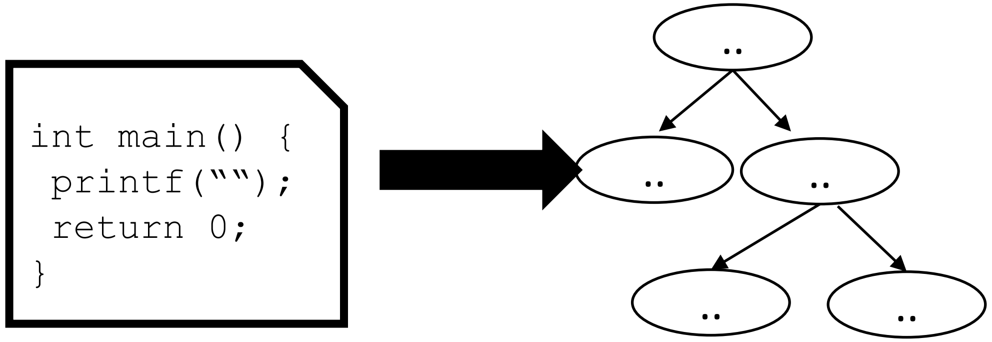
CSE110A: Compilers

April 17, 2024

Topics:

- *Starting Module 2: Parsing*
  - *Introduction*
  - *Production Rules*
  - *Derivations and Parse Trees*
  - *A Simple Expression Grammar*



Announcements

- Starting Module 2: Parsing
  - Material gets a little more complex
  - Readings in the textbook will help out A LOT

- Homework 1 is due on Friday
  - An extra day to cover material needed for homework 2
  - Homework 2 will be released on Friday

- Plenty of tutor/TA/office hours left
  - No help after 5 PM

Announcements

- Homework clarifications

- For part 2:

- **HNUM**: a hexidecimal number. Like in C, it should start with a 0x followed by digits, which can include a-f. The characters should be case insensitive.

All characters are case insensitive!

Announcements

- Homework clarifications
- For part 4: You should ***not*** hard code the RegEx: you should generate it given the list of tokens
- How we will grade:
  - Your tokens will be graded using our solution scanner importing your tokens
  - We will then put in our own tokens to grade your SOS and NG scanners

Quiz

Quiz

Which of the following are token actions NOT great for:

- ○ Changing the value of a token
- ○ Changing the token type
- ○ Splitting a token into multiple tokens
- ○ Keeping track of scanning statistics (e.g. the number of IDs seen)

Examples

Modifying a value

```
def cat_dog(x):
    if x[1] == "Cat":
        return (x[0], "Dog")
    return x
```

Modifying a token type

```
keywords = [("INT", "int"), ("FLOAT", "float"), ("IF", "if")]

def check_keywords(t):
    keyvalues = [x[1] for x in keywords]
    if t[1] in keyvalues:
        lexeme = keywords[keyvalues.index(t[1])]
        return lexeme
    return t
```

Examples

Keeping track of statistics

```
def count_lines(x):
    if x[1] == "\n":
        s.lineno += 1
    return x
```

What other statistics might you want?

Quiz

Which of the following are token actions NOT great for:

- ○ Changing the value of a token
- ○ Changing the token type
- ○ Splitting a token into multiple tokens
- ○ Keeping track of scanning statistics (e.g. the number of IDs seen)

This is really difficult to do with token actions:
token actions take a single lexeme and return a single lexeme

Quiz

Which of the following language features make scanner implementations easier?

- ☐ Regular expression matcher
- ☐ Higher order functions
- ☐ Types
- ☐ Interpreted languages

Quiz

Which of the following language features make scanner implementations easier?

- [ ] Regular expression matcher
- [ ] Higher order functions
- [ ] Types
- [ ] Interpreted languages

Required unless you want to write your own (take CSE211 for an example)

Quiz

Which of the following language features make scanner implementations easier?

- [ ] Regular expression matcher
- [ ] Higher order functions
- [ ] Types
- [ ] Interpreted languages

Great for token actions, custom error functions, etc.

Quiz

Which of the following language features make scanner implementations easier?

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- [ ] Higher order functions
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- [ ] Interpreted languages

Great for making sure your token actions are consistent. This is a shortcoming of Python

Quiz

Which of the following language features make scanner implementations easier?

- [ ] Regular expression matcher
- [ ] Higher order functions
- [ ] Types
- [ ] Interpreted languages

Doesn’t really matter.
Ocaml is great for compilers (compiled)
Scheme is great for compilers (interpreted)

Quiz

All scanner generators have the same interface, which makes it very easy to switch from one generator (e.g. Lex) to another (e.g. PLY)

- ○ True
- ○ False

Scanner generators

- You can assume that all take in Regular expressions
  - Most of the time they have nice optional operators, e.g. [0-9], +, ?
- You can assume that all of them support token actions, but they may be expressed differently.
- You can assume that all of them have a function similar to `token()`
  - In lex it is called `yylex()`

Scanner generators

- You should know that Scanner generators exist
  - Lex
    - Classic C-based Scanner
  - PLY
    - Python implementation of Lex
  - Antlr
    - Modern scanner/parser generator

- Similar interfaces, but not exactly the same
  - PLY lexemes contain line/column numbers
  - PLY using “token()”, lex uses “yylex()”

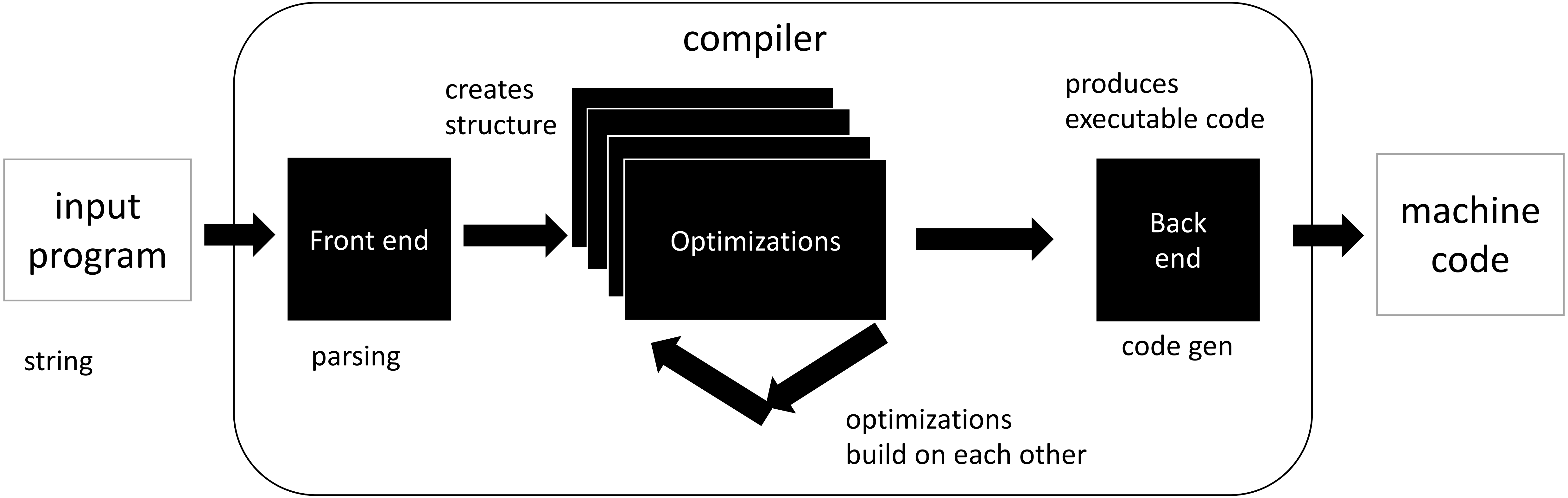
Quiz

If you were given a scanner that you knew was either an EM Scanner, SOS Scanner or NG scanner, and you could instantiate it with any token definitions you want, could you design an experiment (without using timing information) to determine which scanner implementation you had?

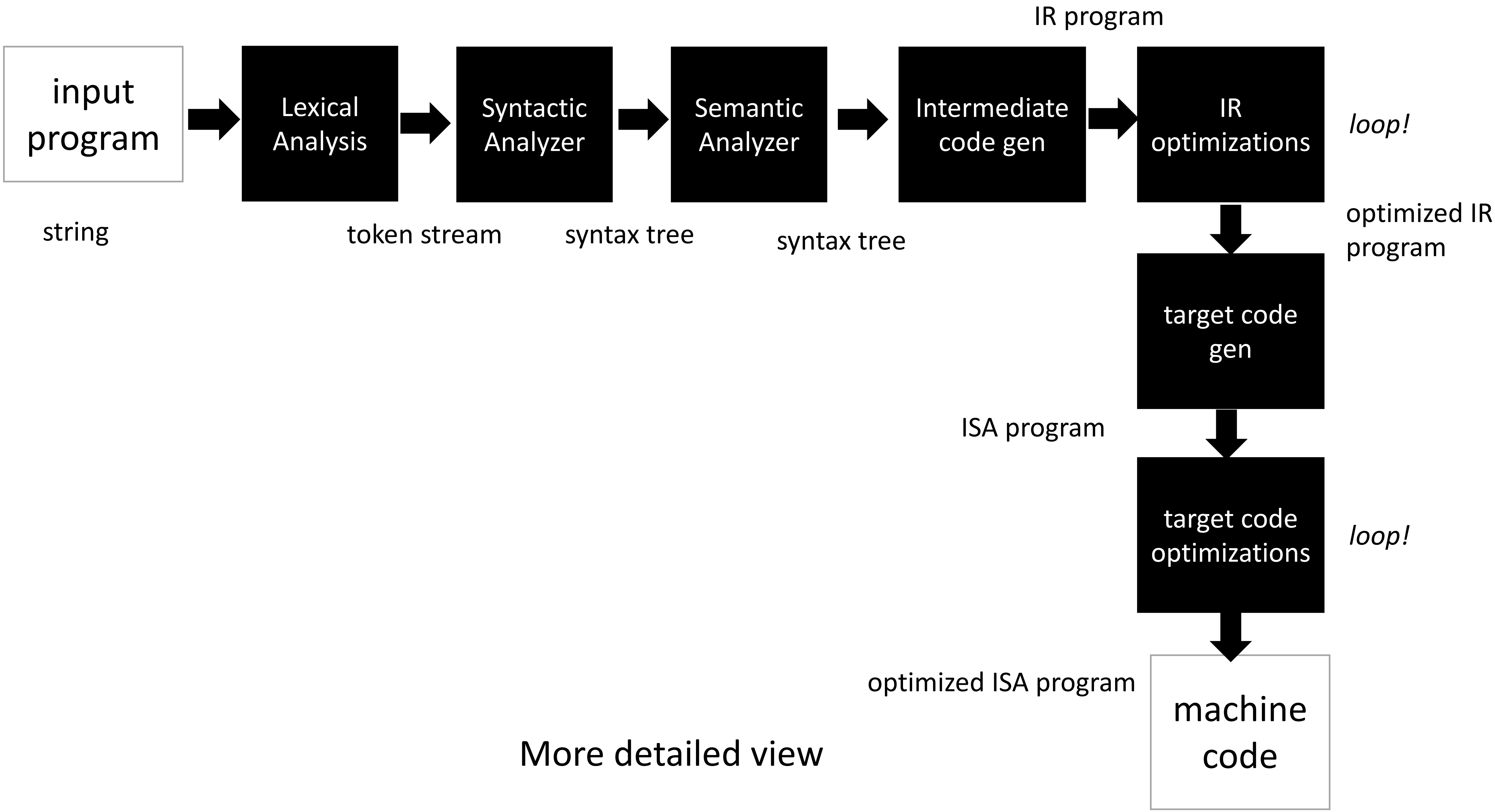
New module

- Parsing:
  - Often times scanning is also included in parsing
  - Specifically this module is about “Syntactic Analysis”

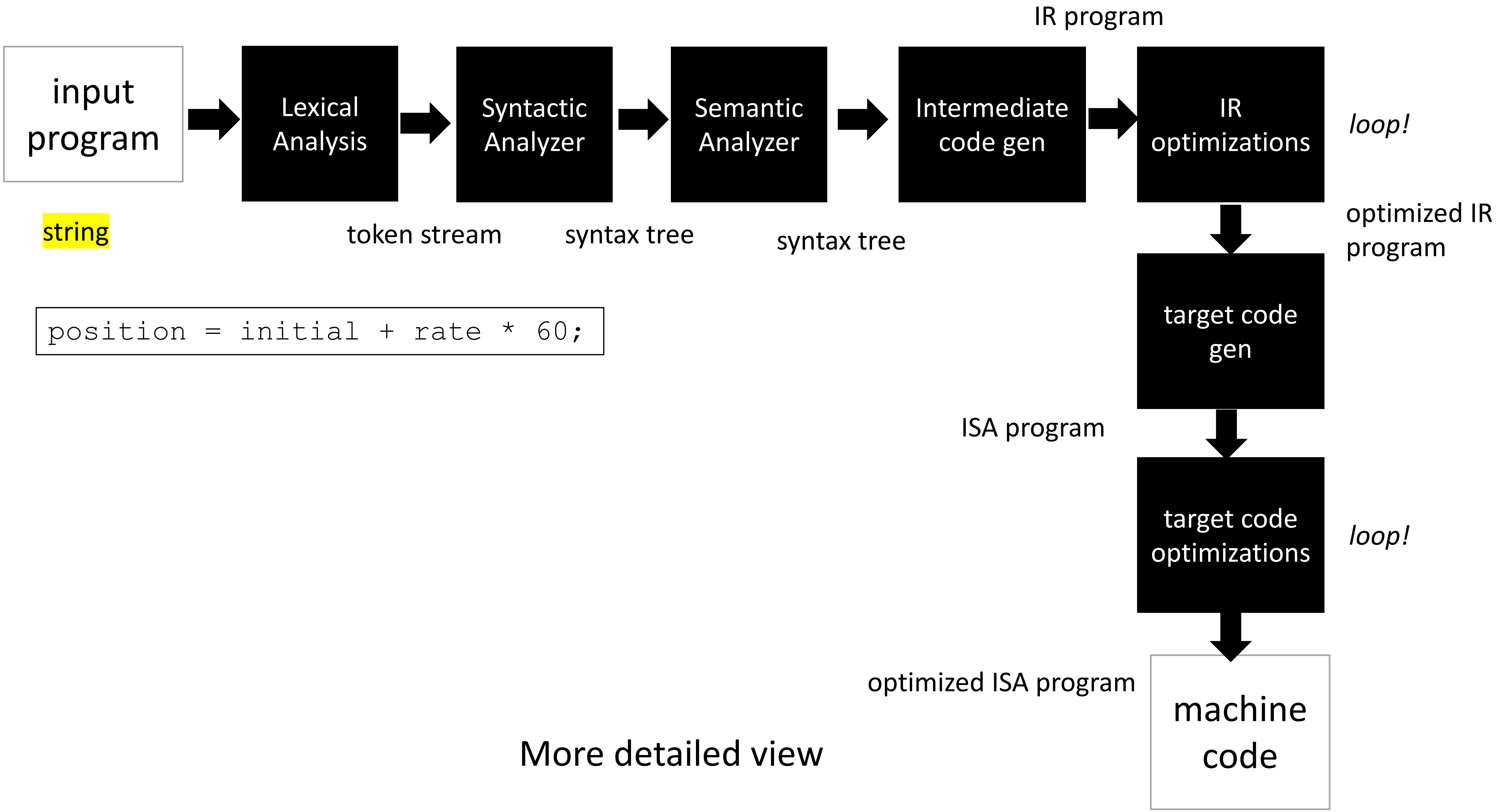
Compiler Architecture



Still working in the front end

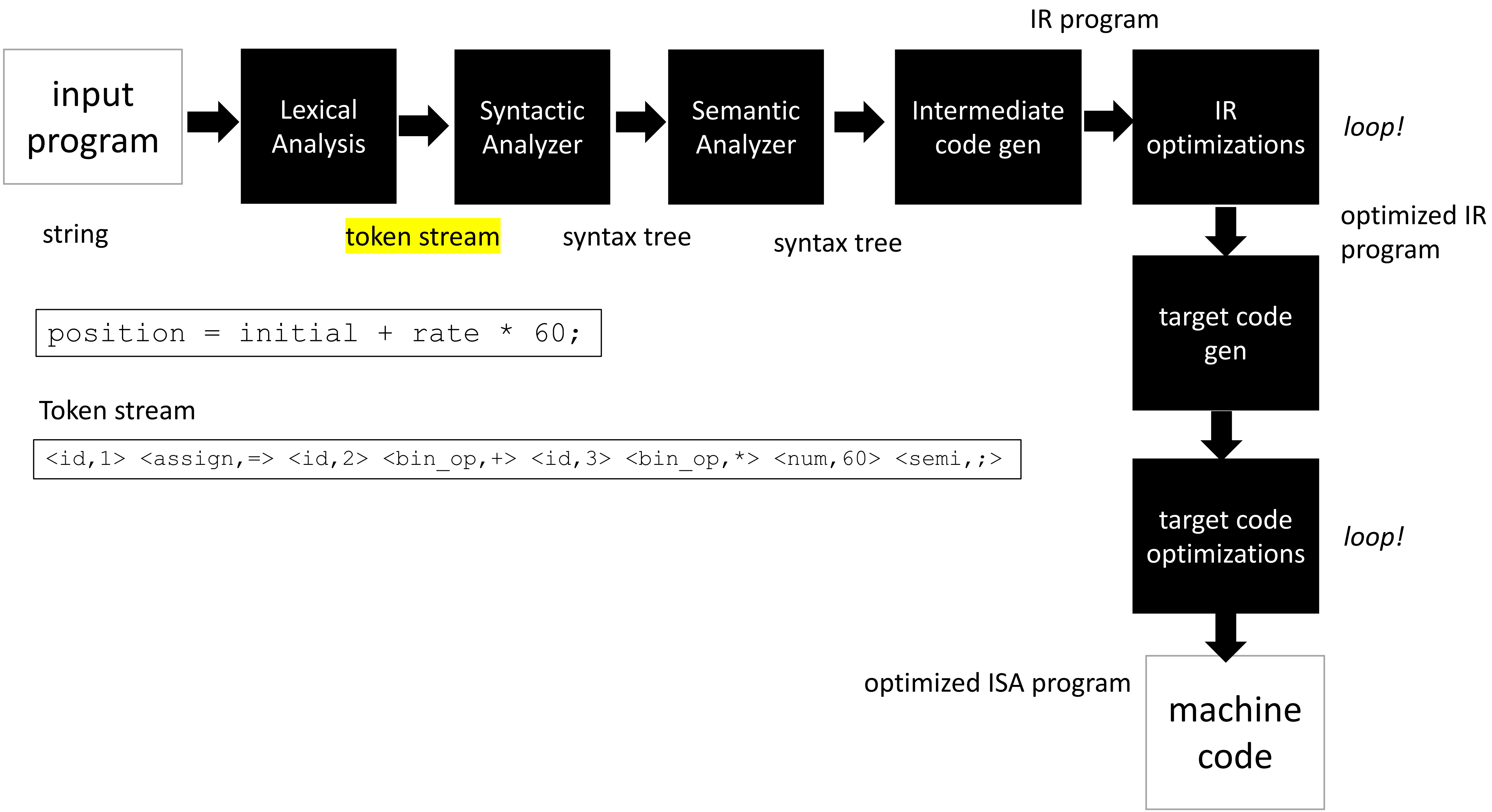


More detailed view




```
position = initial + rate * 60;
```

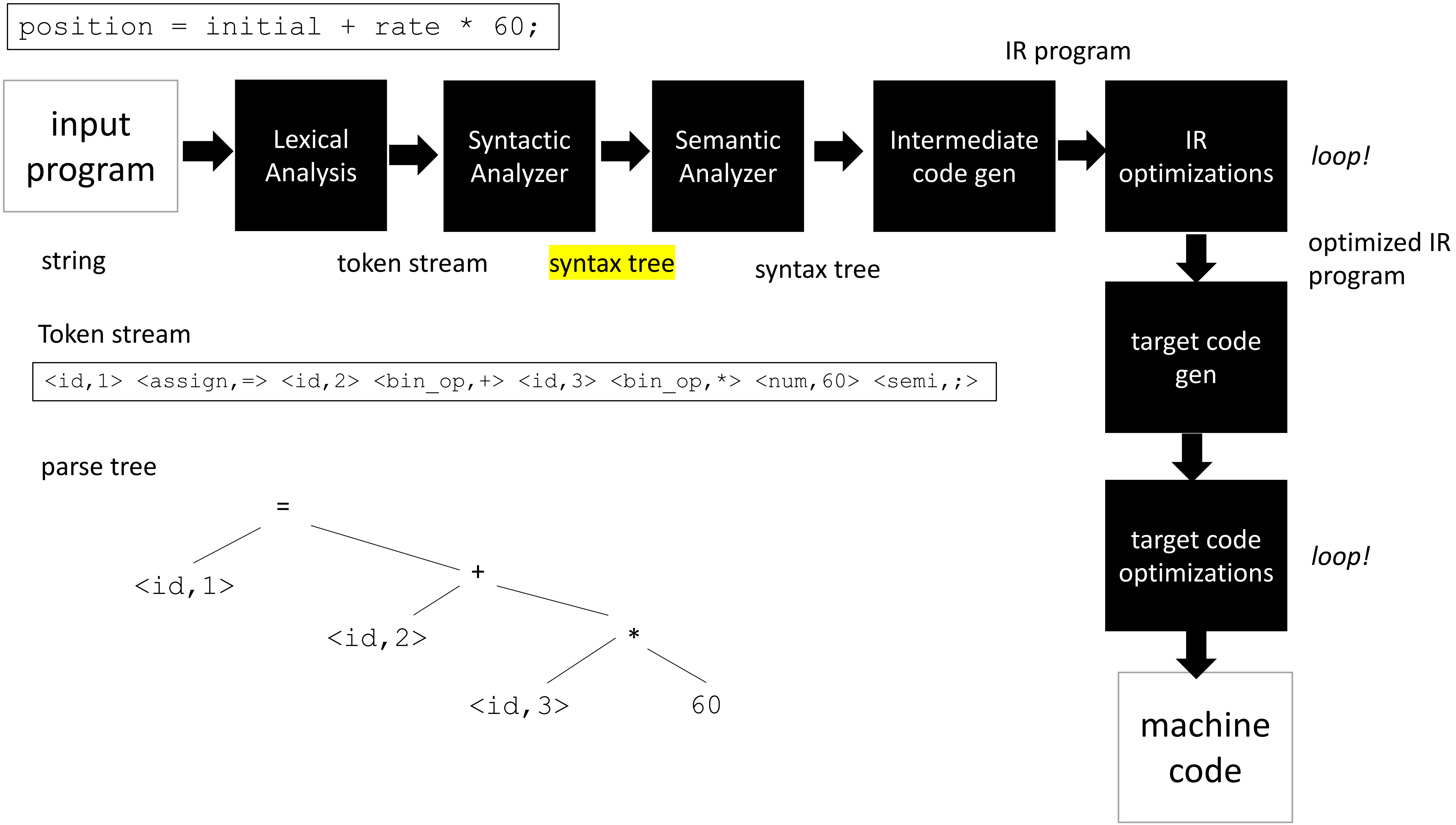
More detailed view




```
position = initial + rate * 60;
```

Token stream

```
<id,1> <assign,=> <id,2> <bin_op,+> <id,3> <bin_op,*> <num,60> <semi,;>
```


position = initial + rate * 60;
IR program
input program
Lexical Analysis
Syntactic Analyzer
Semantic Analyzer
Intermediate code gen
IR optimizations
loop!
string
token stream
syntax tree
syntax tree
optimized IR program
Token stream
<id,1> <assign,=> <id,2> <bin_op,+> <id,3> <bin_op,*> <num,60> <semi,;>
target code gen
parse tree
=
<id,1>
+
<id,2>
*
<id,3>
60
target code optimizations
loop!
machine code

Syntactic Analysis

- Lexical Analysis turns a string into a stream of tokens
- Syntactic Analysis determines if the tokens fit into the syntactic structure of the language
- In our natural language example, it describes the structure of sentences

Syntactic Analysis

- Natural language example

The dog ran across the park

ARTICLE NOUN VERB PREPOSITION ARTICLE NOUN

What are valid sentences?

`ARTICLE NOUN VERB PREPOSITION ARTICLE NOUN`

`ARTICLE ADJECTIVE NOUN VERB`

Now we check if stream of lexemes fits a sentence

How do we express a valid sentence?

- List of tokens:
  - **`ARTICLE NOUN VERB PREPOSITION ARTICLE NOUN`**

- Pros? Cons?

How do we express a valid sentence?

- List of tokens:
  - `ARTICLE NOUN VERB PREPOSITION ARTICLE NOUN`
- Pros? Cons?
  - Simple, but probably too simple

How do we express a valid sentence?

- Several lists of tokens
  - `ARTICLE NOUN VERB PREPOSITION ARTICLE NOUN`
  - `ARTICLE NOUN VERB`
  - `ARTICLE ADJECTIVE NOUN VERB`
  - `ARTICLE ADJECTIVE ADJECTIVE NOUN VERB`
- Pros? Cons?

How do we express a valid sentence?

- Several lists of tokens
  - `ARTICLE NOUN VERB PREPOSITION ARTICLE NOUN`
  - `ARTICLE NOUN VERB`
  - `ARTICLE ADJECTIVE NOUN VERB`
  - `ARTICLE ADJECTIVE ADJECTIVE NOUN VERB`

- Pros? Cons?
  - Potentially infinite choices

How do we express a valid sentence?

- Regular expressions over tokens:
  - `ARTICLE ADJECTIVE* NOUN VERB`
- Pros? Cons?

How do we express a valid sentence?

- Regular expressions over tokens:
  - `ARTICLE ADJECTIVE* NOUN VERB`
- Pros? Cons?
  - Regular expressions worked really well for tokens
  - Provides decent expressivity
  - But what might go wrong?

Mathematical expressions

- tokens:
  - `NUM  = “[0-9]+”`
  - `PLUS = “\+”`
  - `MULT = “\*”`

- Can we describe expressions?

Mathematical expressions

```
NUM ((PLUS | MULT) NUM)*
```

```
5

5 + 6

5 + 6 * 3
```

Mathematical expressions

```
NUM ((PLUS | MULT) NUM)*
```

```
5
```

```
5 + 6
```

```
5 + 6 * 3
```

But what does this one mean? What if we want different precedence?

Mathematical expressions

```
NUM ((PLUS | MULT) NUM)*
```

```
5
```

```
5 + 6
```

```
5 + 6 * 3
```

But what does this one mean? What if we want different precedence?

```
(5 + 6) * 3
```

Can we do this one?

Mathematical expressions

- tokens:
  - `NUM  = “[0-9]+”`
  - `PLUS = “\+”`
  - `MULT = “\*”`
  - `OPAR = “\(“`
  - `CPAR = “\)”`

Mathematical expressions

```
OPAR? NUM ((PLUS | MULT) OPAR? NUM CPAR?)*
```

Add parenthesis tokens

```
5
```

```
5 + 6
```

```
5 + 6 * 3
```

But what does this one mean? What if we want different precedence?

```
(5 + 6) * 3
```

Can we do this one?

Mathematical expressions

```
OPAR? NUM ((PLUS | MULT) OPAR? NUM CPAR?)*
```

Seems like it works! But what is the issue?

Mathematical expressions

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OPAR? NUM ((PLUS | MULT) OPAR? NUM CPAR?)*
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Seems like it works! But what is the issue?

```
(5 + 6 * 3
```

What about this one?

Mathematical expressions

```
OPAR? NUM ((PLUS | MULT) OPAR? NUM CPAR?)*
```

Seems like it works! But what is the issue?

```
(5 + 6 * 3
```

What about this one?

()s are a key part of syntax. They are import for the structure we want to create and we need to reliably detect strings that are not syntactically valid!

Context Free Grammars: A new class of languages

- Regular expressions CANNOT match
  - (),
  - {},
  - HTML start/end tags
  - etc.

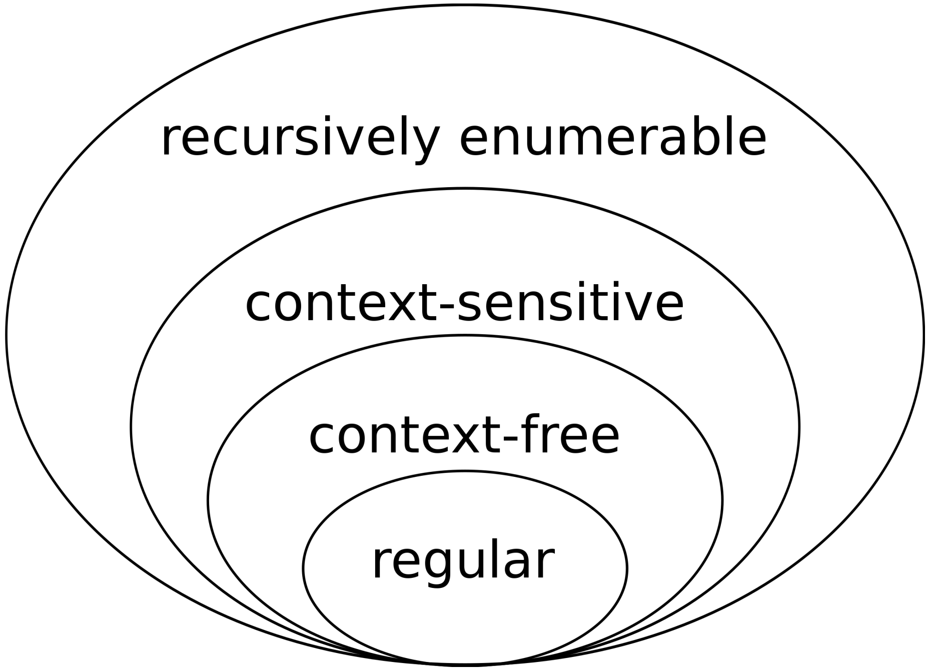
- We will use ***context free grammars***

Recall: Language theory

Some theory:

- Given a language *L*, a string *s* is either part of that language or not
  - Integers are a language: “5”, “6”, “-7” is in the language. “abc” is not.
- Languages are grouped into families depending on how “hard” it is to determine if a string is part of that language.

Recall: Language theory



The simplest languages are regular. We used regular expressions for tokens.

- They are fast, even in the general case
- good level of abstraction for tokens

We will now use context-free languages for Syntactic Analysis

- Fast algorithms exist in many cases (not all)

Determining membership can be even inefficient or even undecidable at higher levels (context-sensitive and recursively enumerable)

image source: wikipedia

Context-free languages

We will define similar to regular languages

- In this *class a context-free language is a language that can be recognized by a context-free grammar*

Context-free languages

We will define similar to regular languages

- In this *class a context-free language is a language that can be recognized by a context-free grammar*

- ....

- What is a context-free grammar?

Context-free grammar

We will use *Backus–Naur form* (BNF) form

```
non-terminal-1 ::= production-rule-1
                |   production-rule-2
                |   ...

non-terminal-2 ::= production-rule-1
                |   production-rule-2
                |   ...

....
```

- non-terminals are language ids. You can have as many as you need.
- each non-terminal maps to one or more production rules.
- one non-terminal is designated as the *start* or *goal* symbol

Context-free grammar

We will use *Backus–Naur form* (BNF) form

- Production rules contain a sequence of either non-terminals or terminals
- In our class, terminals will either be string constants or tokens

```
Examples:

add_expr ::= NUM '+' NUM

mult_expr ::= NUM '*' NUM

joint_expr ::= add_expr '*' add_expr

simple_expr ::= NUM '+' NUM
             |   NUM '*' NUM
```

Deriving strings

A CFG *G* is said to derive a string *s* if *s* is in the language of *G*

We can show a string *s* belongs to *G* by providing a derivation

```
SheepNoise ::= ‘baa’ SheepNoise
            |   ‘baa’
```

Start with a sentinel string: a string containing terminals and non-terminals:

“SheepNoise”

Then pick one of the non-terminals and expand it

Deriving strings

Give each production rule a numeric id

```
1: SheepNoise ::= ‘baa’ SheepNoise
2:            |   ‘baa’
```

“baa”

RULE	Sentential Form
start	SheepNoise

“baa baa”

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Deriving strings

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"baa"

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1	"baa" SheepNoise
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Mathematical expressions

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```
1: Expr ::= ‘(’ Expr ‘)’
2:      |    Expr Op NUM
3:      |    NUM
4: Op   ::= ‘+’
5: Op   |   ‘*’
```

A more complicated example

```
1: Expr ::= '(' Expr ')'
2:       |    Expr Op ID
3:       |    ID
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```

Can we derive the string `(a+b)*c`

RULE	Sentential Form
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A more complicated example

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We can visualize this as a tree:

Expr

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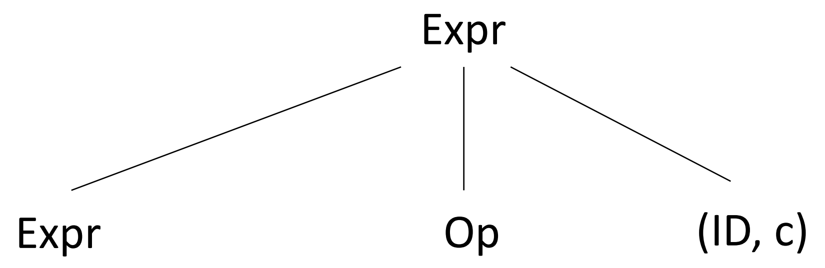

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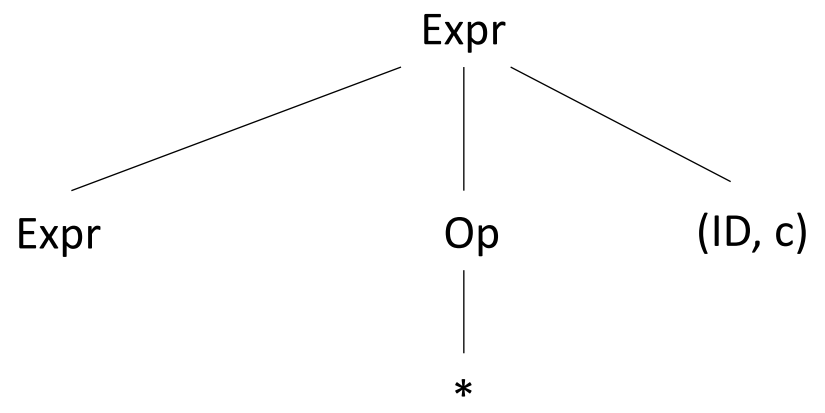

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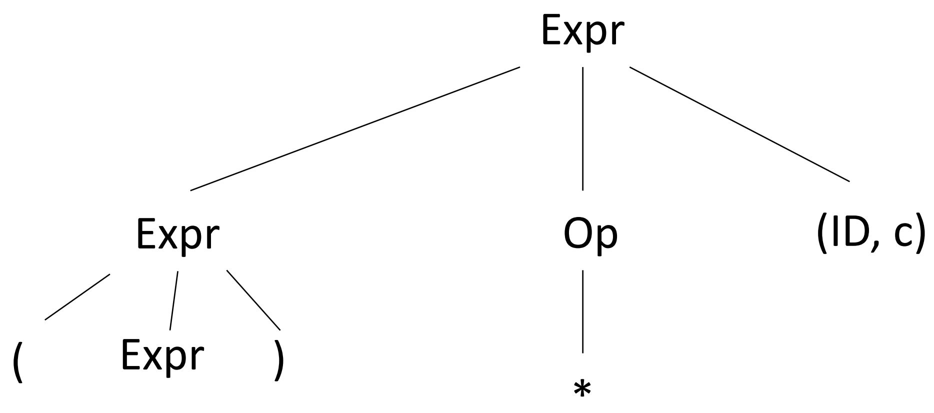

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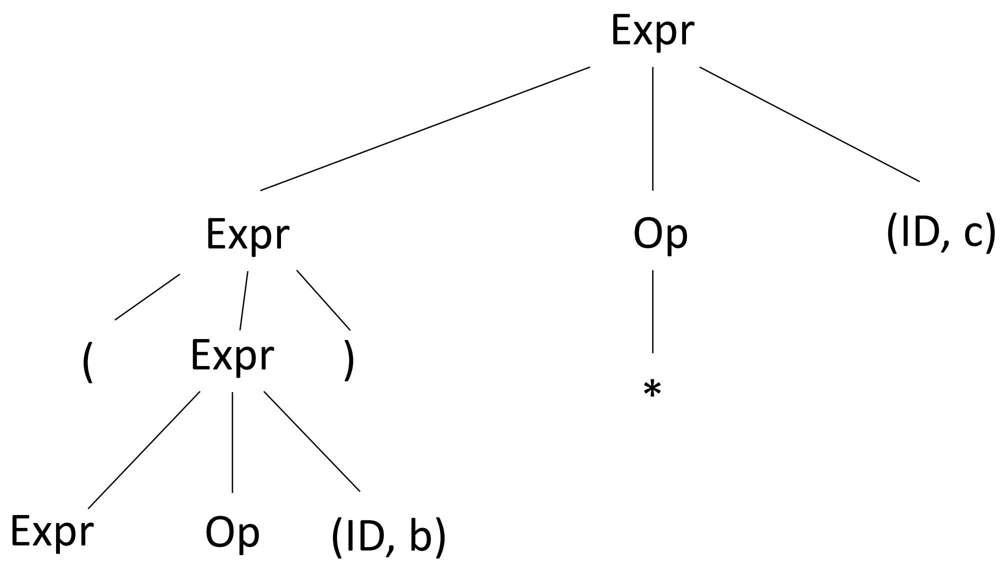

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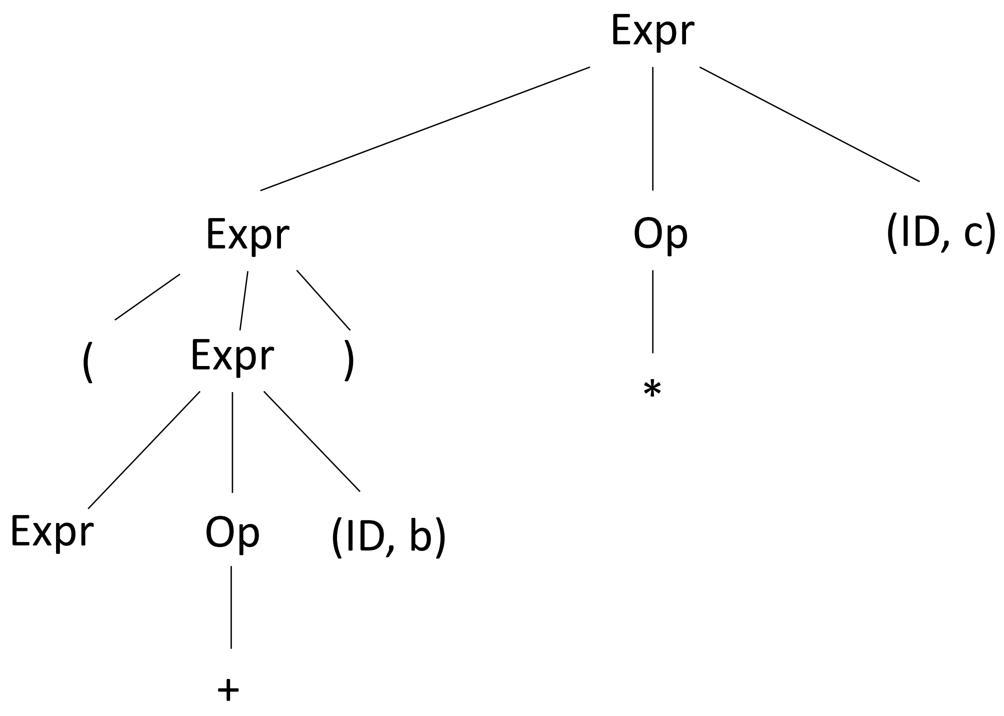

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```

Are there other ways to derive `(a+b)*c`*?*

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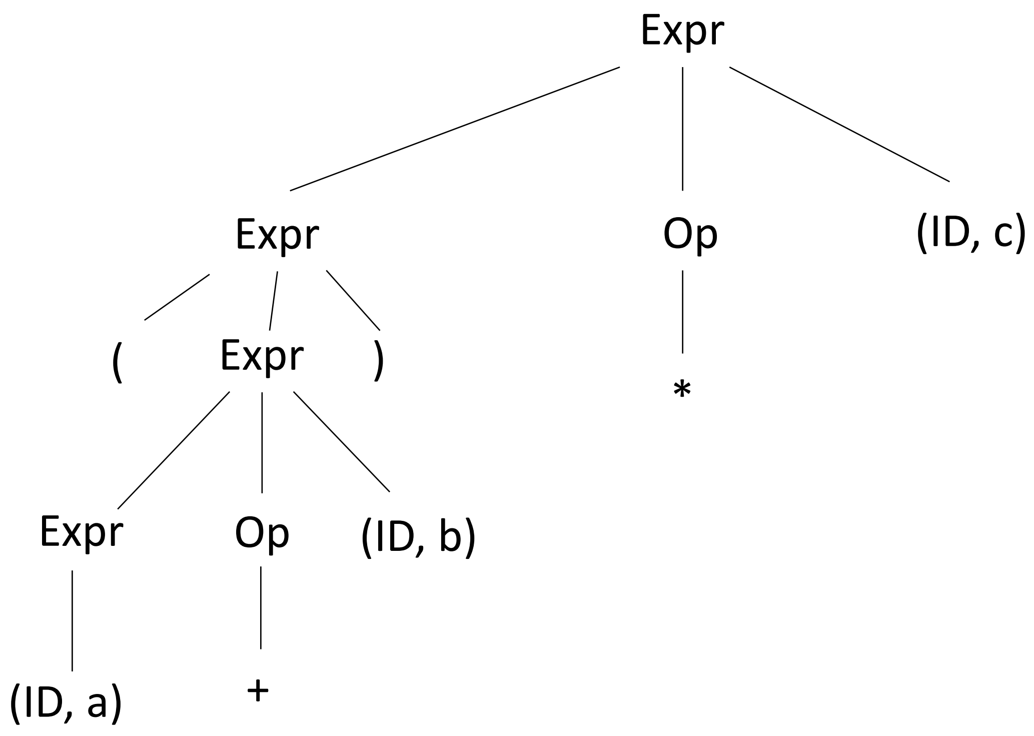

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RULE	Sentential Form
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Are there other ways to derive `(a+b)*c`?

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right derivation

RULE	Sentential Form
start	Expr
2	Expr Op ID
1	(Expr) Op ID
2	(Expr Op ID) Op ID
3	(ID Op ID) Op ID
4	(ID + ID) Op ID
5	(ID + ID) + ID

left derivation

A more complicated example

```
1: Expr ::= '(' Expr ')'
2:      |    Expr Op ID
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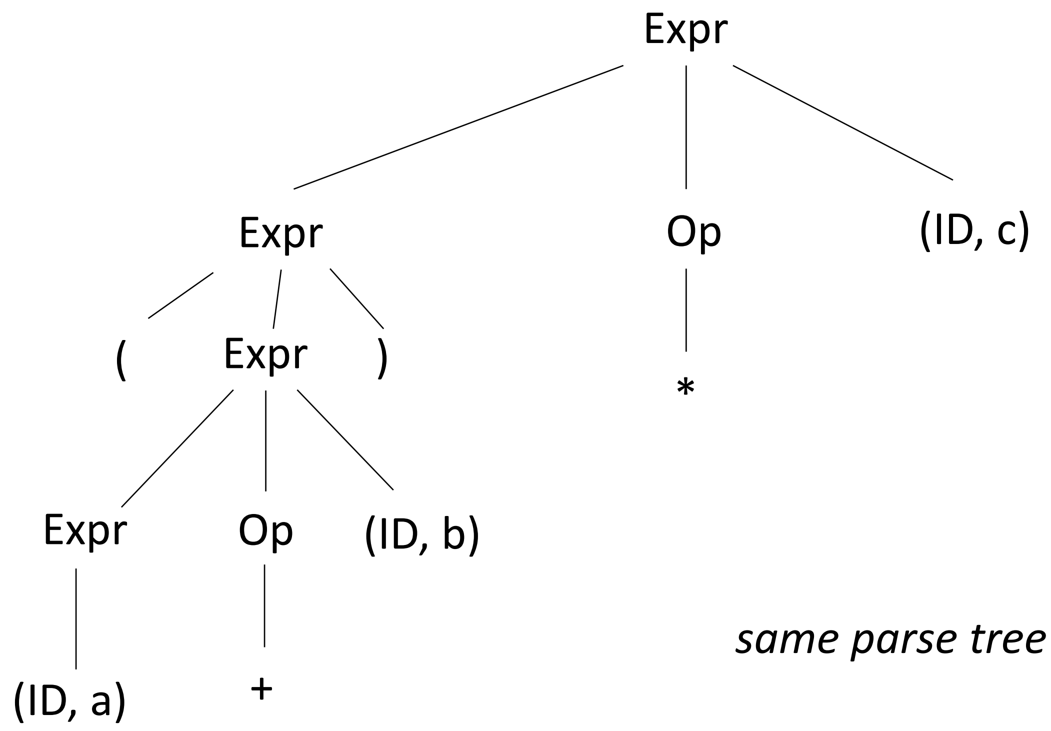
5: Op   |   '*'
```

Are there other ways to derive `(a+b)*c`*?*



same parse tree

RULE	Sentential Form
start	Expr
2	Expr Op ID
1	(Expr) Op ID
2	(Expr Op ID) Op ID
3	(ID Op ID) Op ID
4	(ID + ID) Op ID
5	(ID + ID) + ID

left derivation

Ambiguous grammars

- What happens when different derivations have different parse trees?

```
1: Statement ::= "if" Expr "then" Statement "else" Statement
2:           |   "if" Expr "then" Statement
3:           |    Assignment
4:           |    ....
```

can we derive this string?

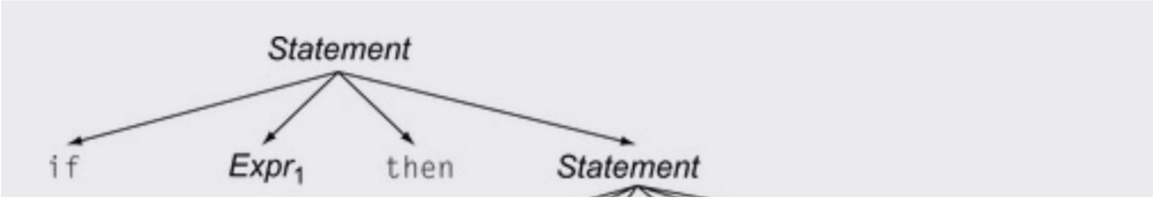
if *Expr1* **then** **if** *Expr2* **then** *Assignment1* **else** *Assignment2*

Next few figures taken from the EAC book (Chapter 3.1)

Ambiguous grammars

```
1: Statement ::= "if" Expr "then" Statement "else" Statement
2:             |  "if" Expr "then" Statement
3:             |   Assignment
4:             |   ....
```

if *Expr*$_1$ **then** **if** *Expr*$_2$ **then** *Assignment*$_1$ **else** *Assignment*$_2$



Ambiguous grammars

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1: Statement ::= "if" Expr "then" Statement "else" Statement
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```
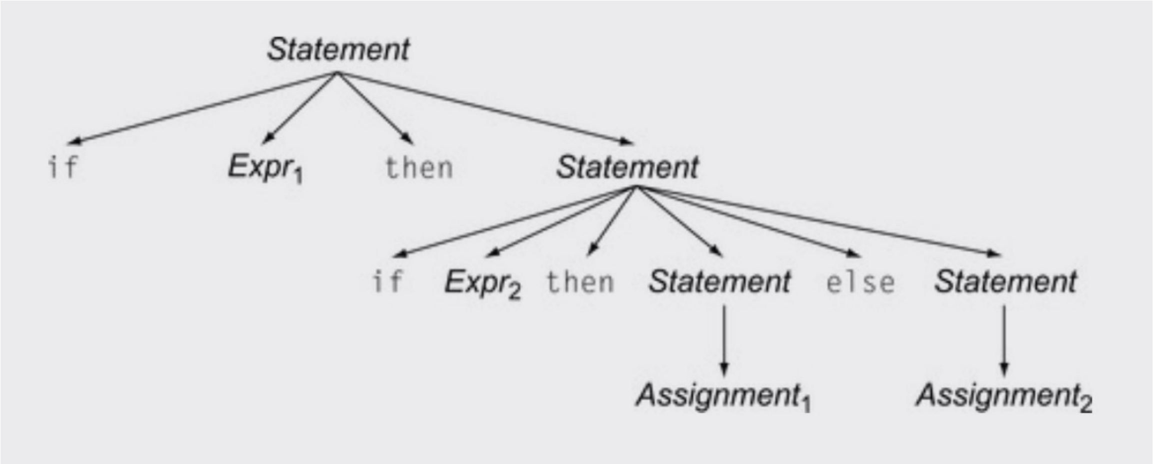

if $Expr_1$ **then** **if** $Expr_2$ **then** $Assignment_1$ **else** $Assignment_2$



Valid derivation

Ambiguous grammars

```
1: Statement ::= "if" Expr "then" Statement "else" Statement
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3:            |   Assignment
4:            |   ....
```
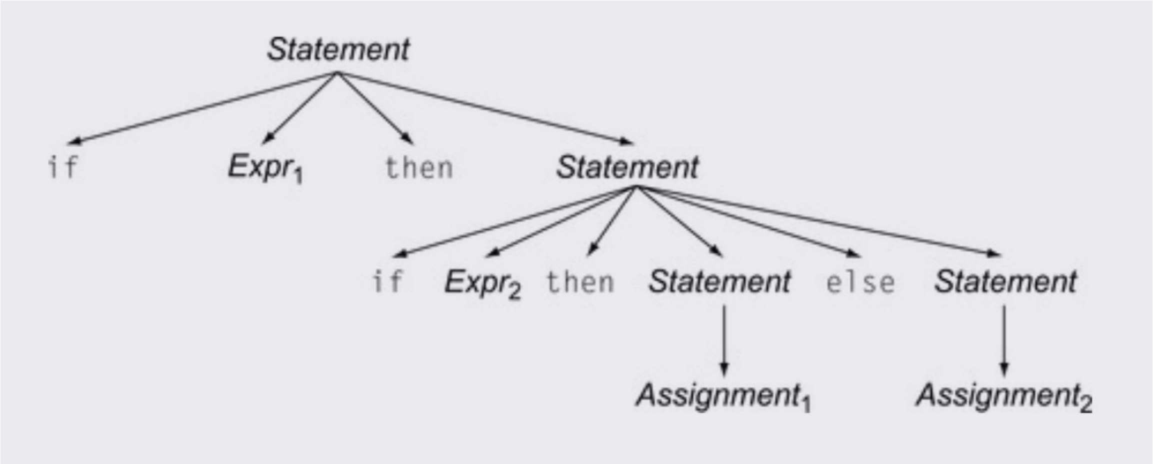
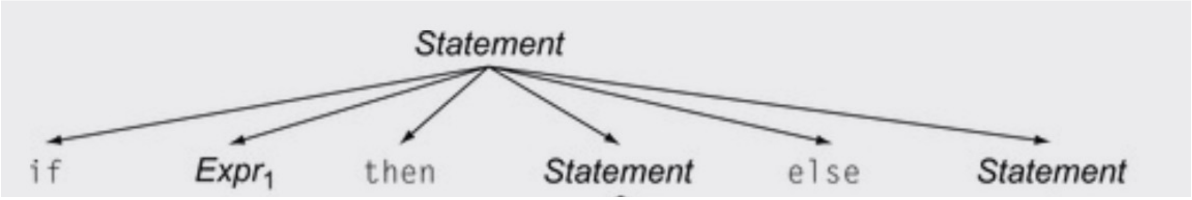

if $Expr_1$ **then** **if** $Expr_2$ **then** $Assignment_1$ **else** $Assignment_2$



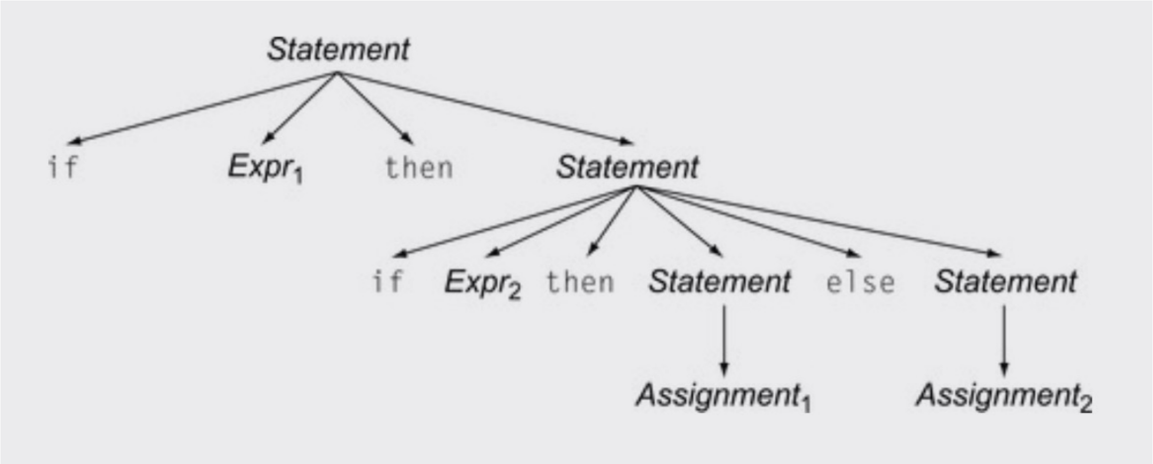
Valid derivation



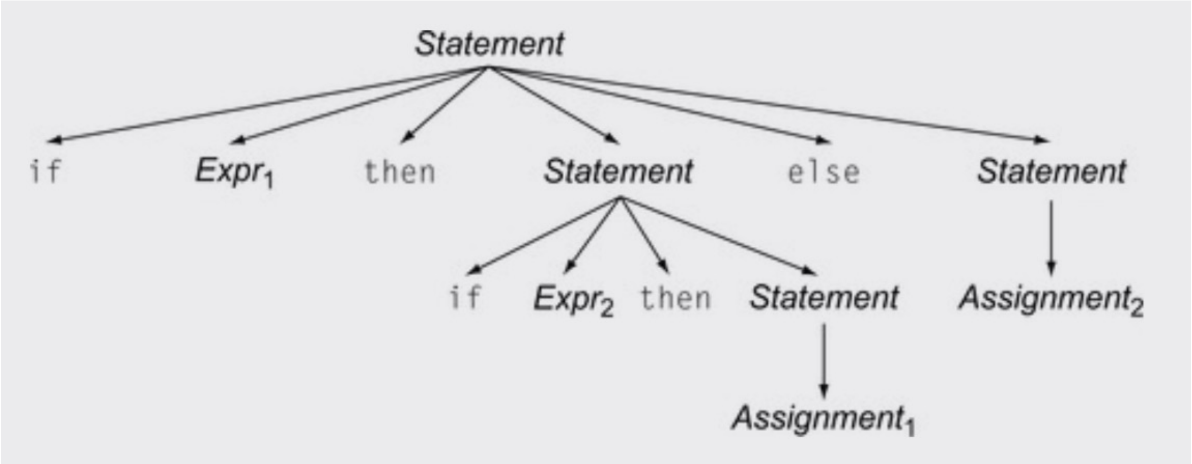
Ambiguous grammars

```
1: Statement ::= "if" Expr "then" Statement "else" Statement
2:           |   "if" Expr "then" Statement
3:           |    Assignment
4:           |    ....
```

if $Expr_1$ **then** **if** $Expr_2$ **then** $Assignment_1$ **else** $Assignment_2$



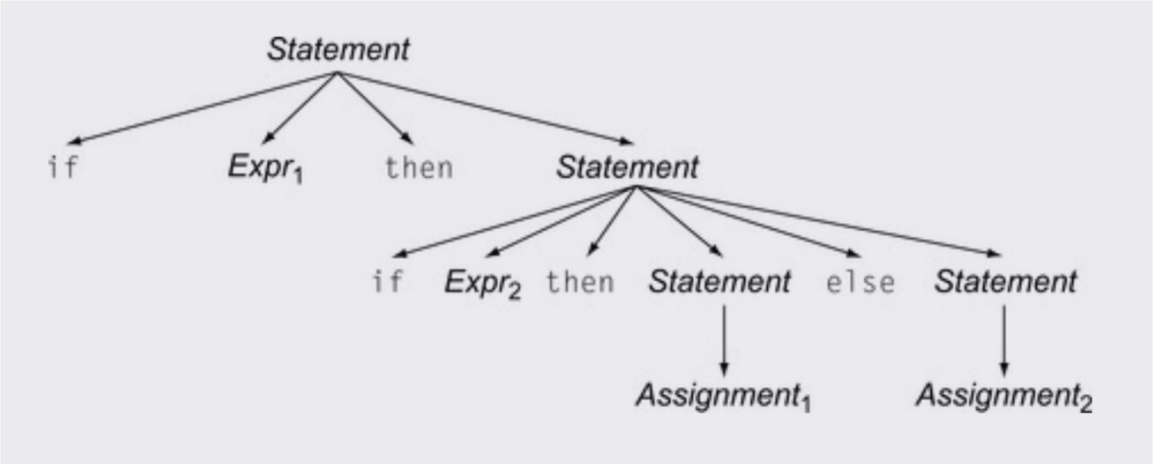
Valid derivation



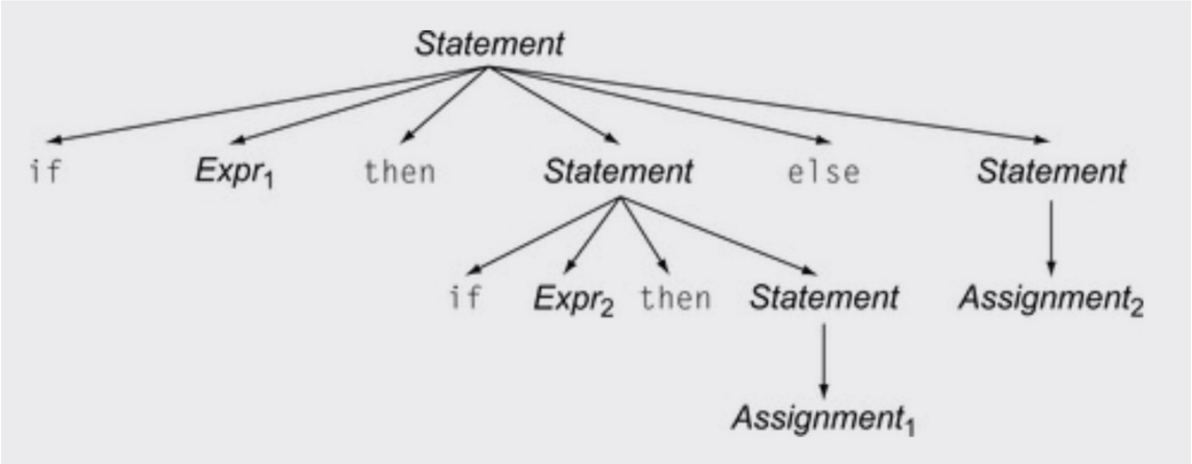
Also a valid derivation

Ambiguous grammars

Is this an issue? Don't we only care if a grammar can derive a string?



Valid derivation



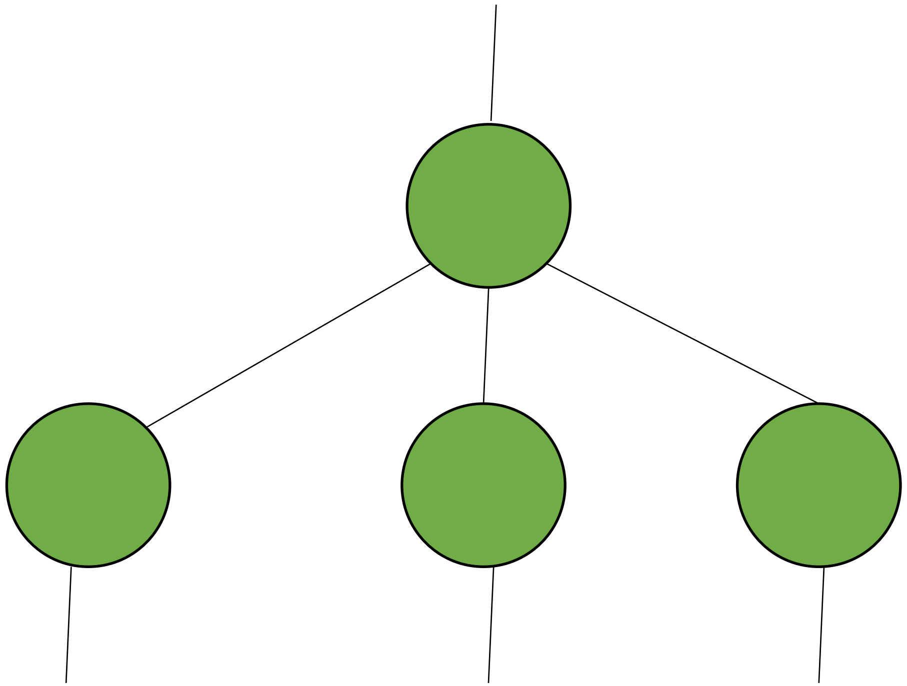
Also a valid derivation

Meaning into structure

- We want to start encoding meaning into the parse structure. We will want as much structure as possible as we continue through the compiler

- The structure is that we want evaluation of program to correspond to a post order traversal of the parse tree (also called the natural traversal)

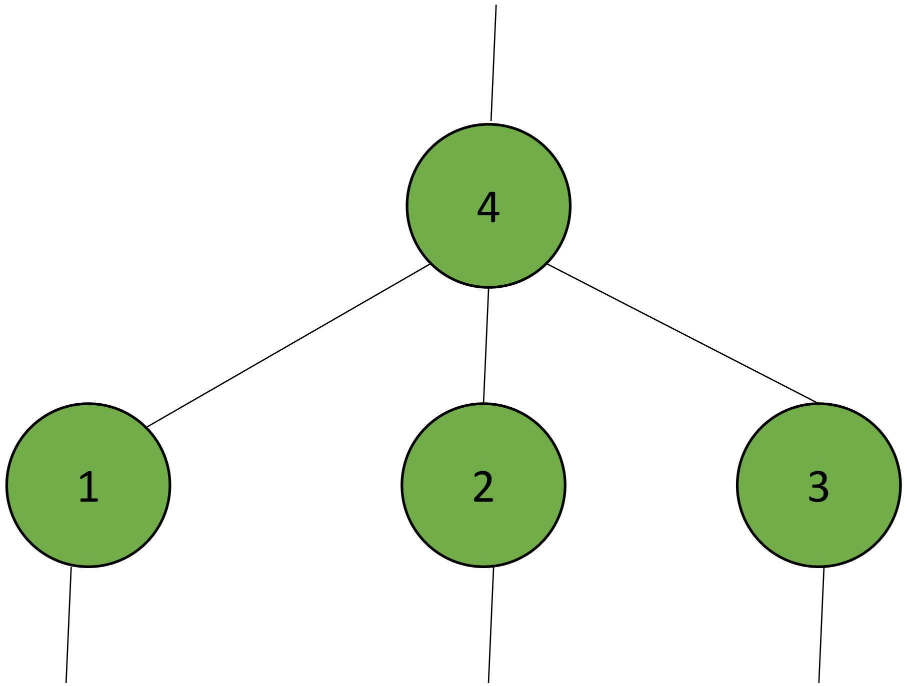
Post order traversal



visiting for for different types of traversals:

pre order?
in order?
post order

Post order traversal

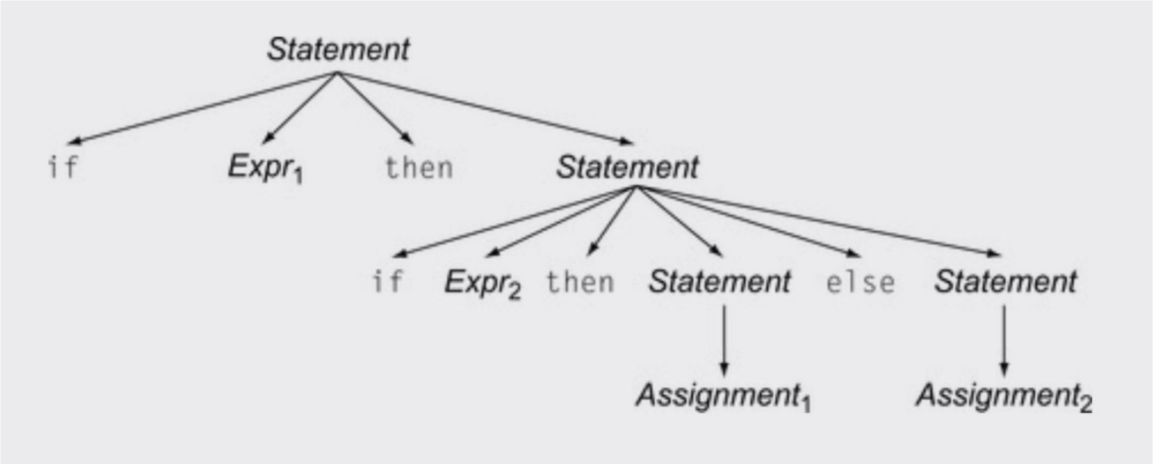


visiting for for different types
of traversals:

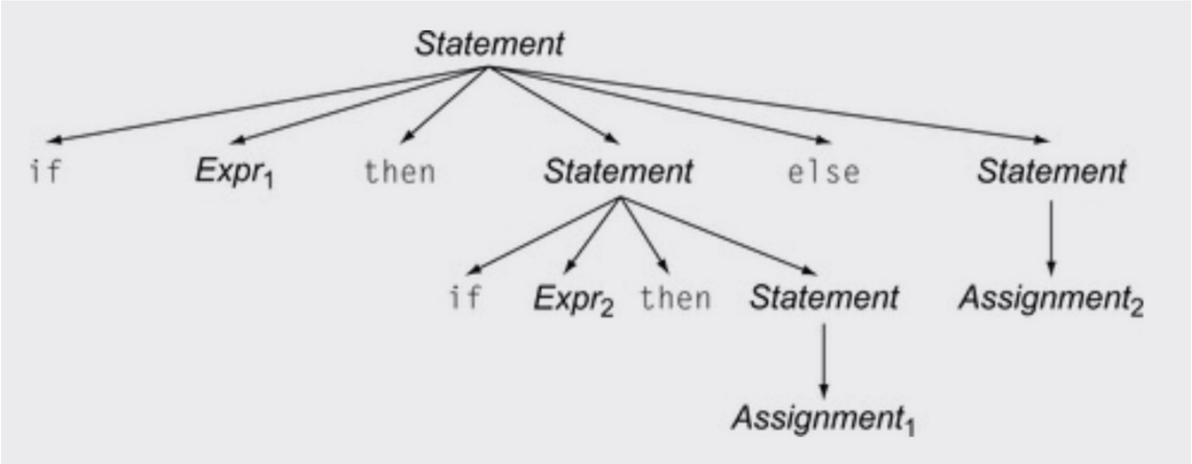
post order

Ambiguous grammars

When we encode meaning into structure, these are very different programs



Valid derivation



Also a valid derivation

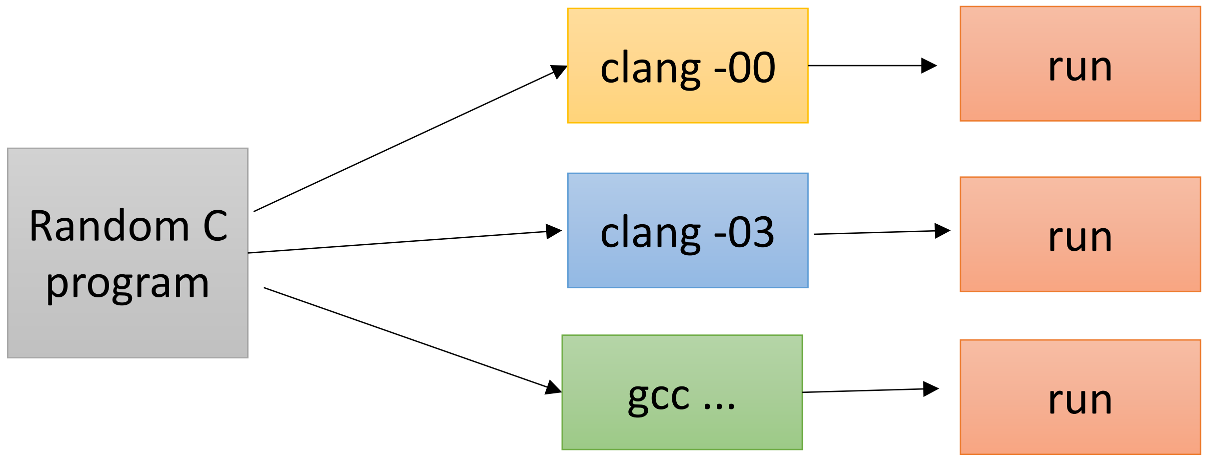
We will study how to eliminate ambiguity

- But I want to close out today with an interesting case study

Case study

- Using a CFG, you can derive random strings in a language

- C-Smith
  - Generates random C programs
  - Used to test compiler correctness

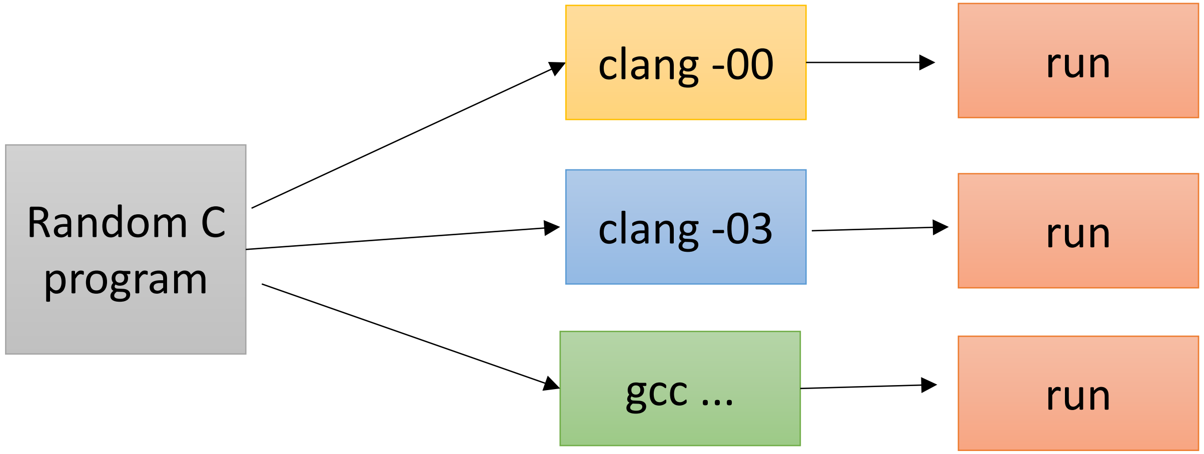


Check outcome. Is it the same? if not, then there is a bug in one of the compilers

Case study

- 400+ compiler bugs found

- Demo



Check outcome. Is it the same? if not, then there is a bug in one of the compilers

Case study

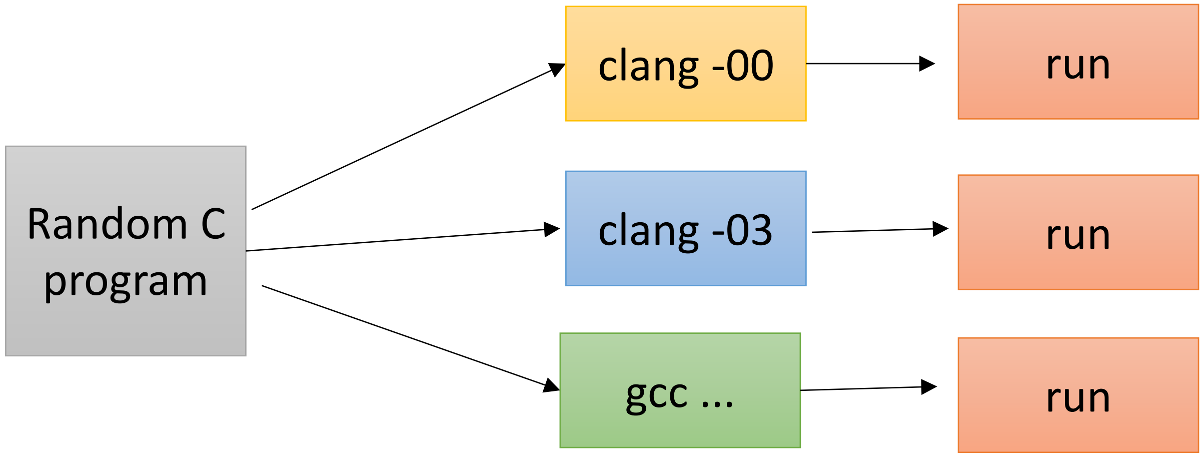
- Big challenge: Undefined behavior

- Even though the program is syntactically valid, the behavior may be undefined

```
int main() {
  int x;
  printf("%d\n", x);
  return 0;
}
```

Uninitialized variables can return anything!

Use advanced compiler analysis to catch these issues



Check outcome. Is it the same? if not, then there is a bug in one of the compilers

On Friday

- How to remove ambiguity from grammars
  - Precedence
  - Associativity