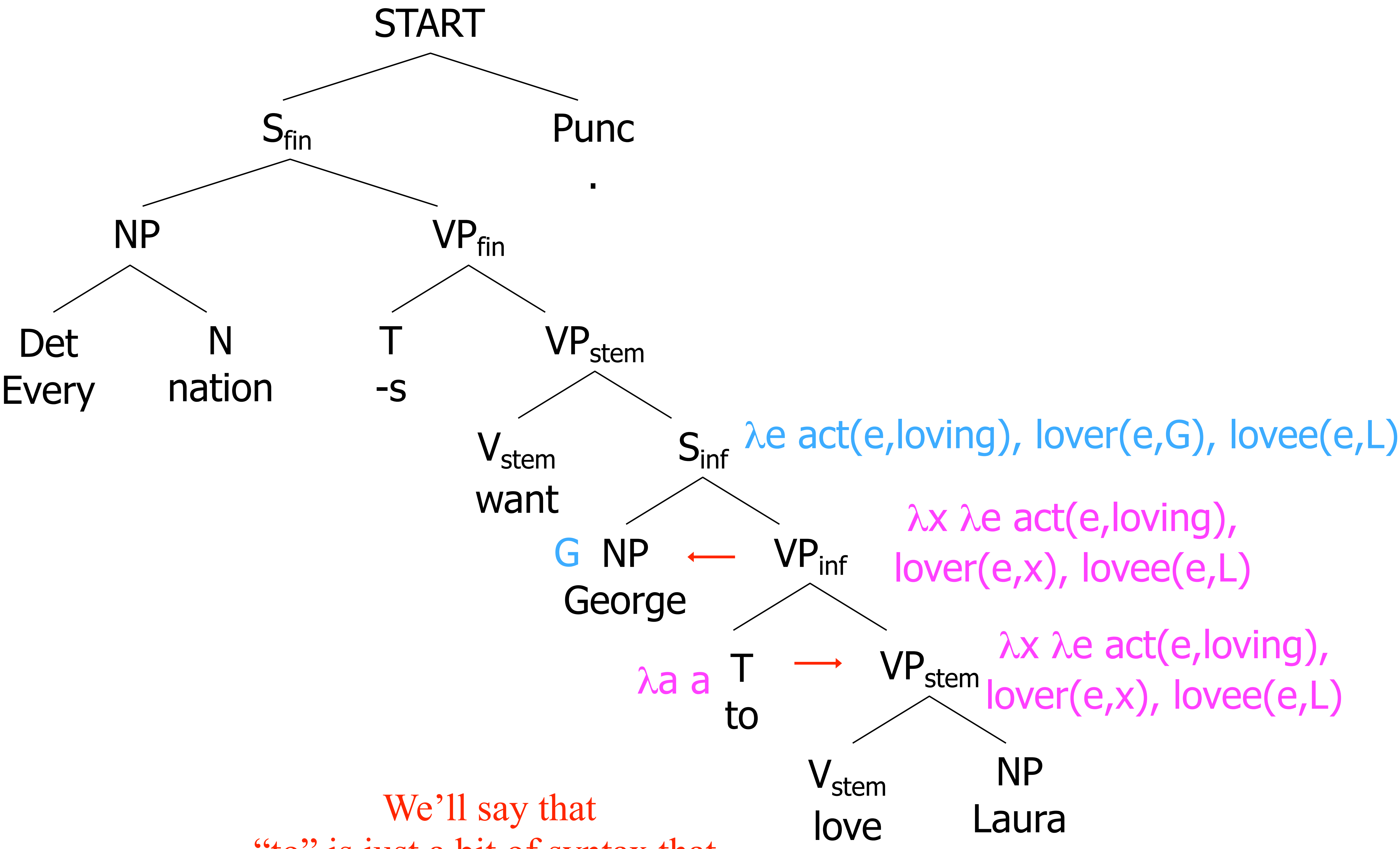
λx λe act(e,loving), lover(e,x), lovee(e,L)

λa a T to ⟶ VP_{stem}

λx λe act(e,loving), lover(e,x), lovee(e,L)

V_{stem} love

NP Laura



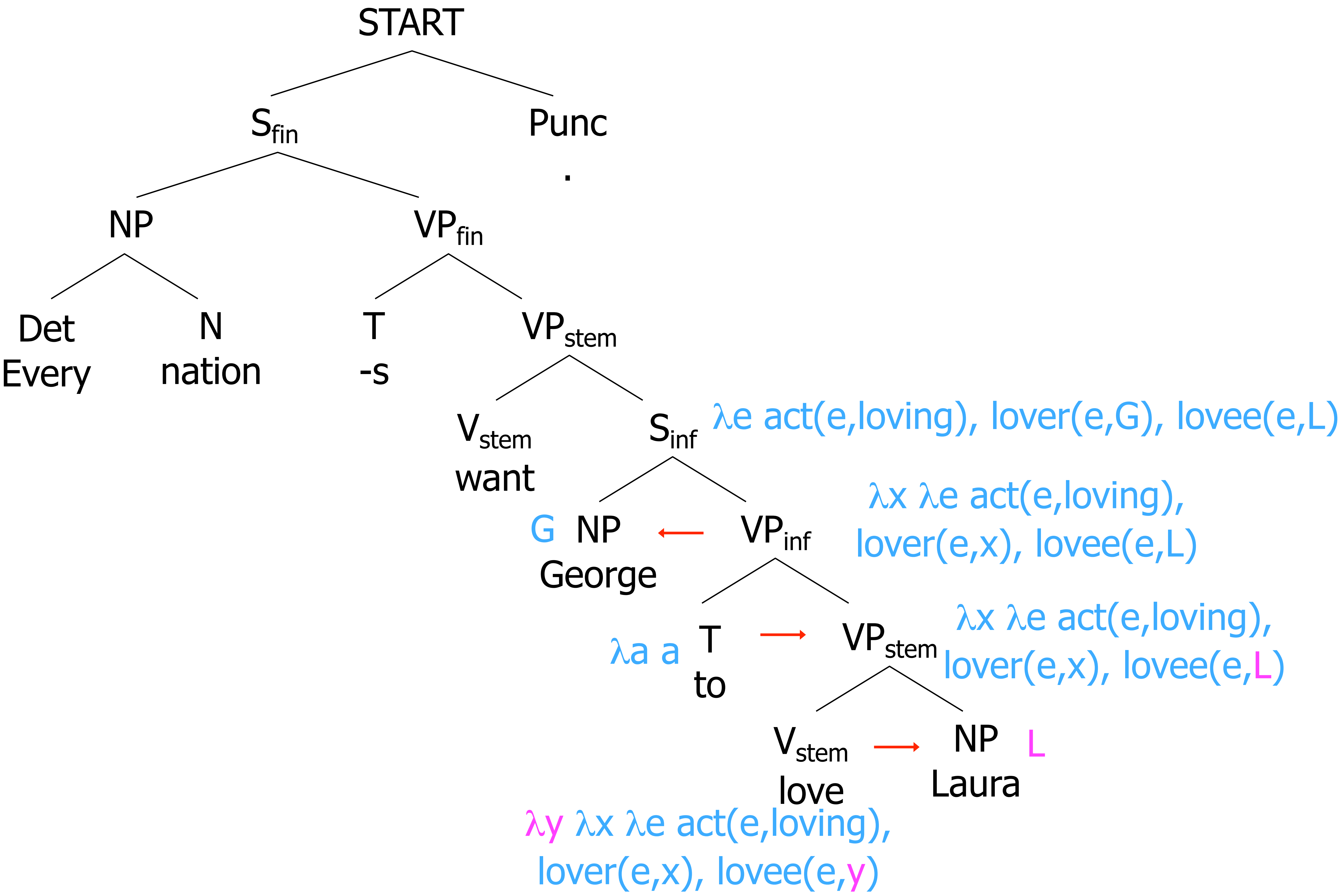
$\lambda e\ act(e,loving), lover(e,G), lovee(e,L)$

$\lambda x\ \lambda e\ act(e,loving),$
$lover(e,x), lovee(e,L)$

$\lambda x\ \lambda e\ act(e,loving),$
$lover(e,x), lovee(e,L)$

$\lambda a\ a$

We'll say that
"to" is just a bit of syntax that
changes a VP_{stem} to a VP_{inf}
with the same meaning.

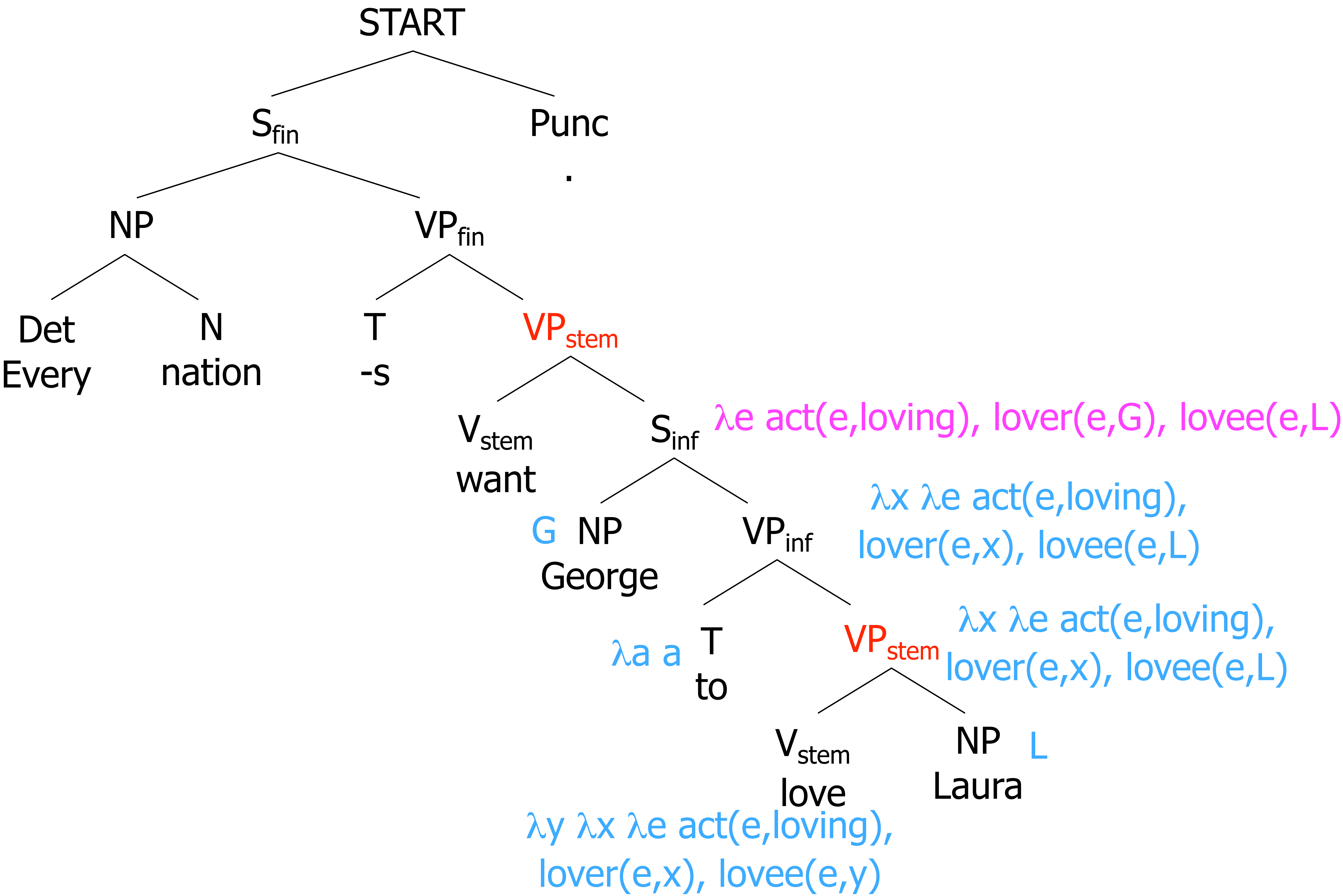


λe act(e,loving), lover(e,G), lovee(e,L)

λx λe act(e,loving), lover(e,x), lovee(e,L)

λx λe act(e,loving), lover(e,x), lovee(e,L)

λy λx λe act(e,loving), lover(e,x), lovee(e,y)

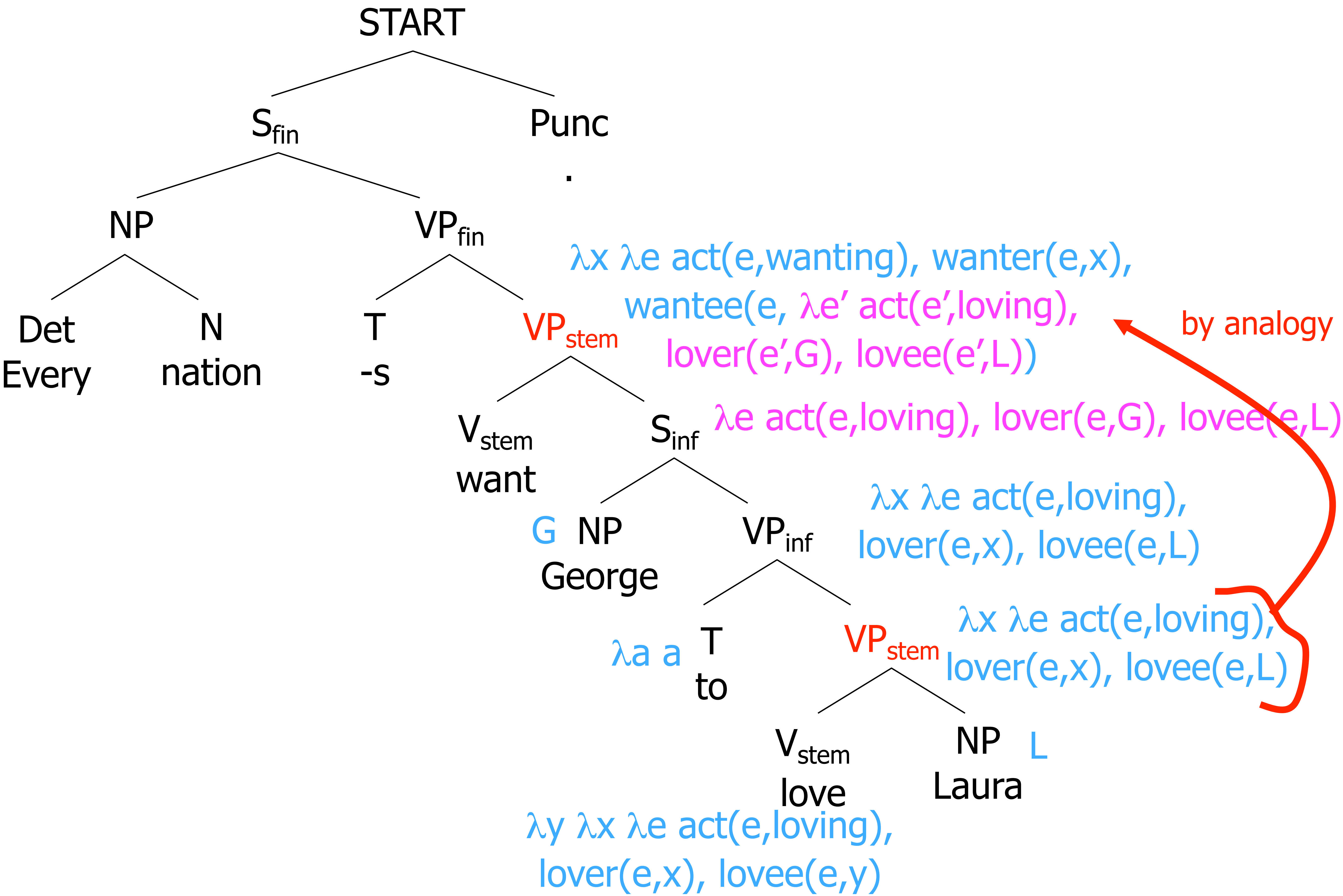


λe act(e,loving), lover(e,G), lovee(e,L)

λx λe act(e,loving),
lover(e,x), lovee(e,L)

λx λe act(e,loving),
lover(e,x), lovee(e,L)

λy λx λe act(e,loving),
lover(e,x), lovee(e,y)



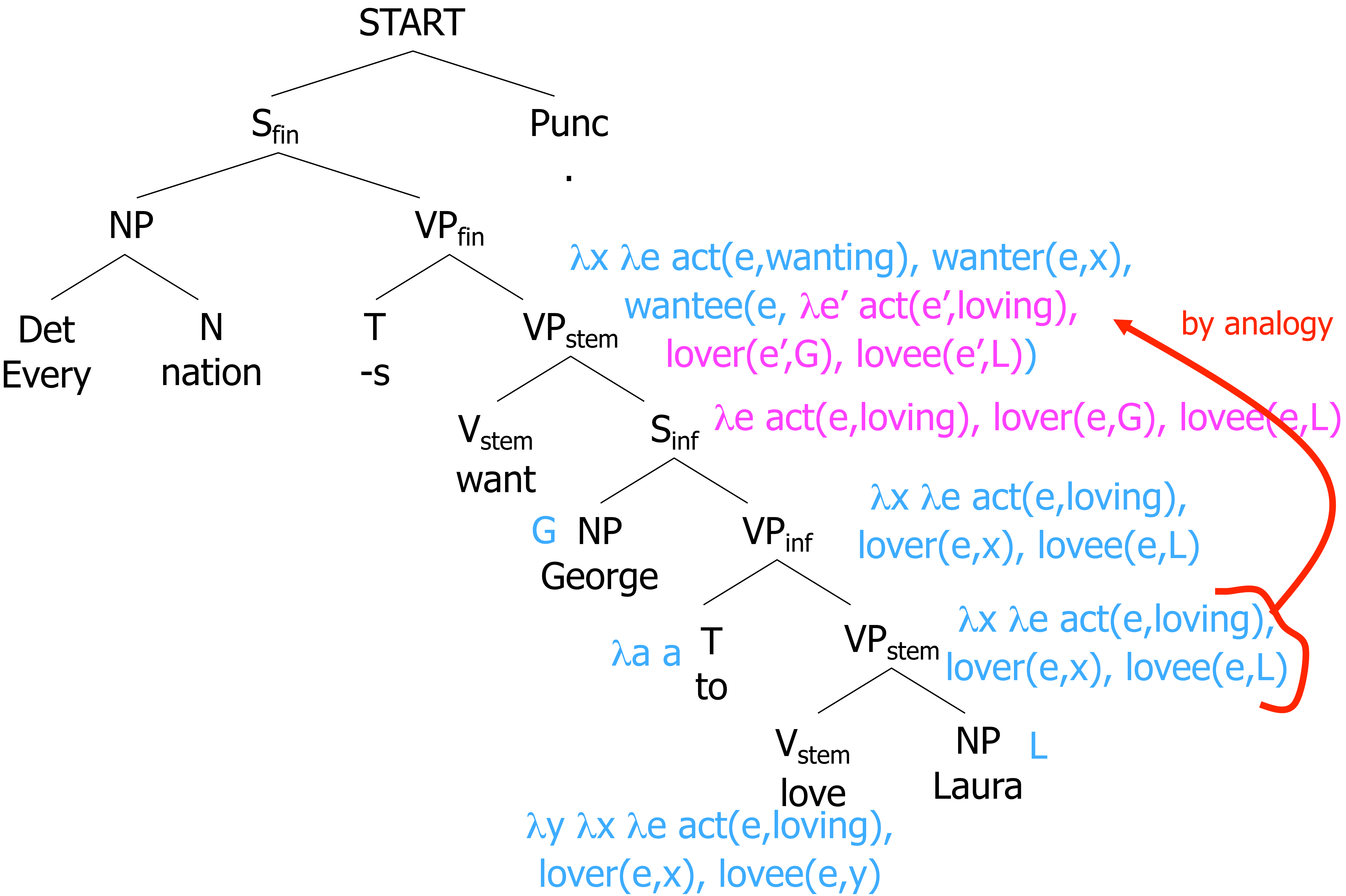
λx λe act(e,wanting), wanter(e,x), wantee(e, λe′ act(e′,loving), lover(e′,G), lovee(e′,L))

λe act(e,loving), lover(e,G), lovee(e,L)

λx λe act(e,loving), lover(e,x), lovee(e,L)

λx λe act(e,loving), lover(e,x), lovee(e,L)

λy λx λe act(e,loving), lover(e,x), lovee(e,y)



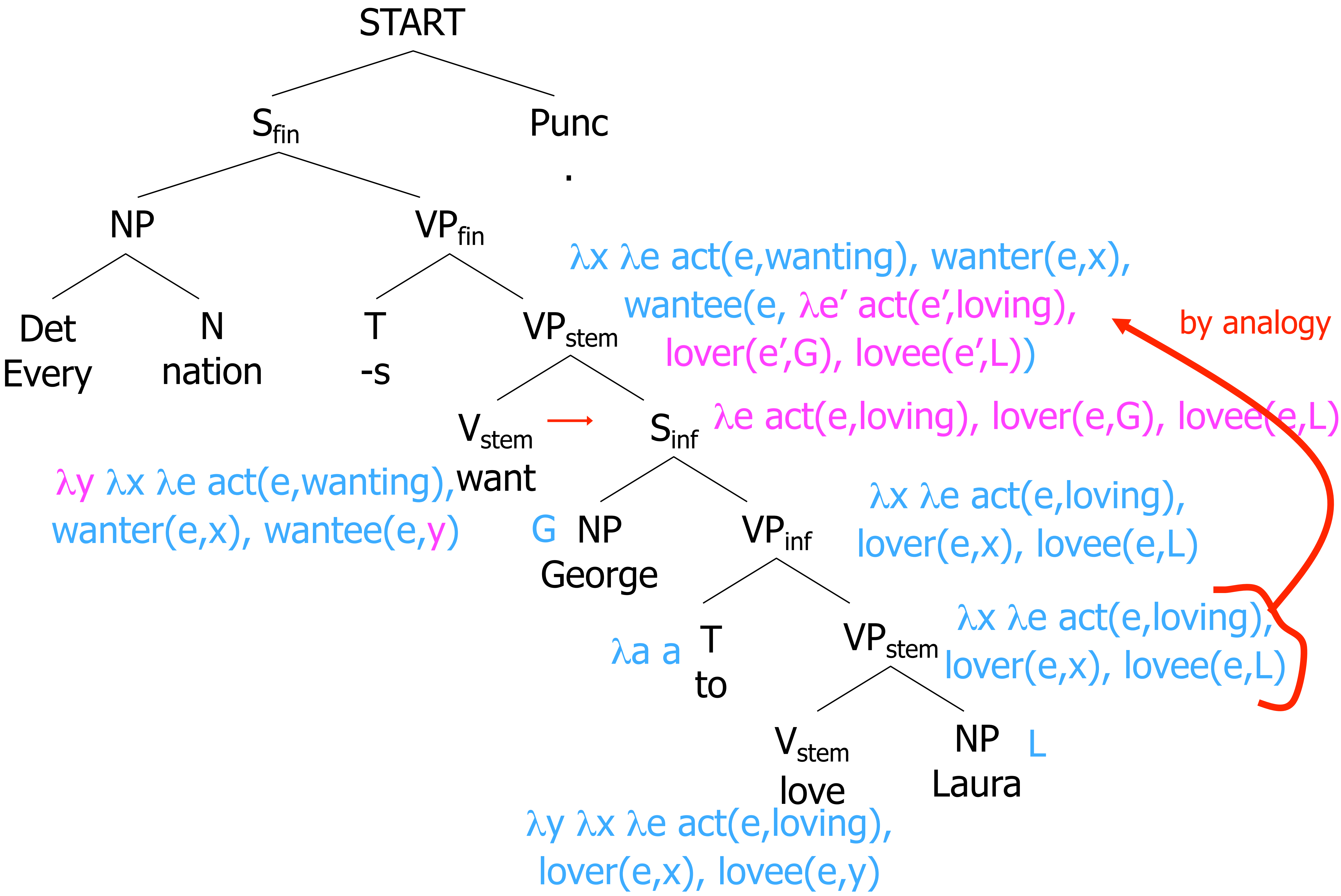
$\lambda x\ \lambda e\ act(e,wanting),\ wanter(e,x),$
$wantee(e,\ \lambda e'\ act(e',loving),$
$lover(e',G),\ lovee(e',L))$

$\lambda e\ act(e,loving),\ lover(e,G),\ lovee(e,L)$

$\lambda x\ \lambda e\ act(e,loving),$
$lover(e,x),\ lovee(e,L)$

$\lambda x\ \lambda e\ act(e,loving),$
$lover(e,x),\ lovee(e,L)$

$\lambda y\ \lambda x\ \lambda e\ act(e,loving),$
$lover(e,x),\ lovee(e,y)$



λx λe act(e,wanting), wanter(e,x), wantee(e, λe′ act(e′,loving), lover(e′,G), lovee(e′,L))

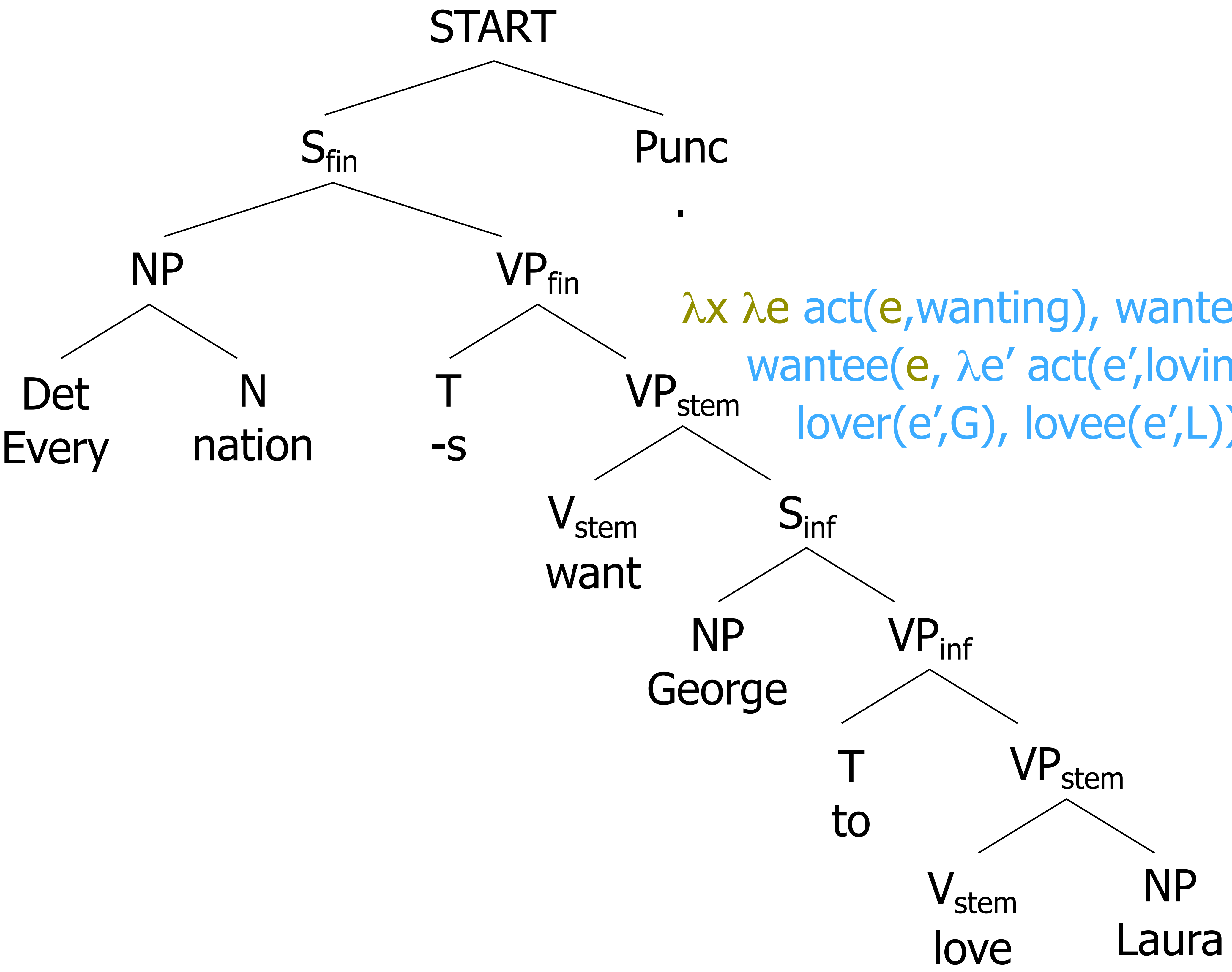
λe act(e,loving), lover(e,G), lovee(e,L)

λy λx λe act(e,wanting), wanter(e,x), wantee(e,y)

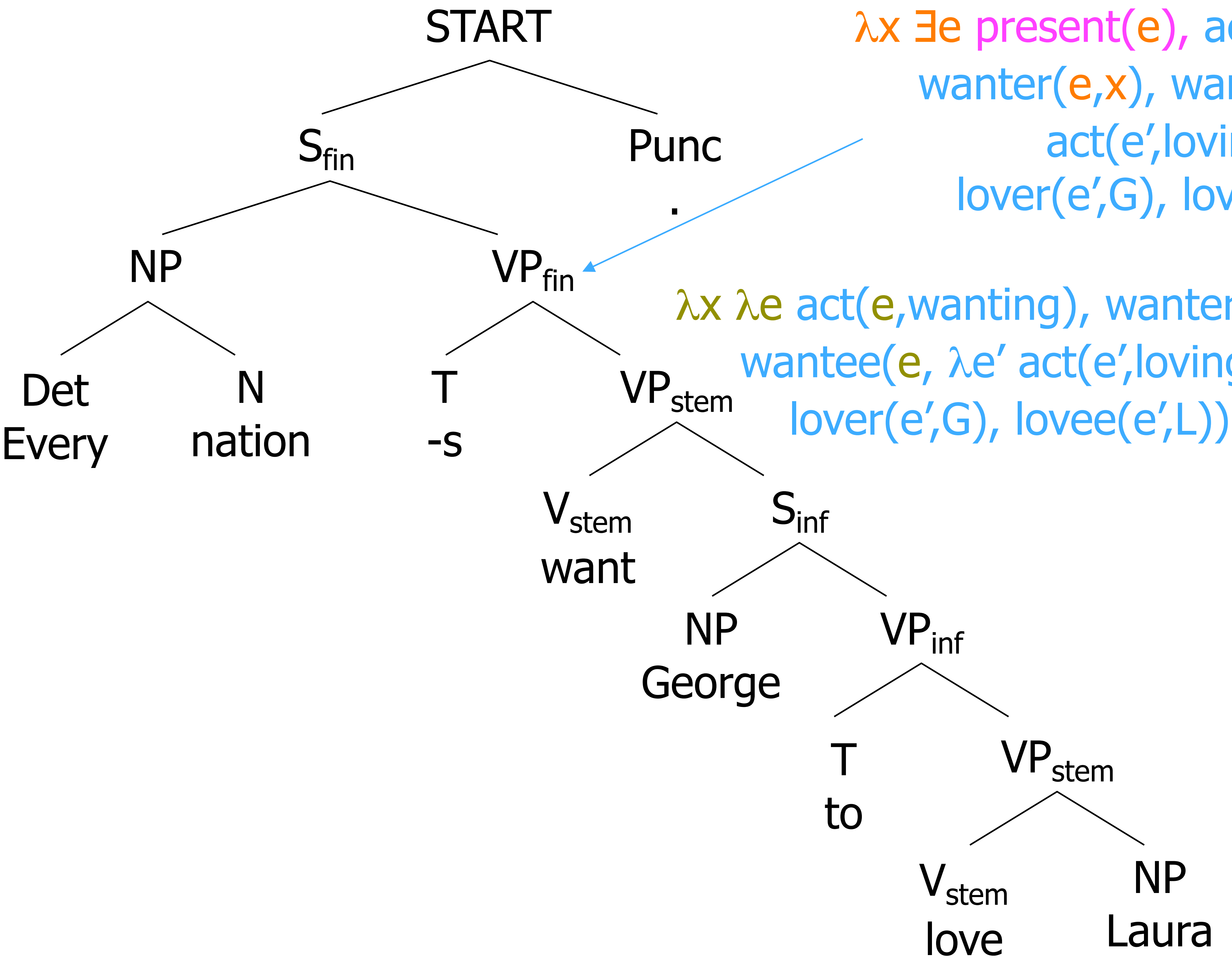
λx λe act(e,loving), lover(e,x), lovee(e,L)

λx λe act(e,loving), lover(e,x), lovee(e,L)

λy λx λe act(e,loving), lover(e,x), lovee(e,y)

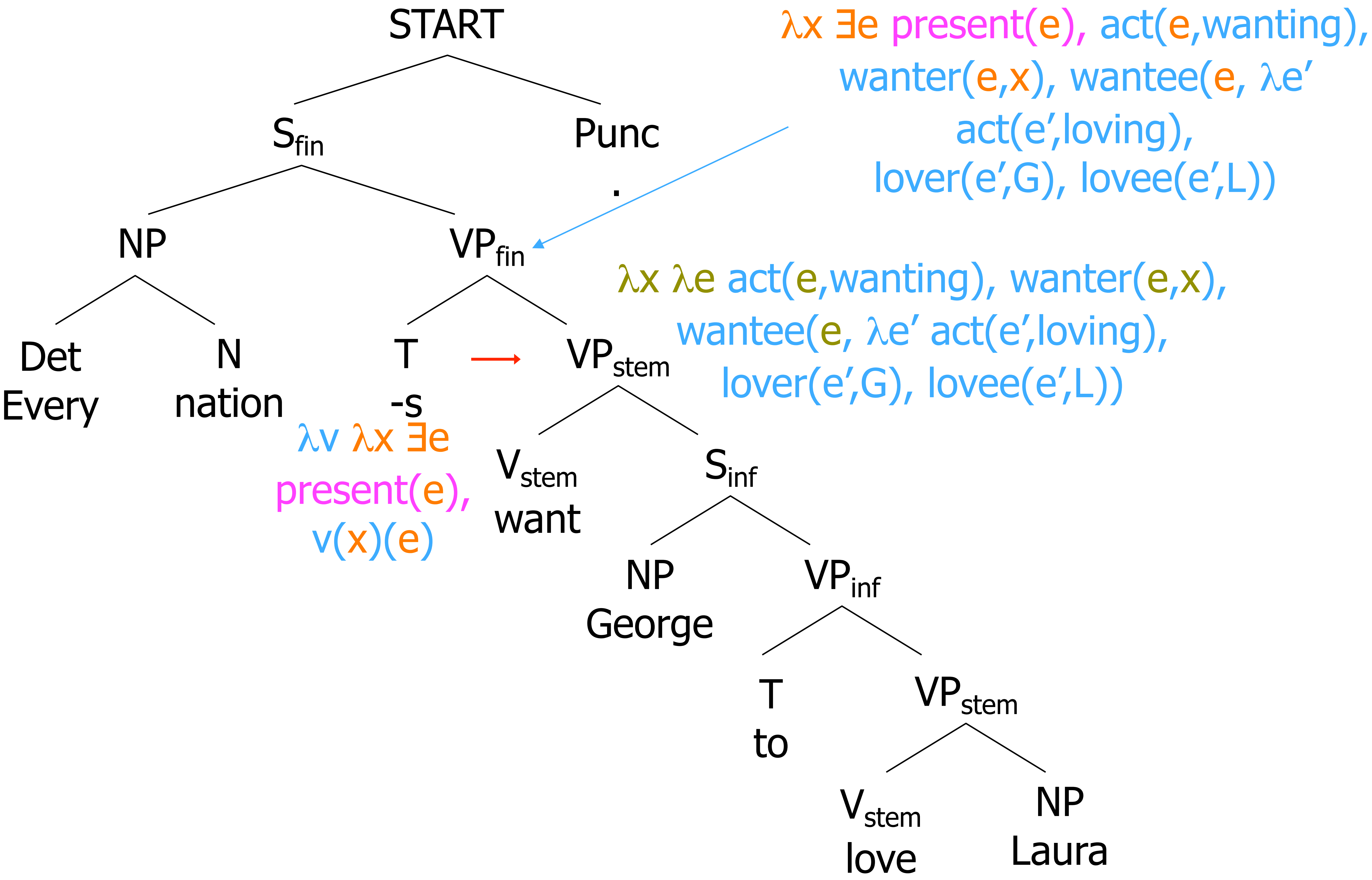


$$\lambda x\ \lambda e\ \text{act}(e,\text{wanting}),\ \text{wanter}(e,x),$$
$$\text{wantee}(e,\ \lambda e'\ \text{act}(e',\text{loving}),$$
$$\text{lover}(e',G),\ \text{lovee}(e',L))$$



λx ∃e present(e), act(e,wanting),
wanter(e,x), wantee(e, λe′
act(e′,loving),
lover(e′,G), lovee(e′,L))

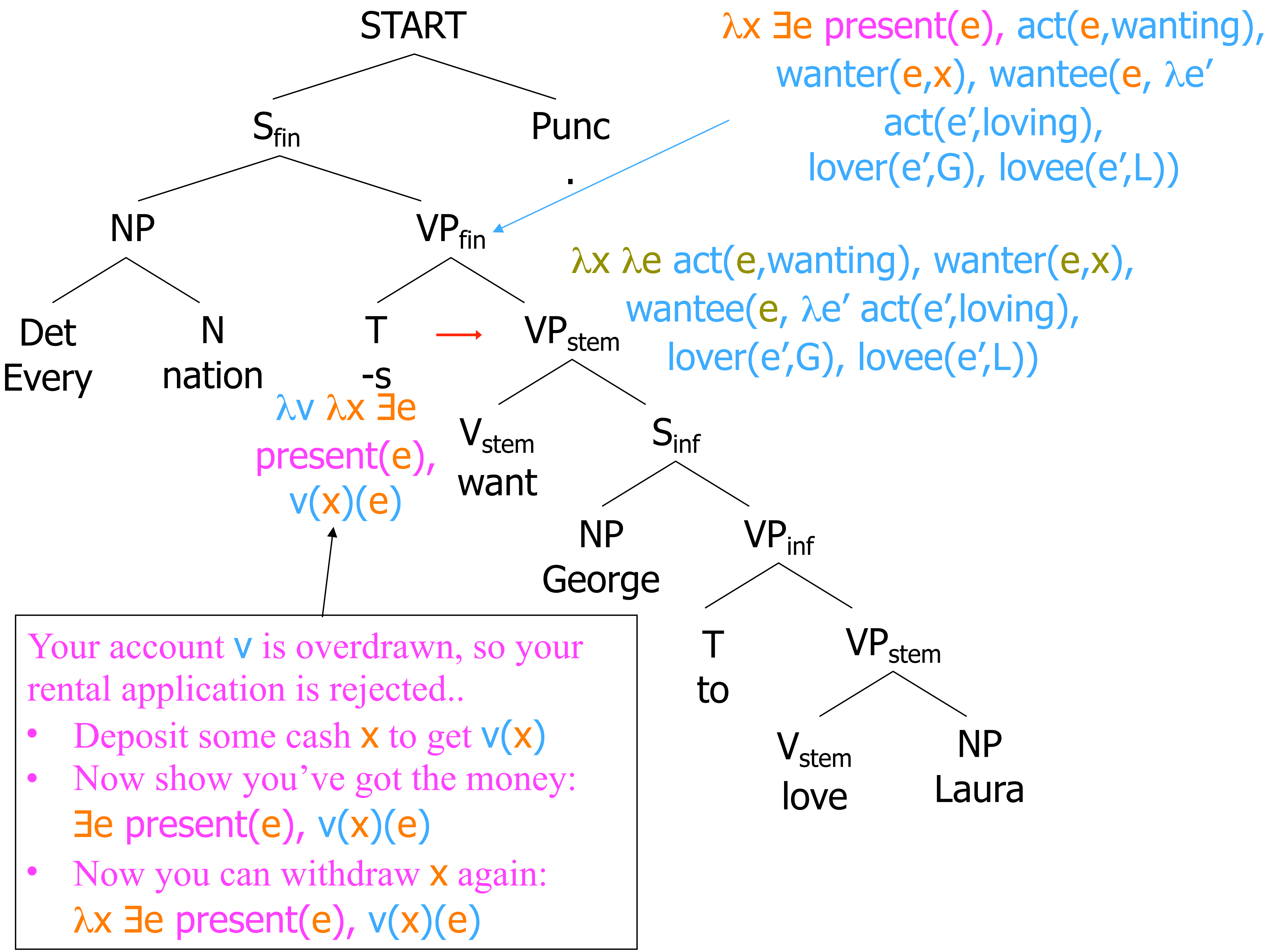
λx λe act(e,wanting), wanter(e,x),
wantee(e, λe′ act(e′,loving),
lover(e′,G), lovee(e′,L))



$$\lambda x\ \exists e\ \mathrm{present}(e),\ \mathrm{act}(e,\mathrm{wanting}),\ \mathrm{wanter}(e,x),\ \mathrm{wantee}(e,\ \lambda e'\ \mathrm{act}(e',\mathrm{loving}),\ \mathrm{lover}(e',G),\ \mathrm{lovee}(e',L))$$

$$\lambda x\ \lambda e\ \mathrm{act}(e,\mathrm{wanting}),\ \mathrm{wanter}(e,x),\ \mathrm{wantee}(e,\ \lambda e'\ \mathrm{act}(e',\mathrm{loving}),\ \mathrm{lover}(e',G),\ \mathrm{lovee}(e',L))$$

$$\lambda v\ \lambda x\ \exists e\ \mathrm{present}(e),\ v(x)(e)$$



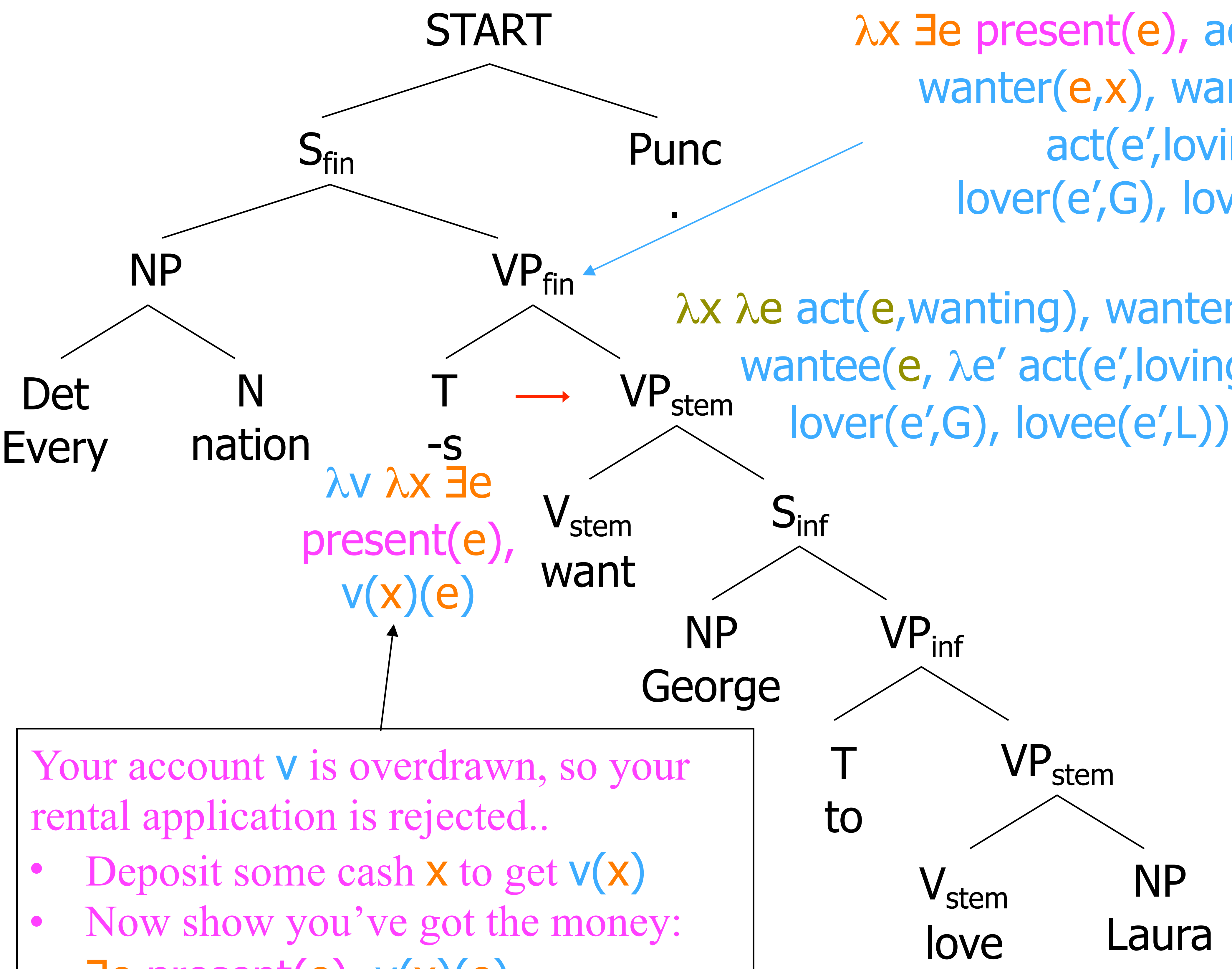
$\lambda x\ \exists e\ \text{present}(e), \text{act}(e,\text{wanting}), \text{wanter}(e,x), \text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}), \text{lover}(e',G), \text{lovee}(e',L))$

$\lambda x\ \lambda e\ \text{act}(e,\text{wanting}), \text{wanter}(e,x), \text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}), \text{lover}(e',G), \text{lovee}(e',L))$

$\lambda v\ \lambda x\ \exists e\ \text{present}(e), v(x)(e)$

Your account v is overdrawn, so your rental application is rejected..

- Deposit some cash x to get v(x)
- Now show you’ve got the money: $\exists e\ \text{present}(e), v(x)(e)$
- Now you can withdraw x again: $\lambda x\ \exists e\ \text{present}(e), v(x)(e)$



$\lambda x\ \exists e\ present(e), act(e,wanting), wanter(e,x), wantee(e, \lambda e'\ act(e',loving), lover(e',G), lovee(e',L))$

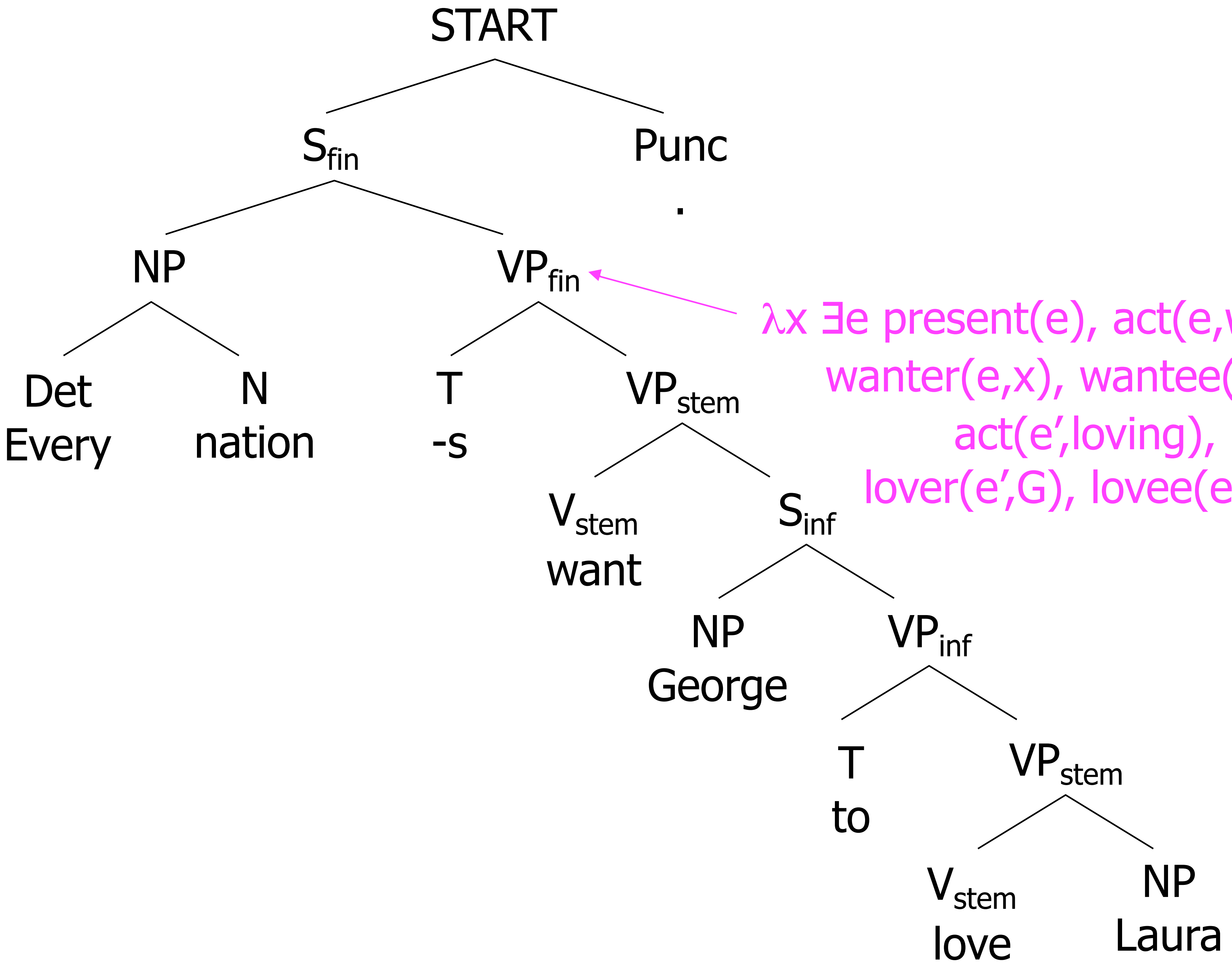
$\lambda x\ \lambda e\ act(e,wanting), wanter(e,x), wantee(e, \lambda e'\ act(e',loving), lover(e',G), lovee(e',L))$

$\lambda v\ \lambda x\ \exists e\ present(e), v(x)(e)$

Your account v is overdrawn, so your rental application is rejected..

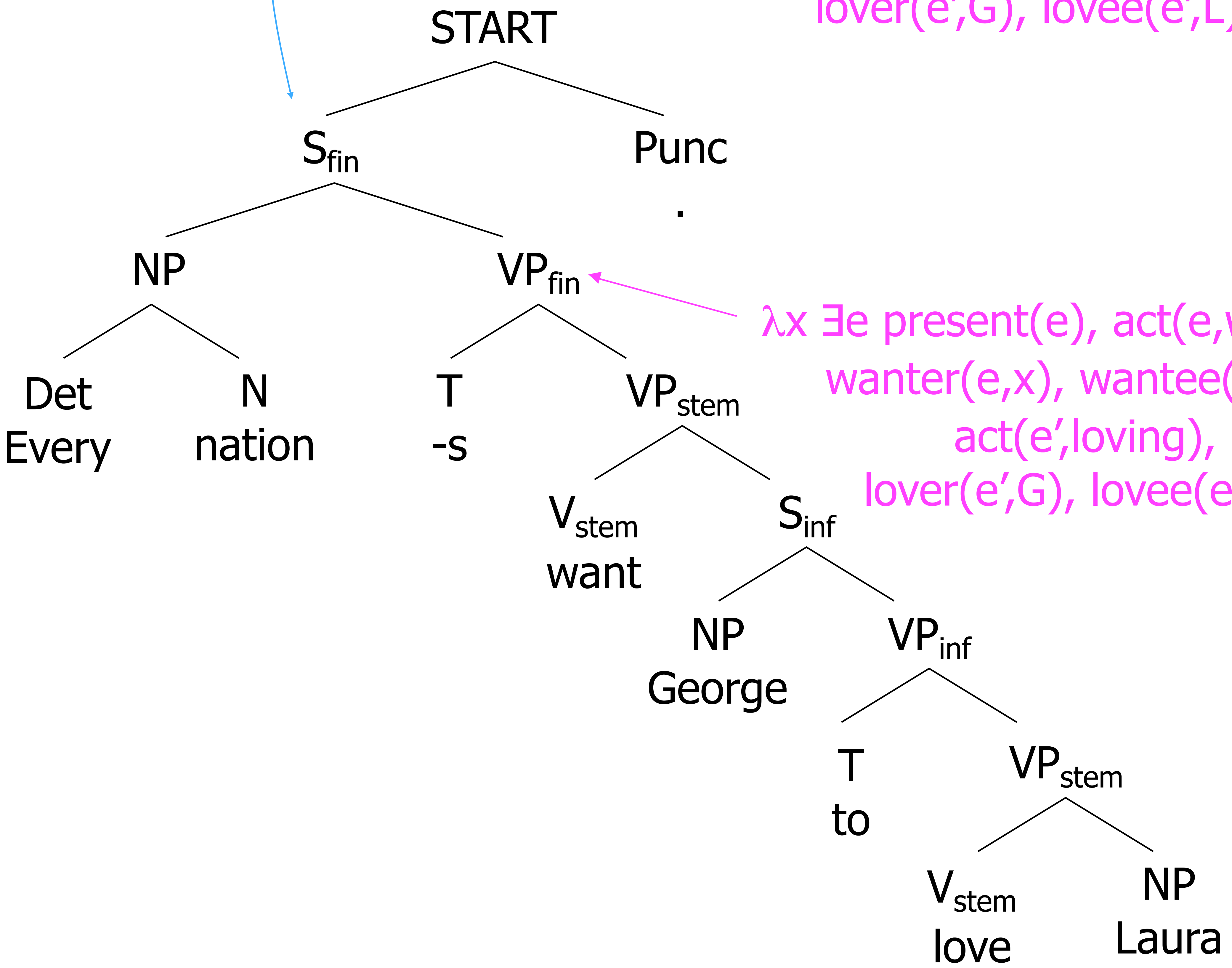
- Deposit some cash x to get $v(x)$
- Now show you've got the money: $\exists e\ present(e), v(x)(e)$
- Now you can withdraw x again: $\lambda x\ \exists e\ present(e), v(x)(e)$

Better analogy: How would you modify the <u>second</u> object on a stack $(\lambda x, \lambda e, act\ldots)$?

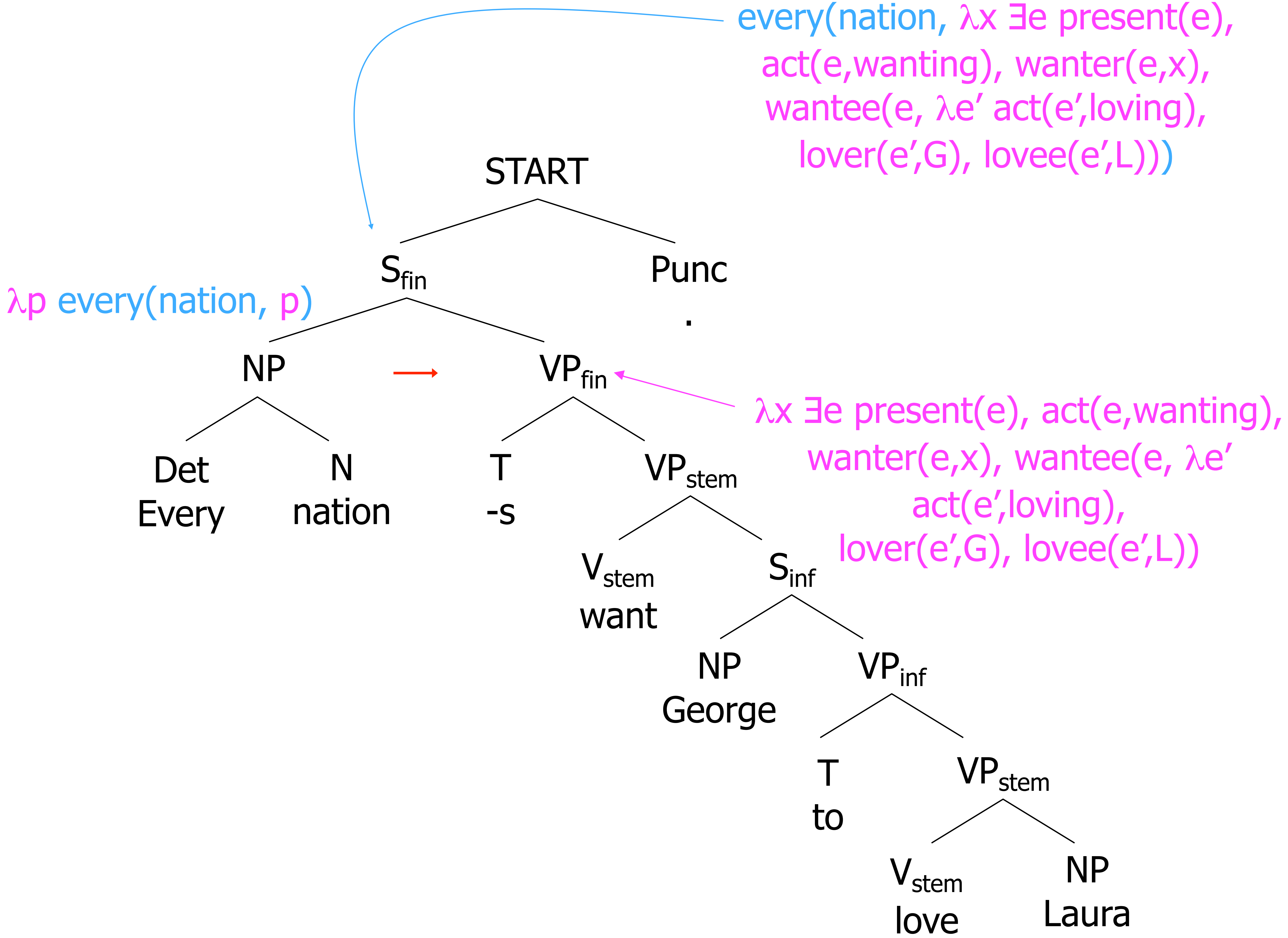


$\lambda x\ \exists e\ \text{present}(e), \text{act}(e,\text{wanting}),$
$\text{wanter}(e,x), \text{wantee}(e, \lambda e'$
$\text{act}(e',\text{loving}),$
$\text{lover}(e',G), \text{lovee}(e',L))$

every(nation, λx ∃e present(e),
act(e,wanting), wanter(e,x),
wantee(e, λe′ act(e′,loving),
lover(e′,G), lovee(e′,L)))



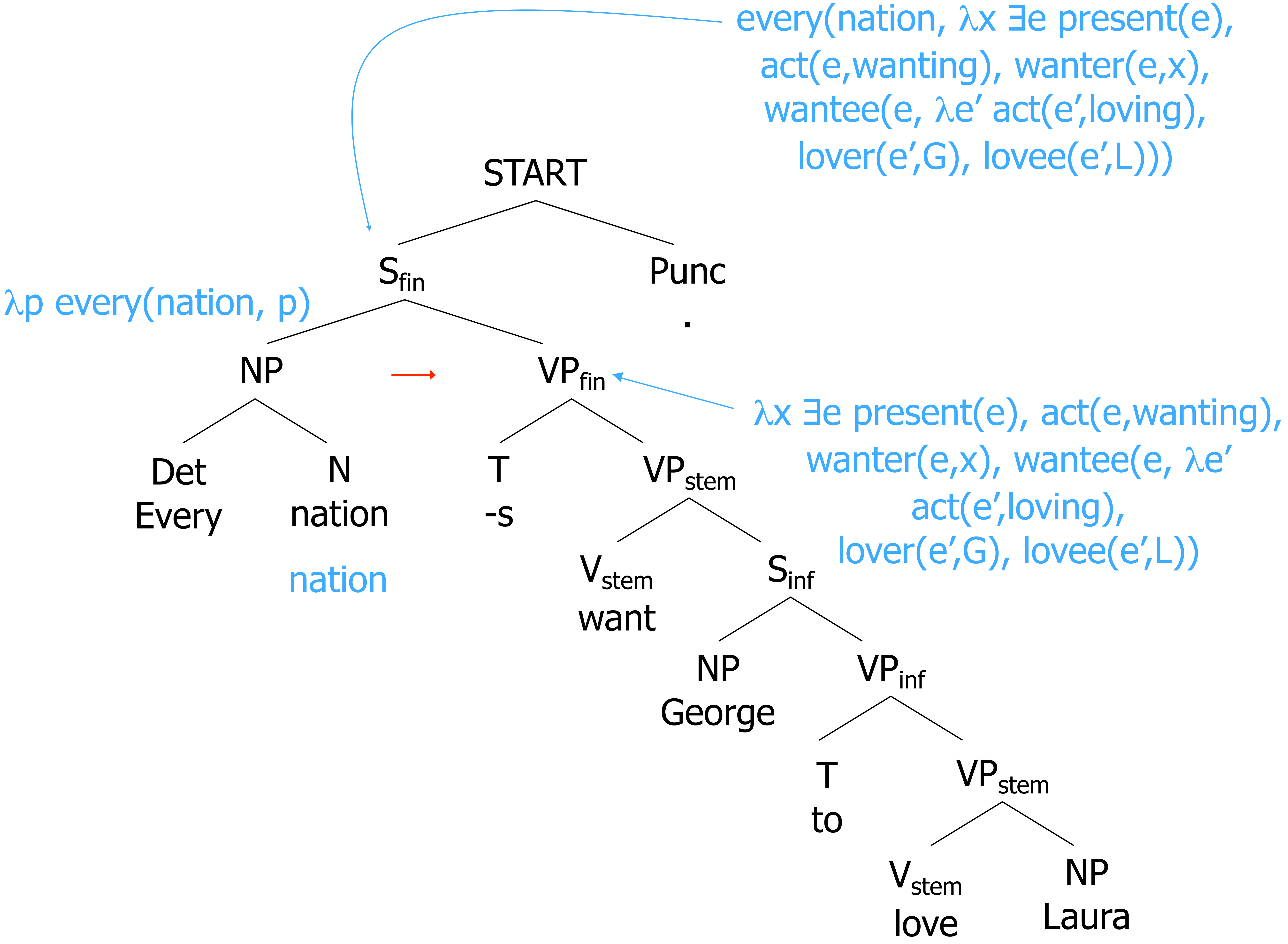
λx ∃e present(e), act(e,wanting),
wanter(e,x), wantee(e, λe′
act(e′,loving),
lover(e′,G), lovee(e′,L))



$\text{every}(\text{nation}, \lambda x\ \exists e\ \text{present}(e), \text{act}(e,\text{wanting}), \text{wanter}(e,x), \text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}), \text{lover}(e',G), \text{lovee}(e',L)))$

$\lambda p\ \text{every}(\text{nation}, p)$

$\lambda x\ \exists e\ \text{present}(e), \text{act}(e,\text{wanting}), \text{wanter}(e,x), \text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}), \text{lover}(e',G), \text{lovee}(e',L))$

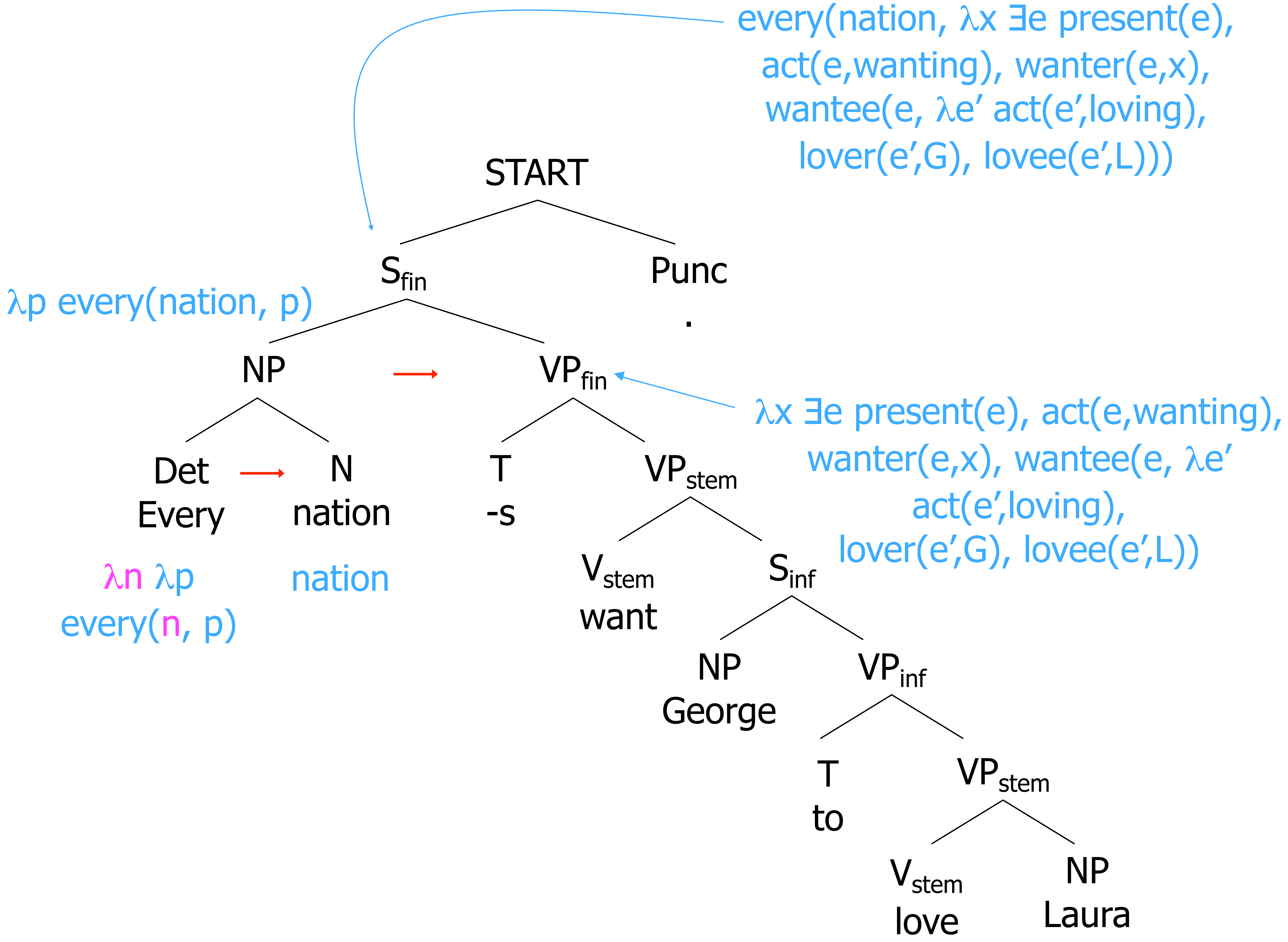


$\text{every}(\text{nation}, \lambda x\ \exists e\ \text{present}(e), \text{act}(e,\text{wanting}), \text{wanter}(e,x), \text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}), \text{lover}(e',G), \text{lovee}(e',L)))$

$\lambda p\ \text{every}(\text{nation}, p)$

$\lambda x\ \exists e\ \text{present}(e), \text{act}(e,\text{wanting}), \text{wanter}(e,x), \text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}), \text{lover}(e',G), \text{lovee}(e',L))$

nation



every(nation, λx ∃e present(e),
act(e,wanting), wanter(e,x),
wantee(e, λe′ act(e′,loving),
lover(e′,G), lovee(e′,L)))

START

S_{fin}

Punc

.

λp every(nation, p)

NP

VP$_{fin}$

λx ∃e present(e), act(e,wanting),
wanter(e,x), wantee(e, λe′
act(e′,loving),
lover(e′,G), lovee(e′,L))

Det
Every

N
nation

T
-s

VP$_{stem}$

λn λp
every(n, p)

nation

V$_{stem}$
want

S$_{inf}$

NP
George

VP$_{inf}$

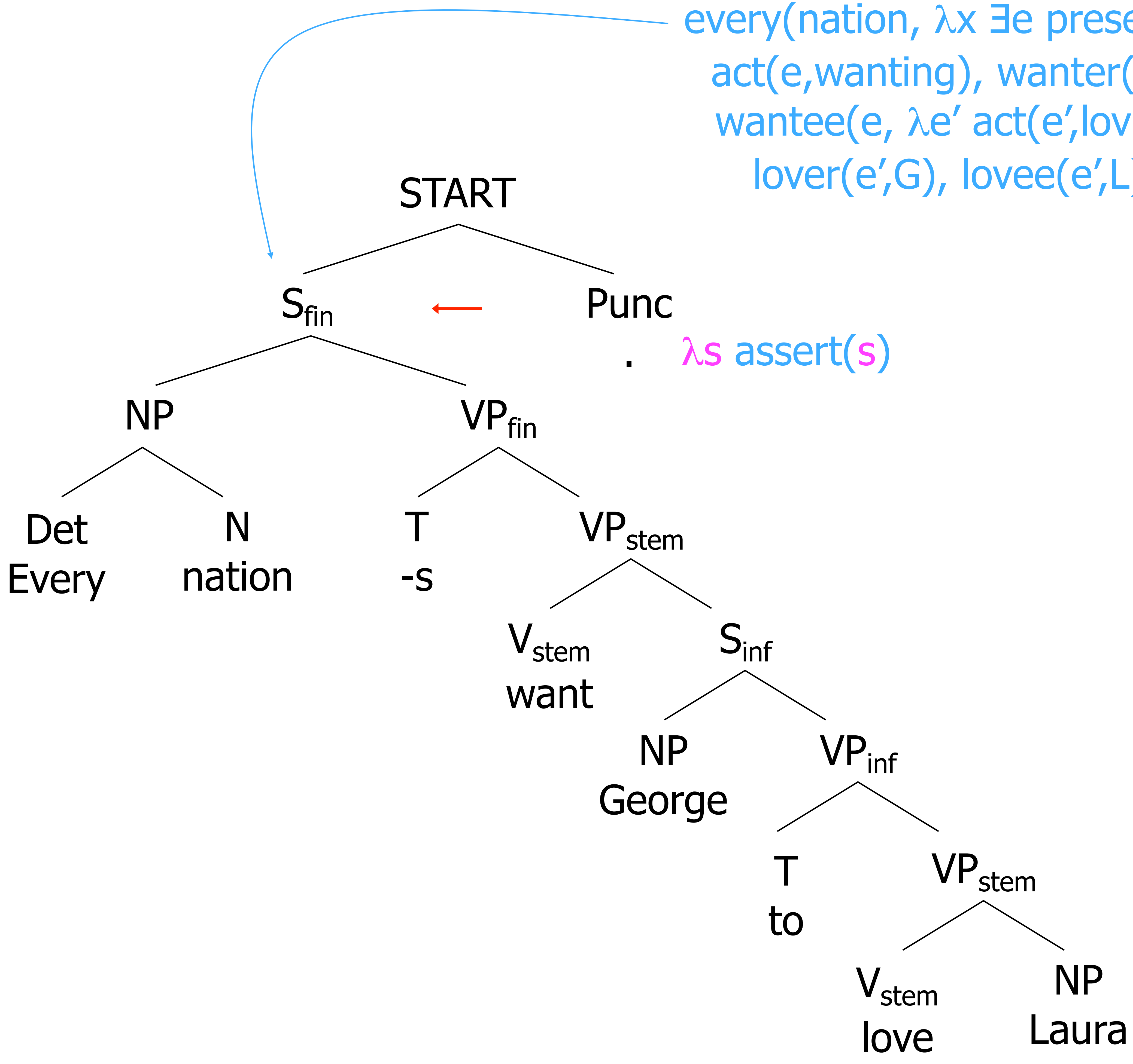
T
to

VP$_{stem}$

V$_{stem}$
love

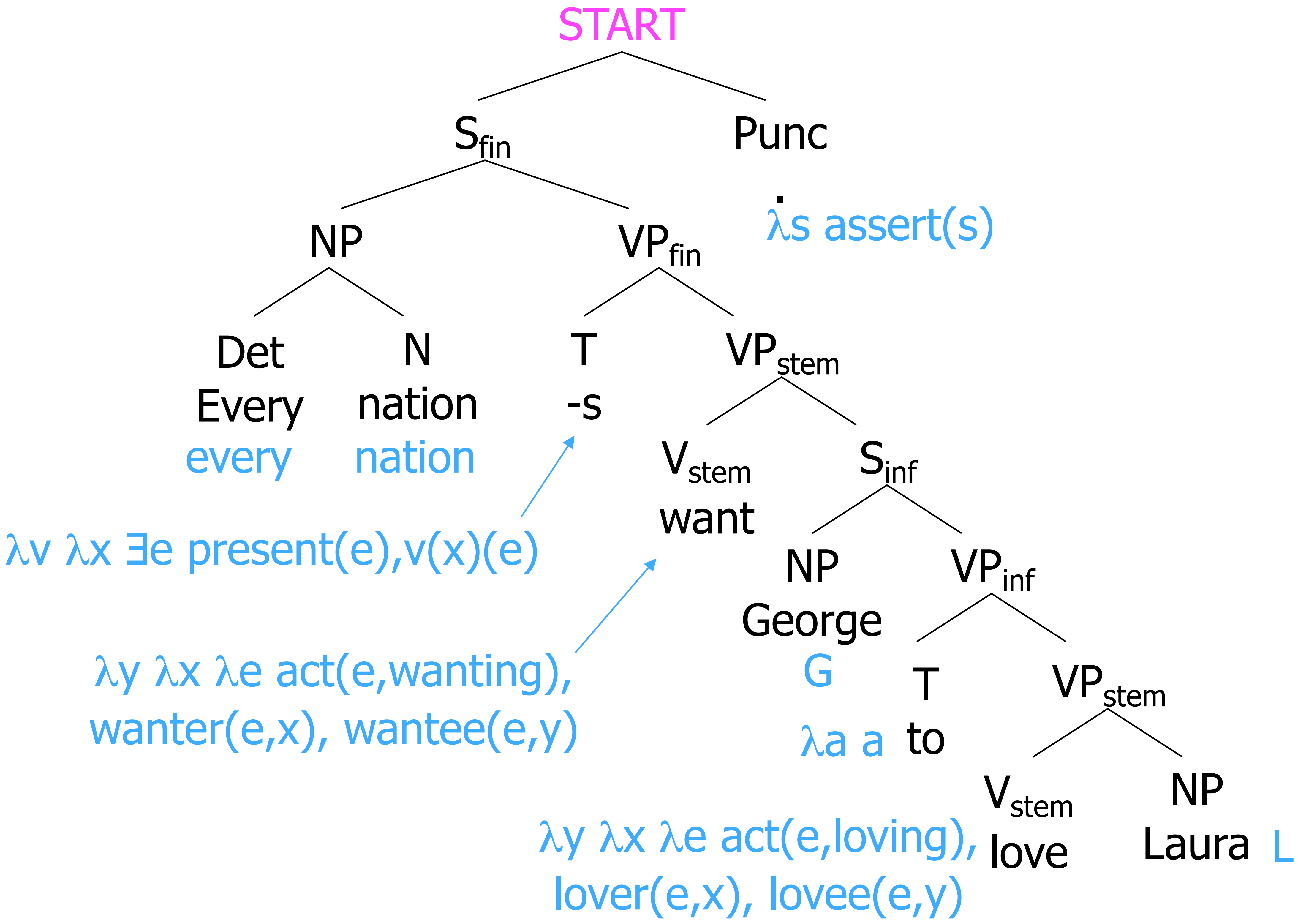
NP
Laura

$$
\begin{gathered}
\text{every}(\text{nation}, \lambda x\ \exists e\ \text{present}(e),\\
\text{act}(e,\text{wanting}), \text{wanter}(e,x),\\
\text{wantee}(e, \lambda e'\ \text{act}(e',\text{loving}),\\
\text{lover}(e',G), \text{lovee}(e',L)))
\end{gathered}
$$



$\lambda s\ \text{assert}(s)$

In Summary: From the Words



START

S_{fin}

Punc

.

λs assert(s)

NP

VP_{fin}

Det

Every

every

N

nation

nation

T

-s

λv λx ∃e present(e),v(x)(e)

VP_{stem}

V_{stem}

want

λy λx λe act(e,wanting), wanter(e,x), wantee(e,y)

S_{inf}

NP

George

G

VP_{inf}

T

to

λa a

VP_{stem}

V_{stem}

love

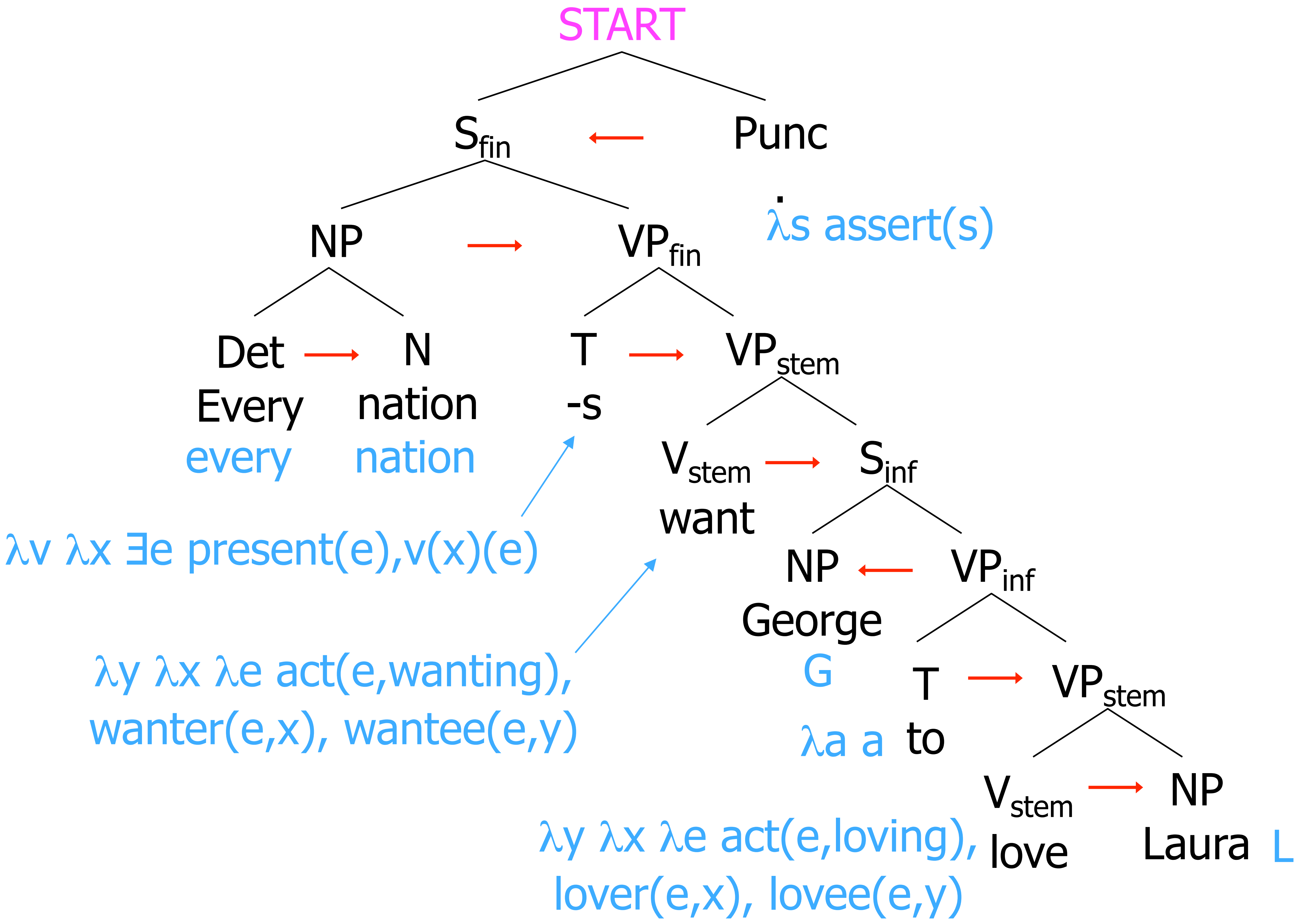
λy λx λe act(e,loving), lover(e,x), lovee(e,y)

NP

Laura

L

In Summary: From the Words



START

S_{fin} ← Punc

.

$\lambda s\ \text{assert}(s)$

NP → VP_{fin}

Det → N

Every nation

every nation

T → VP_{stem}

-s

$\lambda v\ \lambda x\ \exists e\ \text{present}(e), v(x)(e)$

V_{stem} → S_{inf}

want

$\lambda y\ \lambda x\ \lambda e\ \text{act}(e,\text{wanting}),$
$\text{wanter}(e,x), \text{wantee}(e,y)$

NP ← VP_{inf}

George

G

T → VP_{stem}

to

$\lambda a\ a$

V_{stem} → NP

love

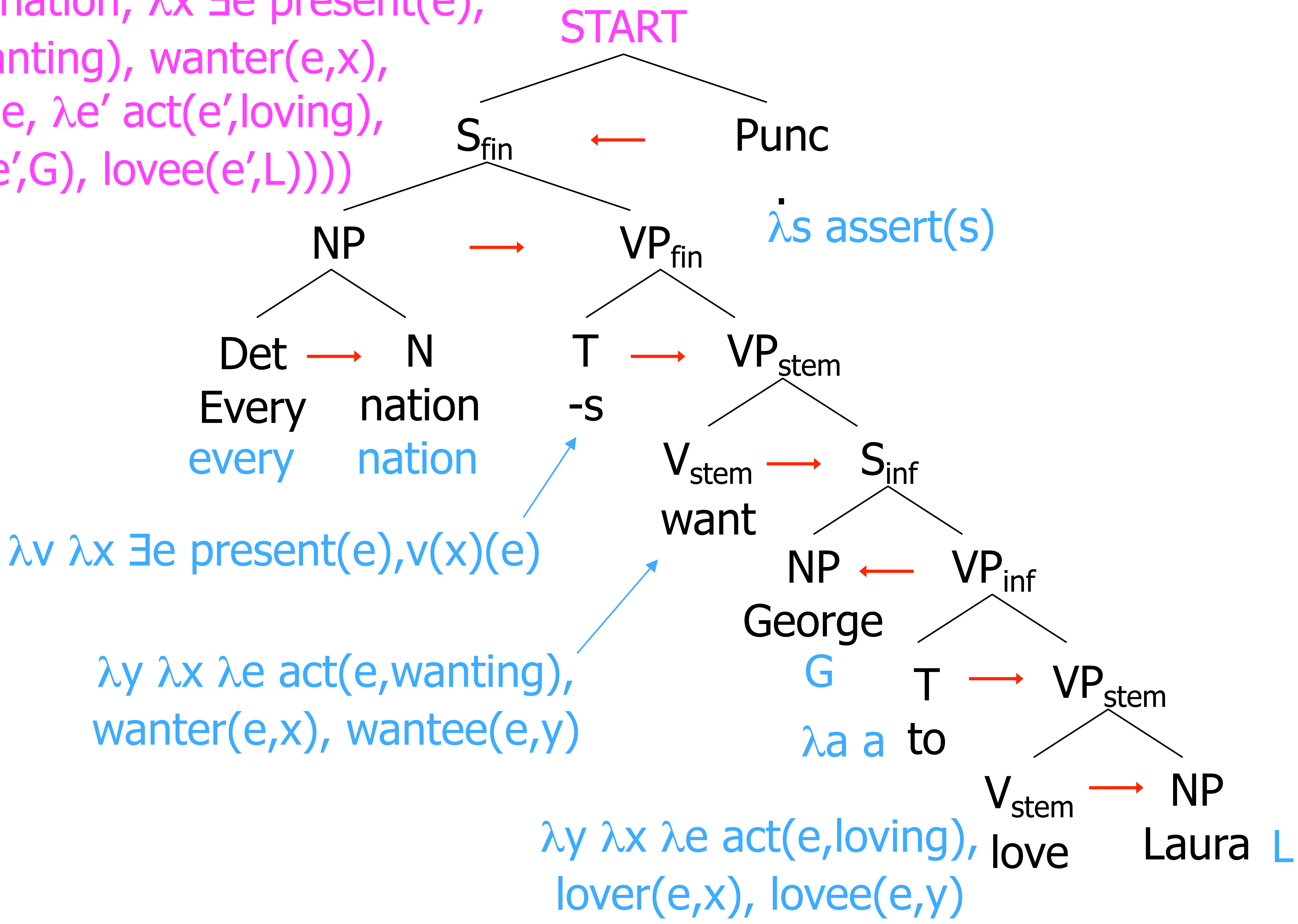
Laura

L

$\lambda y\ \lambda x\ \lambda e\ \text{act}(e,\text{loving}),$
$\text{lover}(e,x), \text{lovee}(e,y)$

In Summary: From the Words

assert(every(nation, λx ∃e present(e),
act(e,wanting), wanter(e,x),
wantee(e, λe′ act(e′,loving),
lover(e′,G), lovee(e′,L))))



λs assert(s)

every

nation

λv λx ∃e present(e),v(x)(e)

λy λx λe act(e,wanting),
wanter(e,x), wantee(e,y)

G

λa a

λy λx λe act(e,loving),
lover(e,x), lovee(e,y)

L

Other Fun Semantic Stuff:
A Few Much-Studied Miscellany

- Temporal logic
  - Gilly had swallowed eight goldfish before Milly reached the bowl
  - Billy said Jilly was pregnant
  - Billy said, "Jilly is pregnant."
- Generics
  - Typhoons arise in the Pacific
  - Children must be carried
- Presuppositions
  - The king of France is bald.
  - Have you stopped beating your wife?
- Pronoun-Quantifier Interaction ("bound anaphora")
  - Every farmer who owns a donkey beats it.
  - If you have a dime, put it in the meter.
  - The woman who every Englishman loves is his mother.
  - I love my mother and so does Billy.

In Summary

- How do we judge a good meaning representation?
- How can we represent sentence meaning with first-order logic?
- How can logical representations of sentences be **composed** from logical forms of words?
- Next time: can we train models to recover logical forms?