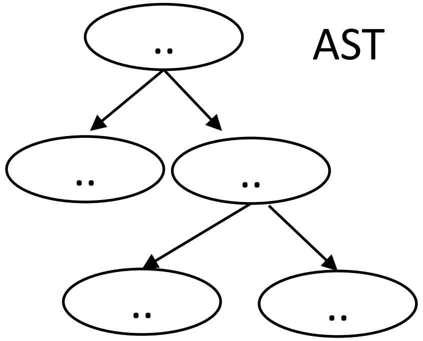
CSE110A: Compilers

May 5, 2023

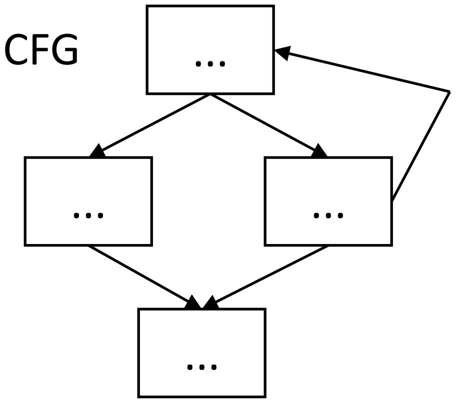
AST



Topics:

- *Module 3: Intermediate representations*
  - *Intro to intermediate representations*
  - *ASTs*
    - *parse trees into ASTs*

CFG



3 address code

```
store i32 0, ptr %2
%3 = load i32, ptr %1
%4 = add nsw i32 %3, 1,
store i32 %4, ptr %1
%5 = load i32, ptr %2
```

Announcements

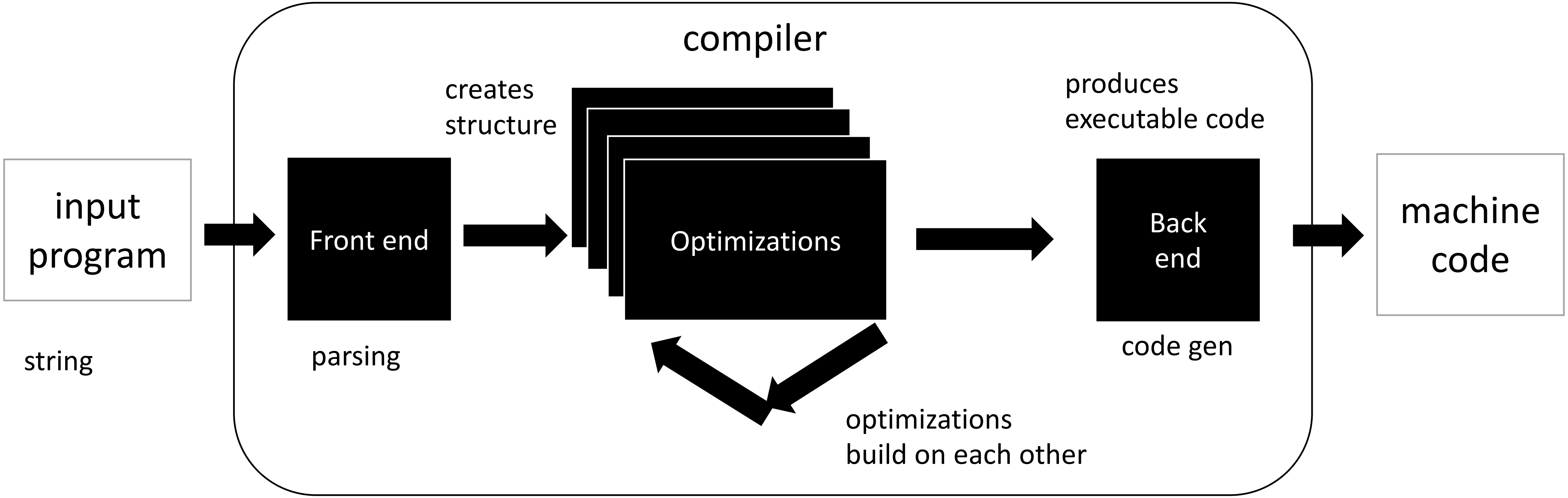
- Homeworks
  - HW 1 grades are coming (ambitiously planning on releasing them today)
  - HW 2 was due yesterday
  - HW 3 will be out Monday
  - Study for the midterm over the weekend!

- Midterm will be given on Monday: May 8
  - Taken during class
  - 3 pages of notes are allowed
  - Study:
    - Slides
    - Homeworks
    - book readings

New module!

- Intermediate representations
- Where are we at in our compiler flow?

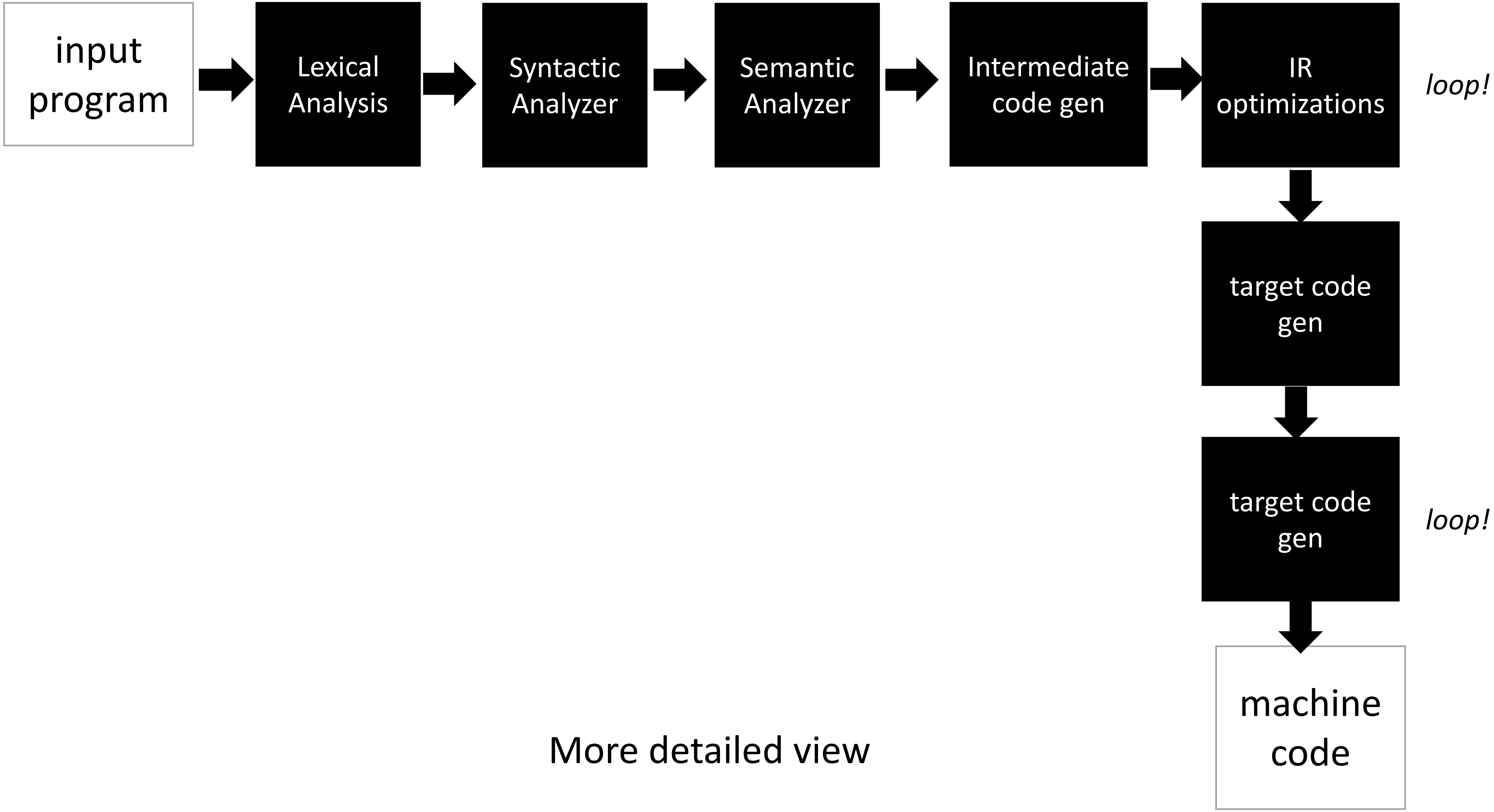
Compiler Architecture



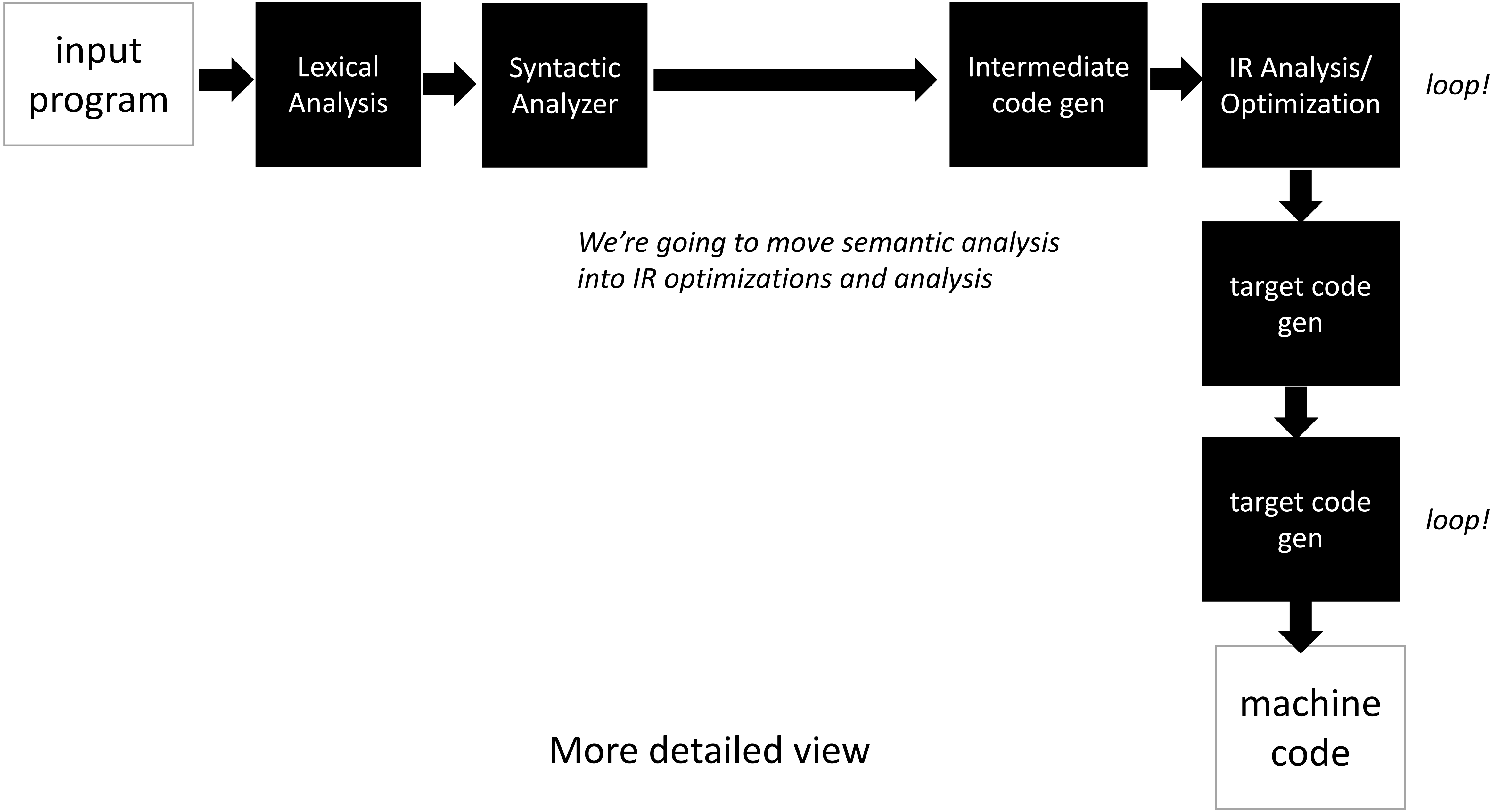
Medium detailed view

more about optimizations: https://stackoverflow.com/questions/15548023/clang-optimization-levels

More detailed view

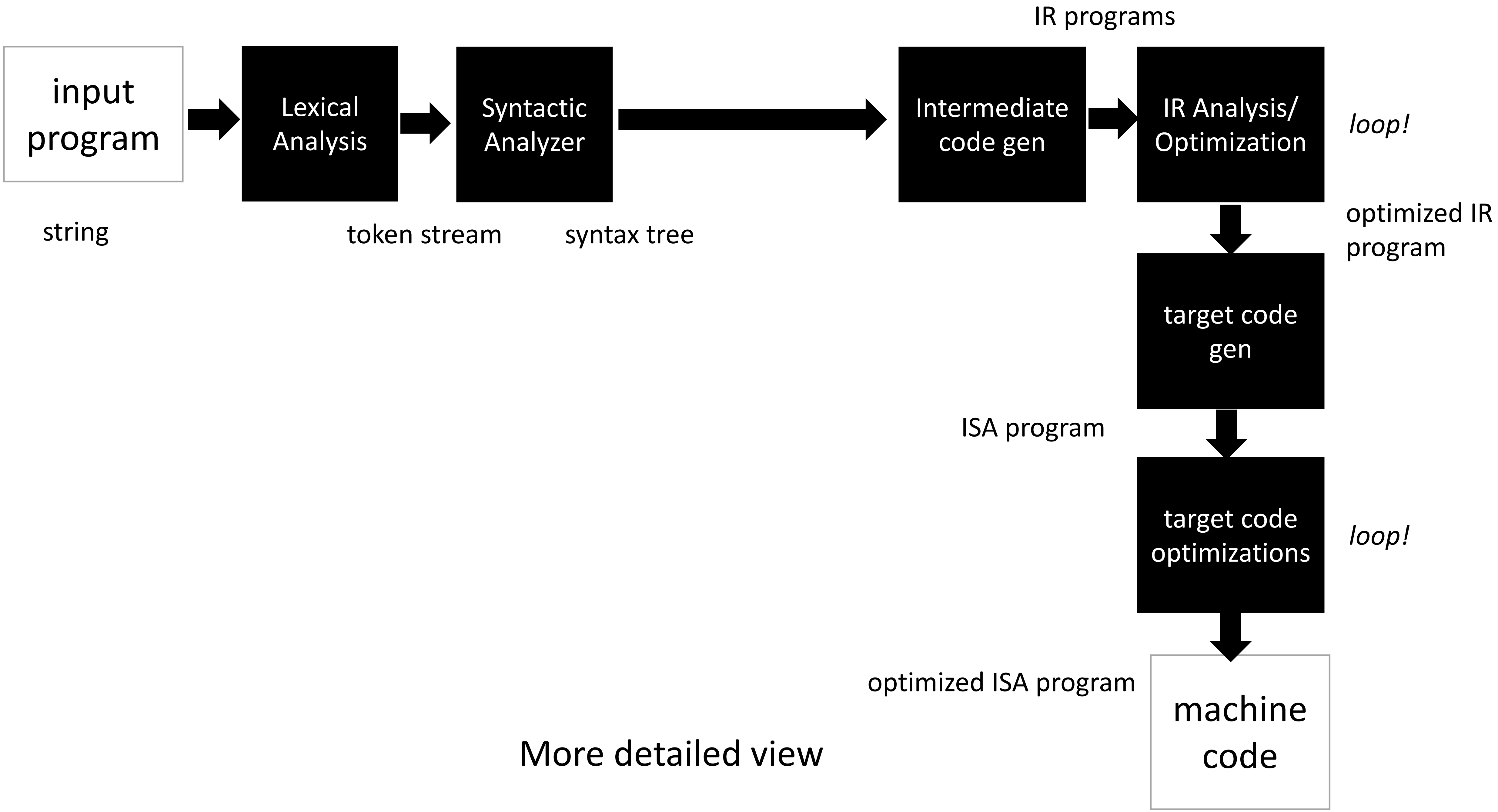


More detailed view



We're going to move semantic analysis into IR optimizations and analysis

More detailed view



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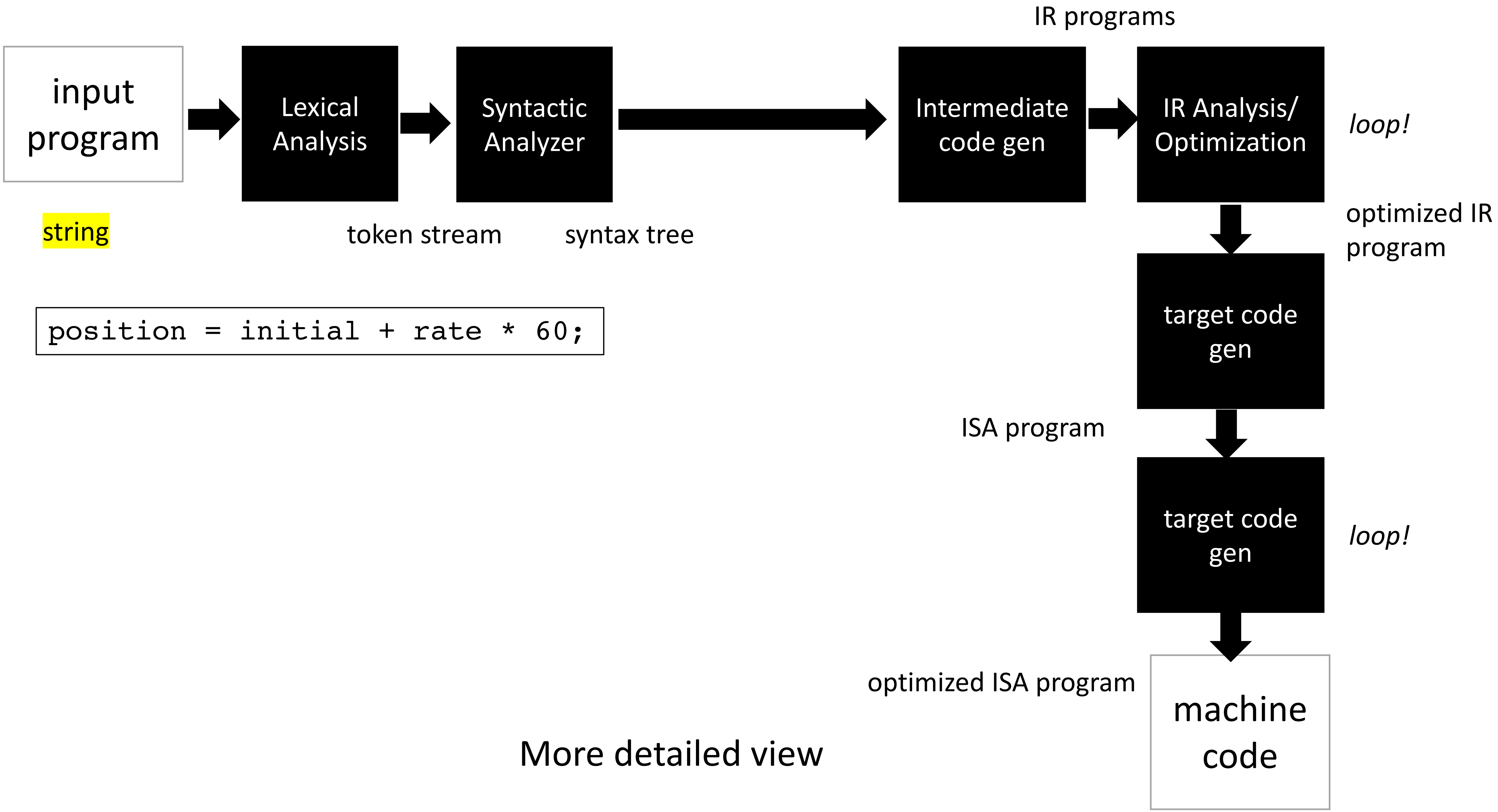

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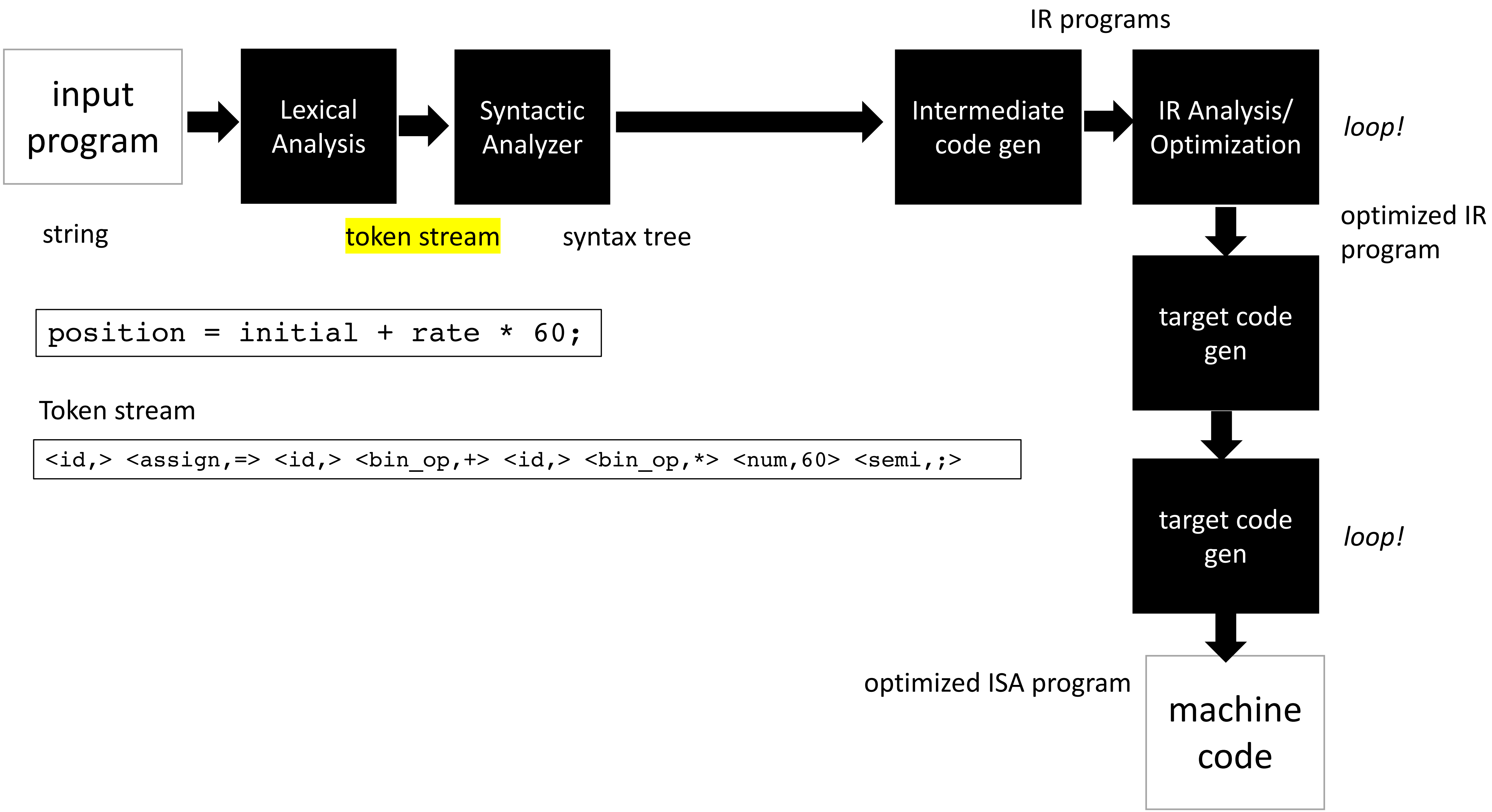
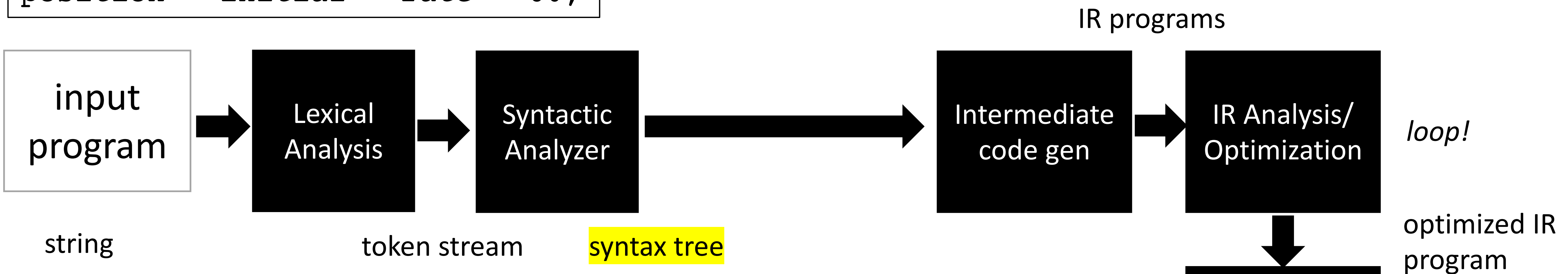
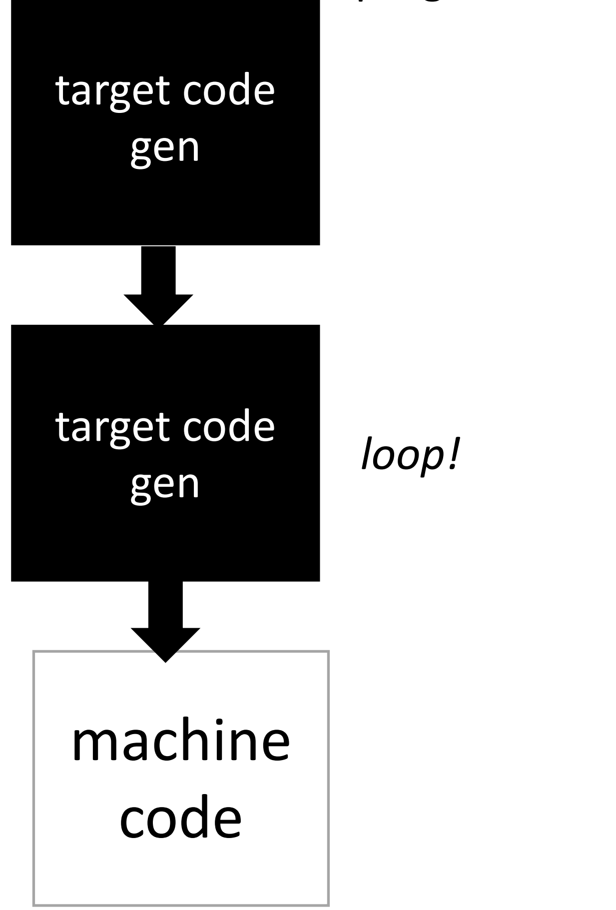

IR programs
input program
Lexical Analysis
Syntactic Analyzer
Intermediate code gen
IR Analysis/ Optimization
loop!
string
token stream
syntax tree
optimized IR program
position = initial + rate * 60;
Token stream
<id,> <assign,=> <id,> <bin_op,+> <id,> <bin_op,*> <num,60> <semi,;>
target code gen
target code gen
loop!
optimized ISA program
machine code

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

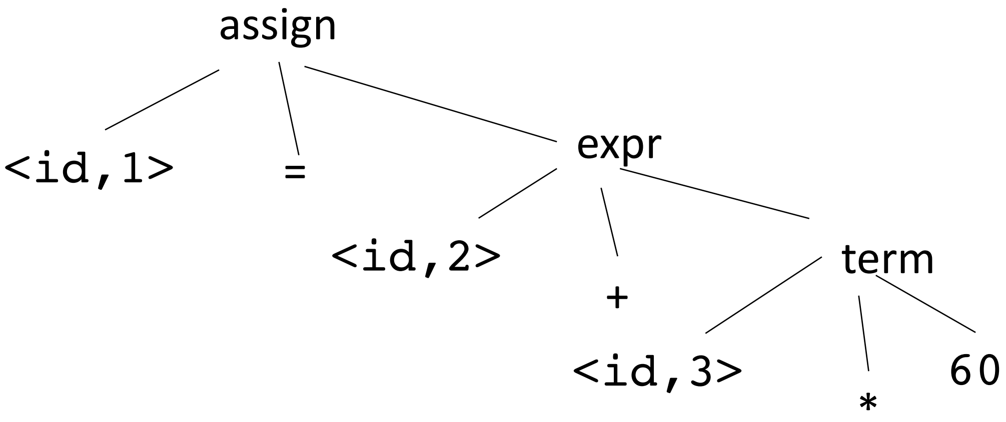




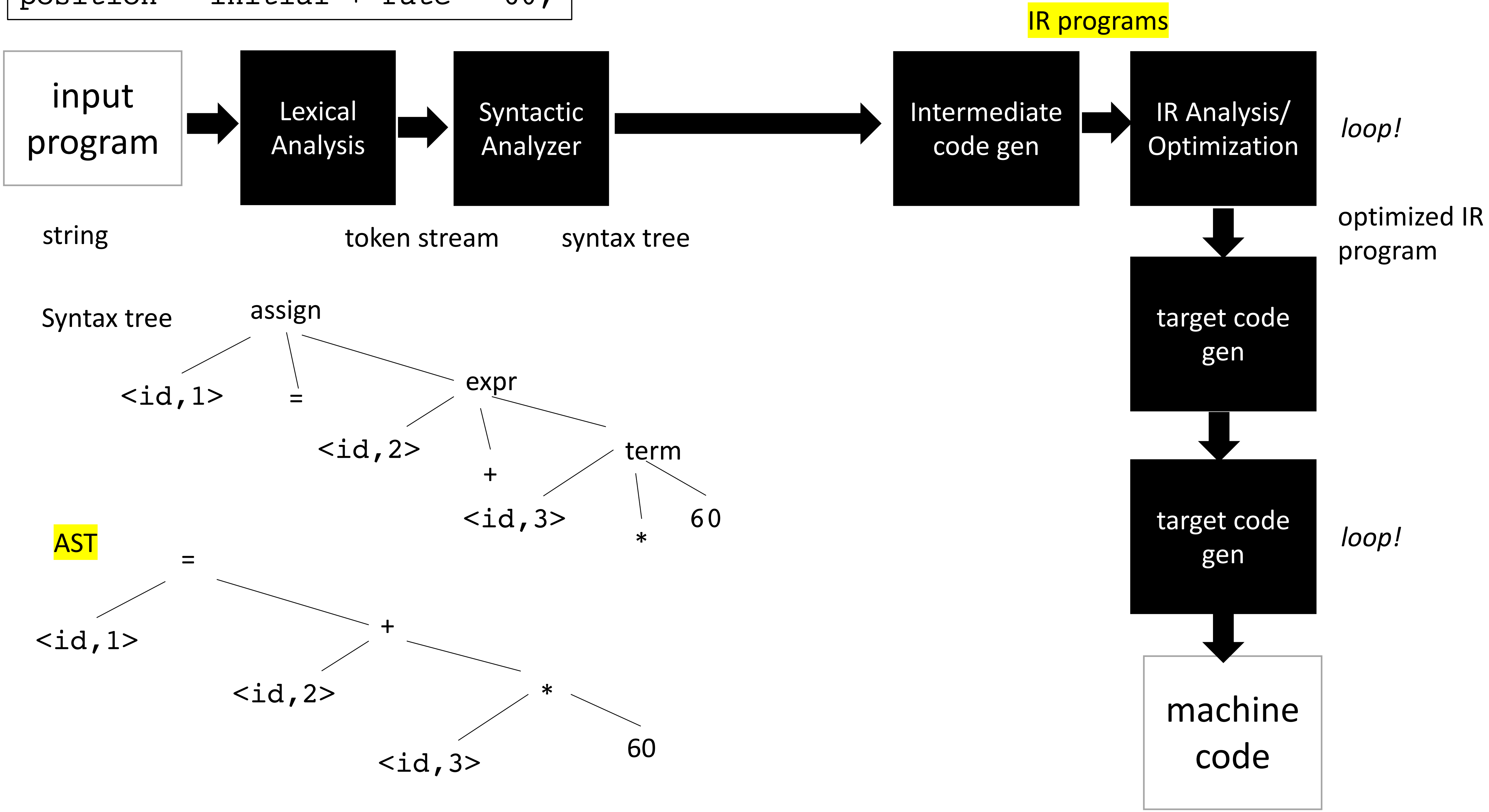
Token stream

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

Syntax tree



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



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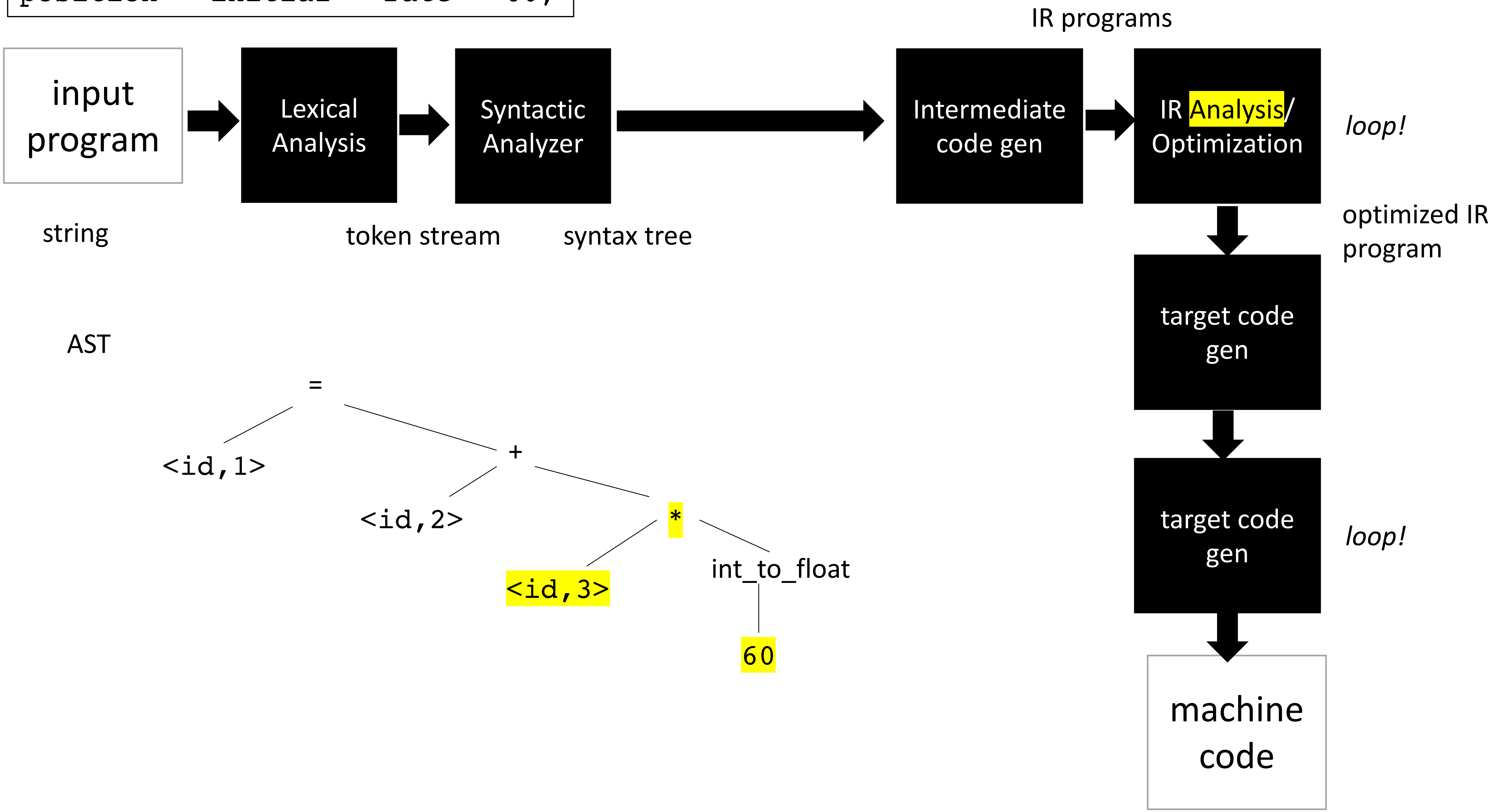

```
position = initial + rate * 60;
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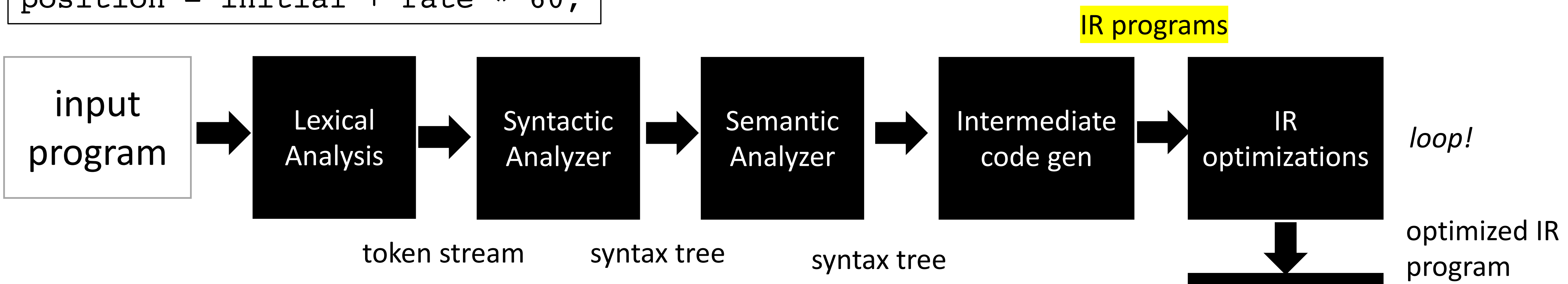
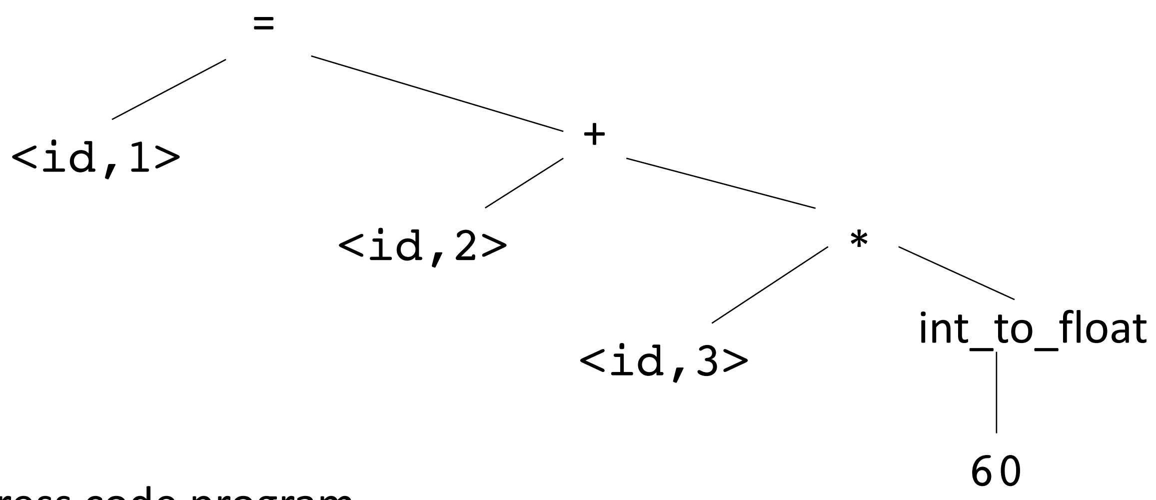
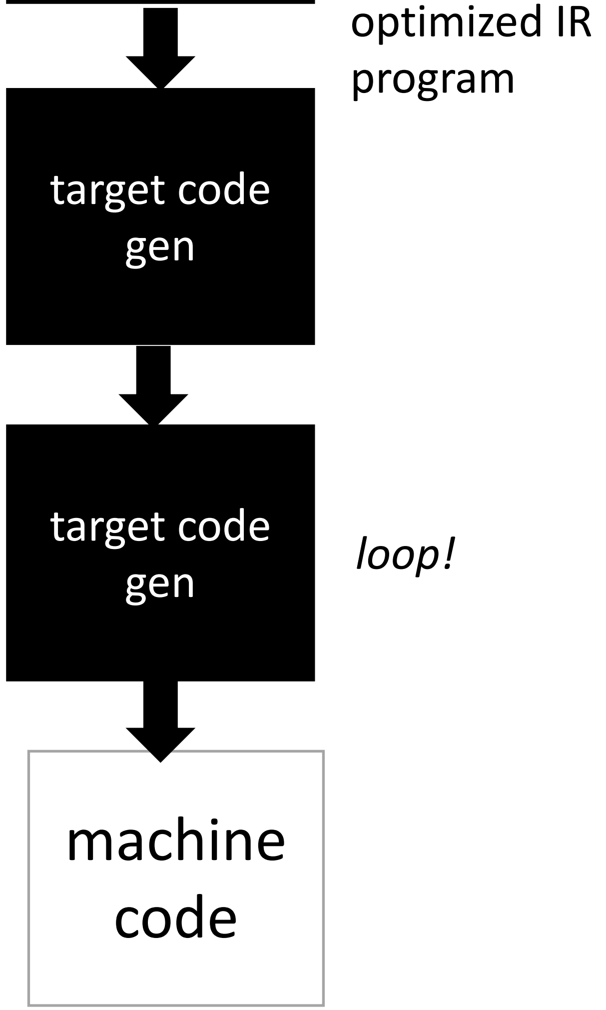


AST





3-address code program

```
%r0 = int_to_float(60);
%r1 = %r0 * id3;
%r2 = %r1 + id2;
%id1 = %r2;
```

Intermediate representations

- Several forms:
  - tree - abstract syntax tree
  - graphs - control flow graph
  - linear program - 3 address code

- Often times the program is represented as a hybrid
  - graphs where nodes are a linear program
  - linear program where expressions are ASTs

- Progression:
  - start close to a parse tree
  - move closer to an ISA

Example Clang and LLVM

- Clang:
  - a parser for C/++
  - compiles down to an IR: LLVM IR

- LLVM (low-level virtual machine)
  - An IR and specification
  - unlimited registers
  - simple expressions

Example Clang and LLVM

Quadratic formula

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

```
x = (-b - sqrt(b*b - 4 * a * c)) / (2*a)
```

use flag: -emit-llvm

Intermediate representations

- Several forms:
  - tree - abstract syntax tree
  - graphs - control flow graph
  - linear program - 3 address code

- Different optimizations and analysis are more suitable for IRs in different forms.

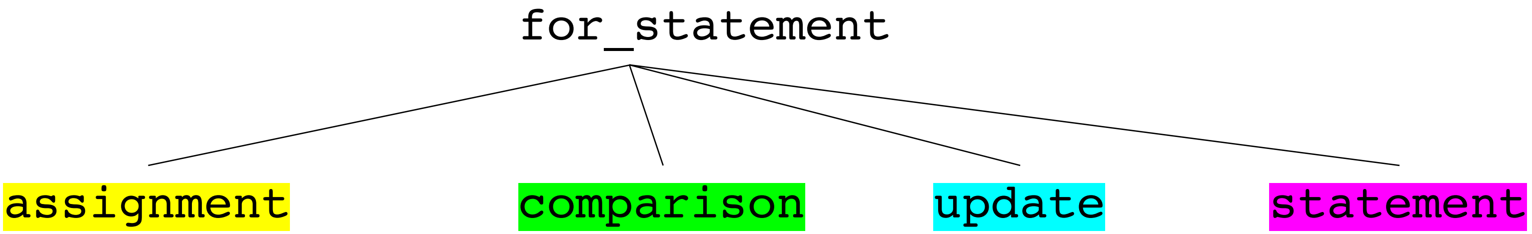
Example: loop unrolling

- Clang:
  - a parser for C/++
  - compiles down to an IR: LLVM IR

```
for (i = 0; i < 100; i = i +1) {
  x = x + 1;
}
```

- LLVM (low-level virtual machine)
  - An IR and specification
  - unlimited registers
  - simple expressions

Example: loop unrolling




```
for (i = 0; i < 100; i = i +1) {
  x = x + 1;
}
```

Example: loop unrolling

for_statement

assignment comparison update statement

```
for (i = 0; i < 100; i = i + 1) {
  x = x + 1;
}
```

Check:

1. Find iteration variable by examining assignment, comparison and update.

2. found i

3. check that statement doesn’t change i.

4. check that comparison goes around an even number of times.

Example: loop unrolling

for_statement

assignment   comparison   update   statement
update
statement

```
for (i = 0; i < 100; i = i + 1) {
  x = x + 1;
}
```

Check:

1. Find iteration variable by examining assignment, comparison and update.

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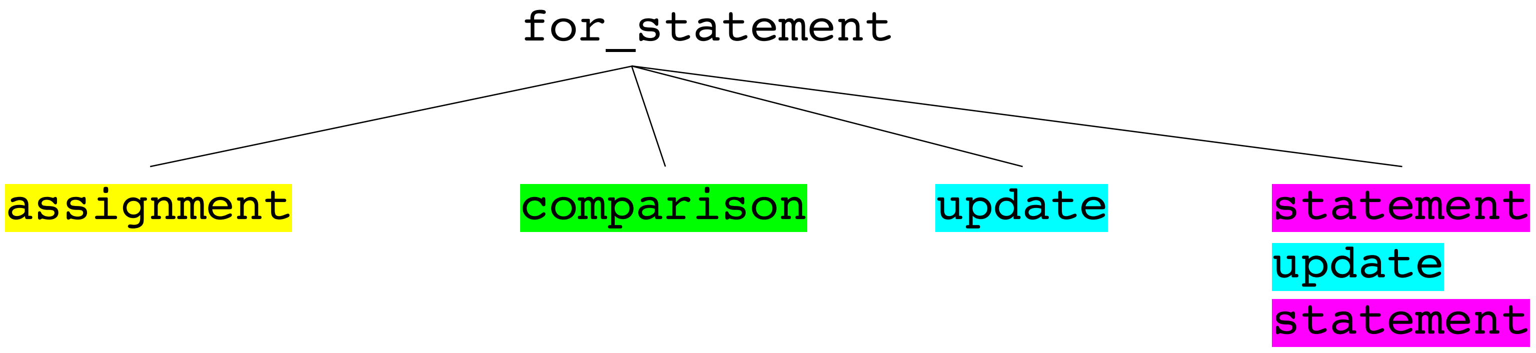
Perform optimization

copy statement and put an update before it

Example: loop unrolling




```
for (i = 0; i < 100; i = i + 1) {
   x = x + 1;
   i = i + 1;
   x = x + 1;
}
```

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Perform optimization

copy statement and put an update before it

Example: loop unrolling

```
br label %3, !dbg !22

3: ; preds = %13, %0
%4 = load i32, ptr %1, align 4, !dbg !23
%5 = icmp slt i32 %4, 100, !dbg !25
br i1 %5, label %6, label %16, !dbg !26

6: ; preds = %3
%7 = load i32, ptr %2, align 4, !dbg !27
%8 = add nsw i32 %7, 1, !dbg !29
store i32 %8, ptr %2, align 4, !dbg !30
%9 = load i32, ptr %1, align 4, !dbg !31
%10 = add nsw i32 %9, 1, !dbg !32
store i32 %10, ptr %1, align 4, !dbg !33
%11 = load i32, ptr %2, align 4, !dbg !34
%12 = add nsw i32 %11, 1, !dbg !35
store i32 %12, ptr %2, align 4, !dbg !36
br label %13, !dbg !37

13: ; preds = %6
%14 = load i32, ptr %1, align 4, !dbg !38
%15 = add nsw i32 %14, 1, !dbg !39
store i32 %15, ptr %1, align 4, !dbg !40
br label %3, !dbg !41, !llvm.loop !42
```

LLVM IR for the for loop. Much harder to analyze!

Check:

1. Find iteration variable by examining assignment, comparison and update.

2. found i

3. check that statement doesn't change i.

4. check that comparison goes around an even number of times.

Perform optimization

copy statement and put an update before it

Example: common subexpression elimination

```
z = x + y;
a = b + c;
d = x + y;
```

Can this be optimized?

Example: common subexpression elimination

```
z = x + y;
a = b + c;
d = x + y;
```

Can this be optimized?

```
z = x + y;
a = b + c;
d = z;
```

remove redundant addition

Easy to do this optimization when code is a low level form like this

Our first IR: abstract syntax tree

- One step away from parse trees
- Great representation for expressions
- Natural representation to apply type checking/inference
- Can view in clang with: -Xclang -ast-dump

What is an AST?

input: 1+5*6

We’ll start by looking at a parse tree:

<table>
<tr><th>Operator</th><th>Name</th><th>Productions</th></tr>
<tr><td>+</td><td><code>expr</code></td><td><code>: expr PLUS term</code>
<code>| term</code></td></tr>
<tr><td>*</td><td><code>term</code></td><td><code>: term TIMES factor</code>
<code>| factor</code></td></tr>
<tr><td>()</td><td><code>factor</code></td><td><code>: LPAREN expr RPAREN</code>
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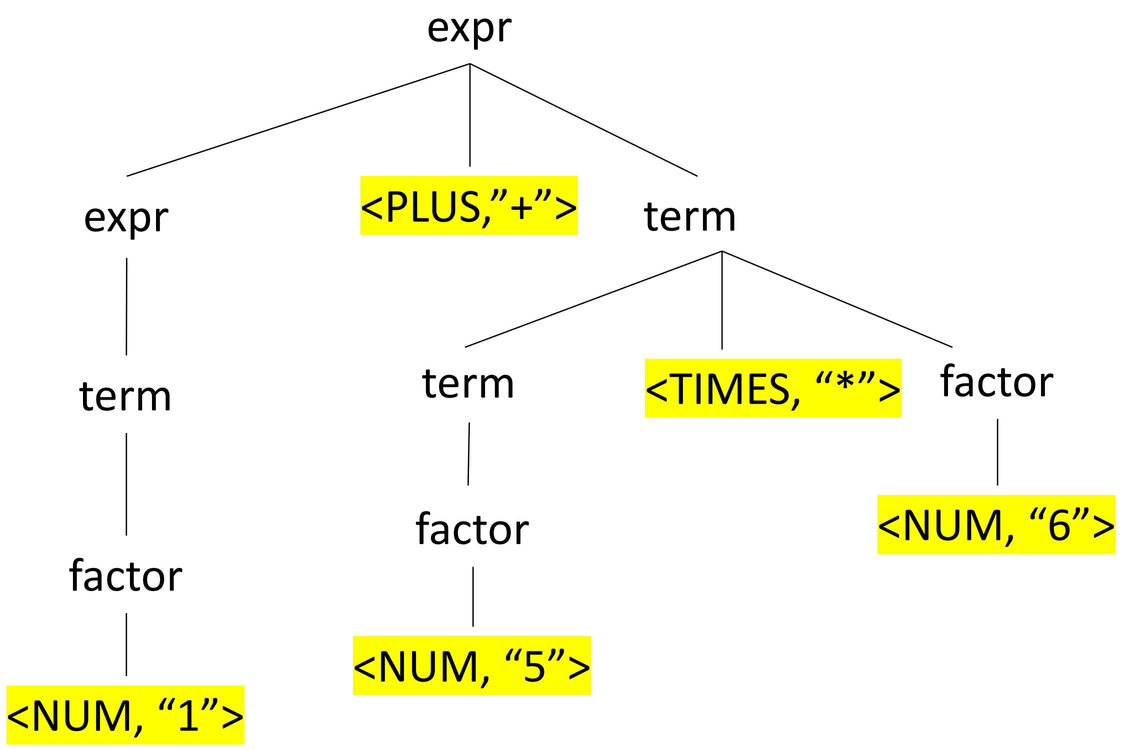
</table>



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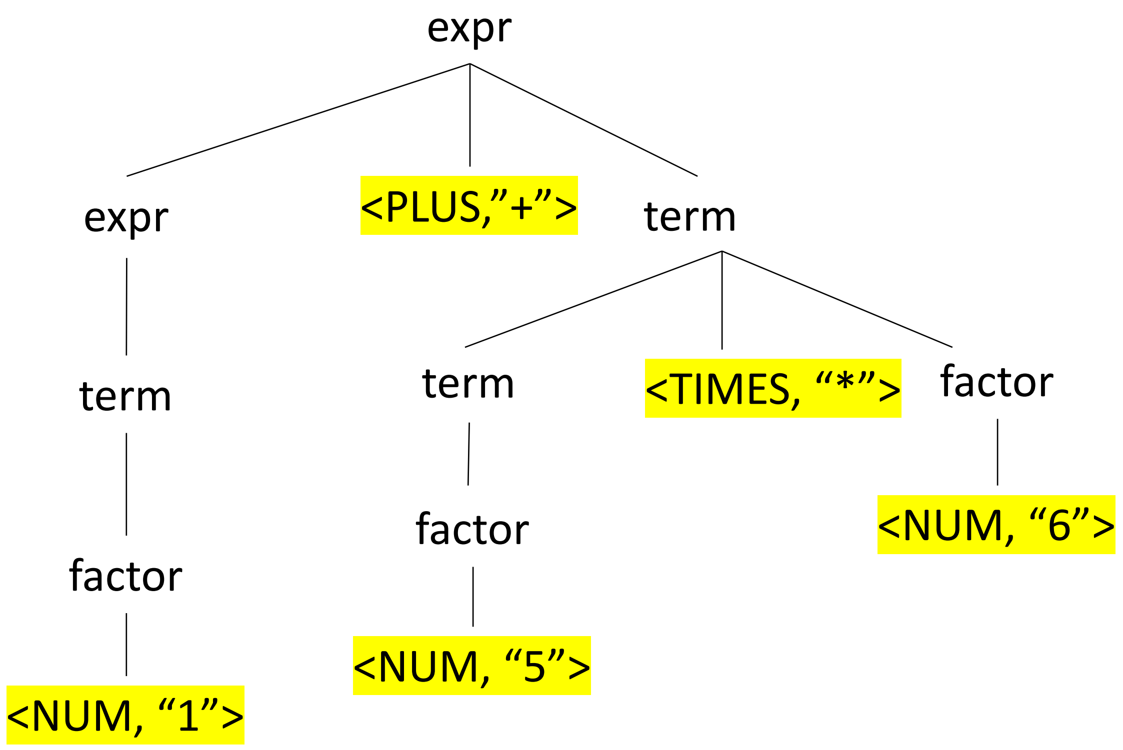

What are leaves?

What is an AST?

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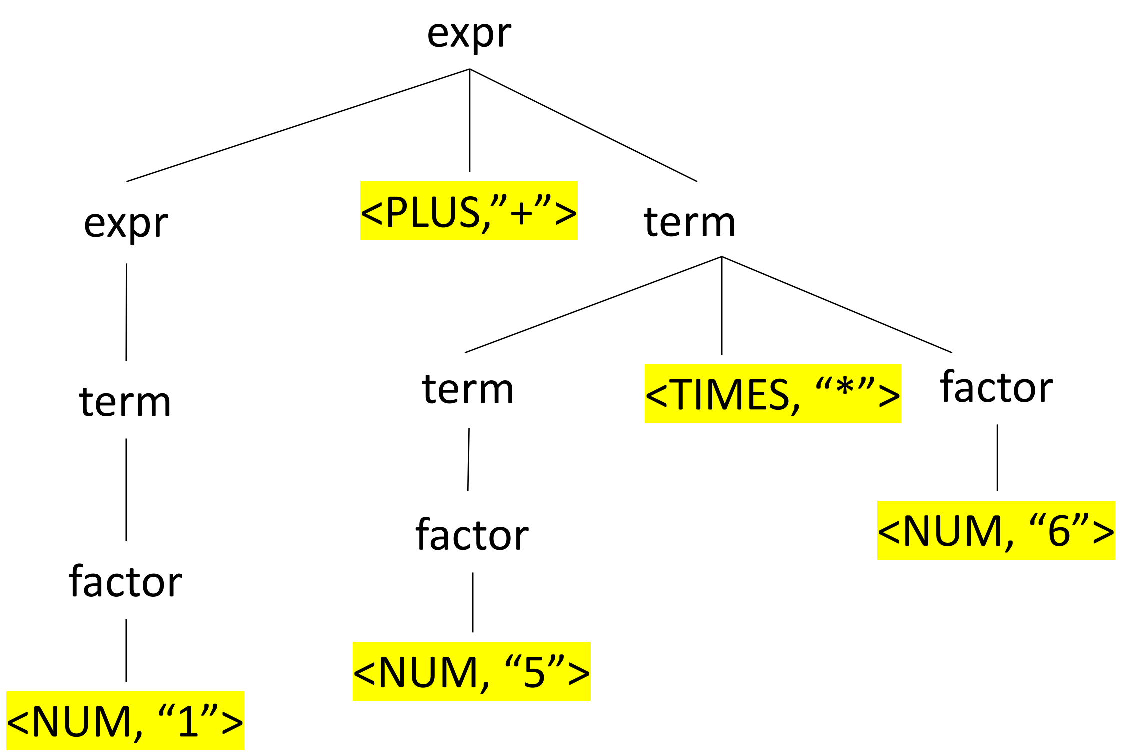

What are leaves? lexemes

What is an AST?

`input: 1+5*6`

We’ll start by looking at a parse tree:

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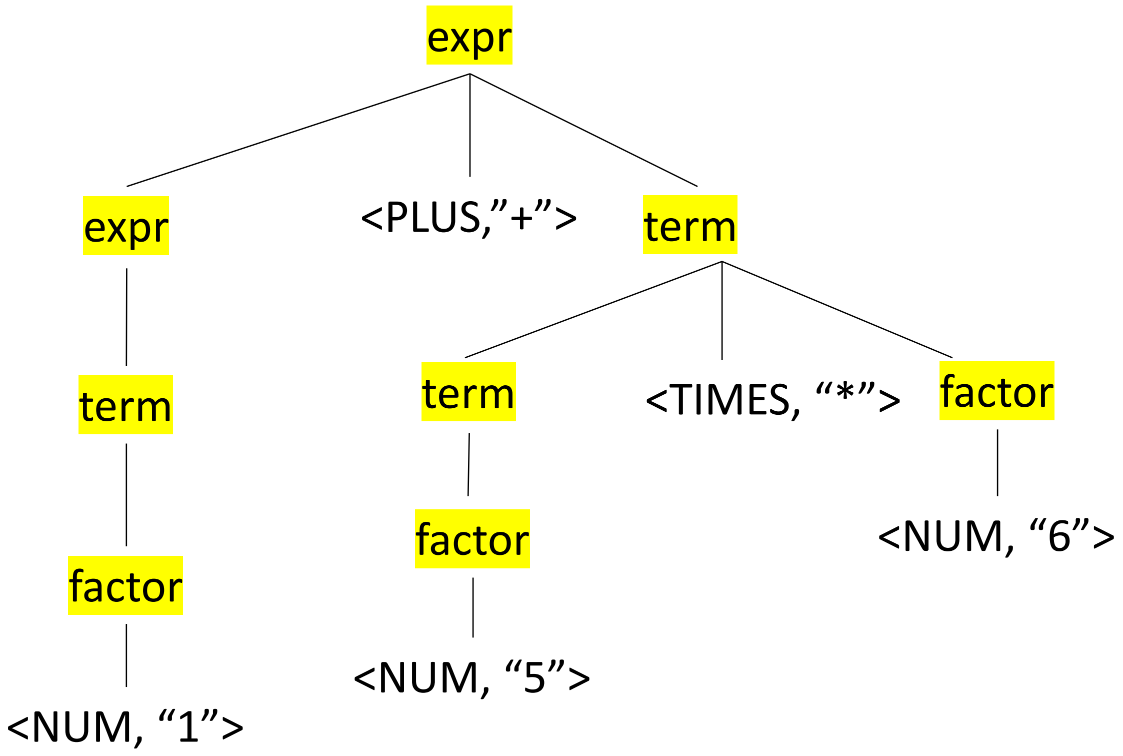

What are nodes?

What is an AST?

```
input: 1+5*6
```

We'll start by looking at a parse tree:

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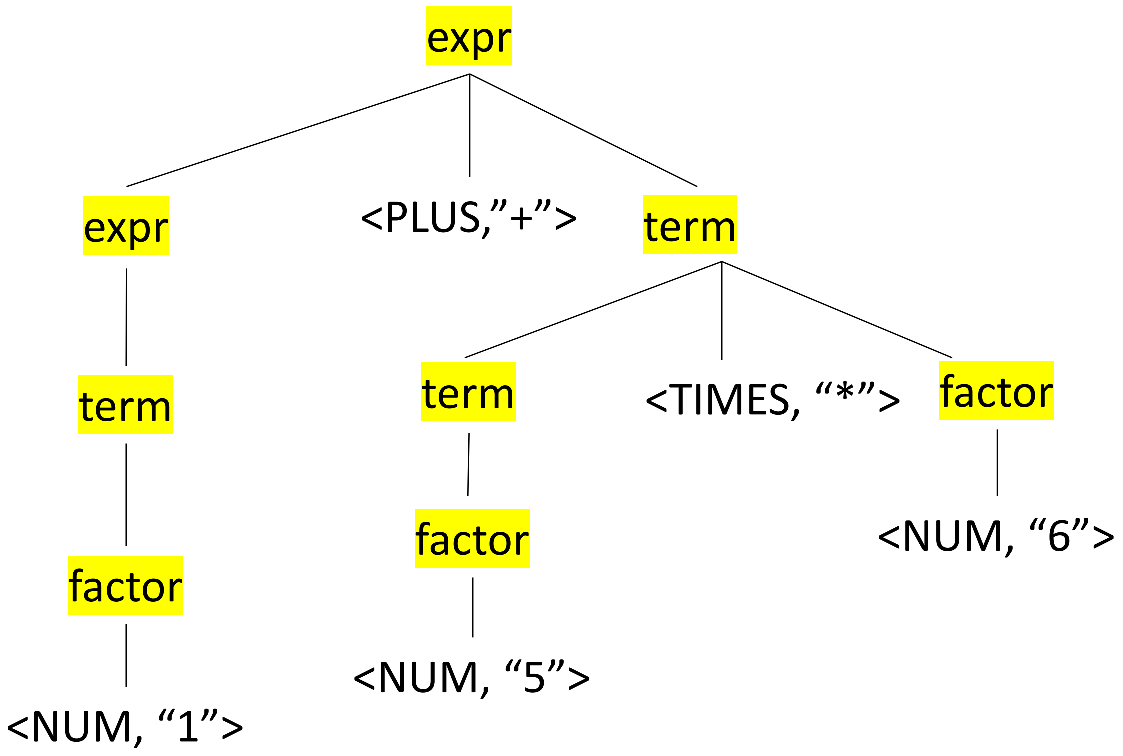


What are nodes? non-terminals

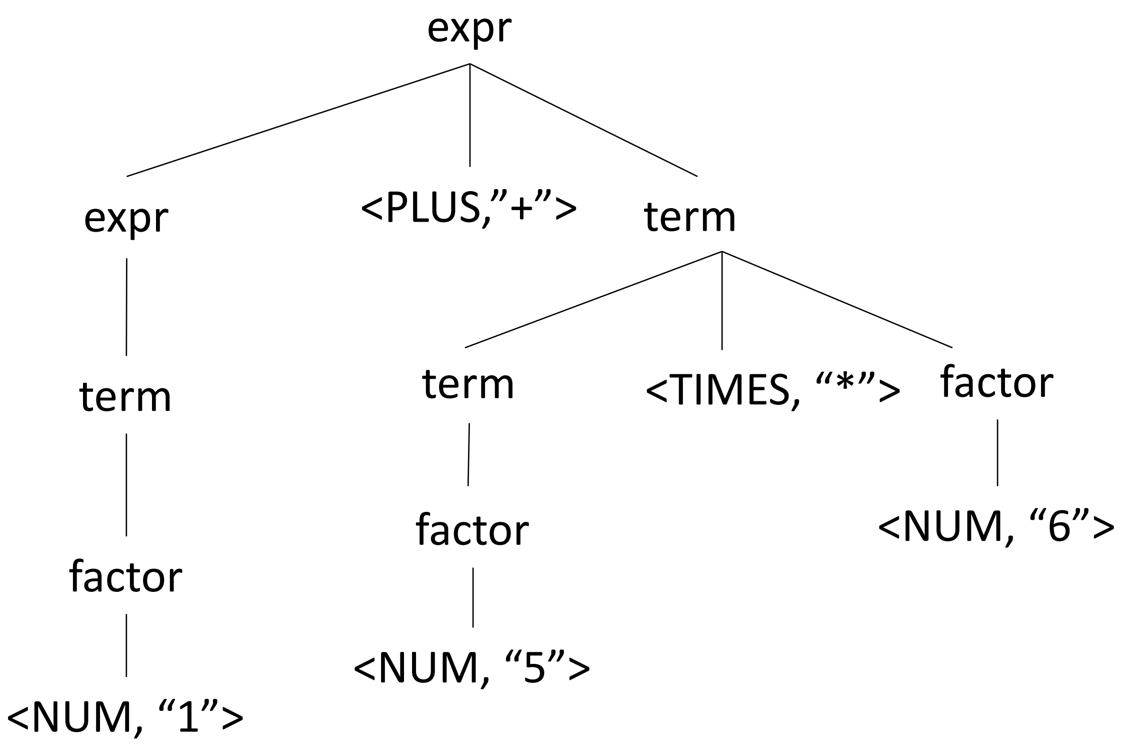
What is an AST?

`input: 1+5*6`

Parse trees are defined by the grammar

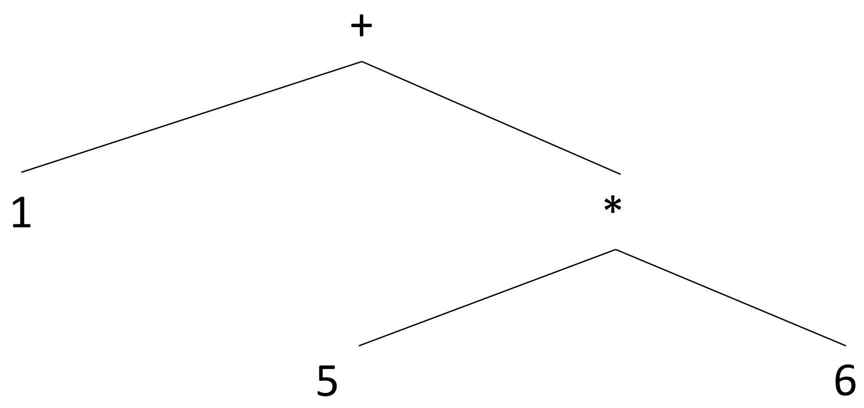
- **Tokens**
- **Production rules**

Parse trees are often not explicitly constructed. We use them to visualize the parsing computation



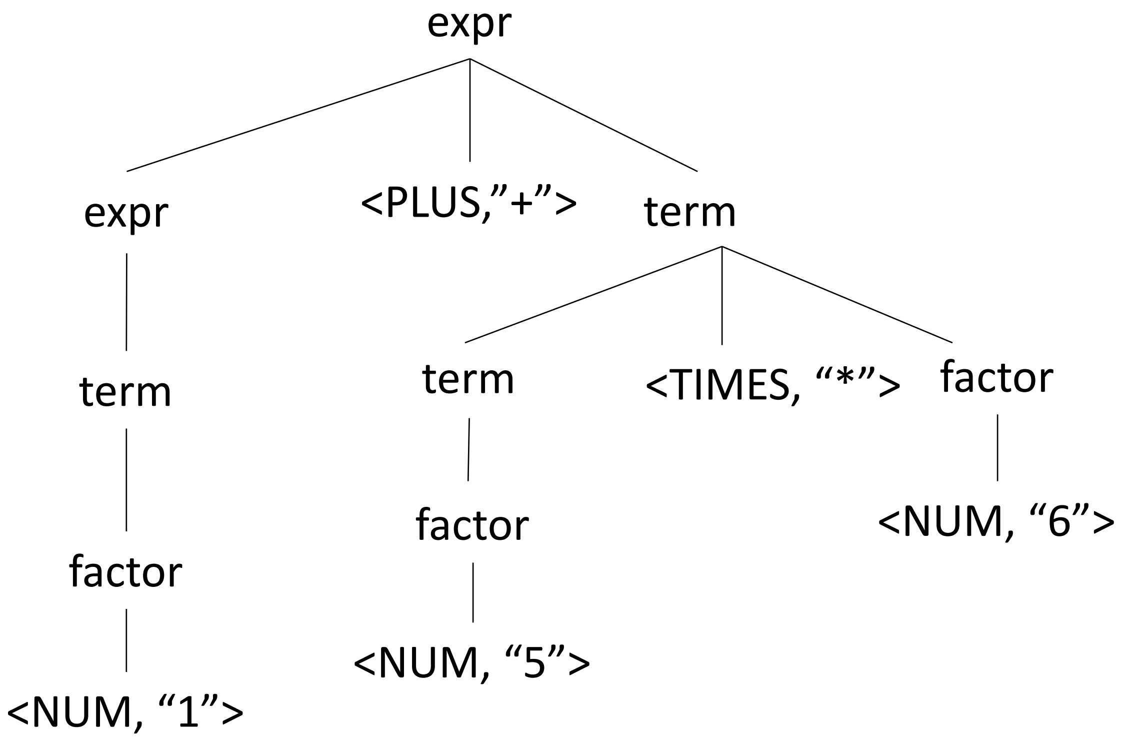
What is an AST?

`input: 1+5*6`



AST

What are some differences?



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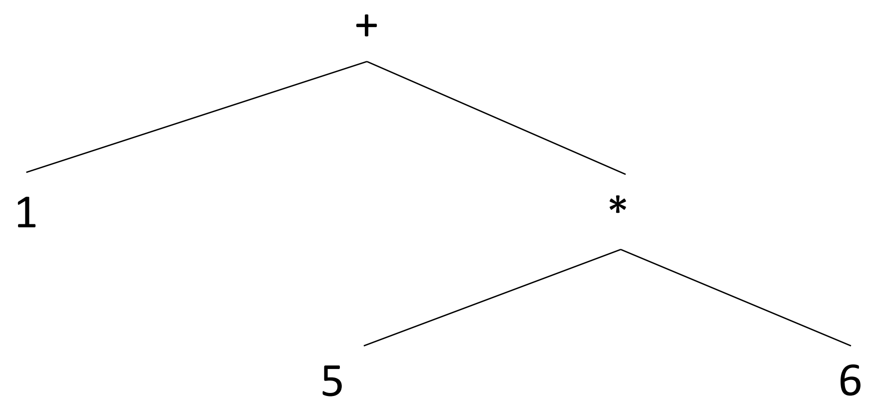
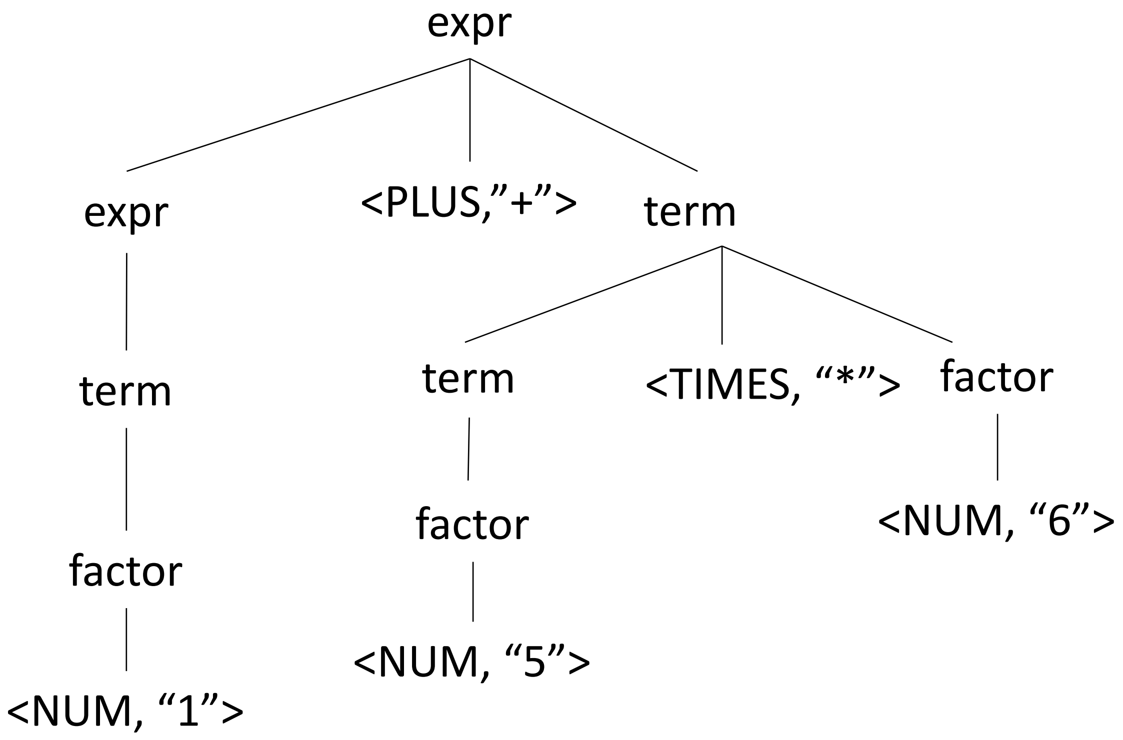


AST



What are some differences?

- disjoint from the grammar
- leaves are data, not lexemes
- nodes are operators, not non-terminals

Example

what happens to ()s in an AST?

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<tr><td>*</td><td>term</td><td>: term TIMES factor
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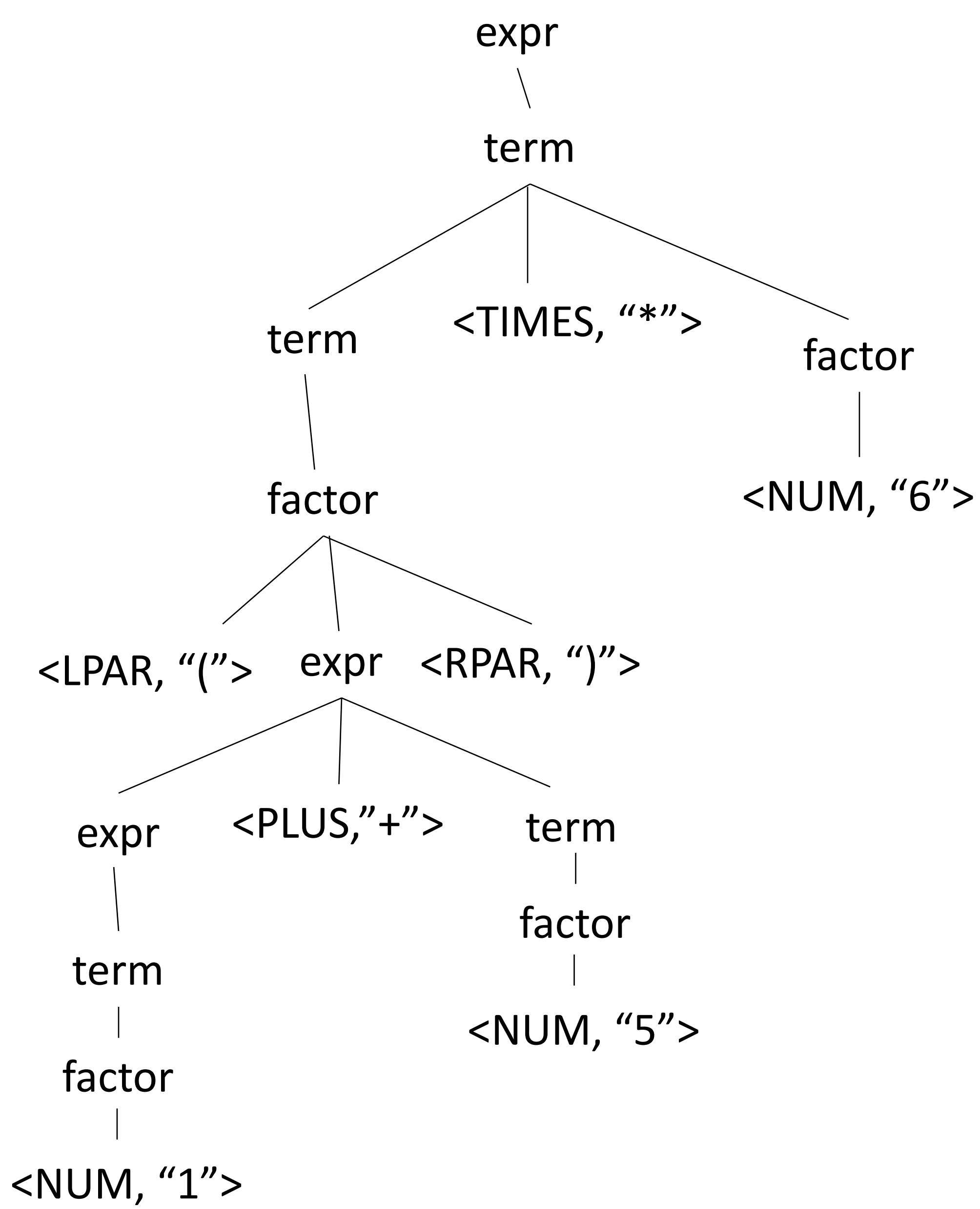
`input: (1+5)*6`



Example

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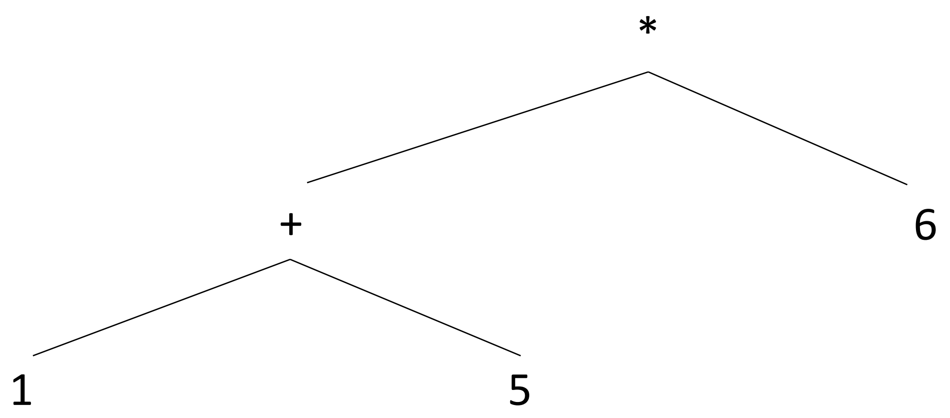
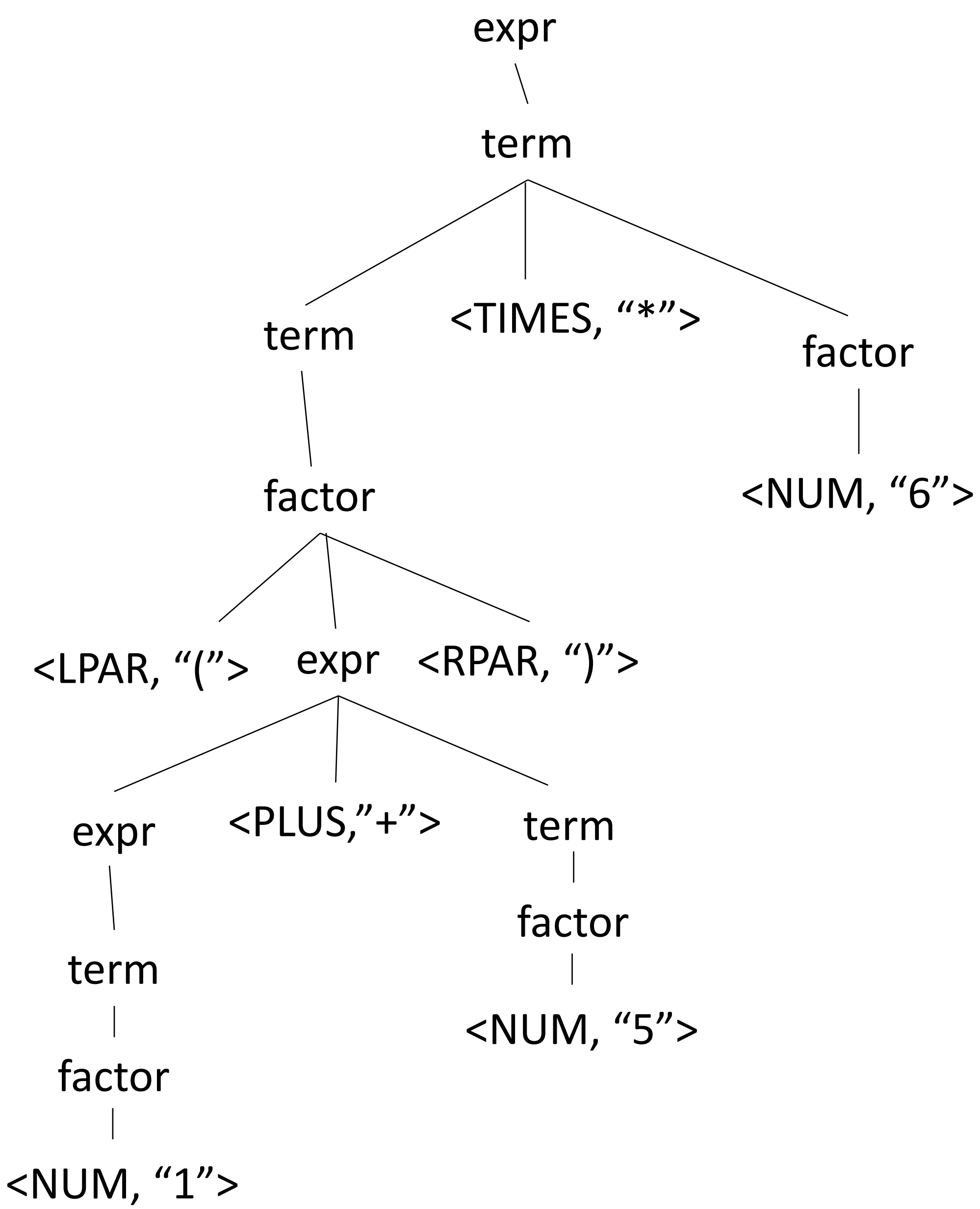
what happens to ()s in an AST?





No need for (), they simply encode precedence. And now we have precedence in the AST tree structure

formalizing an AST

- A tree based data structure, used to represent expressions

- Main building block: Node
  - Leaf node: ID or Number
  - Node with one child: Unary operator (`-`) or type conversion (`int_to_float`)
  - Node with two children: Binary operator (`+`,`*`)

```python
class ASTNode():
    def __init__(self):
        pass
```

```python
class ASTLeafNode(ASTNode):
    def __init__(self, value):
        self.value = value


class ASTNumNode(ASTLeafNode):
    def __init__(self, value):
        super().__init__(value)


class ASTIDNode(ASTLeafNode):
    def __init__(self, value):
        super().__init__(value)
```

```python
class ASTBinOpNode(ASTNode):
    def __init__(self, l_child, r_child):
        self.l_child = l_child
        self.r_child = r_child


class ASTPlusNode(ASTBinOpNode):
    def __init__(self, l_child, r_child):
        super().__init__(l_child,r_child)


class ASTMultNode(ASTBinOpNode):
    def __init__(self, l_child, r_child):
        super().__init__(l_child,r_child)
```

Creating an AST from production rules

Operator	Name	Productions	Production action
+	expr	: expr PLUS term | term	{} {}
*	term	: term TIMES factor | factor	{} {}
()	factor	: LPAR expr RPAR | NUM | ID	{} {} {}

Creating an AST from production rules

Operator	Name	Productions	Production action
+	`expr`	`: expr PLUS term` `│ term`	`{return ASTAddNode($1,$3)}` `{return $1}`
*	`term`	`: term TIMES factor` `│ factor`	`{return ASTMultNode($1,$3)}` `{return $1}`

()	`factor`	`: LPAR expr RPAR`
		`│ NUM`
		`│ ID`
			`{return $2}`
			`{return ASTNumNode($1)}`
			`{return ASTIDNode($1)}`

<table>
<tr><th>Name</th><th>Productions</th><th>Production action</th></tr>
<tr><td><code>expr</code></td><td><code>: expr PLUS term</code>
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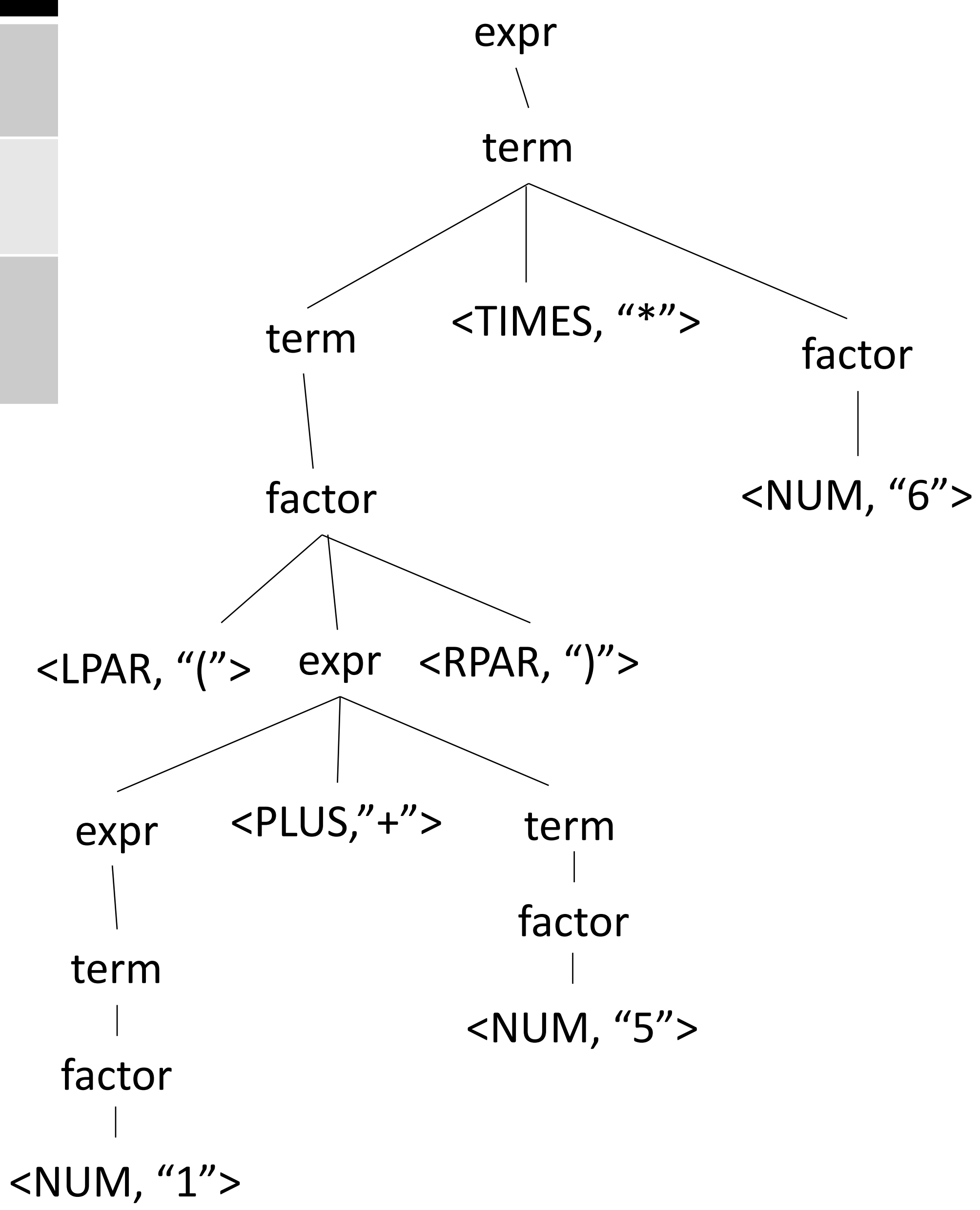
`input: (1+5)*6`



Lets build the AST

AST<?>

<table>
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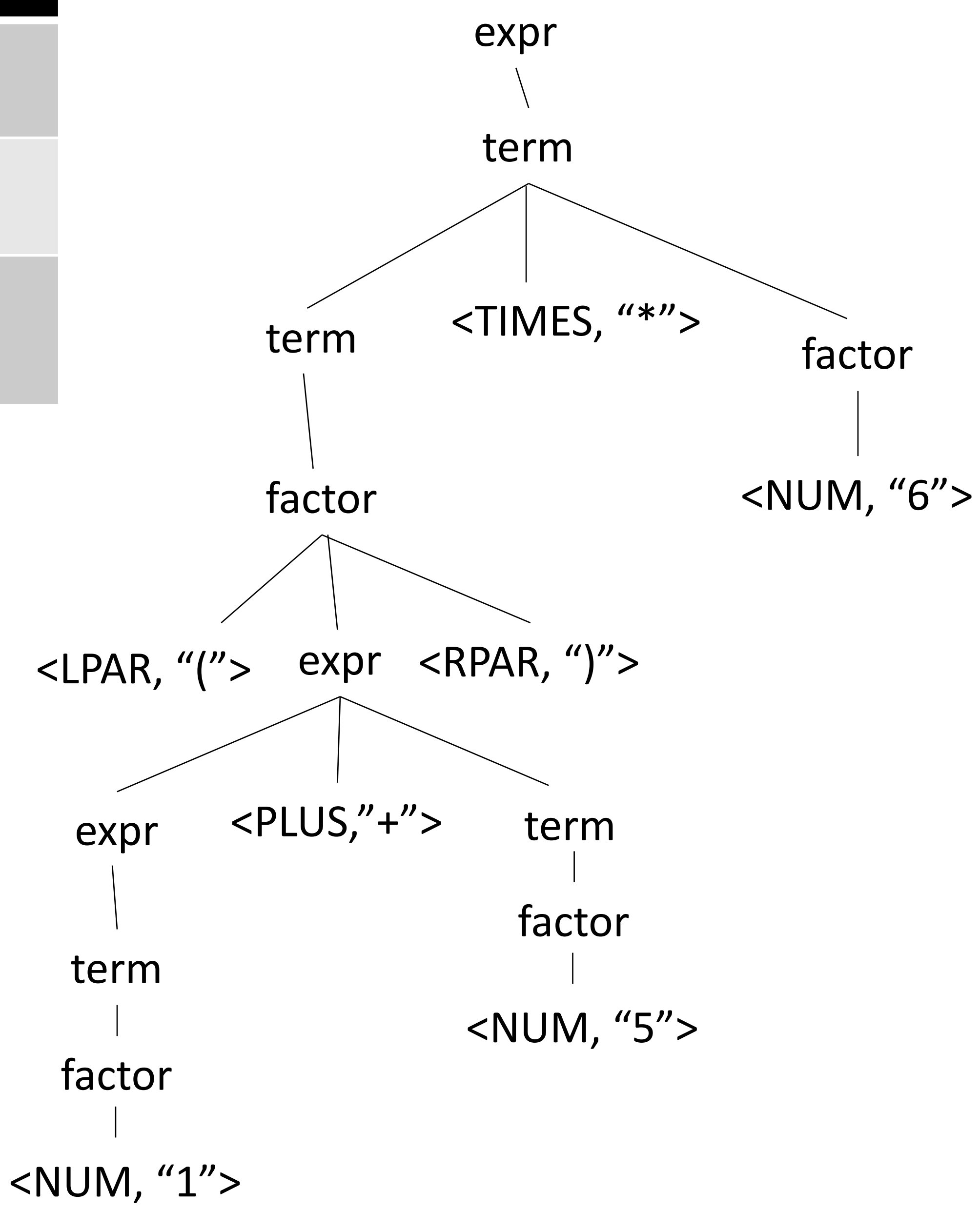
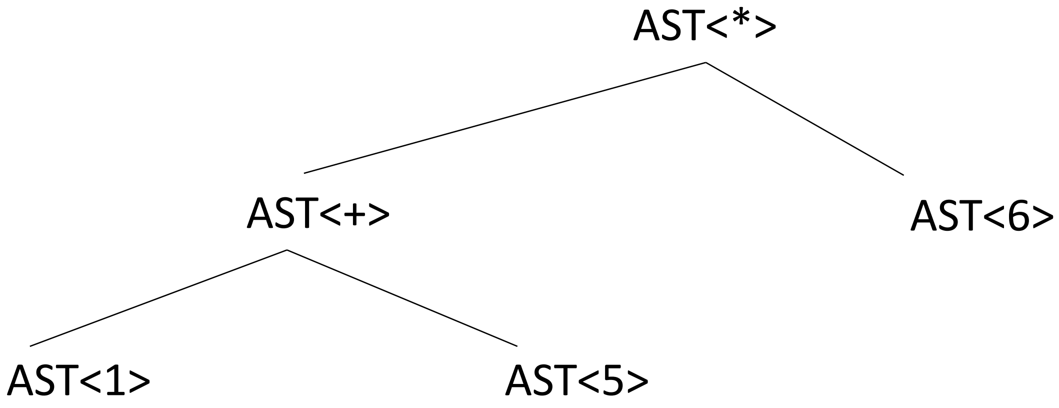
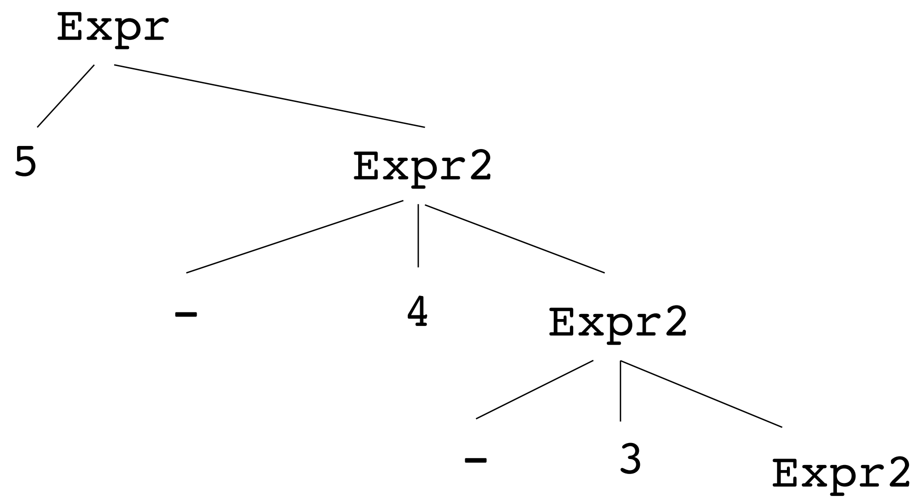




Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
      |    “”
```

5 - 4 - 3



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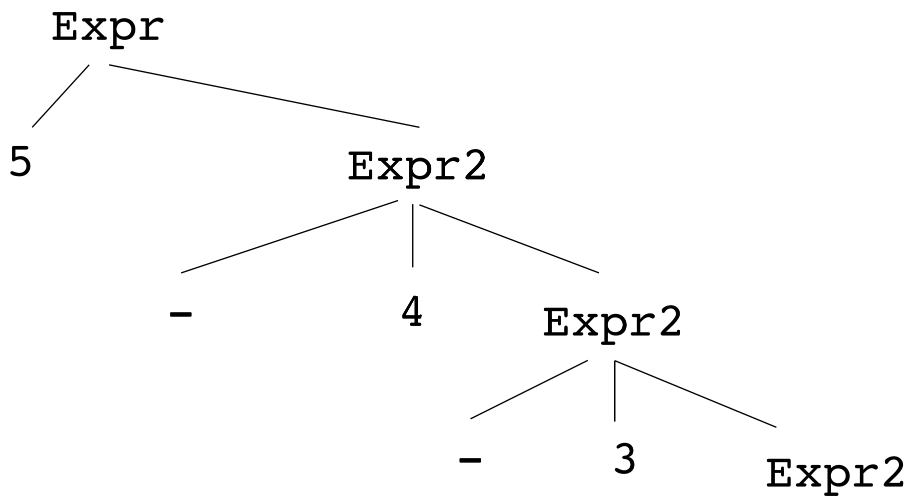
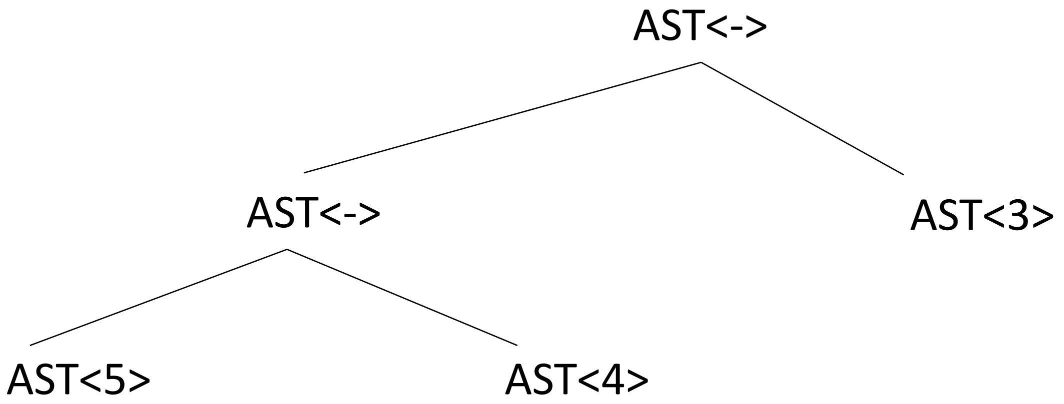
```

`5 - 4 - 3`



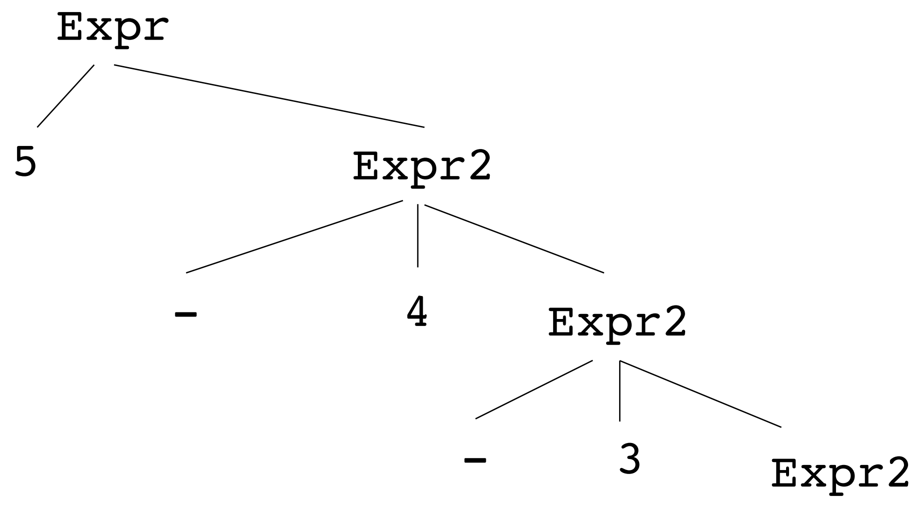


How do we get to the desired parse tree?

Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
      |    ""
```

5 - 4 - 3

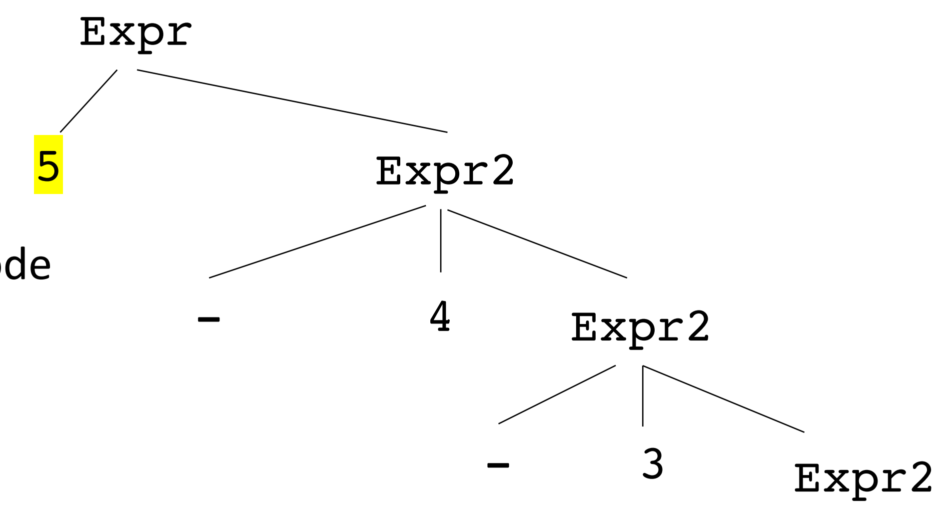


Keep in mind that because we wrote our own parser, we can inject code at any point during the parse.

Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    ""
```

5 - 4 - 3



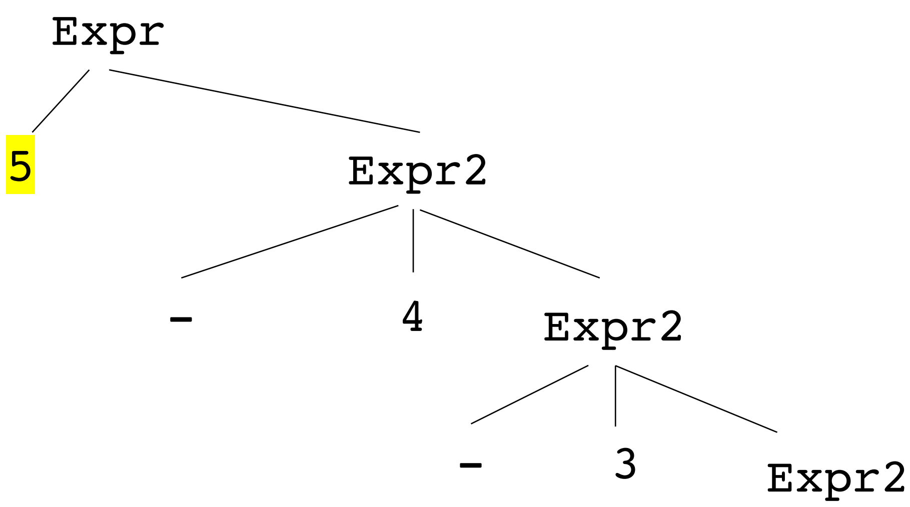
Get number node after we see a number

AST<5>

Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    ""
```

5 - 4 - 3



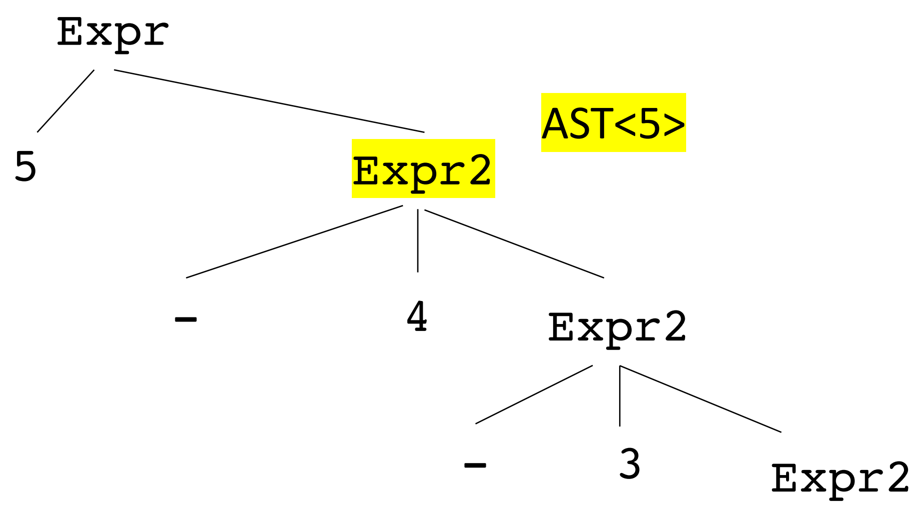
Pass the node down

AST<5>

Creating an AST from top down grammar

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
        |    ""
```

5 - 4 - 3



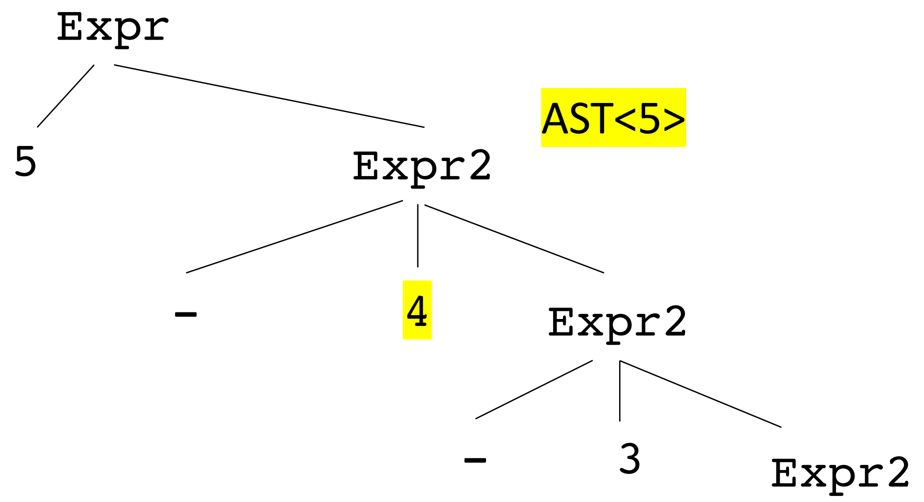
Pass the node down

AST<5>

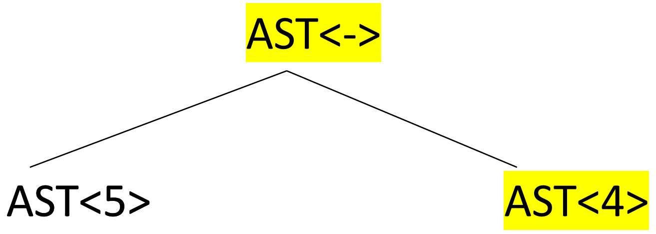
Creating an AST from top down grammar

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
        |    ""
```

`5 - 4 - 3`



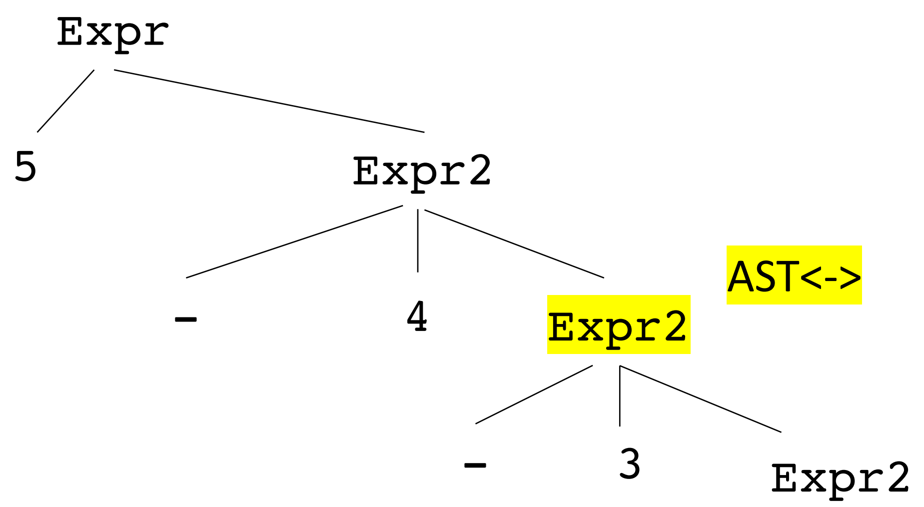
In Expr2, after 4 is parsed, create a number node and a minus node



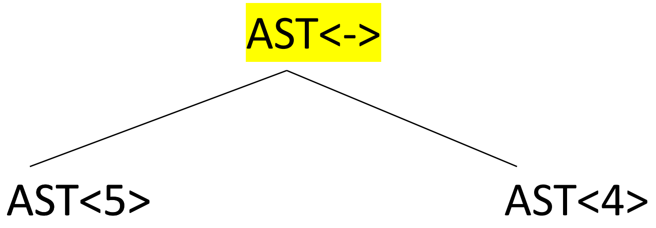
Creating an AST from top down grammar

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
         |    ""
```

5 - 4 - 3



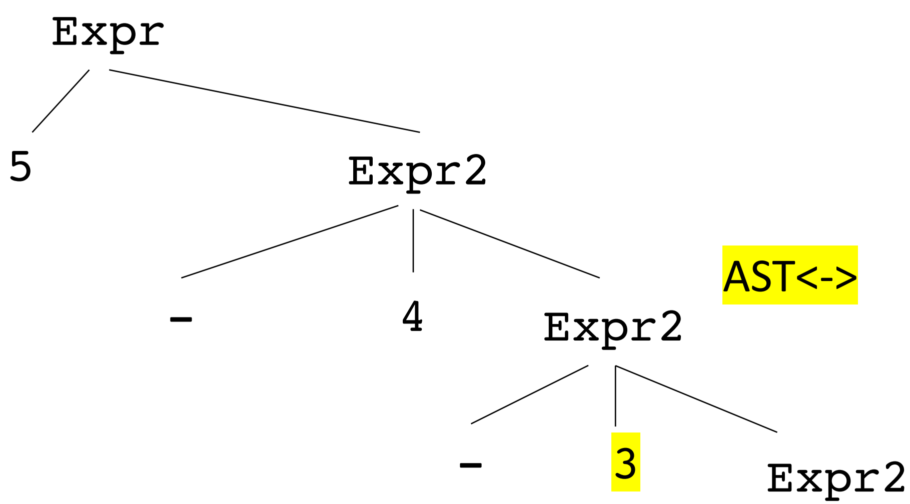
pass the new node down

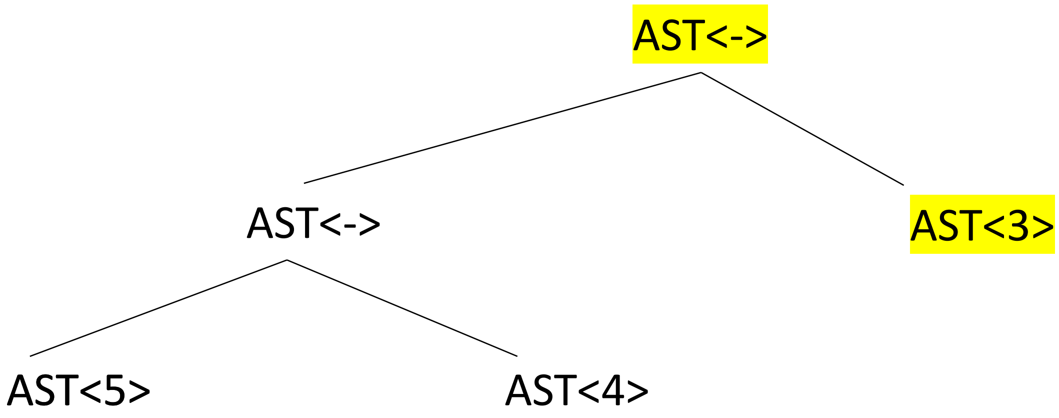


Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    “”
```

5 - 4 - 3

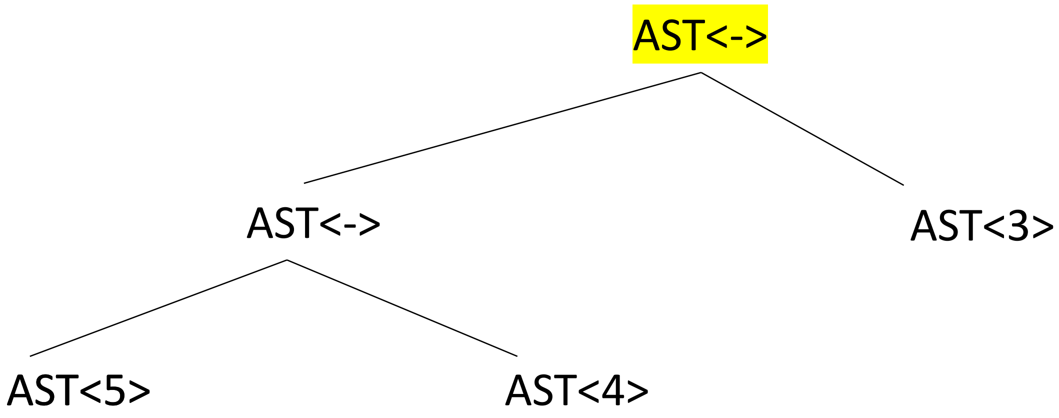




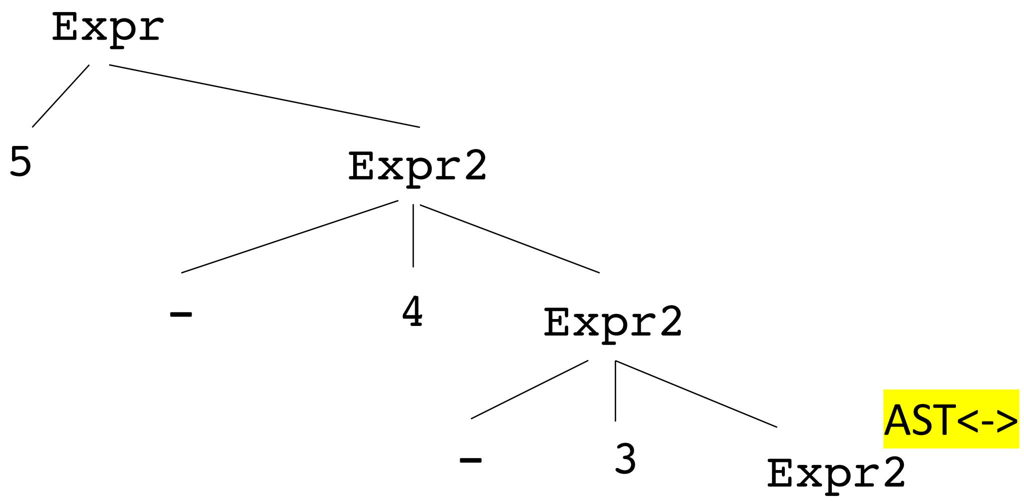
In Expr2, after 3 is parsed, create a number node and a minus node

Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |   ""
```



5 - 4 - 3

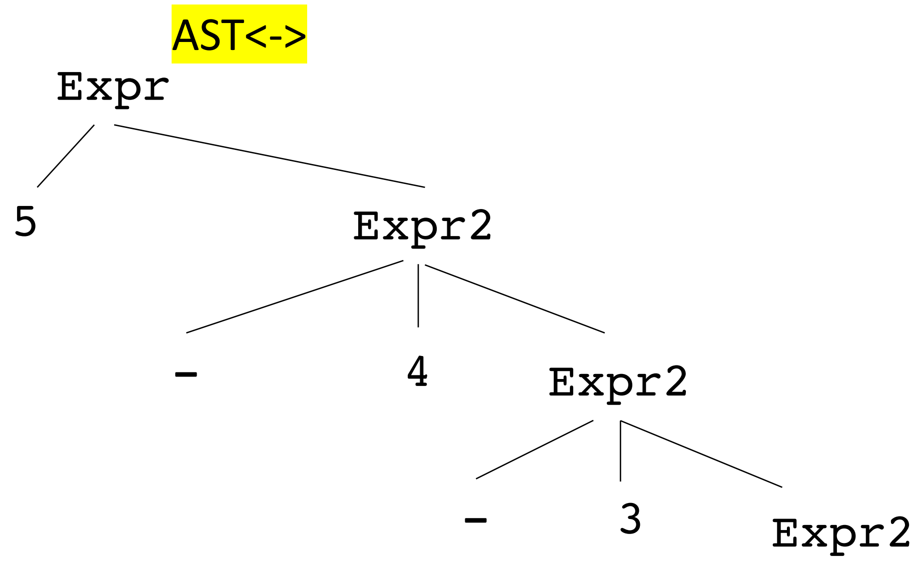


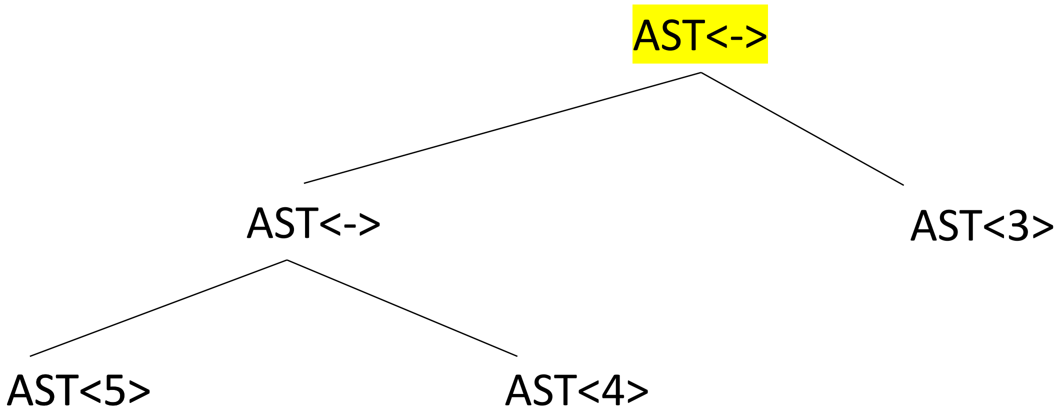
pass down the new node

Creating an AST from top down grammar

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
        |    ""
```

5 - 4 - 3





return the node when there is nothing left to parse

Creating an AST from top down grammar

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
        |    ""
```

```python
def parse_expr(self):
    #get the value from the lexeme
    value = self.to_match.value
    node = ASTNumNode(value)
    self.eat("NUM")
    return self.parse_expr2(node)
```

Creating an AST from top down grammar

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
         |    “”
```

```
def parse_expr(self):
    #get the value from the lexeme
    value = self.to_match.value
    node = ASTNumNode(value)
    self.eat("NUM")
    return self.parse_expr2(node)
```

```
def parse_expr2(self, lhs_node):
        # ... for applying the first production rule
        self.eat("MINUS")
        value = self.to_match.value
        rhs_node = ASTNumNode(value)
        self.eat("NUM")
        node = ASTMinusNode(lhs_node, rhs_node)
        return self.parse_expr2(node)
```

Creating an AST from top down grammar

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
        |    ""
```

```
def parse_expr(self):
    #get the value from the lexeme
    value = self.to_match.value
    node = ASTNumNode(value)
    self.eat("NUM")
    return self.parse_expr2(node)
```

```
def parse_expr2(self, lhs_node):
    # ... for applying the second production rule
    return lhs_node
```

Creating an AST from top down grammar

```
Expr   ::= Term Expr2
Expr2  ::= MINUS Term Expr2
        |    ""
```

```python
def parse_expr(self):
    #get the value from the lexeme
    value = self.to_match.value
    node = ASTNumNode(value)
    self.eat("NUM")
    return self.parse_expr2(node)
```

In a more realistic grammar, you might have more layers: e.g. a Term

how to adapt?

```python
def parse_expr2(self, lhs_node):
        # ... for applying the first production rule
        self.eat("MINUS")
        value = self.to_match.value
        rhs_node = ASTNumNode(value)
        self.eat("NUM")
        node = ASTMinusNode(lhs_node, rhs_node)
        return self.parse_expr2(node)
```

Creating an AST from top down grammar

```
Expr   ::= Term Expr2
Expr2  ::= MINUS Term Expr2
        |    ""
```

In a more realistic grammar, you might have more layers: e.g. a Term

how to adapt?

```
def parse_expr(self):
    node = self.parse_term()
    return self.parse_expr2(node)
```

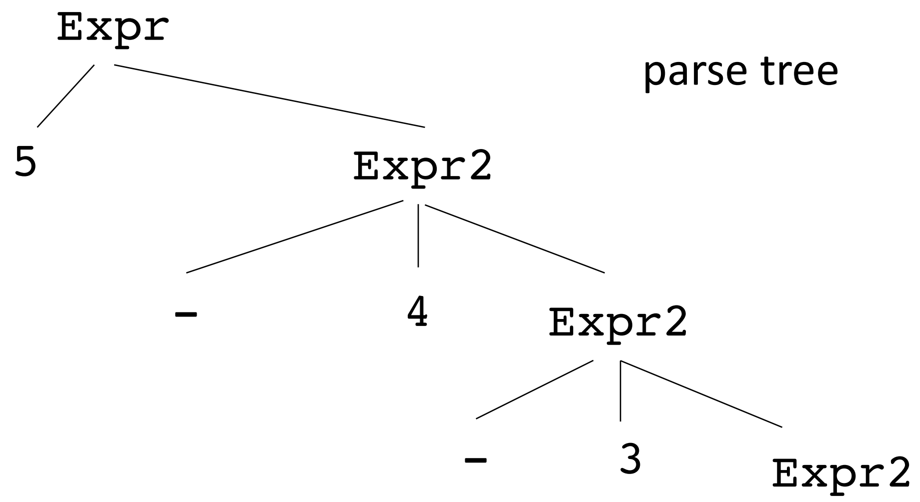
```
def parse_expr2(self, lhs_node):
        # ... for applying the first production rule
        self.eat("MINUS")
        rhs_node = self.parse_term()
        node = ASTMinusNode(lhs_node, rhs_node)
        return self.parse_expr2(node)
```

The parse_term will figure out how to get you an AST node for that term.

Evaluate an AST by doing a post order traversal

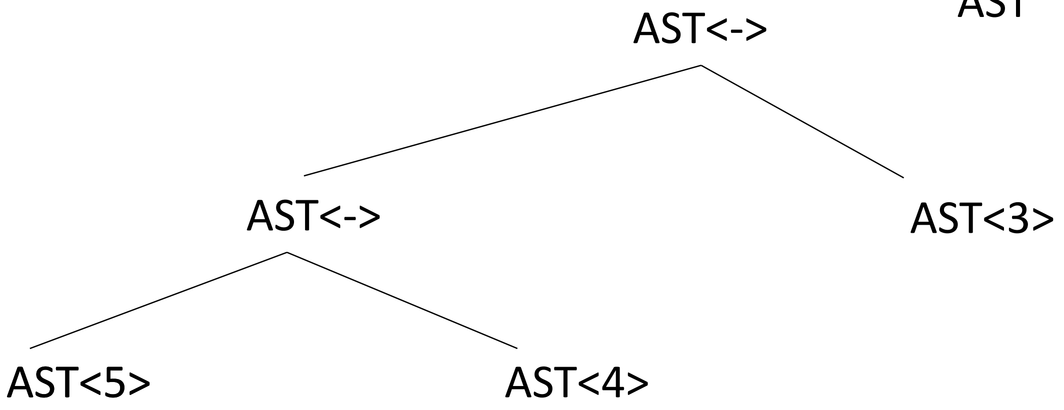
```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    ""
```

`5 - 4 - 3`



parse tree

AST



Parse trees cannot always be evaluated in post-order. An AST should always be

Example

- Python AST

```python
import ast

print(ast.dump(ast.parse('5-4-2')))
```

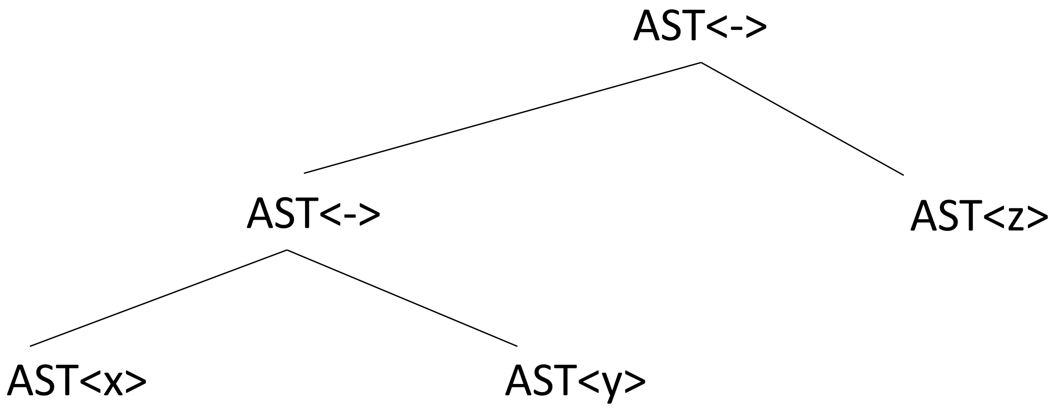
```
Expr(value=BinOp(left=BinOp(left=Num(n=5), op=Sub(), right=Num(n=4)), op=Sub(), right=Num(n=2)))
```

Evaluate an AST by doing a post order traversal

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    ""
```

What if you cannot evaluate it?
What else might you do?

`x - y - z`

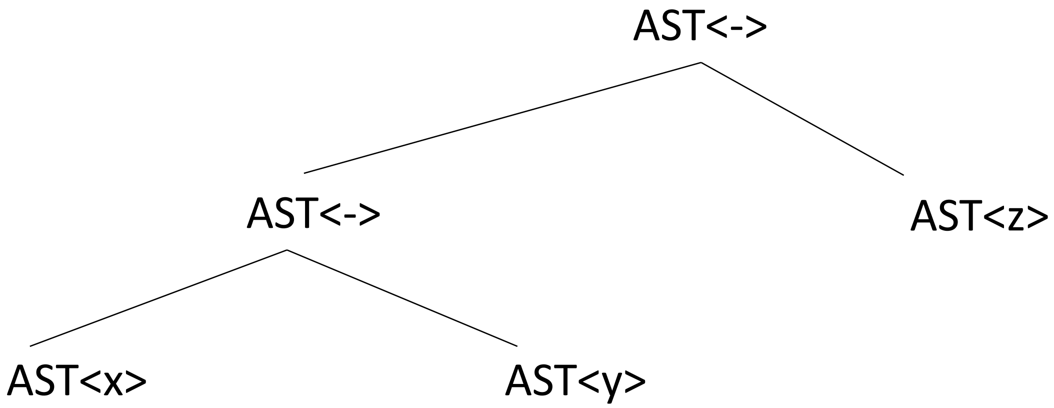


Evaluate an AST by doing a post order traversal

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    “”
```

What if you cannot evaluate it?
What else might you do?

```
int x;
int y;
float z;
float w;
w = x - y - z
```



How does this change things?

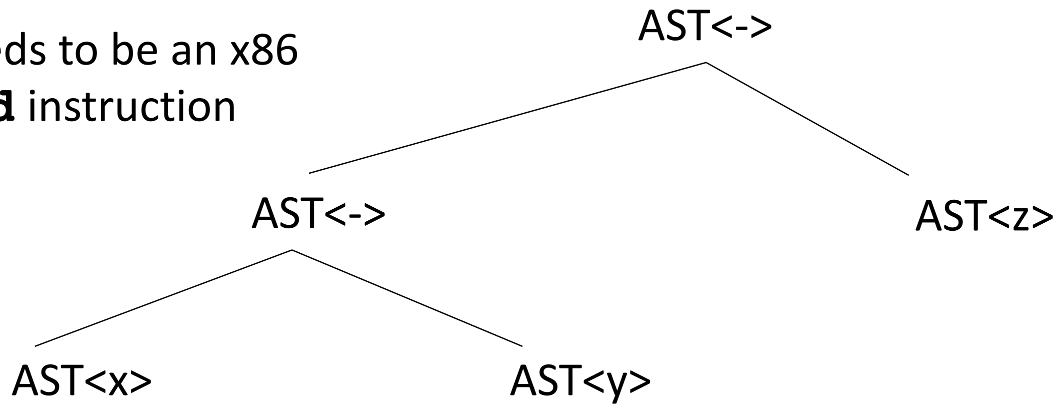
Evaluate an AST by doing a post order traversal

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    “”
```

What if you cannot evaluate it?
What else might you do?

needs to be an x86
addss instruction

needs to be an x86
add instruction




```
int x;
int y;
float z;
float w;
w = x - y - z
```

How does this change things?

Is this all?

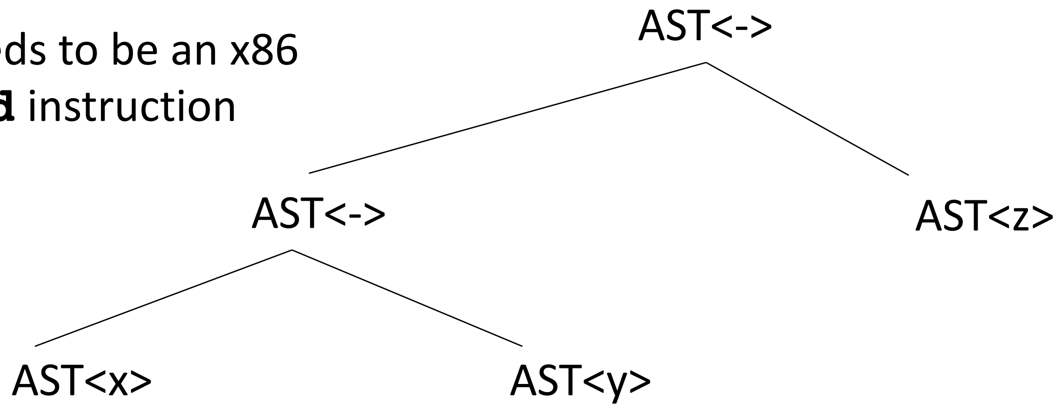
Evaluate an AST by doing a post order traversal

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
      |    “”
```

```
int x;
int y;
float z;
float w;
w = x - y - z
```

needs to be an x86 **`addss`** instruction

needs to be an x86 **`add`** instruction



Lets do some experiments.

What should 5 - 5.0 be?

Is this all?

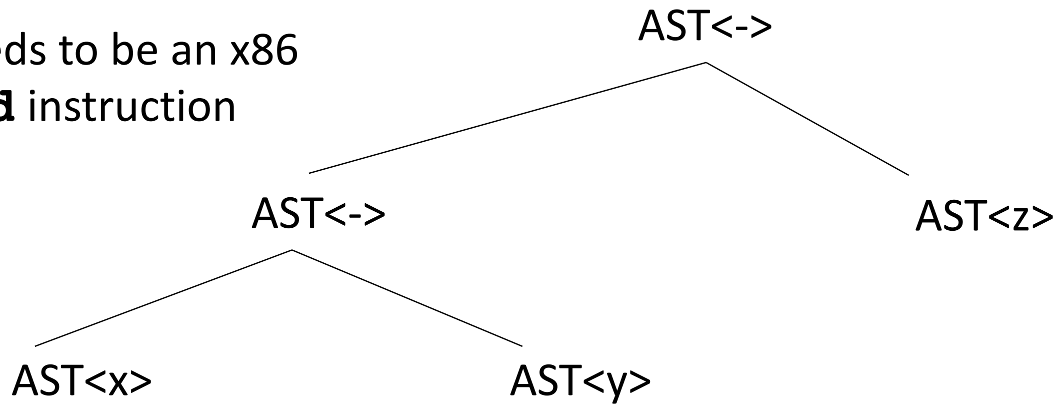
Evaluate an AST by doing a post order traversal

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    “”
```

```
int x;
int y;
float z;
float w;
w = x - y - z
```

needs to be an x86
addss instruction

needs to be an x86
add instruction



Is this all?

Lets do some experiments.

What should 5 - 5.0 be?

but

`addss r1 r2`

interprets both registers
as floats

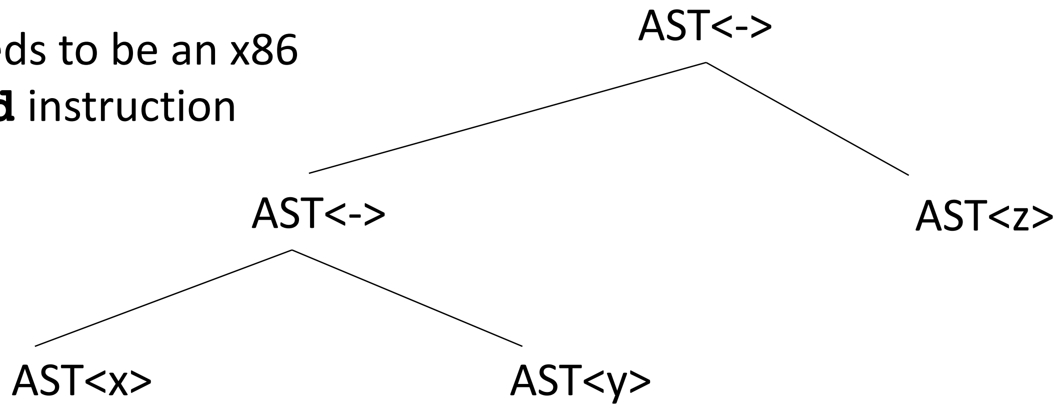
Evaluate an AST by doing a post order traversal

```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |    ""
```

```
int x;
int y;
float z;
float w;
w = x - y - z
```

needs to be an x86
addss instruction

needs to be an x86
add instruction



But the binary of 5 is 0b101
the float value of 0b101 is 7.00649232162e-45

We cannot just subtract them!

Is this all?

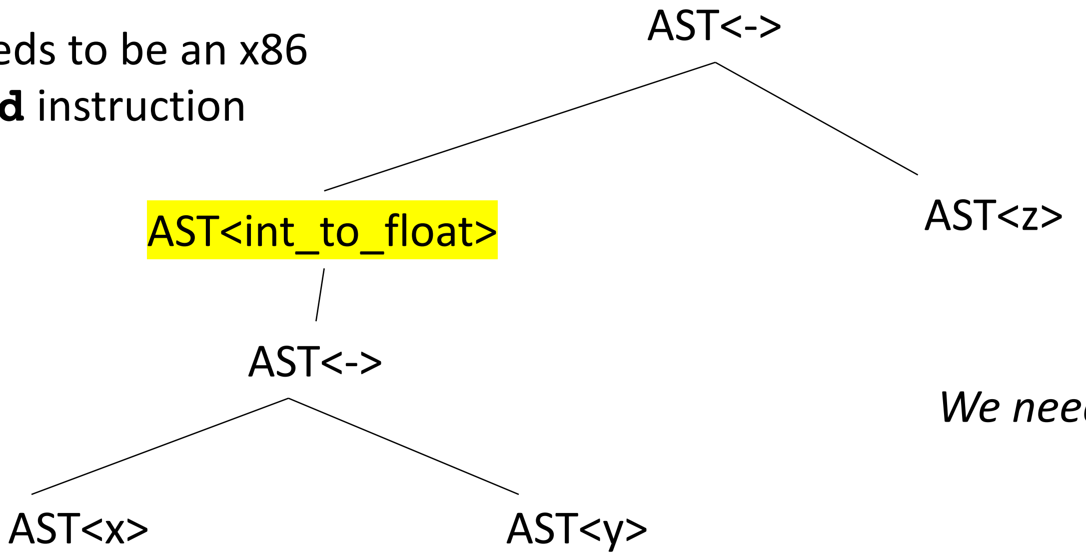
Evaluate an AST by doing a post order traversal

```
Expr   ::= NUM Expr2
Expr2  ::= MINUS NUM Expr2
        |    ""
```

```
int x;
int y;
float z;
float w;
w = x - y - z
```

needs to be an x86
addss instruction

needs to be an x86
add instruction



We need to make sure our operands are in the right format!

Type systems

- Given a language a type system defines:
  - The primitive (base) types in the language
  - How the types can be converted to other types
    - implicitly or explicitly
  - How the user can define new types

Type checking and inference

- Check a program to ensure that it adheres to the type system

Especially interesting for compilers as a program given in the type system for the input language must be translated to a type system for lower-level program

See everyone on Monday

- Study for the test!