CSL302: Compiler Design

Syntax Analysis

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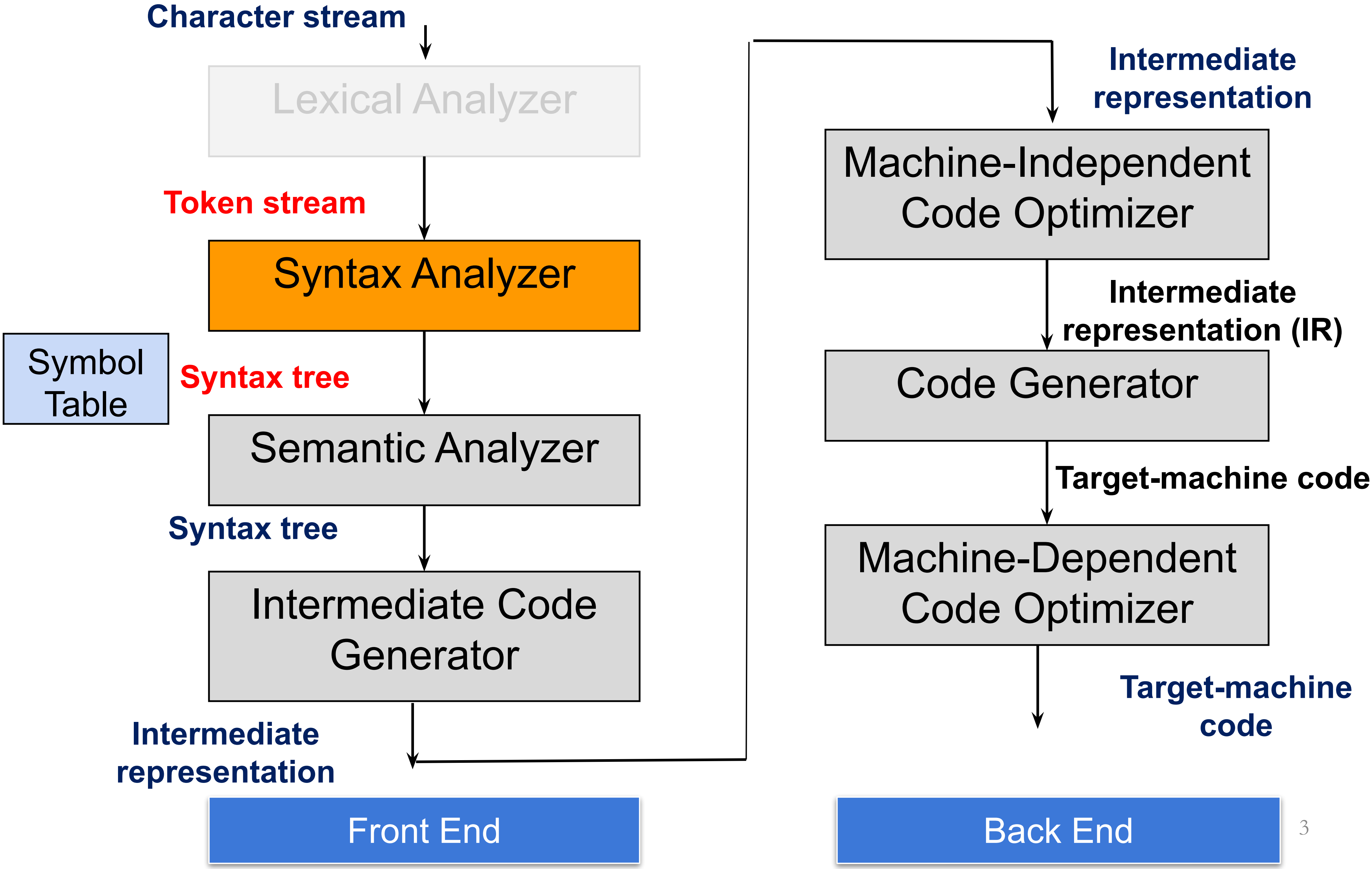
Acknowledgement

- References for today's slides
  - *Stanford University:*
    - *https://web.stanford.edu/class/archive/cs/cs143/cs143.1128/*
  - *Lecture notes of Prof. Amey Karkare (IIT Kanpur) and Late Prof. Sanjeev K Aggarwal (IIT Kanpur)*

Compiler Design


Character stream
Lexical Analyzer
Token stream
Syntax Analyzer
Symbol Table
Syntax tree
Semantic Analyzer
Syntax tree
Intermediate Code Generator
Intermediate representation
Front End
Intermediate representation
Machine-Independent Code Optimizer
Intermediate representation (IR)
Code Generator
Target-machine code
Machine-Dependent Code Optimizer
Target-machine code
Back End

Context Free Grammar

- Write a CFG for Statement in C language.
    - Statement can be Simple stmt, If-else stmt, While stmt, do-while

CFGs for Programming Languages

```
STMT    →  EXPR;
        |  if (EXPR) BLOCK
        |  while (EXPR) BLOCK
        |  do BLOCK while (EXPR);
        |  BLOCK
        |  …

EXPR    →  identifier
        |  constant
        |  EXPR + EXPR
        |  EXPR – EXPR
        |  EXPR * EXPR
        |  ...
```

CFGs for Programming Languages

```
BLOCK    →  STMT
         |  { STMTS }

STMTS    →  ε
         |  STMT STMTS

STMT     →  EXPR ;
         |  if (EXPR) BLOCK
         |  while (EXPR) BLOCK
         |  do BLOCK while (EXPR);
         |  BLOCK
         |  ...

EXPR     →  identifier
         |  constant
         |  EXPR + EXPR
         |  EXPR – EXPR
         |  EXPR * EXPR
         |  ...
```

Some CFG Notation

- Capital letters at the beginning of the alphabet will represent nonterminals.
  - i.e. A, B, C, D
- Lowercase letters at the end of the alphabet will represent terminals.
  - i.e. **`t`**, **`u`**, **`v`**, **`w`**
- Lowercase Greek letters will represent arbitrary strings of terminals and nonterminals.
  - i.e. $\boldsymbol{\alpha}$, $\boldsymbol{\gamma}$, $\boldsymbol{\omega}$

Derivations

E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E * (E Op E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int Op int)

⇒ int * (int + int)

- This sequence of steps is called a **derivation**.
- A string $\alpha A \omega$ **yields** string $\alpha\gamma\omega$ iff $A \to \gamma$ is a production.
- If α yields β, we write $\alpha \Rightarrow \beta$.
- We say that α **derives** β iff there is a sequence of strings where

$$\alpha \Rightarrow \alpha_1 \Rightarrow \alpha_2 \Rightarrow \dots \Rightarrow \beta$$

- If α derives β, we write $\alpha \Rightarrow^* \beta$.

Derivations

- A leftmost derivation is a derivation in which each step expands the leftmost nonterminal.
- A rightmost derivation is a derivation in which each step expands the rightmost nonterminal.

Leftmost Derivation

E → int | E Op E | (E)

Op → + | - | * | /

⇒ int * (int + int)

E

⇒ E Op E

⇒ int Op E

⇒ int * E

⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int + E)

⇒ int * (int + int)

Leftmost and Rightmost Derivations

E

⇒ E Op E

⇒ int Op E

⇒ int * E

⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int + E)

⇒ int * (int + int)

Leftmost Derivation

E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)

⇒ E Op (int + int)

⇒ E * (int + int)

⇒ int * (int + int)

Rightmost Derivation

Leftmost Derivations

```
BLOCK →  STMT
      |  { STMTS }

STMTS →  ε
      |  STMT STMTS
STMT  →  EXPR;
      |  if (EXPR) BLOCK
      |  while (EXPR) BLOCK
      |  do BLOCK while (EXPR);
      |  BLOCK
      |  …

EXPR  →  identifier
      |  constant
      |  EXPR + EXPR
      |  EXPR – EXPR
      |  EXPR * EXPR
      |  EXPR = EXPR
      |  …
```

Can you derive `id = id + constant;`

```
⇒ BLOCK
⇒ STMT
⇒ EXPR;
⇒ EXPR = EXPR;
⇒ id = EXPR;
⇒ id = EXPR + EXPR;
⇒ id = id + EXPR;
⇒ id = id + constant;
```

Derivations

- A derivation encodes two pieces of information:
    - What productions were applied produce the resulting string from the start symbol?
    - In what order were they applied?
- Multiple derivations might use the same productions, but apply them in a different order.
- Encoding the derivation steps in a tree leads to parse-tree.

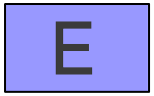
Parse Trees

$\Rightarrow$ `int * (int + int)`

E

Parse Trees

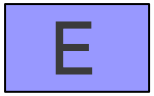
⇒ `int * (int + int)`



E

Parse Trees

⇒ `int * (int + int)`



E

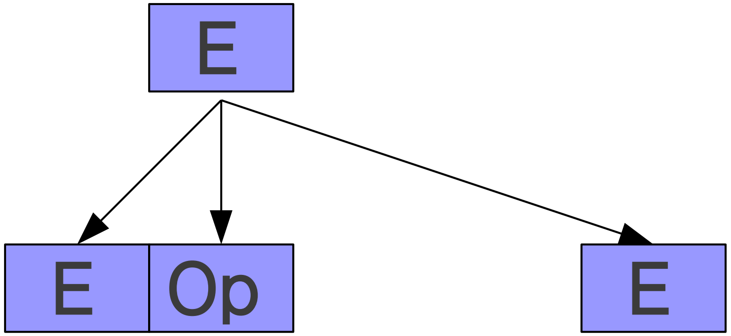
⇒ E Op E

Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E



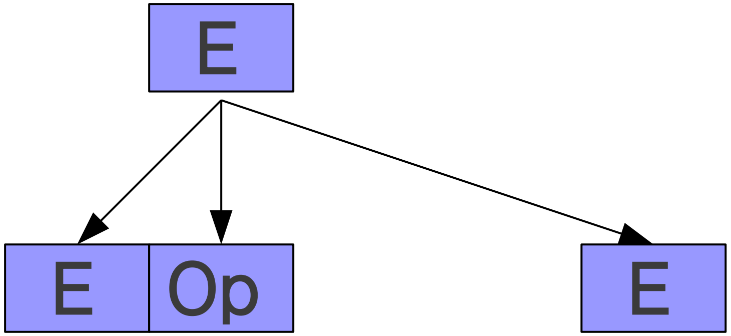
Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ `int` Op E



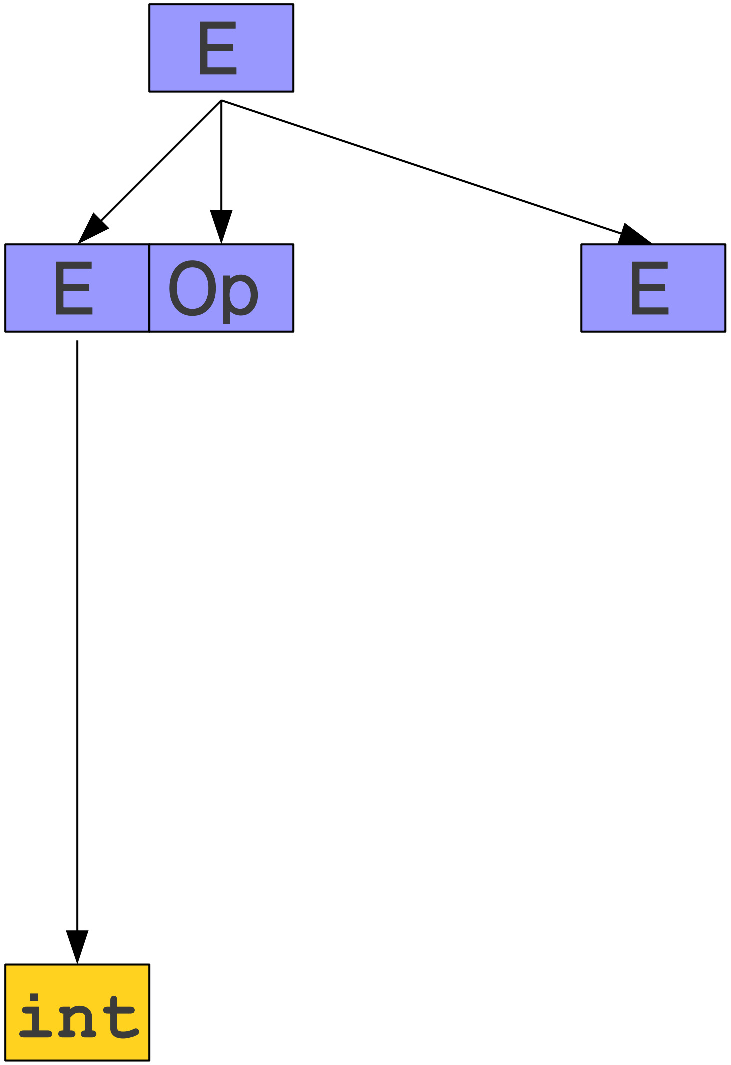
Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ `int` Op E



Parse Trees

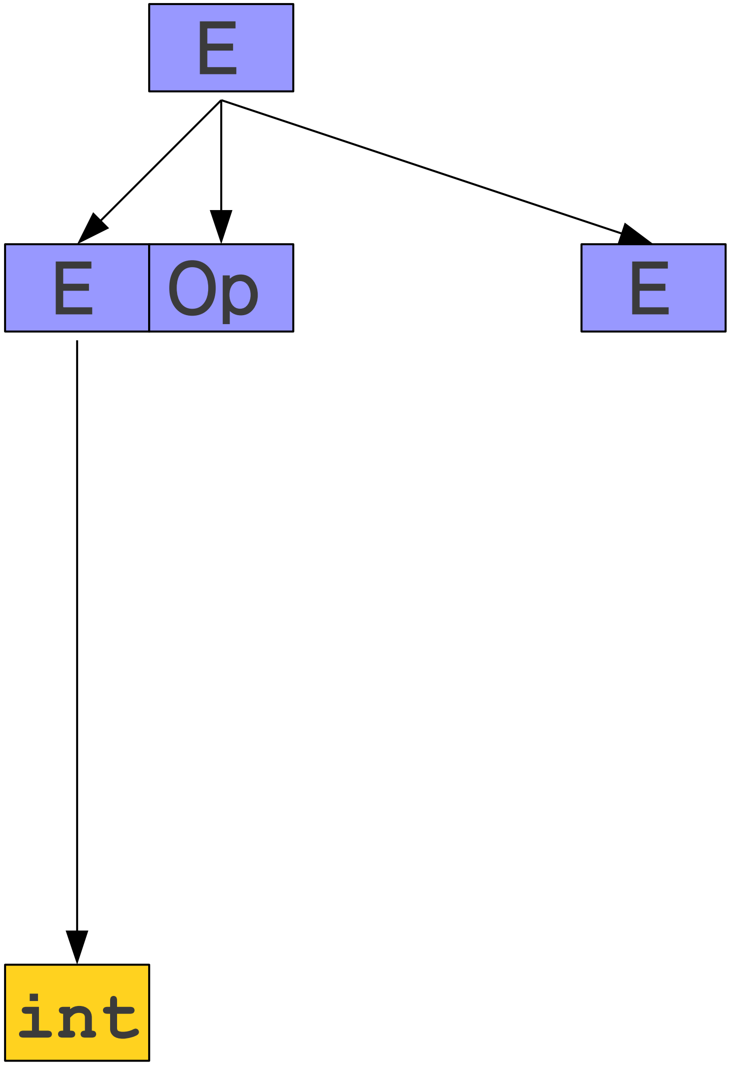
⇒ `int * (int + int)`

E

⇒ E Op E

⇒ `int` Op E

⇒ `int *` E



Parse Trees

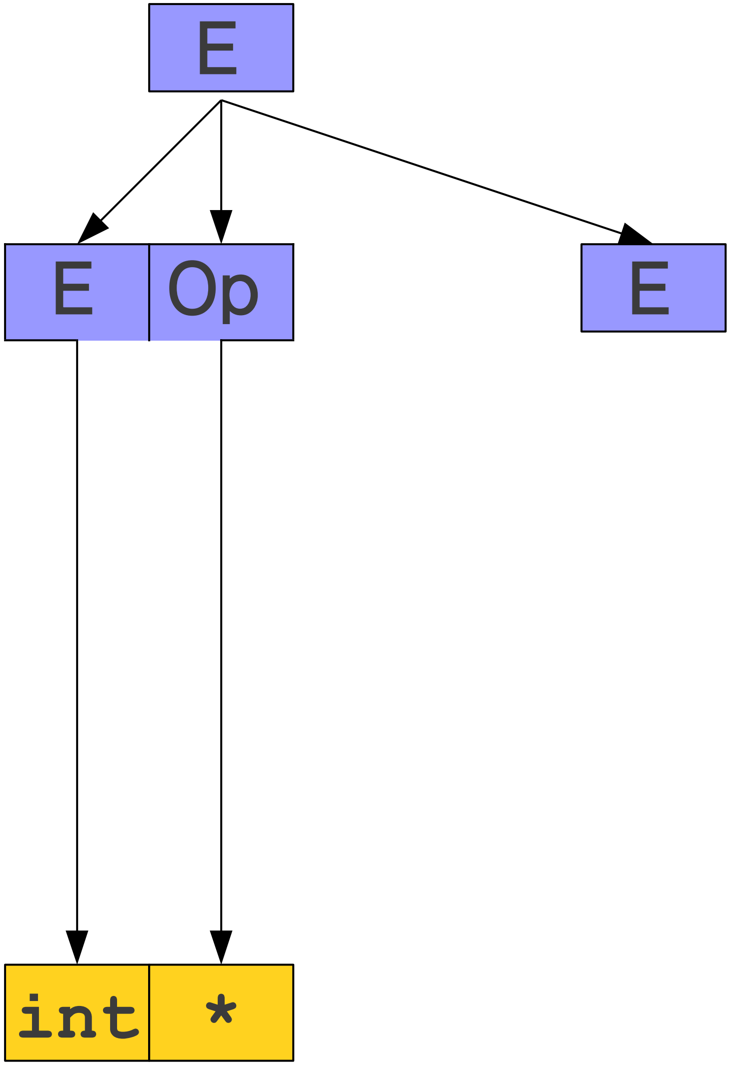
⇒ `int * (int + int)`

E

⇒ E Op E

⇒ `int` Op E

⇒ `int *` E



Parse Trees

⇒ `int * (int + int)`

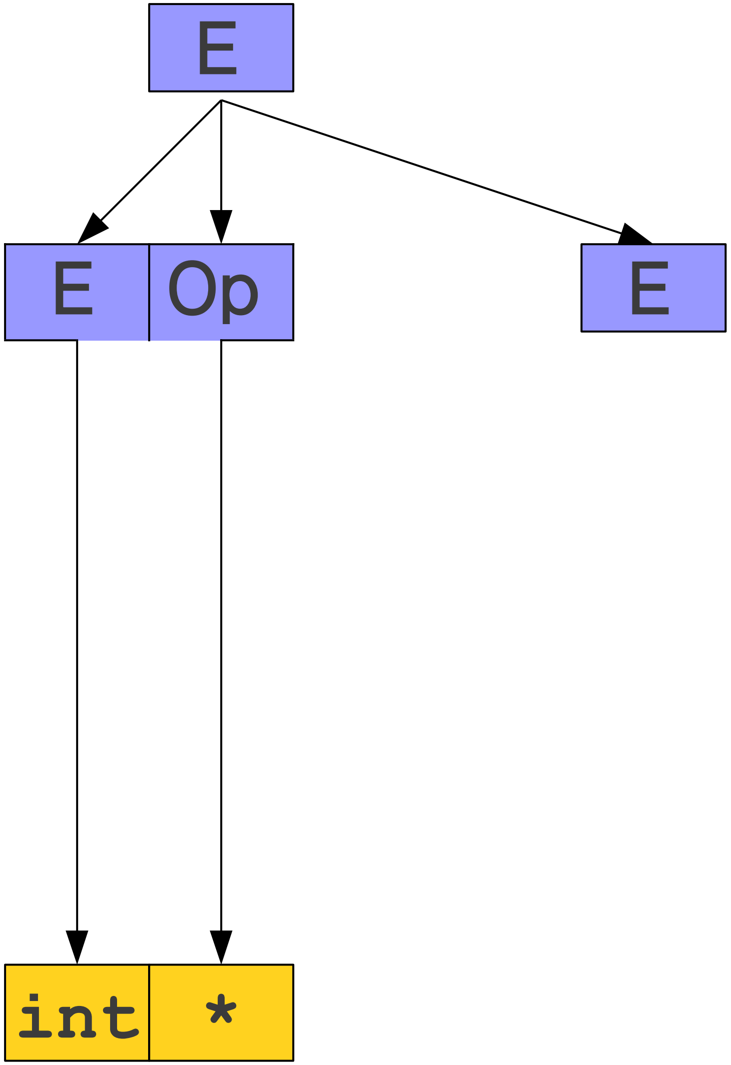
E

⇒ E Op E

⇒ `int` Op E

⇒ `int *` E

⇒ `int *` (E)



Parse Trees

⇒ `int * (int + int)`

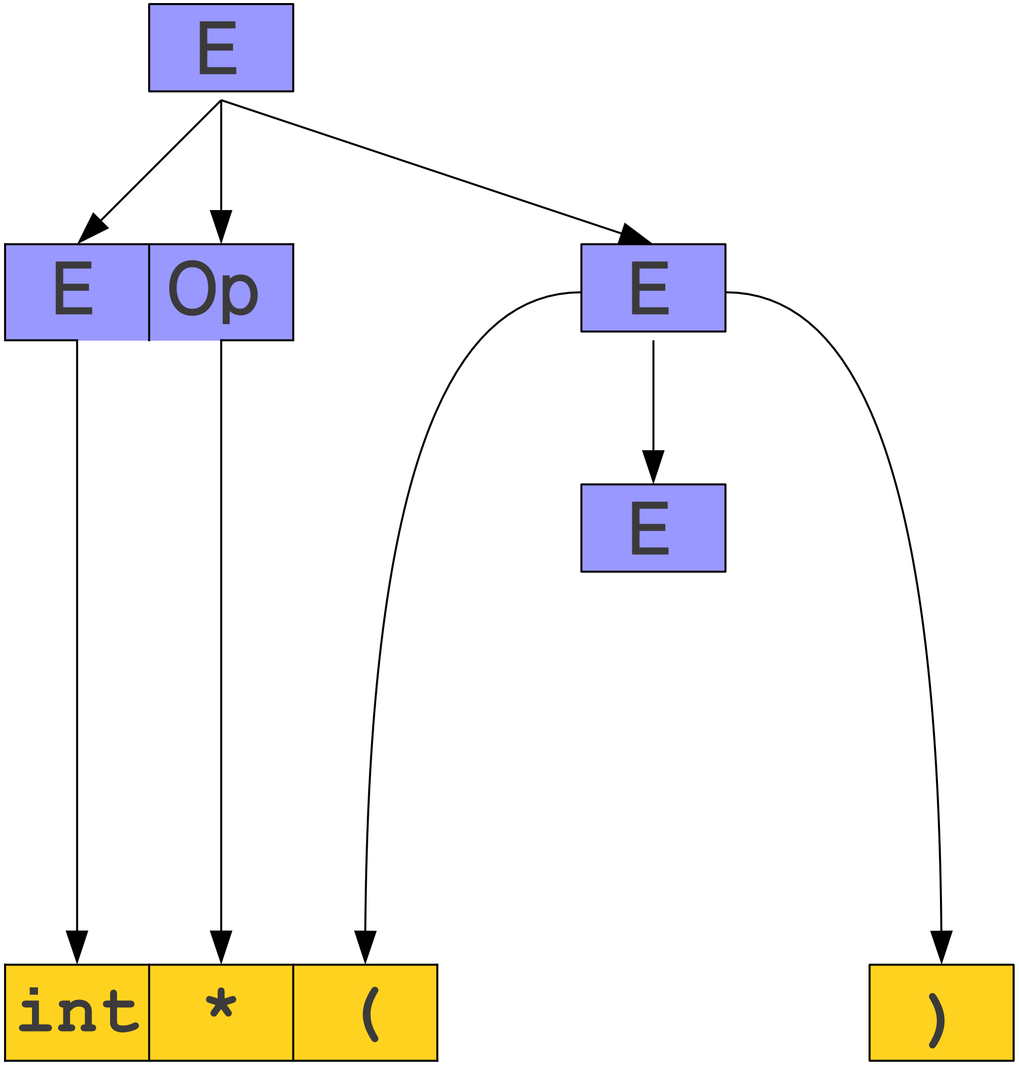
E

⇒ E Op E

⇒ `int` Op E

⇒ `int *` E

⇒ `int * (`E`)`



Parse Trees

⇒ `int * (int + int)`

E

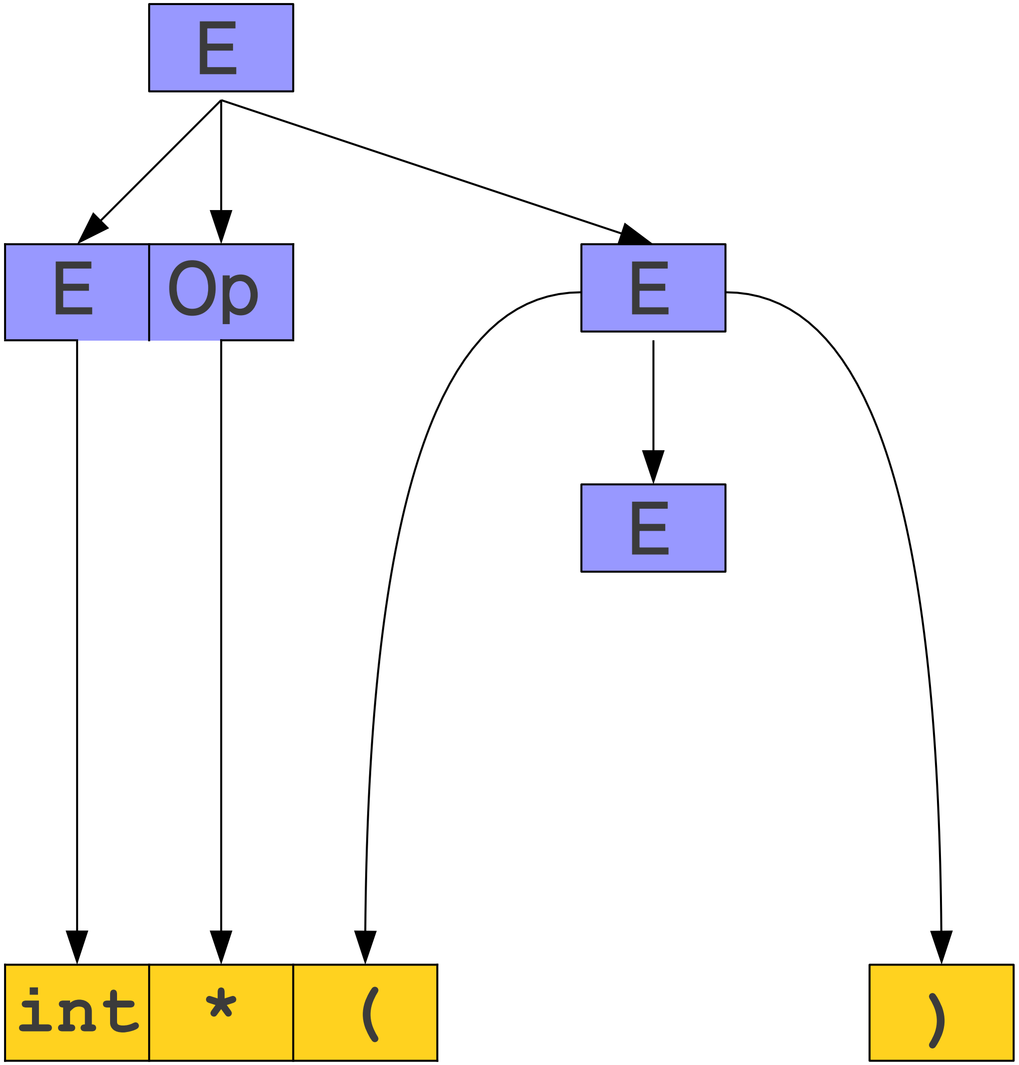
⇒ E Op E

⇒ `int` Op E

⇒ `int *` E

⇒ `int *` (E)

⇒ `int *` (E Op E)



Parse Trees

⇒ `int * (int + int)`

E

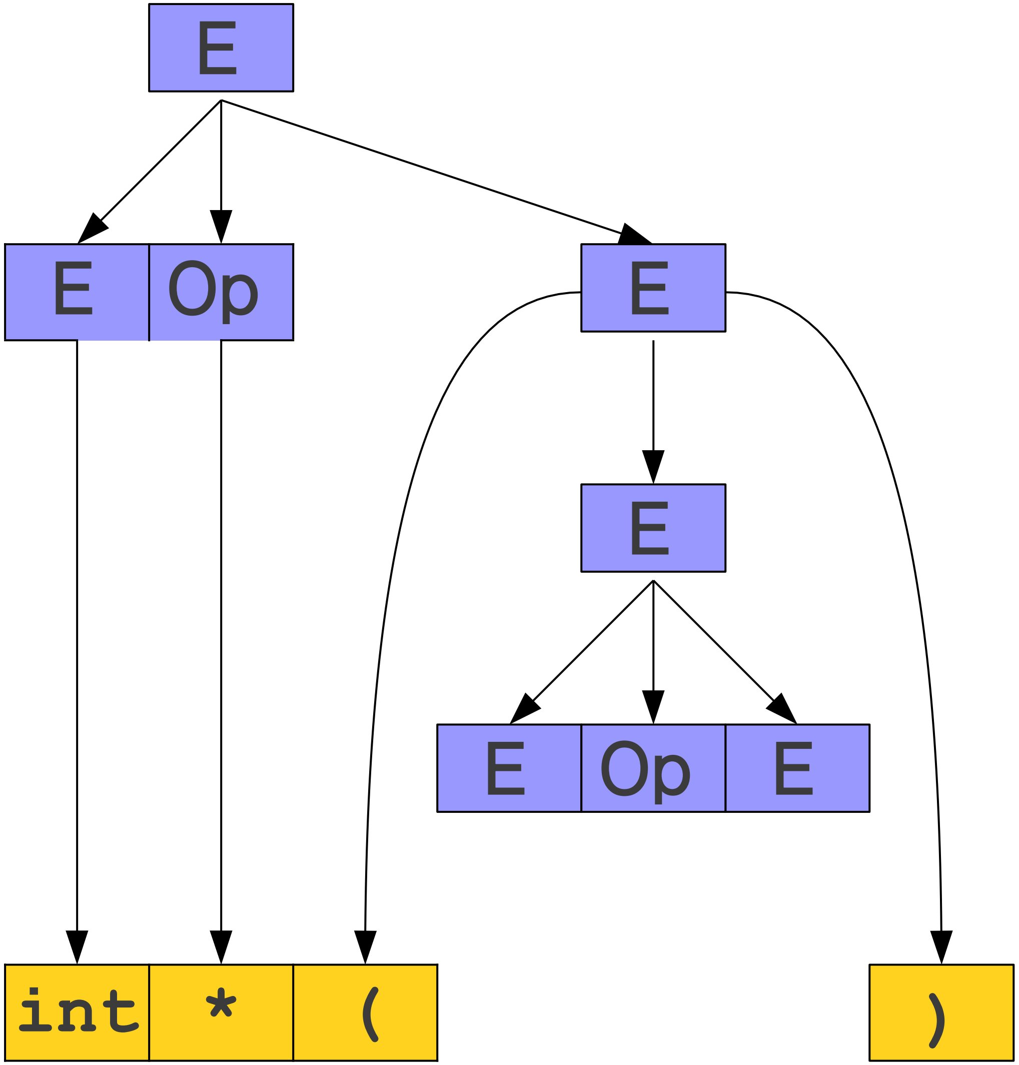
⇒ E Op E

⇒ `int` Op E

⇒ `int *` E

⇒ `int *` (E)

⇒ `int *` (E Op E)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

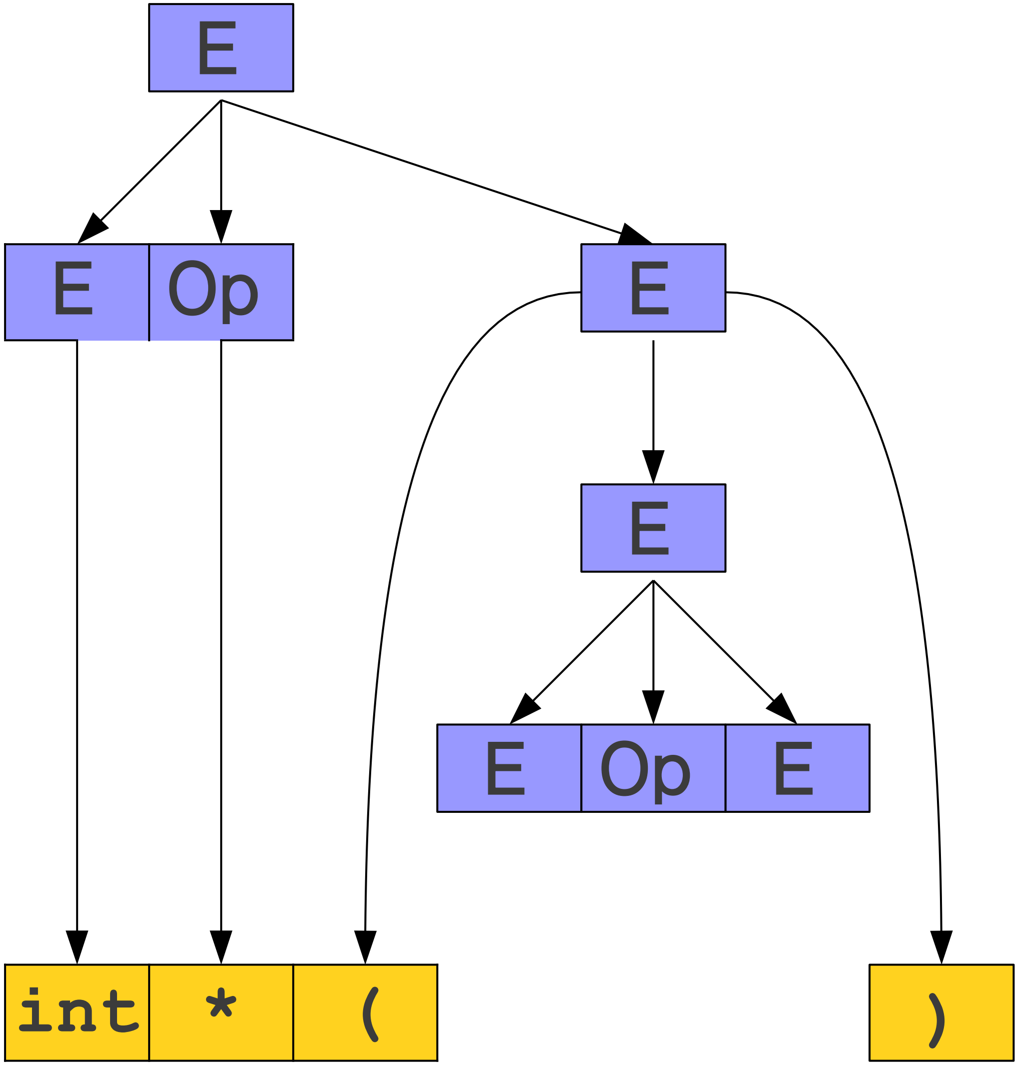
⇒ int Op E

⇒ int * E

⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)



Parse Trees

⇒ int * (int + int)

E

⇒ E Op E

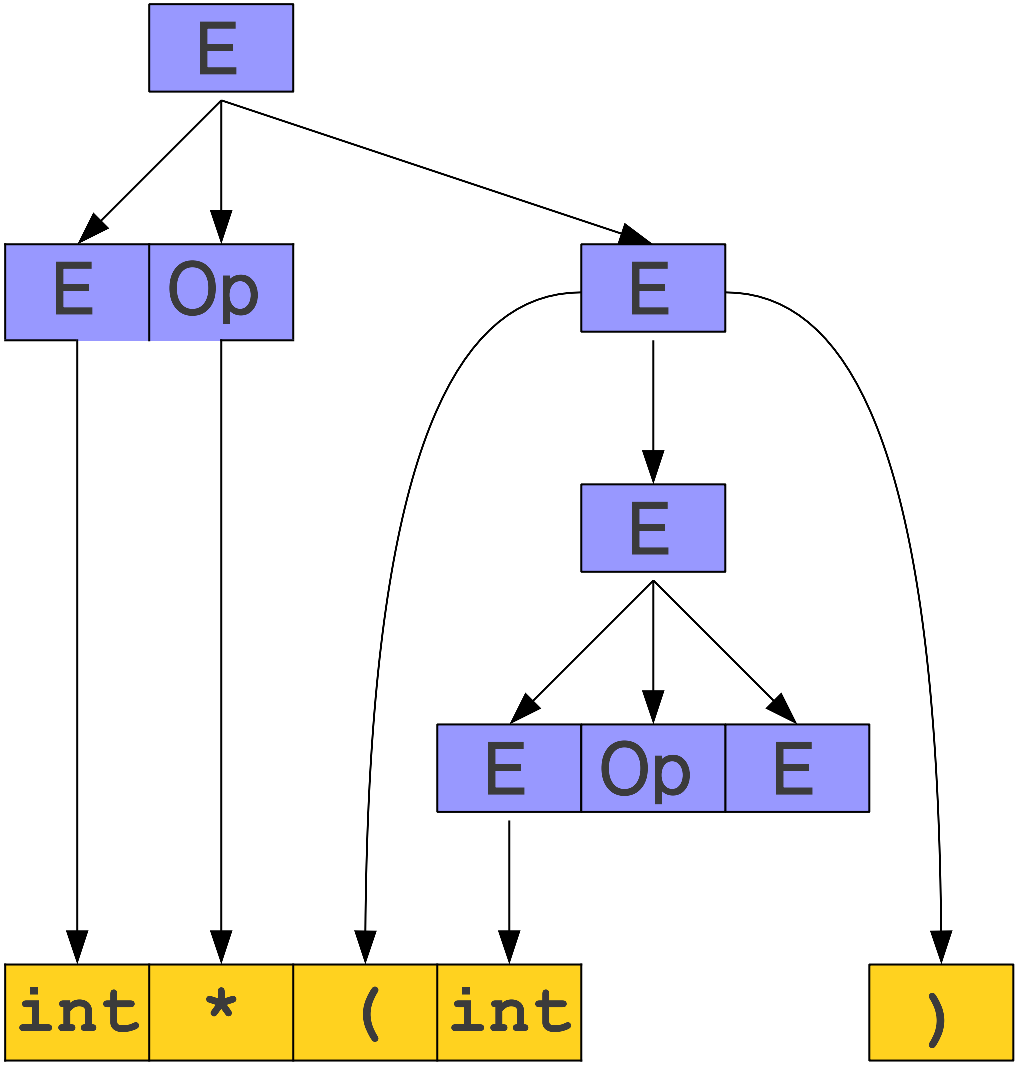
⇒ int Op E

⇒ int * E

⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ int Op E

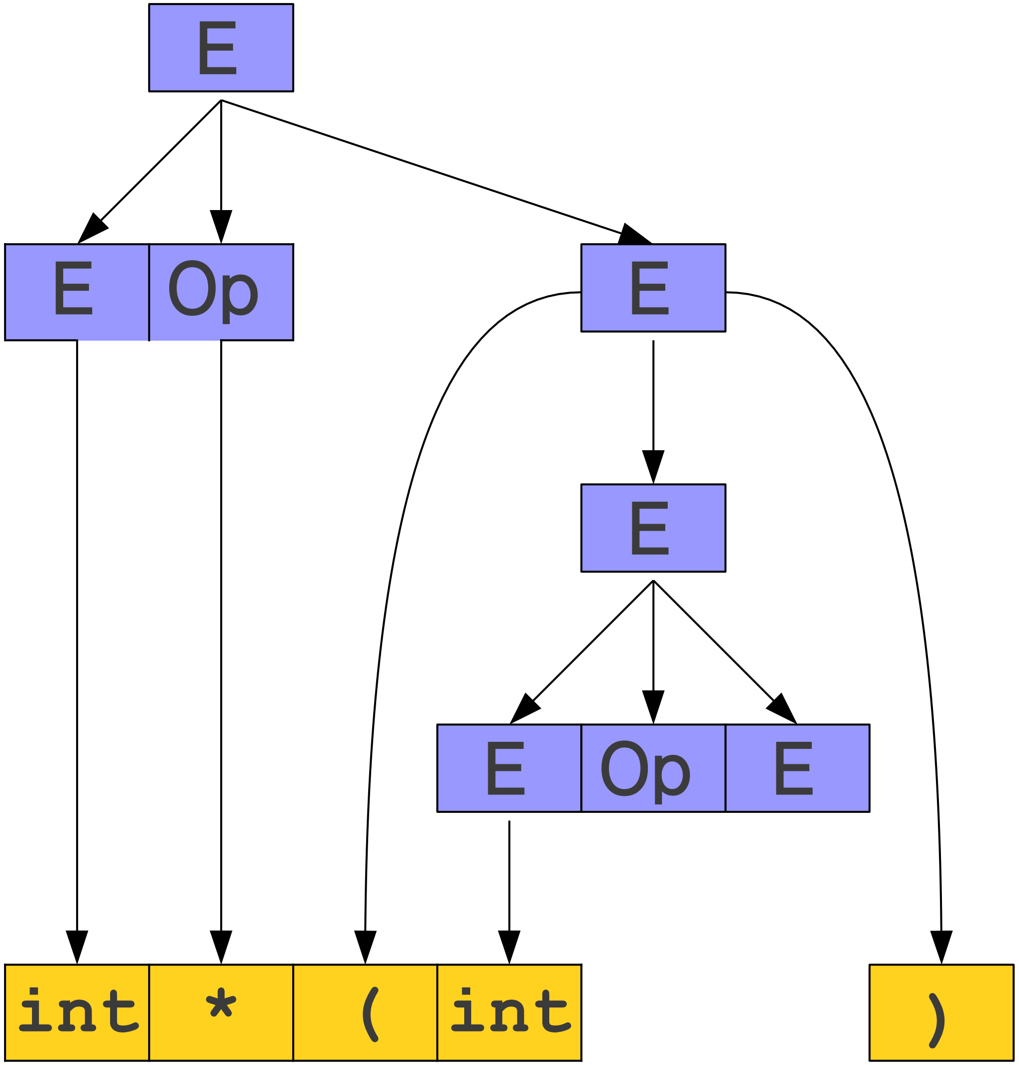
⇒ int * E

⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int + E)



Parse Trees

⇒ int * (int + int)

E

⇒ E Op E

⇒ int Op E

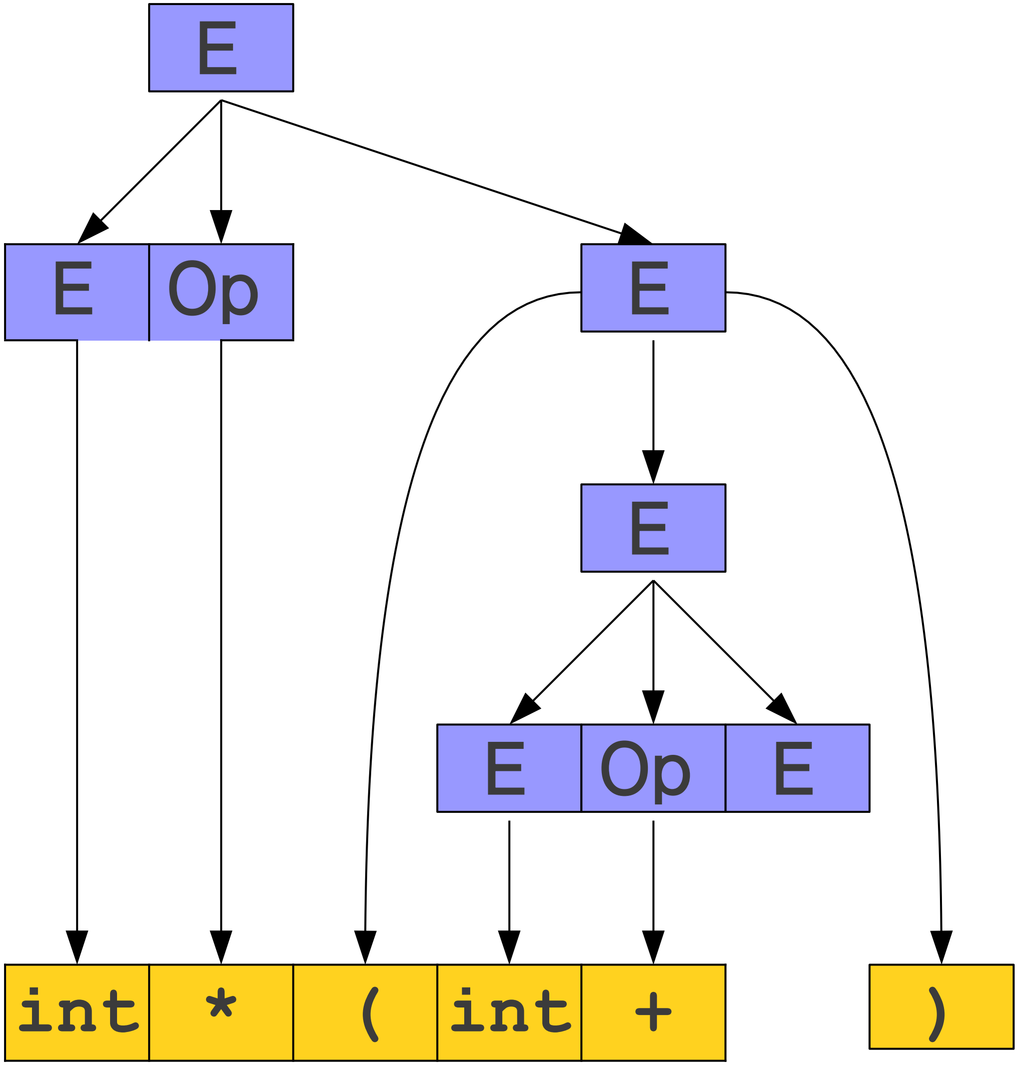
⇒ int * E

⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int + E)



Parse Trees

⇒ int * (int + int)

E

⇒ E Op E

⇒ int Op E

⇒ int * E

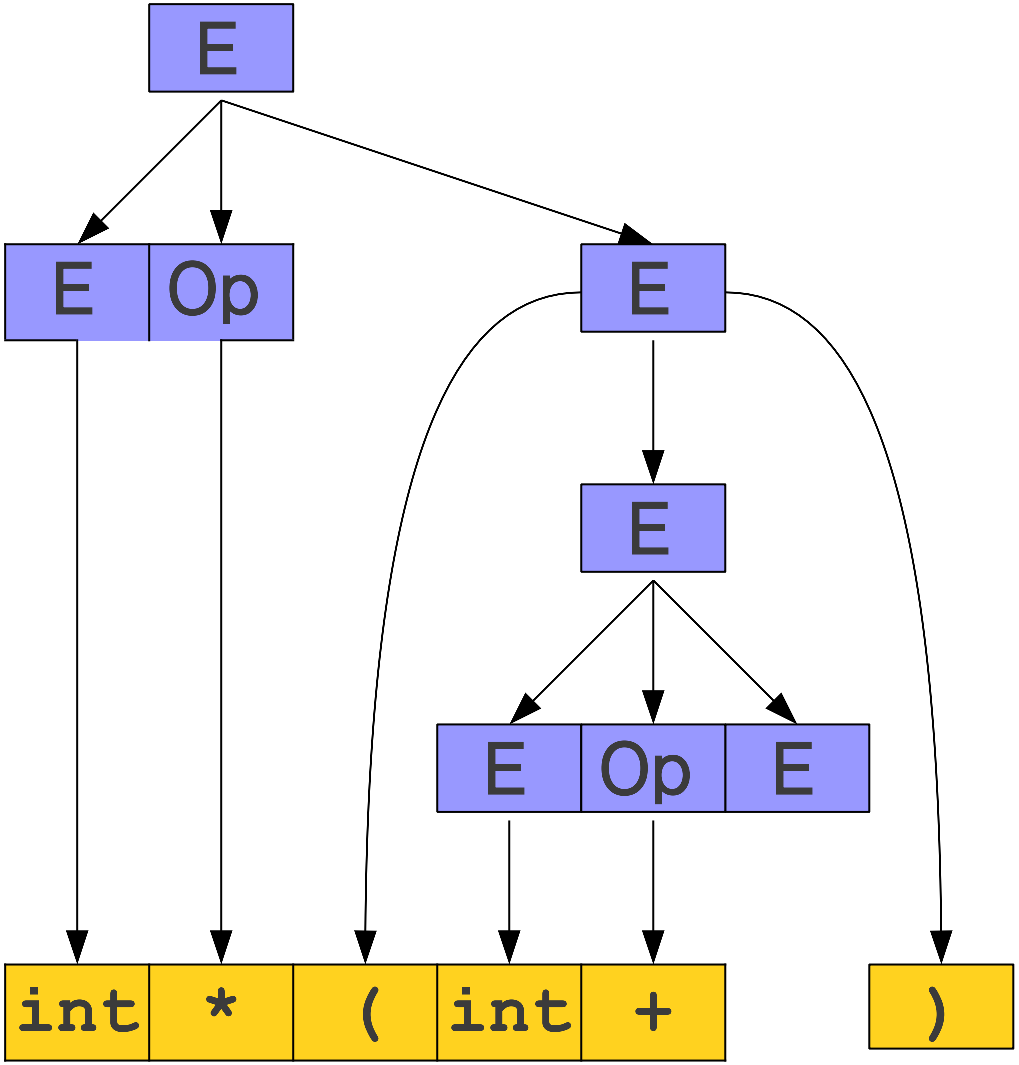
⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int + E)

⇒ int * (int + int)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ int Op E

⇒ int * E

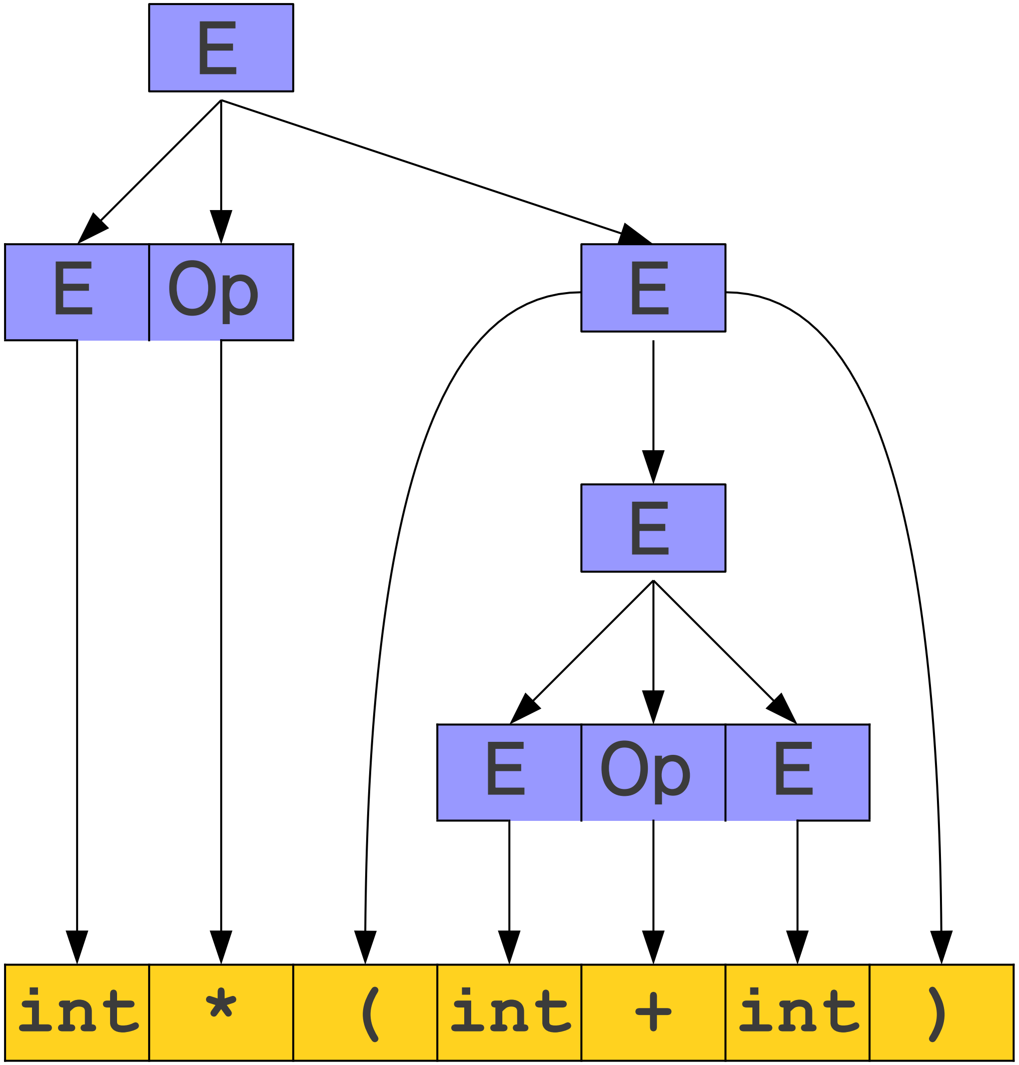
⇒ int * (E)

⇒ int * (E Op E)

⇒ int * (int Op E)

⇒ int * (int + E)

⇒ int * (int + int)



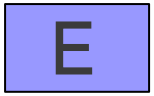
Parse Trees

⇒ `int * (int + int)`

E

Parse Trees

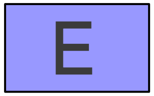
⇒ **`int * (int + int)`**


E

E

Parse Trees

⇒ `int * (int + int)`



E

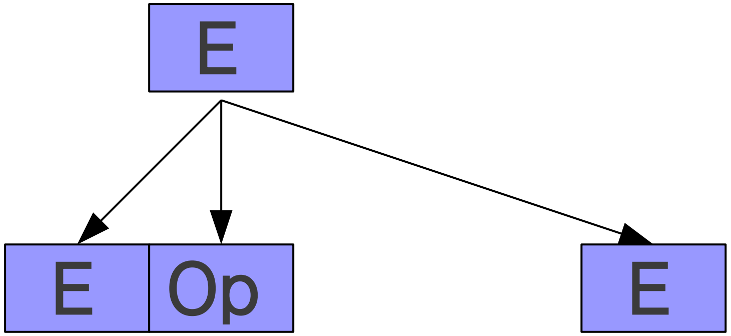
⇒ E Op E

Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E



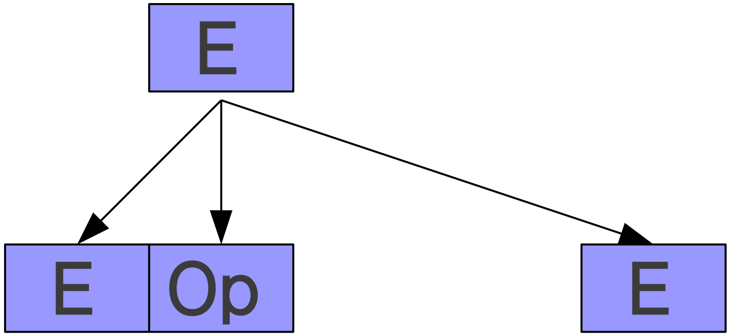
Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)



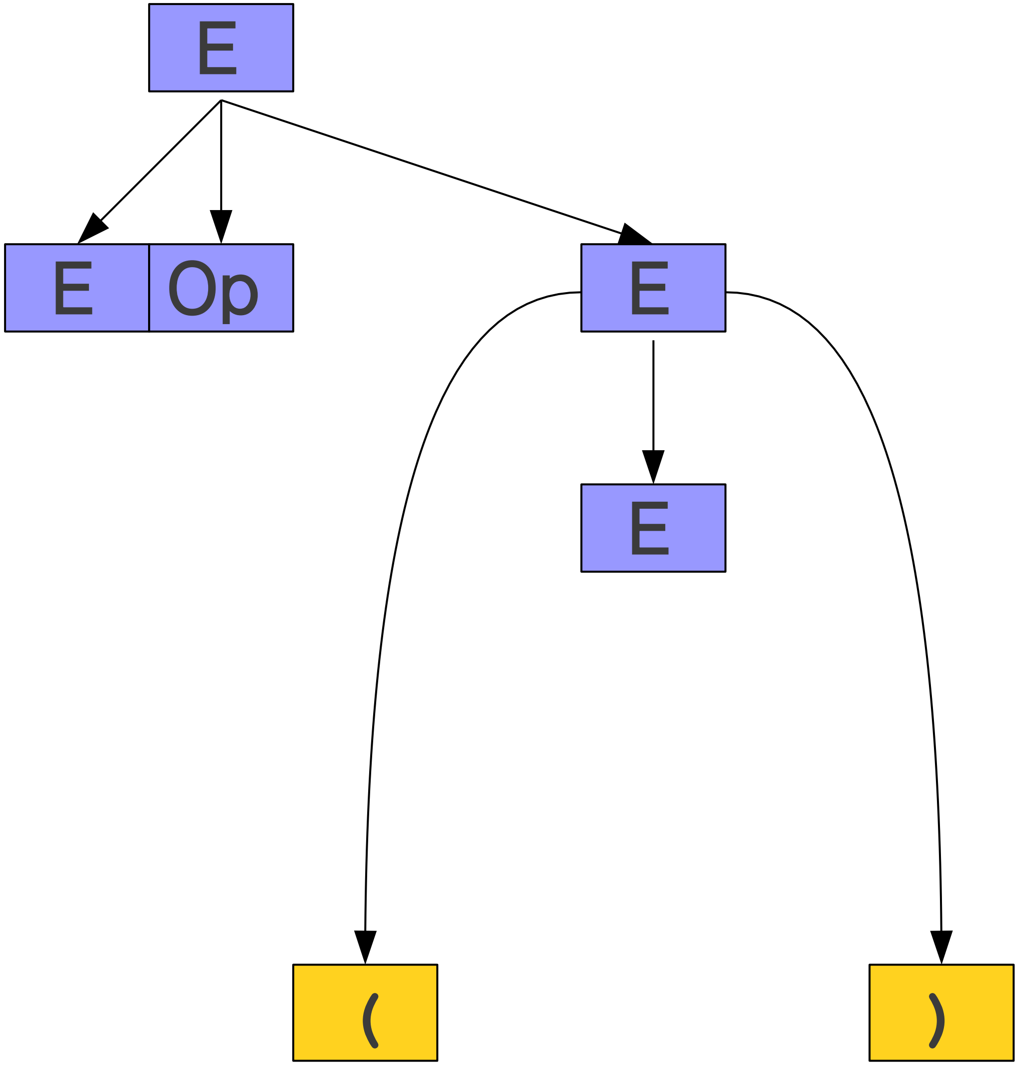
Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)



Parse Trees

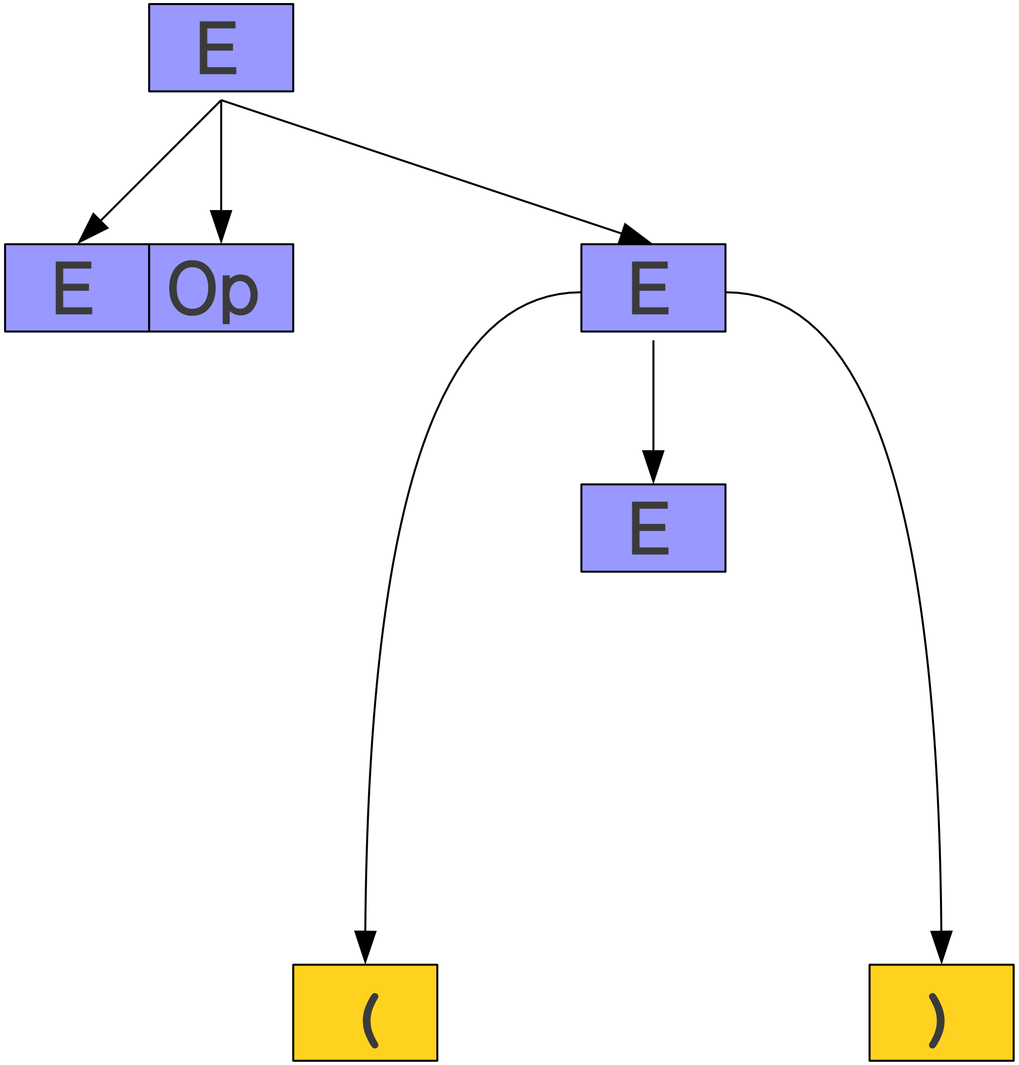
⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)



Parse Trees

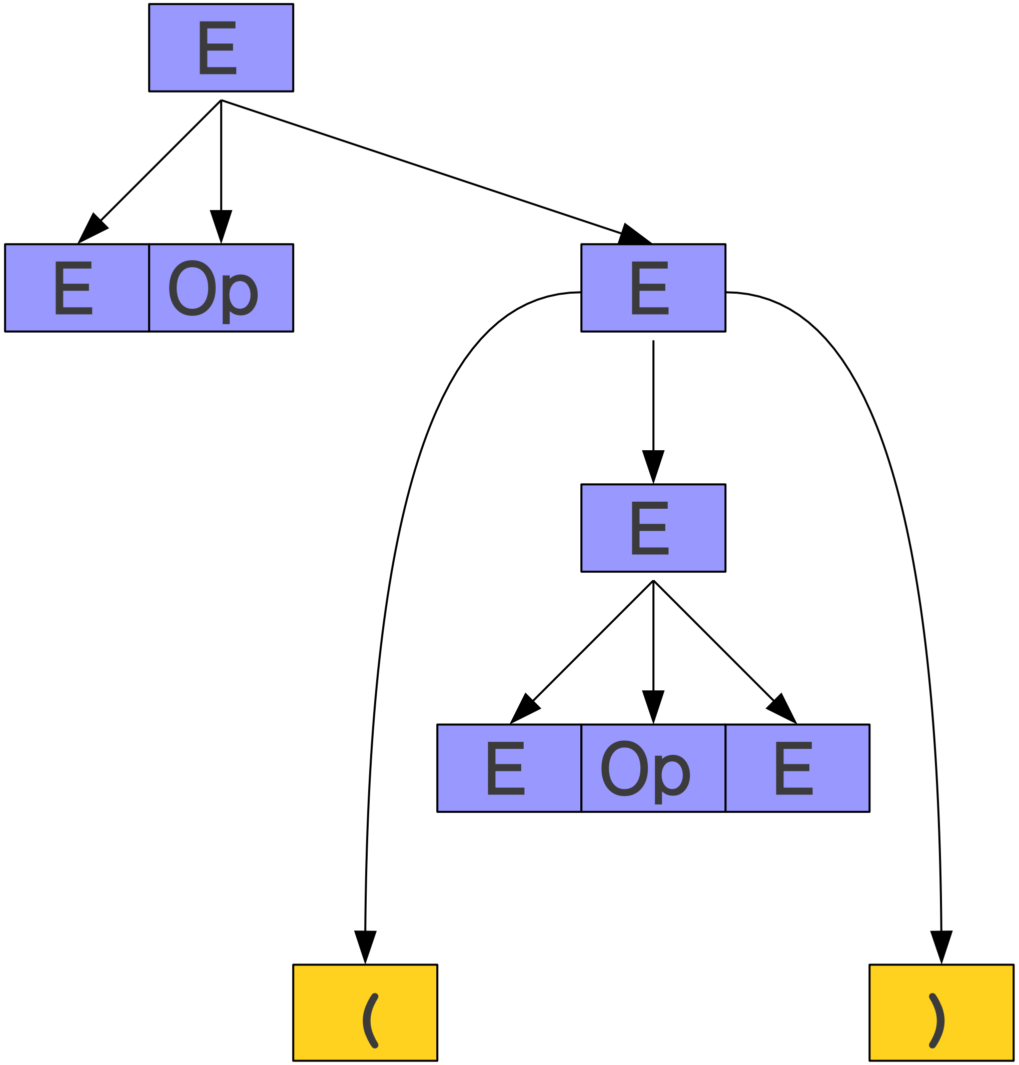
⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)



Parse Trees

⇒ `int * (int + int)`

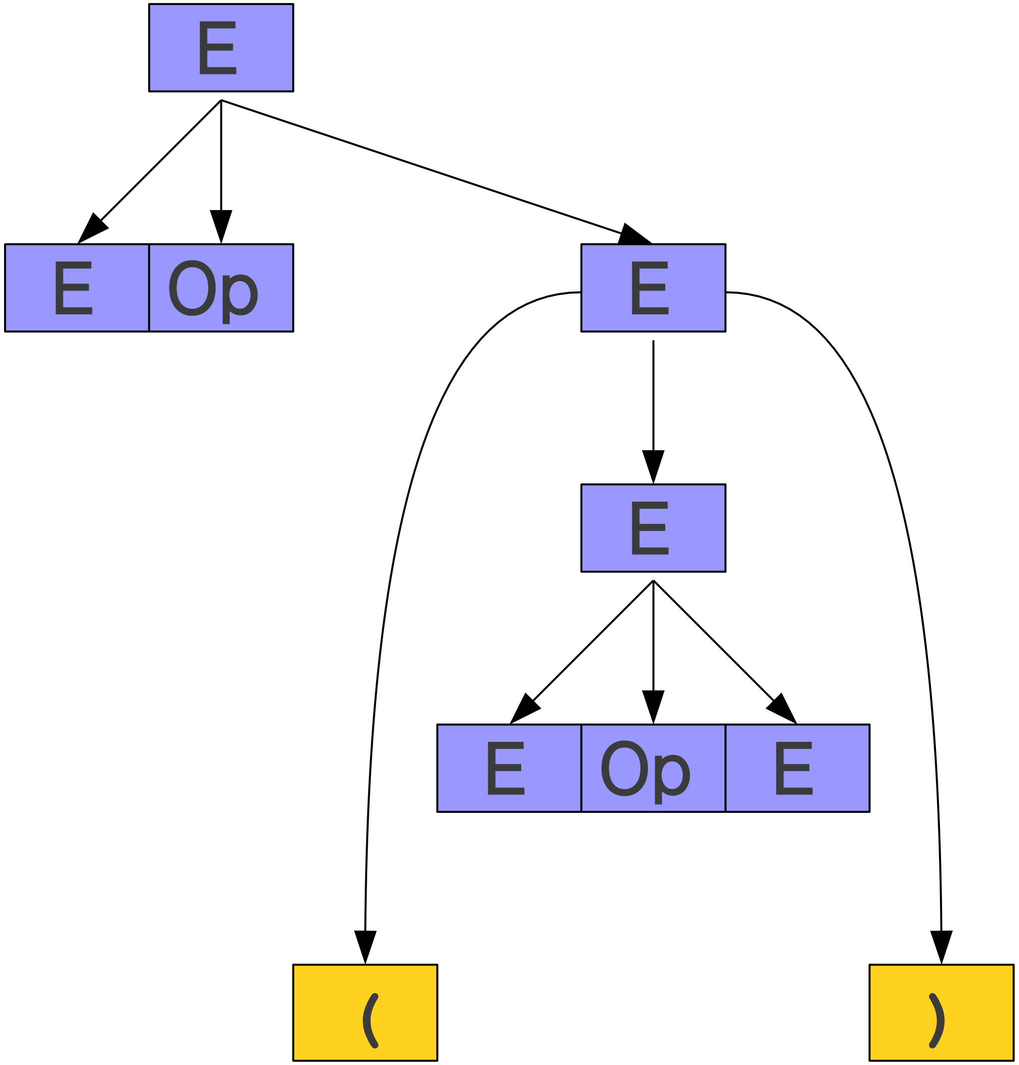
E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)



Parse Trees

⇒ `int * (int + int)`

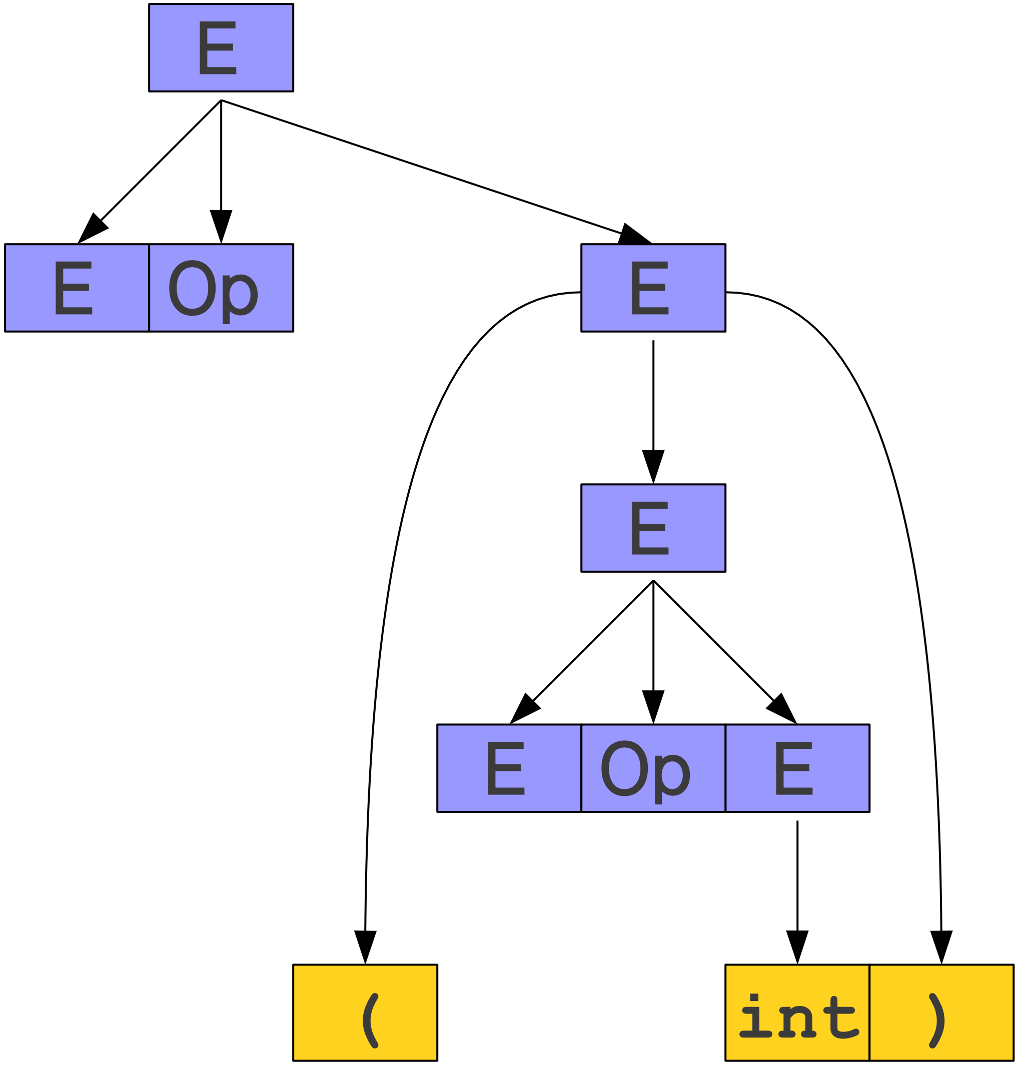
E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)



Parse Trees

⇒ `int * (int + int)`

E

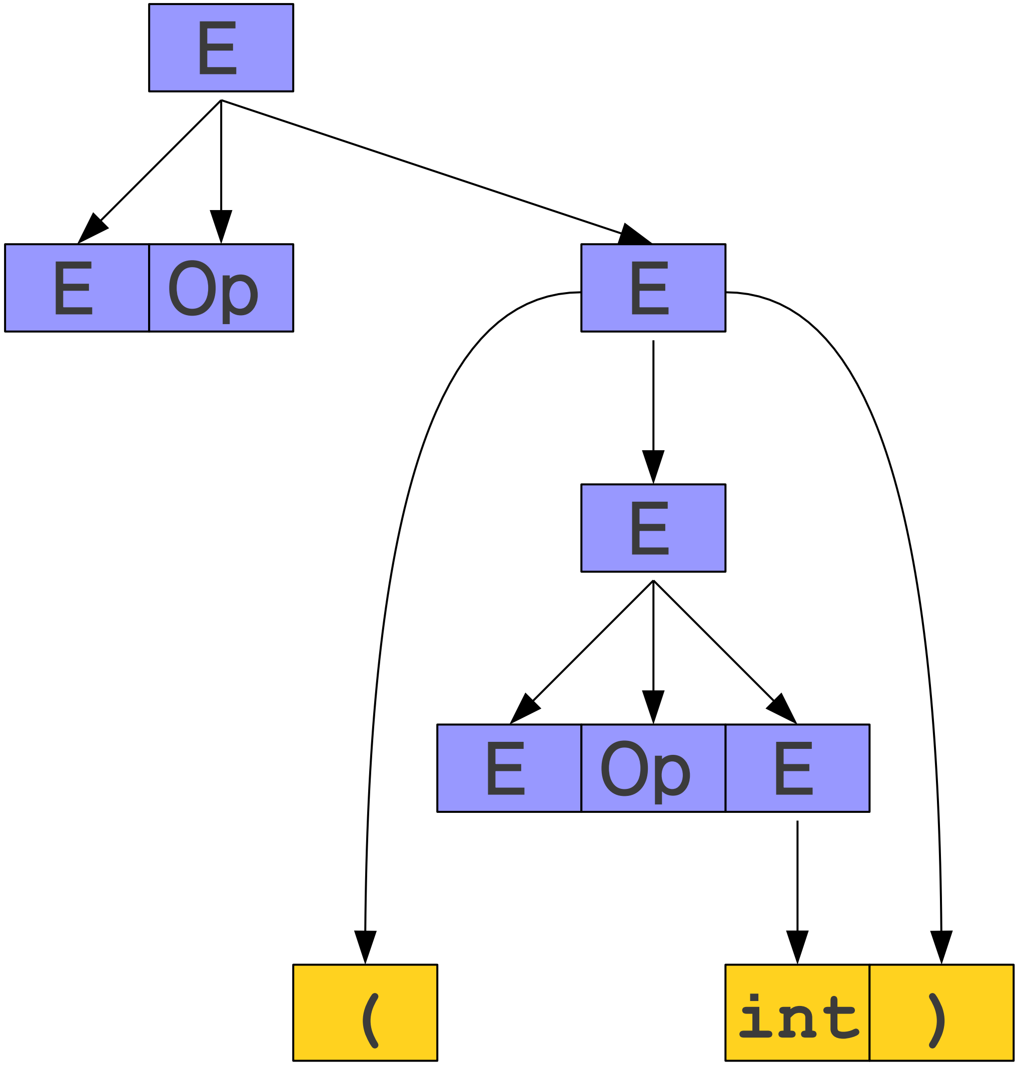
⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)



Parse Trees

⇒ int * (int + int)

E

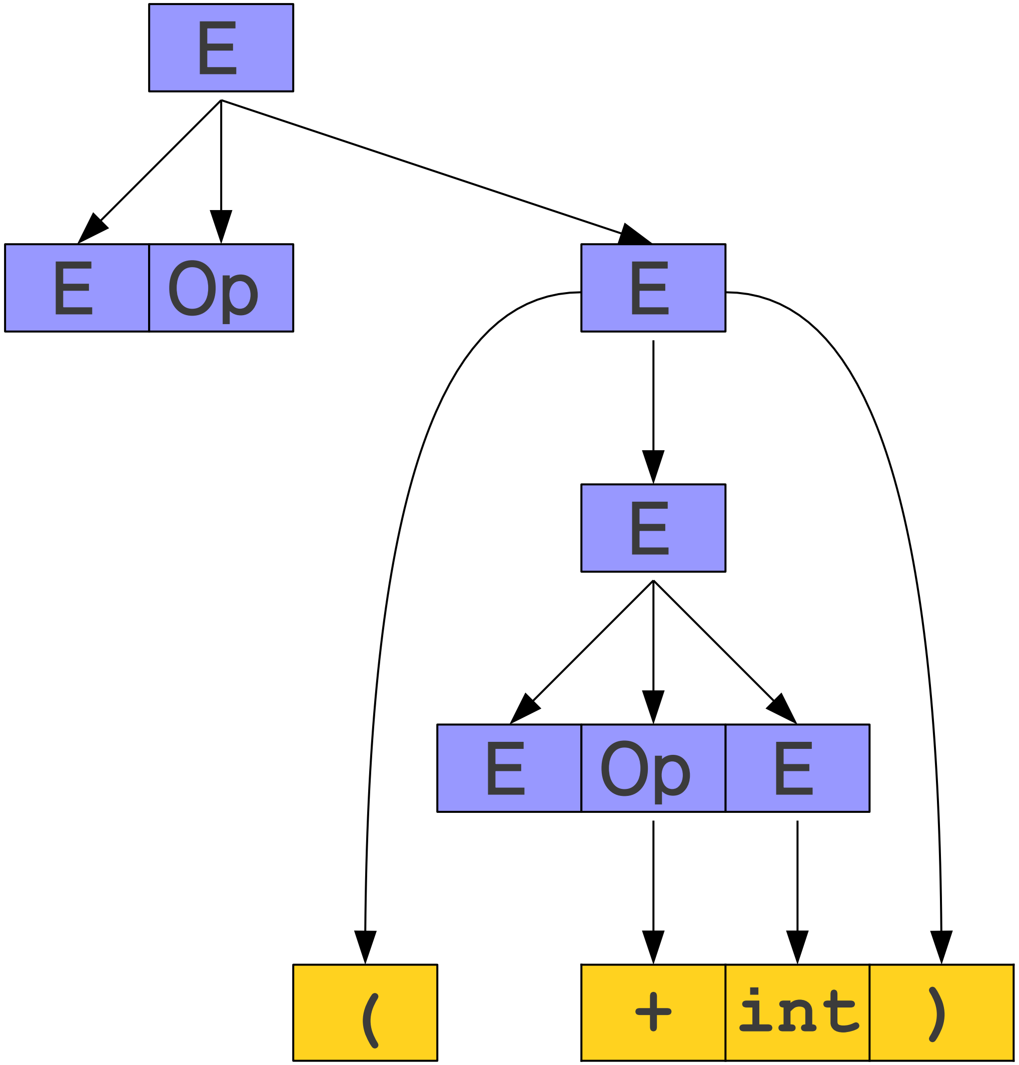
⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)



Parse Trees

⇒ int * (int + int)

E

⇒ E Op E

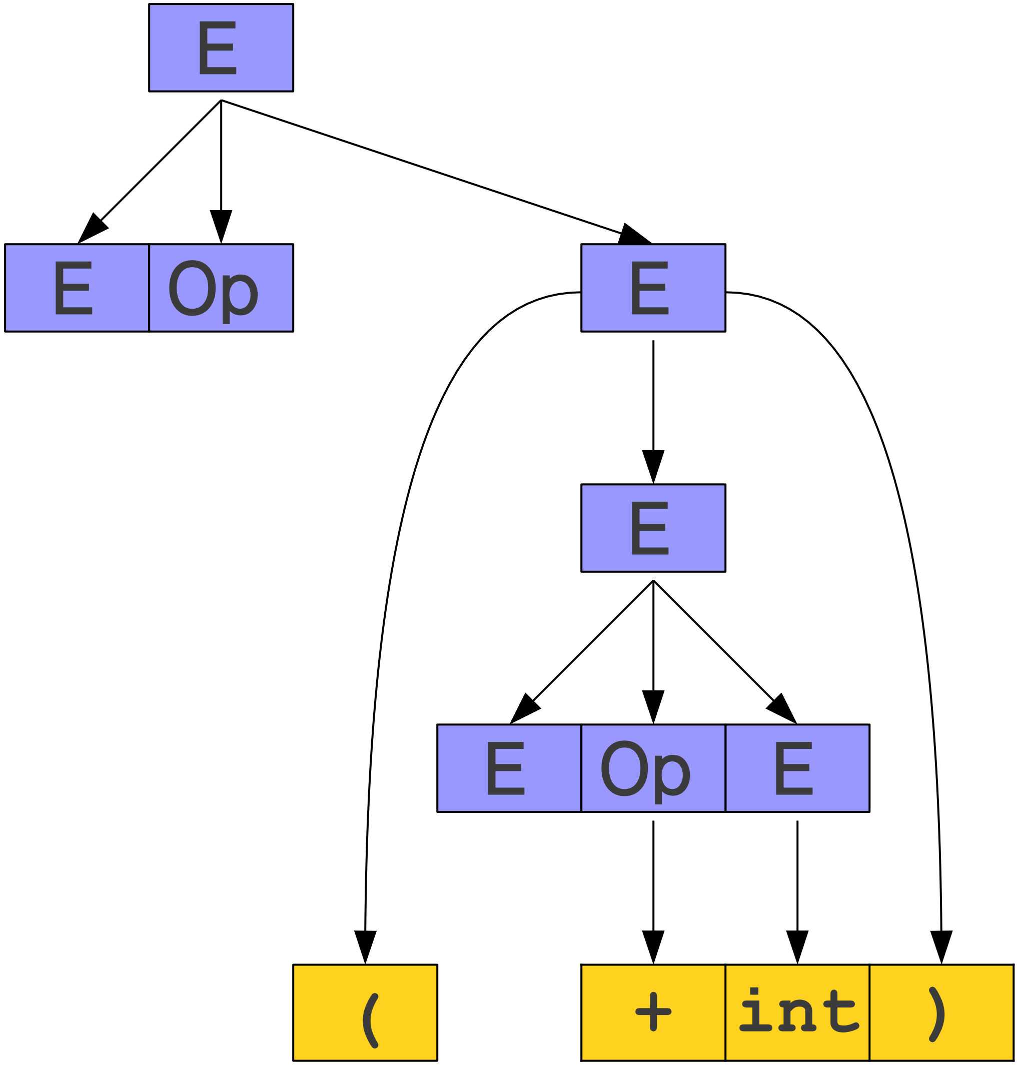
⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)

⇒ E Op (int + int)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

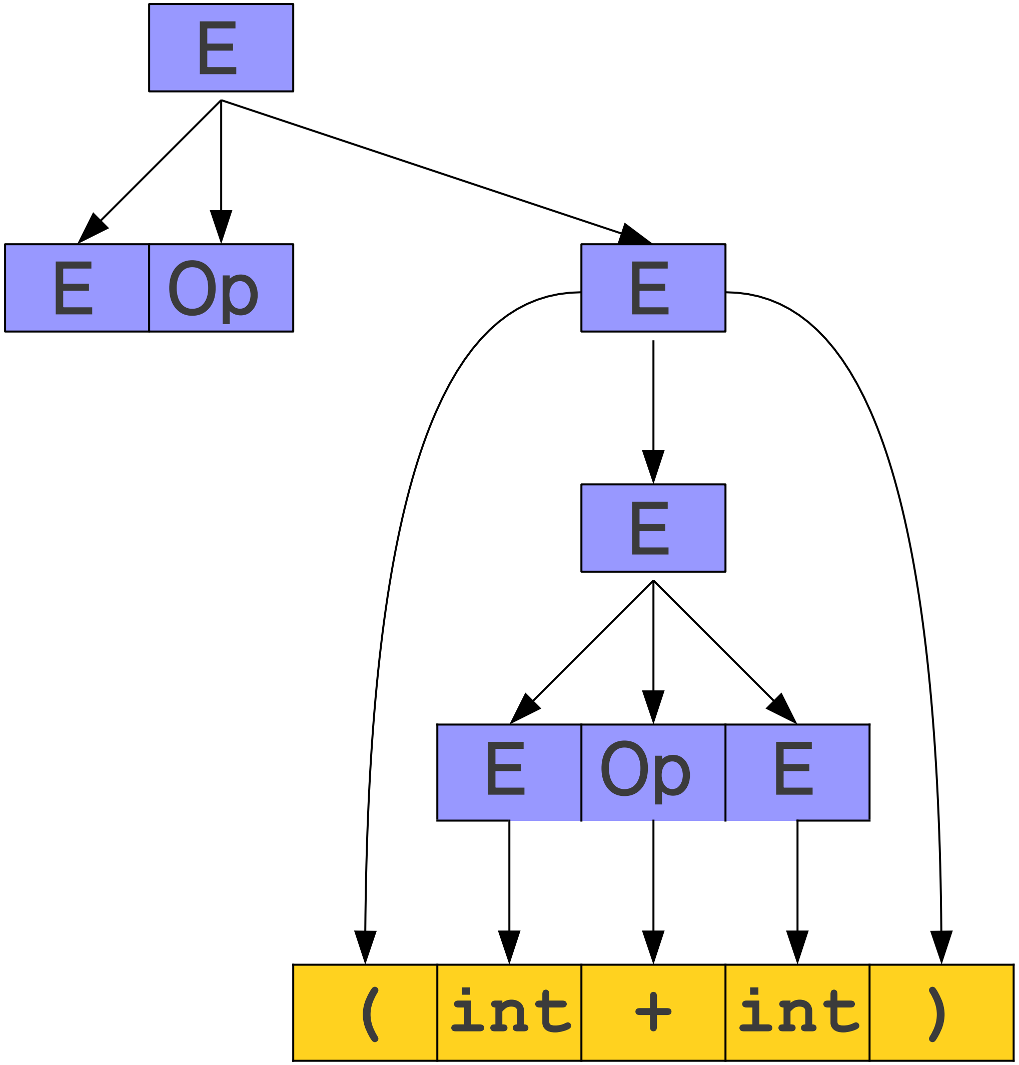
⇒ E Op (E)

⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)

⇒ E Op (int + int)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)

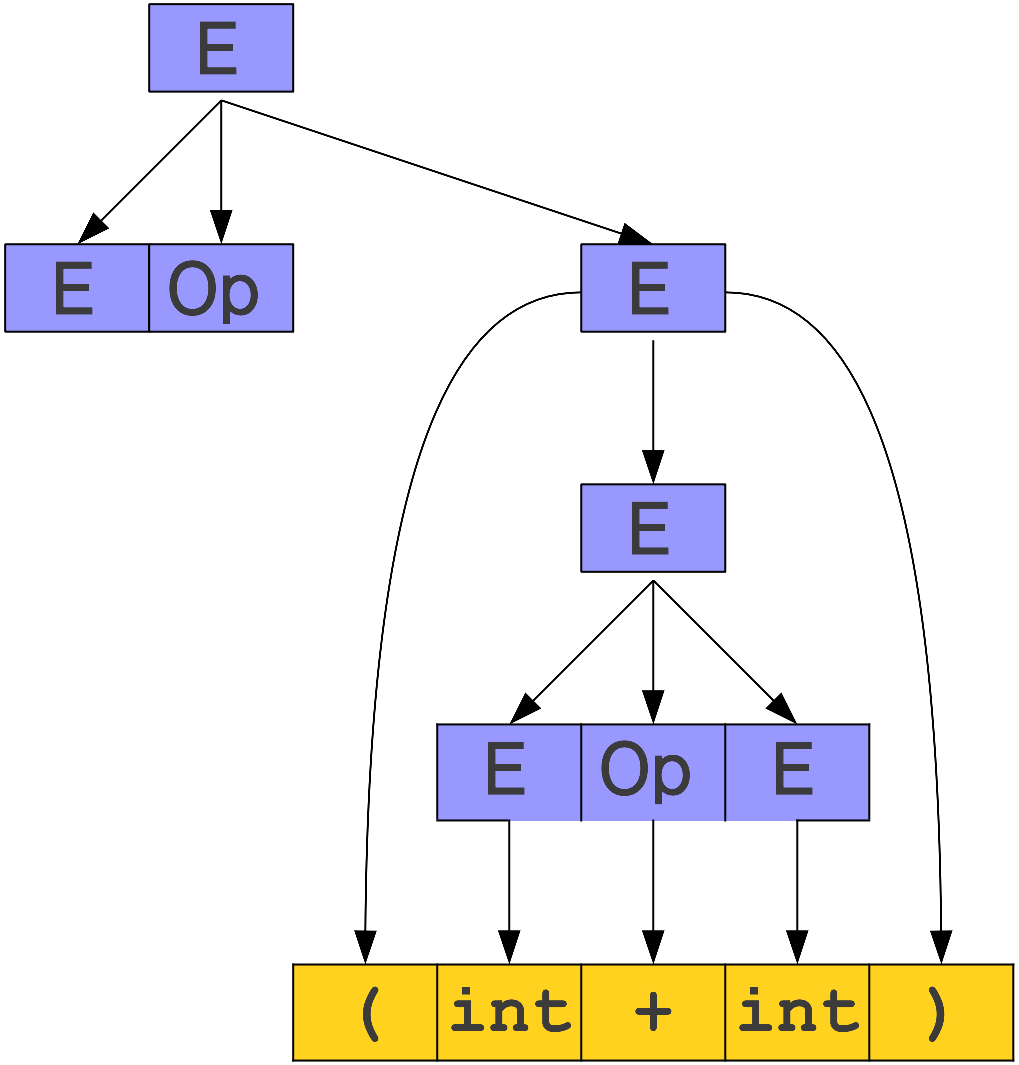
⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)

⇒ E Op (int + int)

⇒ E * (int + int)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)

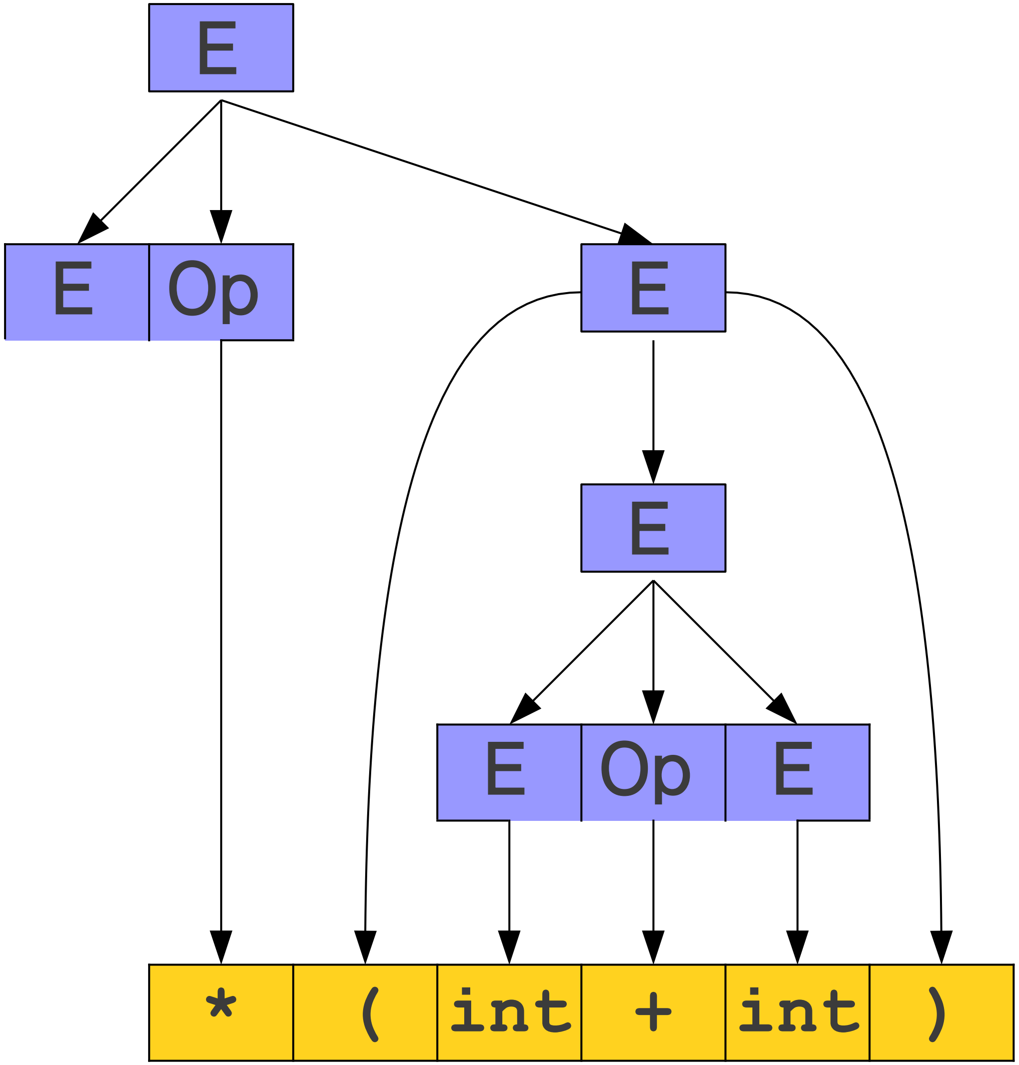
⇒ E Op (E Op E)

⇒ E Op (E Op int)

⇒ E Op (E + int)

⇒ E Op (int + int)

⇒ E * (int + int)



Parse Trees

⇒ `int * (int + int)`

E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

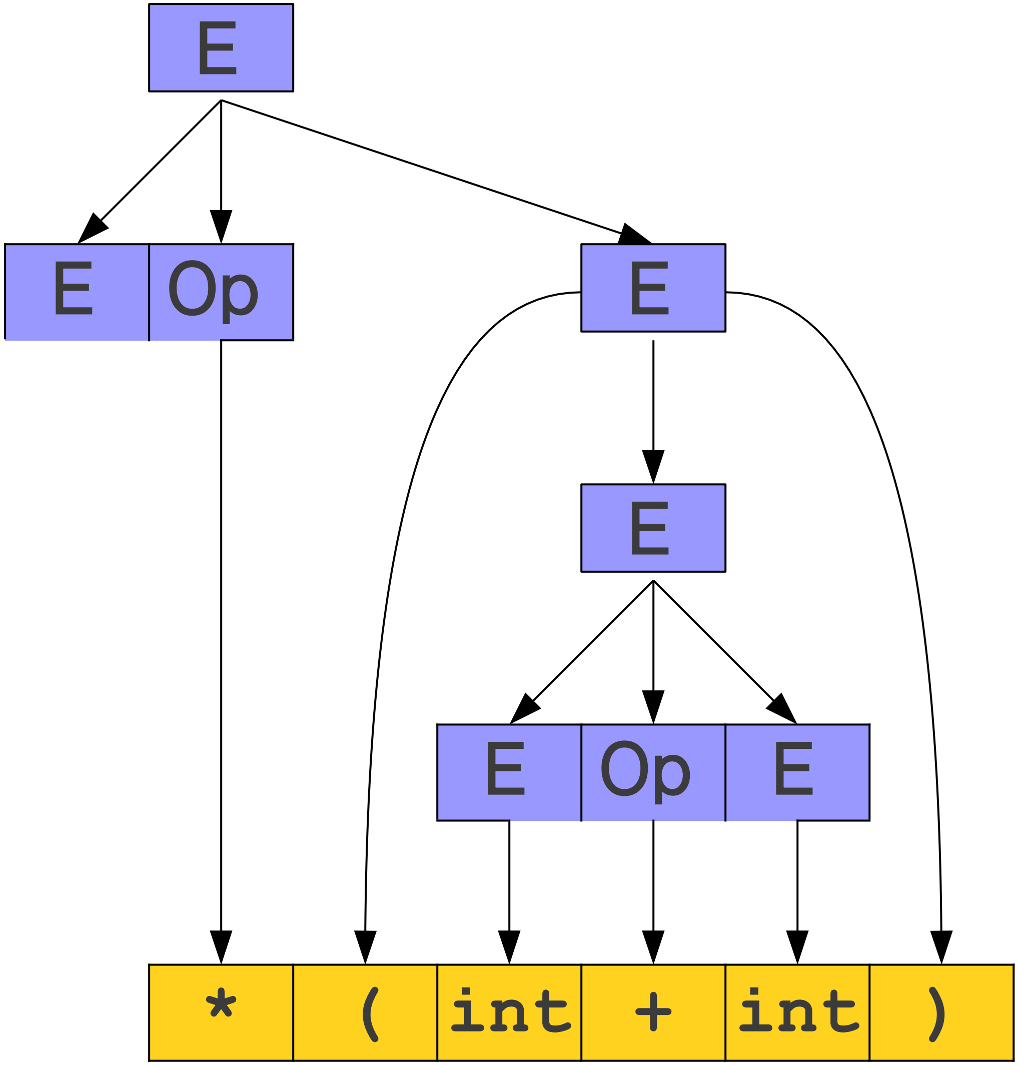
⇒ E Op (E Op `int`)

⇒ E Op (E + `int`)

⇒ E Op (`int + int`)

⇒ E `* (int + int)`

⇒ `int * (int + int)`



Parse Trees

⇒ int * (int + int)

E

⇒ E Op E

⇒ E Op (E)

⇒ E Op (E Op E)

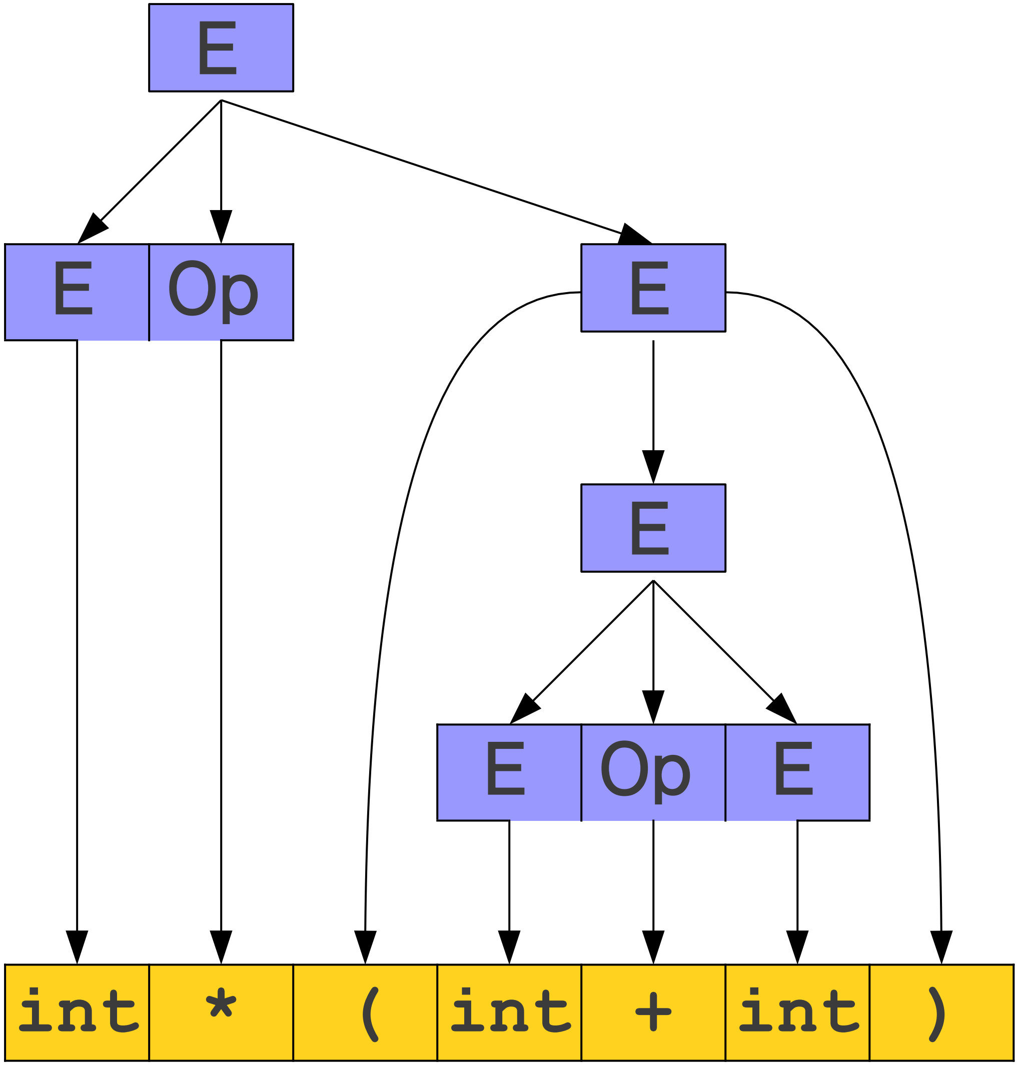
⇒ E Op (E Op int)

⇒ E Op (E + int)

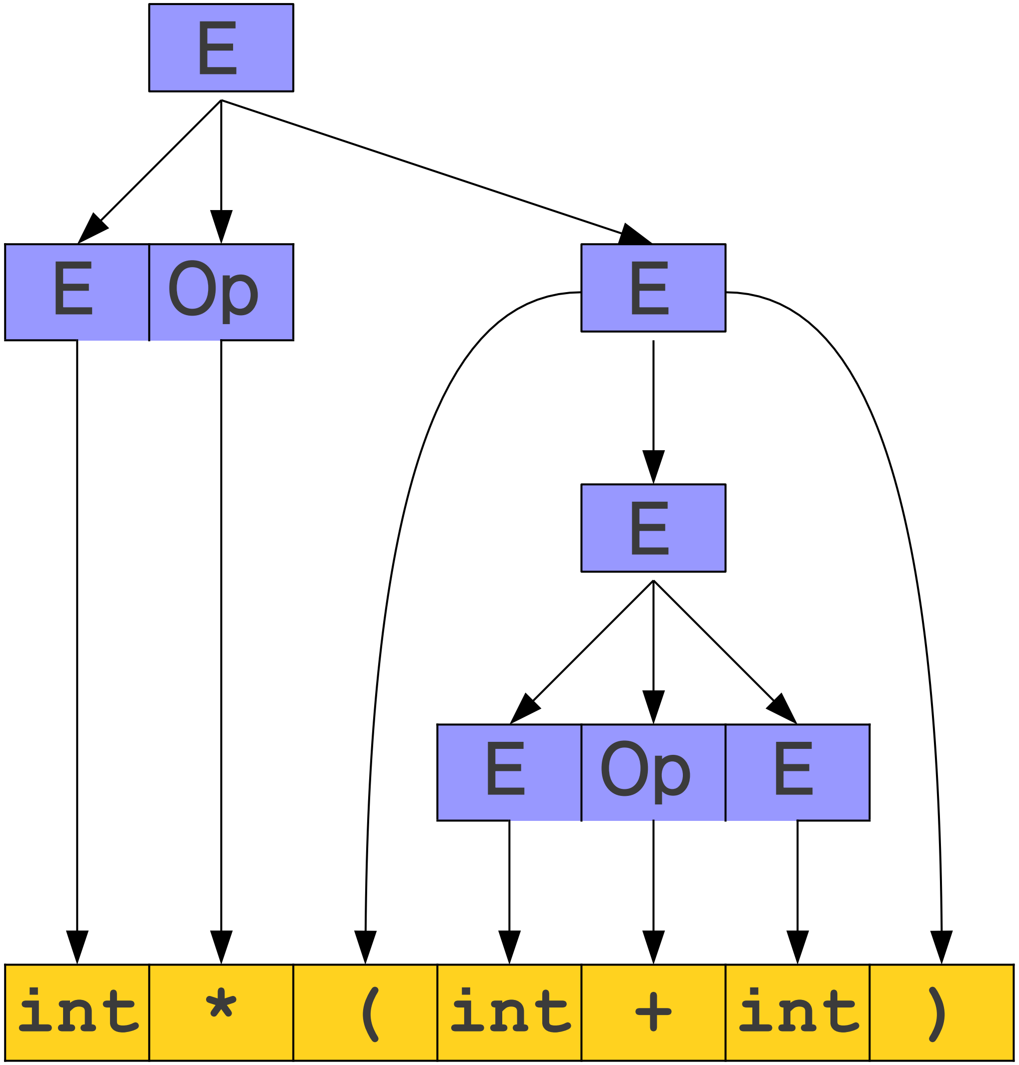
⇒ E Op (int + int)

⇒ E * (int + int)

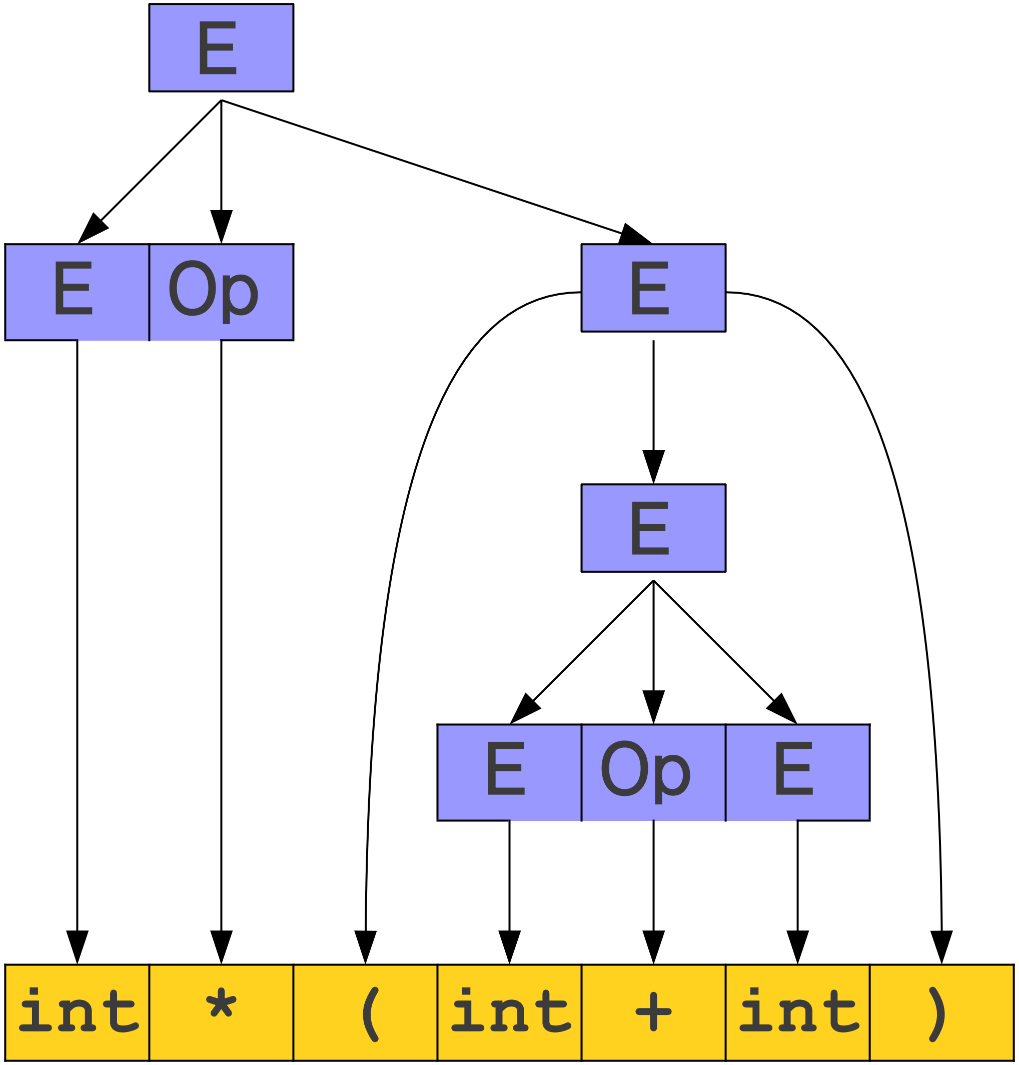
⇒ int * (int + int)



For Comparison



Parse Tree with
Leftmost Derivation



Parse Tree with
Rightmost Derivation

Parse Trees

- A parse tree is a tree encoding the steps in a derivation.
- Internal nodes represent nonterminal symbols used in the production.
- Encodes what productions are used, not the order in which those productions are applied.

The Goal of Parsing

- Goal of syntax analysis: Recover the structure described by a series of tokens.
- If language is described as a CFG, goal is to recover a parse tree for the the input string.
- We'll discuss how to do this next week.

Challenges in Parsing

Challenge

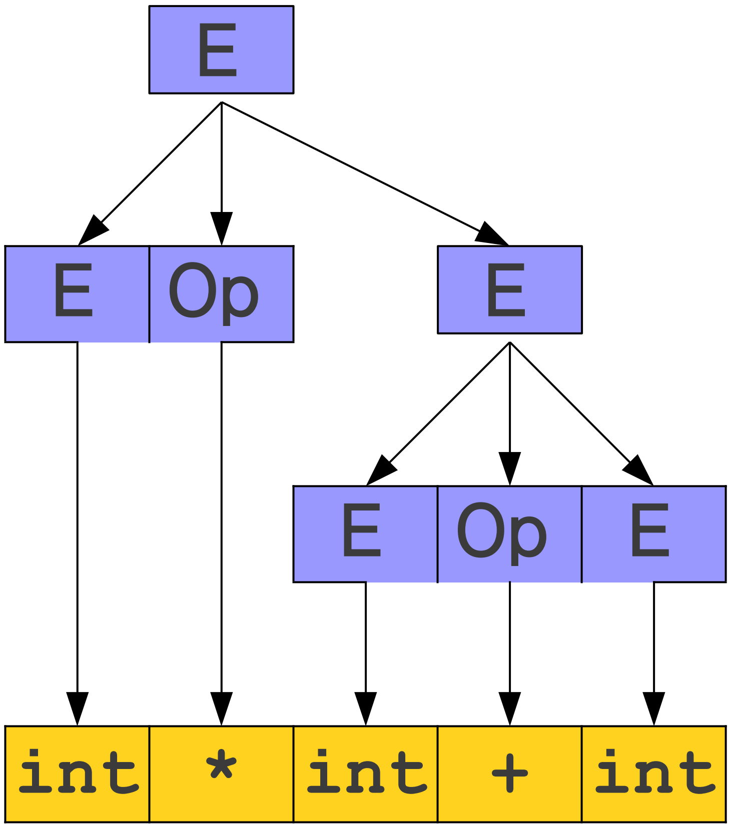
E → int | E Op E

Op → + | * |

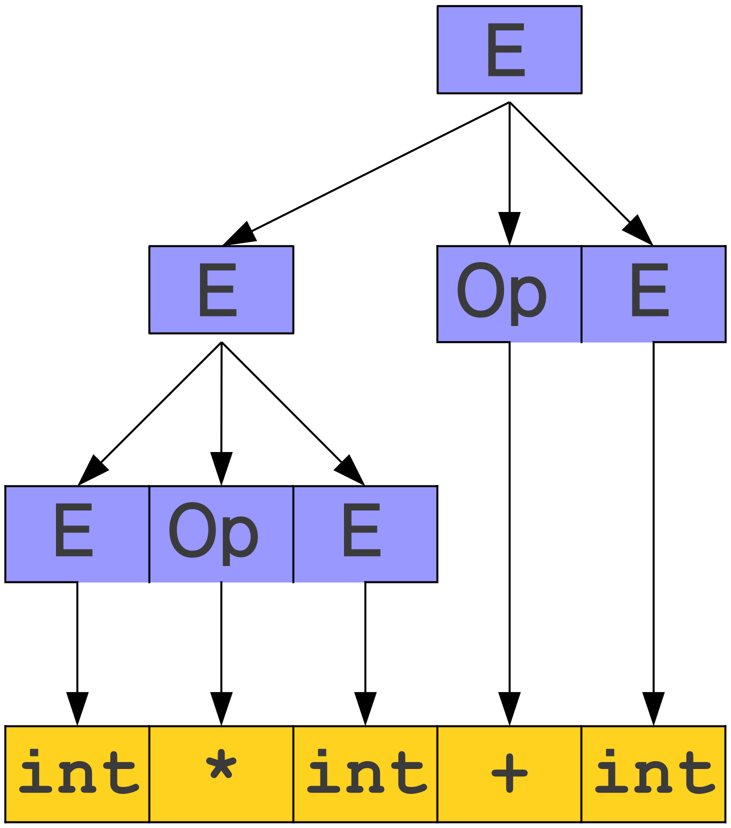
int * int + int

Can you construct Parse Tree?

A Serious Problem



int * (int + int)



(int * int) + int

Ambiguity

- A CFG is said to be ambiguous if there is at least one string with two or more parse trees.

Is Ambiguity a Problem?

- Depends on semantics .

$$E \rightarrow \mathtt{int} \mid E + E$$

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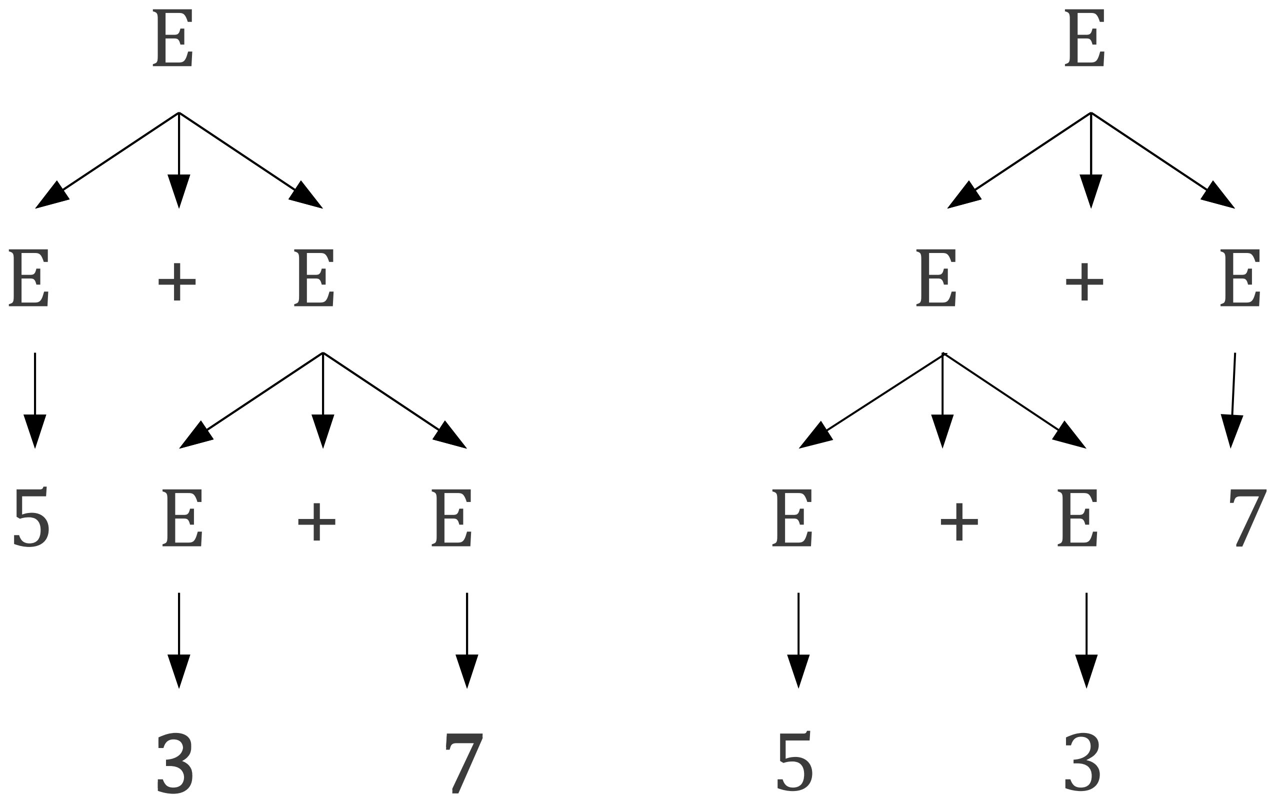

E
E + E
5 E + E
3 7

E
E + E
E + E 7
5 3

Is Ambiguity a Problem?

- Depends on semantics .

$$E \rightarrow \texttt{int} \mid E + E \mid E - E$$

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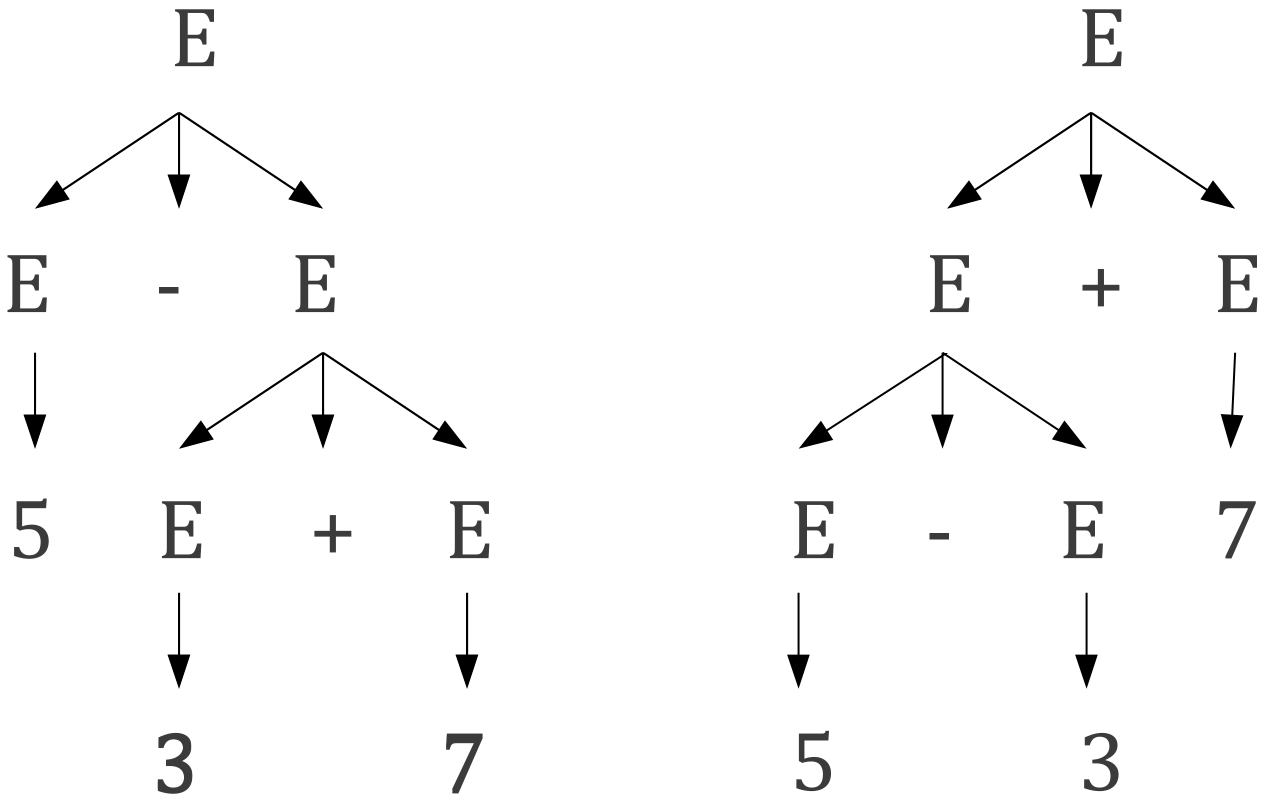


Ambiguity

- Ambiguity is problematic because meaning of the programs can be incorrect
- Ambiguity can be handled in several ways
  - Enforce associativity and precedence
  - Rewrite the grammar (cleanest way)
- There is no algorithm to convert automatically any ambiguous grammar to an unambiguous grammar accepting the same language
- Worse, there are inherently ambiguous languages!

Ambiguity in Programming Lang.

- Dangling else problem

  stmt ⟶ if expr stmt

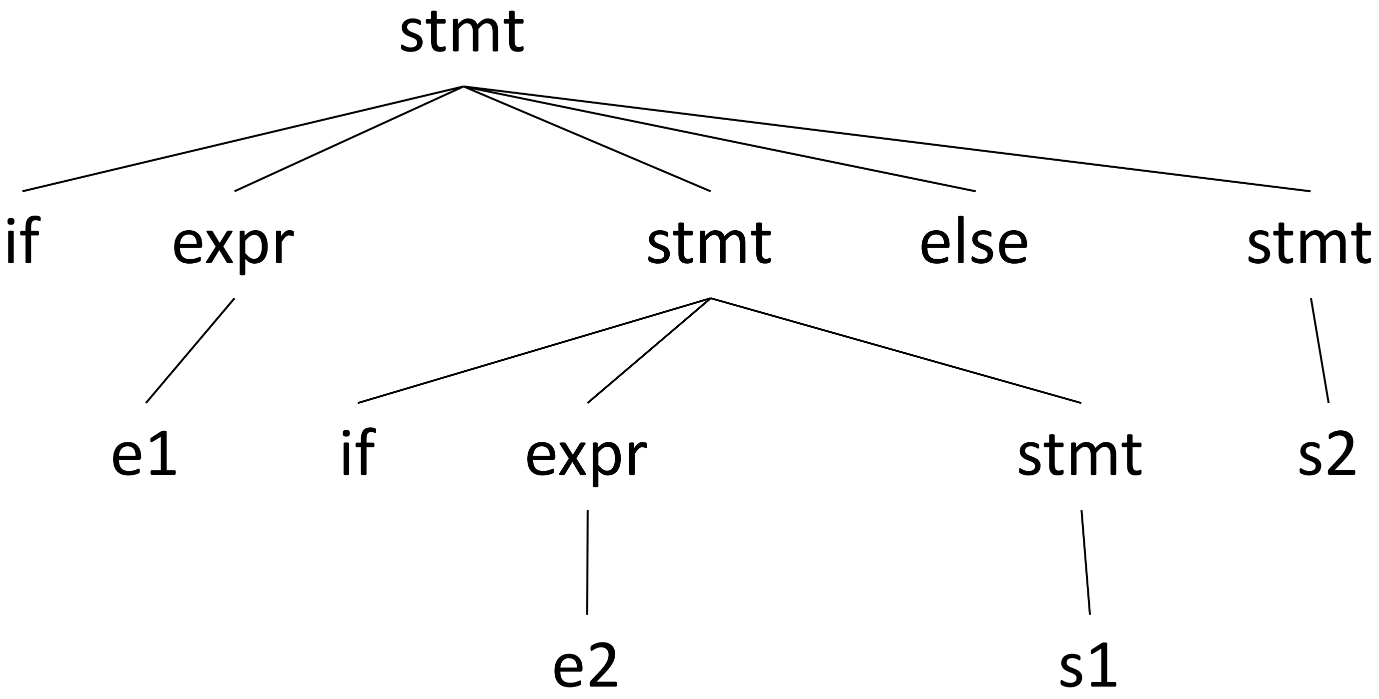
  | if expr stmt else stmt

- For this grammar, the string

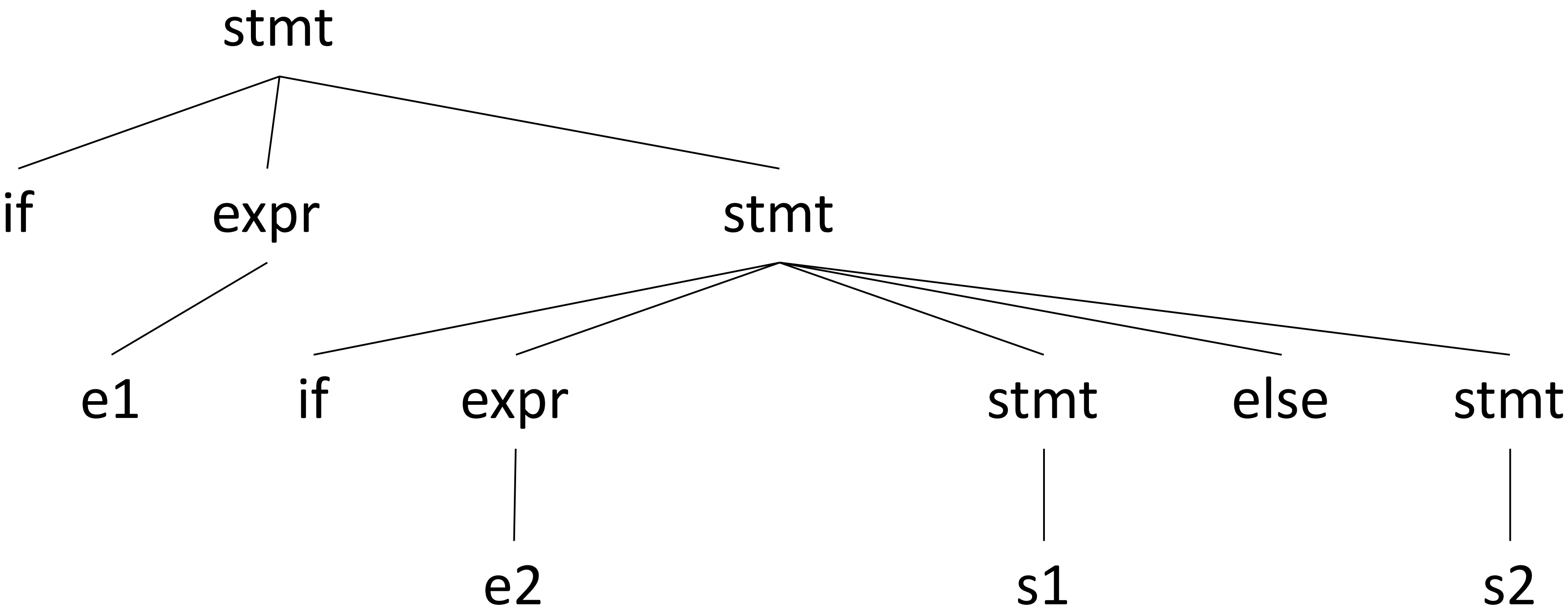
  if e1 if e2 then s1 else s2

  has two parse trees

```
if e1
   if e2
      s1
else s2
```



```
if e1
   if e2
      s1
  else s2
```



Resolving dangling else problem

- General rule: match each **else** with the closest previous **unmatched if**.

Precedence

- String a+5*2 has two possible interpretations because of two different parse trees corresponding to

  (a+5)*2 and a+(5*2)
- Precedence determines the correct interpretation.
- Next lectures, we will see more details about precedence/associativity on resolving the ambiguity

Summary

- A **parse tree** shows how a string can be **derived** from a grammar.
- A grammar is **ambiguous** if it can derive the same string multiple ways.
- Next time: Parsing algorithms
  - Top-Down Parsing
  - Bottom-Up Parsing