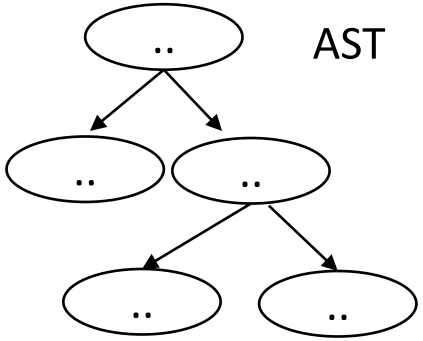
CSE110A: Compilers

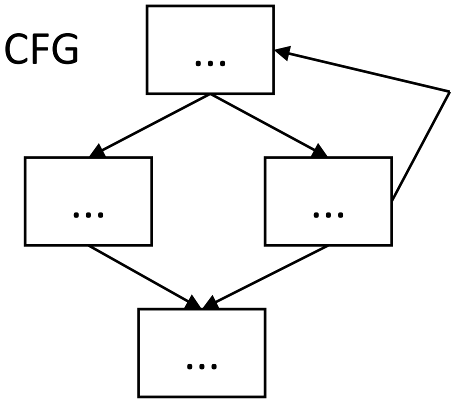
AST



Topics:

- *Module 3: Intermediate representations*
  - *ASTs*
  - *Type checking*

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
```

ASTs: Abstract Syntax Trees

```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 a parser

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

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```
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        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

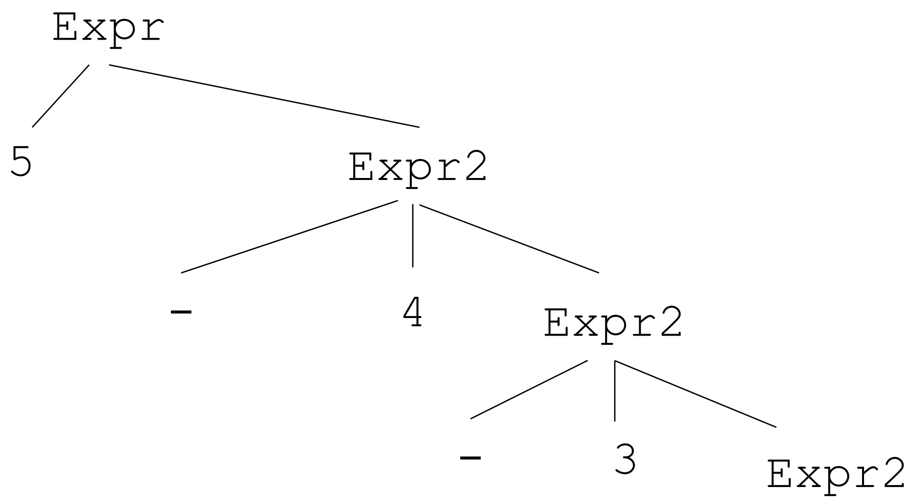
Operator	Name	Productions	Production action
+	`expr`	`: expr PLUS term` `| term`	`{return ASTAddNode($1,$3)}` `{return $1}`
*	`term`	`: term TIMES factor` `| factor`	`{return ASTMultNode($1,$3)}` `{return $1}`

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

Creating an AST from top down grammar

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

5 - 4 - 3



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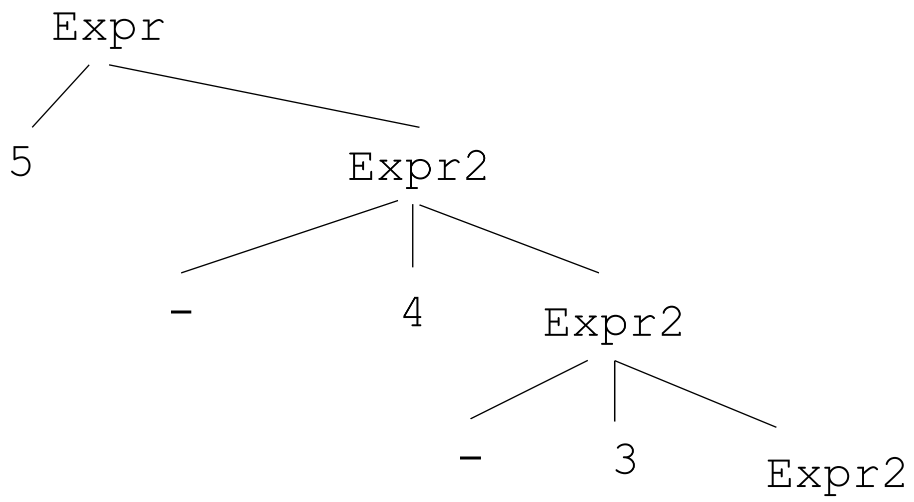
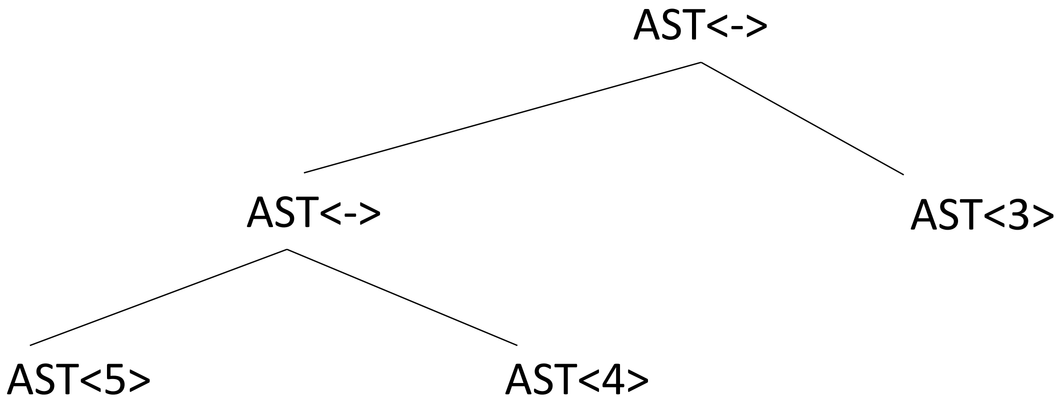


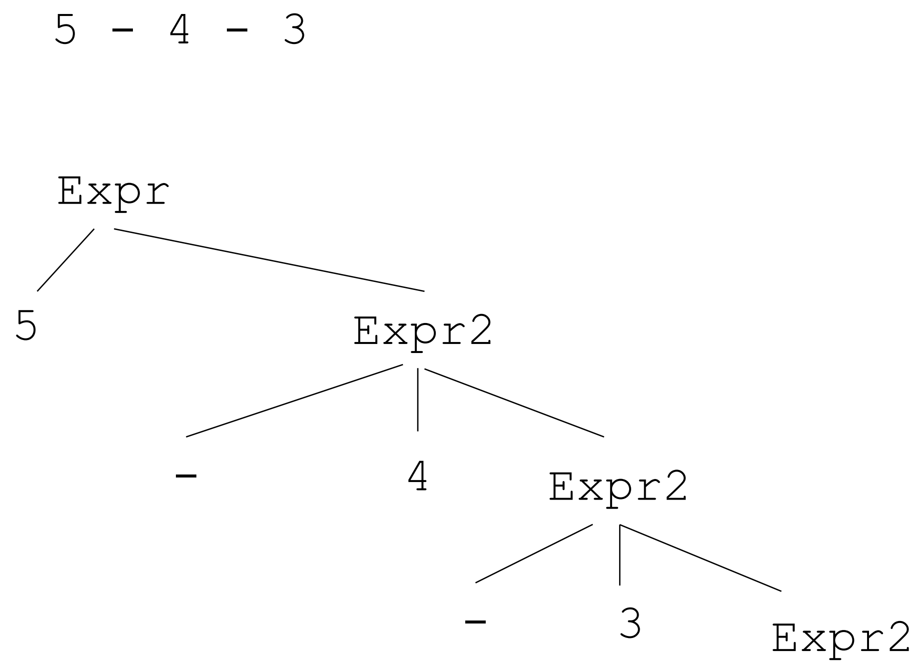


How do we get to the desired parse tree?

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.



Creating an AST from top down grammar

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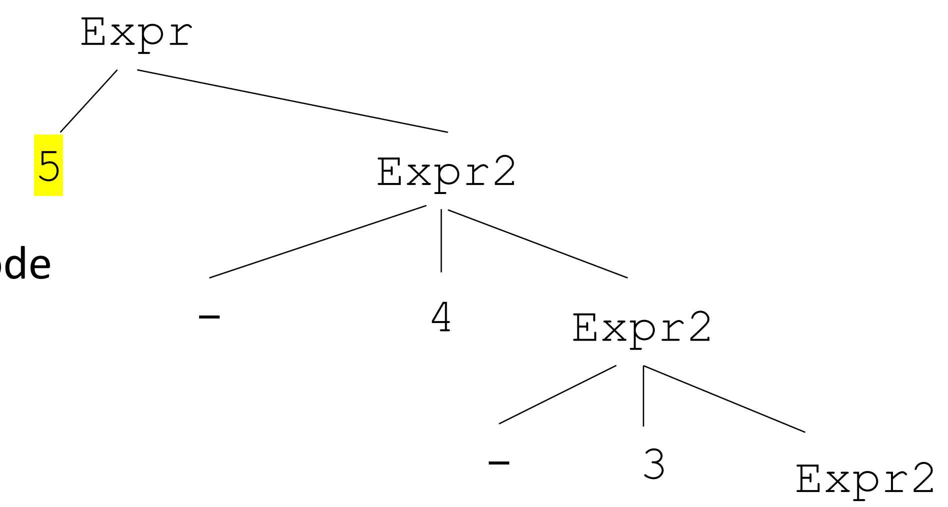

5 - 4 - 3



Get number node after we see a number

AST<5>

Creating an AST from top down grammar

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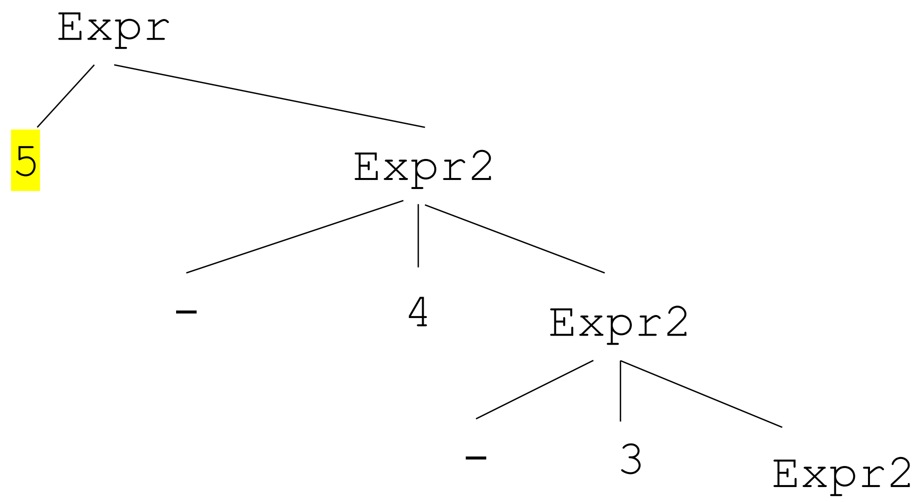
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |   ""
```

5 - 4 - 3



Pass the node down

AST<5>

Creating an AST from top down grammar

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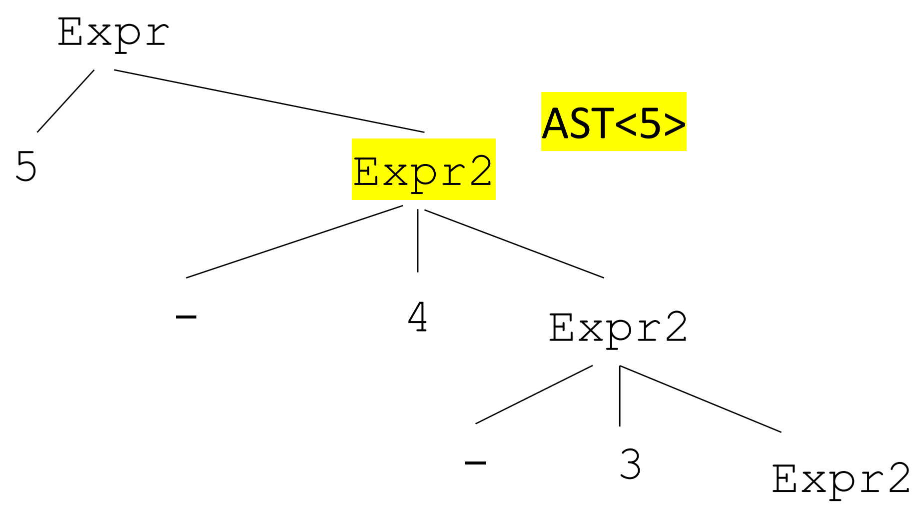

Pass the node down

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Creating an AST from top down grammar

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       |   ""
```
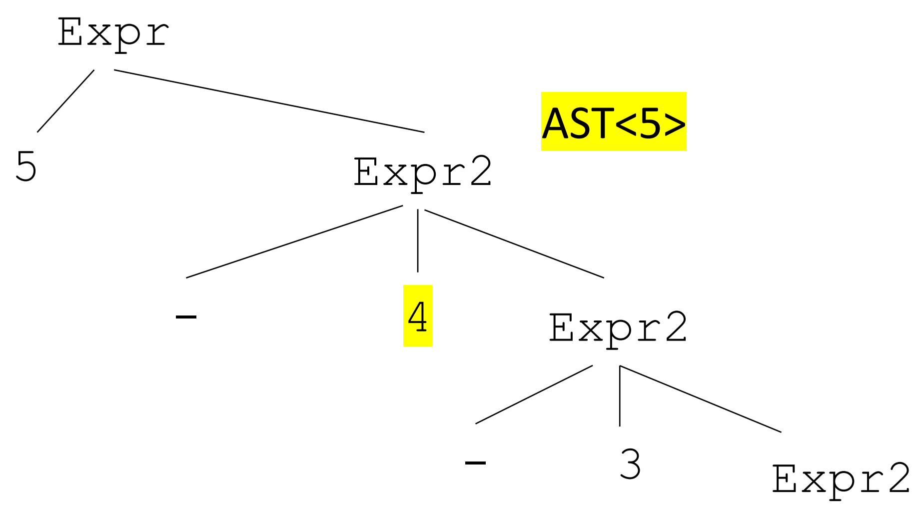
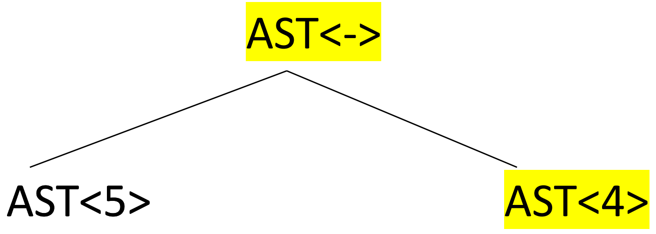

5 - 4 - 3



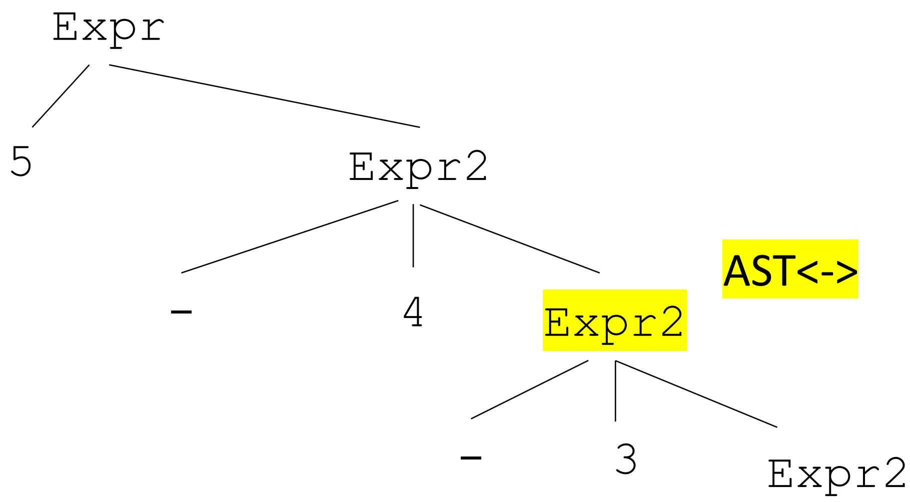
In Expr2, after 4 is parsed, create a number node and a minus node



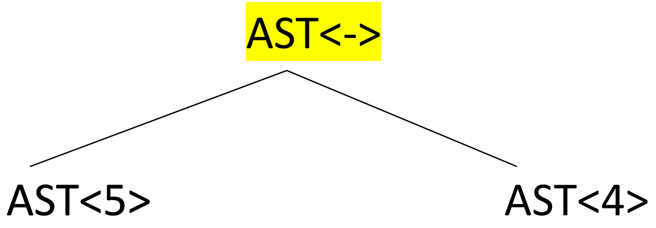
Creating an AST from top down grammar

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

5 - 4 - 3

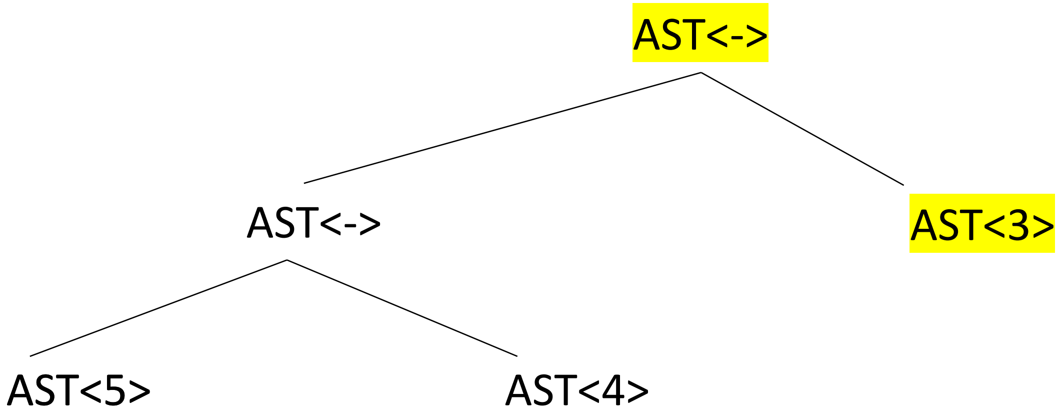


pass the new node down



Creating an AST from top down grammar

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



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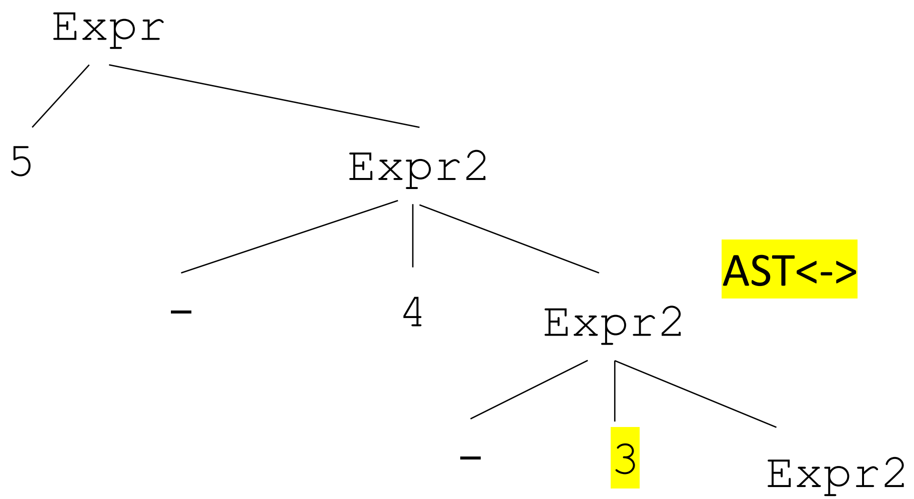
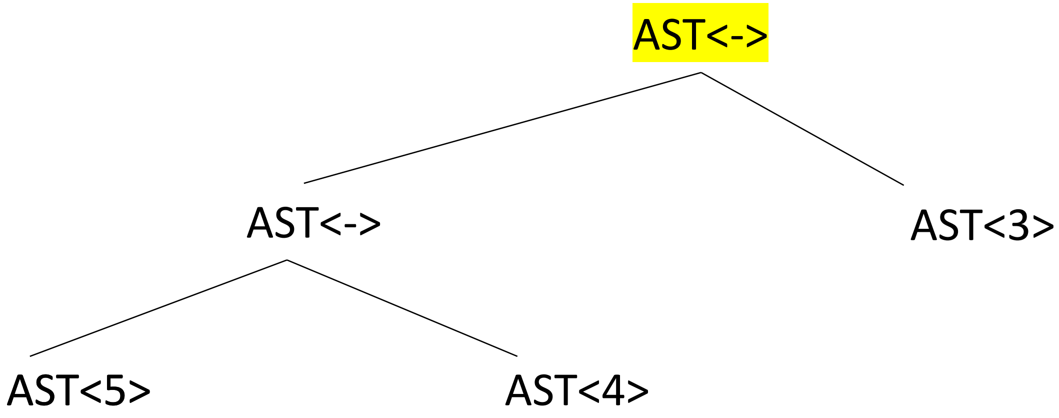


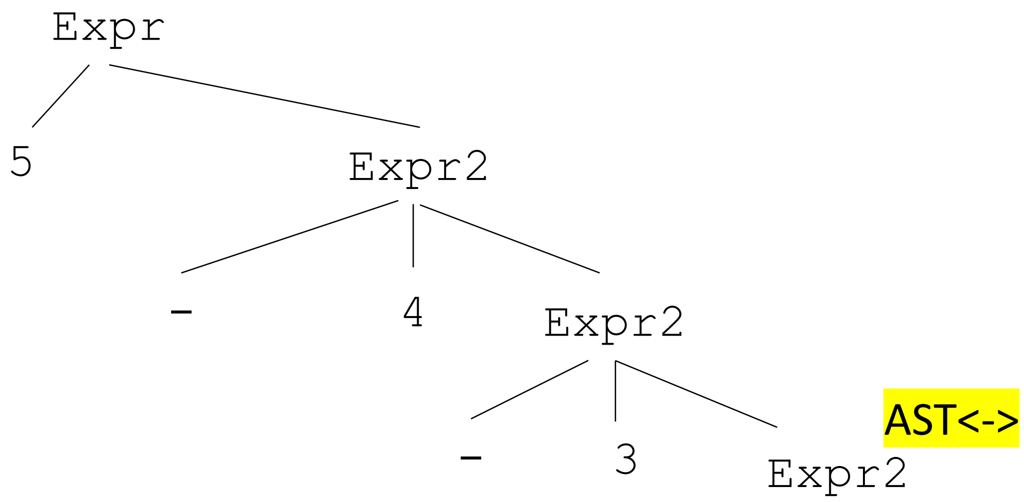
In Expr2, after 3 is parsed, create a number node and a minus node

Creating an AST from top down grammar

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



`5 - 4 - 3`

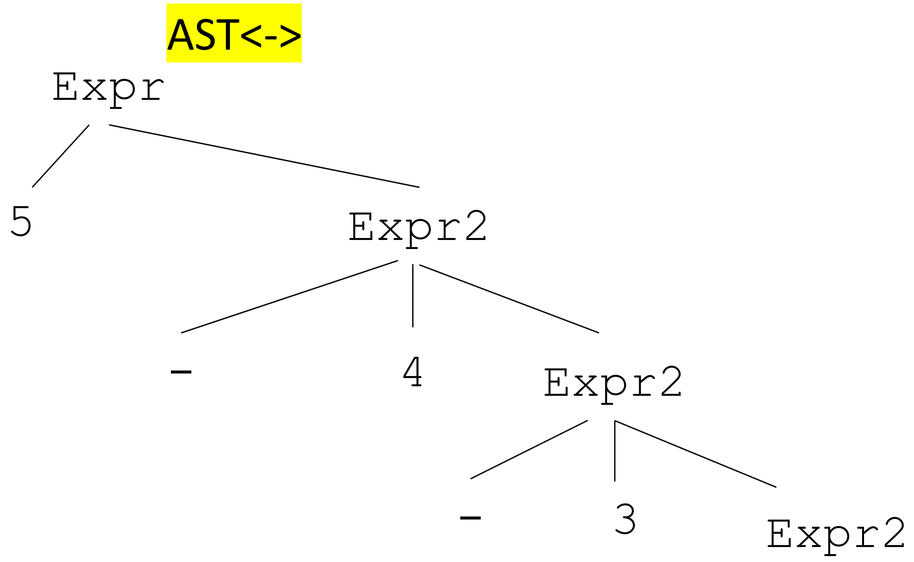


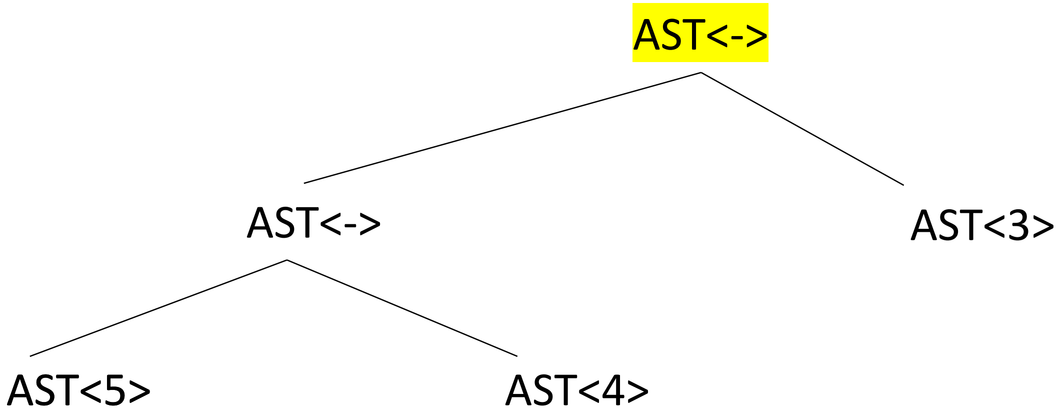
pass down the new node

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       # the next terminal, a NUM
   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                  # the value of next terminal a NUM
    rhs_node = ASTNumNode(value)                 # build that node
    self.eat("NUM")
    node = ASTMinusNode(lhs_node, rhs_node)     # build the Expr2 dyadic node
    return self.parse_expr2(node)               # return the dyadic 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 of Expr2, when there is no MINUS
    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?

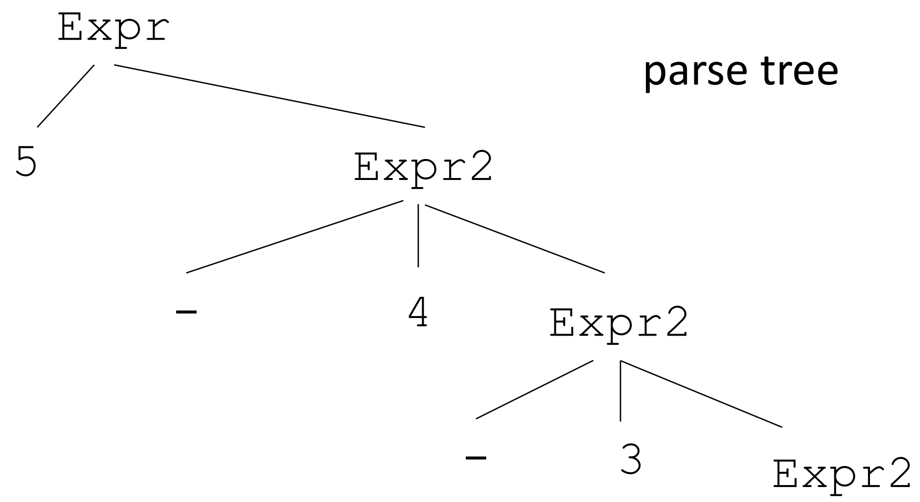
```
def parse_expr2(self, lhs_node):
    # ... for applying the first production rule
    self.eat("MINUS")
    rhs_node = self.parse_term()
    node = ASTMinusNode(lhs_node, rhs_node)
    return self.parse_expr2(node)
```

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

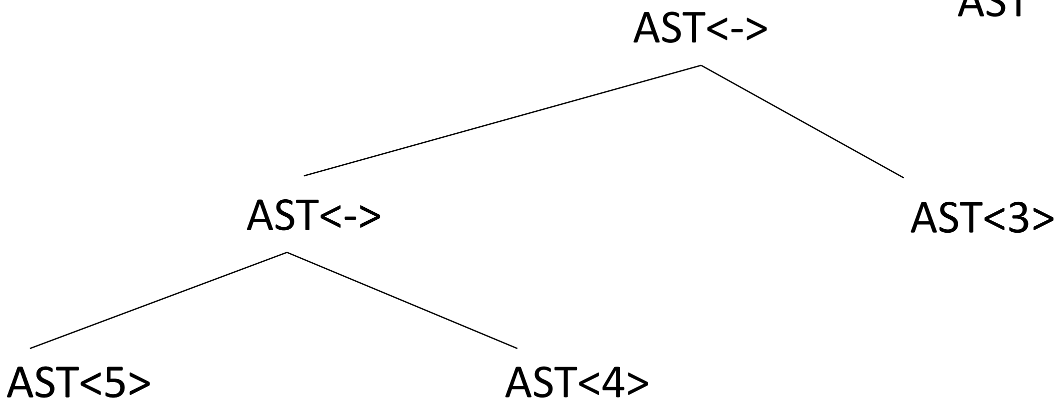
```
Expr  ::= NUM Expr2
Expr2 ::= MINUS NUM Expr2
       |   “”
```

`5 - 4 - 3`



parse tree

AST

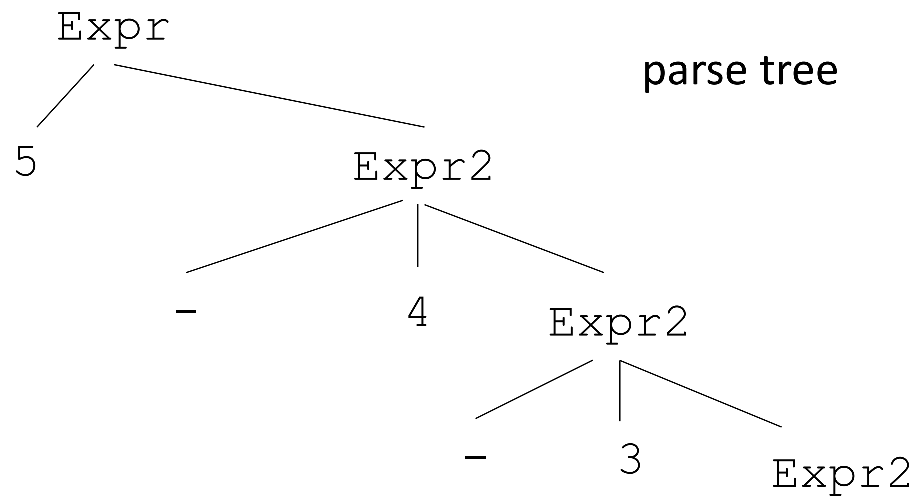


Parse trees cannot always be evaluated in post-order. An AST should always be

Strategy to Build AST with Top-Down Parsing

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

5 - 4 - 3



parse tree

Strategy: Build AST as You Return from Recursive Calls

- Each function corresponds to a grammar rule.
- When you parse a component like an expr, your return an ASTNode.
- You construct the node *after* parsing its subparts — so **you build bottom-up**, even though you're recursing top-down.

This means: You build AST nodes in a way that **resembles post-order**, even though your parser runs top-down.

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')))
```

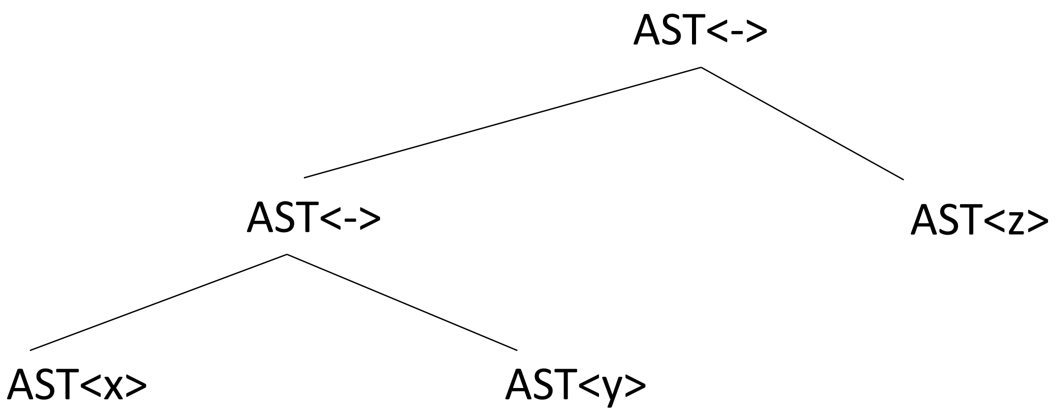
```
Expr(value=BinOp(left=BinOp(left=Num(n=5), op=Sub(), right=Num(n=4)), op=Sub(), right=Num(n=2)))
```

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

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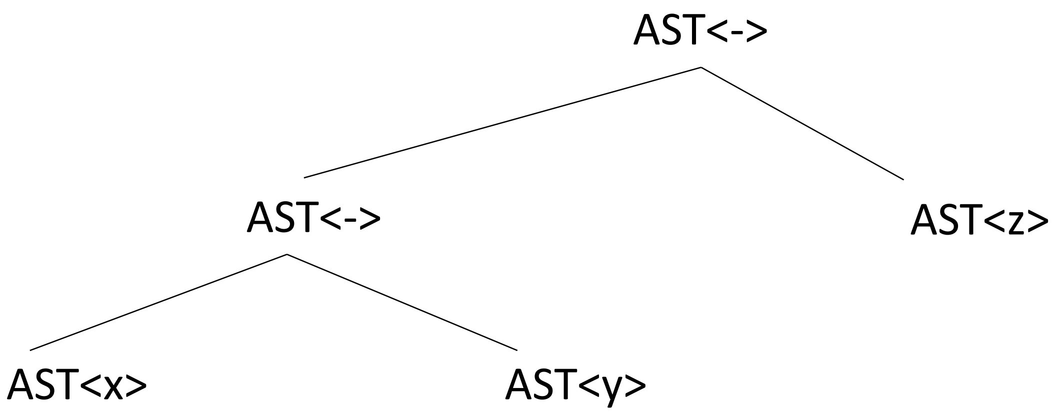
      |   “”
```



What if you cannot evaluate it as is?
The primitive types do not match.

What else might you do?

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

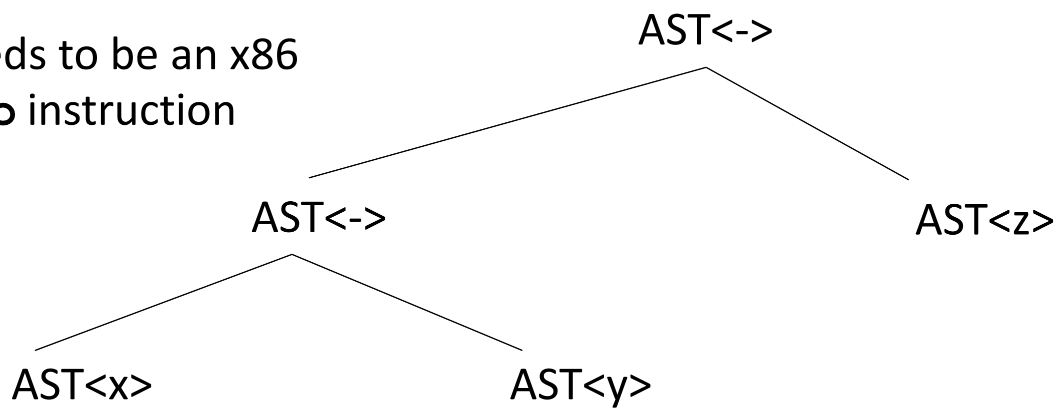
How does this change things?

Evaluate an AST by doing a post order traversal

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

needs to be an x86
`subss` instruction

needs to be an x86
`sub` instruction



Is this all?

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```
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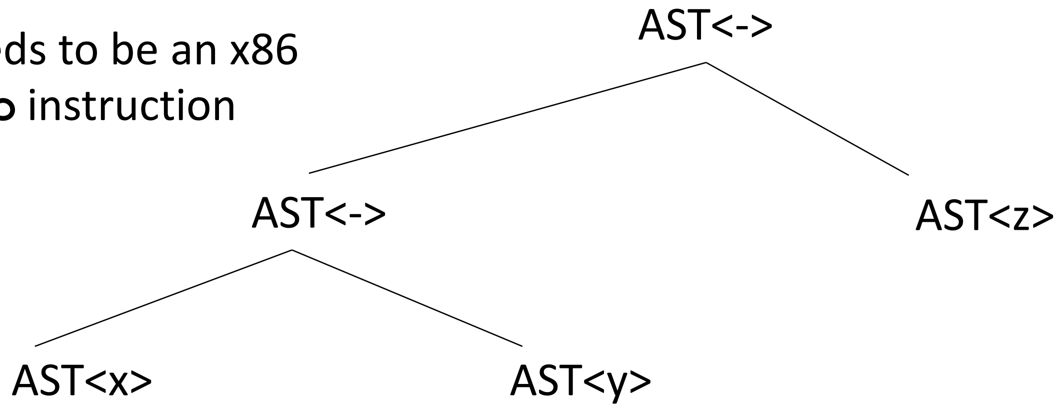


Let’s do some experiments.

What should 5 - 5.0 be?

Is this all?

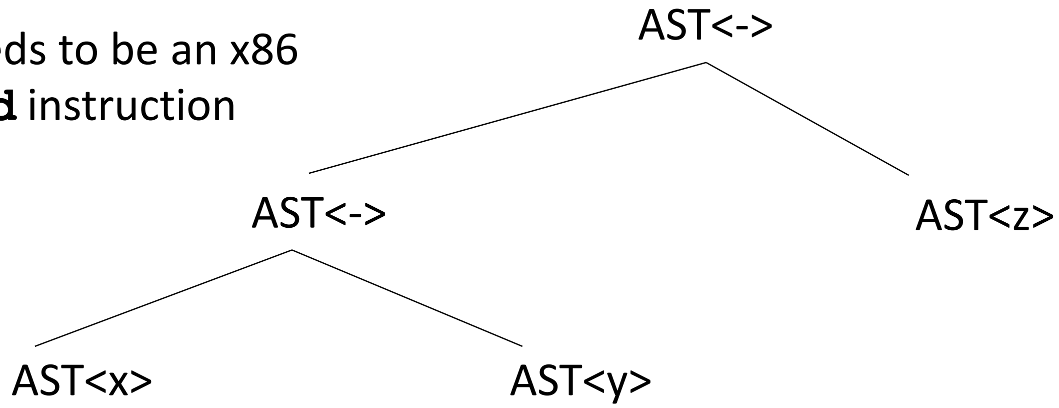
Evaluate an AST by doing a post order traversal

```
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

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

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

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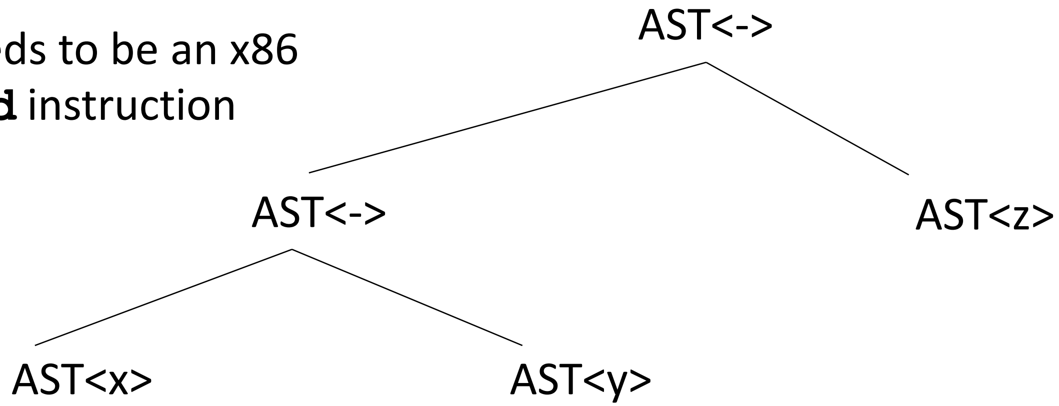
`addss` instruction

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
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         |   ""
```

```
int x;
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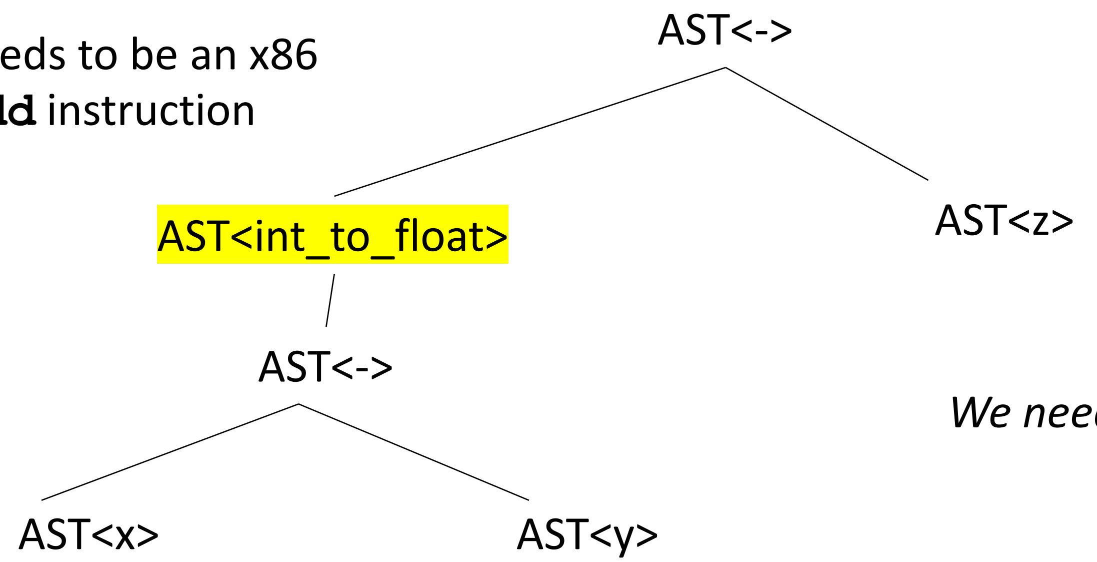

We need to make sure our operands are in the right format!

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

Type systems

- Different types of Type Systems for languages:
  - **statically typed**: types can be determined at compile time
  - **dynamically typed**: types are determined at runtime
  - **untyped**: the language has no types

- What are examples of each?
- What are pros and cons of each?

Type systems

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- What are examples of each?
- What are pros and cons of each?

do type conversion at compile time otherwise you have to check without static types, this would need to be translated to:

```
x + y
```

```
if type(x) == int and type(y) == int:
  add(x,y)
if type(x) == int and type(y) == float:
  addss(int_to_float(x), y)
if ...
```

Type systems

- Different types of Type Systems for languages:
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  - **untyped**: the language has no types

- What are examples of each?
- What are pros and cons of each?

Can write more generic code

```
def add(x,y):
  return x + y
```

You would need to write many different functions for each type

Type systems

- Different types of Type Systems for languages:
  - **statically typed**: types can be determined at compile time
  - **dynamically typed**: types are determined at runtime
  - **untyped**: the language has no types

- What are examples of each?
- What are pros and cons of each?

Very close to assembly. You can write really optimized code. But very painful

Type systems

Considerations:

Type systems

Considerations:

- Base types:
  - ints
  - chars
  - strings
  - floats
  - bool

- How to combine types in expressions:
  - int and float?
  - int and char?
  - int and bool?

Type systems

Considerations:

- Base types:
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Type systems

Considerations:

- Base types:
  - ints
  - chars
  - strings
  - floats
  - bool

- How to combine types in expressions:
  - int and float?
  - int and char?
  - int and bool?

What do each of these do if they are +'ed together?

Type checking

Two components

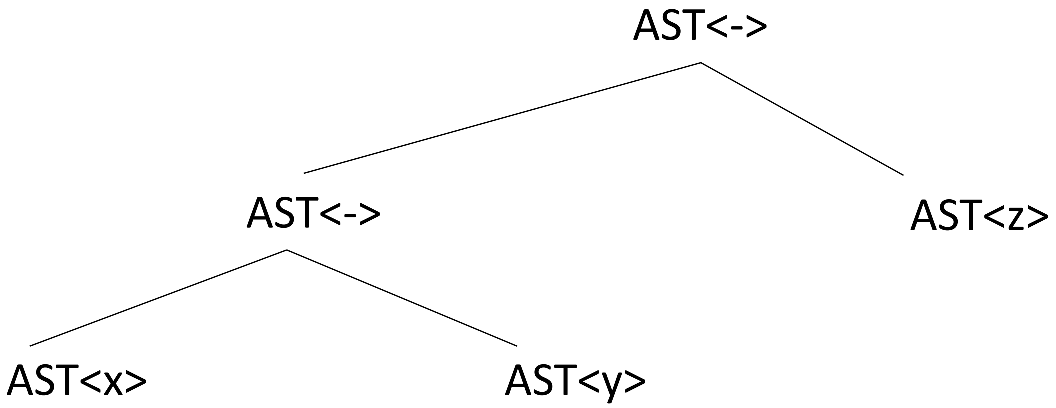
- Type inference
  - Determines a type for each AST node
  - Modifies the AST into a type-safe form

- Catches type-related errors

Type checking on an AST

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

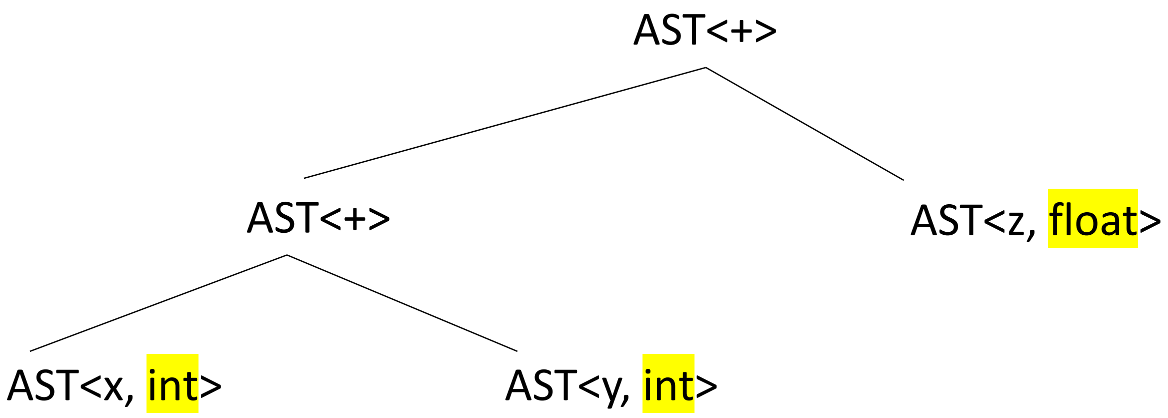
each node additionally gets a type



Type checking on an AST

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

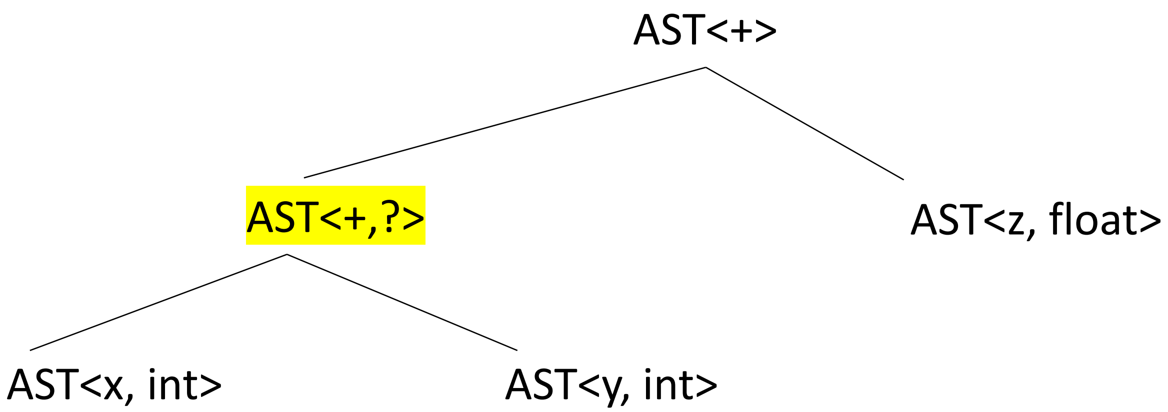
each node additionally gets a type
we can get this from the symbol table for the leaves or based on the input (e.g. 5 vs 5.0)



Type checking on an AST

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

How do we get the type for this one?



Type checking on an AST

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

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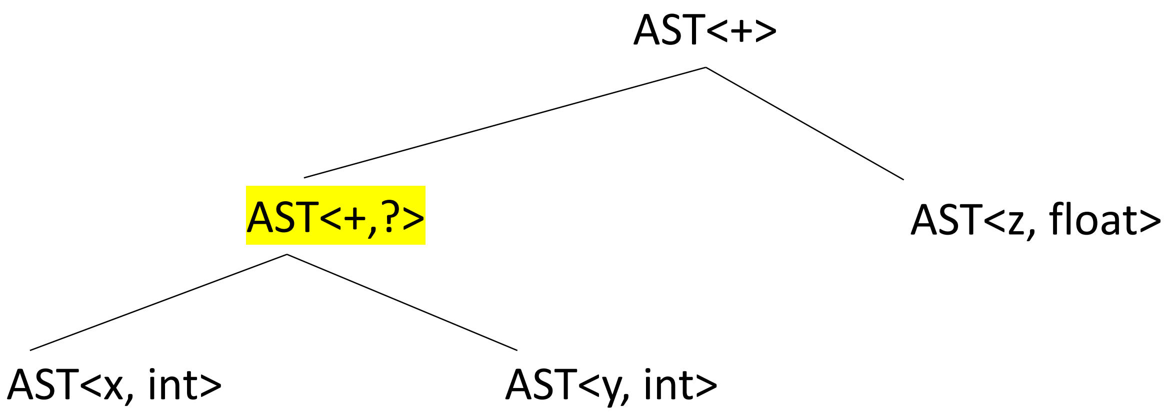

inference rules for addition:

first	second	result
int	int	int
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float	int	float
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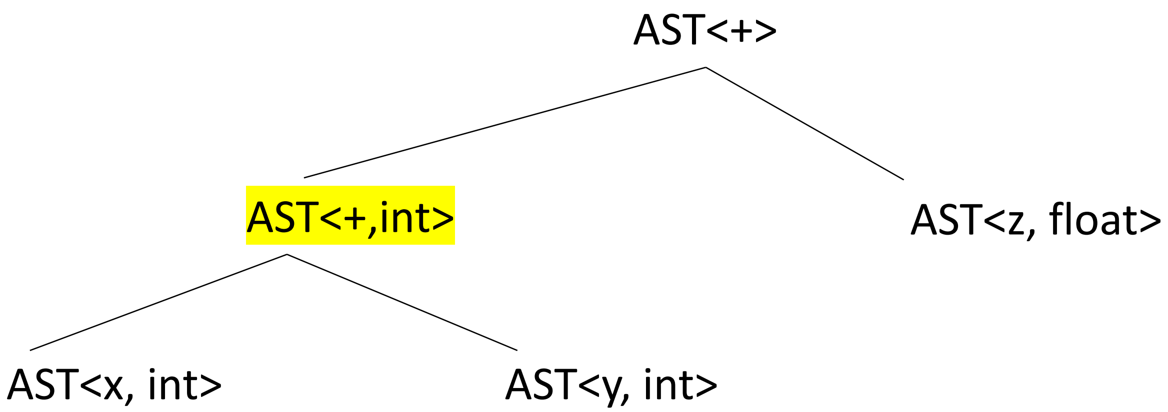

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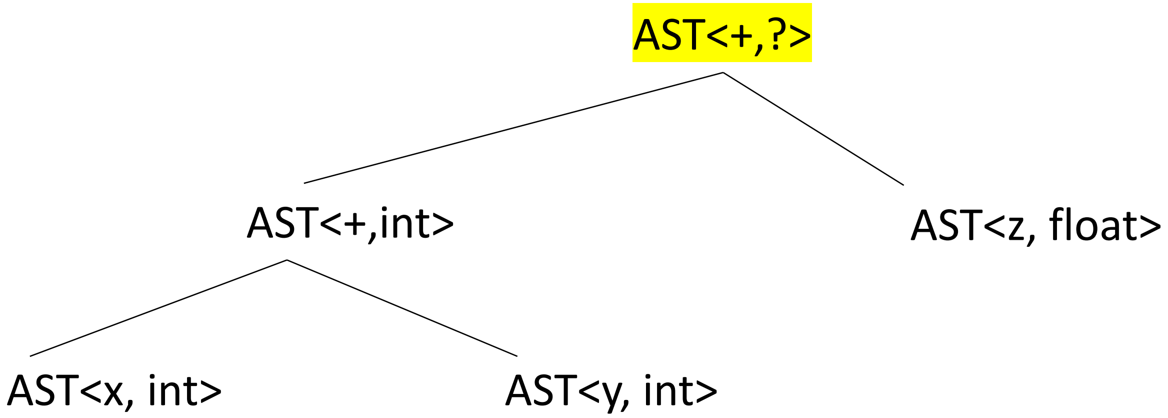

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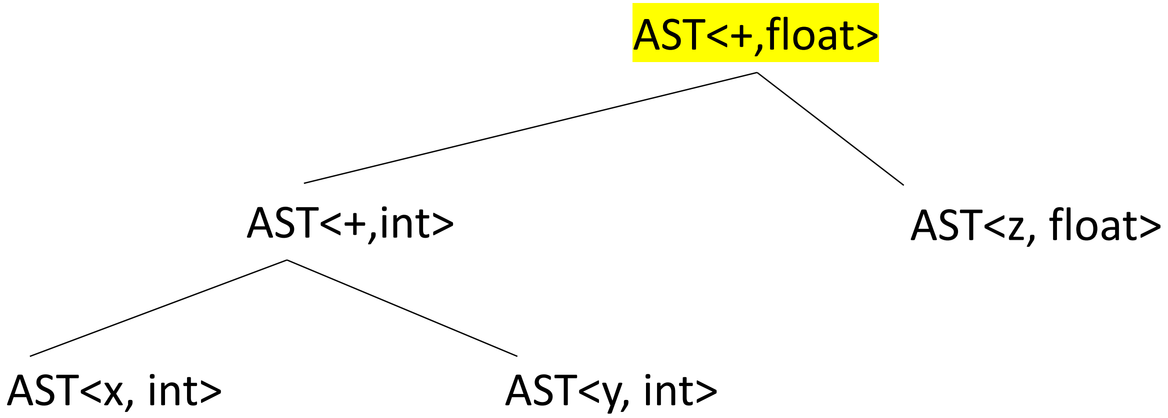

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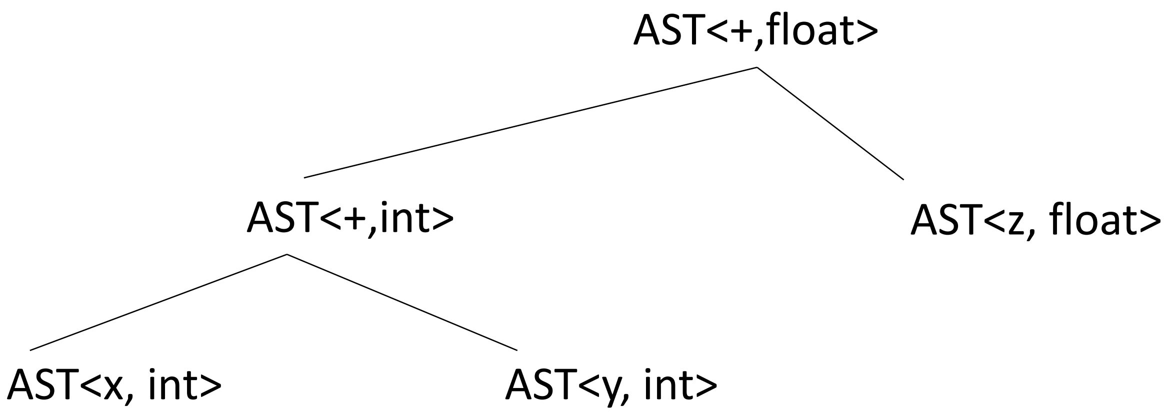

inference rules for addition:

first	second	result
`int`	`int`	`int`
`int`	`float`	`float`
`float`	`int`	`float`
`float`	`float`	`float`

what else?

Type checking on an AST

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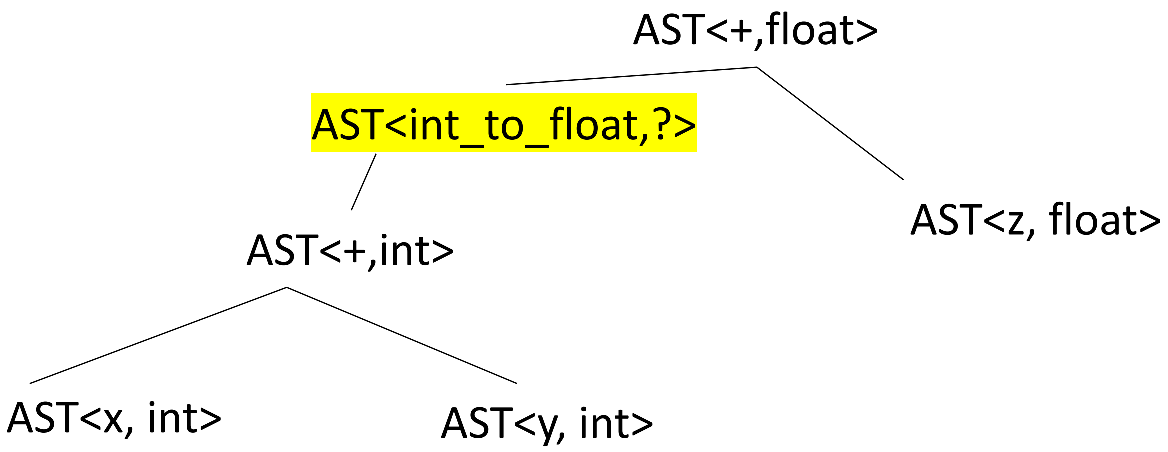
float z;
float w;
w = x + y + z
```

How do we get the type for this one?



inference rules for addition:

first	second	result
`int`	`int`	`int`
`int`	`float`	`float`
`float`	`int`	`float`
`float`	`float`	`float`

what else? need to convert the int to a float

```
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)
```

Enum for types

```
from enum import Enum

class Types(Enum):
    INT = 1
    FLOAT = 2
```

Now we need to set the types for the leaf nodes

Our base AST Node needs a type

```
class ASTNode():
    def __init__(self):
        self.node_type = None
        pass

    def set_type(self, t):
        self.node_type = t

    def get_type(self):
        return self.node_type
```

Enum for types

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from enum import Enum

class Types(Enum):
    INT = 1
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    def set_type(self, t):
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    def get_type(self):
        return self.node_type
```

Now we need to set the types for the leaf nodes

```
class ASTNumNode(ASTLeafNode):
    def __init__(self, value):
        super().__init__(value)
        if is_int(value):
            self.set_type(Types.INT)
        else:
            self.set_type(Types.FLOAT)
```

Enum for types

```
from enum import Enum

class Types(Enum):
    INT = 1
    FLOAT = 2
```

Our base AST Node needs a type

```
class ASTNode():
    def __init__(self):
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        if is_int(value):
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        else:
            self.set_type(Types.FLOAT)
```

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

Where can we get the value type for an ID?

Symbol Table

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

- `SymbolTable ST;`

(TYPE, 'int') (ID, 'x')

declare_statement ::= TYPE ID SEMI

```
{
   eat(TYPE)
   id_name = self.to_match.value
   eat(ID)
   ST.insert(id_name, None)
   eat(SEMI)
}
```

in homework 2 and 3 we didn't record any information in the symbol table

Symbol Table

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

- `SymbolTable ST;`

(TYPE, 'int') (ID, 'x')

declare_statement ::= TYPE ID SEMI

```
{
  value_type = self.to_match.value
  eat(TYPE)
  id_name = self.to_match.value
  eat(ID)
  ST.insert(id_name, value_type)
  eat(SEMI)
}
```

previously we weren't saving any information about the ID

record the type in the symbol table

Enum for types

```
from enum import Enum

class Types(Enum):
    INT = 1
    FLOAT = 2
```

Our base AST Node needs a type

```
class ASTNode():
    def __init__(self):
        self.node_type = None
        pass

    def set_type(self, t):
        self.node_type = t

    def get_type(self):
        return self.node_type
```

Now we need to set the types for the leaf nodes

Number impies a type: e.g. 134 vs. 134.5

```
class ASTNumNode(ASTLeafNode):
    def __init__(self, value):
        super().__init__(value)
        if is_int(value):
            self.set_type(Types.INT)
        else:
            self.set_type(Types.FLOAT)
```

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

Where can we get the value type for an ID?

But that doesn’t get us here yet...

add the type at parse time

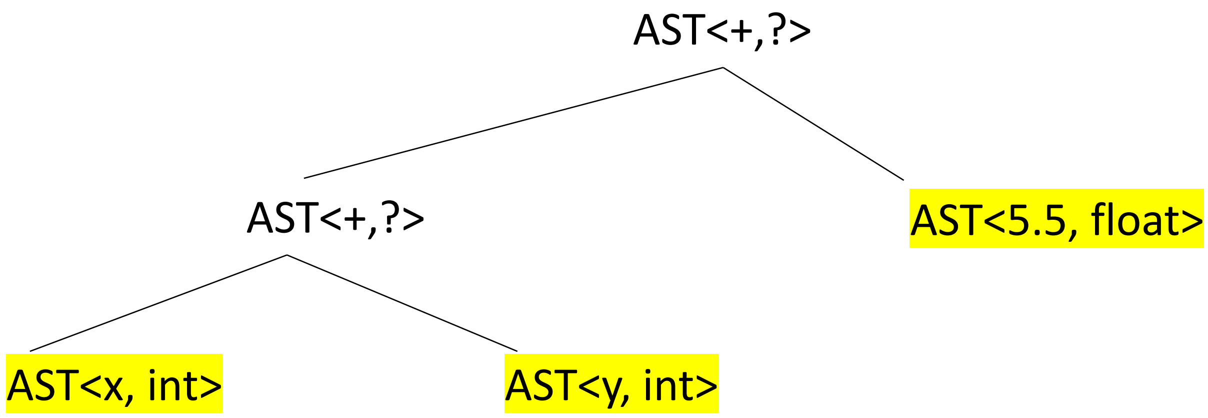
```
Unit ::= ID
     |   NUM
```

```
def parse_unit(self, lhs_node):
    # ... for applying the first production rule (ID)
    value = self.next_word.value
    # ... Check that value is in the symbol table
    node = ASTIDNode(value, ST[value])
    return node
```

Type inference

- We now have the types for the leaf nodes

```
int x;
int y;
float w;
w = x + y + 5.5
```



Type inference

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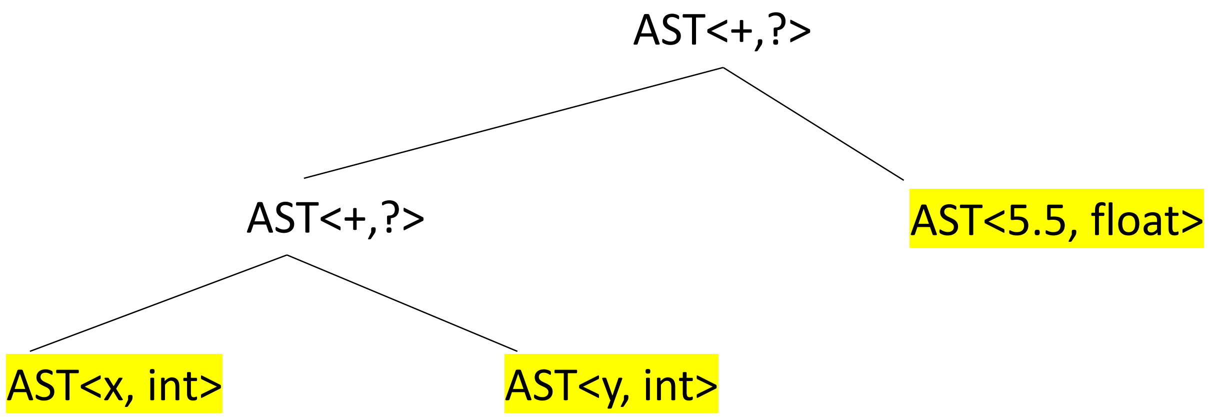

Next steps:

we do a post order traversal
on the AST and do a type inference

Type inference

```
def type_inference(n):
```

Given a node n: find its type and the types of any of its children

Type inference

def type_inference(n):

Given a node n: find its type and the types of any of its children

```
case split on node n:

if n is a leaf node:
  return n.get_type()
```

base case

Type inference

def type_inference(n):

Given a node n: find its type and the types of any of its children

```
case split on node n:

if n is a leaf node:
  return n.get_type()

if n is a plus node:
   ...
```

Type inference

def **type_inference**(n):

Given a node n: find its type and the types of any of its children

```
case split on node n:

if n is a leaf node:
  return n.get_type()

if n is a plus node:
   return lookup type from table
```

lookup the rule for plus

inference rules for plus

left	right	result
int	int	int
int	float	float
float	int	float
float	float	float

Type inference

def type_inference(n):

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inference rules for **plus**

left	right	result
`int`	`int`	`int`
`int`	`float`	`float`
`float`	`int`	`float`
`float`	`float`	`float`

but we're missing a few things

Type inference

def type_inference(n):

Given a node n: find its type and the types of any of its children

```
case split on n:

if n is a leaf node:
  return n.get_type()

if n is a plus node:
   do type inference on children
   return lookup type from table
```

we need to make sure the children have types!

inference rules for **plus**

left	right	result
int	int	int
int	float	float
float	int	float
float	float	float

Type inference

def **type_inference**(n):

Given a node n: find its type and the types of any of its children

```
case split on n:

if n is a leaf node:
  return n.get_type()

if n is a plus node:
   do type inference on children
   t = lookup type from table
   set n type to t
   return t
```

we should record our type

inference rules for **plus**

left	right	result
int	int	int
int	float	float
float	int	float
float	float	float

Type inference

def type_inference(n):

Given a node n: find its type and the types of any of its children

```
case split on n:

if n is a leaf node:
  return n.get_type()

do type inference on children
if n is a plus node:

   t = lookup type from table
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   return t
```

is this just for plus?

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```

is this just for plus?

most language promote types, e.g. ints to float for expression operators

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int	int	int
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Type inference

def type_inference(n):

Given a node n: find its type and the types of any of its children

```
case split on n:

if n is a leaf node:
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if n is a bin op node:
   do type inference on children
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is this just for plus?

most language promote types, e.g. ints to float for expression operators

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Type inference

Assignments are expressions in C/C++

def type_inference(n):

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```

What about for assignments?

```
int x;
cout << (x = 5.5) << endl;
```

What does this return?

left	right	result
int	int	int
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float	int	float
float	float	float

Type inference

Assignments are
expressions in C/C++

def type_inference(n):

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case split on n:

if n is a leaf node:
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if n is a bin op node:
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   t = lookup type from table
   set n type to t
   return t
```

What about for assignments?

```
int x;
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```

What does this return?

left	right	result
int	int	int
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whatever the left is (the type of the ID)

Type inference

Assignments are expressions in C/C++

def type_inference(n):

```
 case split on n:

 if n is a leaf node:
   return n.get_type()

 if n is an assignment:
   ....

 if n is a bin op node:
    ...
```

What about for assignments?

```
int x;
cout << (x = 5.5) << endl;
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What does this return?

left	right	result
int	int	int
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whatever the left is (the type of the ID)