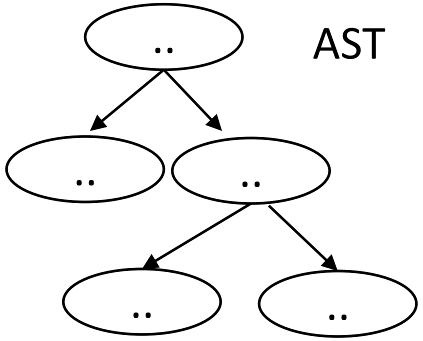
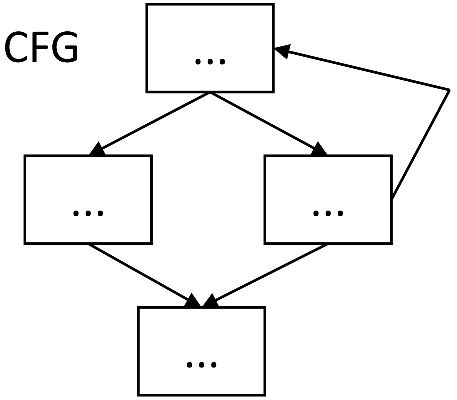
CSE110A: Compilers



Topics:

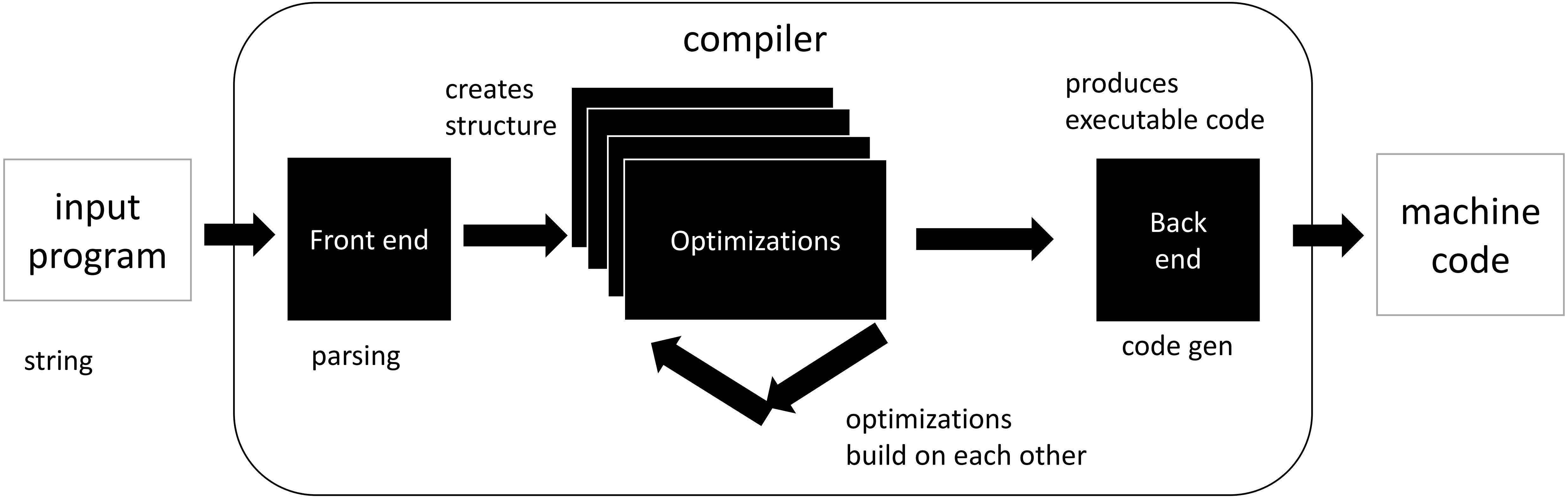
- *Module 3: Intermediate representations*
  - *Intro to intermediate representations*
  - *ASTs*



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
```

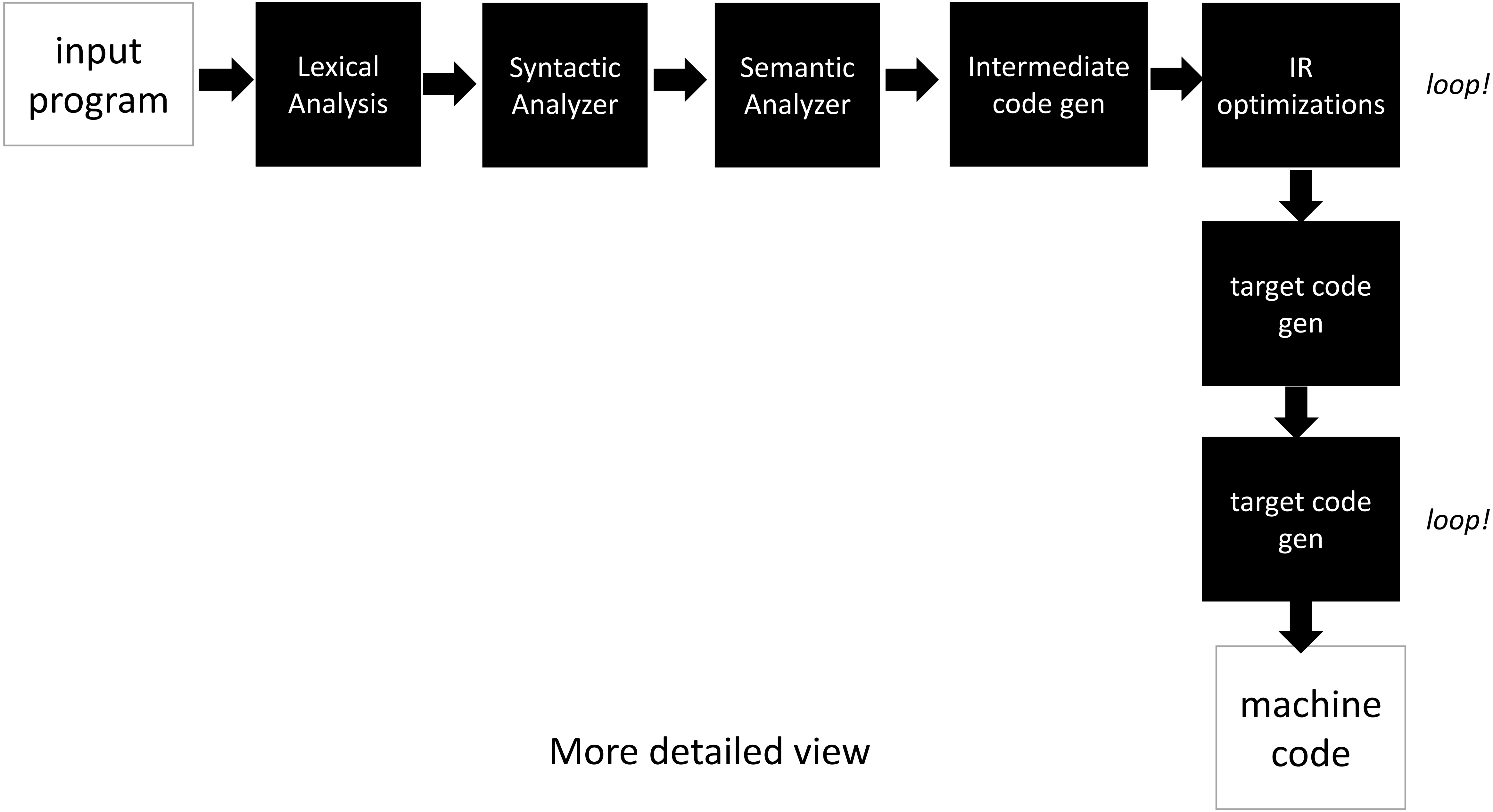
Compiler Architecture



Medium detailed view

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

More detailed view



input program

Lexical Analysis

Syntactic Analyzer

Semantic Analyzer

Intermediate code gen

IR optimizations

loop!

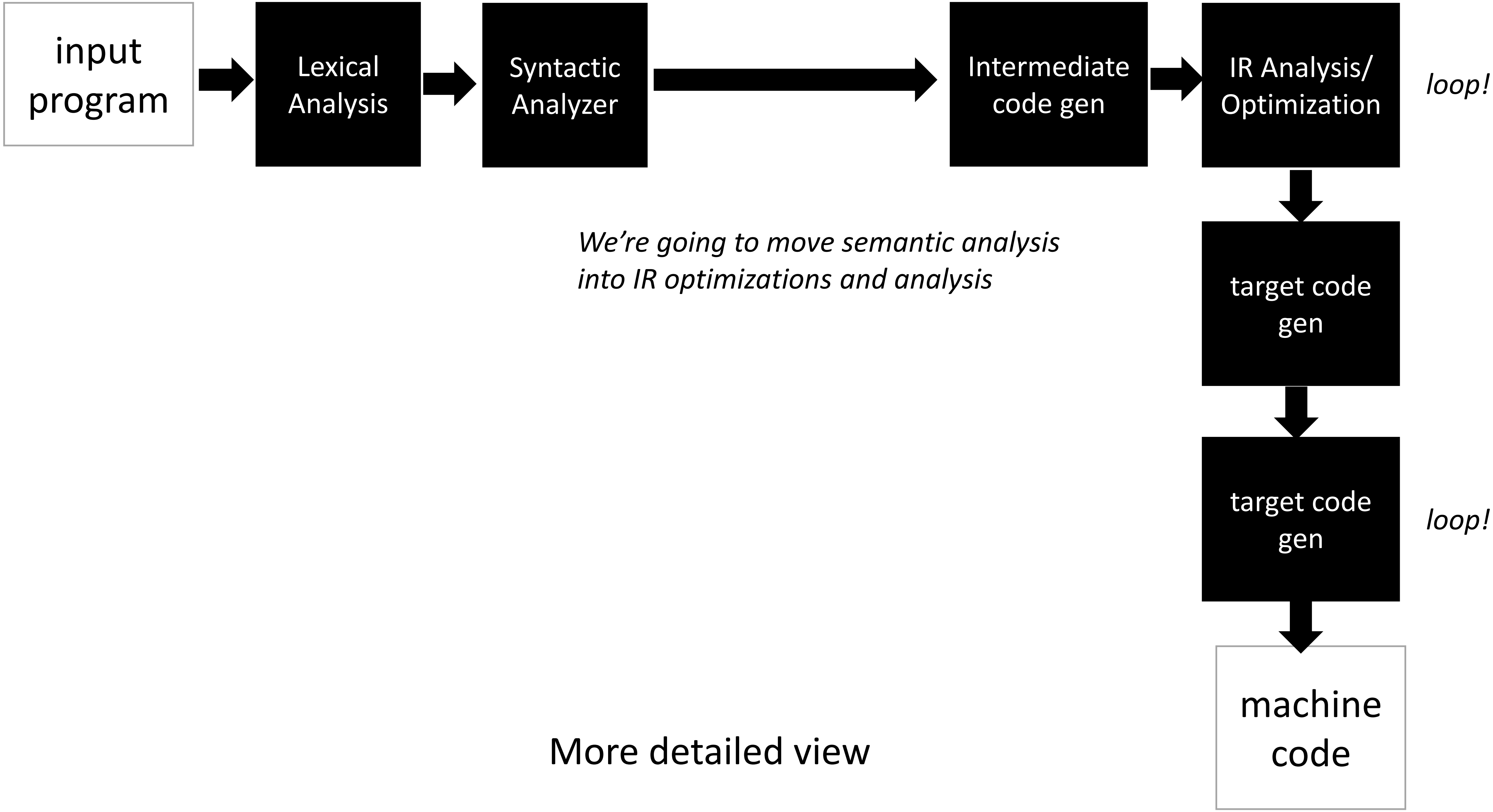
target code gen

target code gen

loop!

machine code

More detailed view



input program

Lexical Analysis

Syntactic Analyzer

Intermediate code gen

IR Analysis/ Optimization

loop!

target code gen

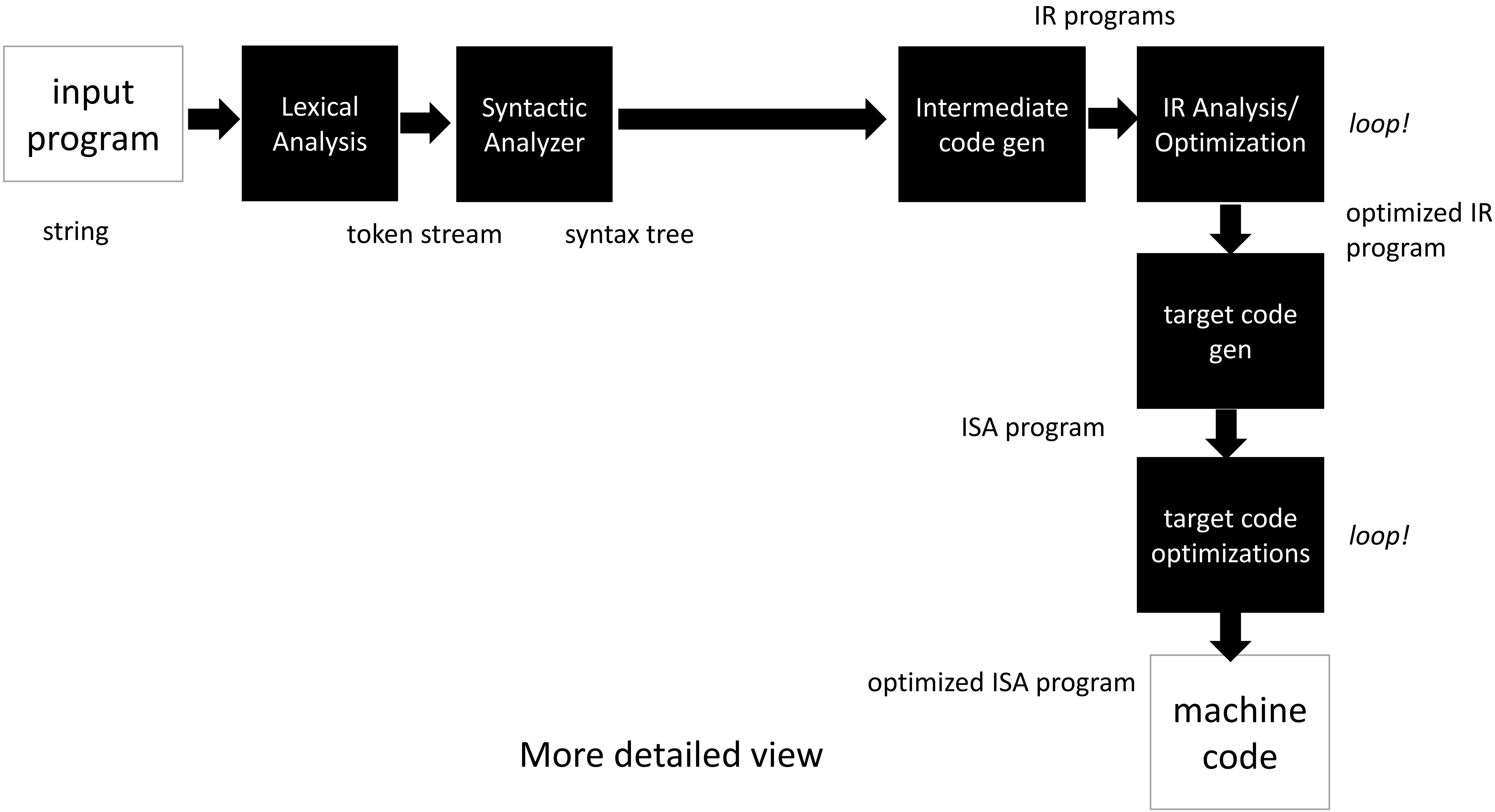
target code gen

loop!

machine code

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

More detailed view



input program

string

Lexical Analysis

token stream

Syntactic Analyzer

syntax tree

Intermediate code gen

IR programs

IR Analysis/ Optimization

loop!

optimized IR program

target code gen

ISA program

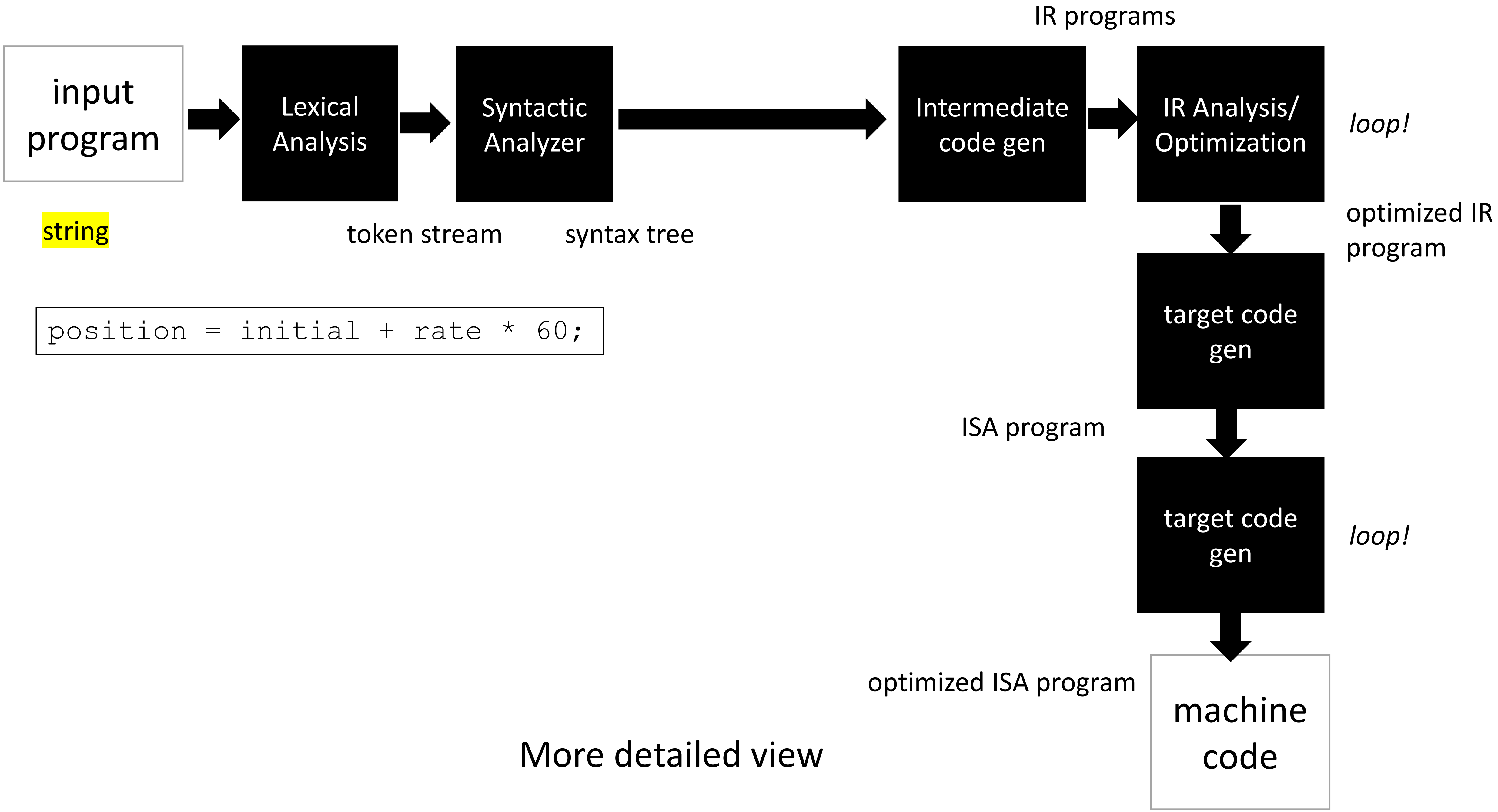
target code optimizations

loop!

optimized ISA program

machine code

More detailed view



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IR Analysis/ Optimization

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optimized IR program

target code gen

ISA program

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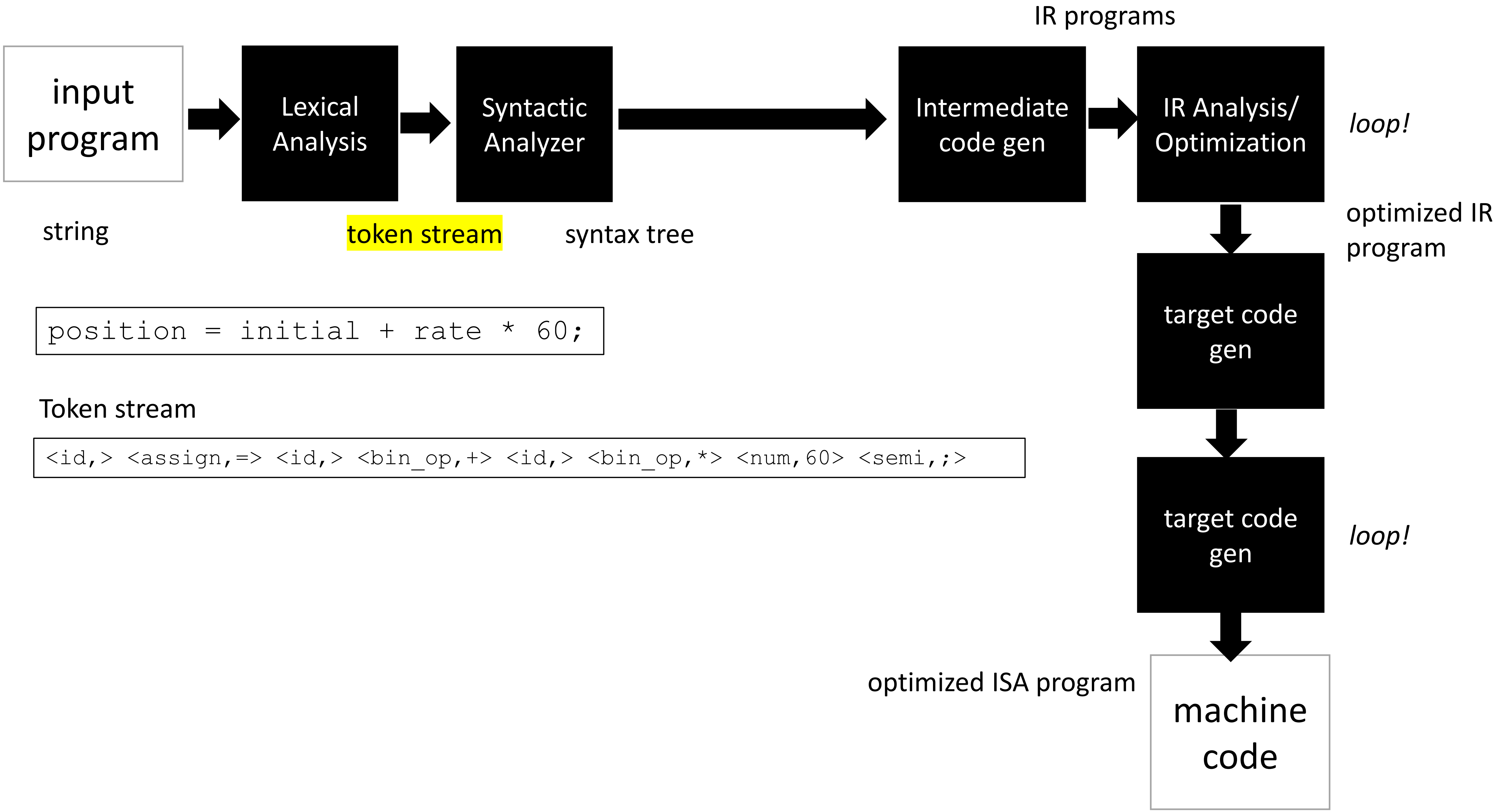
loop!

optimized ISA program

machine code

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

More detailed view



IR programs

input program

Lexical Analysis

Syntactic Analyzer

Intermediate code gen

IR Analysis/ Optimization

loop!

string

token stream

syntax tree

optimized IR program

target code gen

target code gen

loop!

optimized ISA program

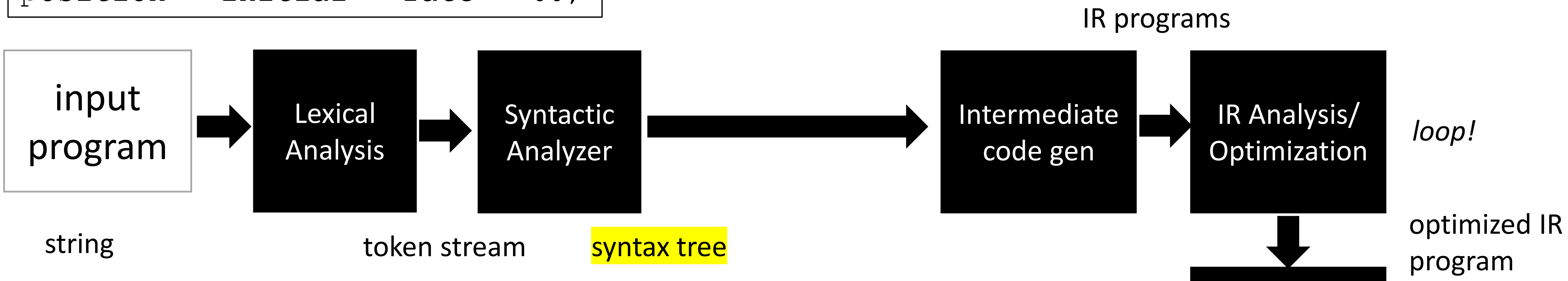
machine code

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

Token stream

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

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



IR programs

input program → Lexical Analysis → Syntactic Analyzer → Intermediate code gen → IR Analysis/ Optimization

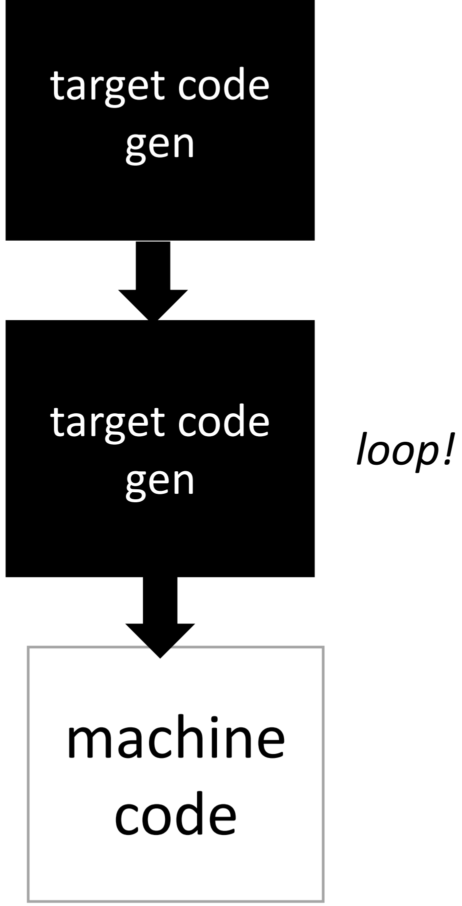
loop!

string

token stream

syntax tree

optimized IR program



target code gen

target code gen

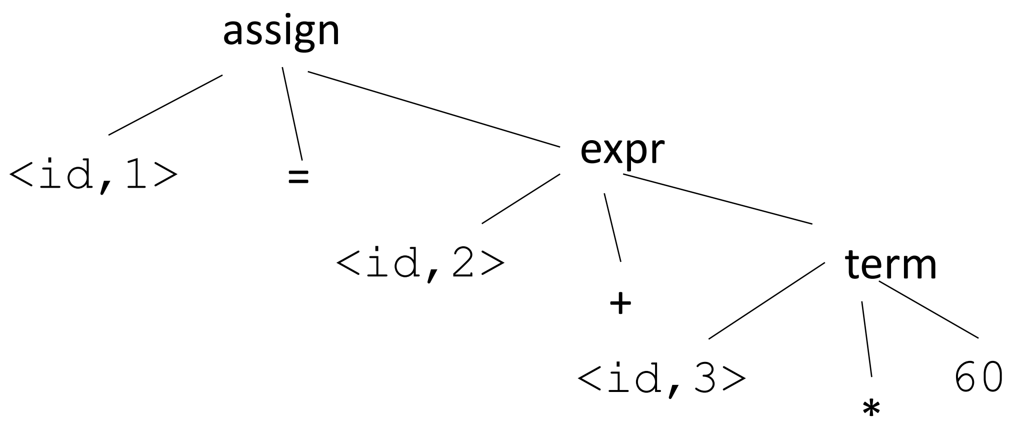
loop!

machine code

Token stream

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

Syntax tree



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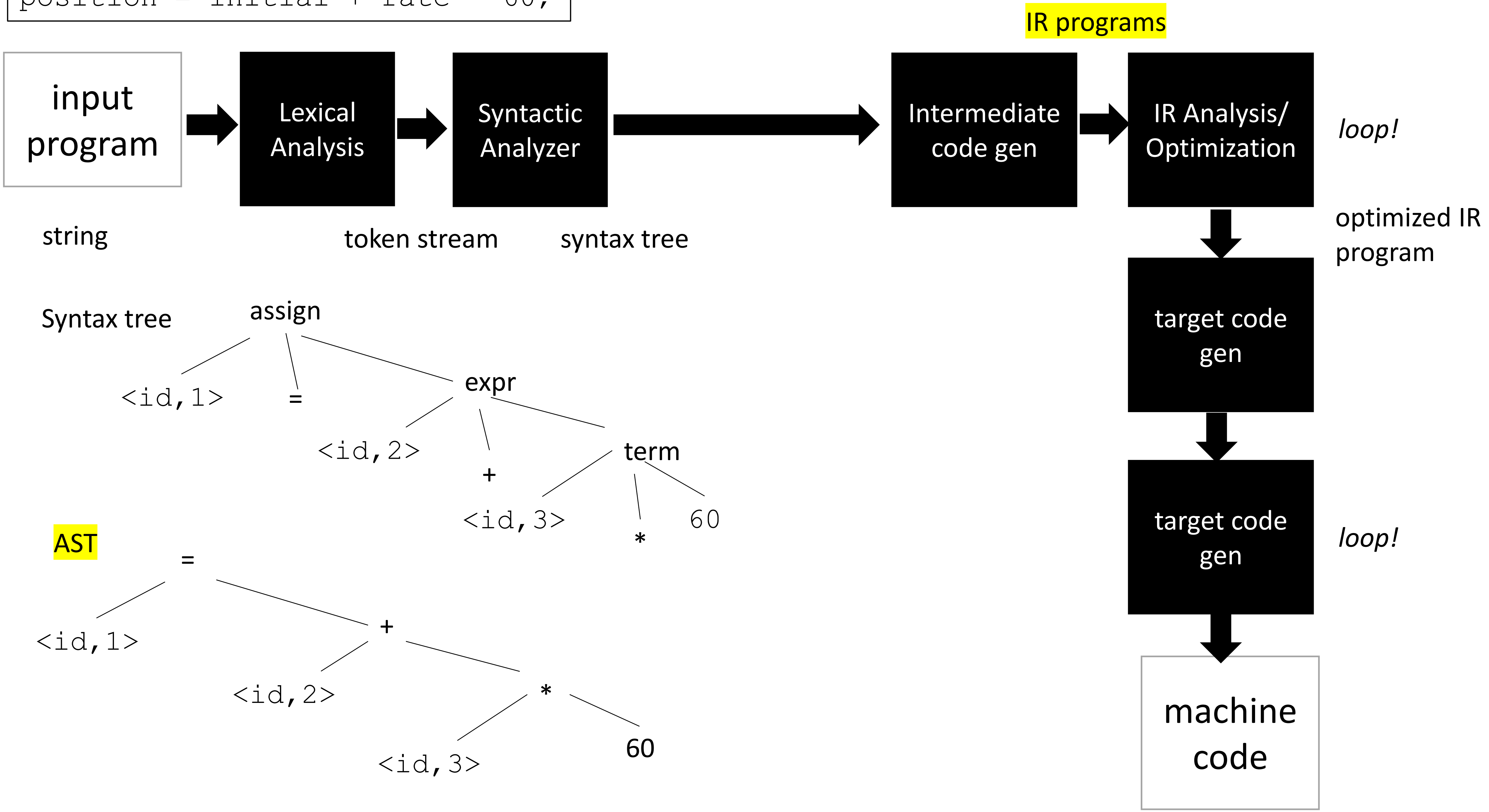

IR programs

input program

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Intermediate code gen

IR Analysis/ Optimization

loop!

string

token stream

syntax tree

optimized IR program

target code gen

target code gen

loop!

machine code

Syntax tree

assign

<id,1>

=

expr

<id,2>

+

term

<id,3>

*

60

AST

=

<id,1>

+

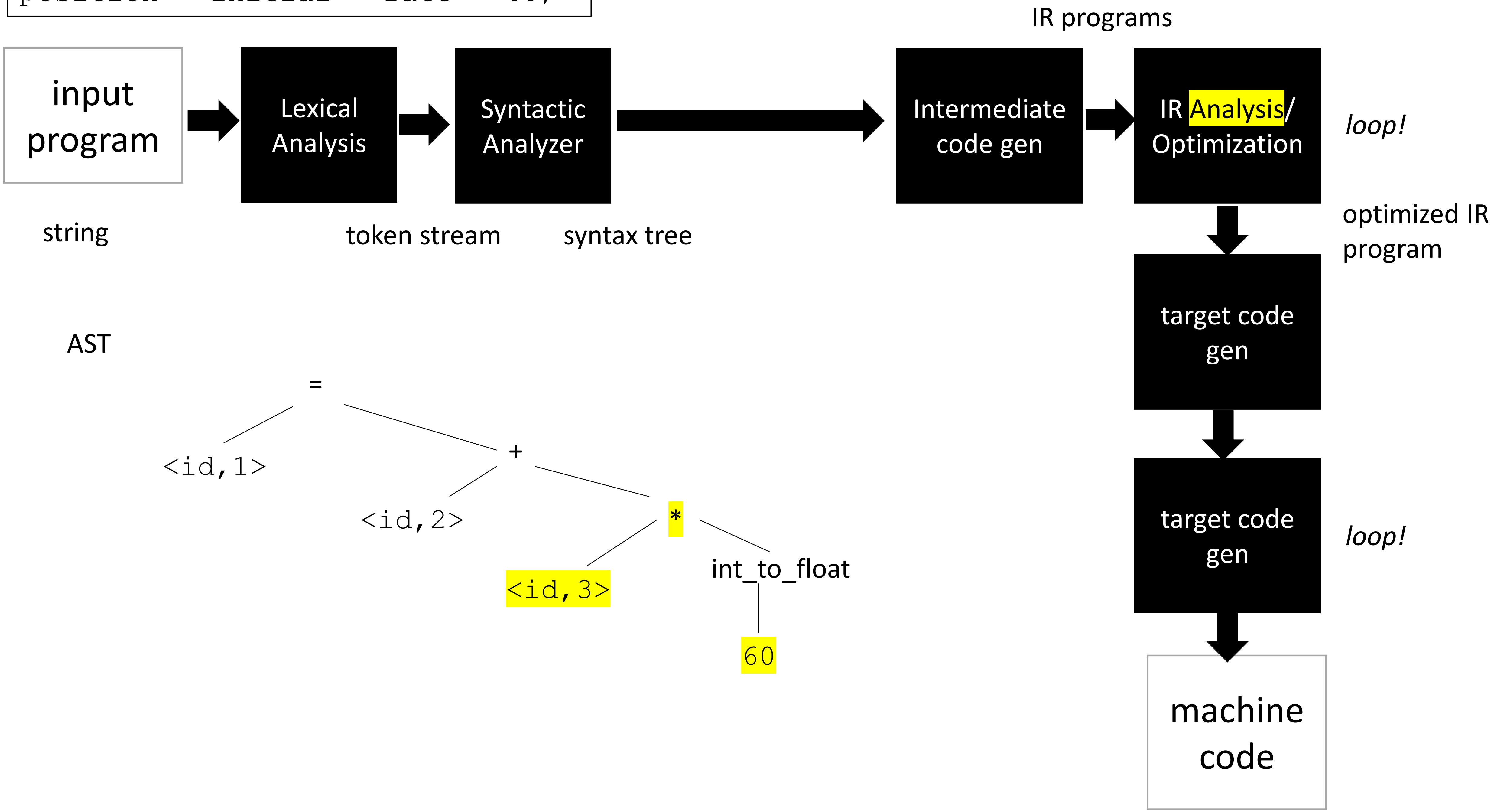
<id,2>

*

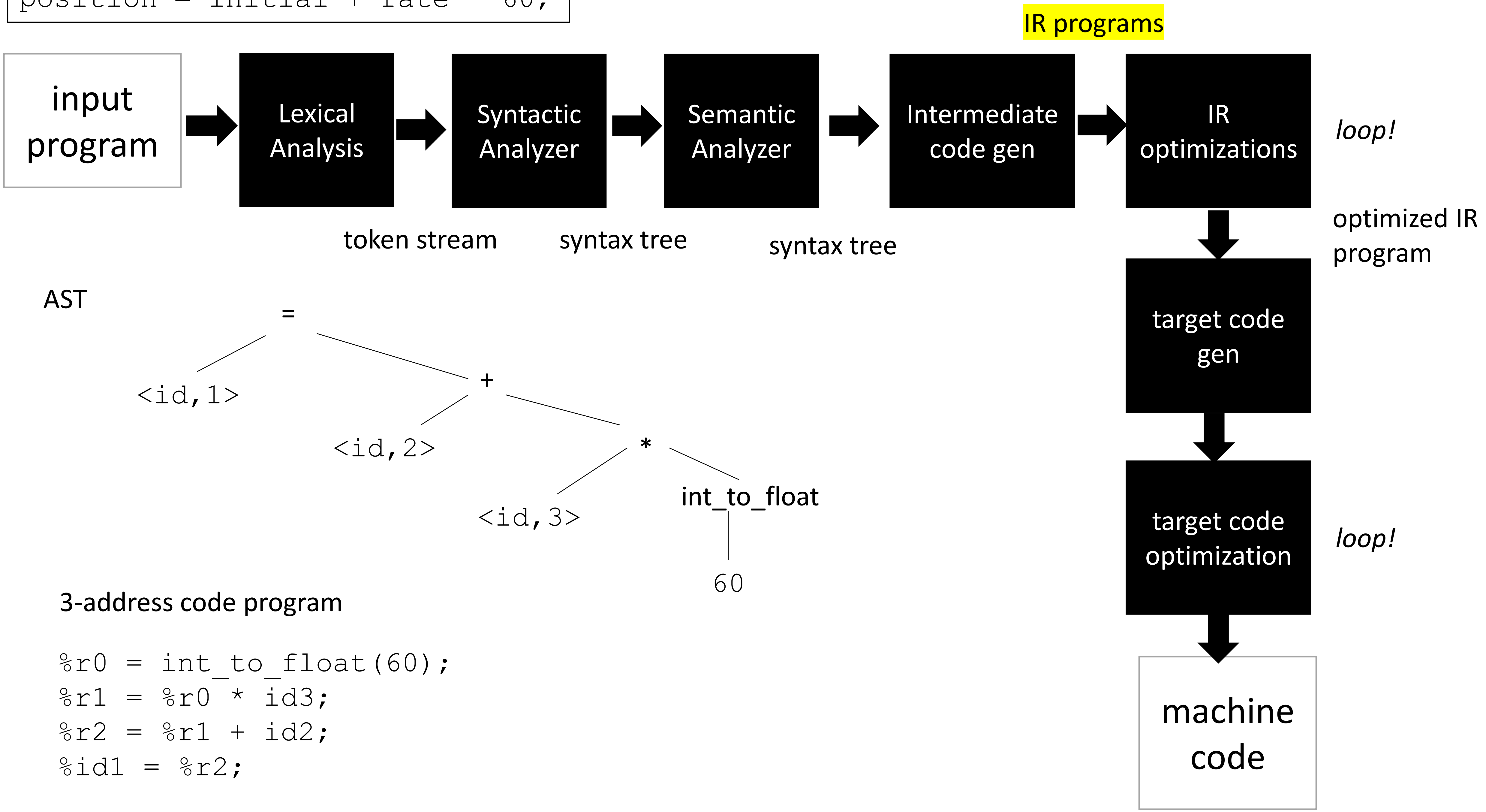
<id,3>

60

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



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



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 or 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

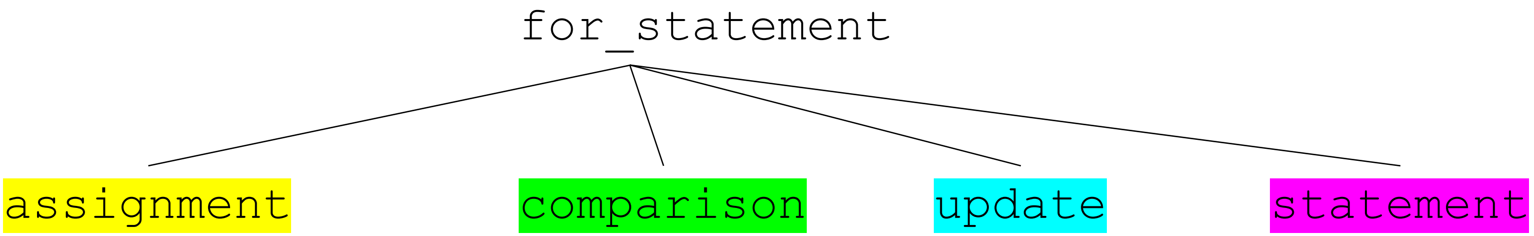
- Several forms:
    - tree - abstract syntax tree
    - graphs - control flow graph
    - linear program - 3 address code

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

Example: loop unrolling

```
for (i = 0; i < 102; i = i + 1) {
   x = x + 1;
   i = i + 1;
   x = x + 1;
   i = i + 1;
   x = x + 1;
}
```

Example: loop unrolling



for_statement

assignment

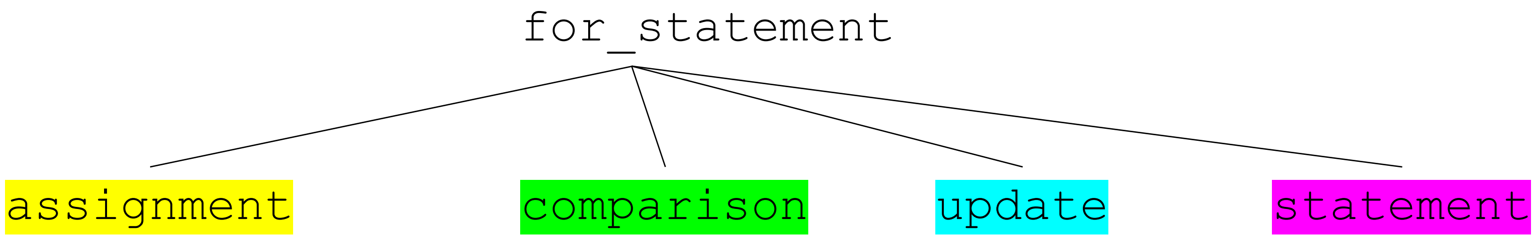
comparison

update

statement

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

Example: loop unrolling



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

Check:

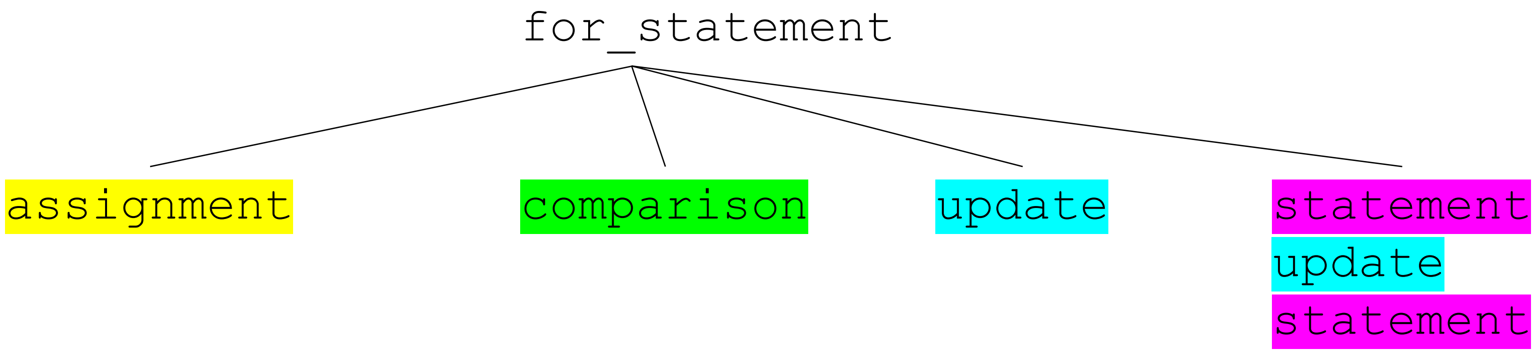
1. Find iteration variable by examining assignment, comparison and update.

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

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for (i = 0; i < 100; i = i + 1) {
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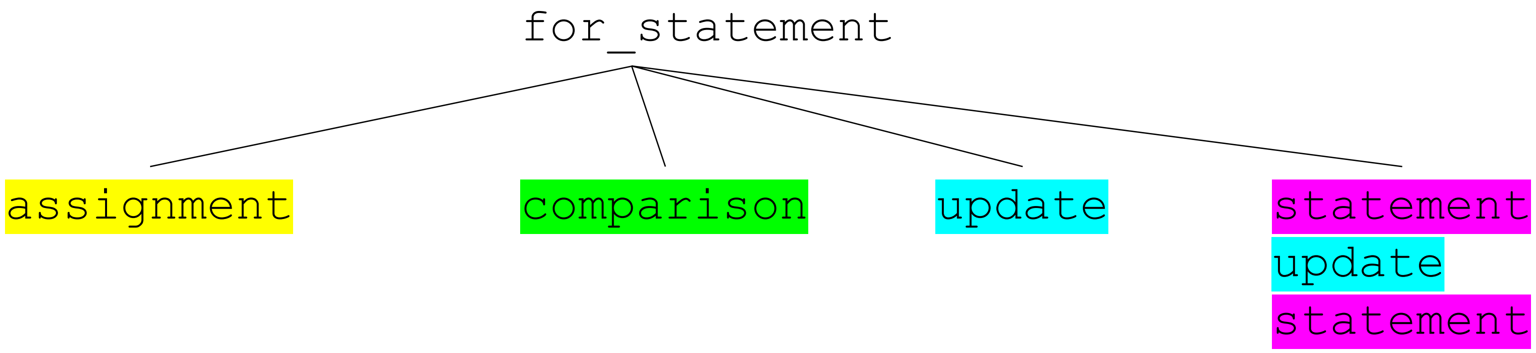
Perform optimization

copy statement and put an update before it

Example: loop unrolling



```
for (i = 0; i < 100; i = i + 1) {
   x = x + 1;
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}
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4. check that comparison goes around an even number of times.

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`

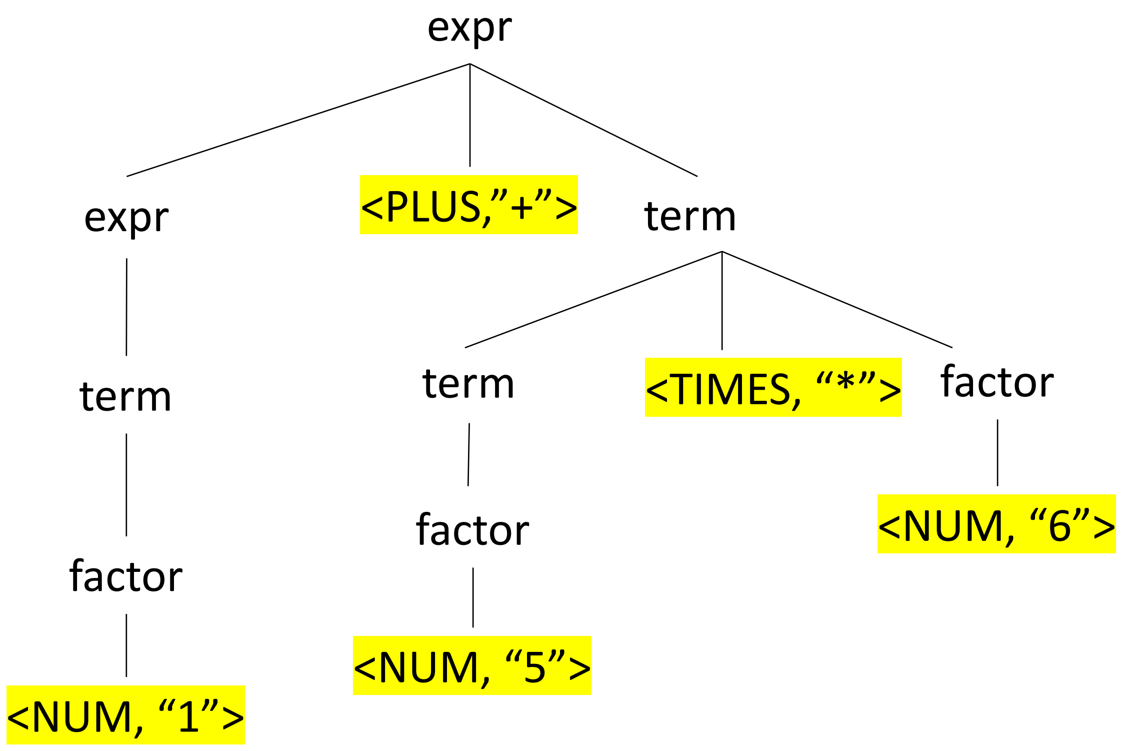
We'll start by looking at a parse tree:

Operator	Name	Productions

+	`expr`	`: expr PLUS term`
		`| term`

*	`term`	`: term TIMES factor`
		`| factor`

()	`factor`	`: LPAREN expr RPAREN`
		`| NUM`



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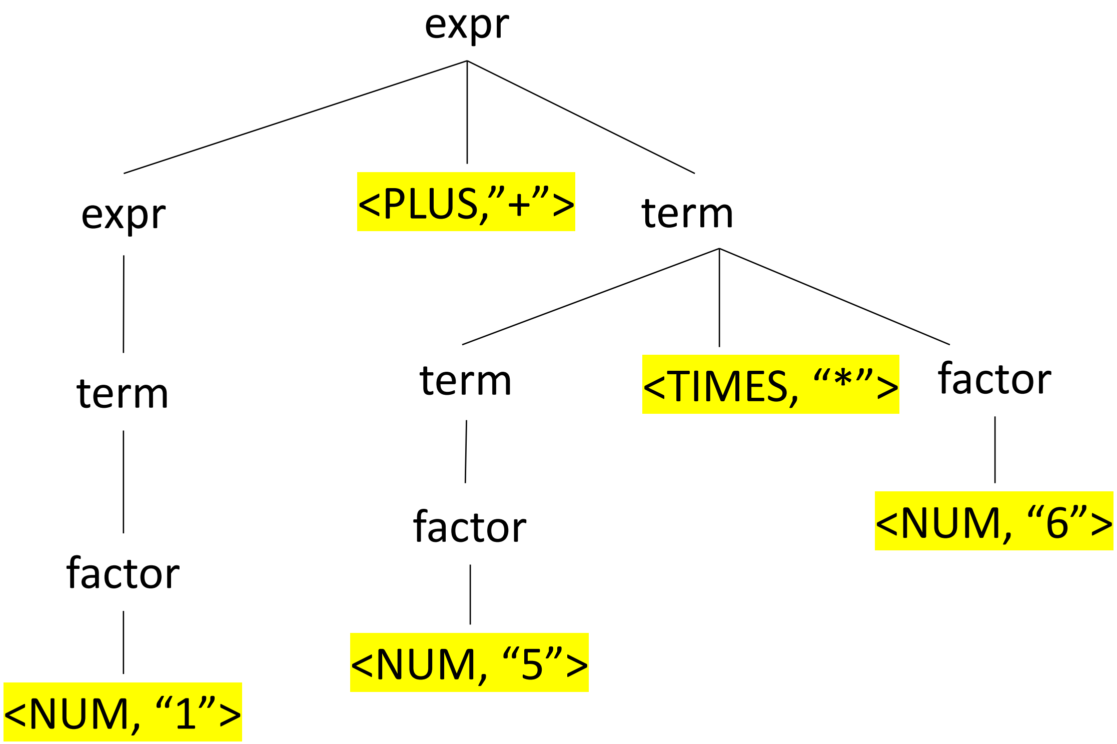

What are leaves?

What is an AST?

`input: 1+5*6`

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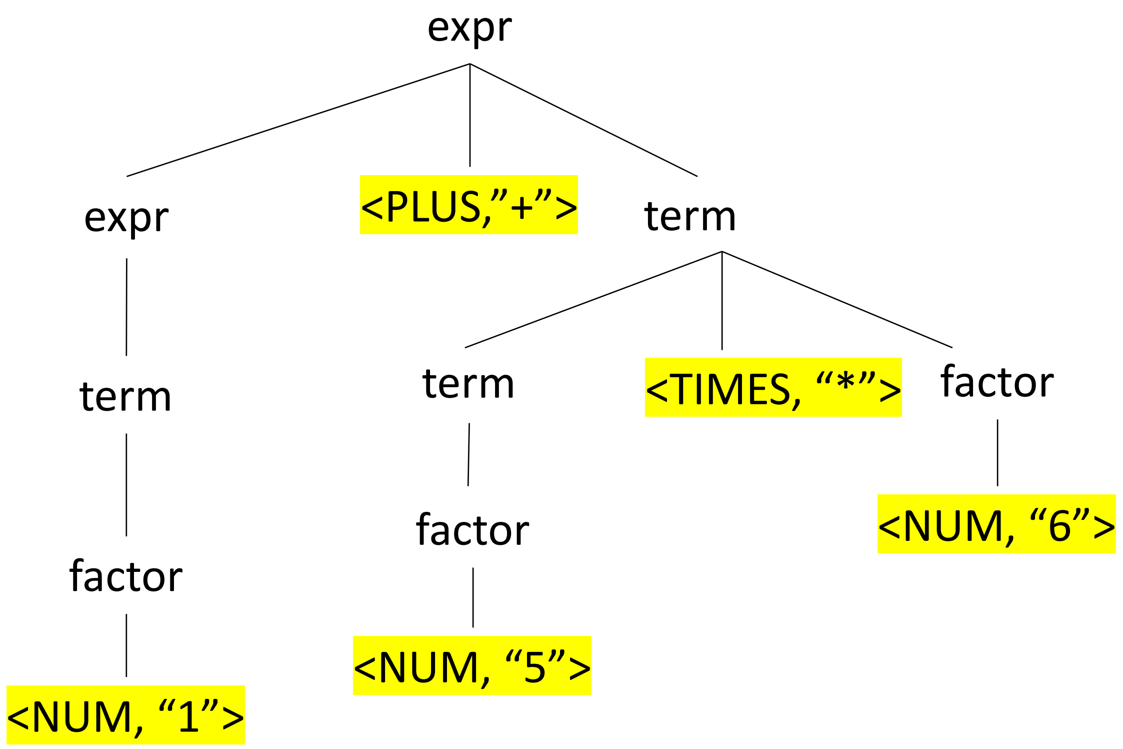

What are leaves? lexemes

What is an AST?

`input: 1+5*6`

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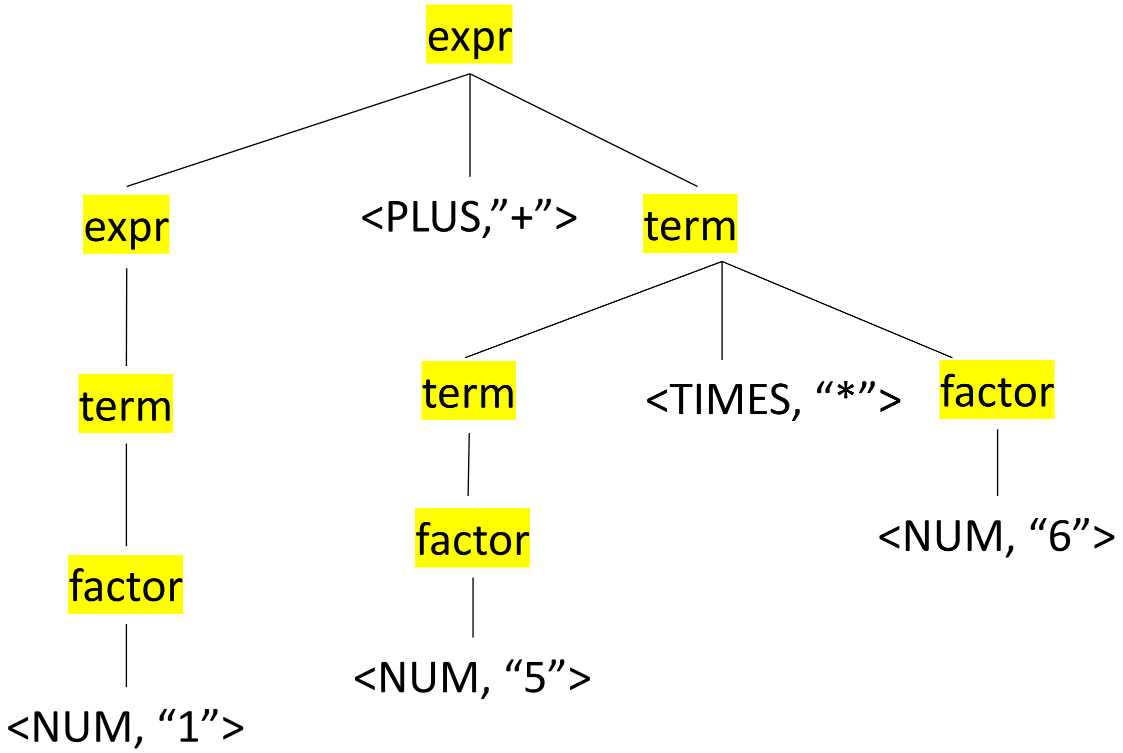


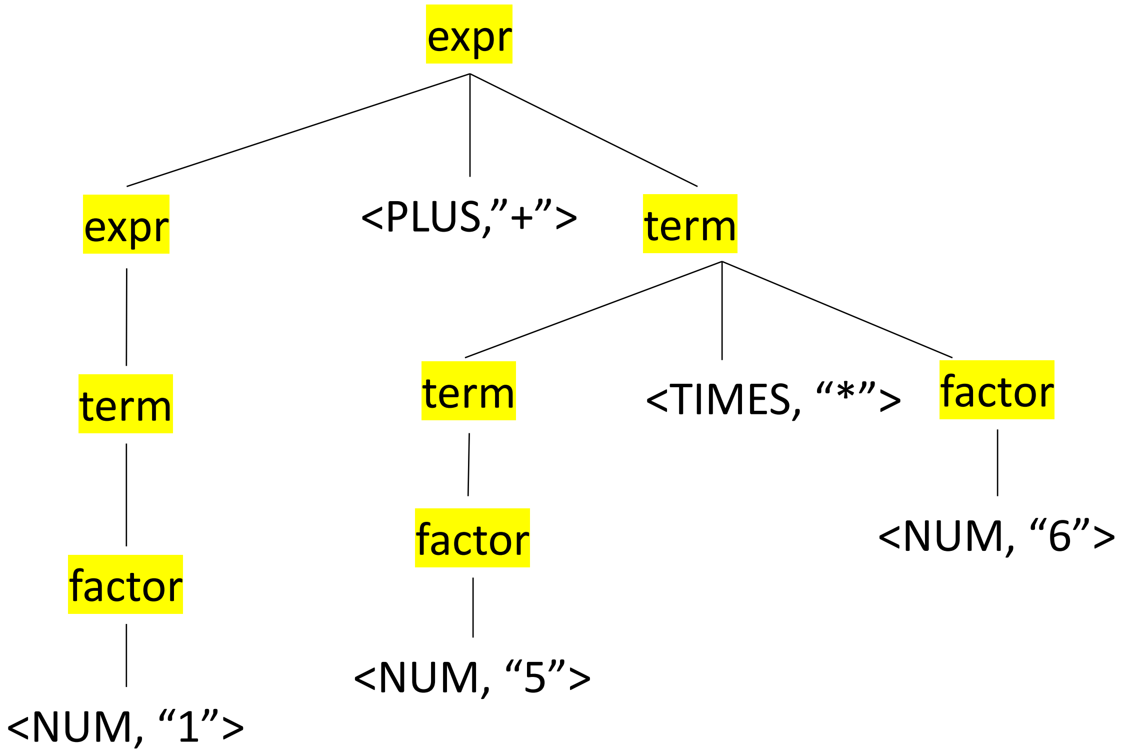
What are nodes?

What is an AST?

input: 1+5*6

We'll start by looking at a parse tree:

Operator	Name	Productions
+	expr	: expr PLUS term | term
*	term	: term TIMES factor | factor
()	factor	: LPAREN expr RPAREN | NUM



What are nodes? non-terminals

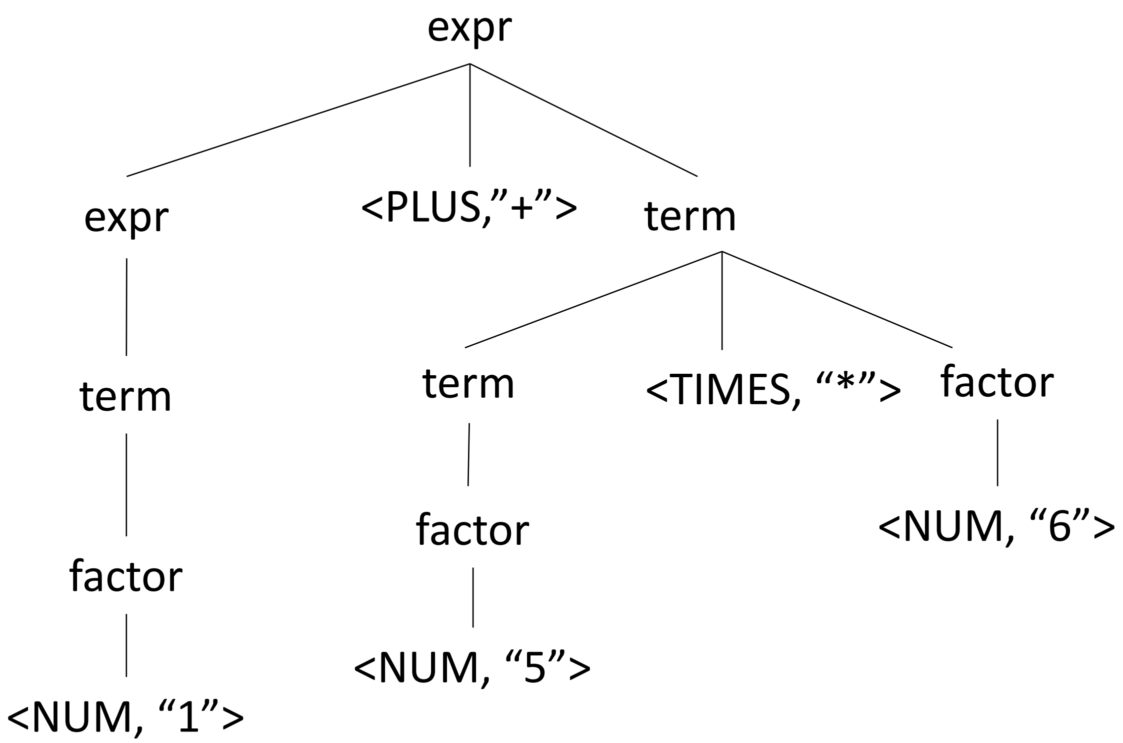
What is an AST?

Parse trees are defined by the grammar

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

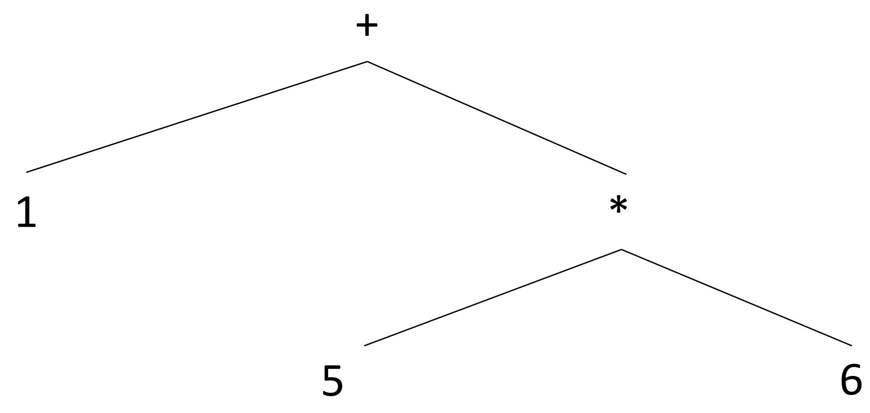
Parse trees are often not explicitly constructed. We use them to visualize the parsing computation

`input: 1+5*6`



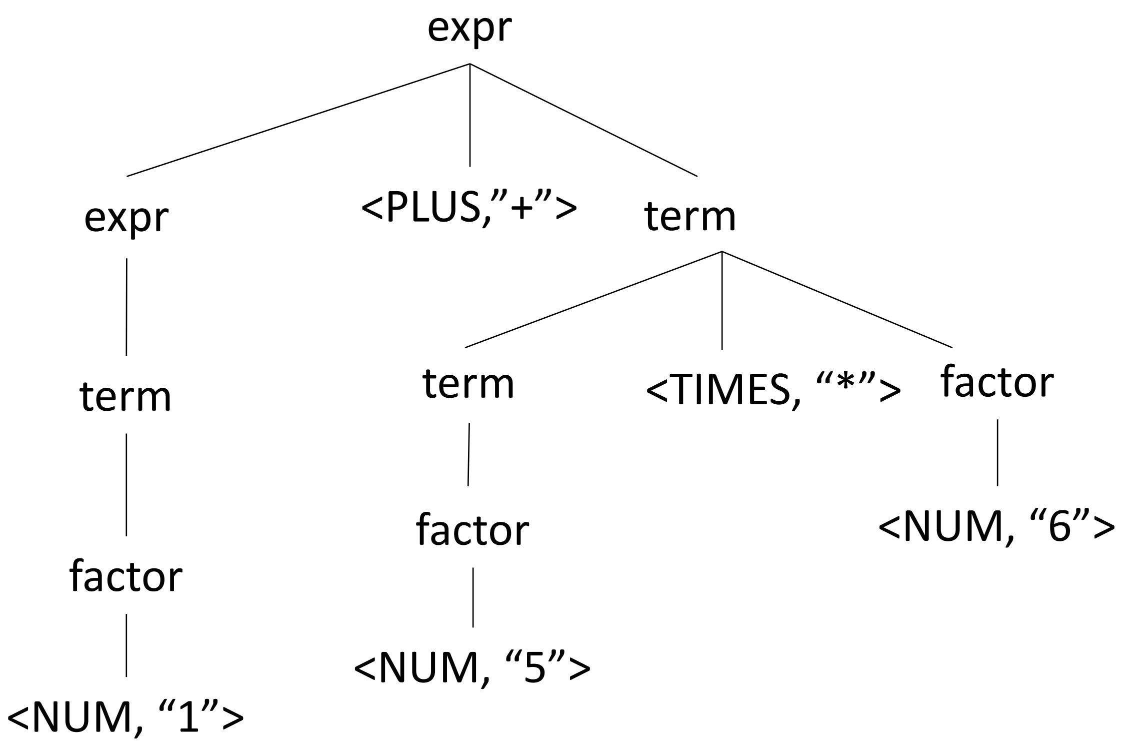
What is an AST?

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



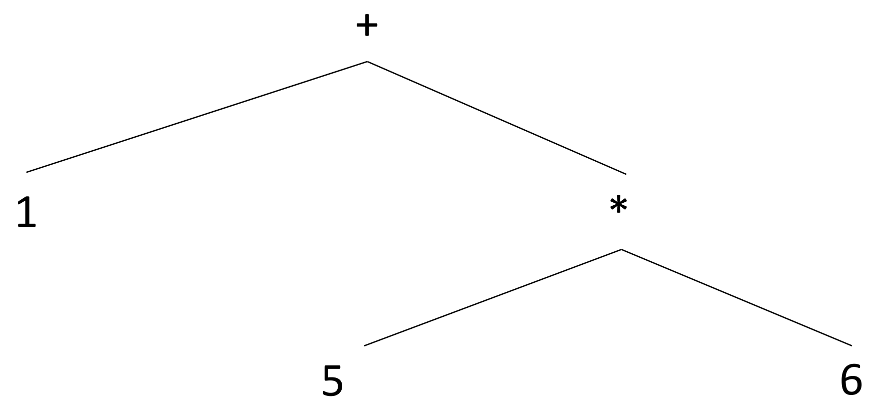
AST

What are some differences?

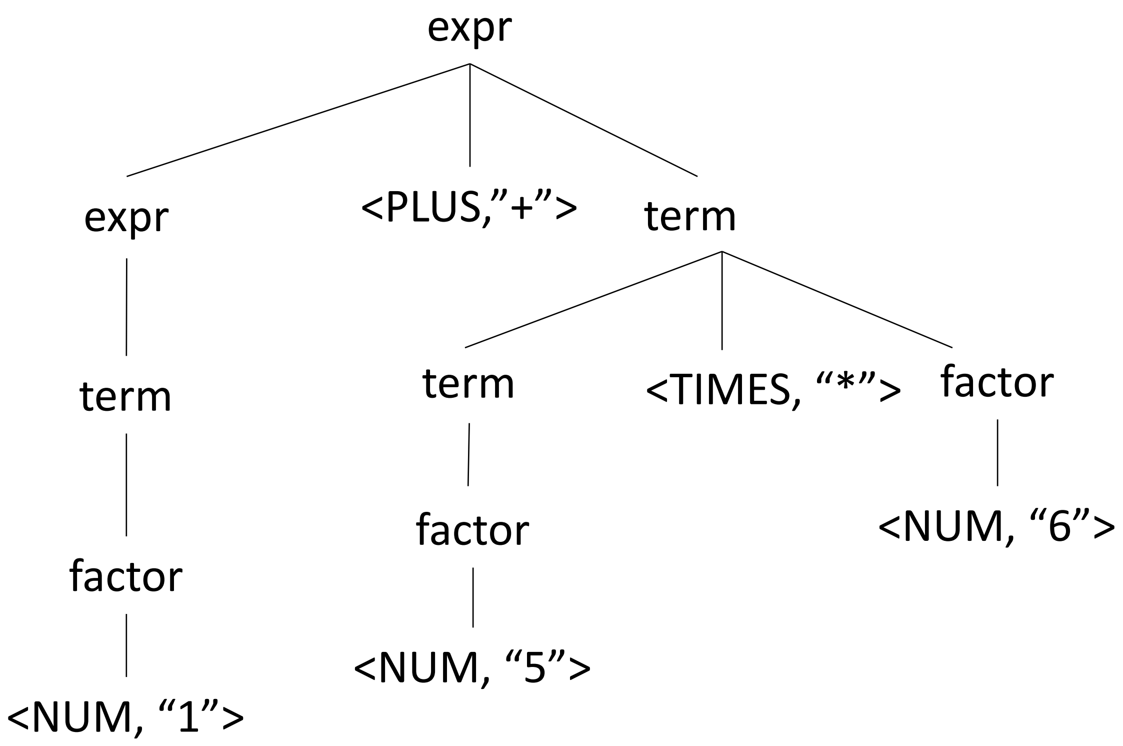


What is an AST?

`input: 1+5*6`



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?

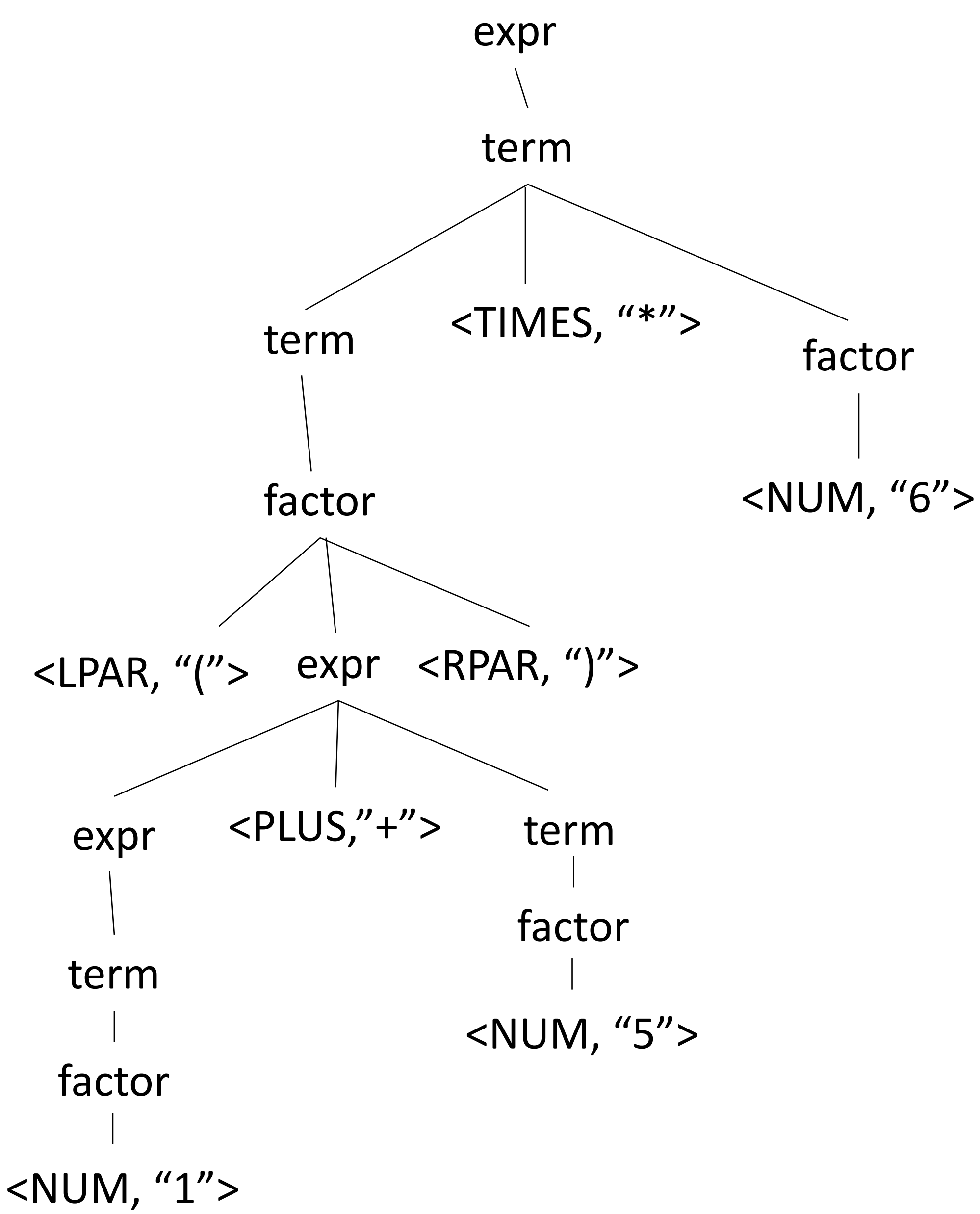
Operator	Name	Productions

+	`expr`	`: expr PLUS term`
		`| term`

*	`term`	`: term TIMES factor`
		`| factor`

()	`factor`	`: LPAR expr RPAR`
		`| NUM`

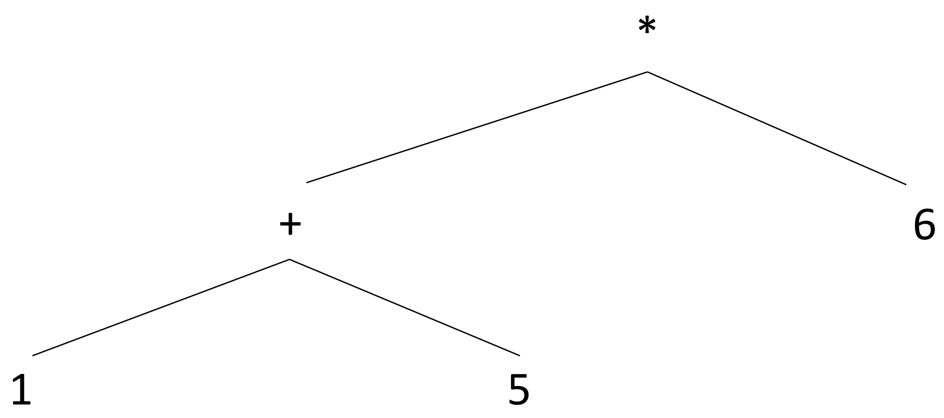
`input: (1+5)*6`



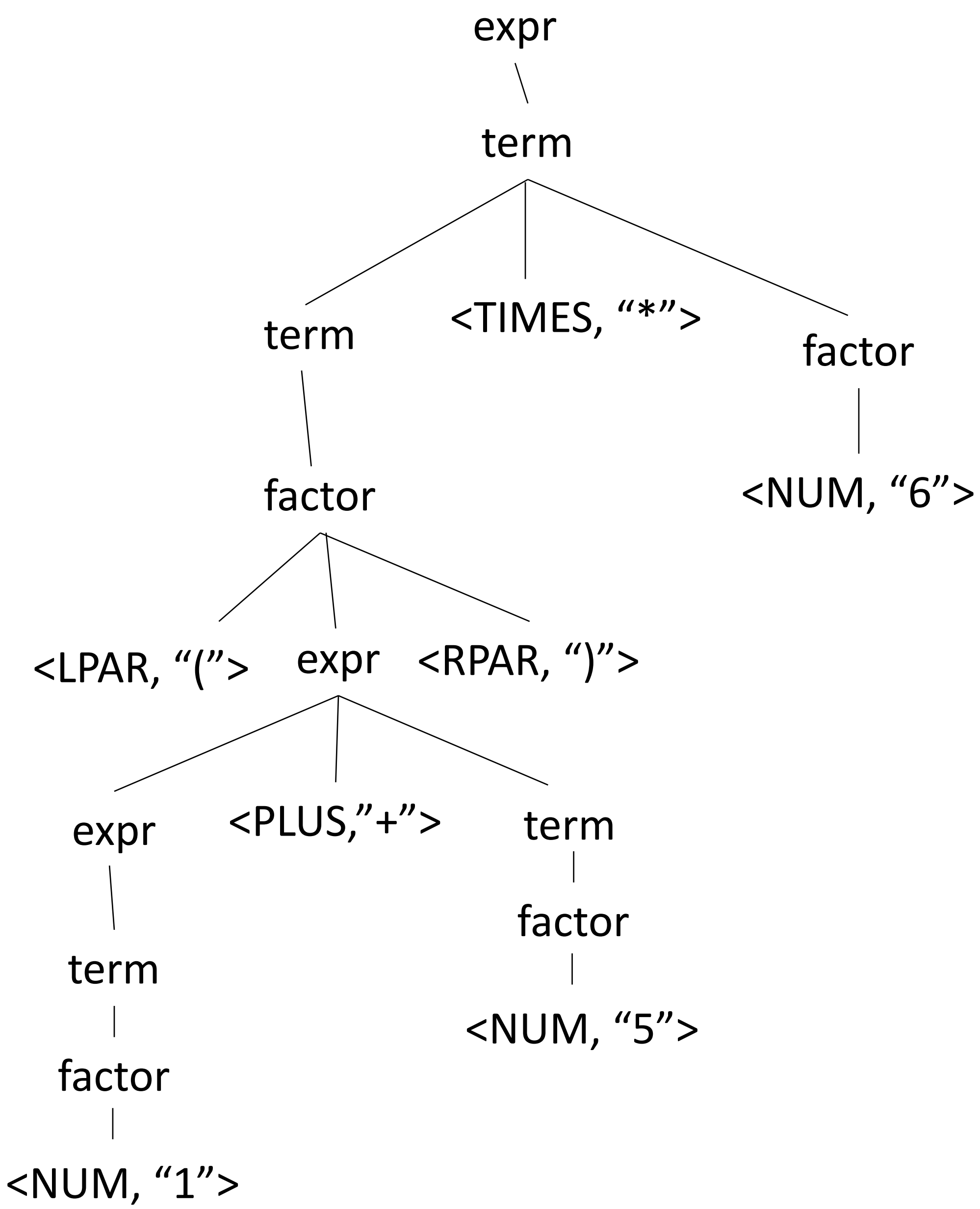
Example

`input: (1+5)*6`

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 (`+`, `*`)

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

```
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)
```

```
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 a parser

Parser actions

- Like token actions: perform an action each time a production option is matched.

- Typically performed after the entire production action is matched

- Can be useful for catching errors early as well.

Example

Say we are matched the statement:
`int x;`

- `SymbolTable ST;`

Parser actions would be written like this

```
                     $1   $2   $3
declare_statement ::= TYPE ID SEMI
{
  ST.insert($2, None);
}
```

*result of each symbol.
For a terminal it will be
the value*

always some way to refer to symbol value, e.g. an array

What values get returned from non-terminals?

```
1: Expr   ::= Expr ‘+’ Unit     {print $1}
2:          |   Expr ‘-’ Unit
3:          |   Unit
4: Unit   ::= ‘(‘ Expr ‘)’
5:          |    NUM
```

What does this print?

What values get returned from non-terminals?

```
1: Expr   ::= Expr '+' Unit      {print $1; return "expr"}
2:          |   Expr '-' Unit      {return "expr"}
3:          |   Unit               {...}
4: Unit   ::= '(' Expr ')'
5:          |    NUM
```

Each production rule
needs to return something

What values get returned from non-terminals?

building a calculator

```
1: Expr  ::= Expr ‘+’ Unit     {}
2:         |   Expr ‘-’ Unit     {}
3:         |   Unit              {}
4: Unit  ::= ‘(‘ Expr ‘)’      {}
5:         |    NUM              {}
```

What values get returned from non-terminals?

building a calculator

```
1: Expr  ::= Expr ‘+’ Unit     {return $1 + $3}
2:        |   Expr ‘-’ Unit     {return $1 - $3}
3:        |   Unit              {return $1}
4: Unit  ::= ‘(‘ Expr ‘)’      {return $2}
5:        |    NUM              {return $1}
```

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`
			`{}`
			`{}`
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```
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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
			{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)}

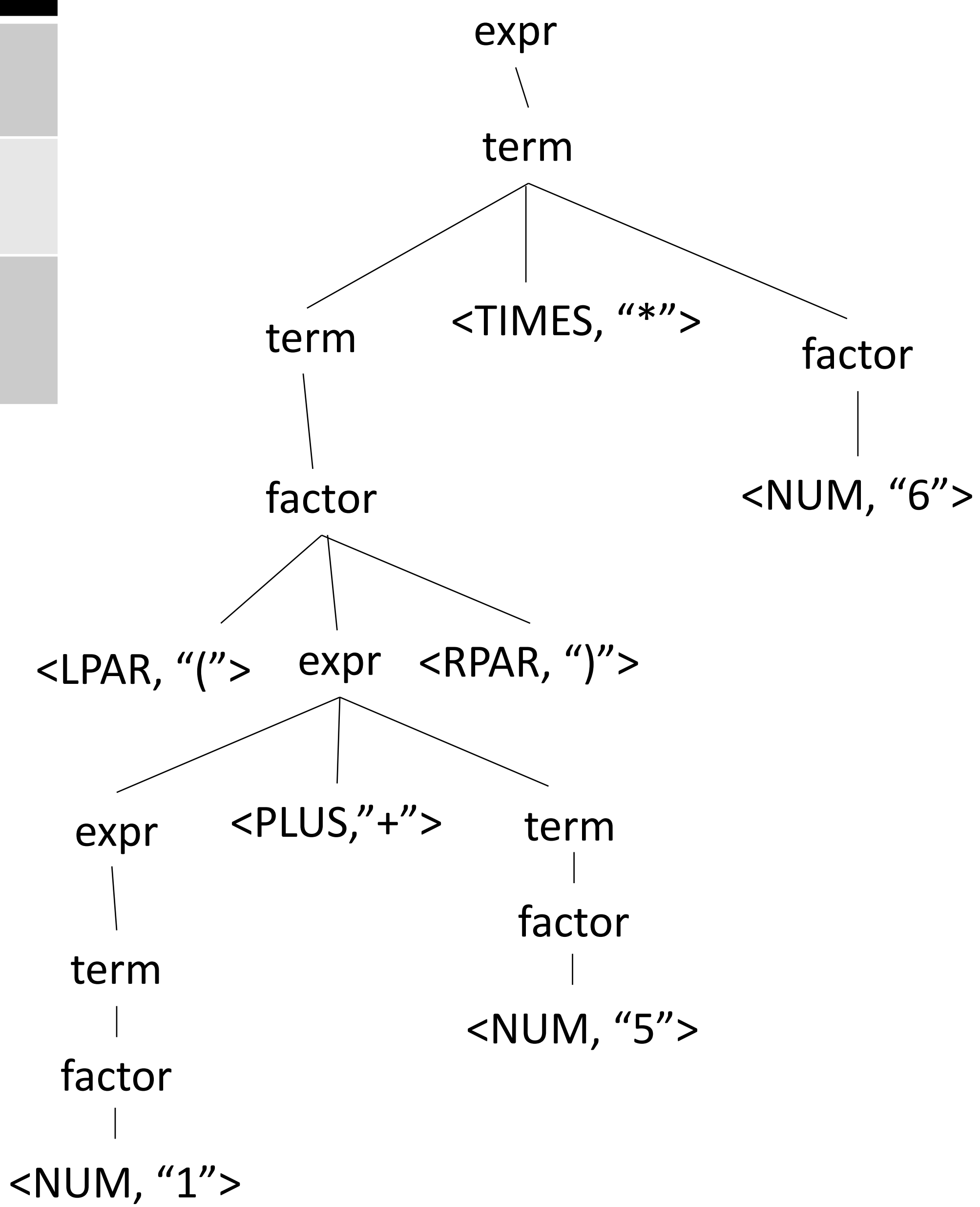
Name	Productions	Production action

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)}

input: (1+5)*6



Lets build the AST

AST<?>

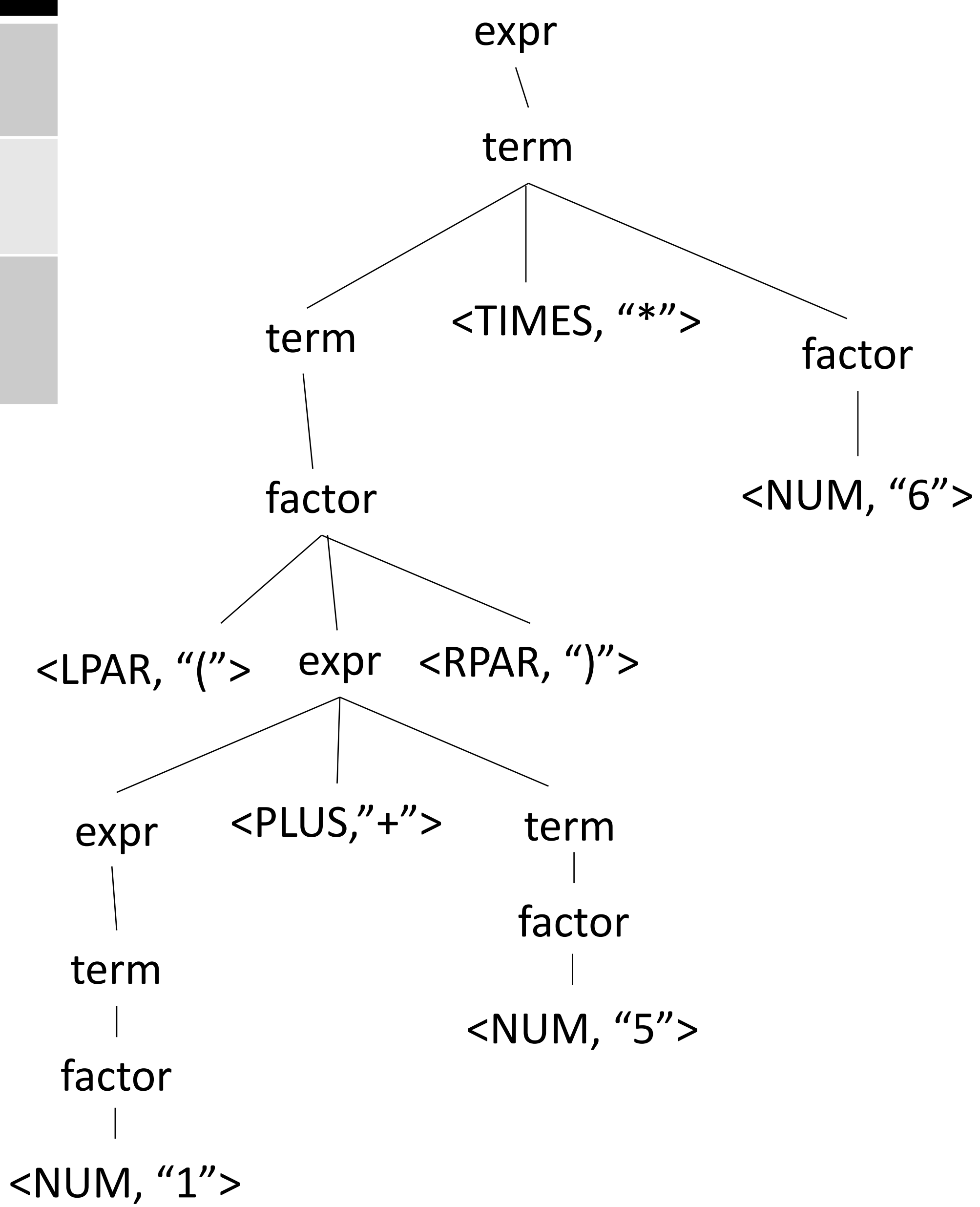
Name	Productions	Production action

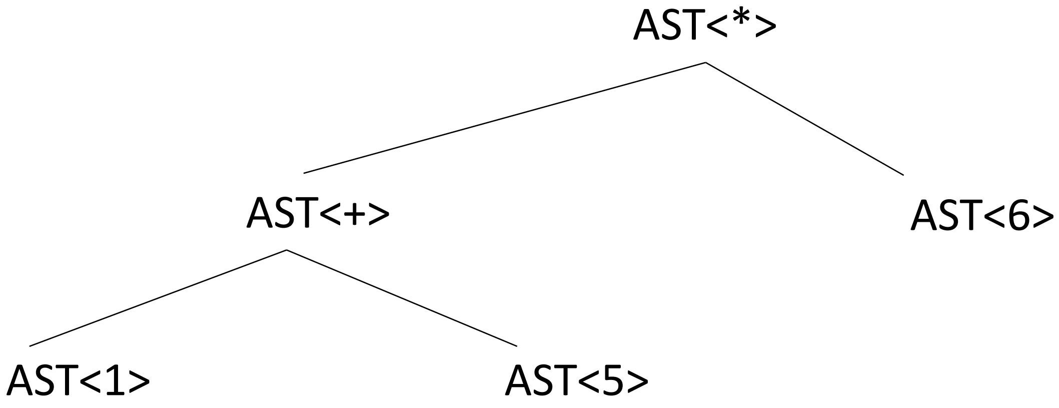
`expr`	`: expr PLUS term`
	`| term`
		`{return ASTAddNode($1,$3)}`
		`{return $1}`

`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)}`

`input: (1+5)*6`

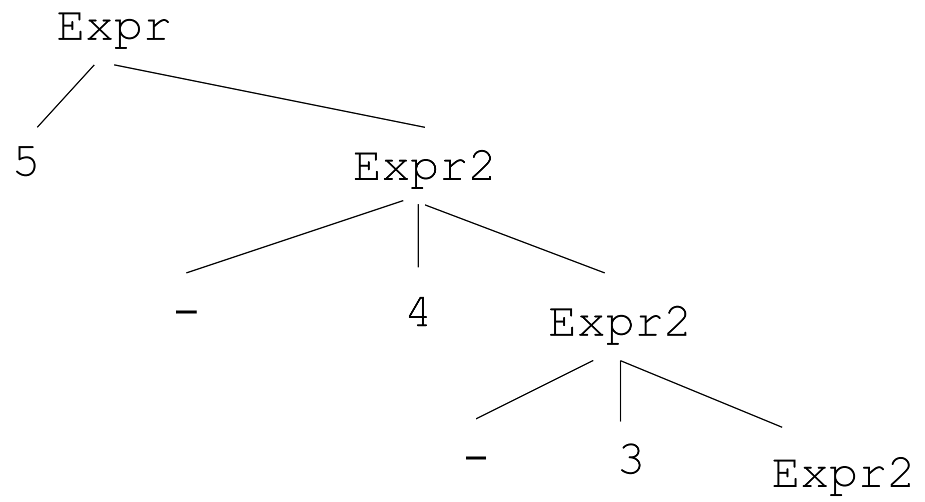




Creating an AST from top down grammar

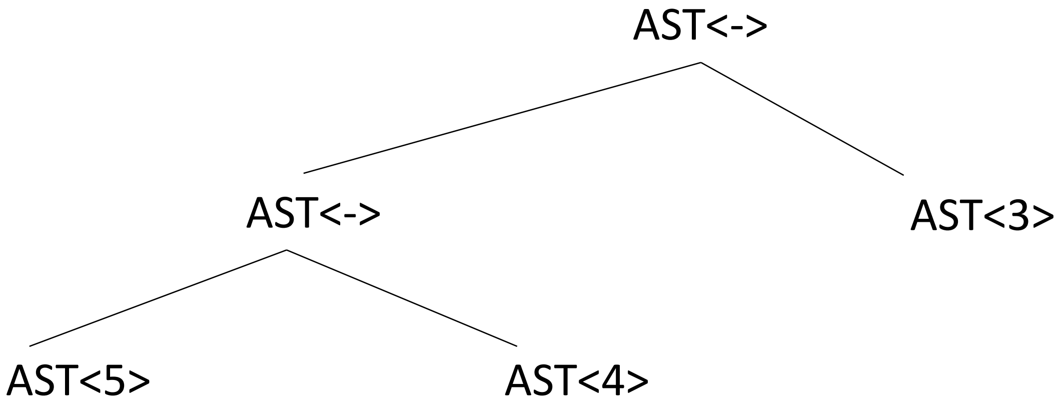
```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |   “”
```

5 - 4 - 3

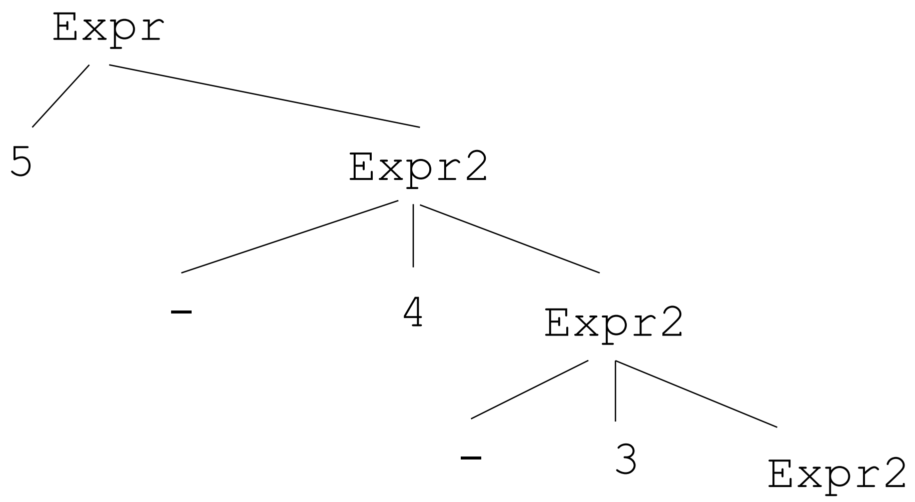


Creating an AST from top down grammar

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



```
5 - 4 - 3
```



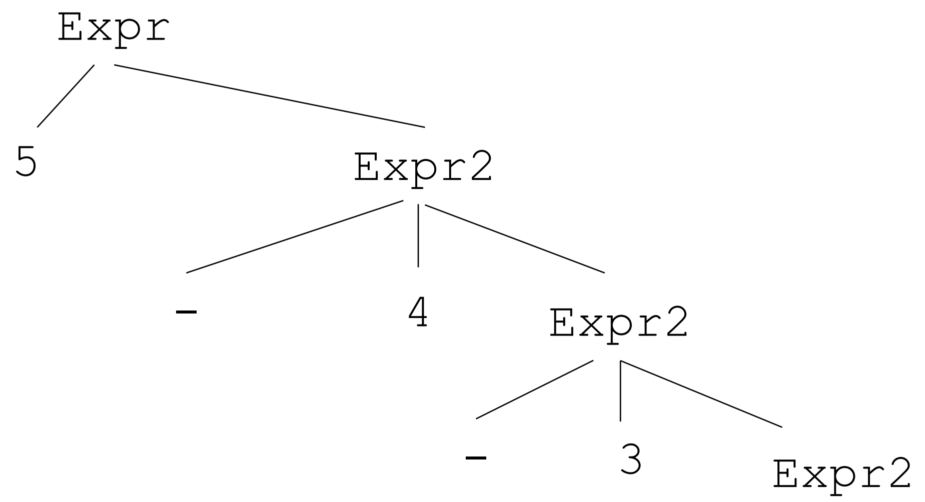
How do we get to the desired parse tree?

Creating an AST from top down grammar

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

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

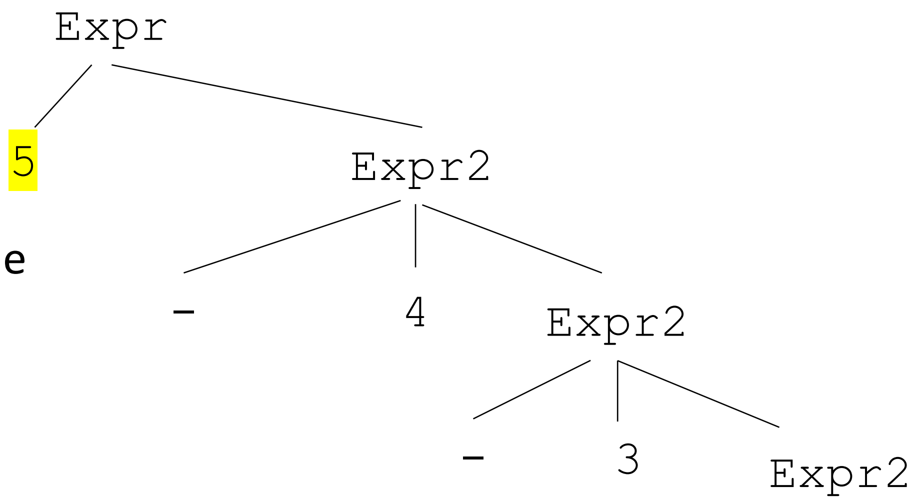
5 - 4 - 3



Creating an AST from top down grammar

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

`5 - 4 - 3`



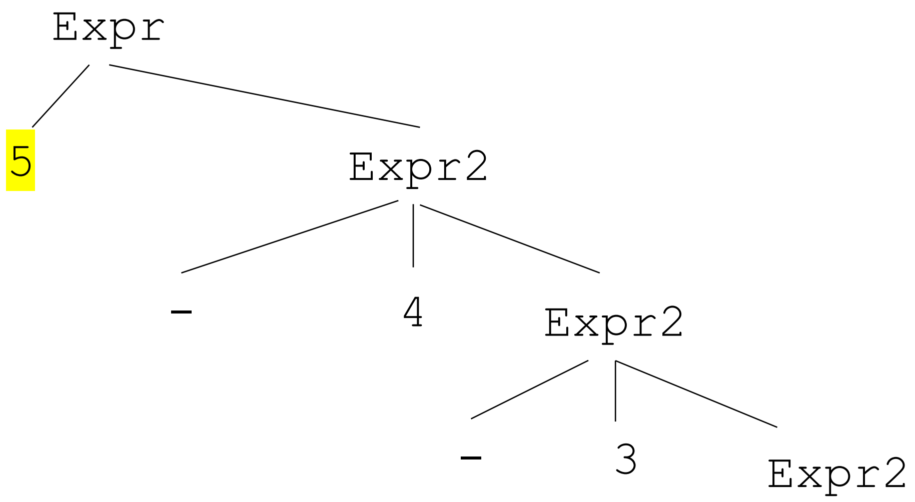
Get number node after we see a number

AST<5>

Creating an AST from top down grammar

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

5 - 4 - 3

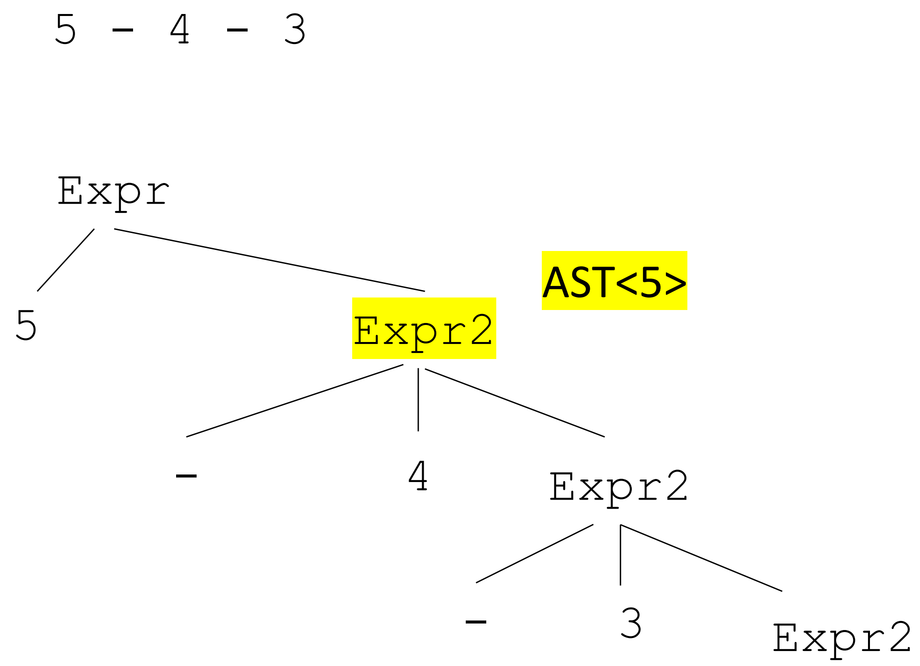

Expr
5
Expr2
-
4
Expr2
-
3
Expr2

Pass the node down

AST<5>

Creating an AST from top down grammar

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



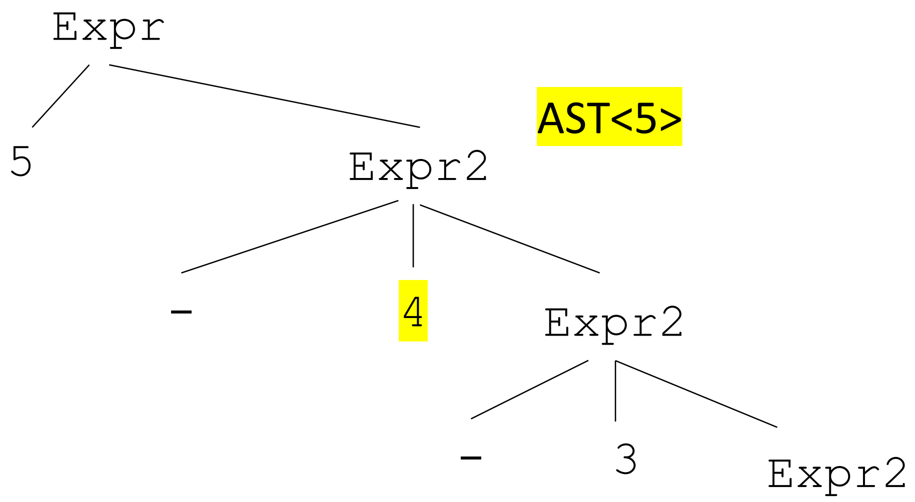
Pass the node down

AST<5>

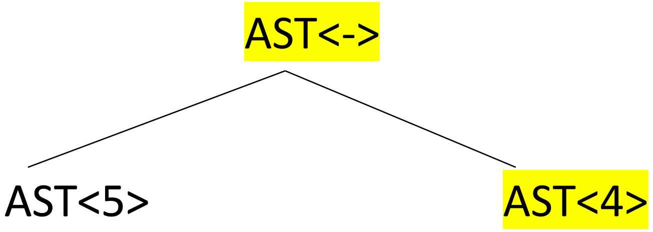
Creating an AST from top down grammar

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

5 - 4 - 3



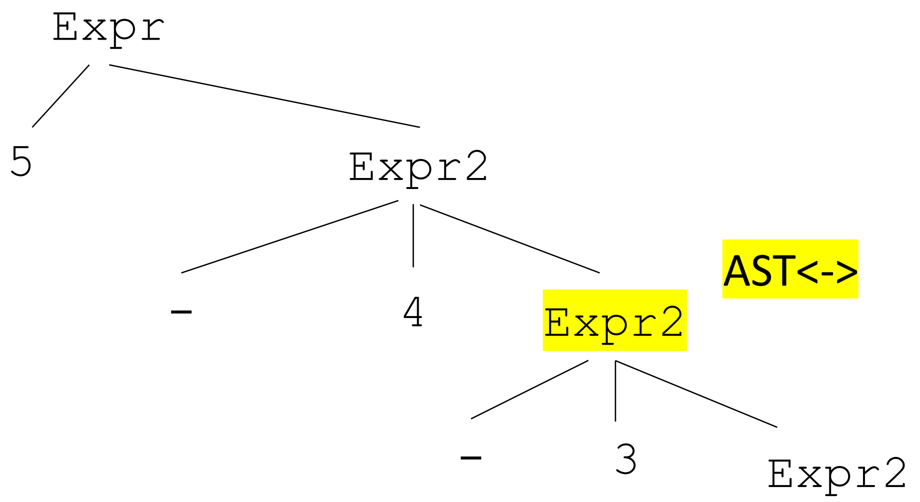
In Expr2, after 4 is parsed, create a number node and a minus node



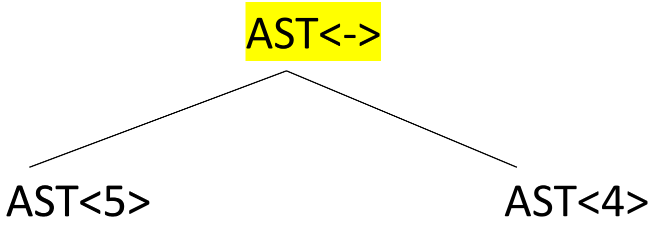
Creating an AST from top down grammar

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

5 - 4 - 3



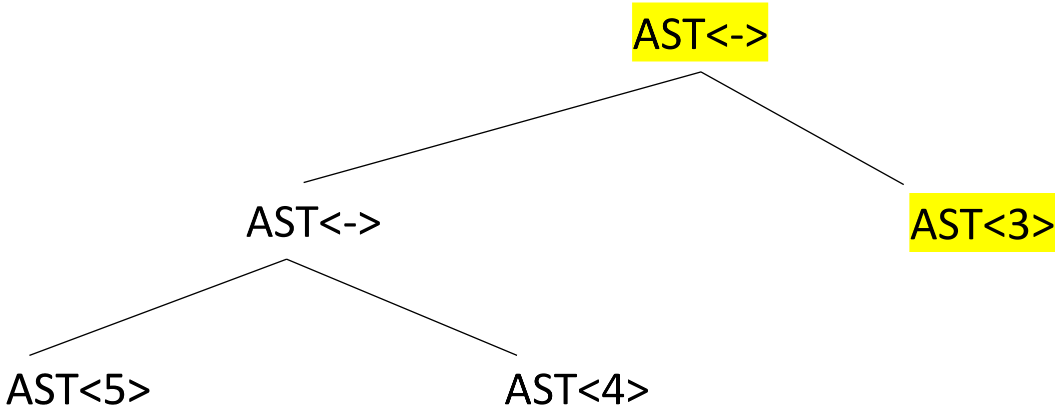
pass the new node down

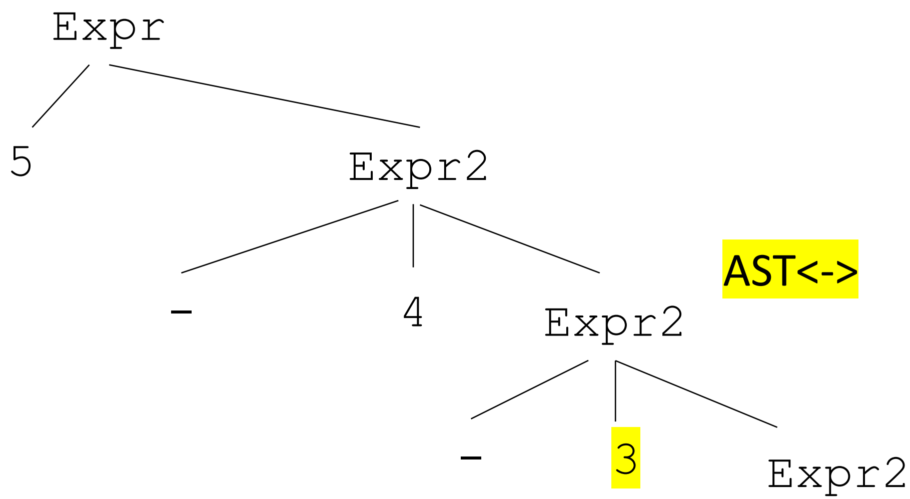


Creating an AST from top down grammar

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

5 - 4 - 3



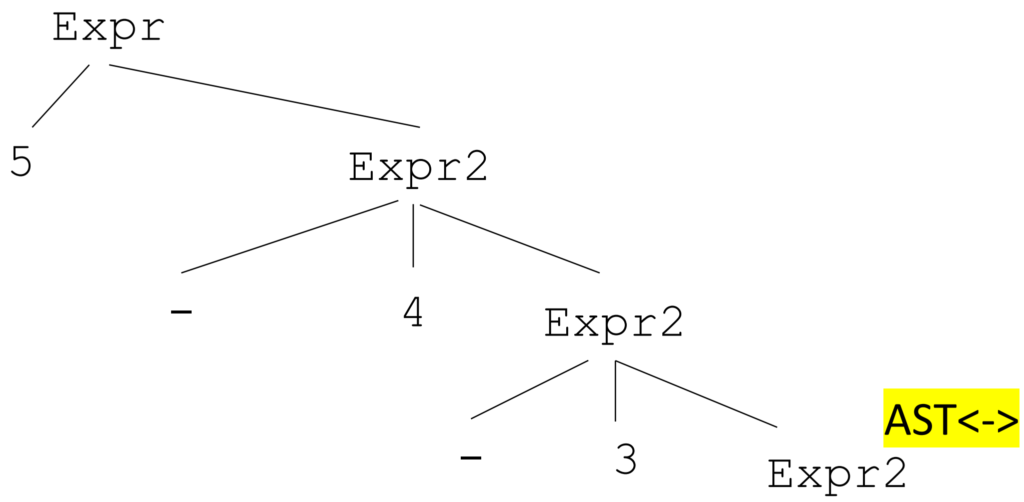


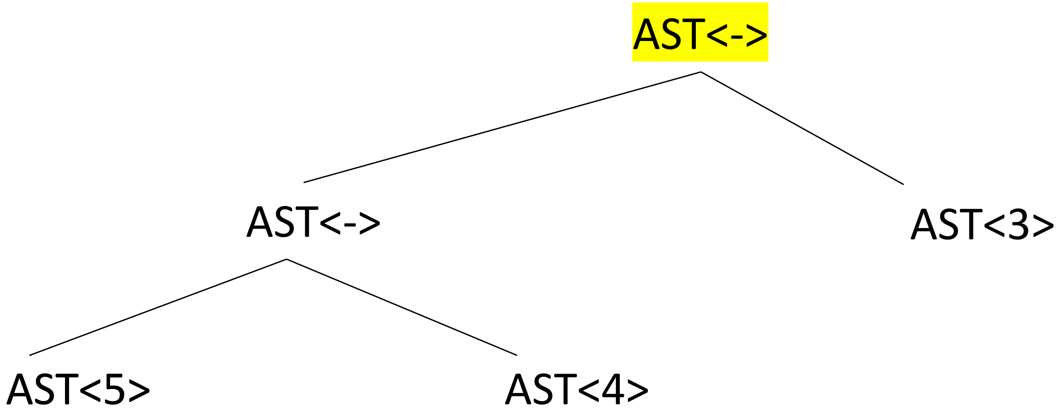
In Expr2, after 3 is parsed, create a number node and a minus node

Creating an AST from top down grammar

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

5 - 4 - 3



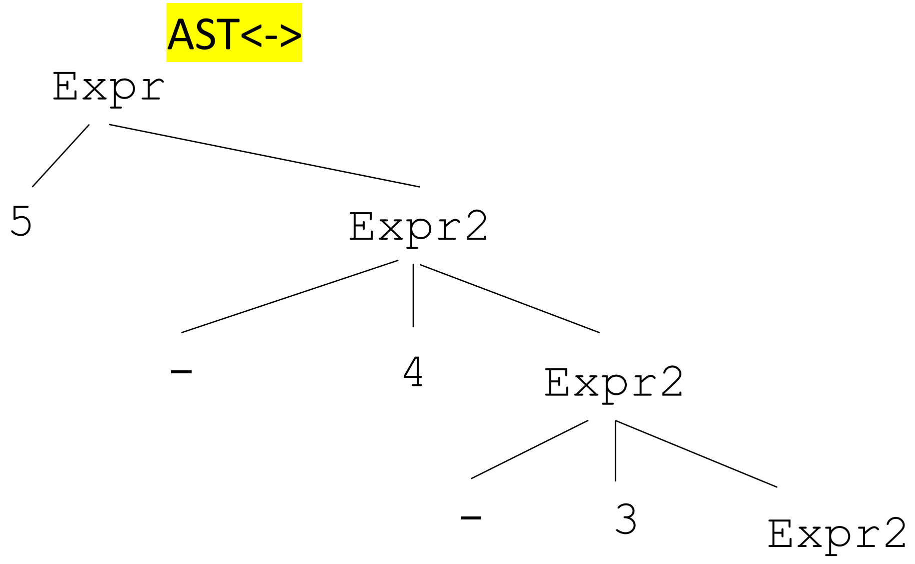


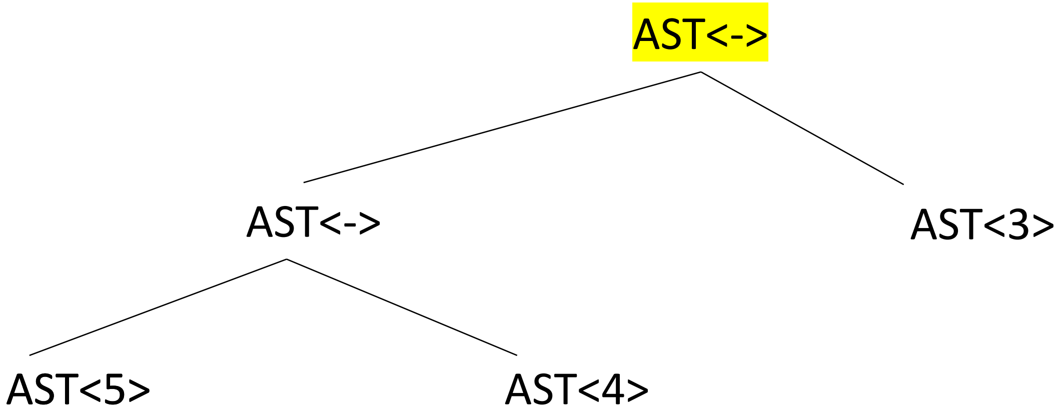
pass down the new node

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
        |    “”
```

```
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
       |    ""
```

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

how to adapt?

```
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   ::= Term Expr2
Expr2  ::= MINUS Term Expr2
        |    “”
```

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

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

how to adapt?

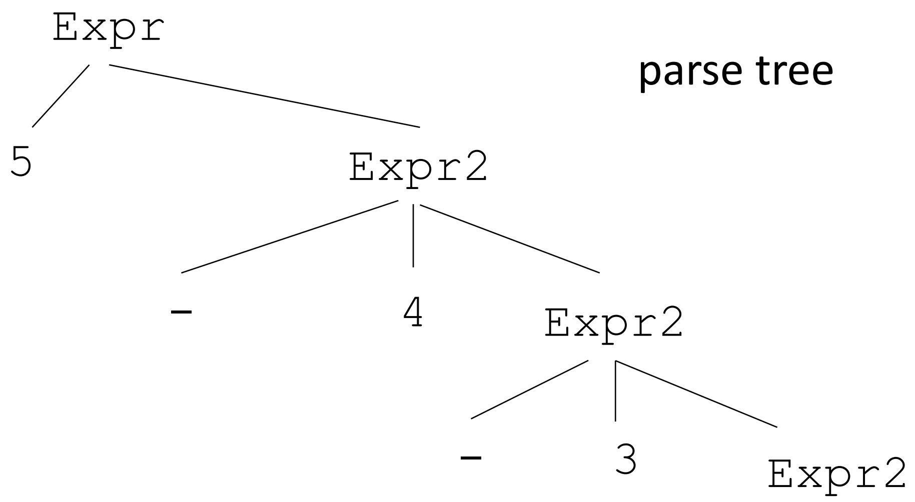
```
def parse_expr2(self, lhs_node):
    # ... for applying the first production rule
    self.eat("MINUS")
    rhs_node = self.parse_term()
    node = ASTMinusNode(lhs_node, rhs_node)
    return self.parse_expr2(node)
```

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

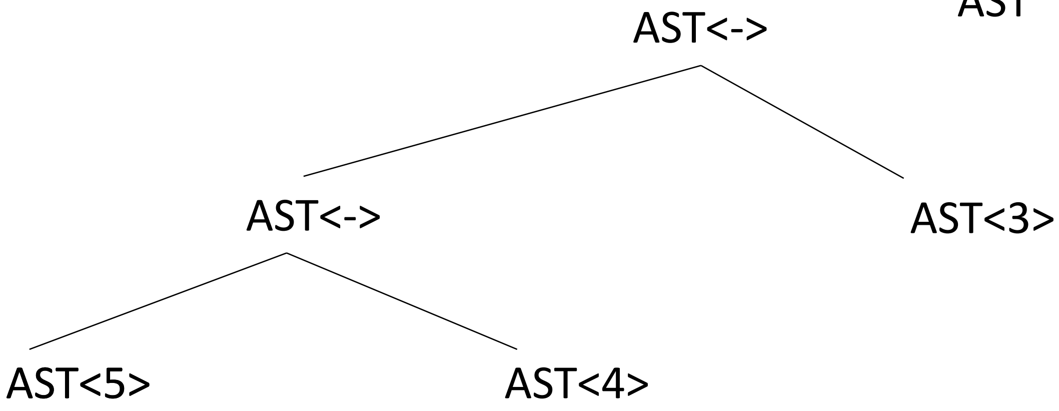
```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |   “”
```

`5 - 4 - 3`



parse tree

AST



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

Example

- Python AST

```
import ast

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

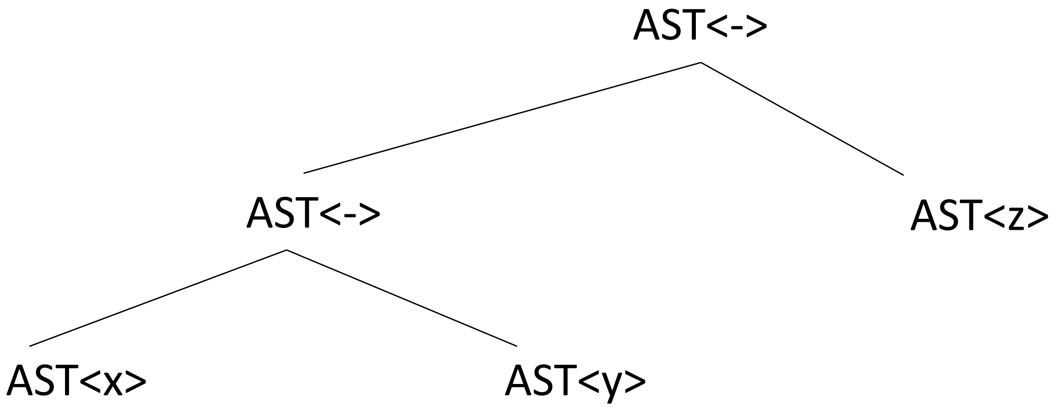
```
Expr(value=BinOp(left=BinOp(left=Num(n=5), op=Sub(), right=Num(n=4)), op=Sub(), right=Num(n=2)))
```

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
```



AST<->

AST<->

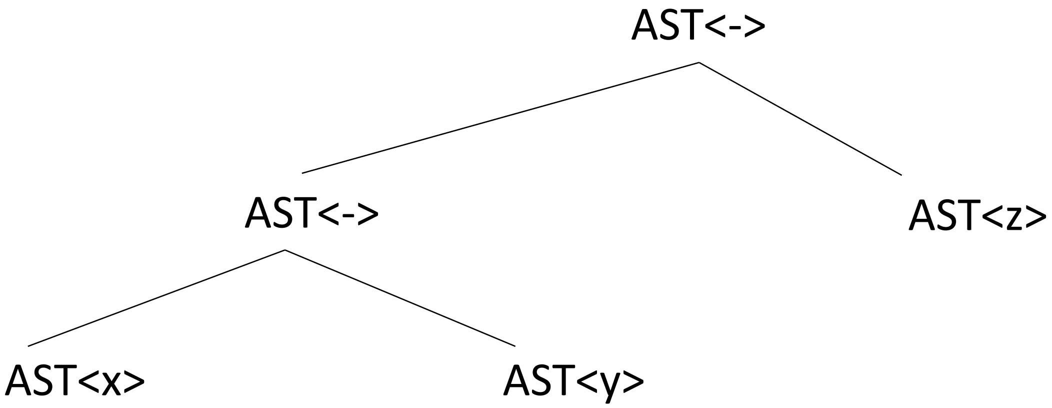
AST<z>

AST<x>

AST<y>

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
```

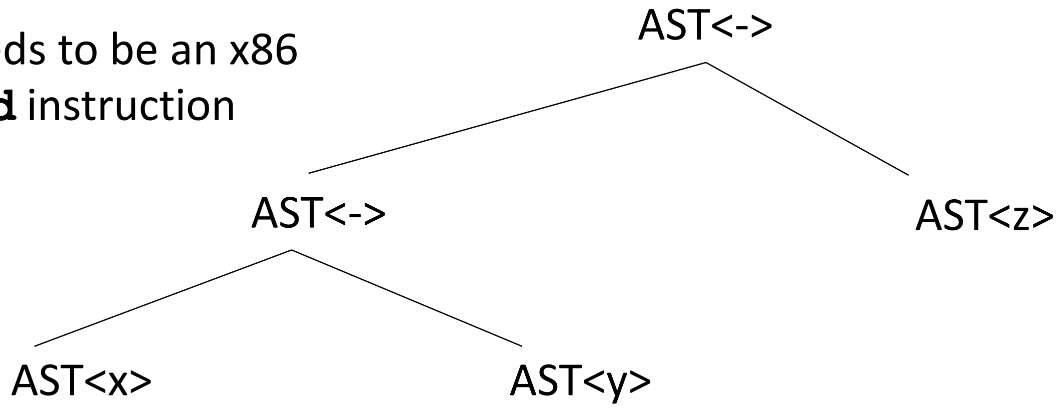
How does this change things?

Evaluate an AST by doing a post order traversal

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

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

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



AST<->

AST<->

AST<z>

AST<x>

AST<y>

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

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

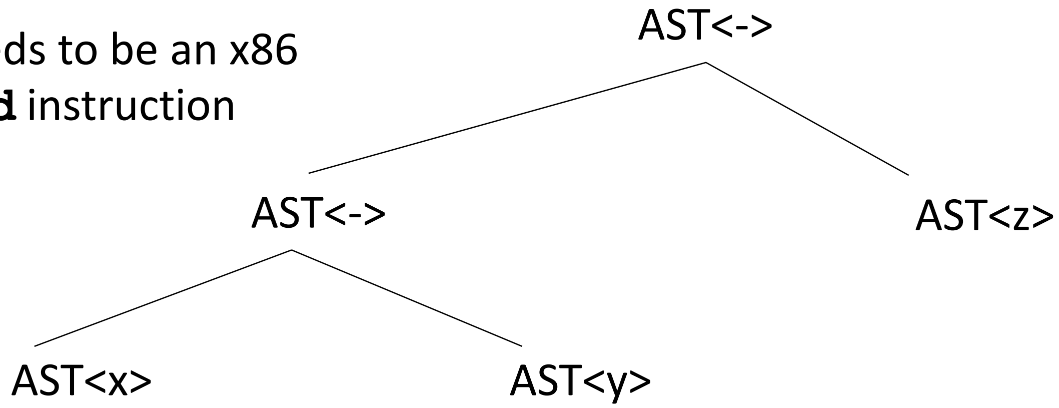
How does this change things?

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?

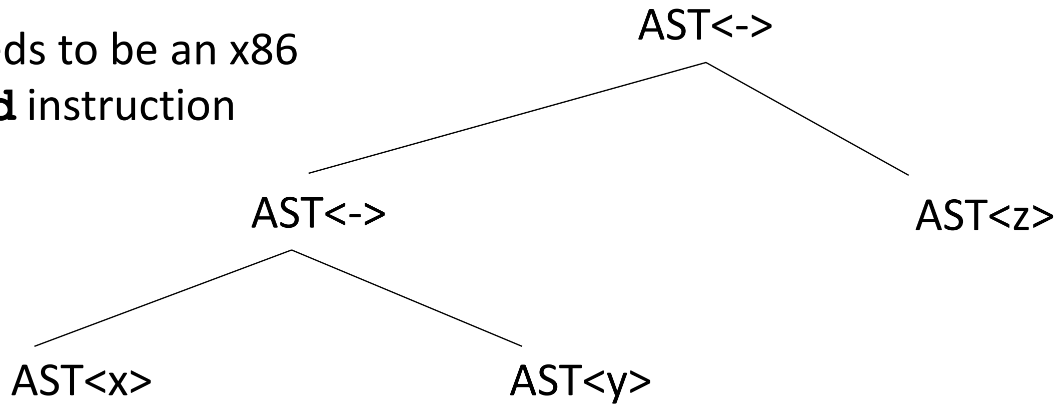
Evaluate an AST by doing a post order traversal

```
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



AST<->

AST<->

AST<z>

AST<x>

AST<y>

Is this all?

Lets do some experiments.

What should 5 - 5.0 be?

but

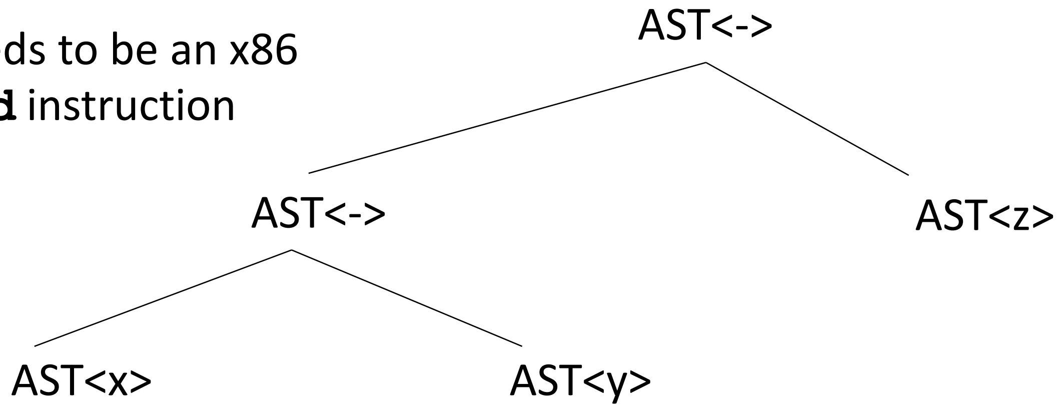
addss r1 r2

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?

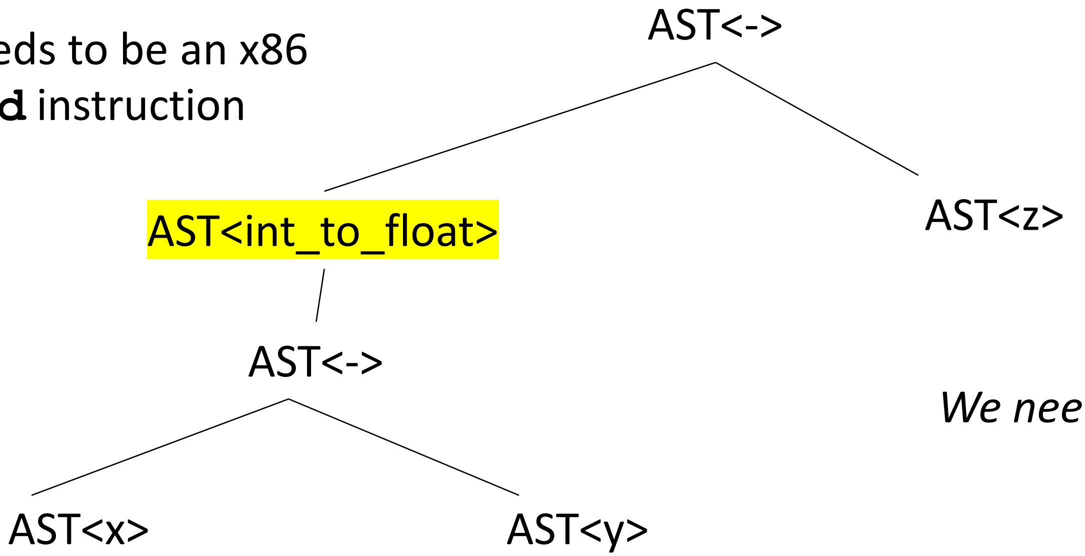
Evaluate an AST by doing a post order traversal

```
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



AST<->

AST<int_to_float>

AST<z>

AST<->

AST<x>

AST<y>

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