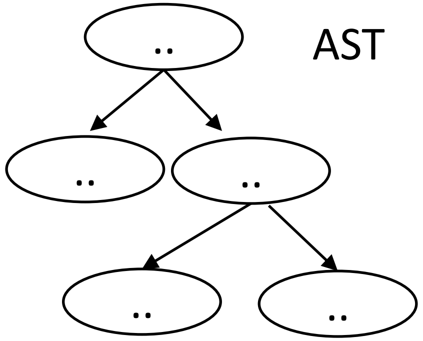
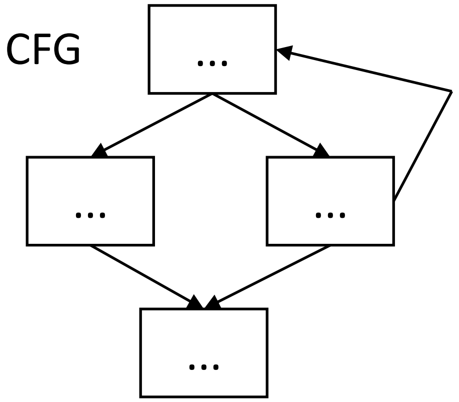
CSE110A: Compilers

May 2, 2022



Topics:

- *ASTs*
  - *type checking*



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

- HW 1 grades are released
  - Let us know in 1 week if there are any issues
  - Please let us know through a private piazza post
  - Do not ask TAs or Tutors directly about changing your grade

- Midterm is posted
  - I have updated the document once (as documented in the announcement)
  - I have started a piazza note with clarifications

Announcements

- Midterm rules
  - Ask any questions as a private piazza post
  - Do not discuss any part of it with classmates (e.g. tests, concepts, or approaches)
  - Do not ask questions online or google for exact questions
    - And if you happen to stumble across answers online, please let me know!
  - Document your answers so we can give as much partial credit as possible!
  - No late midterms will be accepted, so please plan ahead!

Announcements

- HW 2 is due today
  - Please try to get it in on time!

- It is a difficult homework; as such I will provide a life preserve
  - If you submit by the deadline you get 10 extra points
    - that can count towards 100% (but not over 100%)
  - At midnight, we will release a solution to part 1:
    - A grammar along with a First+ set
  - You can use this grammar to help you with part 2 and part 3
    - Late penalties still apply. No extra points

  - The intent is this:
    - If you got a decent solution turned in, you can be done with this homework as planned
    - If you were completely stuck, you can use the grammar and first+ sets to submit something in the next few days

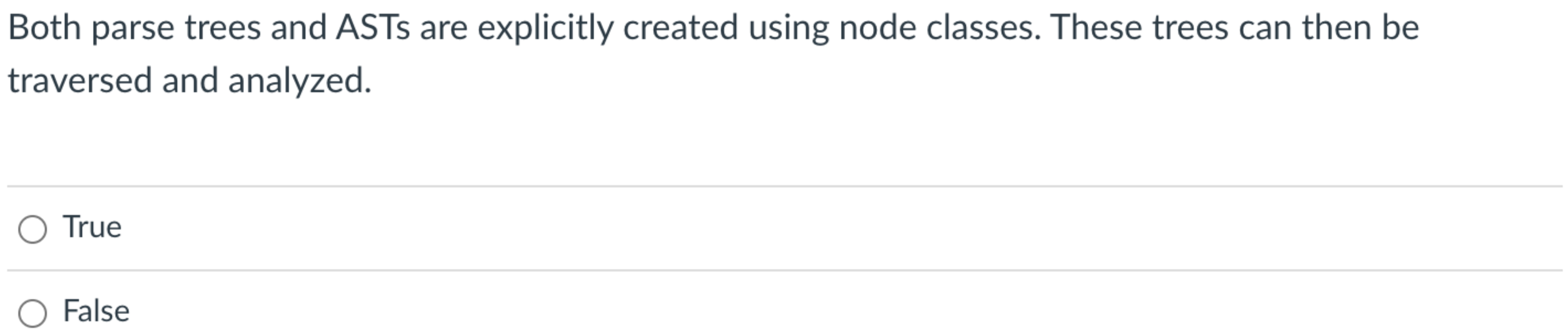
  - We will only grade one solution and we will grade the latest solution submitted

Homework 2 clarifications

- What information for each variable does the symbol table hold?
    - For this assignment, nothing! It just keeps track of which variables have been declared and in which scope.
    - For the next homework we will add type information to the symbol table

Quiz

Quiz



Both parse trees and ASTs are explicitly created using node classes. These trees can then be traversed and analyzed.

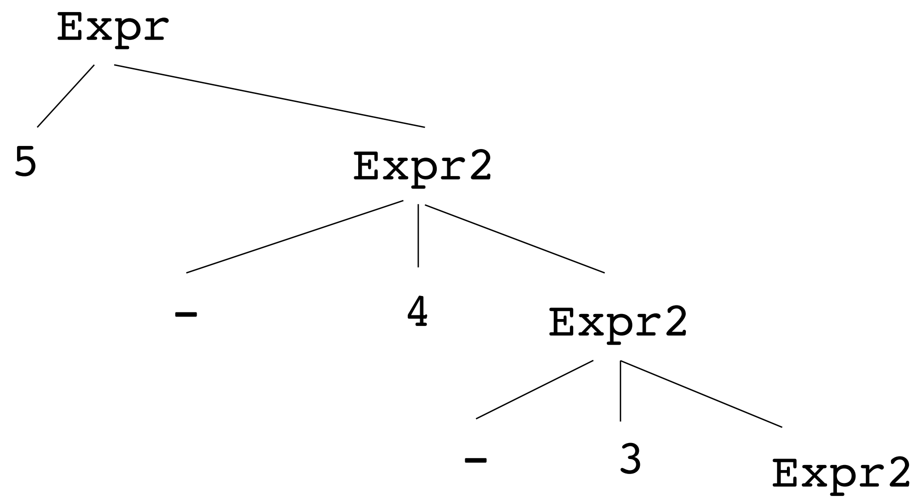
○ True

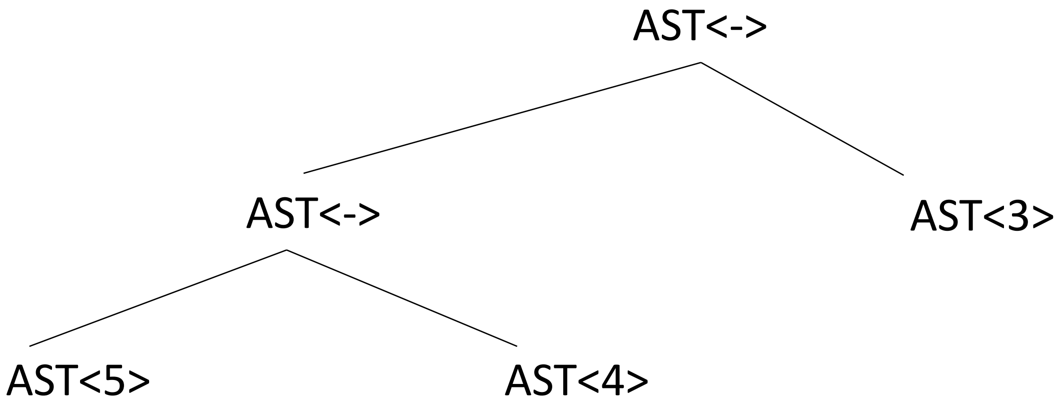
○ False

Creating an AST from predictive grammar

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

```
5 - 4 - 3
```





How do we get to the desired parse tree?

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

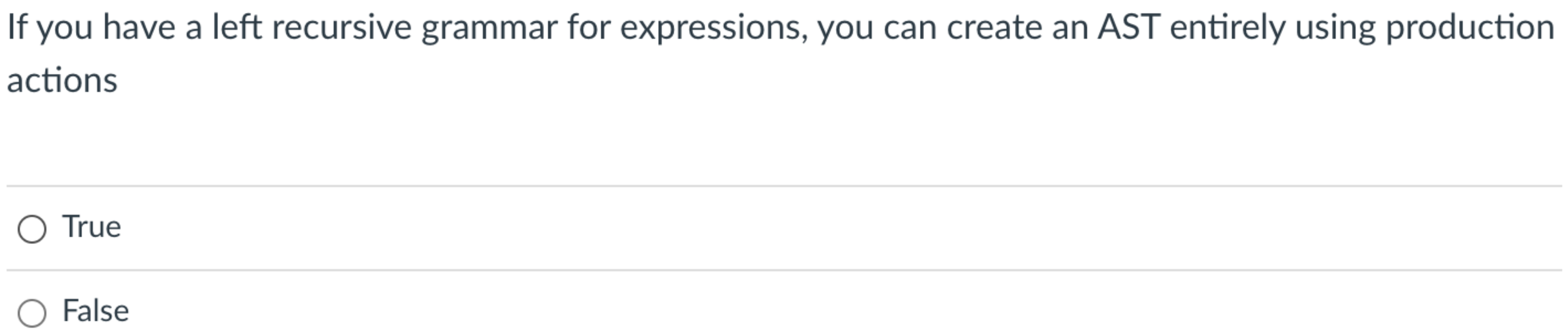
```python
class ASTLeafNode(ASTNode):
    def __init__(self, value):
        self.value = value


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)
```

Quiz



If you have a left recursive grammar for expressions, you can create an AST entirely using production actions

○ True

○ False

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)}`
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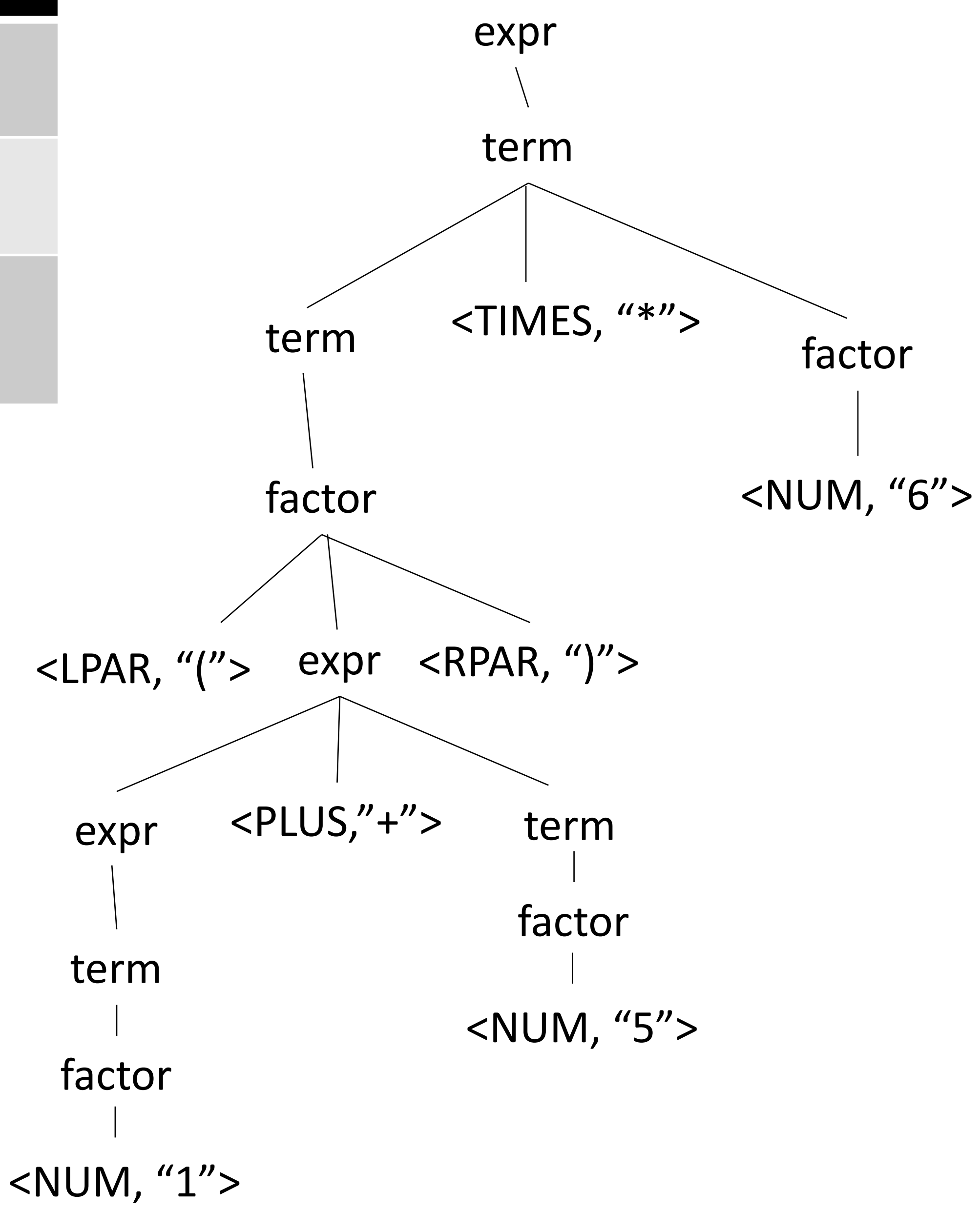
`input: (1+5)*6`



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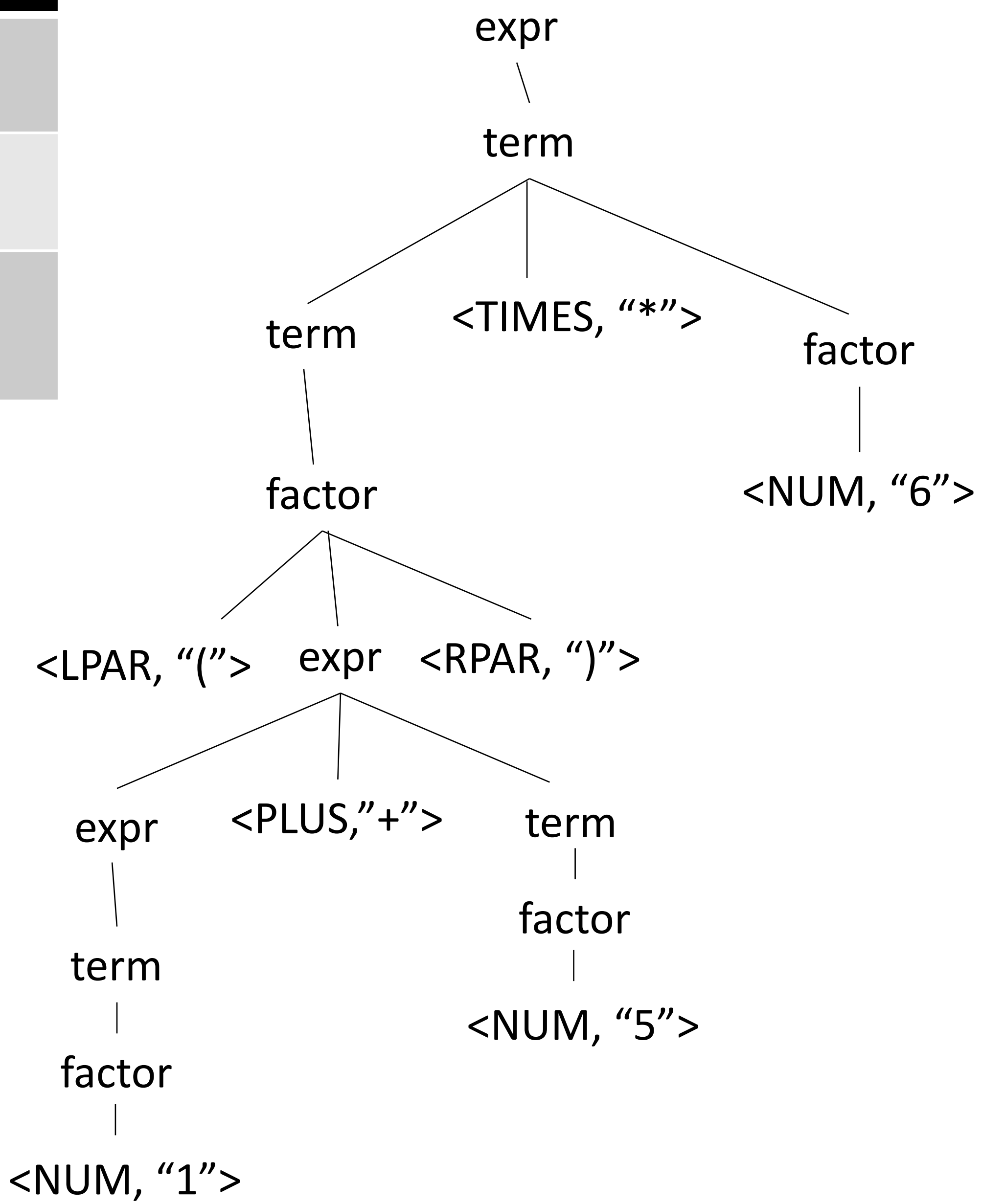

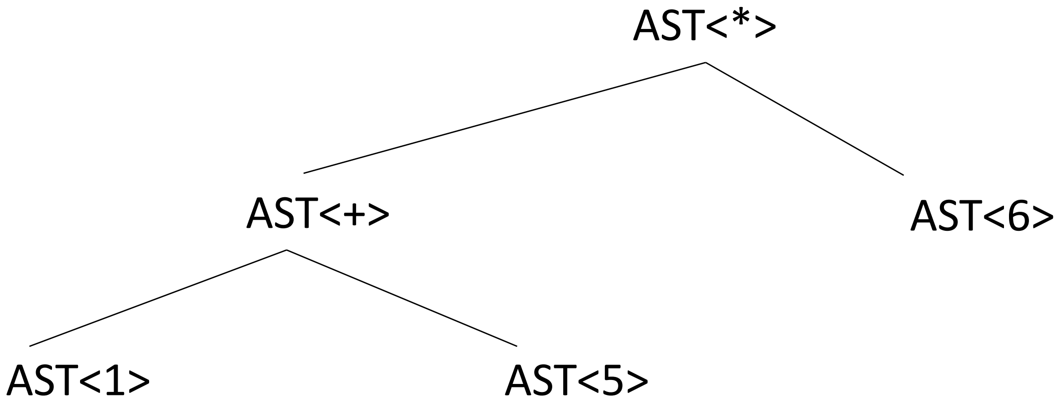

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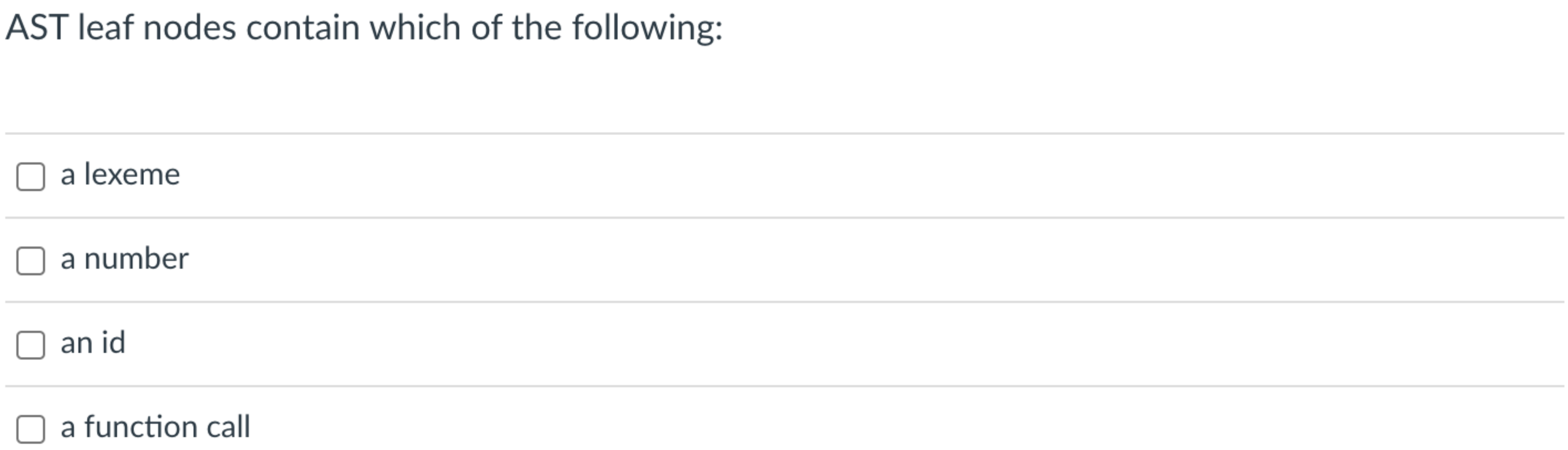

AST leaf nodes contain which of the following:

- □ a lexeme
- □ a number
- □ an id
- □ a function call

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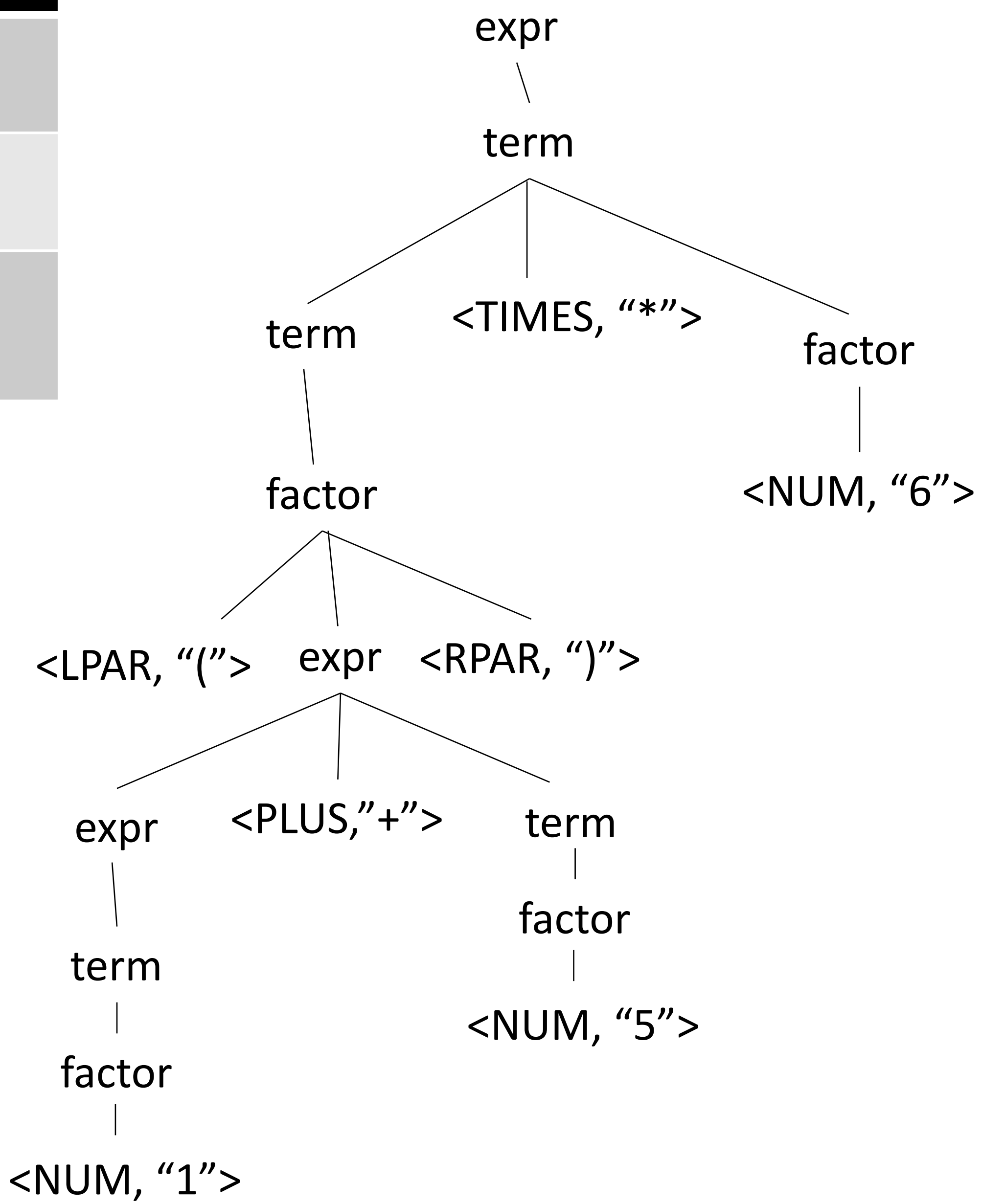

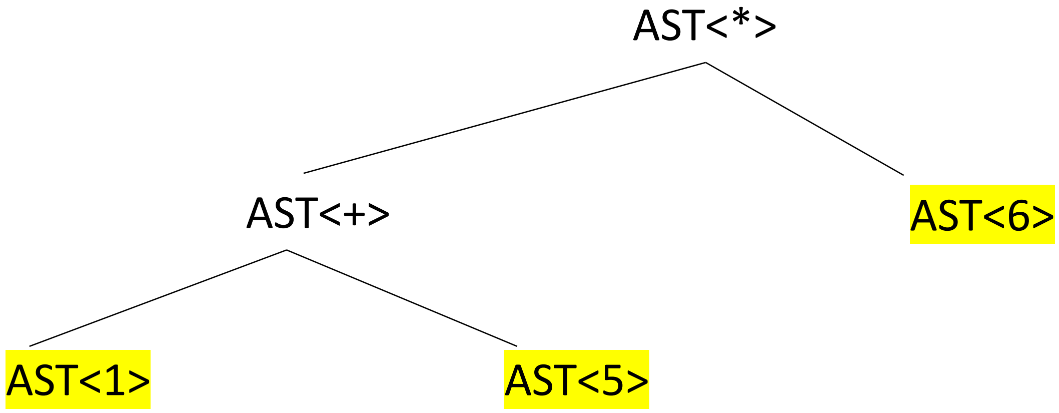

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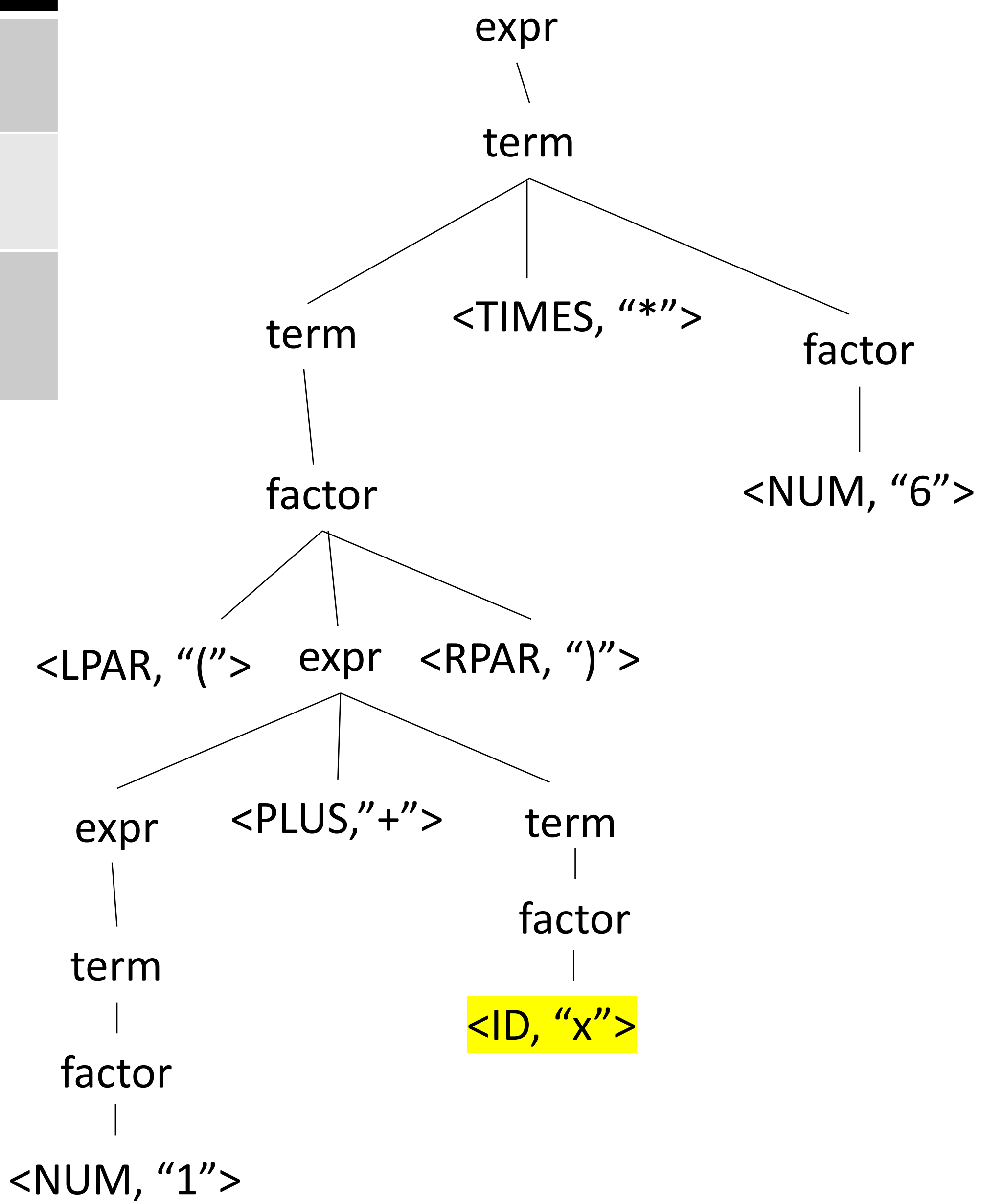
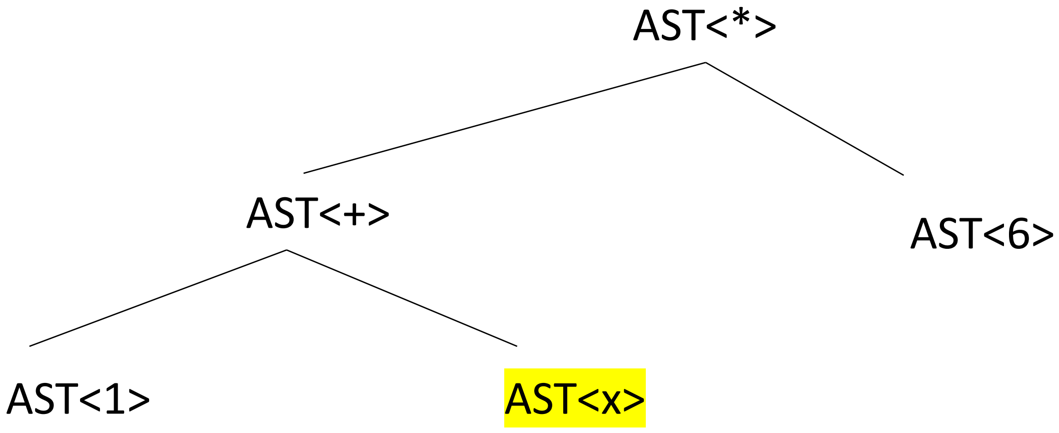
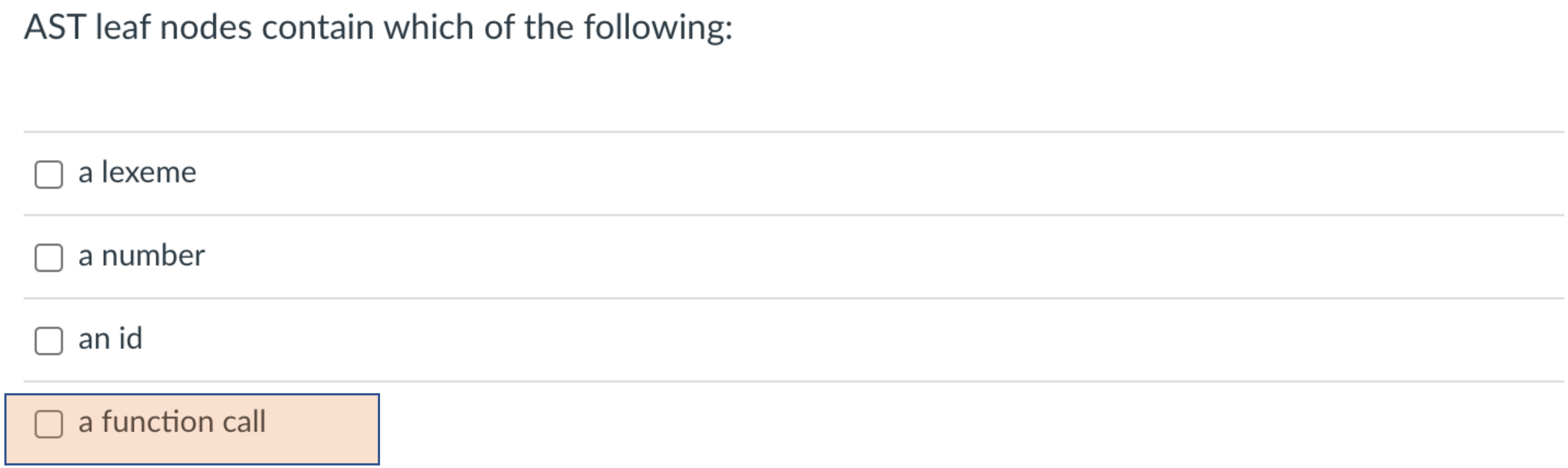
`input: (1+x)*6`





Quiz



AST leaf nodes contain which of the following:

- □ a lexeme
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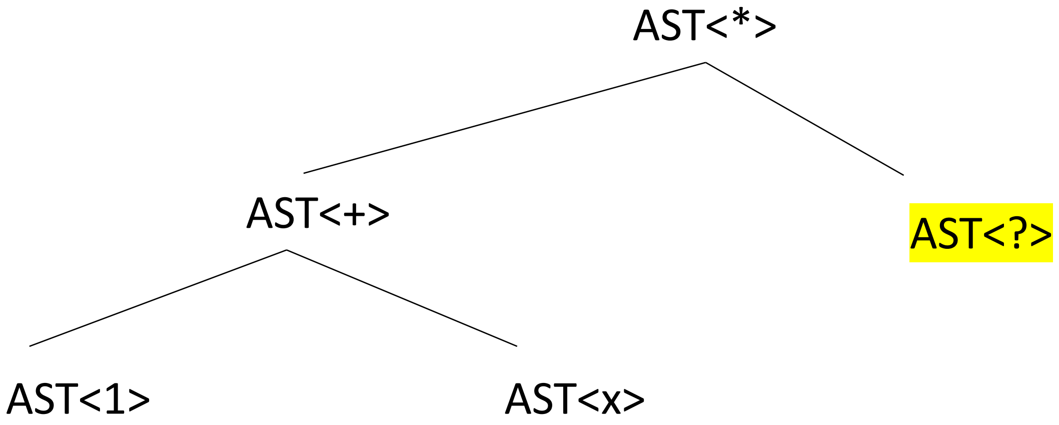
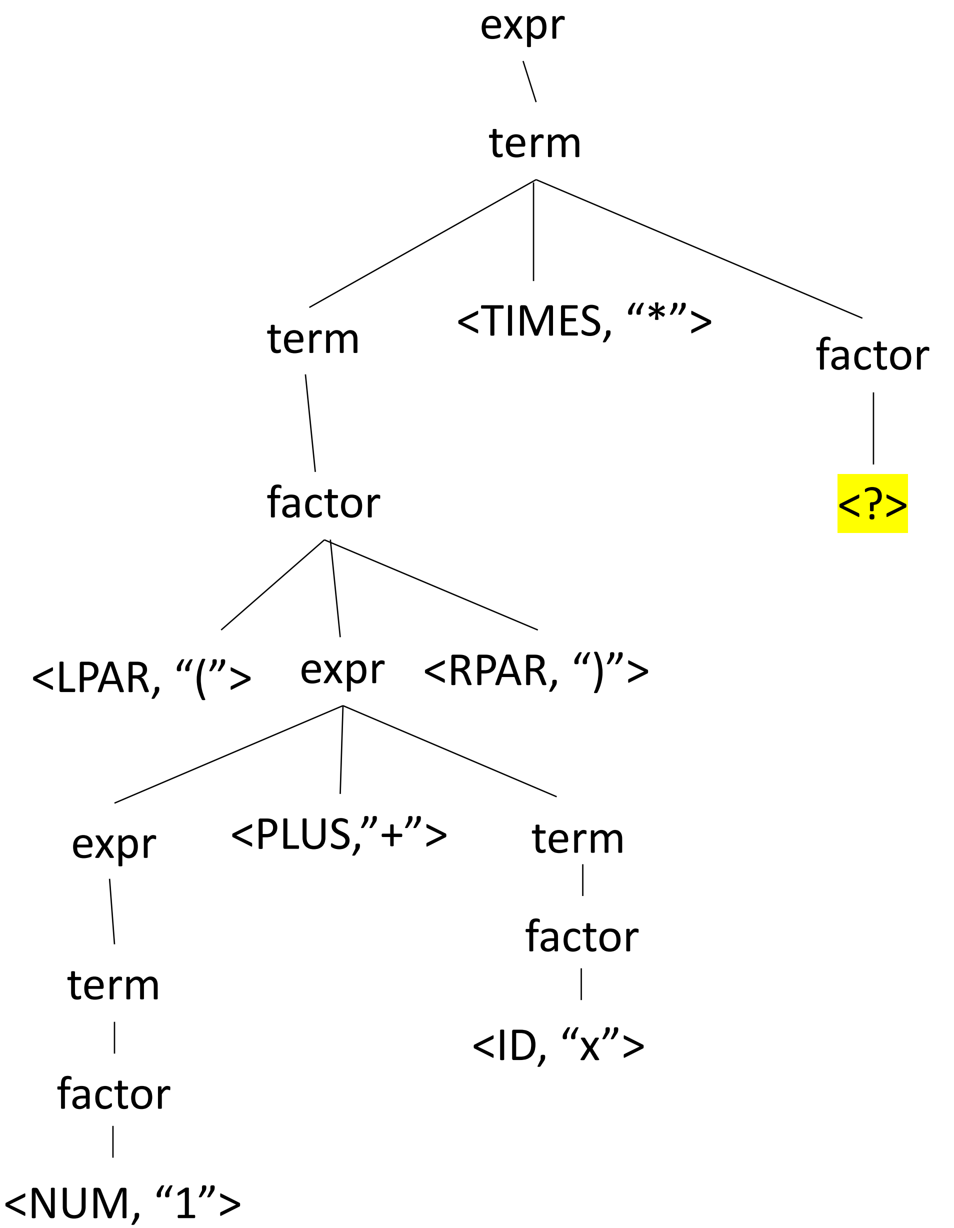
Our language doesn't have function calls, but what do we think?



`(1+x)*sqrt(x)`



Quiz

Write a few sentences about the differences between a parse tree and an AST

Review

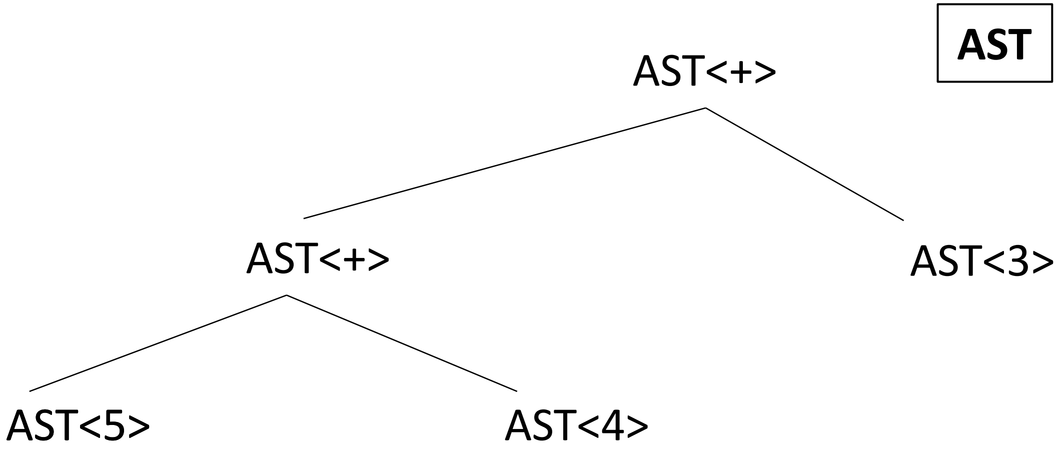
The quiz was a good review of the material

New material

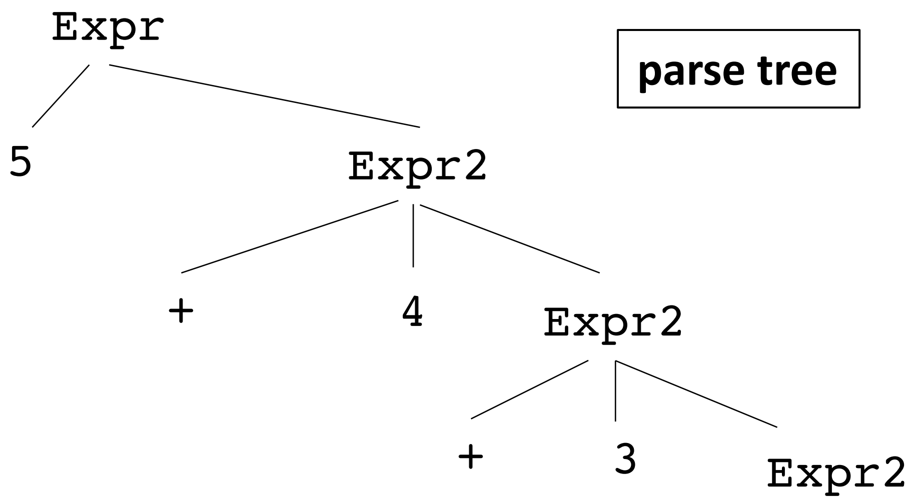
- Type systems
  - Evaluating an AST
  - Type systems
  - Type checking

Evaluate an AST by doing a post order traversal

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



`5 + 4 + 3`



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

Evaluate an AST by doing a post order traversal

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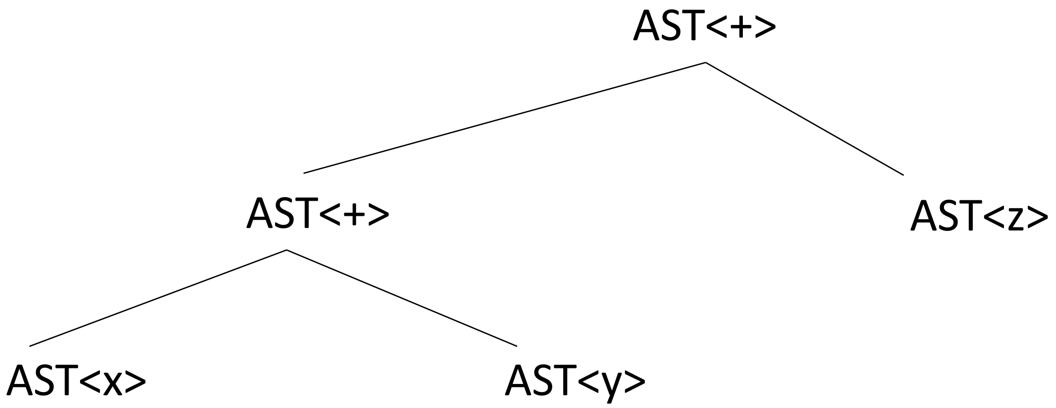

What if you cannot evaluate it?
What else might you do?

```
x + y + z
```

Evaluate an AST by doing a post order traversal

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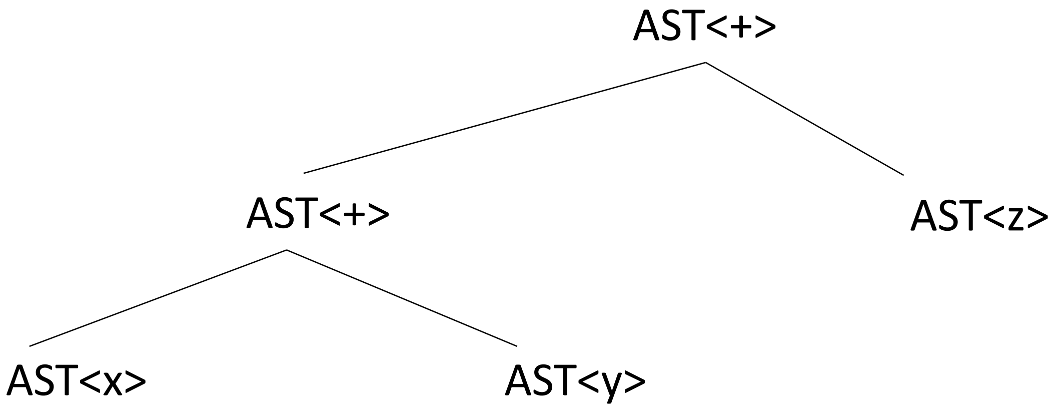

What if you cannot evaluate it?
What else might you do?

```
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

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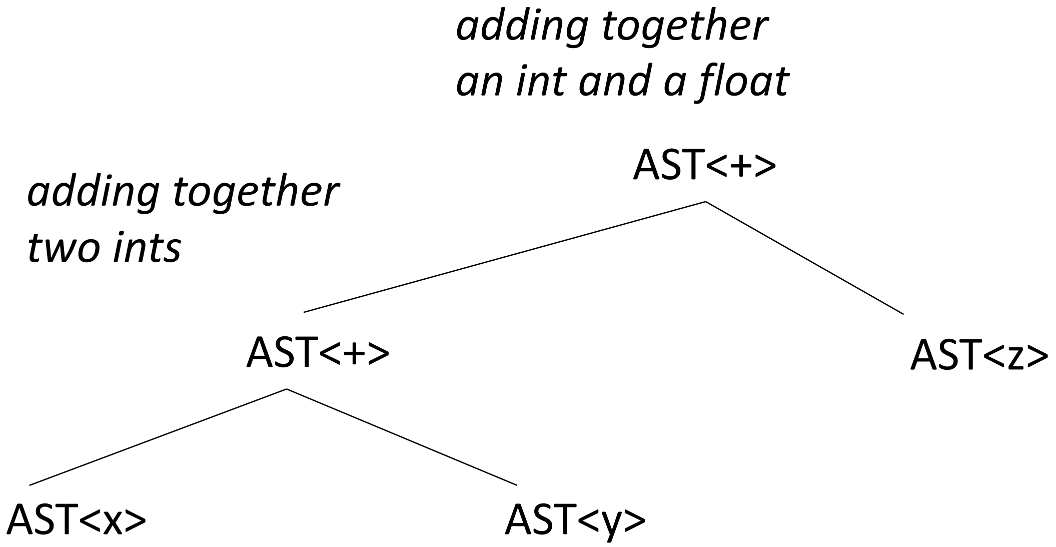

adding together an int and a float

adding together two ints

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?

in many languages this is fine, but we are working towards assembly language

Evaluate an AST by doing a post order traversal

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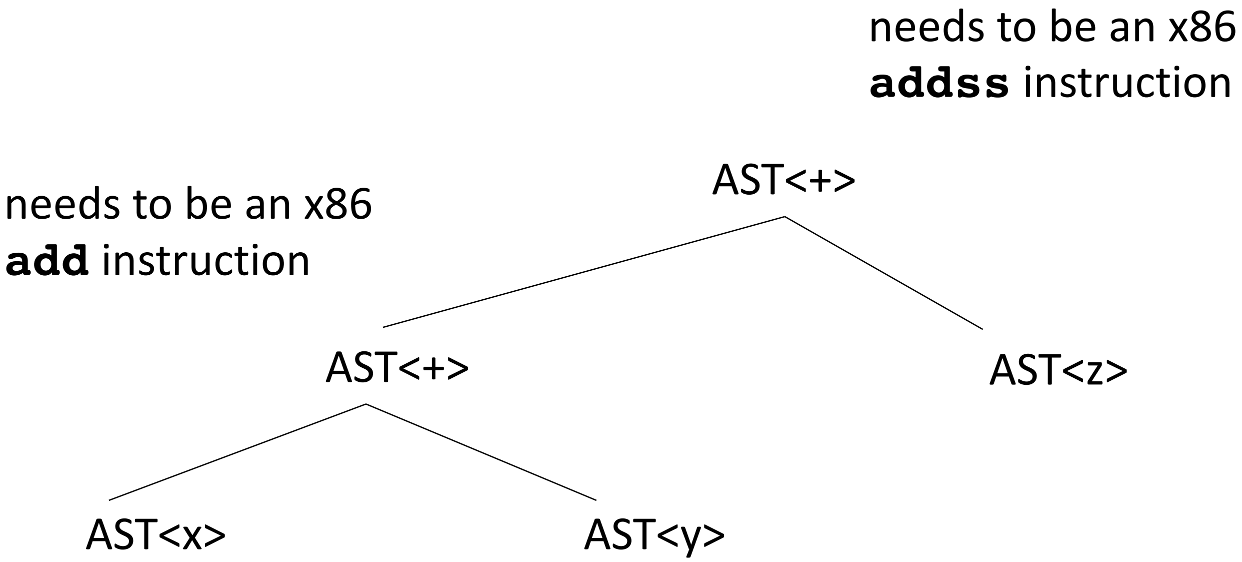
       |    “”
```



needs to be an x86 **addss** instruction

needs to be an x86 **add** instruction

add r0 r1 - interprets the bits in the registers as integers and adds them together

addss r0 r1 - interprets the bits in the registers as floats and adds them together

Evaluate an AST by doing a post order traversal

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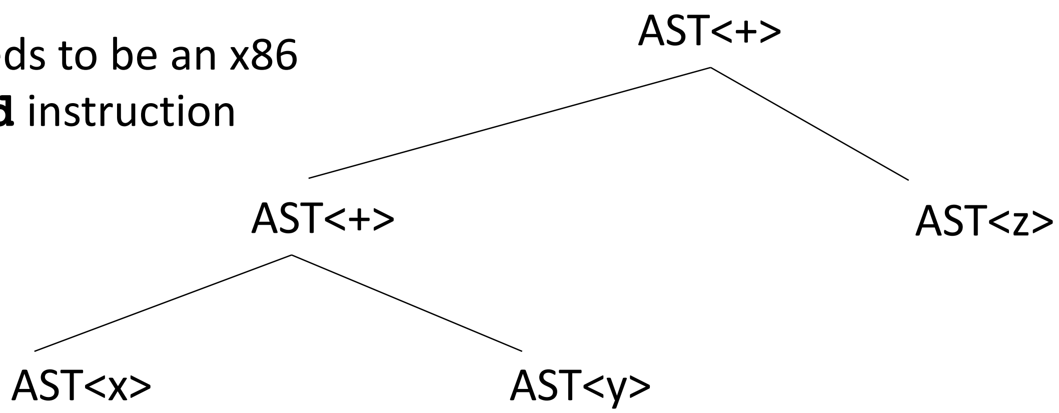
AST<+>
AST<+>
AST<z>
AST<x>
AST<y>

Lets do some experiments.

What should 5 + 5.0 be?

Is this all?

Evaluate an AST by doing a post order traversal

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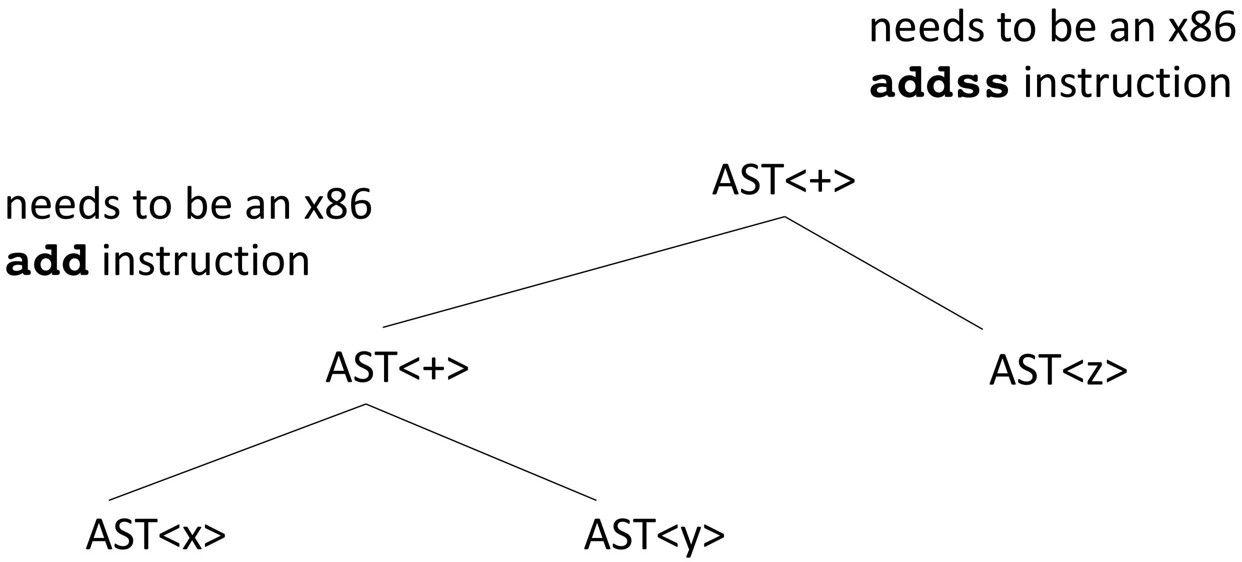
Expr2 ::= PLUS NUM Expr2
      |   “”
```



needs to be an x86 **addss** instruction

AST<+>

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AST<+>

AST<z>

AST<x>

AST<y>

Is this all?

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

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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       |    “”
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int x;
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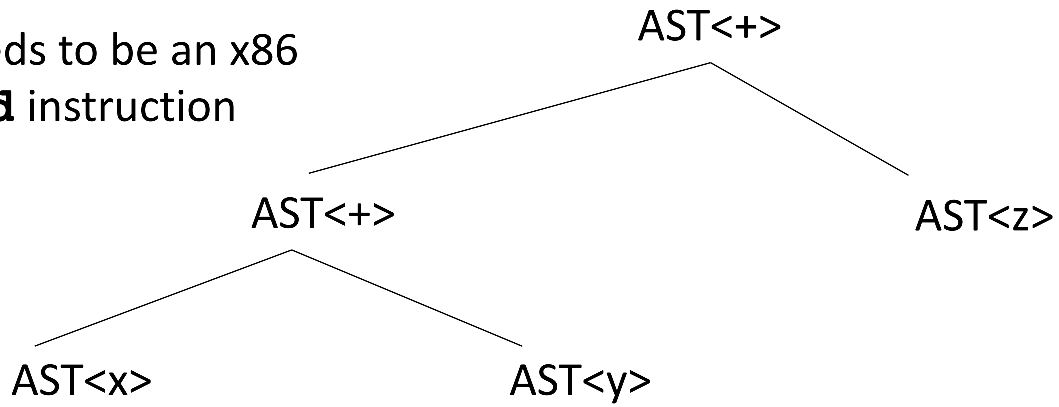

AST<+>

AST<+>

AST<z>

AST<x>

AST<y>

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

We cannot just add them!

Is this all?

Evaluate an AST by doing a post order traversal

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```
int x;
int y;
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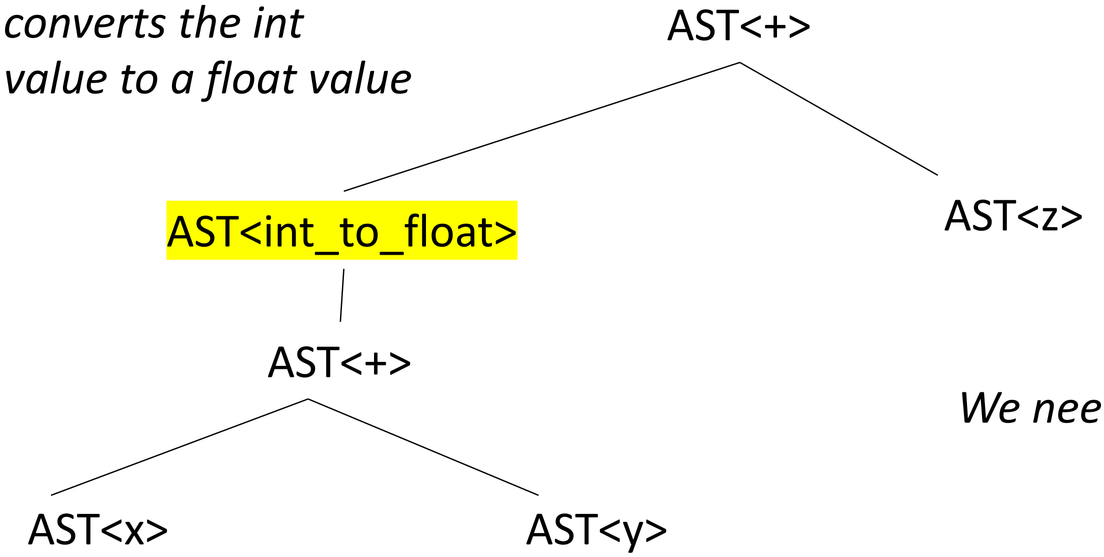

converts the int value to a float value

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

Type systems

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 systems

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  - 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

- 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?

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- What are examples of each?
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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 ...
```

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- 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

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

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?
- In this class, we will be:
  - Compiling a statically typed language (similar to C)
  - into an untyped language (similar to an ISA)
  - using a dynamically typed language (python)

Type systems

Considerations:

Type systems

Considerations:

- Base types in the language:
  - 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:
    - ints
    - chars
    - strings
    - floats
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size of ints?
How does C do it?
How does Python do it?
Pros and cons?

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

Type systems

Considerations:

- Base types:
  - ints
  - chars
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Are strings a base type? In C? In Python?

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

Type systems

Considerations:

- Base types:
  - ints
  - chars
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How are bools handled? in C? in Python

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

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

Type checking

Two components

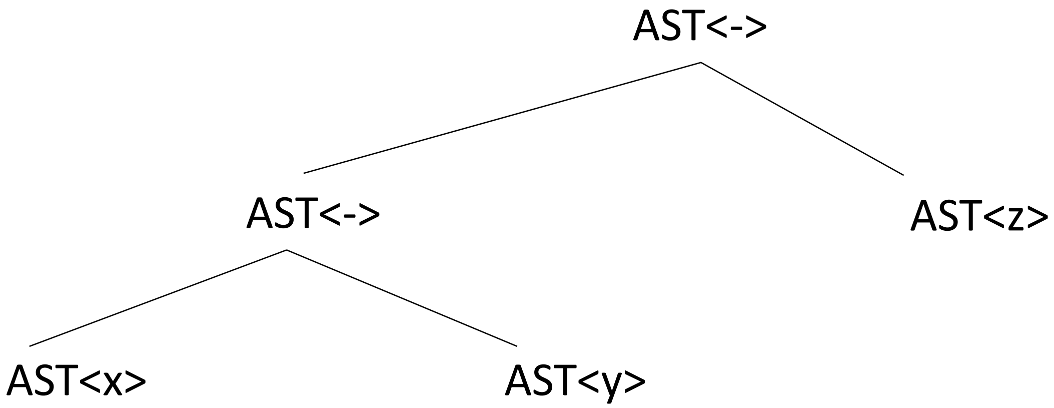
- Type inference
  - Determines a type for each AST node
  - Modifies the AST into a type-safe form

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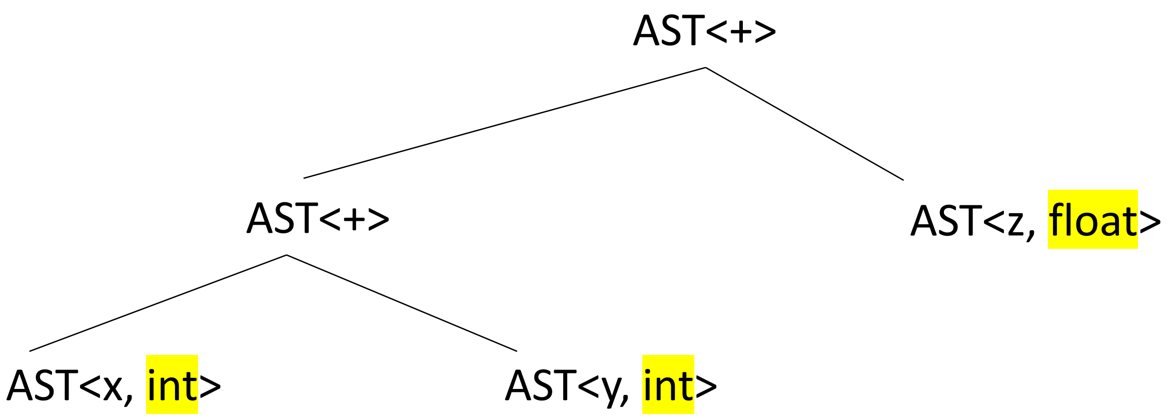
each node additionally gets a type
we can get this from the symbol table for the leaves or based on the input (e.g. 5 vs 5.0)



Type checking on an AST

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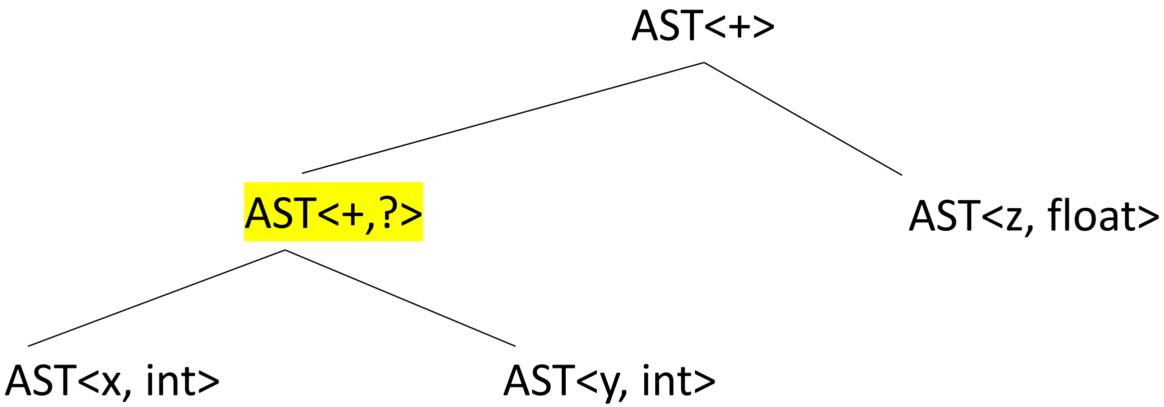
How do we get the type for this one?



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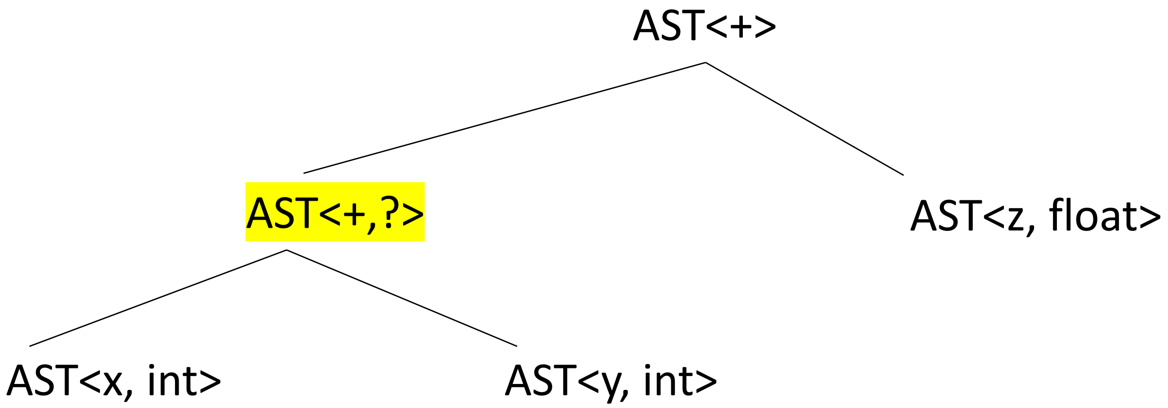

inference rules for addition:

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

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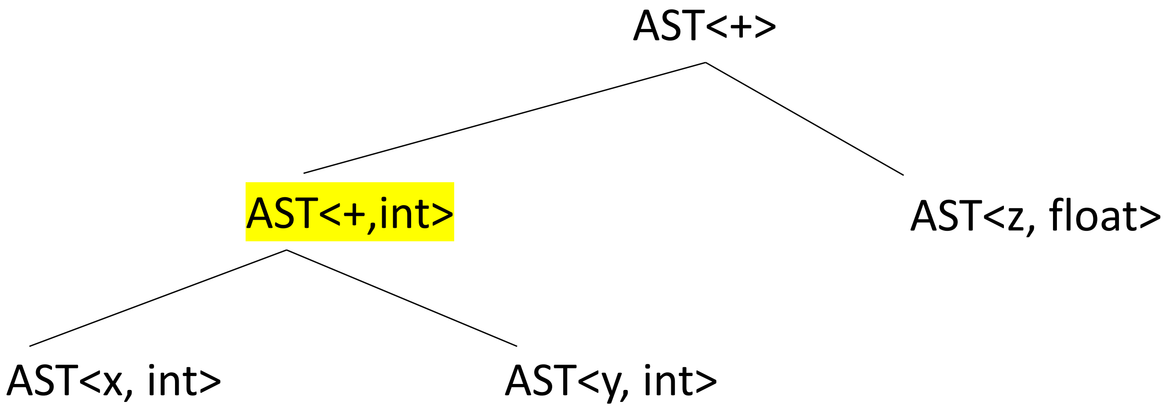

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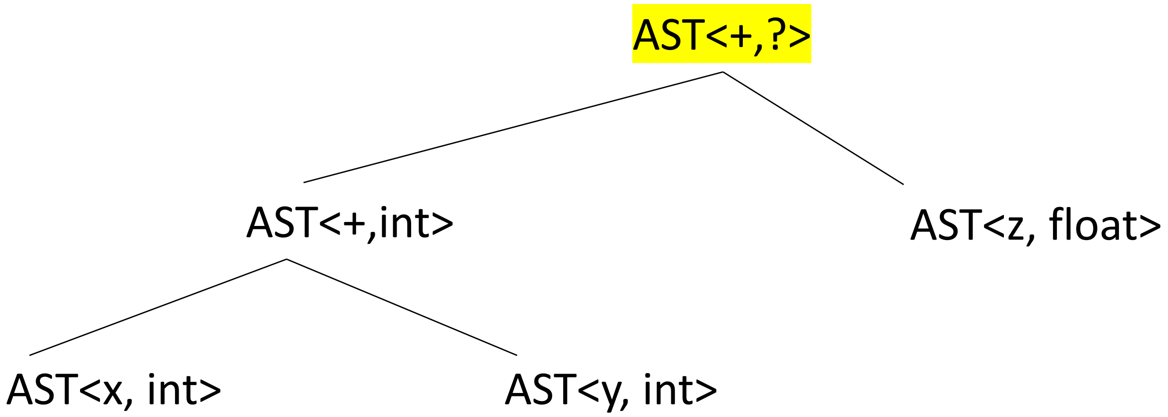
float w;
w = x + y + z
```

How do we get the type for this one?



AST<+,?>

AST<+,int>

AST<z, float>

AST<x, int>

AST<y, int>

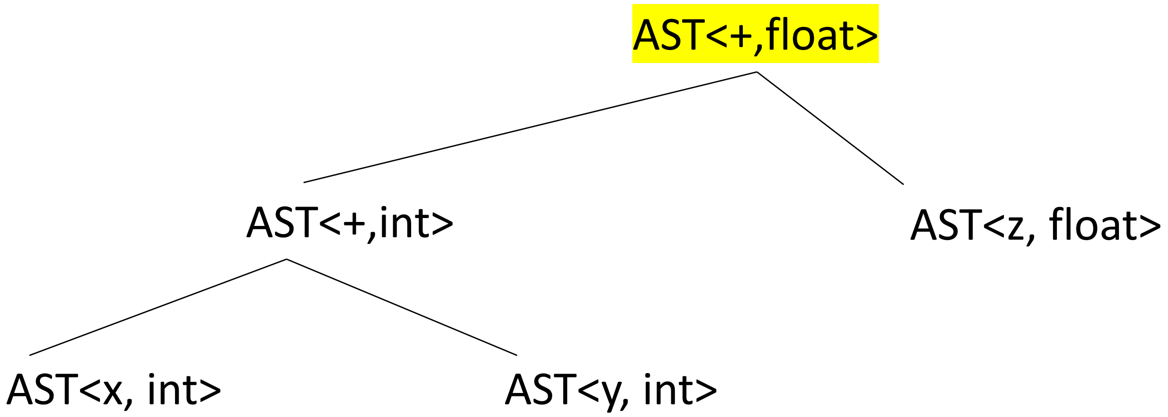
inference rules for addition:

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

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?



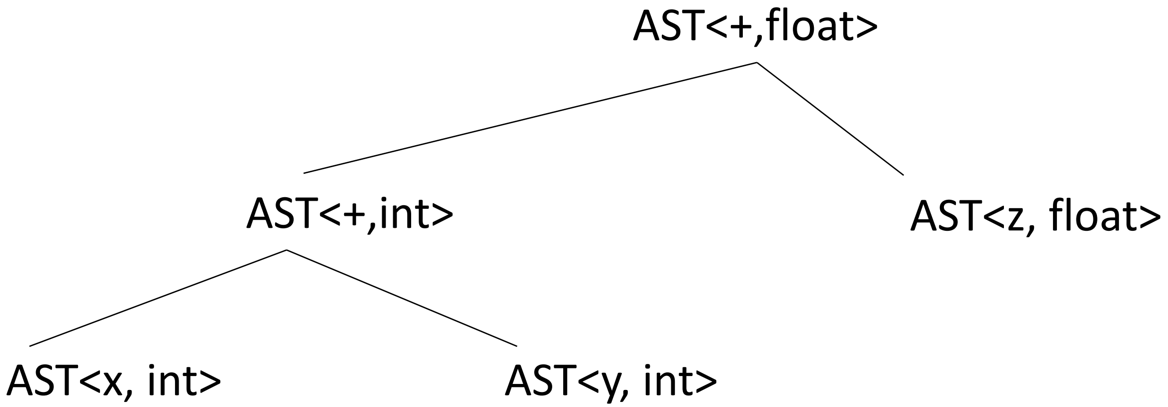
inference rules for addition:

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

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?



AST<+,float>

AST<+,int>

AST<z, float>

AST<x, int>

AST<y, int>

inference rules for addition:

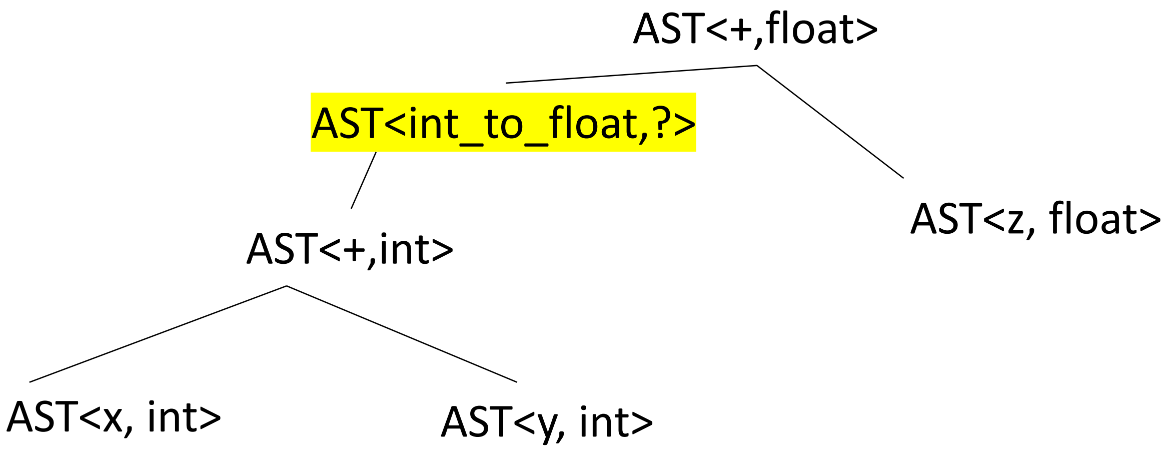
first	second	result
`int`	`int`	`int`
`int`	`float`	`float`
`float`	`int`	`float`
`float`	`float`	`float`

what else?

Type checking on an AST

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

How do we get the type for this one?



AST<+,float>

AST<int_to_float,?>

AST<z, float>

AST<+,int>

AST<x, int>

AST<y, int>

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

```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)
```

Enum for types

```python
from enum import Enum

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

Our base AST Node needs a type

```python
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

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

```
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):
        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

```
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?

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[1]
  eat(ID)
  ST.insert(id_name, None)
  eat(SEMI)
}
```

in homework 2 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[1]
  eat(TYPE)
  id_name = self.to_match[1]
  eat(ID)
  ST.insert(id_name, value_type)
  eat(SEMI)
}
```

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

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

```
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

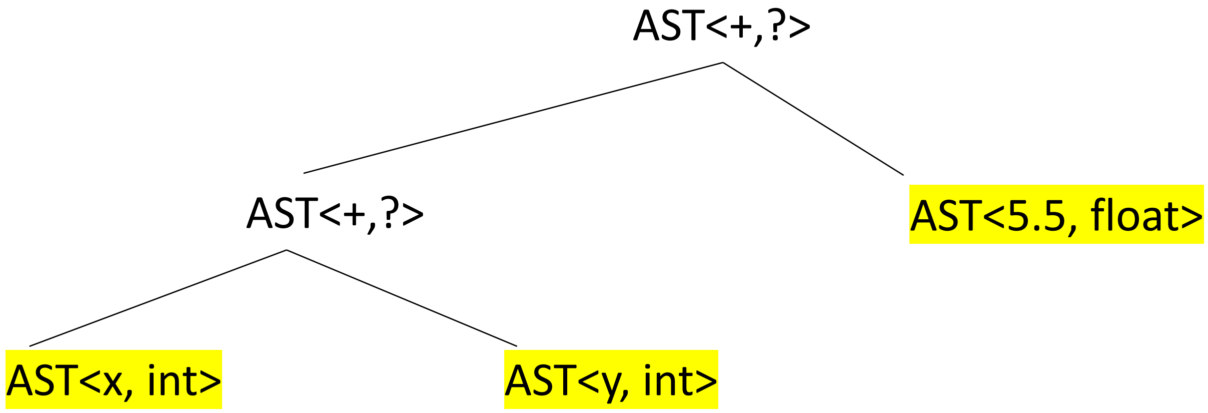
```
Unit ::= ID
      |   NUM
```

```
def parse_unit(self, lhs_node):
    # ... for applying the first production rule (ID)
    value = self.next_word[1]
    # ... 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
```



AST<+,?>

AST<+,?>

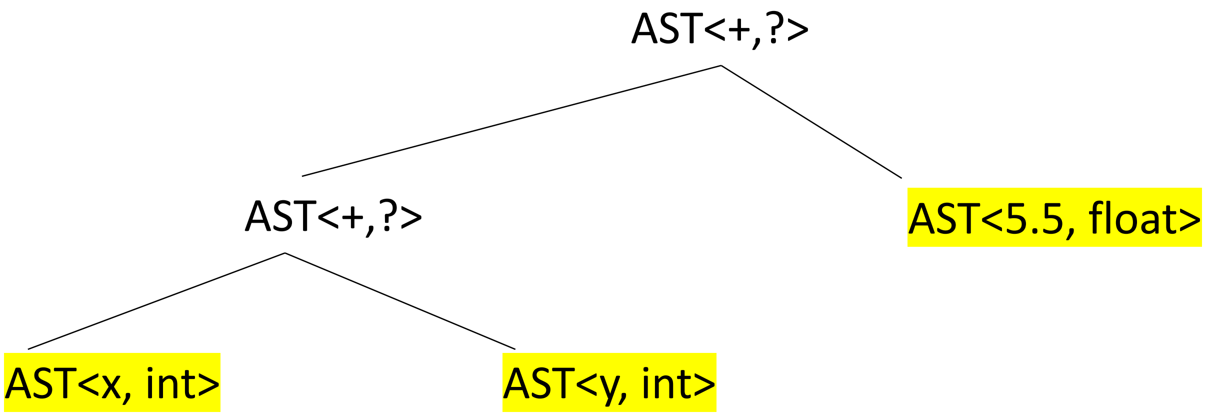
AST<5.5, float>

AST<x, int>

AST<y, int>

Type inference

- We now have the types for the leaf nodes



AST<+,?>

AST<+,?>

AST<5.5, float>

AST<x, int>

AST<y, int>

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 n:

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

base case

Type inference

```
def type_inference(n):

 case split on n:

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

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

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 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):

  case split on n:

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

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

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

lookup the rule for plus

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):

  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
```

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

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):

 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
```

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

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):

 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
```

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

is this just 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
```

is this just for plus?

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

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 bin op node:
    do type inference on children
    t = lookup type from table
    set n type to t
    return t
```

is this just for plus?

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

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

Type inference

```
def type_inference(n):

 case split on n:

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

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

What about for assignments?

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

What does this return?

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

Type inference

```
def type_inference(n):

 case split on n:

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

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

What about for assignments?

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

What does this return?

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

whatever the left is

Type inference

```
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;
```

What does this return?

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

whatever the left is

Type checking

- Checking for errors

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
    if t is None:
       throw type exception
    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()

if n is a plus node:
   do type inference on children
   t = lookup type from table
   if t is None:
      throw type exception
   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
string	int	None

like in Python

Type inference

```
def type_inference(n):

 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
    if t is None:
       throw type exception
    set n type to t
    return t
```

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

we should record our type

inference rules for plus

left	right	result
int	int	int
int	float	float
float	int	float
float	float	float
string	int	None

like in Python

See everyone on Wednesday

- We will discuss linearizing code