

Semantic Analysis

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Semantic Analysis

Perform various checks:

- Type checking
 - $1 + \text{"1"}$
- Scopes
 - Undefined variables
- Other
 - Division by zero
 - Visibility semantics in classes (public, private, ...)

Visitor Design Pattern

Perform computations over tree-like data structures

visit(node):

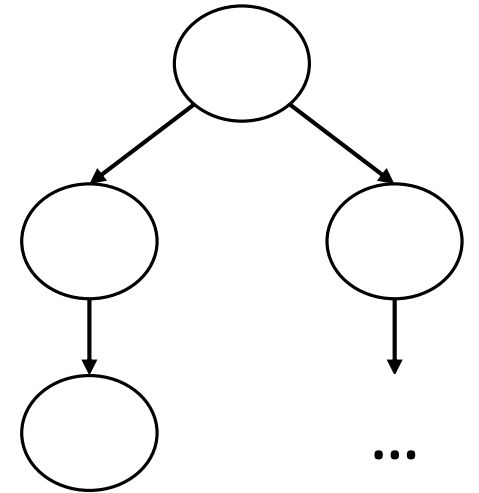
// do something with node

$r_1 = \text{visit}(\text{node.child}_1)$

$r_2 = \text{visit}(\text{node.child}_2)$

...

// do something with r_1, r_2, \dots



Visitor Design Pattern: Example

Printing the AST

```
visit(node):  
    print(node)  
    for child in node.children:  
        visit(child)
```

Symbol Table

- Stack of scopes
- Each scope contains information about identifiers
 - Name
 - Type (int, string, ...)
 - Kind (variable, function, method, ...)

Symbol Table



Symbol Table Operations

- **Insert** symbol
- **Lookup** symbol
- **Enter** scope
- **Exit** scope

Symbol Table: Insert

Example:

- Insert(z, int, variable)

main scope

ID	Type	Kind
x	int	variable
y	int	variable

scope₁

ID	Type	Kind
tmp	int	variable

scope₂



Symbol Table: Insert

Example:

- Insert(z, int, variable)

main scope

ID	Type	Kind
x	int	variable
y	int	variable

scope₁

ID	Type	Kind
tmp	int	variable
z	int	variable

scope₂

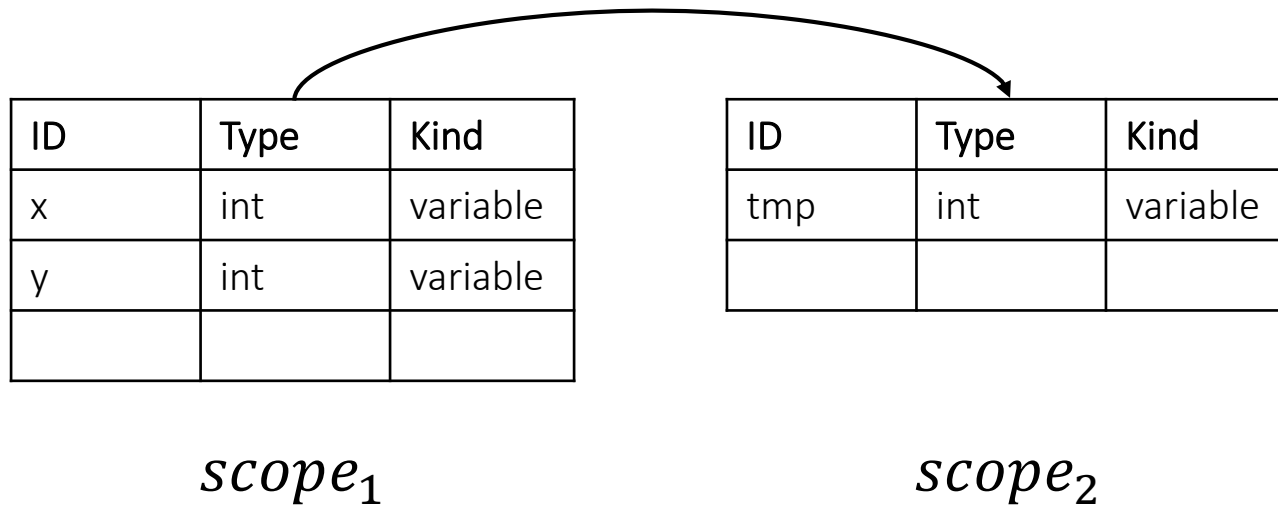


Symbol Table: Lookup

Example:

- Lookup(y)
 - Start from the top of the stack, return **first** match

main scope

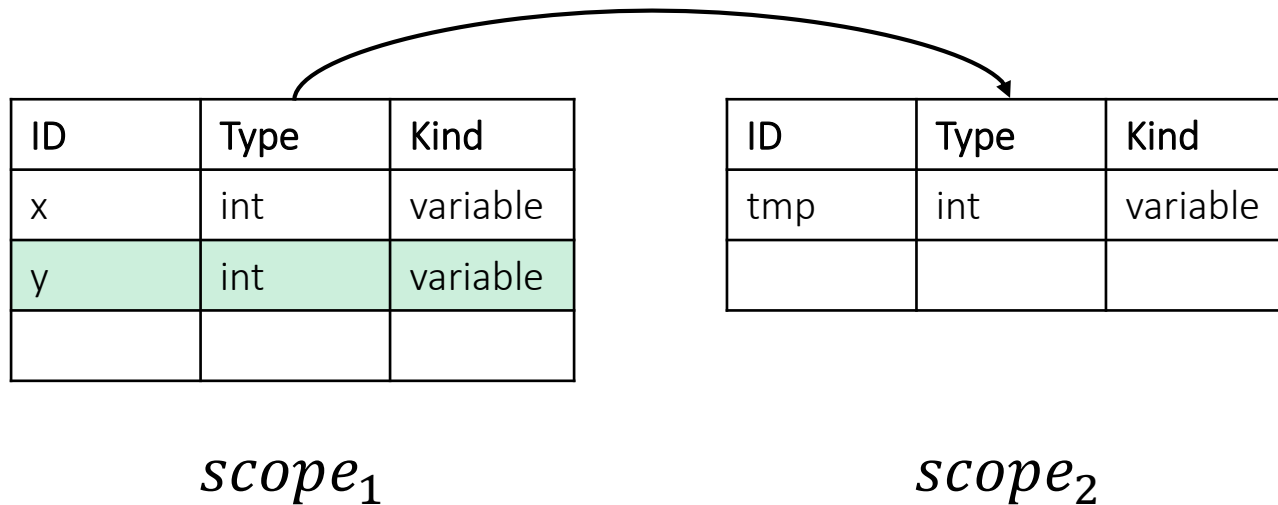


Symbol Table: Lookup

Example:

- Lookup(y)
 - Start from the top of the stack, return **first** match

main scope



Symbol Table: Enter

main scope

ID	Type	Kind
x	int	variable
y	int	variable

scope₁

ID	Type	Kind
tmp	int	variable

scope₂



Symbol Table: Enter

main scope

ID	Type	Kind
x	int	variable
y	int	variable

$scope_1$

ID	Type	Kind
tmp	int	variable

$scope_2$

ID	Type	Kind

$scope_3$



Symbol Table: Exit

main scope

ID	Type	Kind
x	int	variable
y	int	variable

scope₁

ID	Type	Kind
tmp	int	variable

scope₂



Symbol Table: Exit

main scope

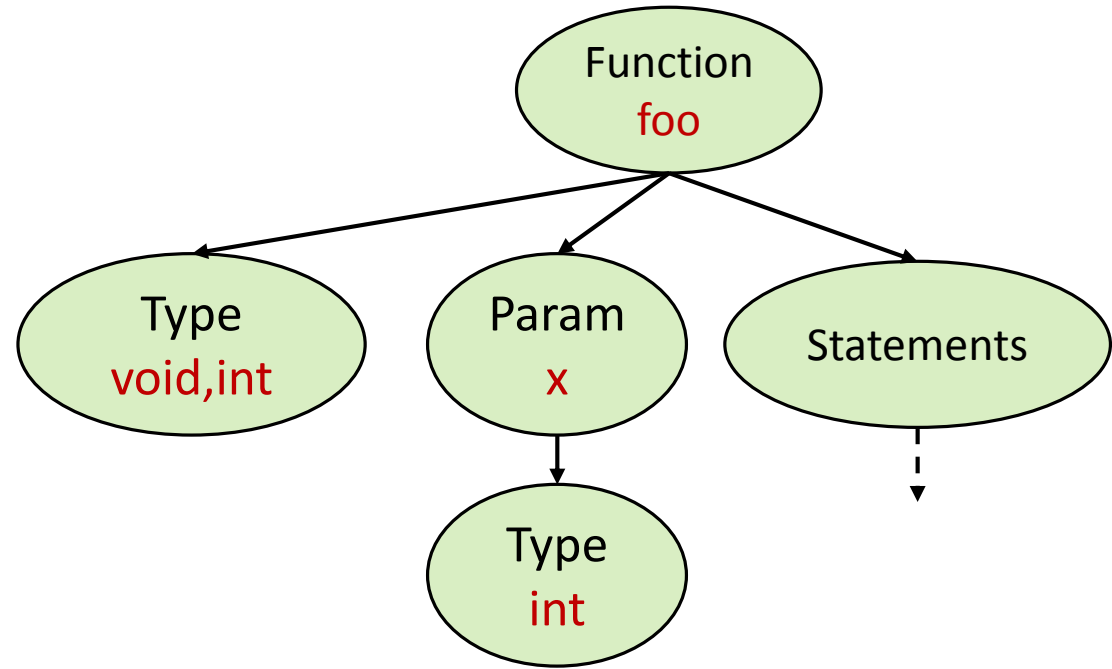
ID	Type	Kind
x	int	variable
y	int	variable

scope₁

Symbol Table Construction

- Identifier declaration
 - Insert
- Identifier reference
 - Lookup
- When visiting a new block
 - Enter
- When leaving a block
 - Exit

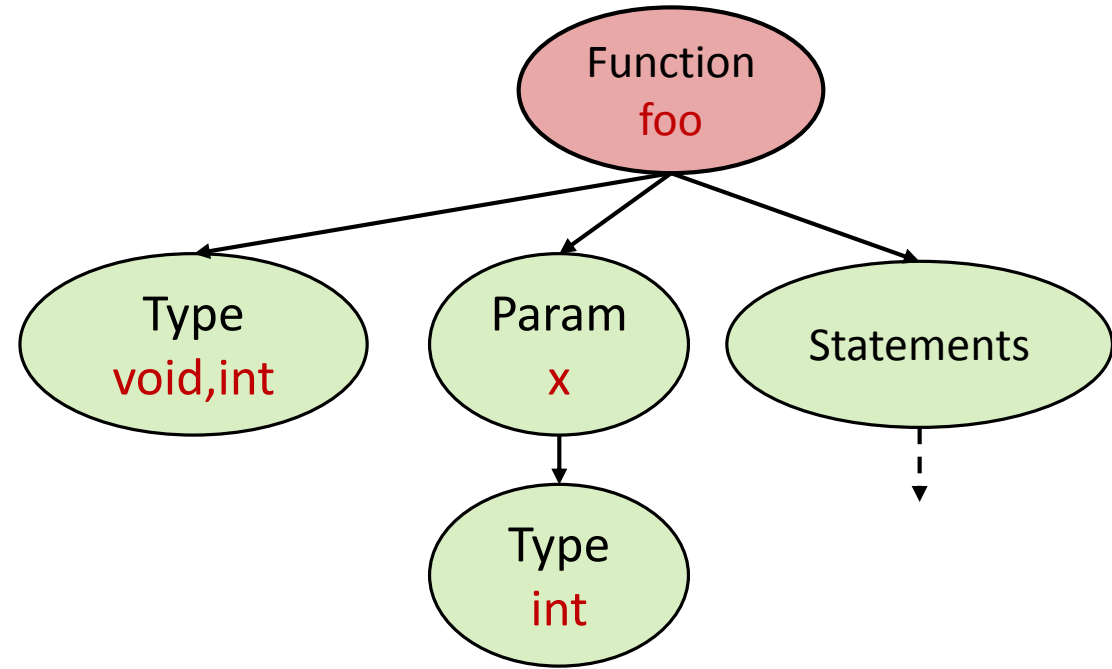

```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```





```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

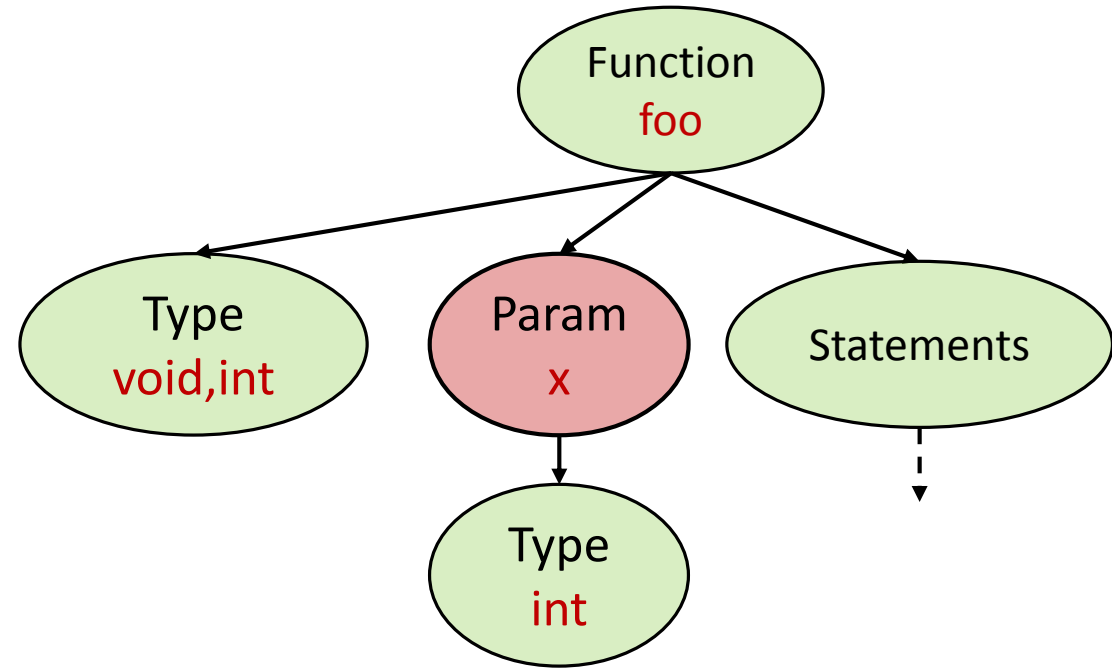




```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable

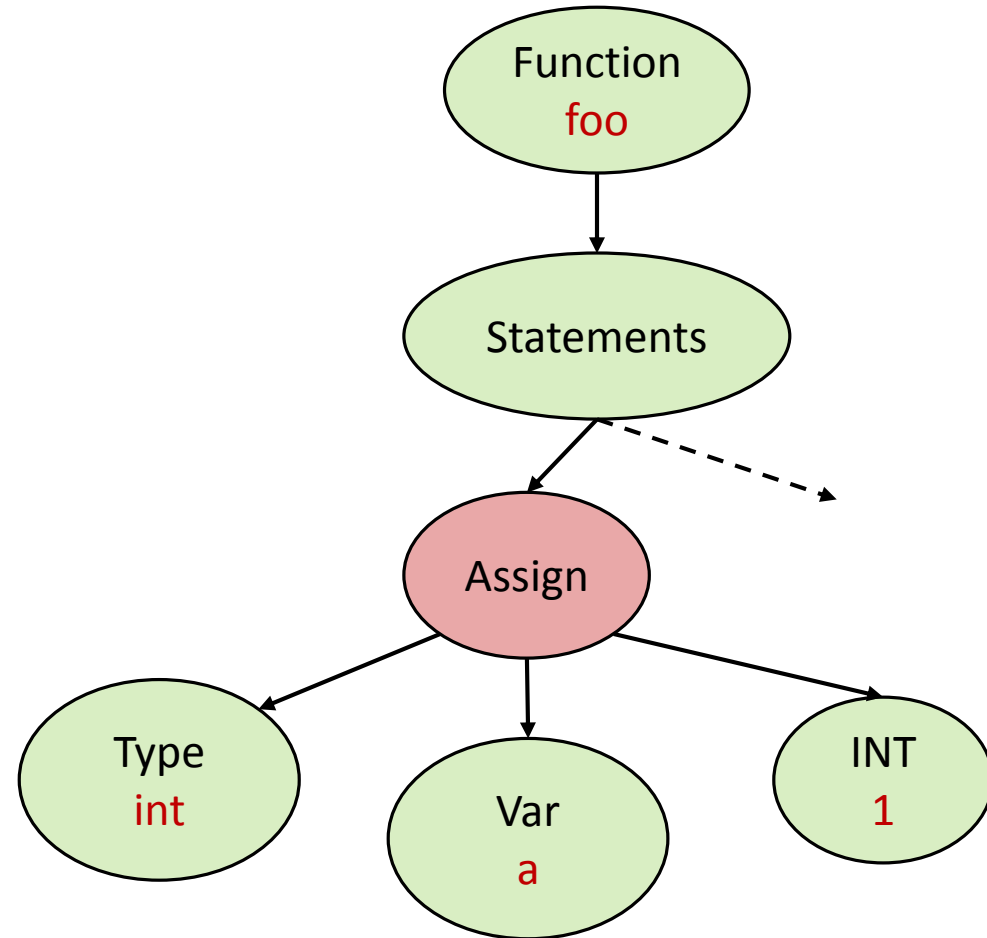




```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable

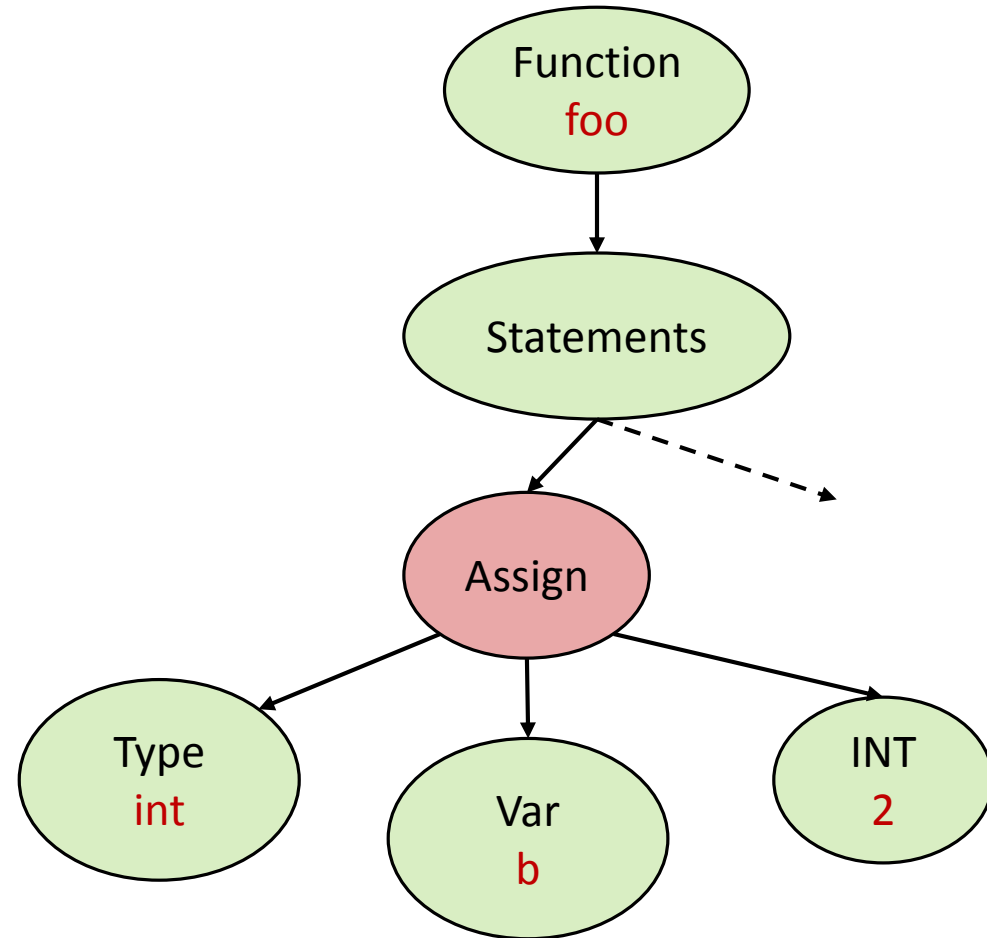




```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable



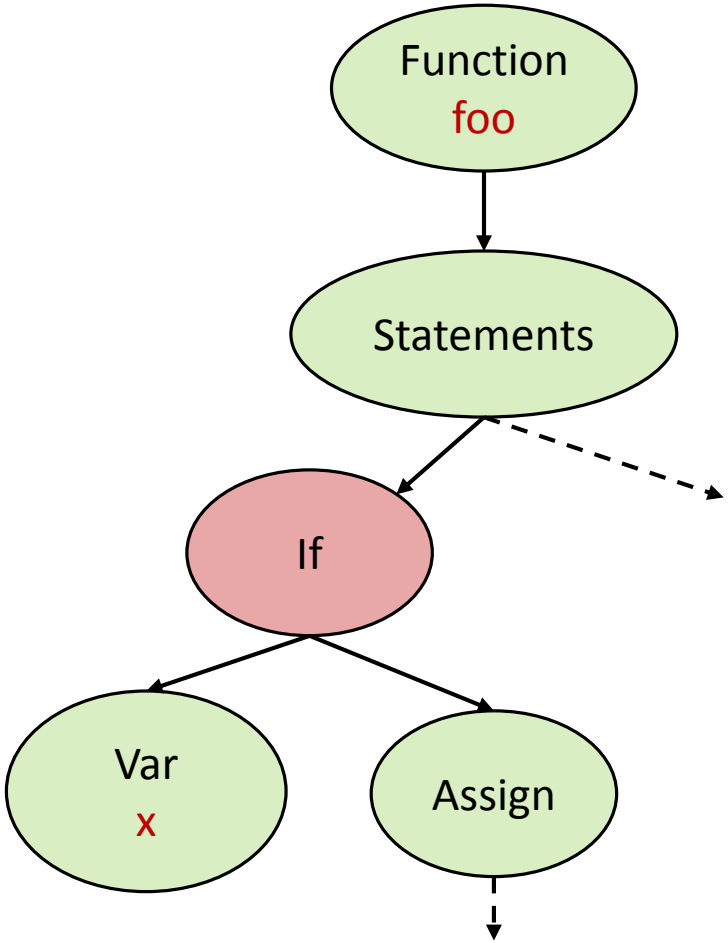


```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable

ID	Type	Kind



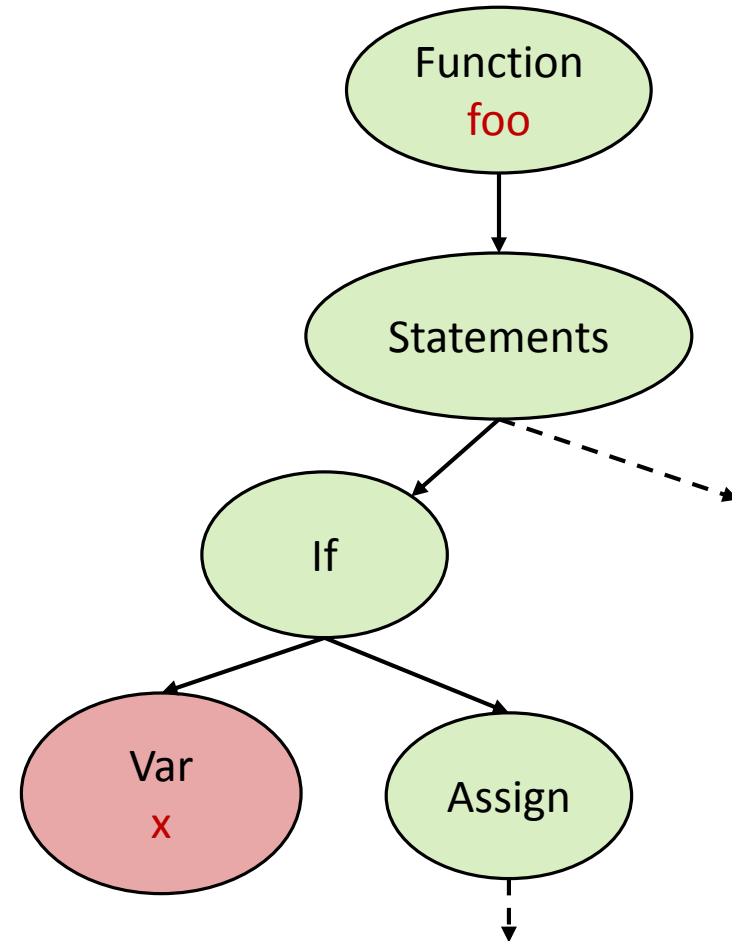


```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable

ID	Type	Kind



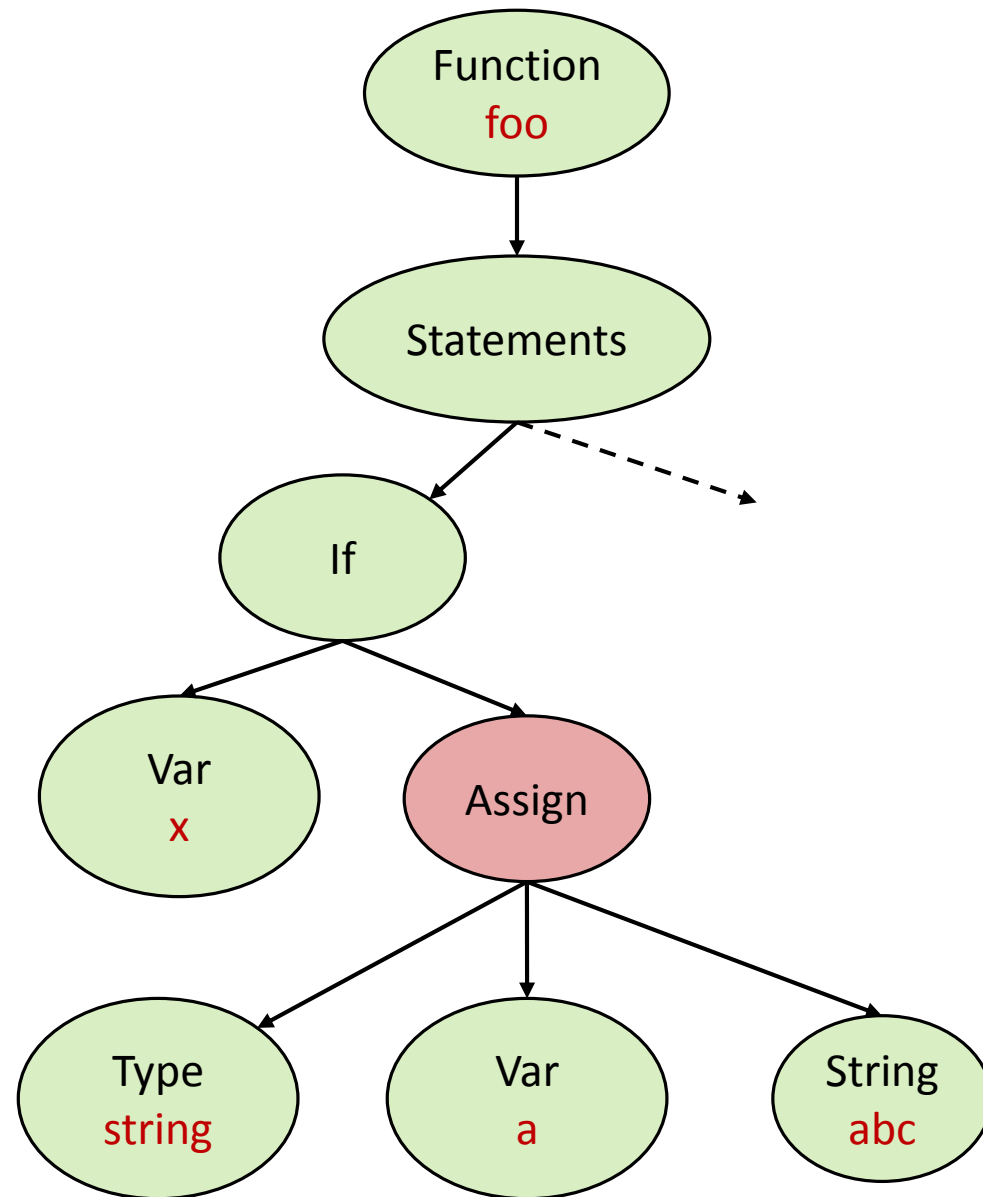


```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable

ID	Type	Kind
a	string	variable



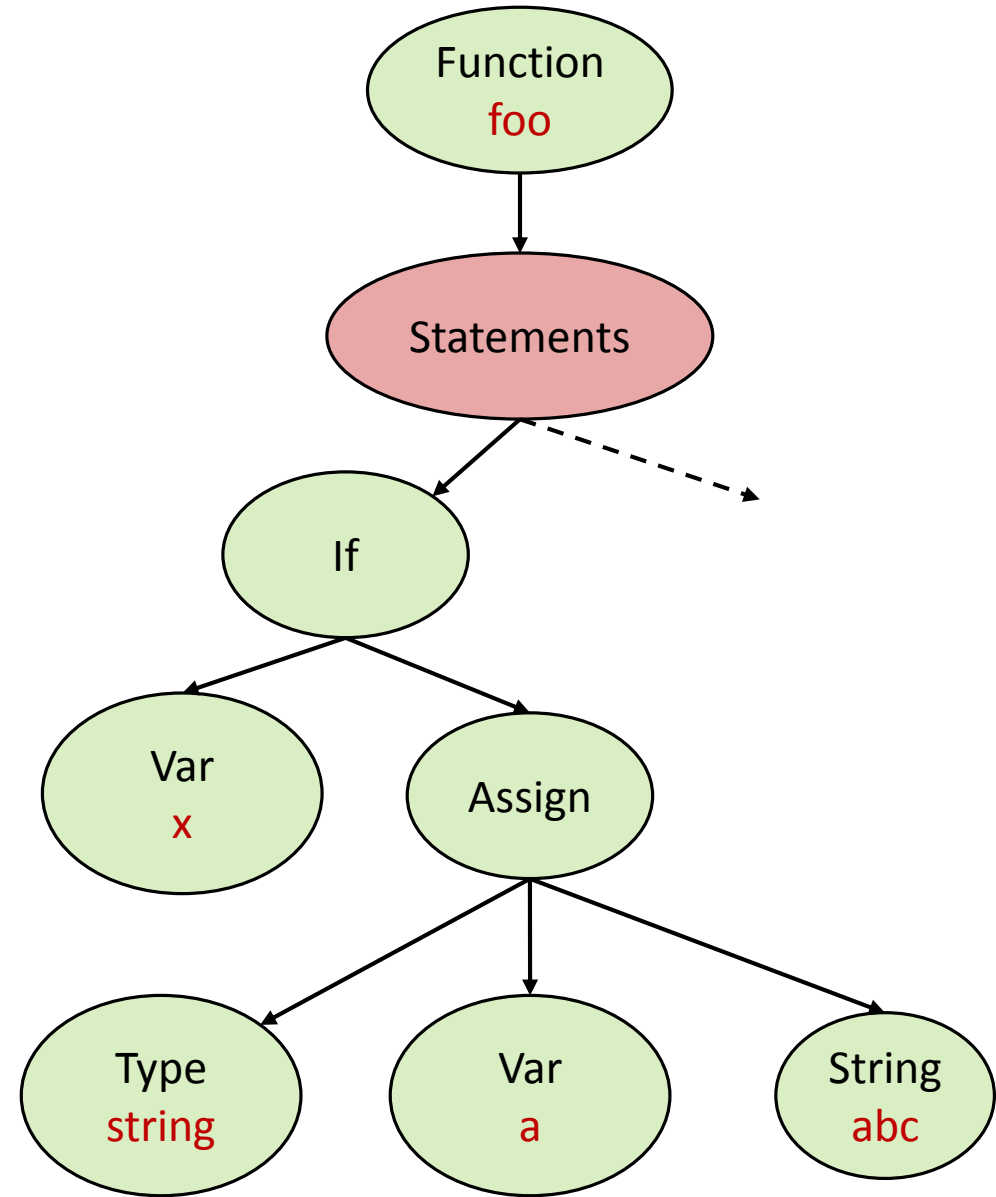

```

void foo(int x) {
    int a = 1;
    int b = 2;
    if (x) {
        string a = "abc";
    }
}

```

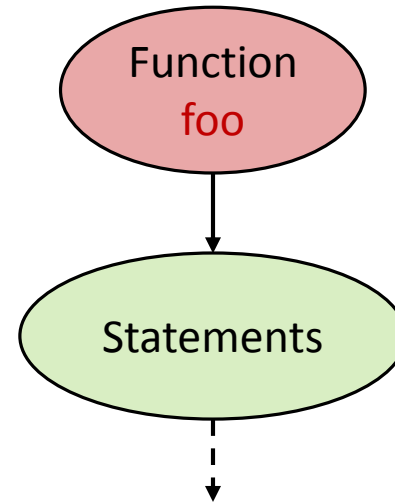
ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable



```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function



```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

Type Checking

Goals:

- Type correctness of expressions
- Compute type of expressions

Performed using:

- AST visitor
- Symbol table

Type Checking

Basic algorithm:

visit(node):

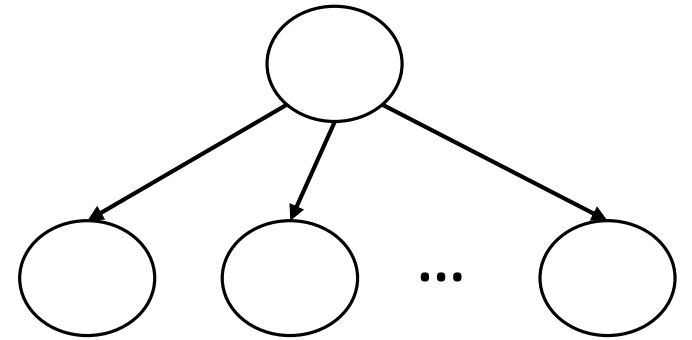
$t_1 = \text{visit}(\text{node.child}_1)$

...

$t_n = \text{visit}(\text{node.child}_n)$

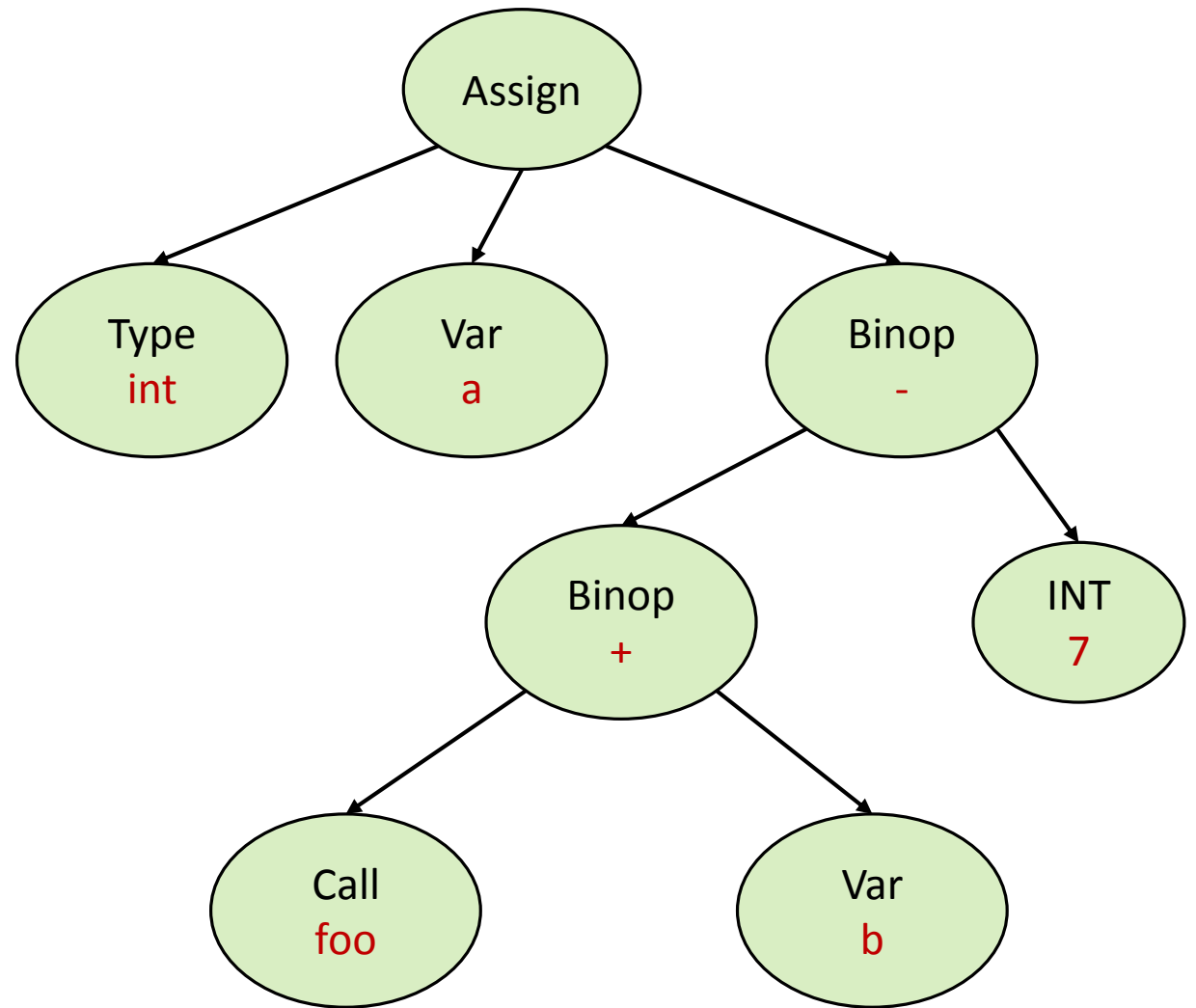
$\text{return } \underbrace{\text{compute_type}(t_1, \dots, t_n)}$

node specific



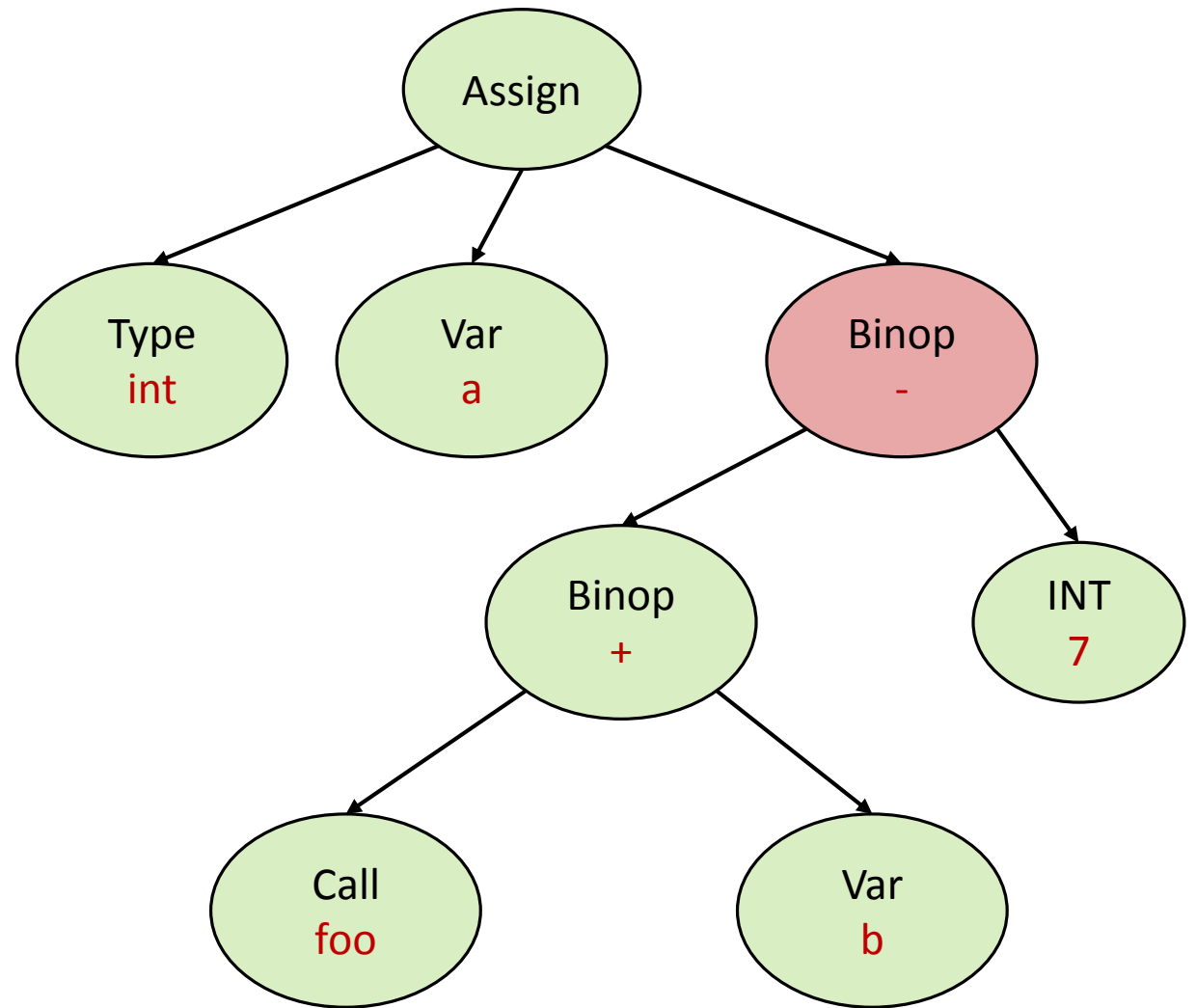
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



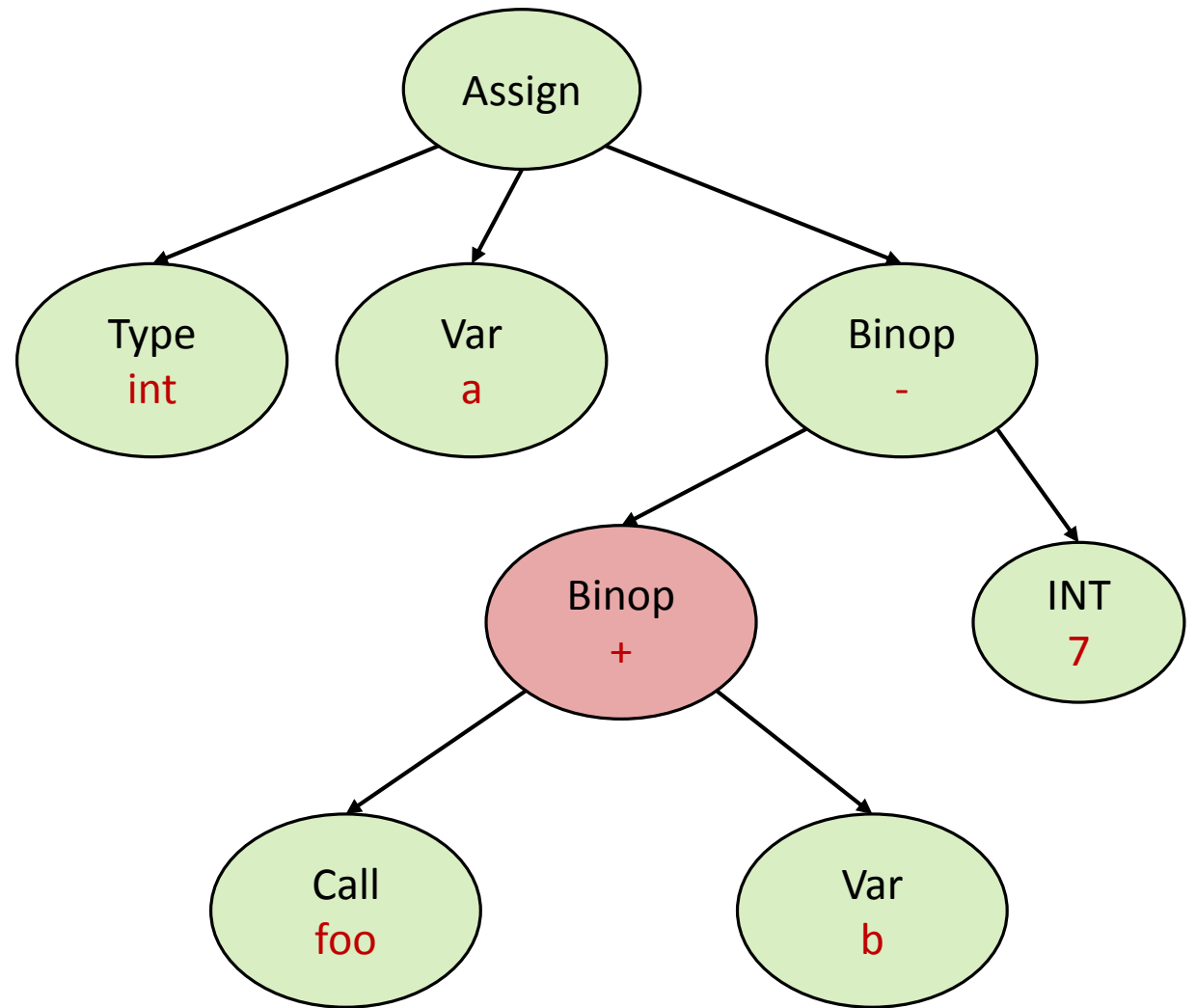
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



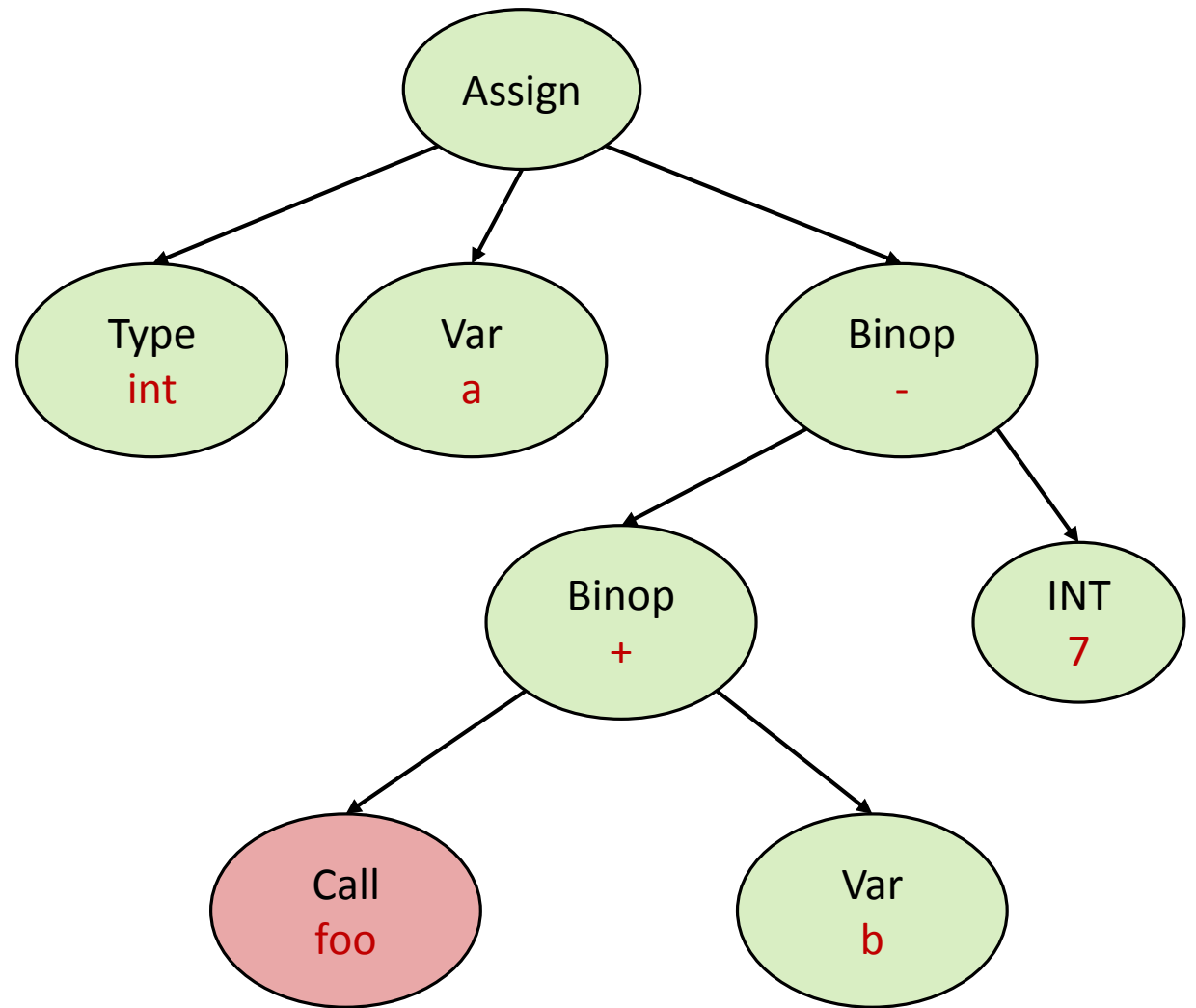
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



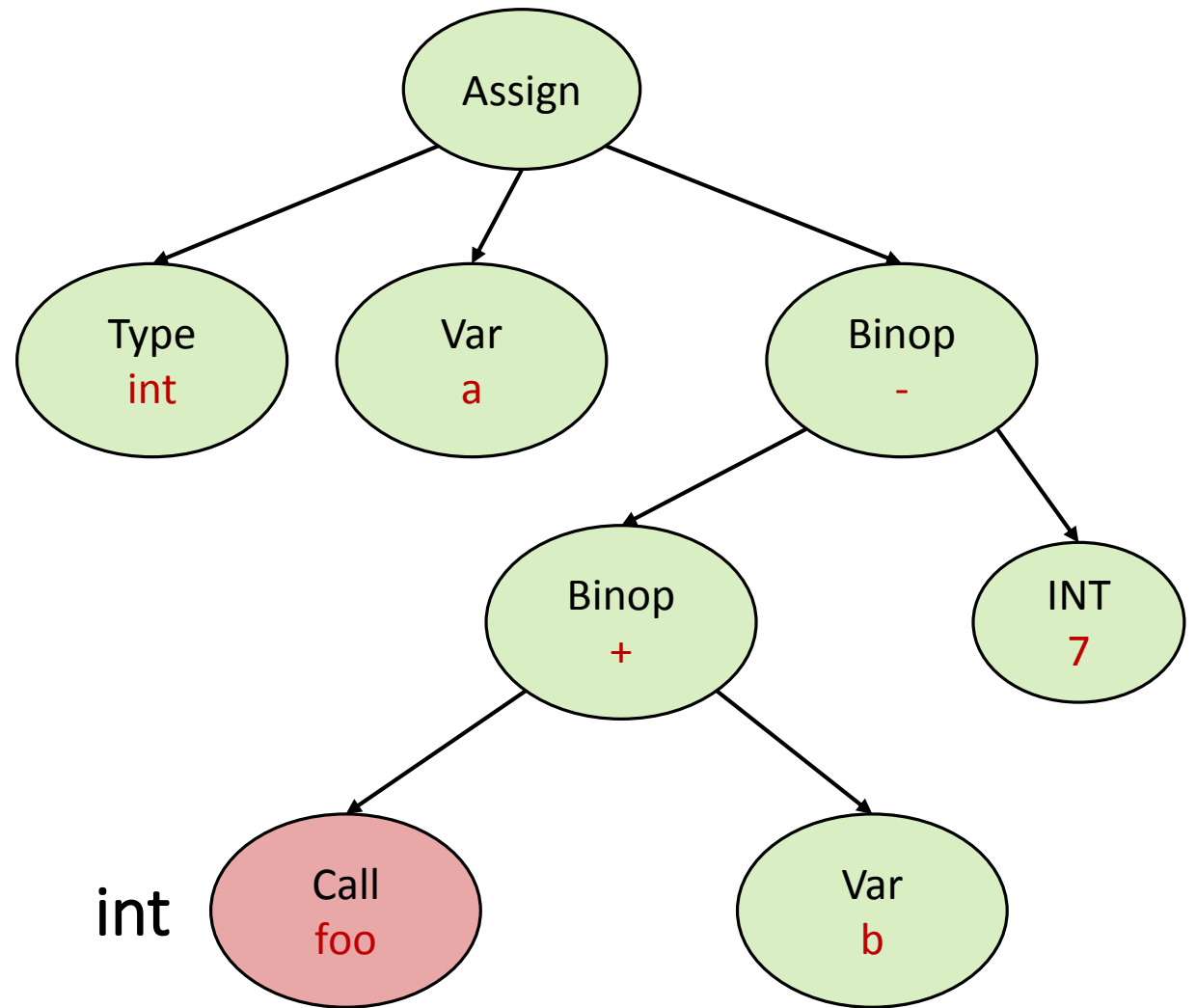

```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



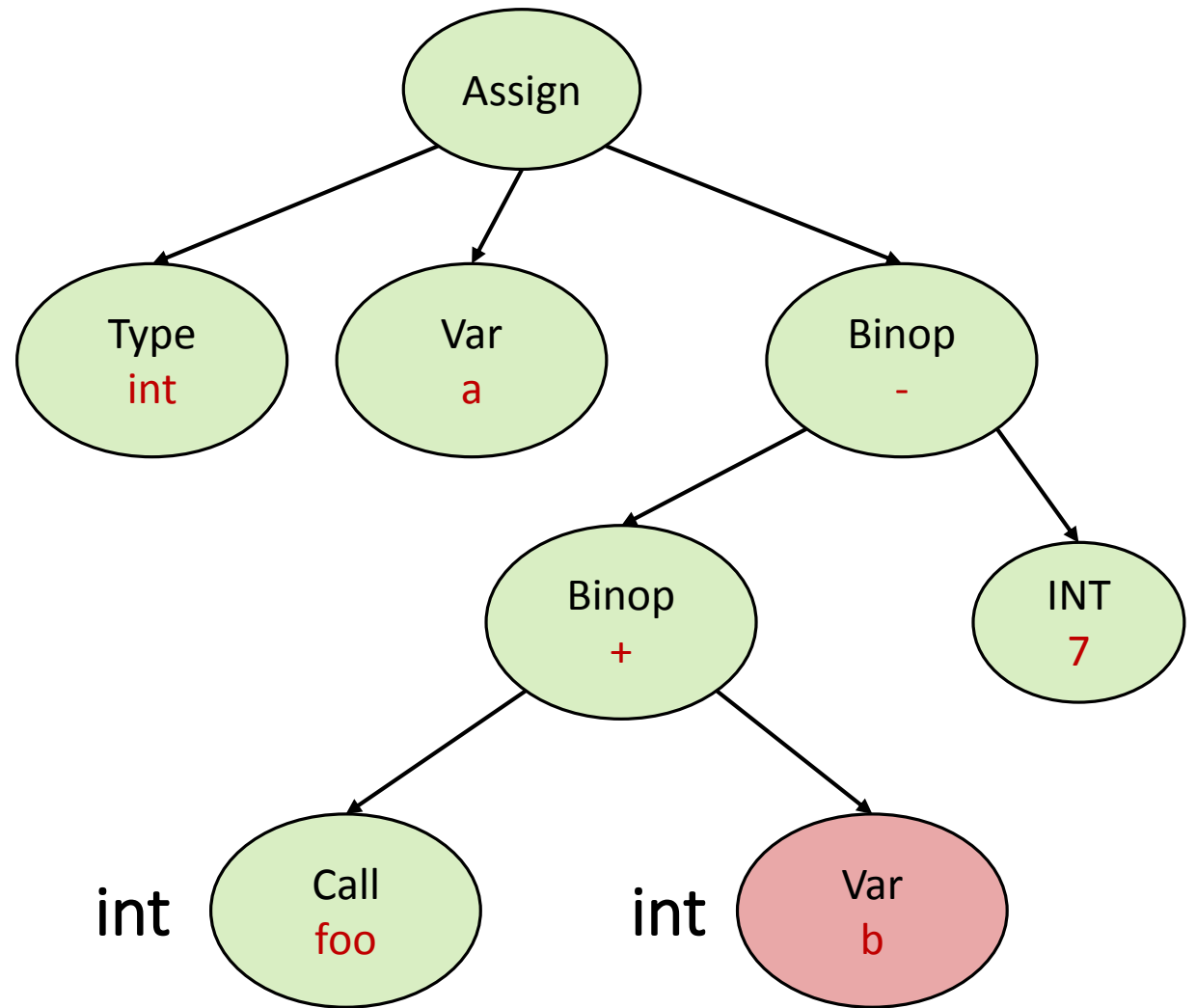
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



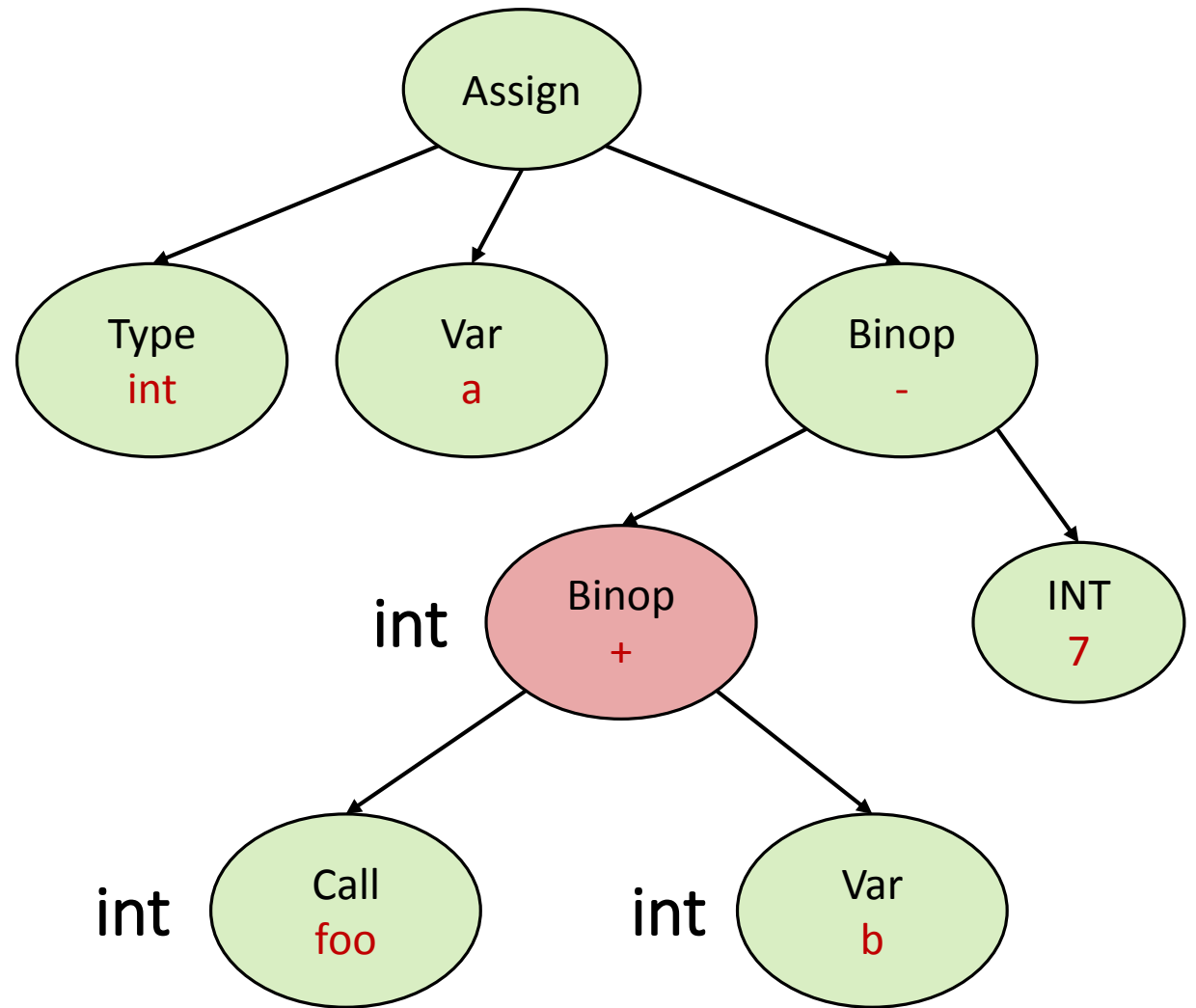
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



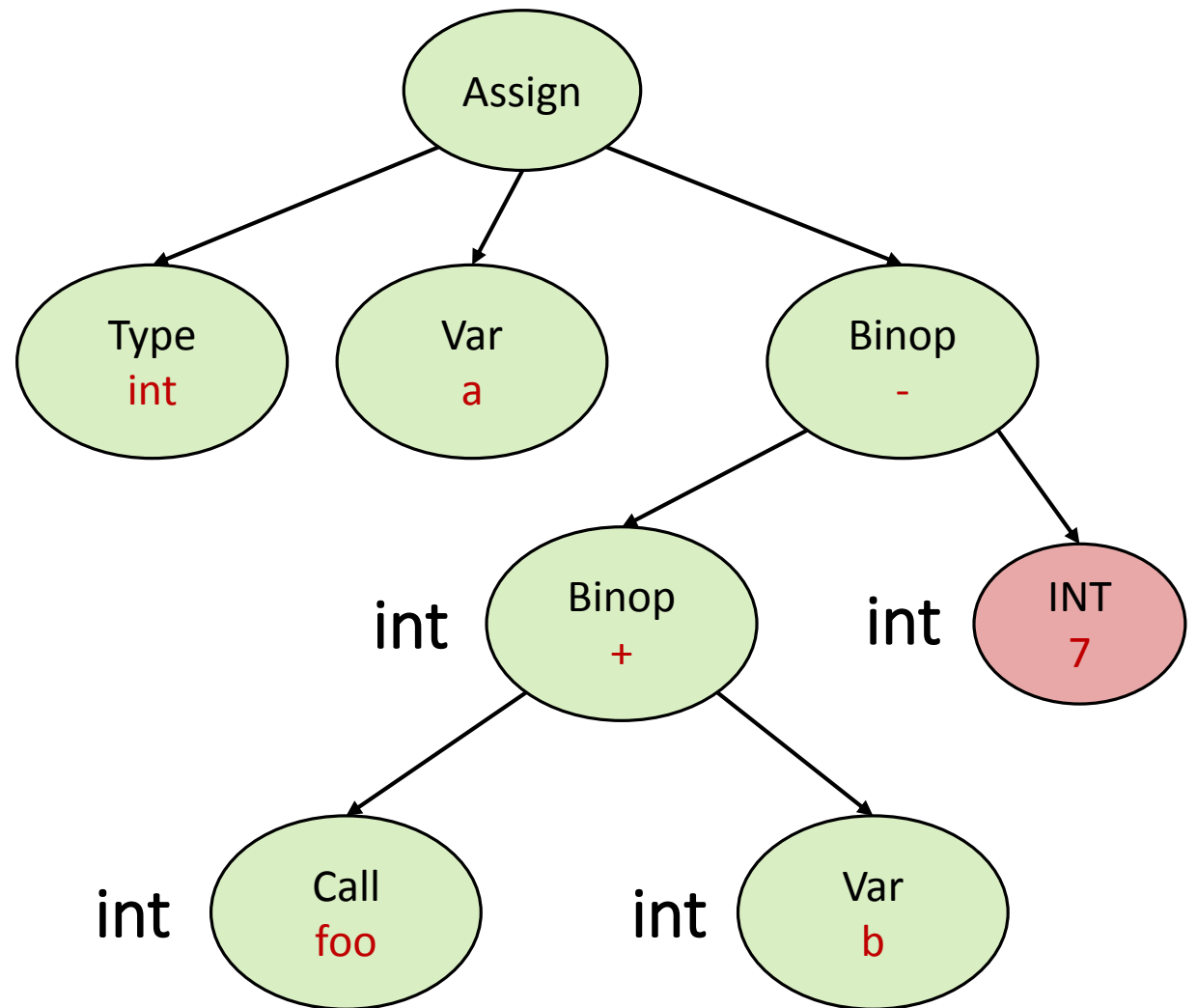
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



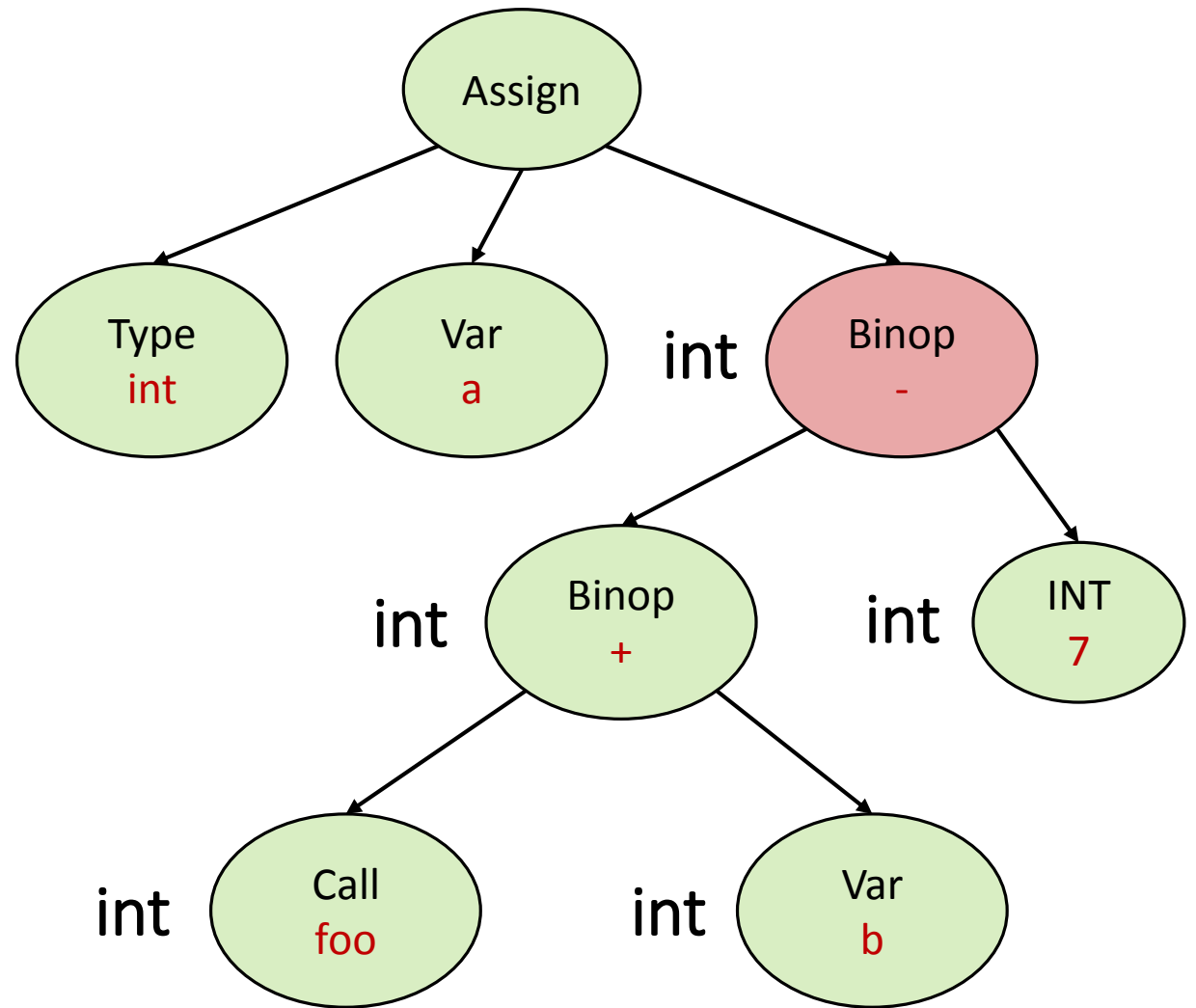
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



```
int a = foo() + b - 7;  
...
```

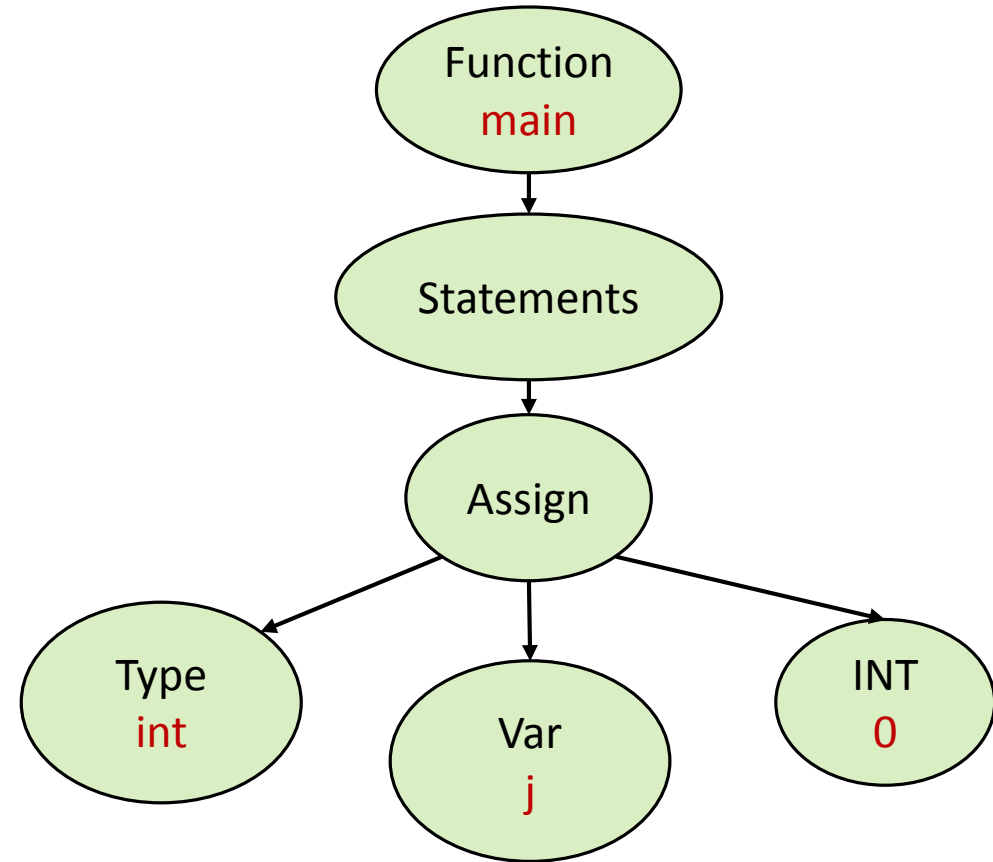
ID	Type	Kind
foo	int,void	function
b	int	variable



Examples

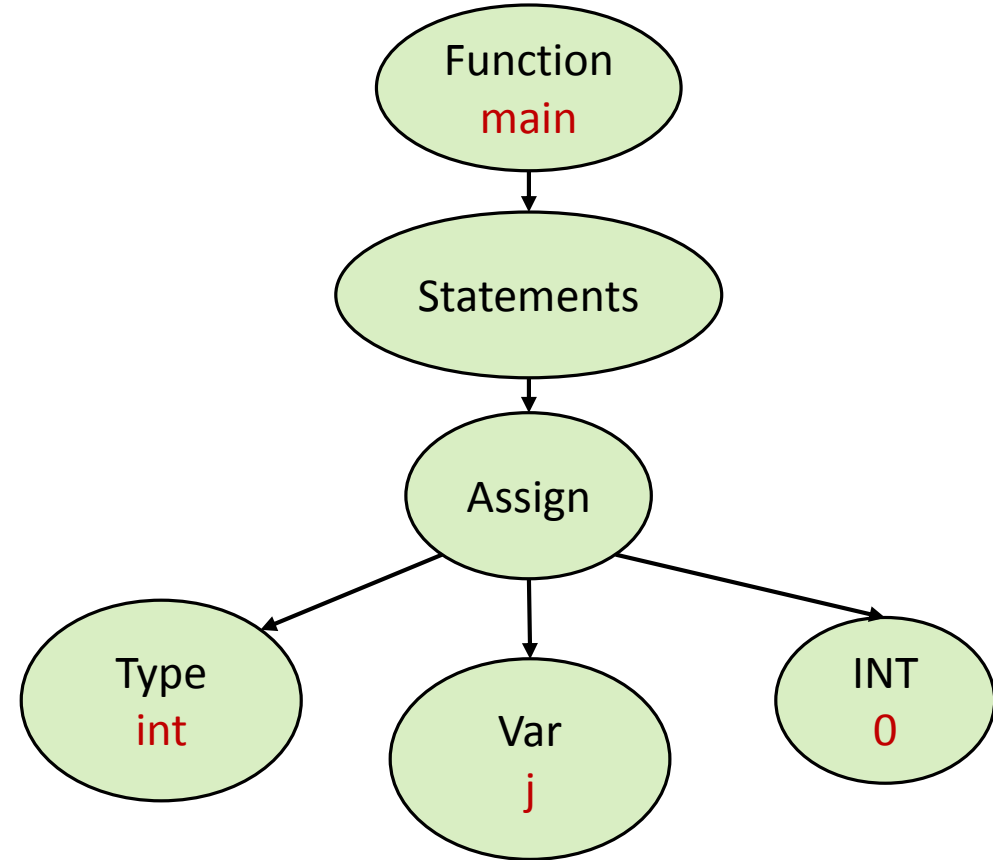
Assignments

```
void main() {  
    int j = 0;  
}
```



Assignments

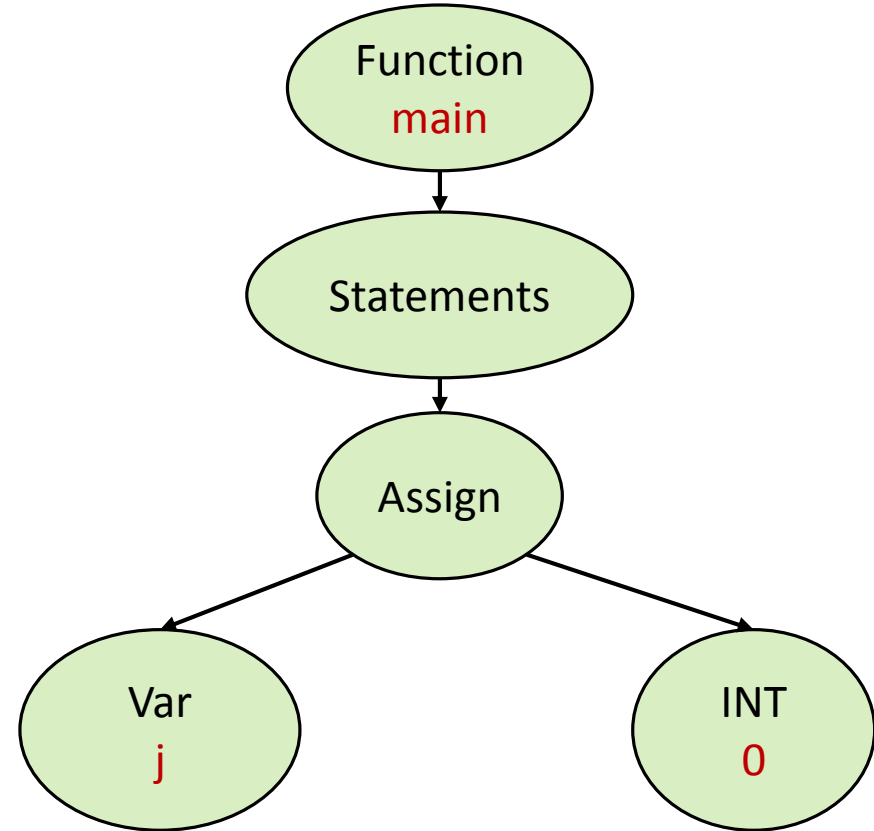
```
void main() {  
    int j = 0;  
}
```



Valid

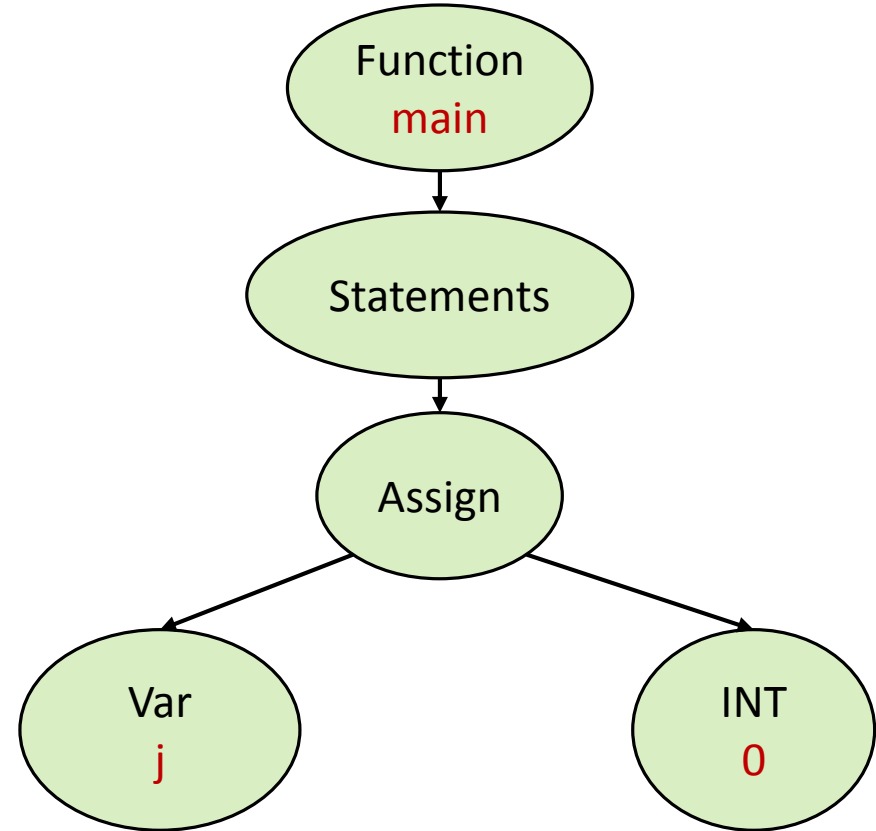
Assignments

```
void main() {  
    j = 0;  
}
```



Assignments

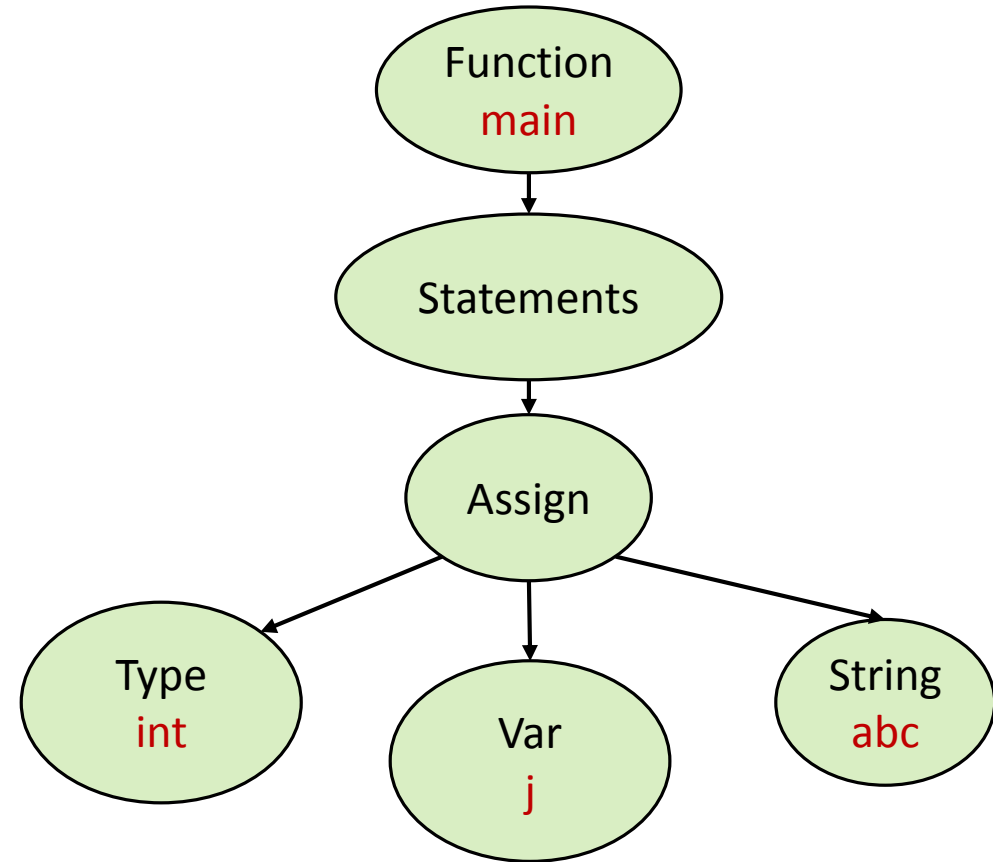
```
void main() {  
    j = 0;  
}
```



Invalid

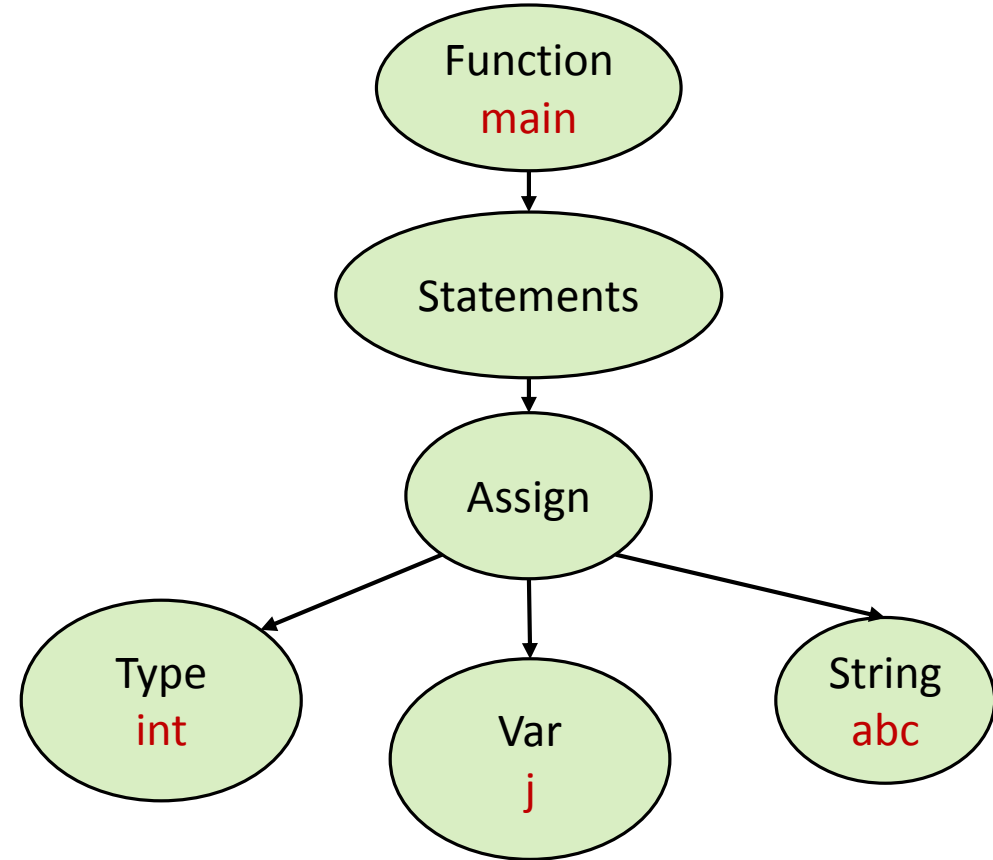
Assignments

```
void main() {  
    int j = "abc";  
}
```



Assignments

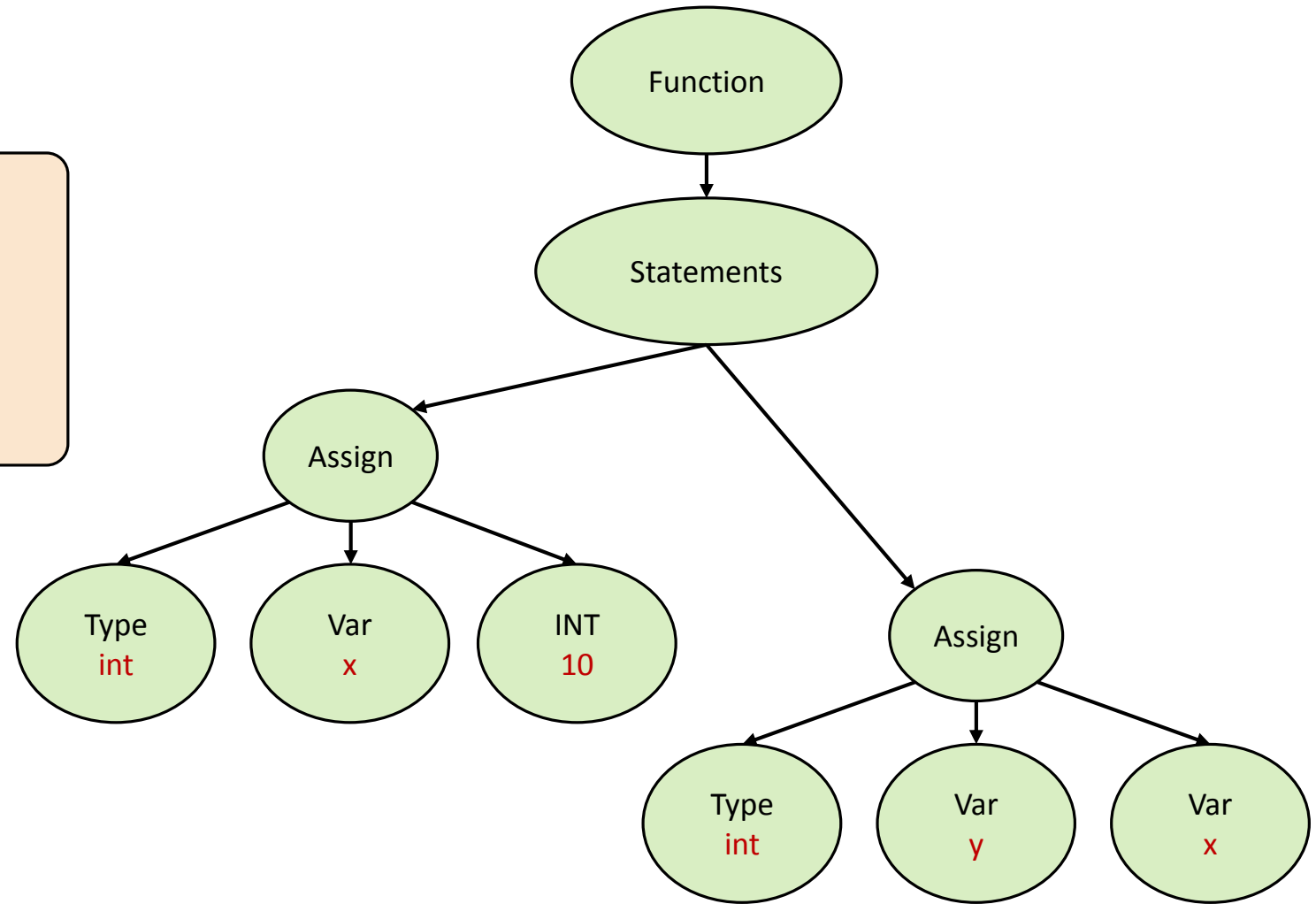
```
void main() {  
    int j = "abc";  
}
```



Invalid

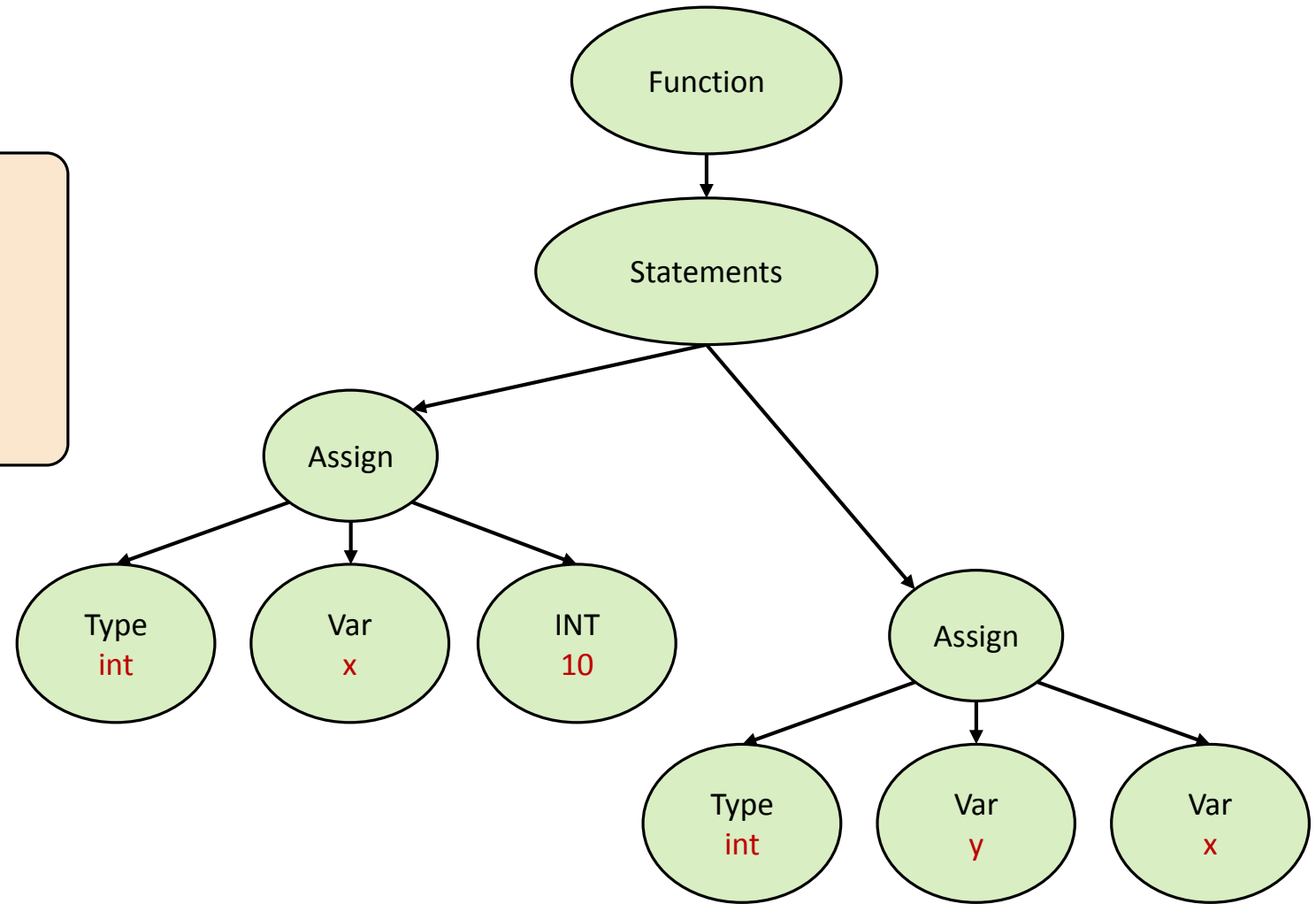
Assignments

```
void main() {  
    int x = 10;  
    int y = x;  
}
```



Assignments

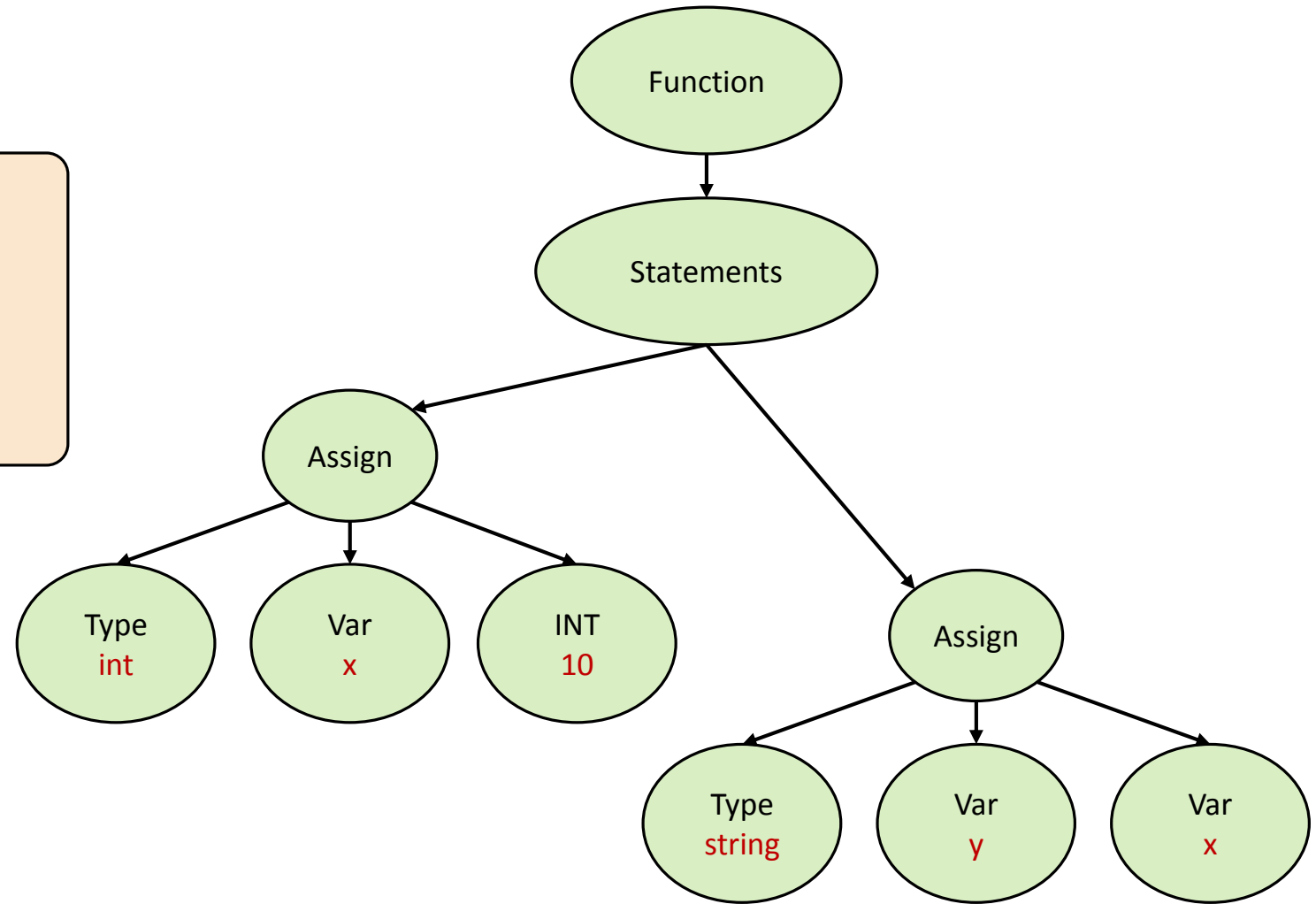
```
void main() {  
    int x = 10;  
    int y = x;  
}
```



Valid

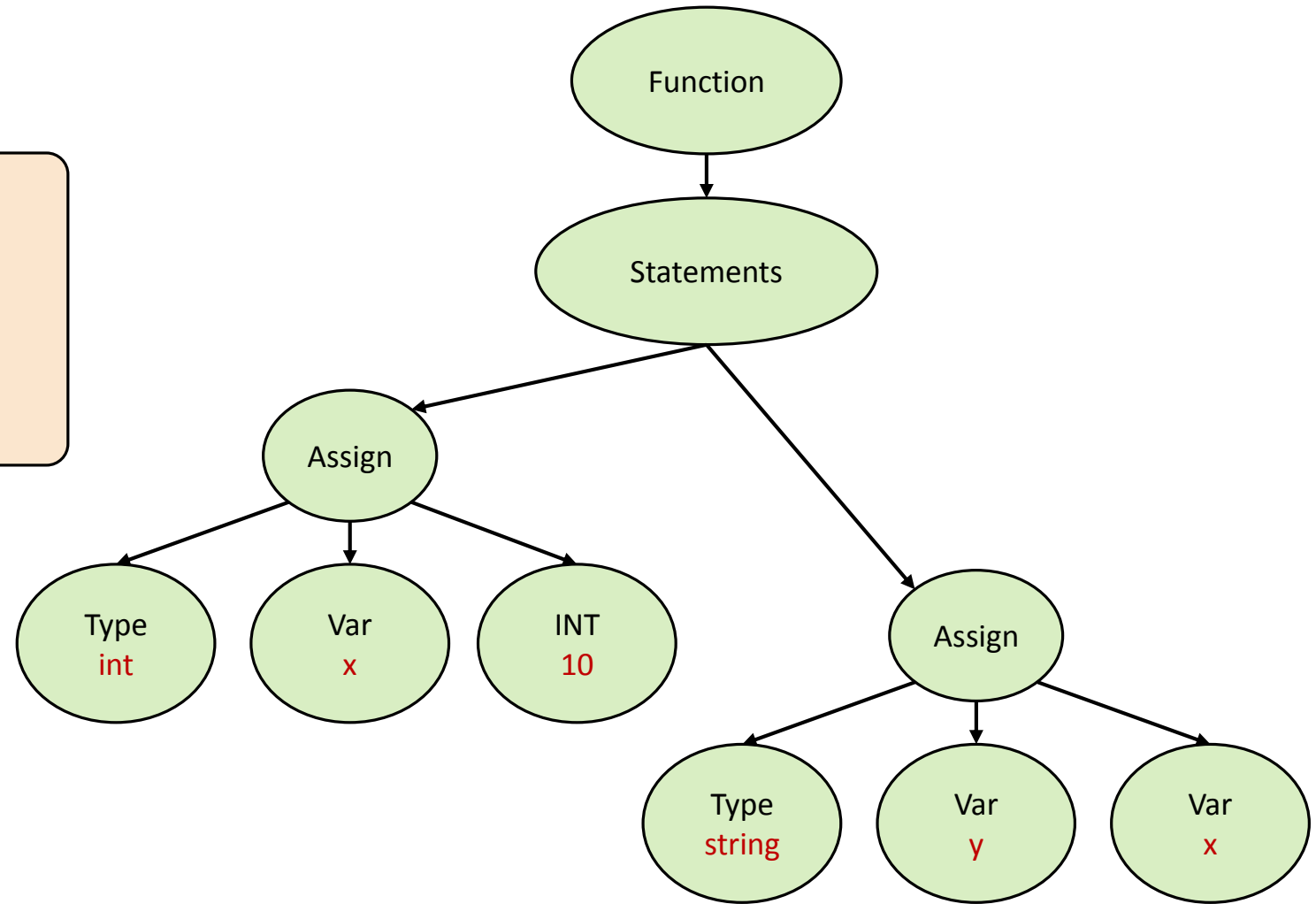
Assignments

```
void main() {  
  int x = 10;  
  string y = x;  
}
```



Assignments

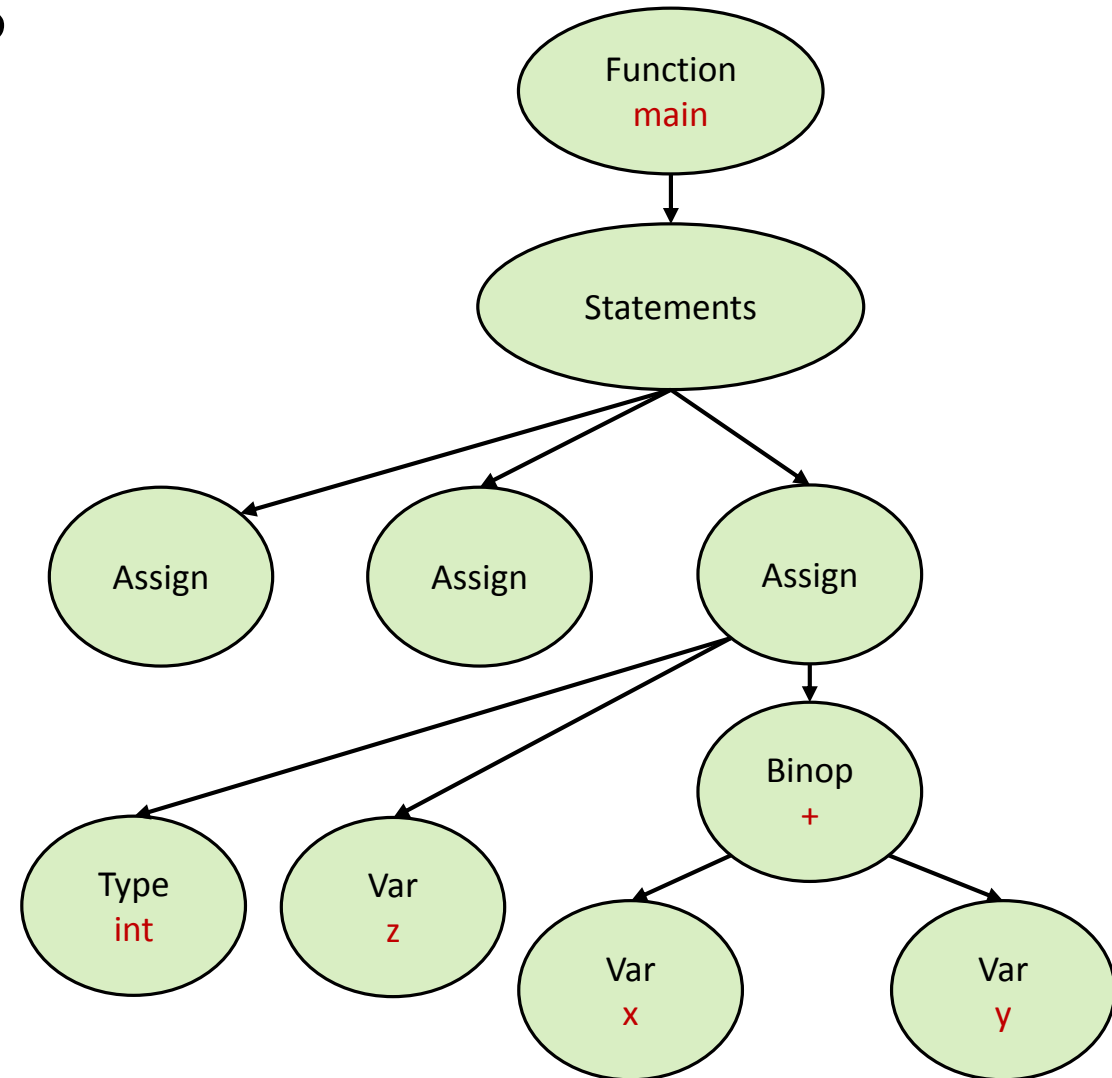
```
void main() {  
    int x = 10;  
    string y = x;  
}
```



Invalid

Binary Operations

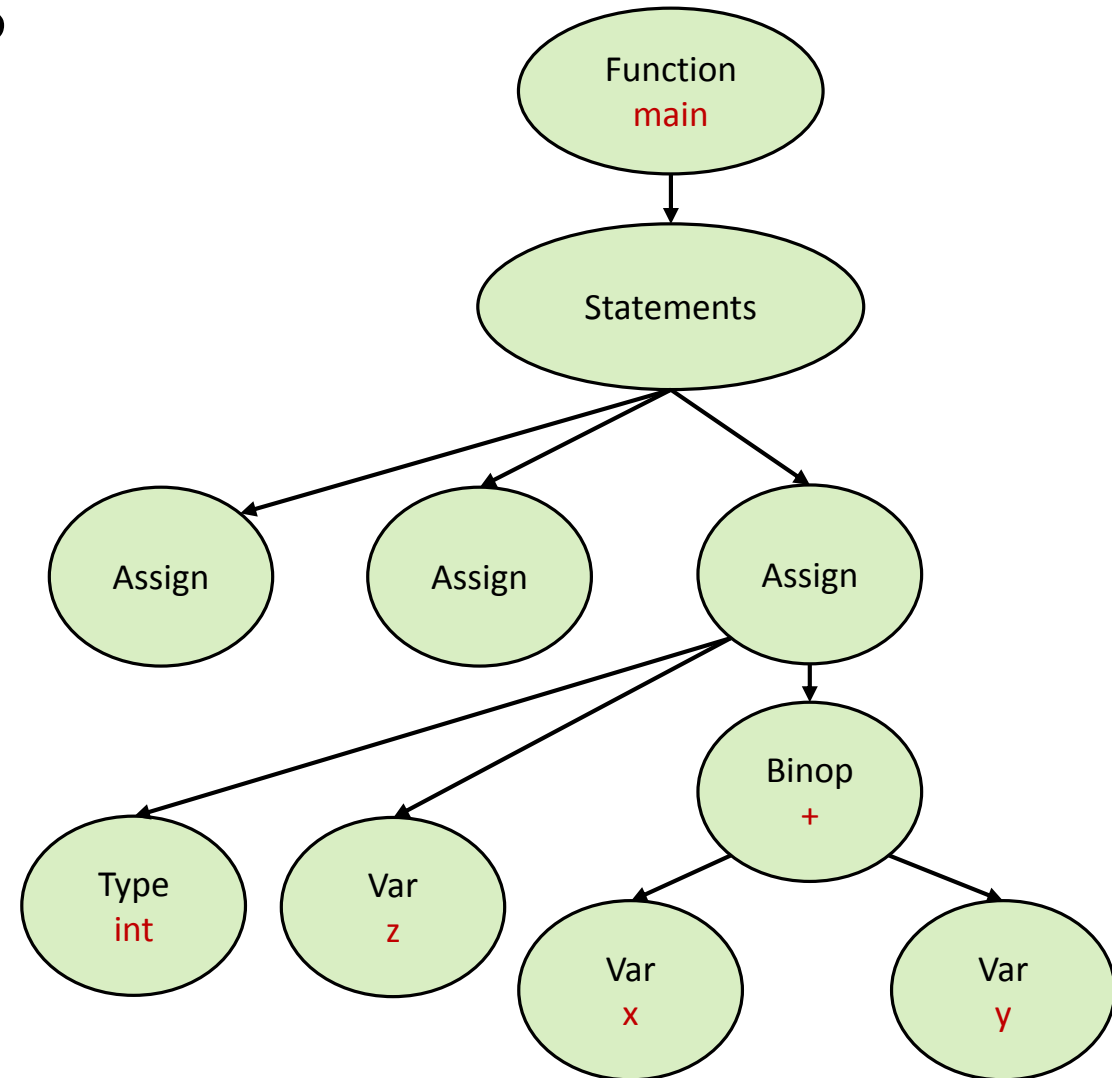
```
void main() {  
    int x = 1;  
    int y = 2;  
    int z = x + y;  
}
```



Binary Operations

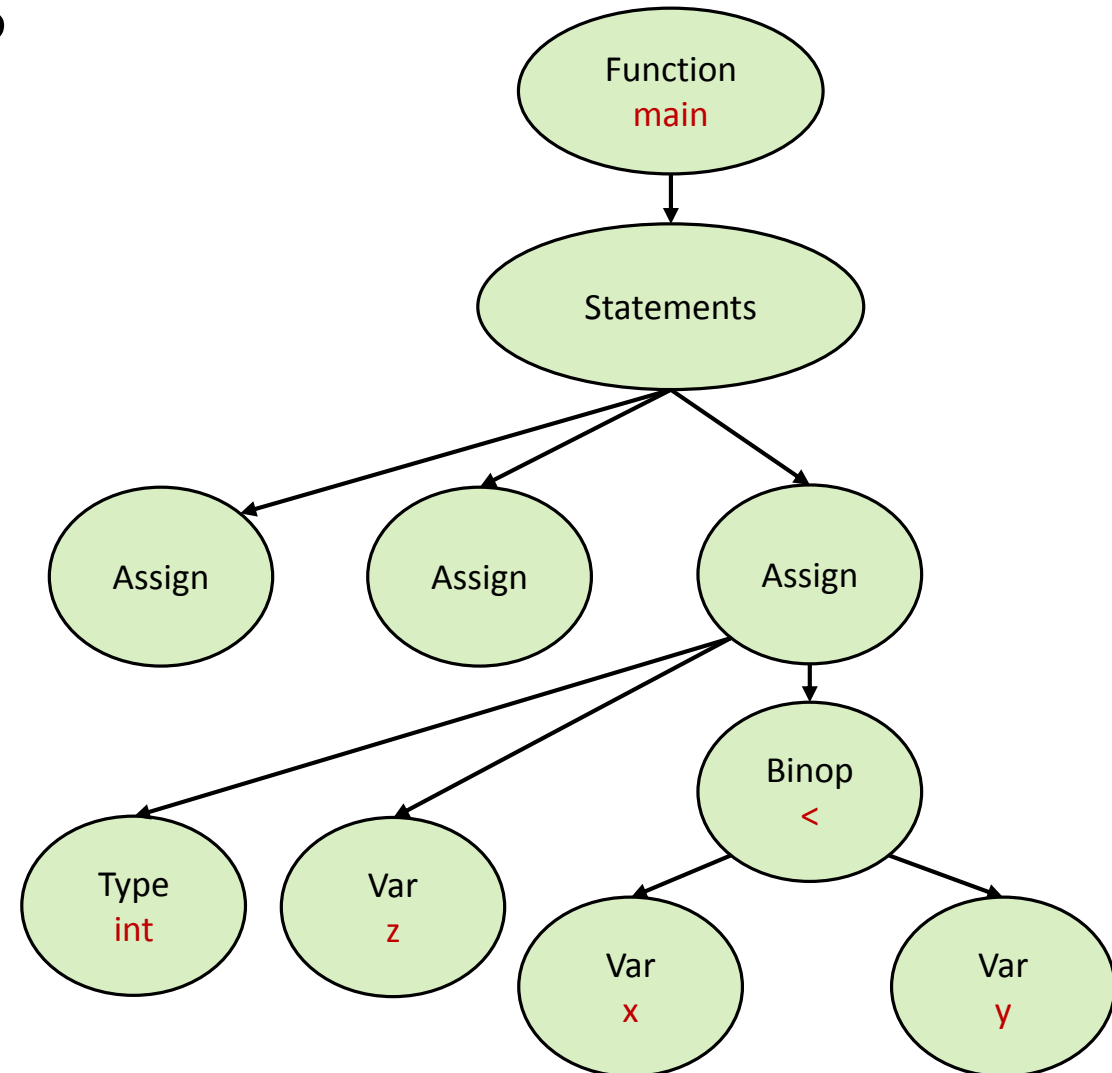
```
void main() {  
    int x = 1;  
    int y = 2;  
    int z = x + y;  
}
```

Valid



Binary Operations

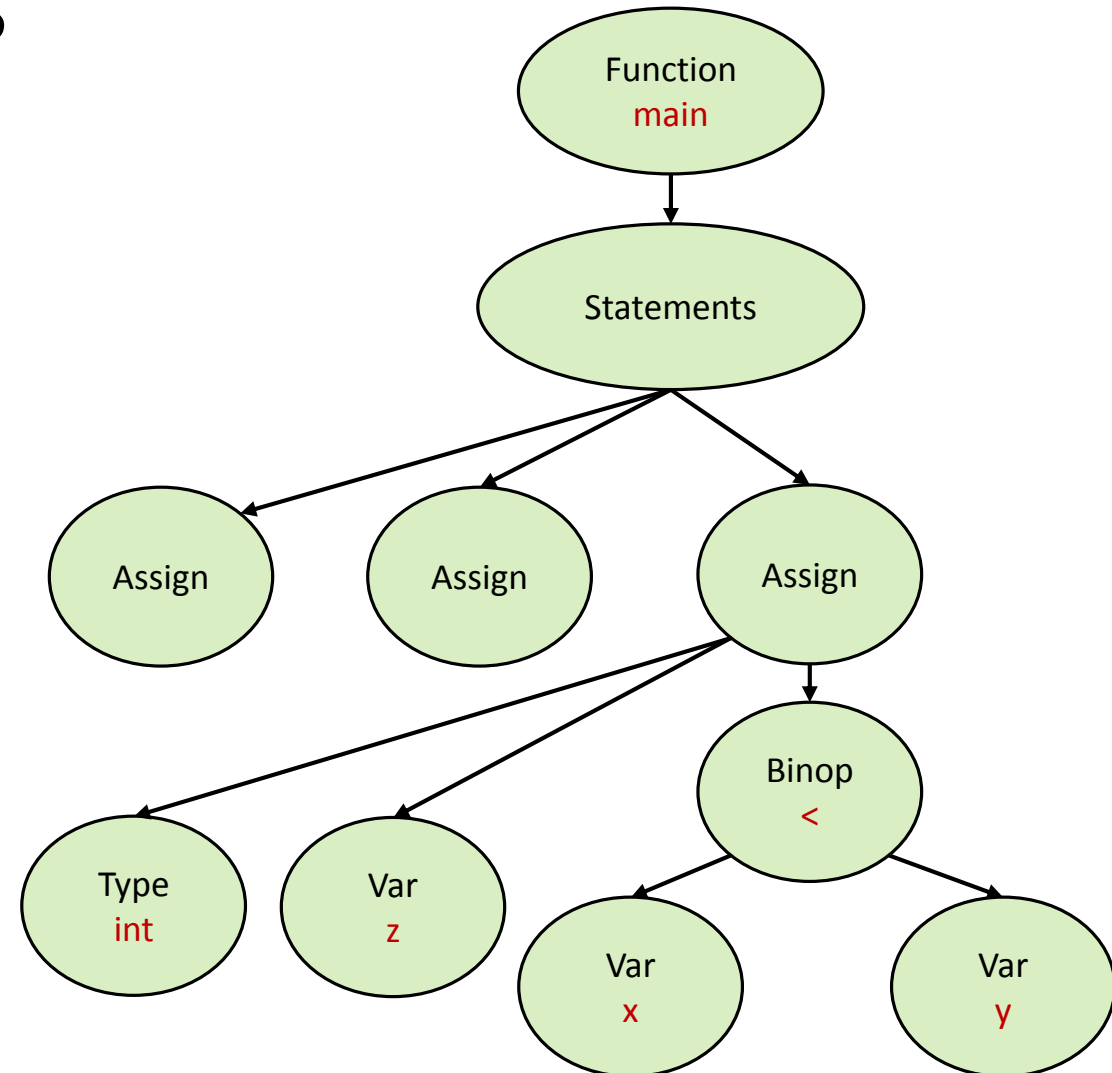
```
void main() {  
    int x = 1;  
    string y = "A";  
    int z = x < y;  
}
```



Binary Operations

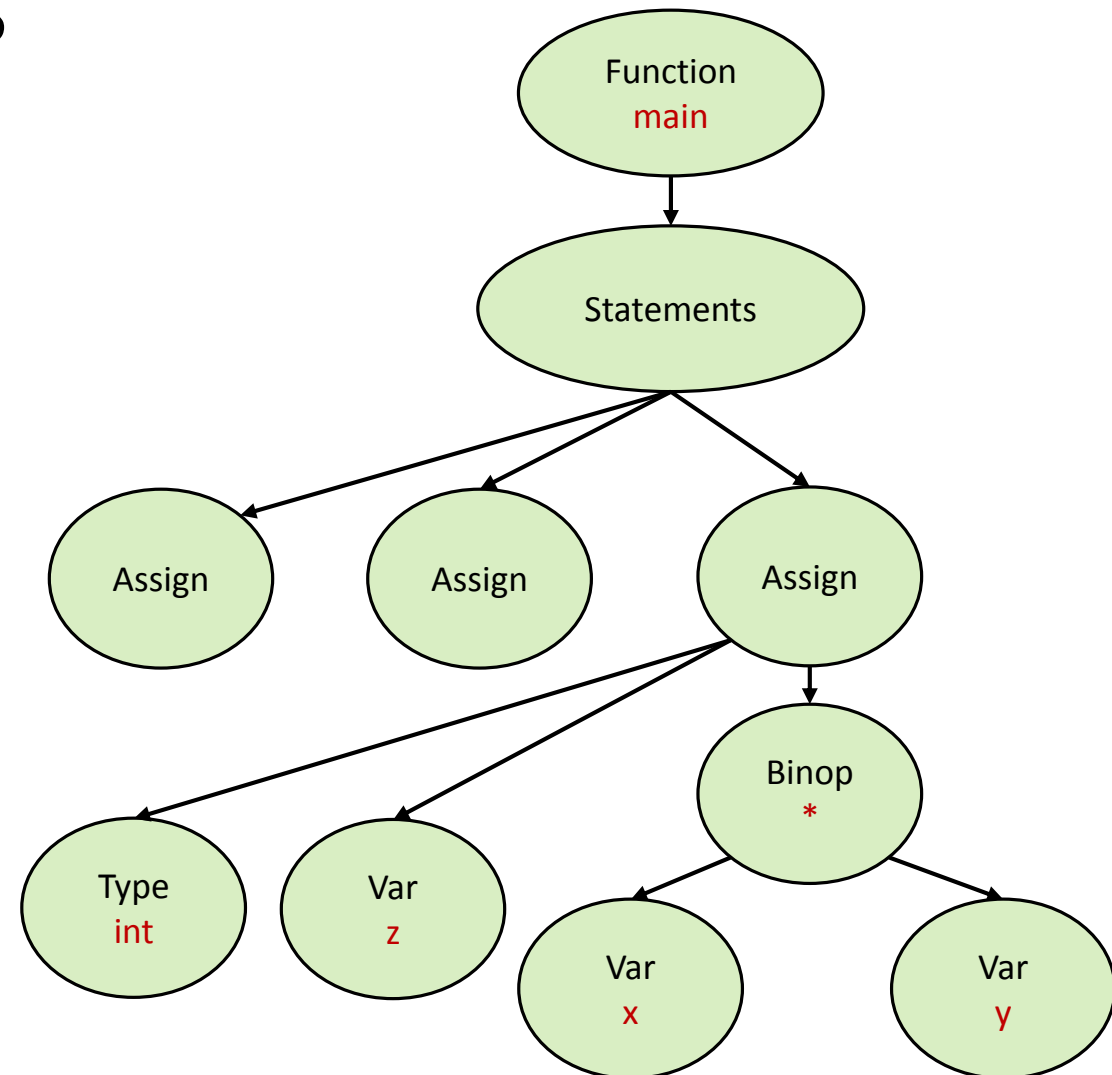
```
void main() {  
    int x = 1;  
    string y = "A";  
    int z = x < y;  
}
```

Invalid



Binary Operations

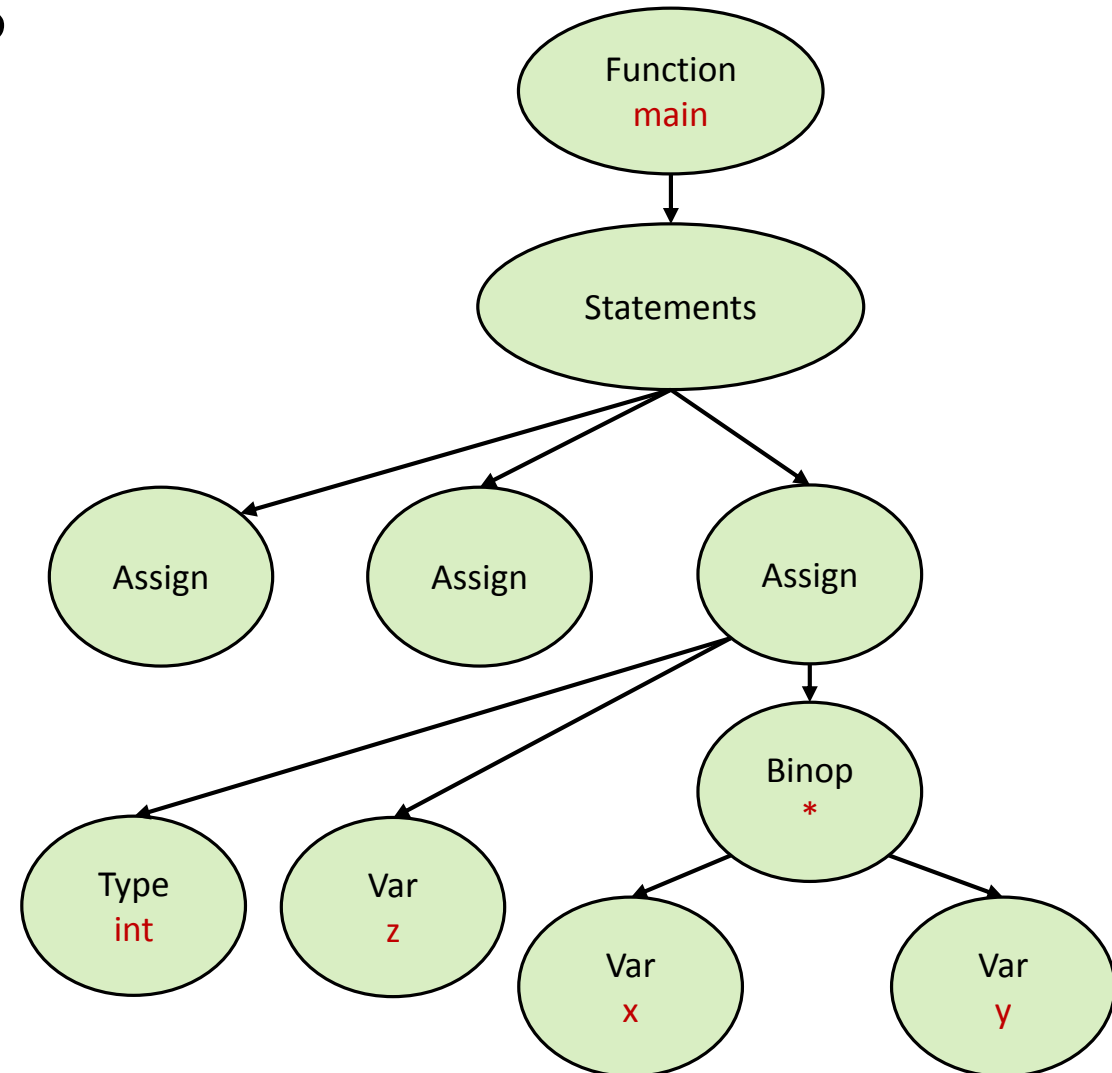
```
void main() {  
    string x = "A";  
    string y = "B";  
    string z = x * y;  
}
```



Binary Operations

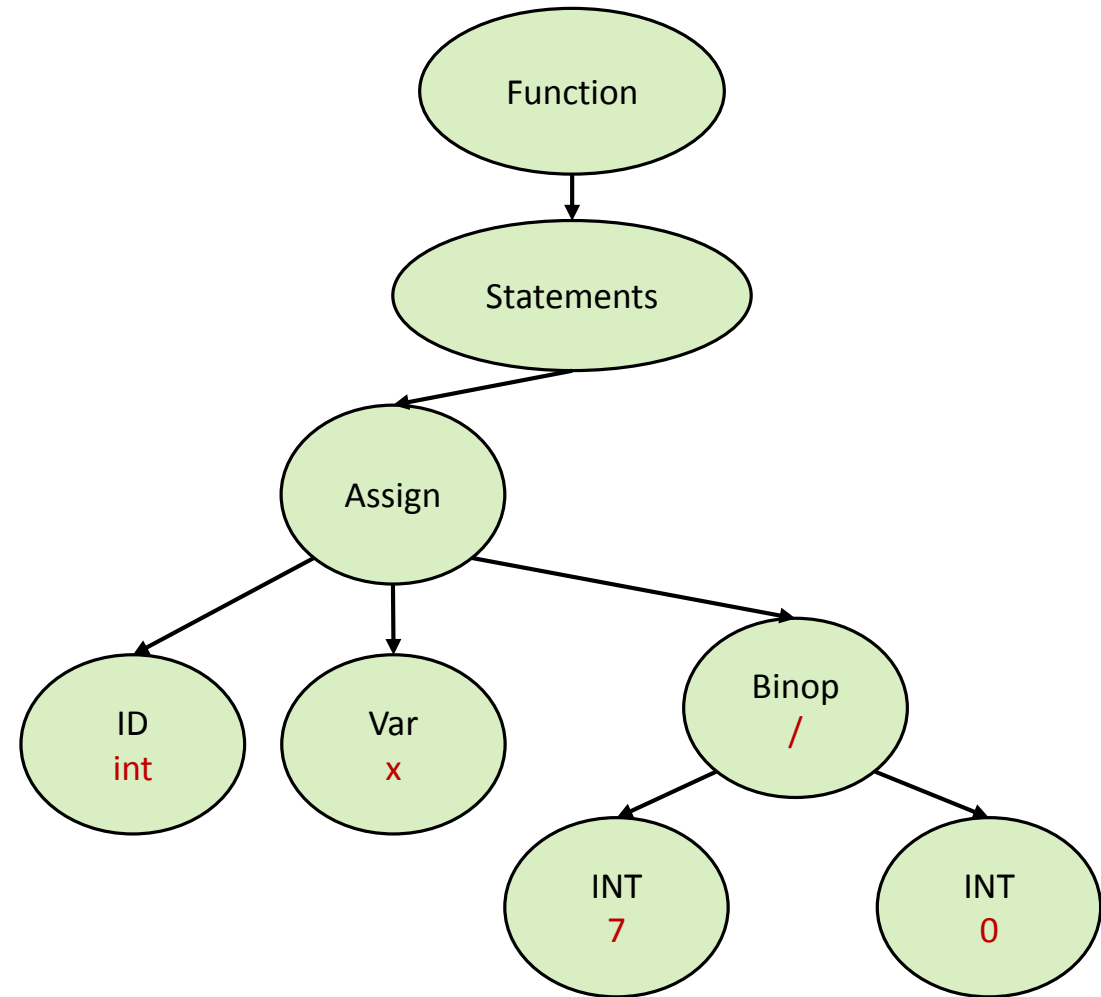
```
void main() {  
    string x = "A";  
    string y = "B";  
    string z = x * y;  
}
```

Invalid



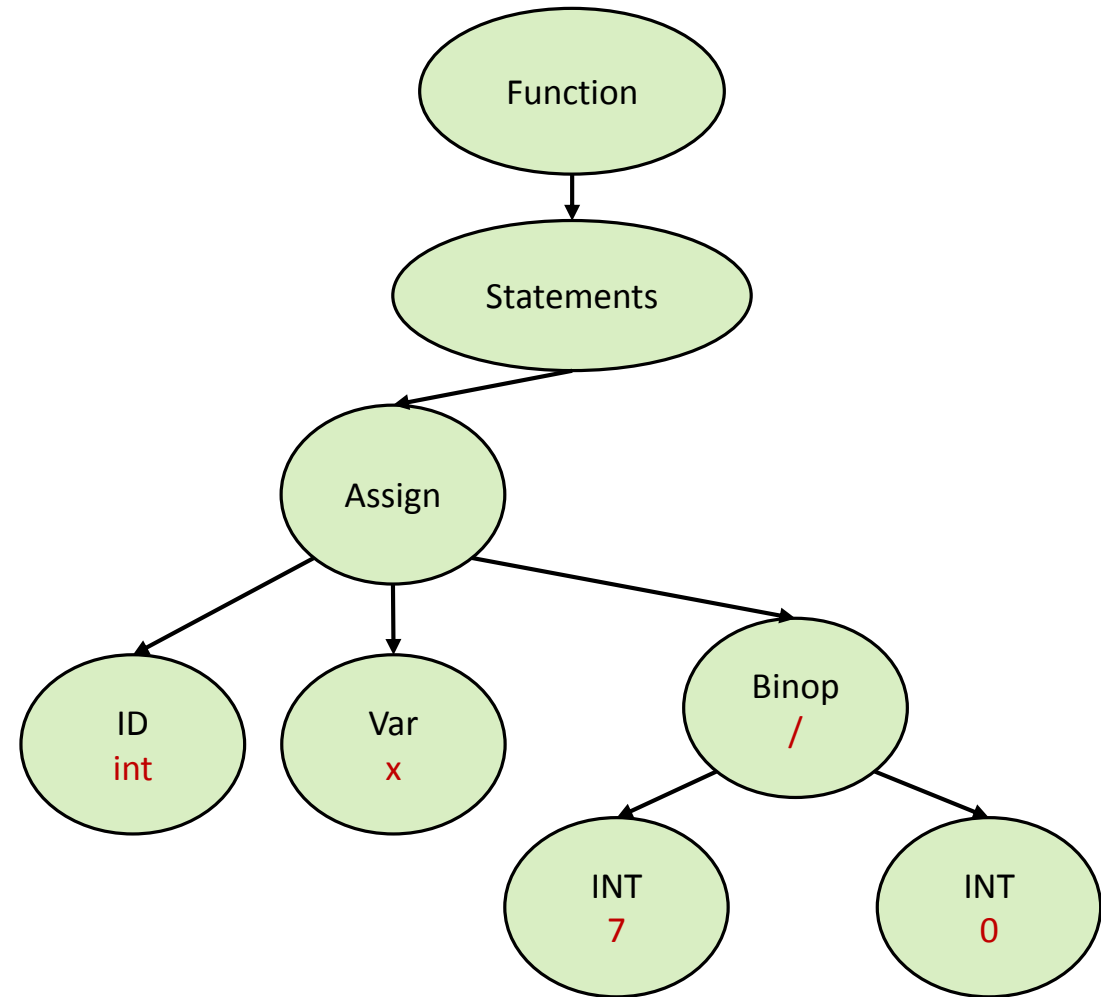
Binary Operations

```
void main() {  
    int x = 7 / 0;  
}
```



Binary Operations

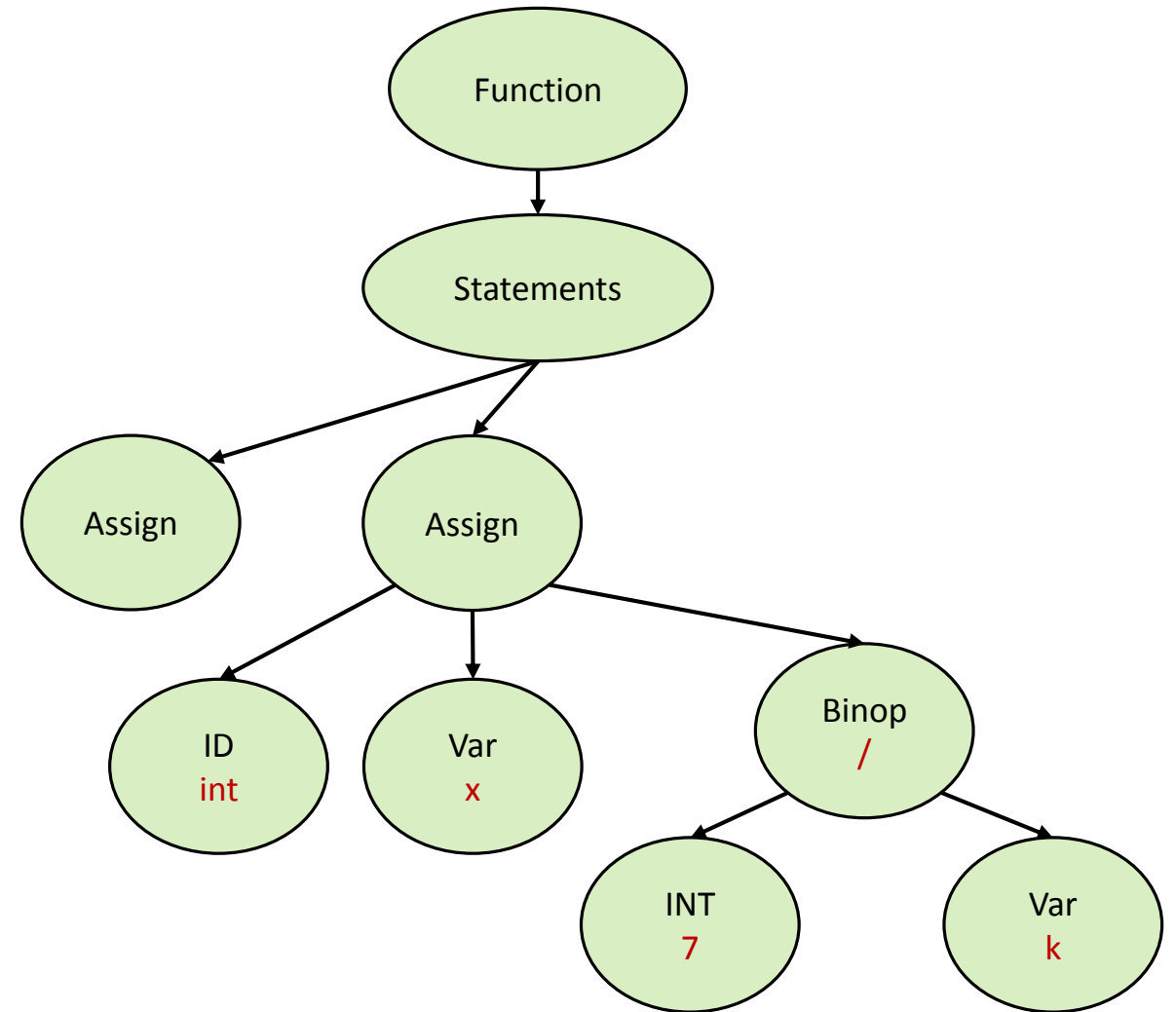
```
void main() {  
    int x = 7 / 0;  
}
```



Invalid

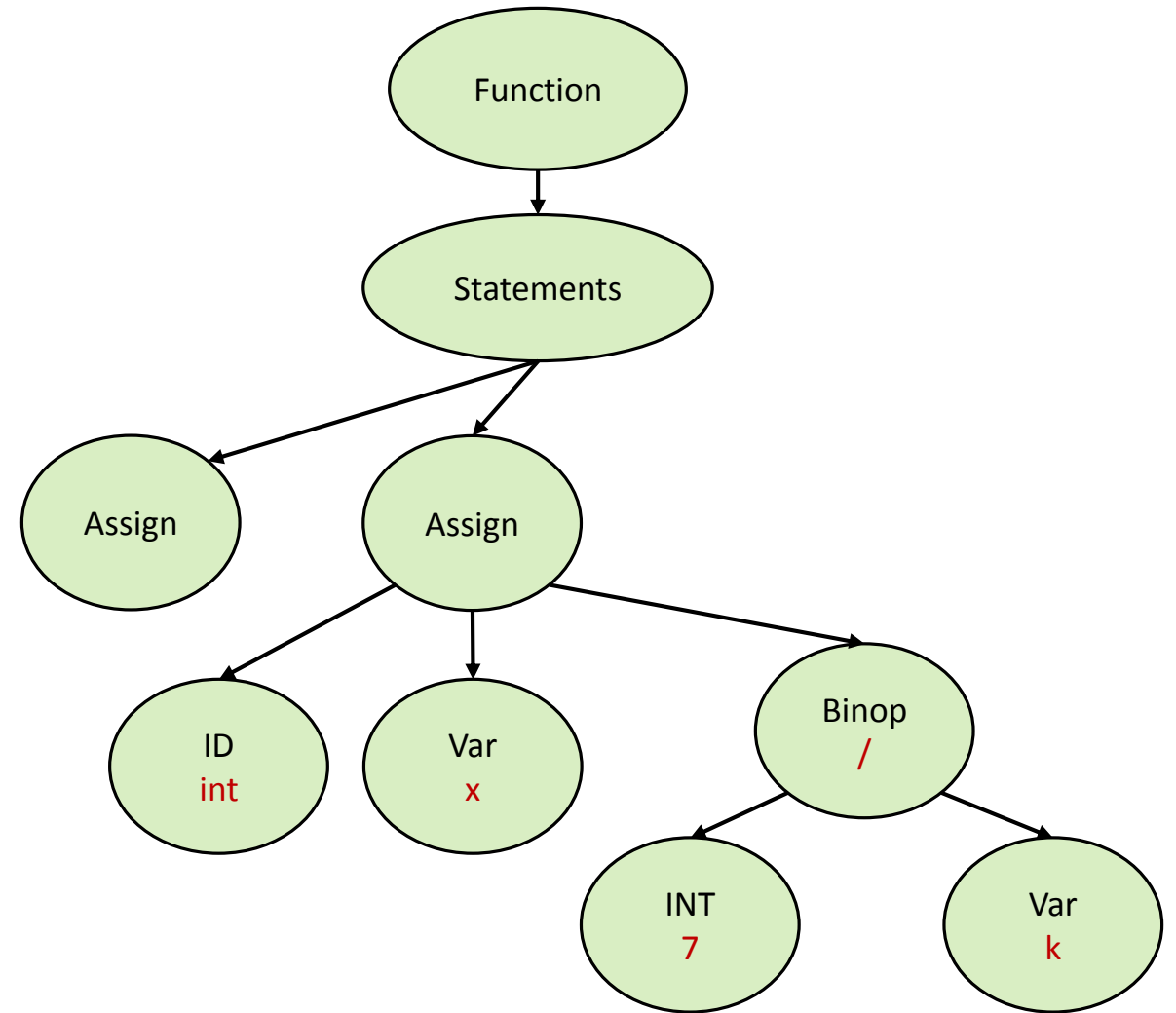
Binary Operations

```
void main() {  
    int k = 0;  
    int x = 7 / k;  
}
```



Binary Operations

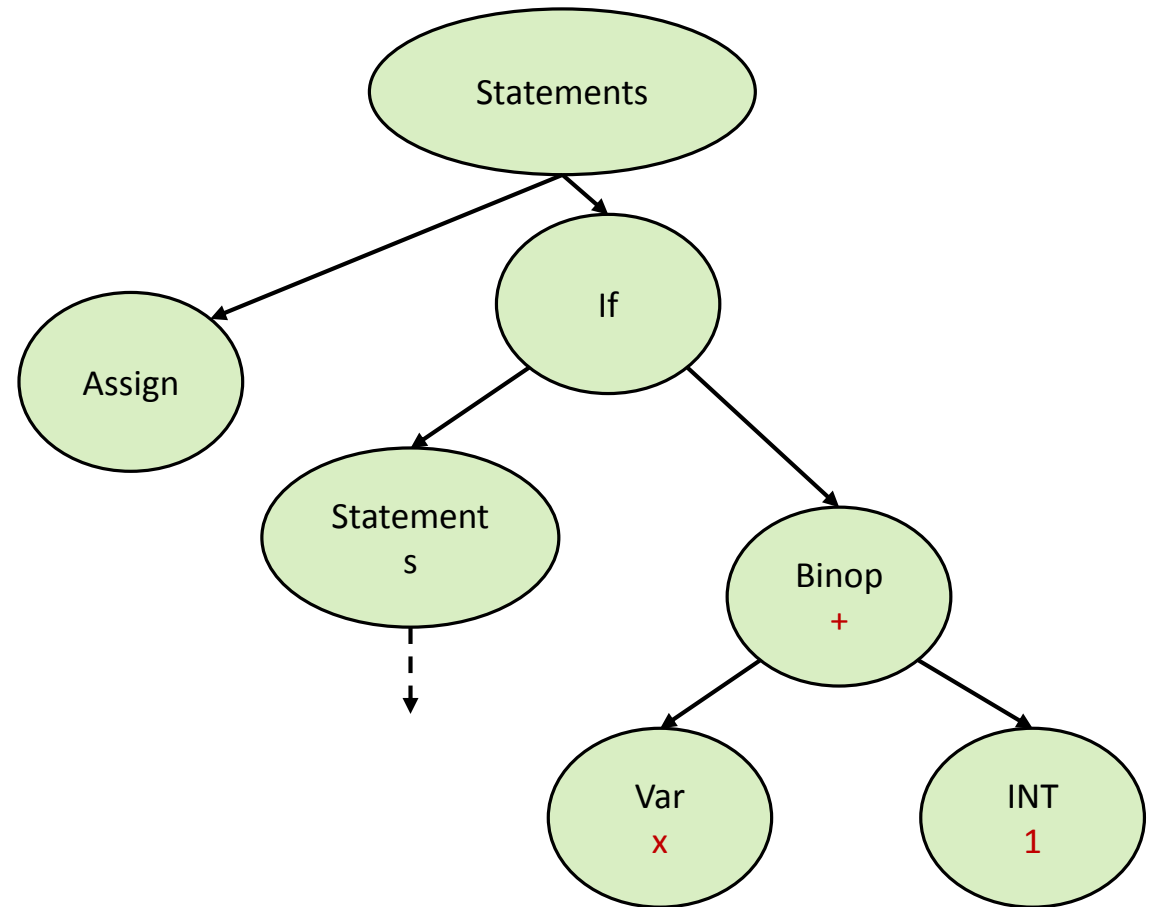
```
void main() {  
    int k = 0;  
    int x = 7 / k;  
}
```



Depends

If, While, ...

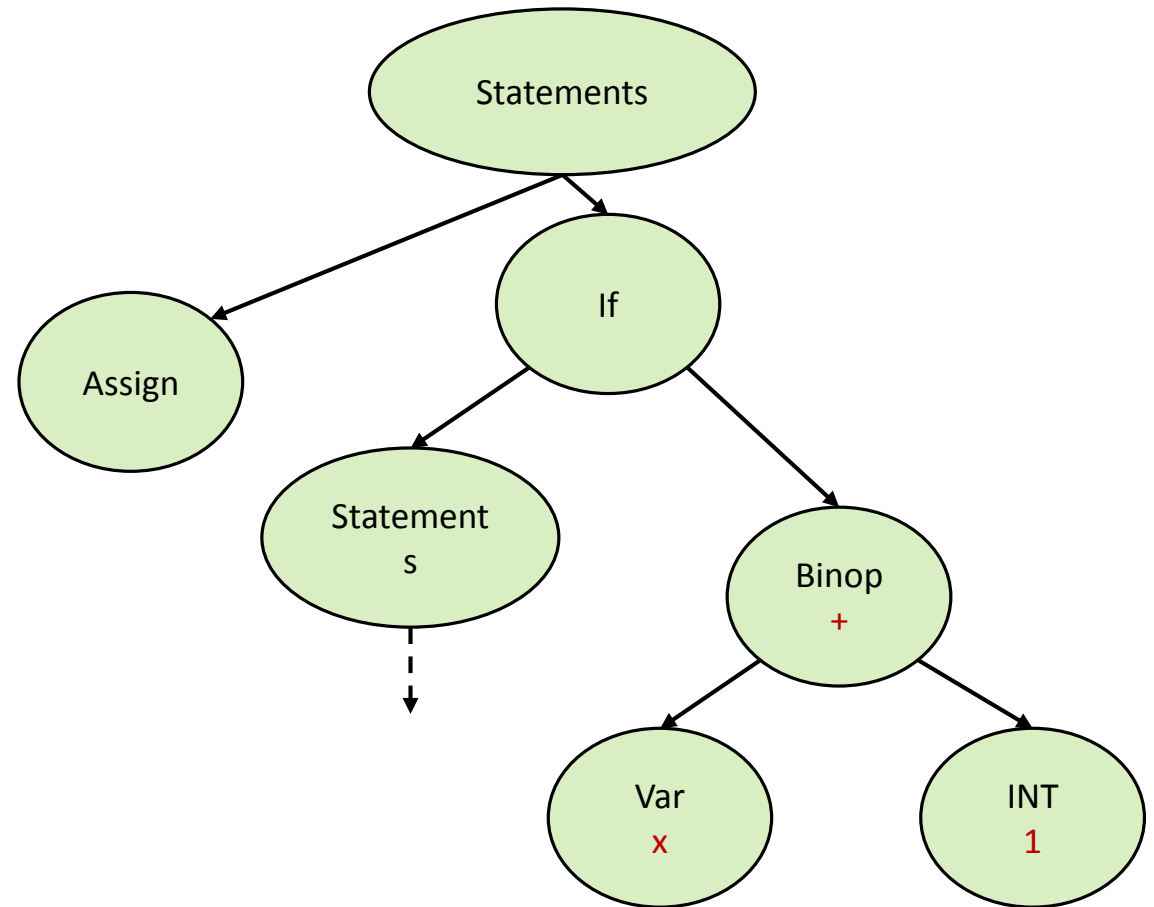
```
void main() {  
    int x = 1;  
    if (x + 1) {  
        int z = 2;  
    }  
}
```



If, While, ...

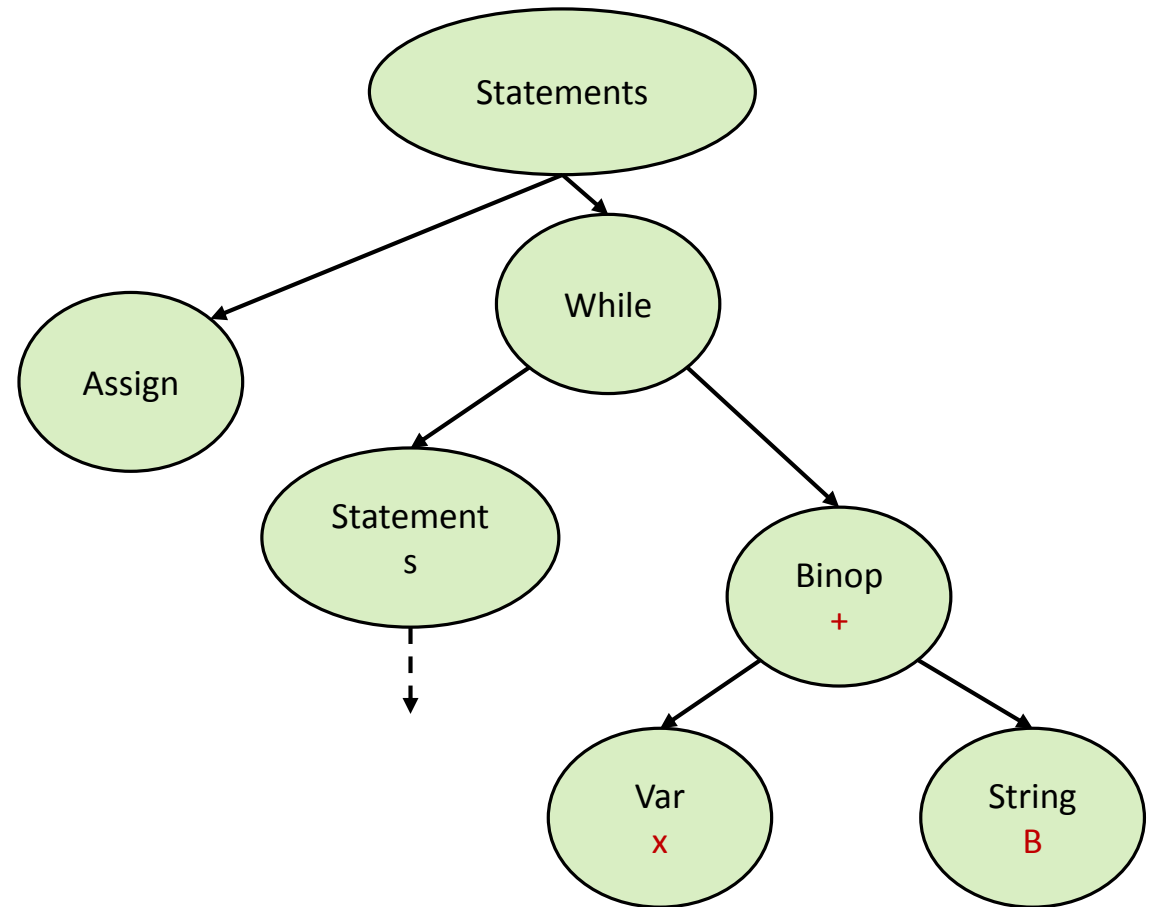
```
void main() {  
    int x = 1;  
    if (x + 1) {  
        int z = 2;  
    }  
}
```

Valid



If, While, ...

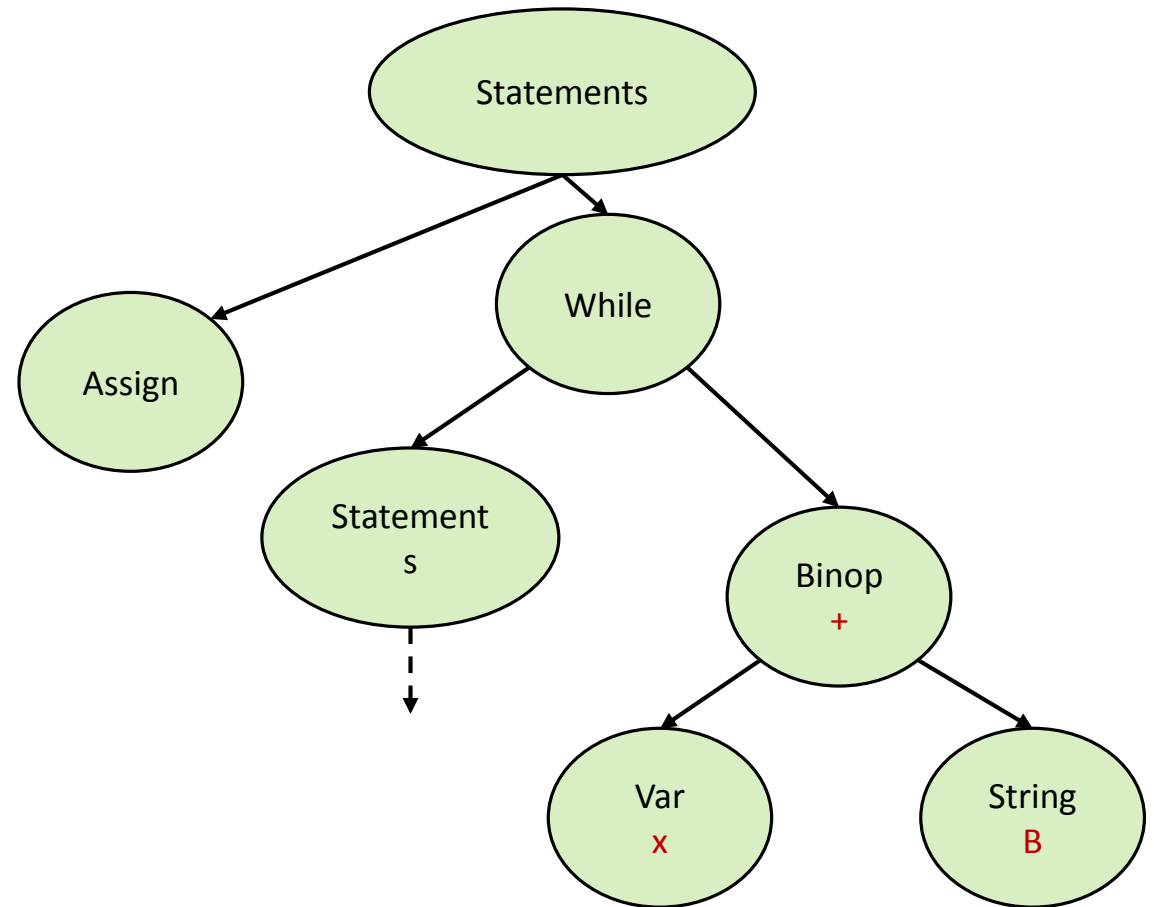
```
void main() {  
    string x = "A";  
    while (x + "B") {  
        int z = 2;  
    }  
}
```



If, While, ...

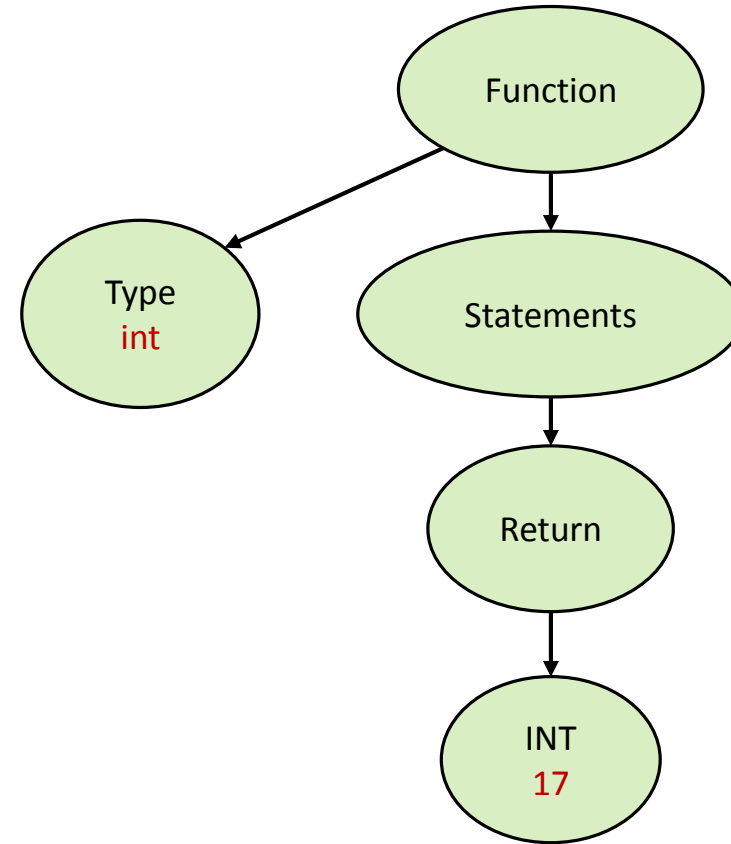
```
void main() {  
    string x = "A";  
    while (x + "B") {  
        int z = 2;  
    }  
}
```

Invalid



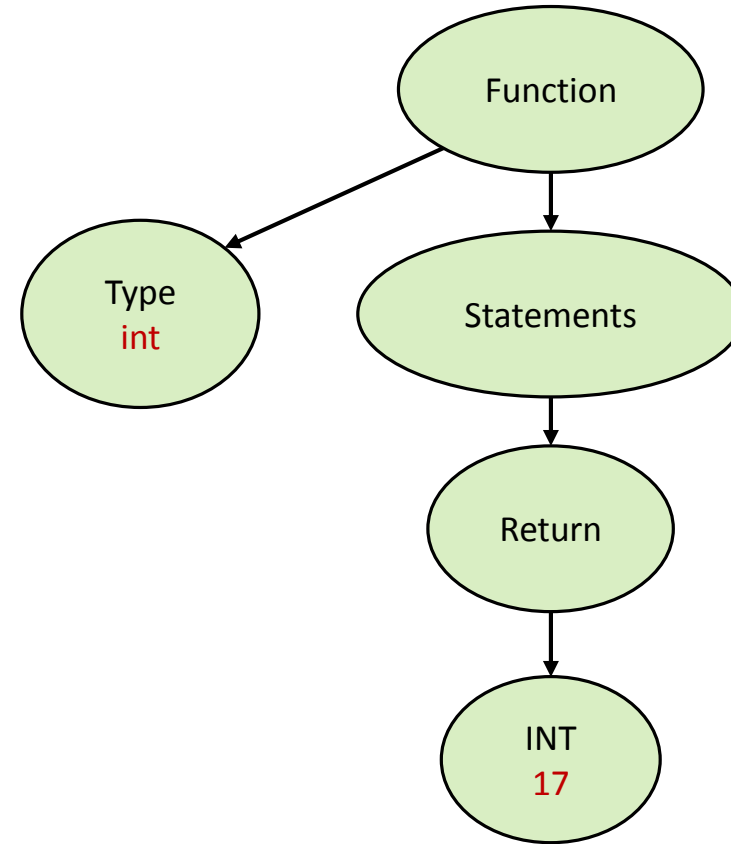
Return Statement

```
int main() {  
    return 17;  
}
```



Return Statement

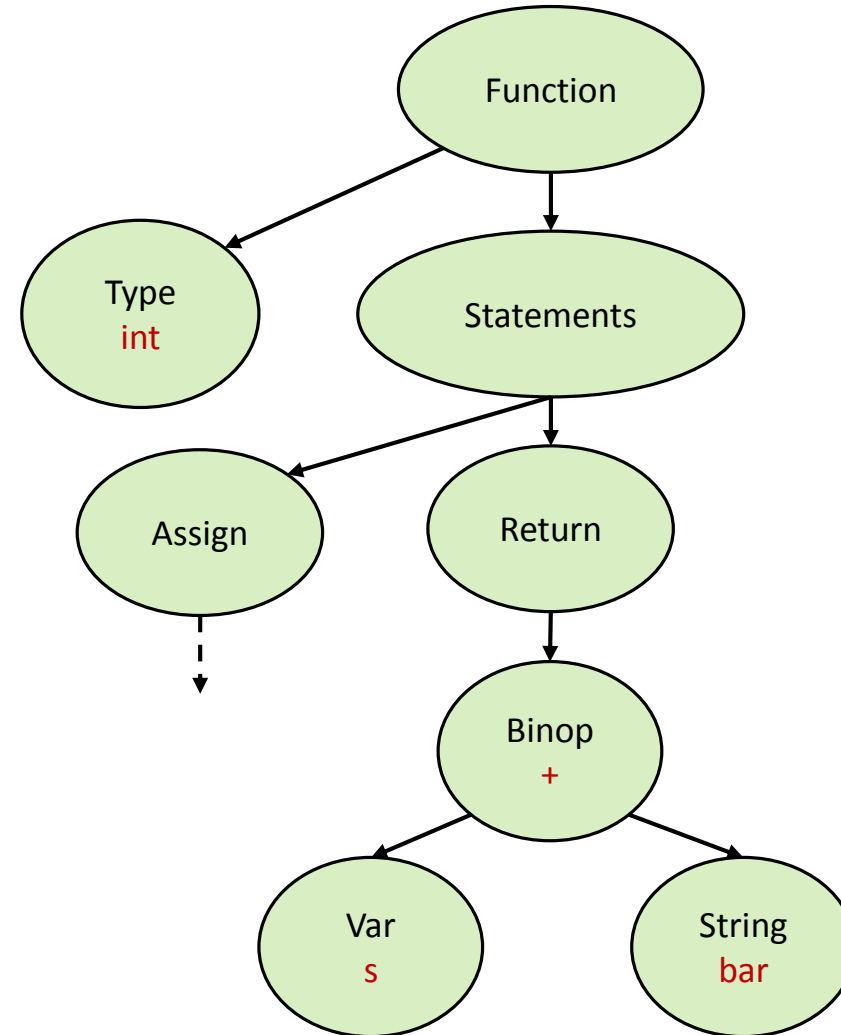
```
int main() {  
    return 17;  
}
```



Valid

Return Statement

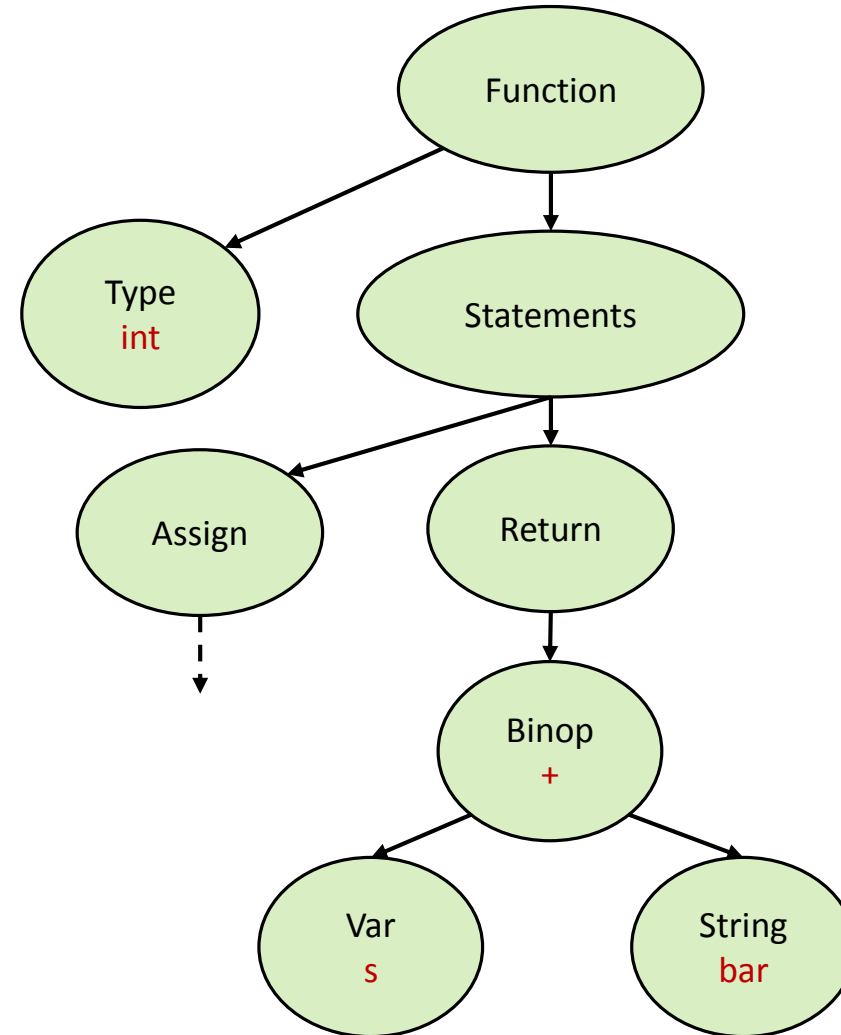
```
int main() {  
    string s = "foo"  
    return s + "bar";  
}
```



Return Statement

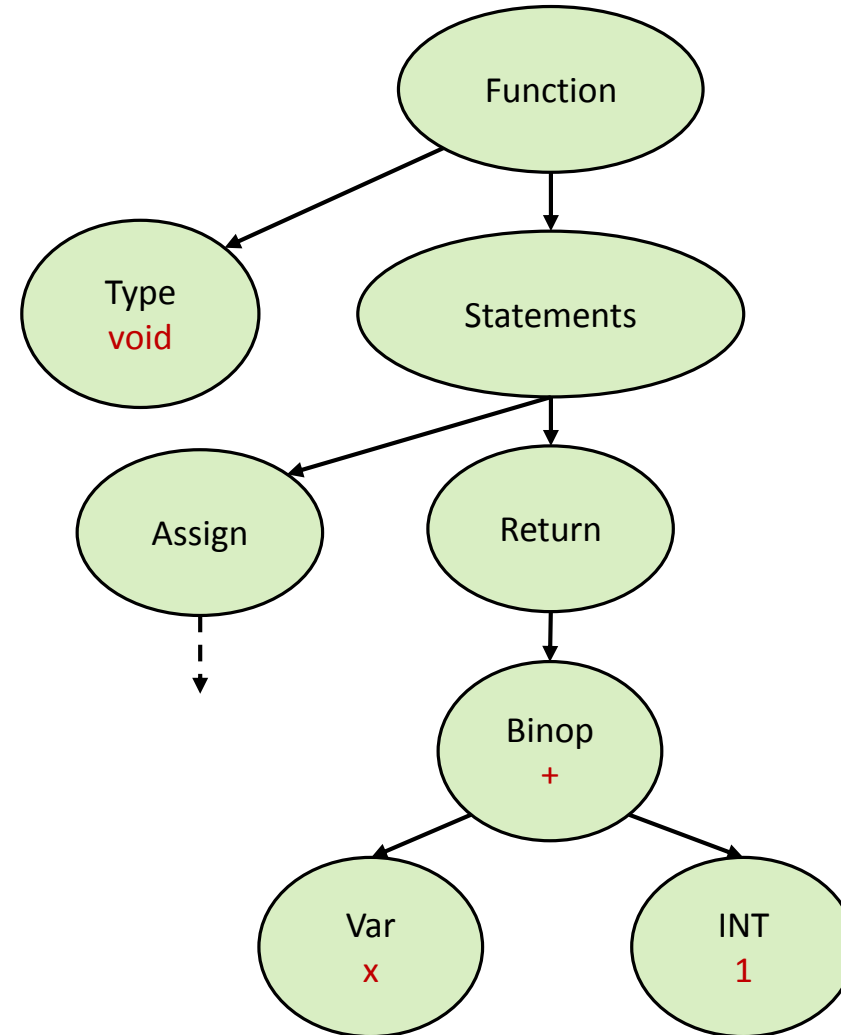
```
int main() {  
    string s = "foo"  
    return s + "bar";  
}
```

Invalid



Return Statement

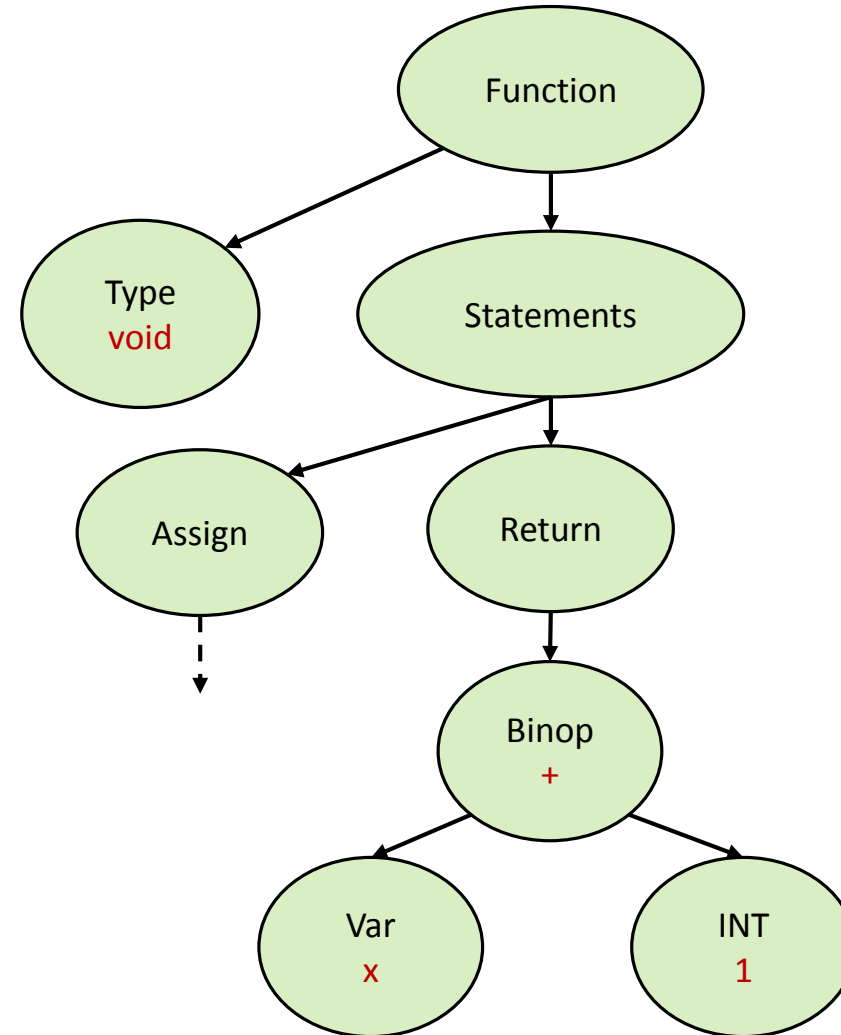
```
void main() {  
    int x = 1;  
    return x + 1;  
}
```



Return Statement

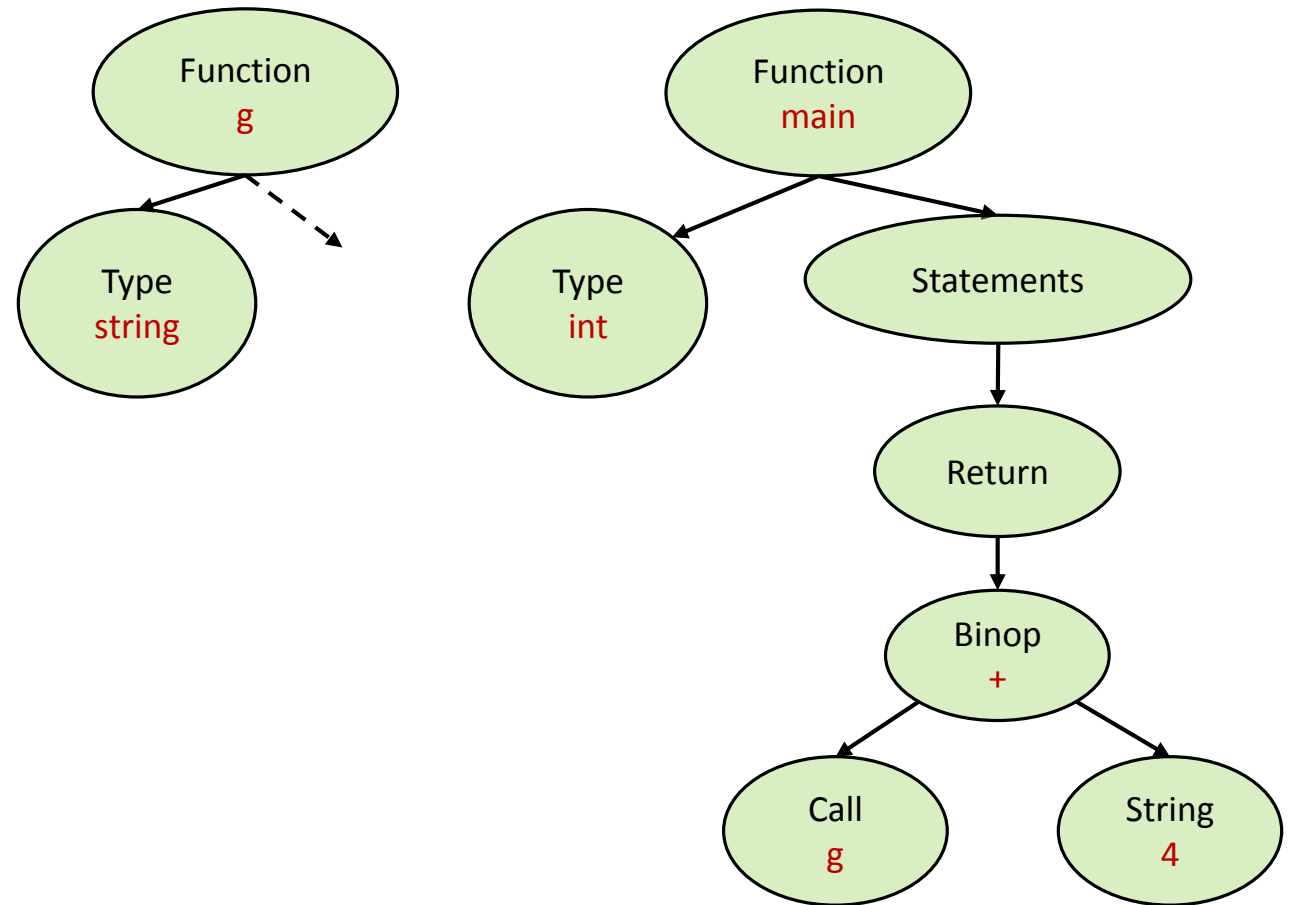
```
void main() {  
    int x = 1;  
    return x + 1;  
}
```

Invalid



Return Statement

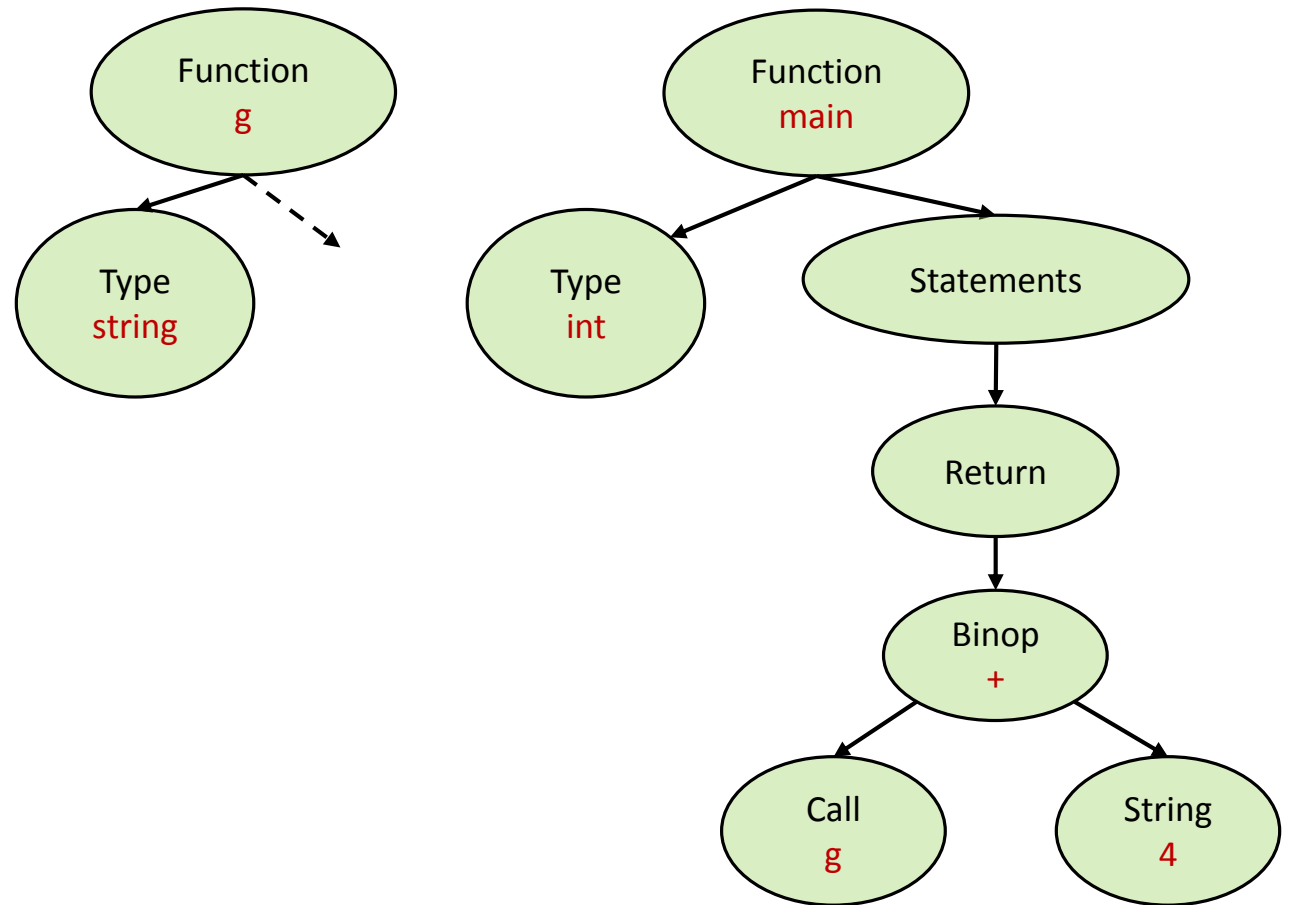
```
string g() {  
    return "123";  
}  
int main() {  
    return g() + "4";  
}
```



Return Statement

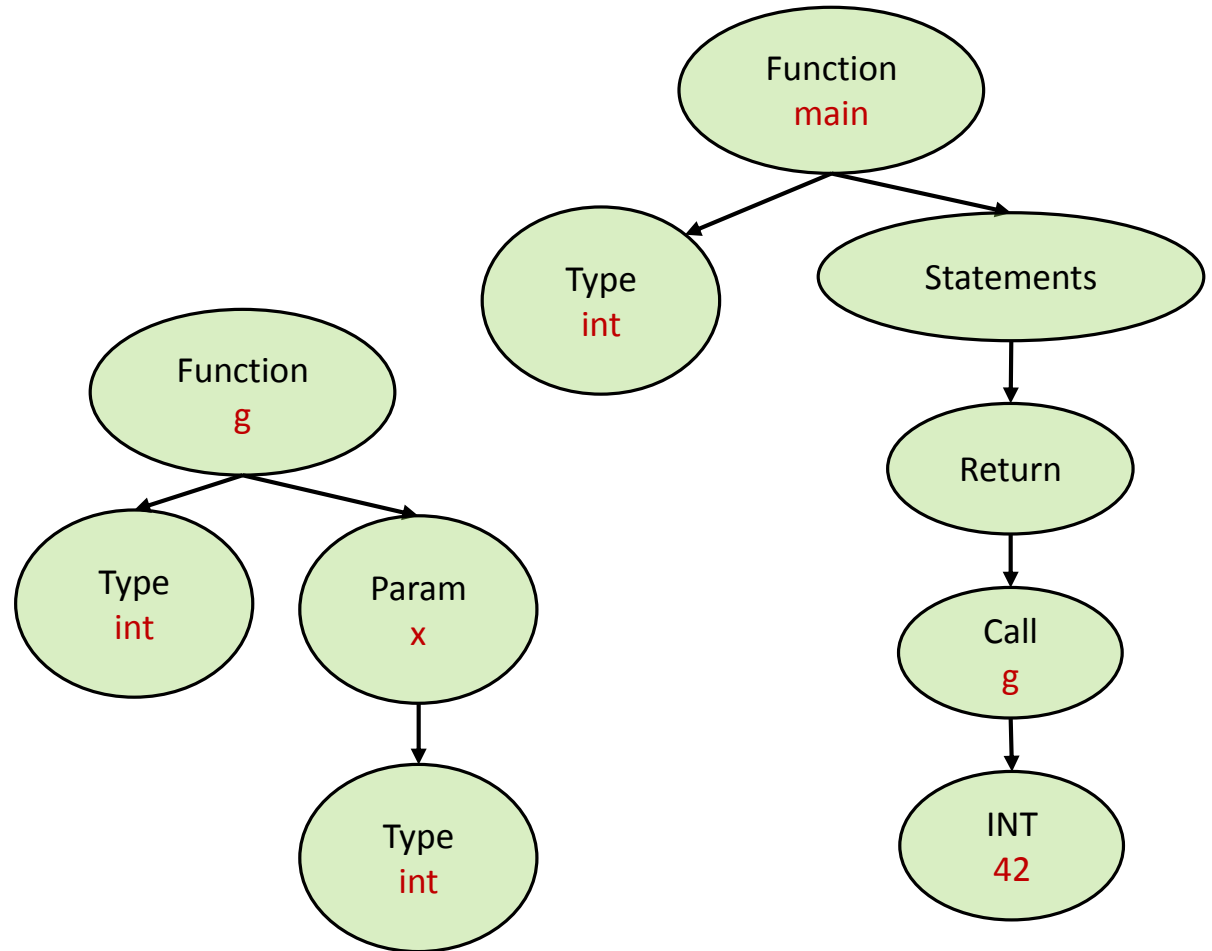
```
string g() {  
    return "123";  
}  
int main() {  
    return g() + "4";  
}
```

Invalid



Function Calls

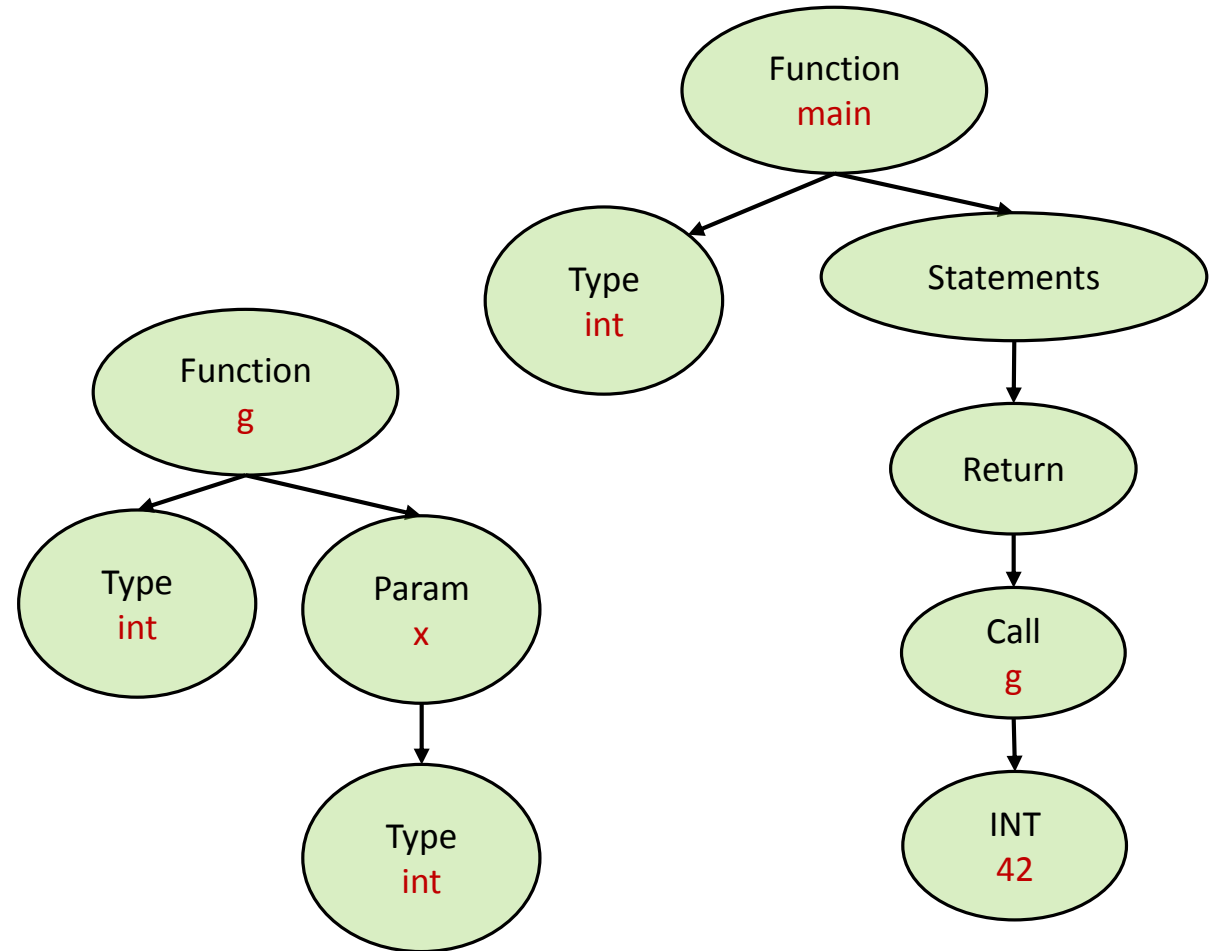
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    return g(42);  
}
```



Function Calls

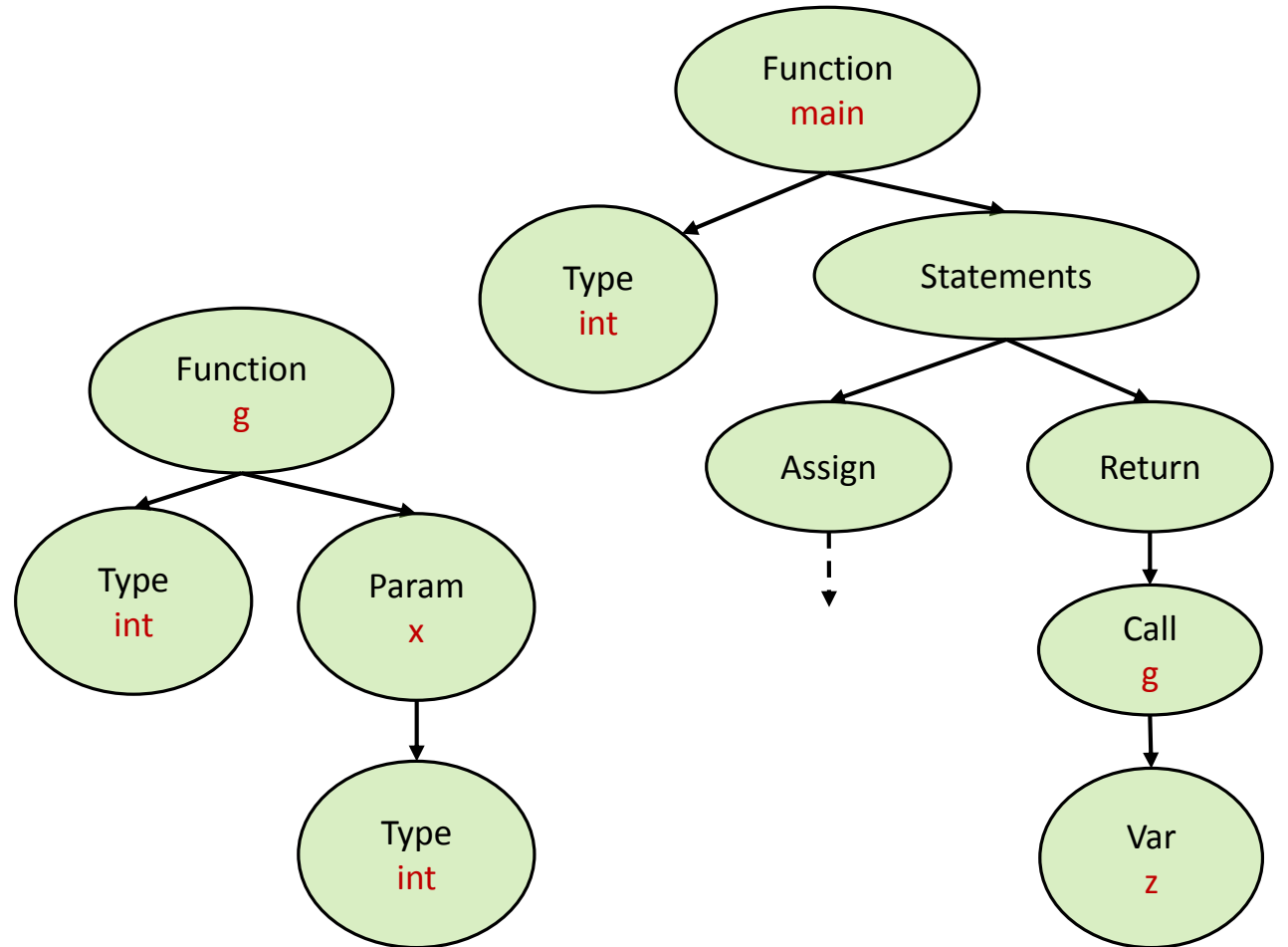
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    return g(42);  
}
```

Valid



Function Calls

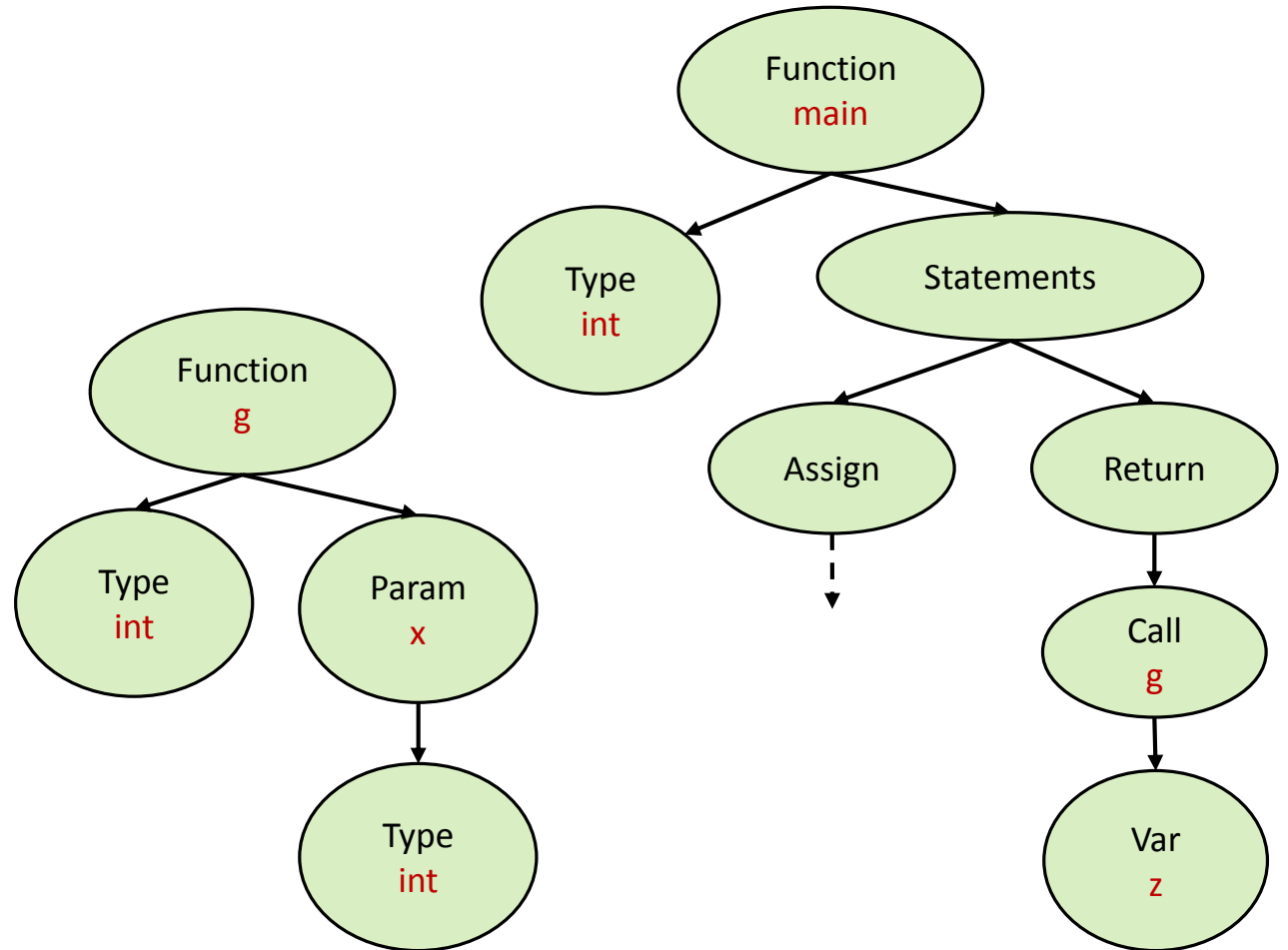
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    string z = "..."  
    return g(z);  
}
```



Function Calls

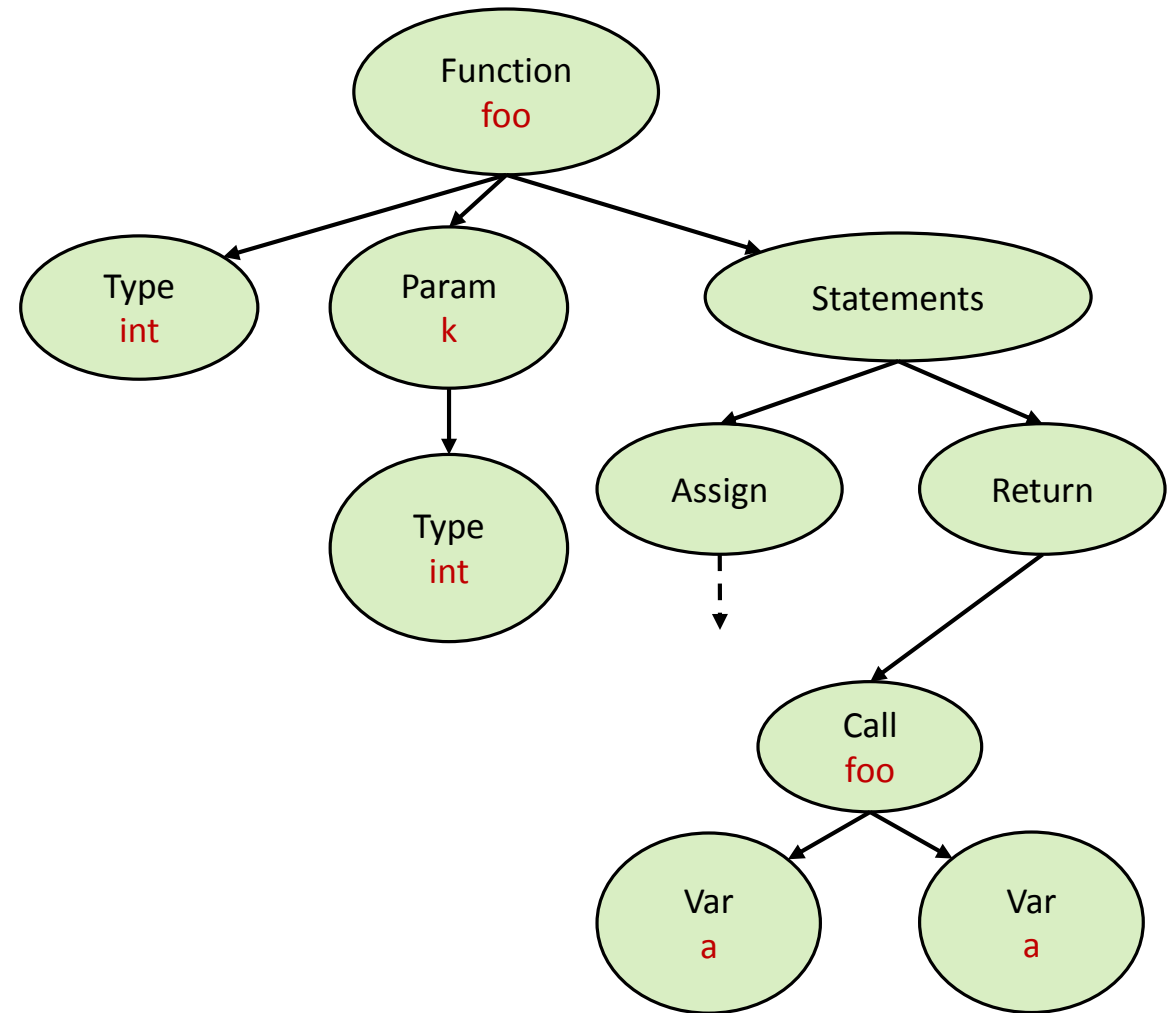
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    string z = "..."  
    return g(z);  
}
```

Invalid



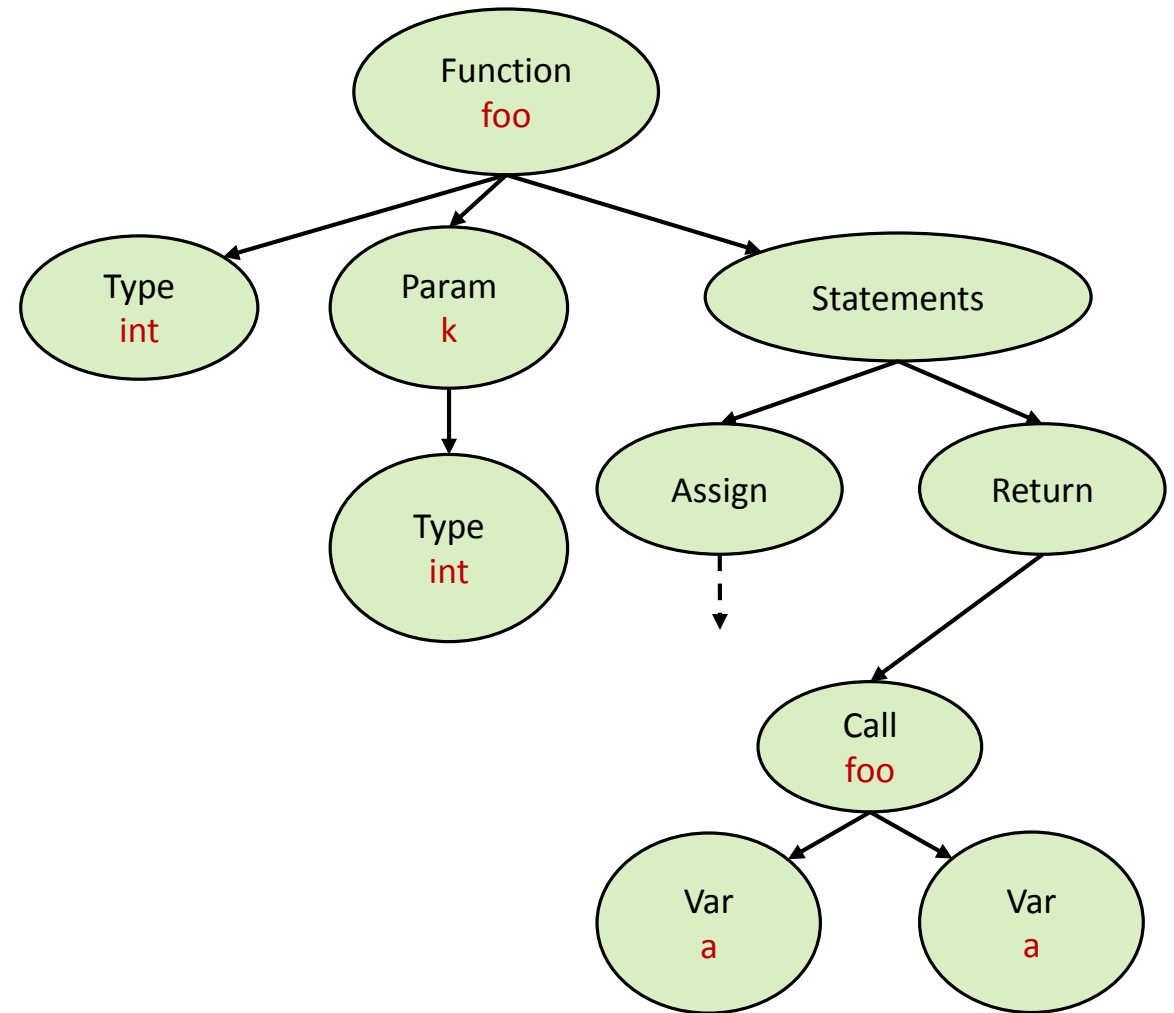
Function Calls

```
int foo(int k) {  
    int a = k * 10;  
    return foo(a, a);  
}
```



Function Calls

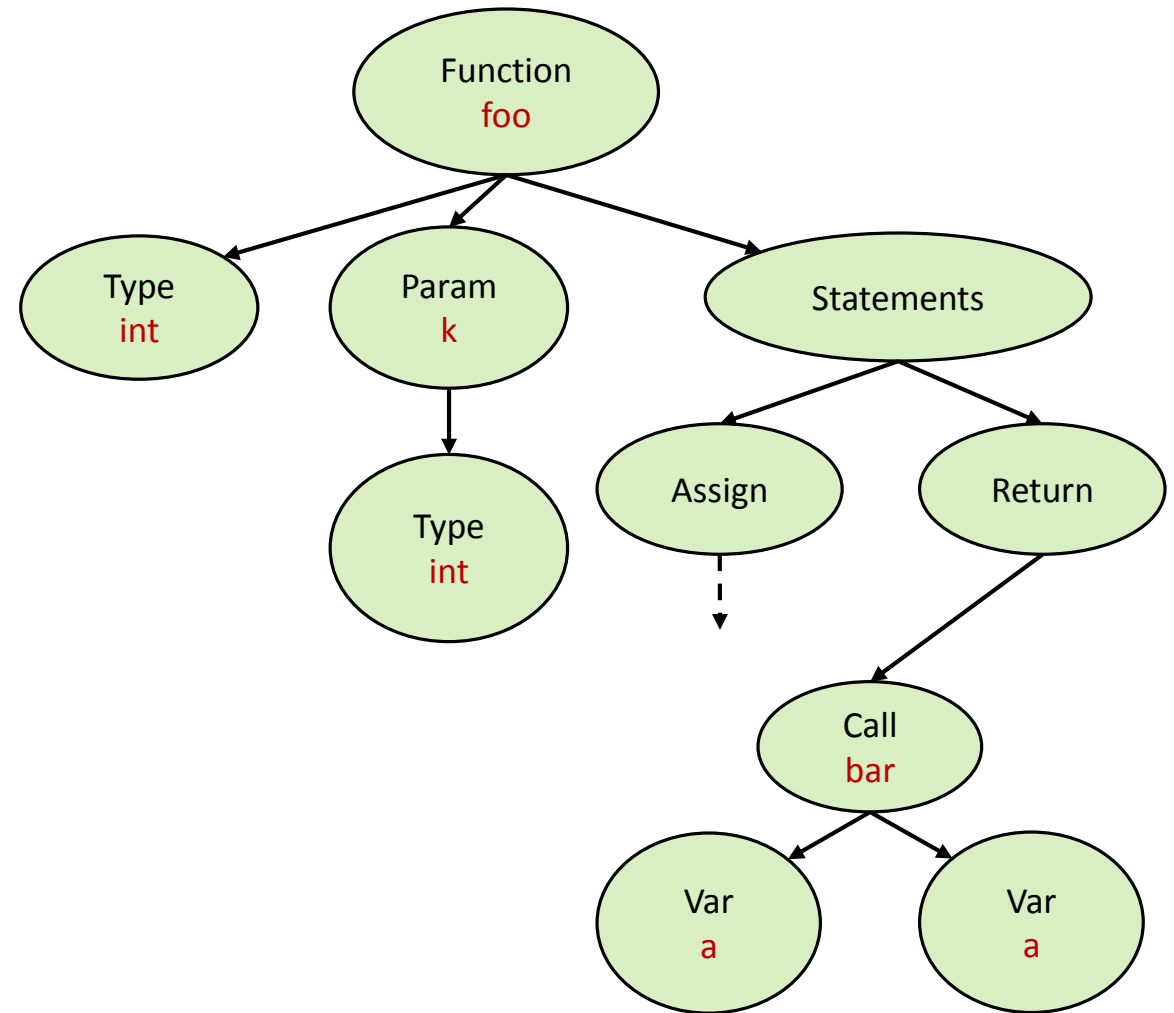
```
int foo(int k) {  
    int a = k * 10;  
    return foo(a, a);  
}
```



Invalid

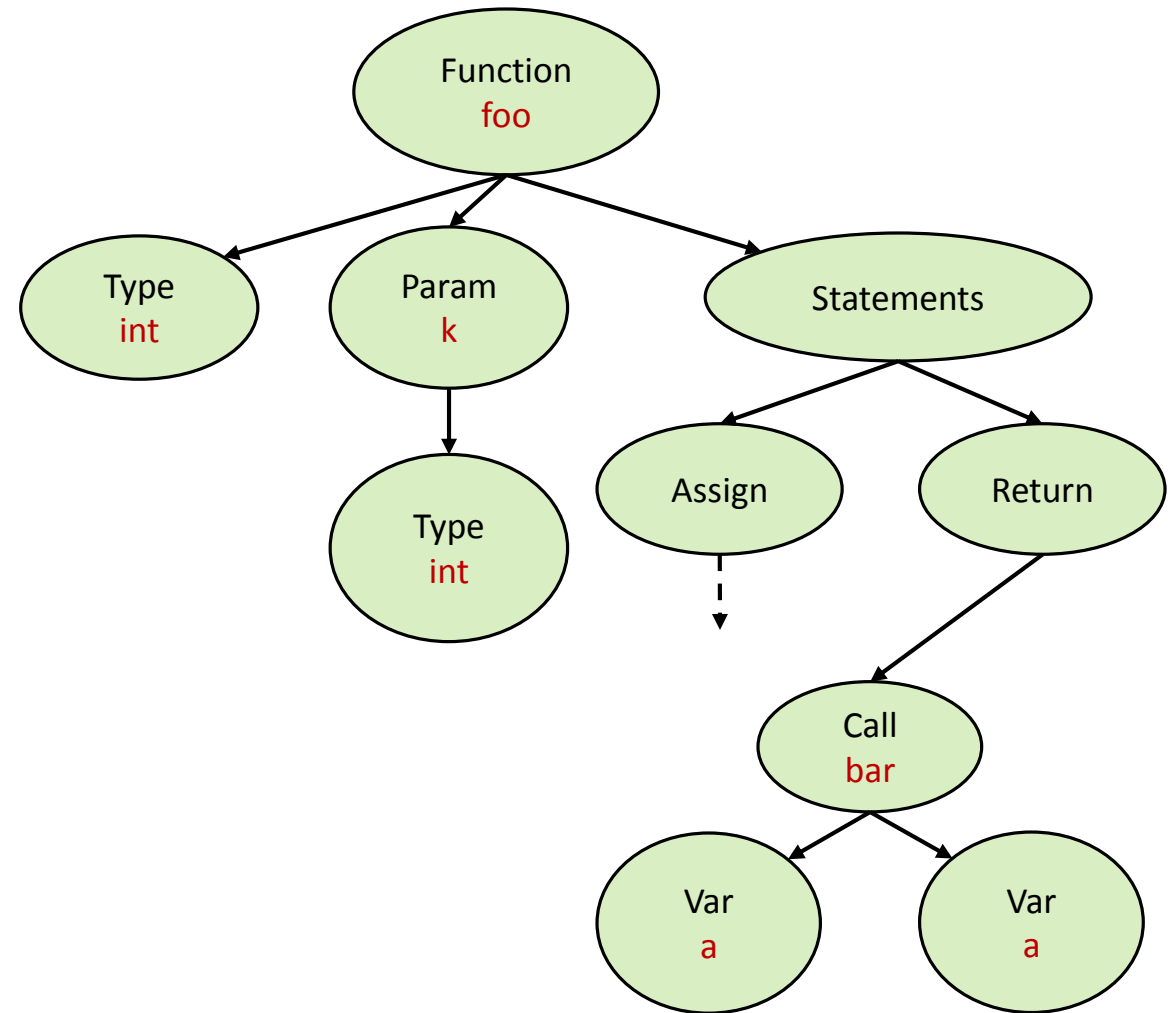
Function Calls

```
int foo(int k) {  
    int a = k * 10;  
    return bar(a, a);  
}
```



Function Calls

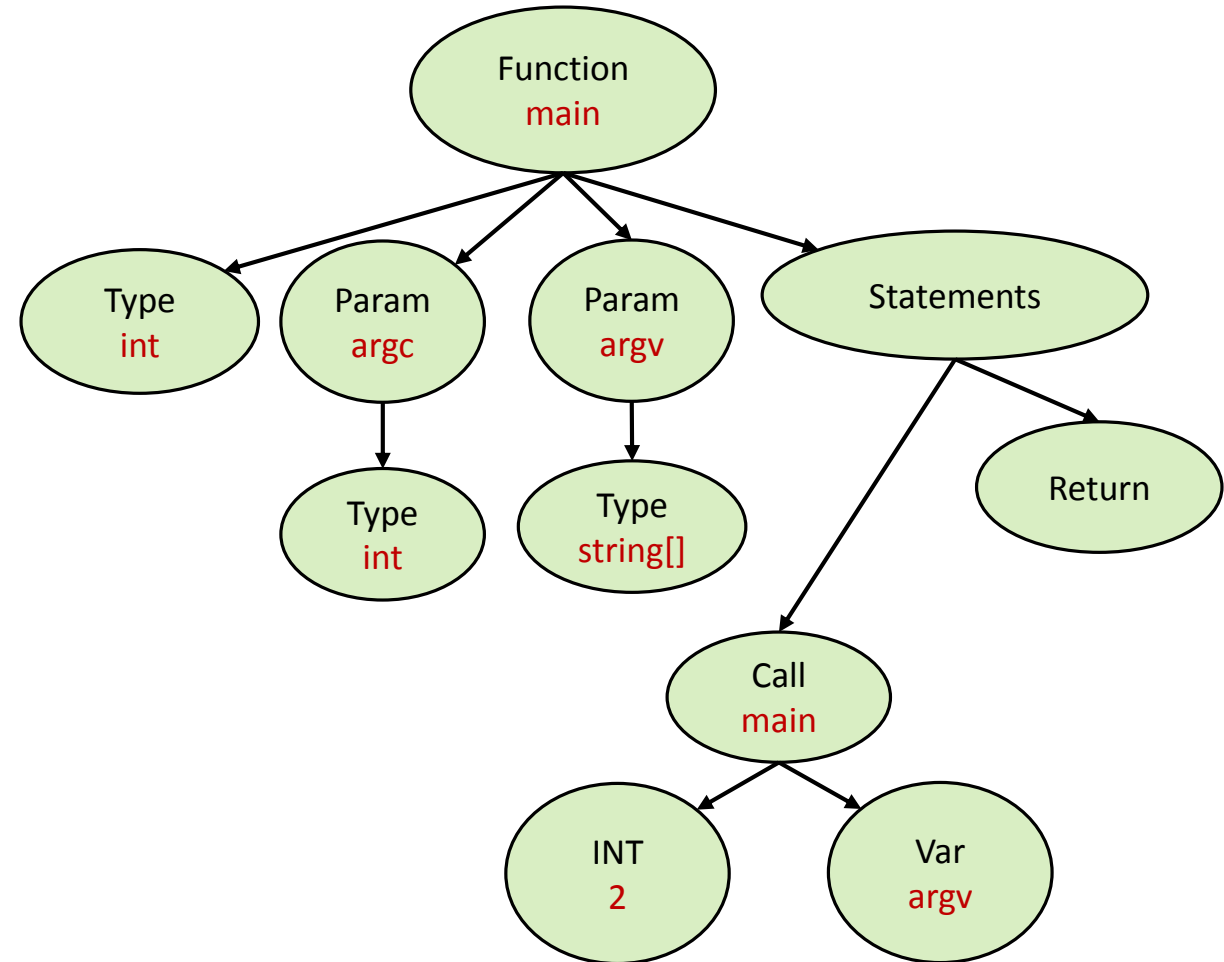
```
int foo(int k) {  
    int a = k * 10;  
    return bar(a, a);  
}
```



Invalid

Function Calls

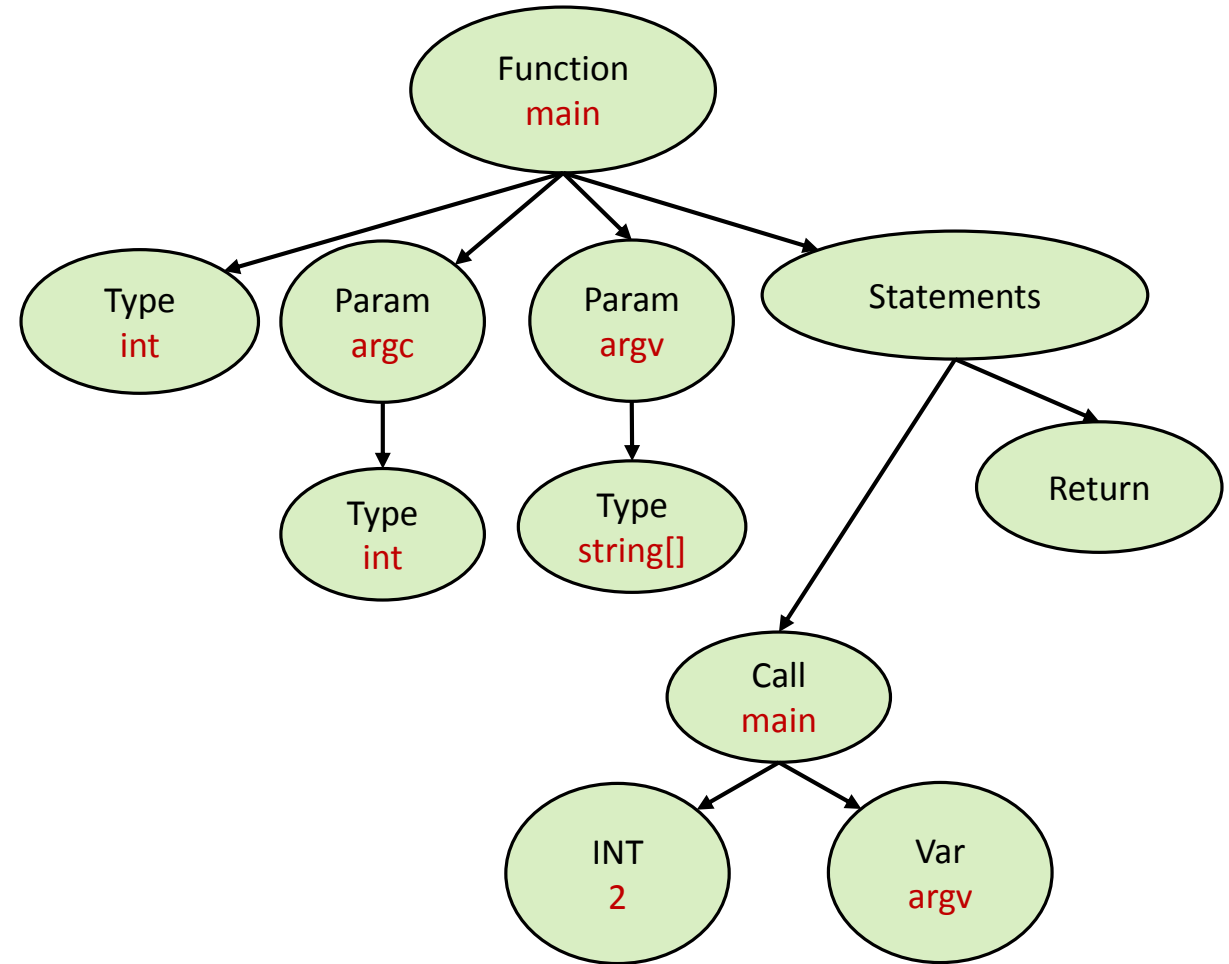
```
int main(int argc,  
          string argv[]){  
    main(2, argv);  
    return 0;  
}
```



Function Calls

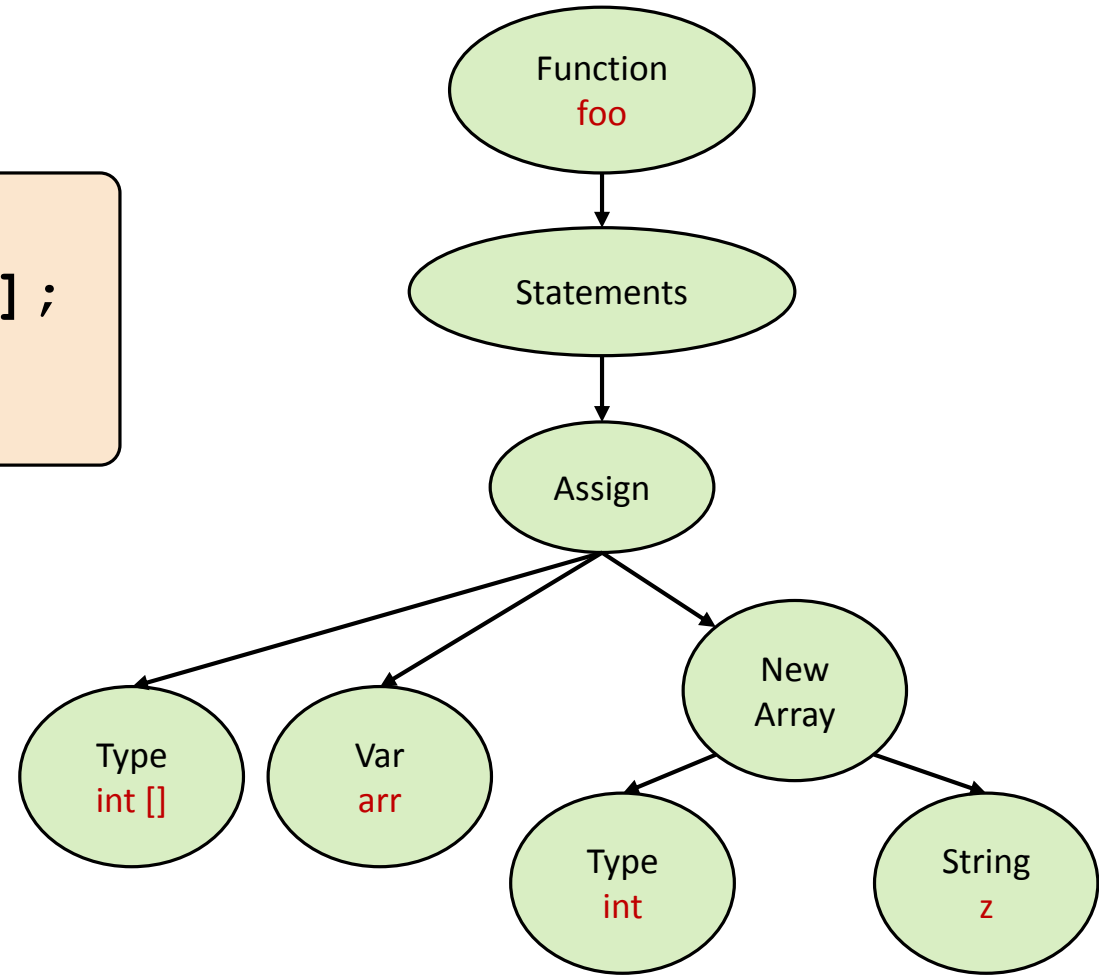
```
int main(int argc,  
          string argv[]){  
    main(2, argv);  
    return 0;  
}
```

Valid



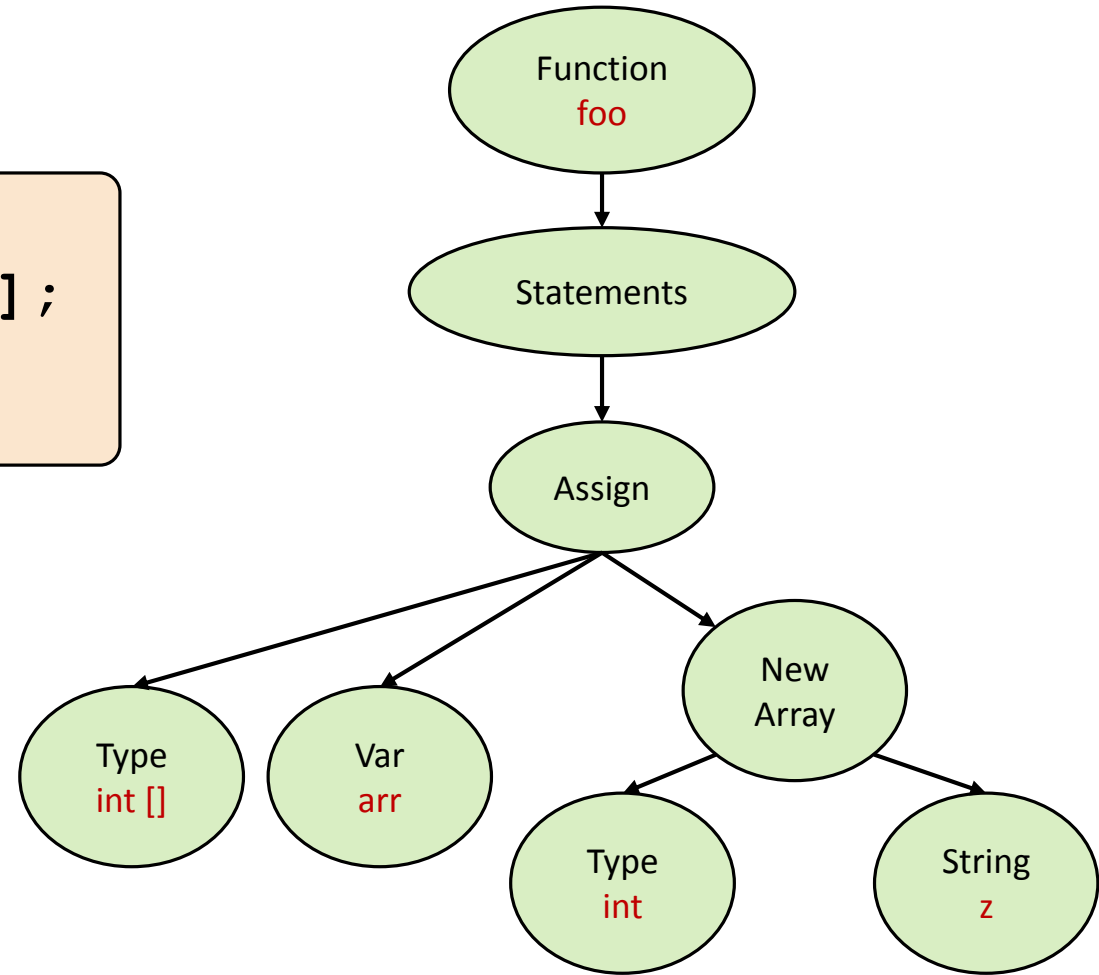
Arrays

```
void foo(void) {  
    int[] arr = new int["z"];  
}
```



Arrays

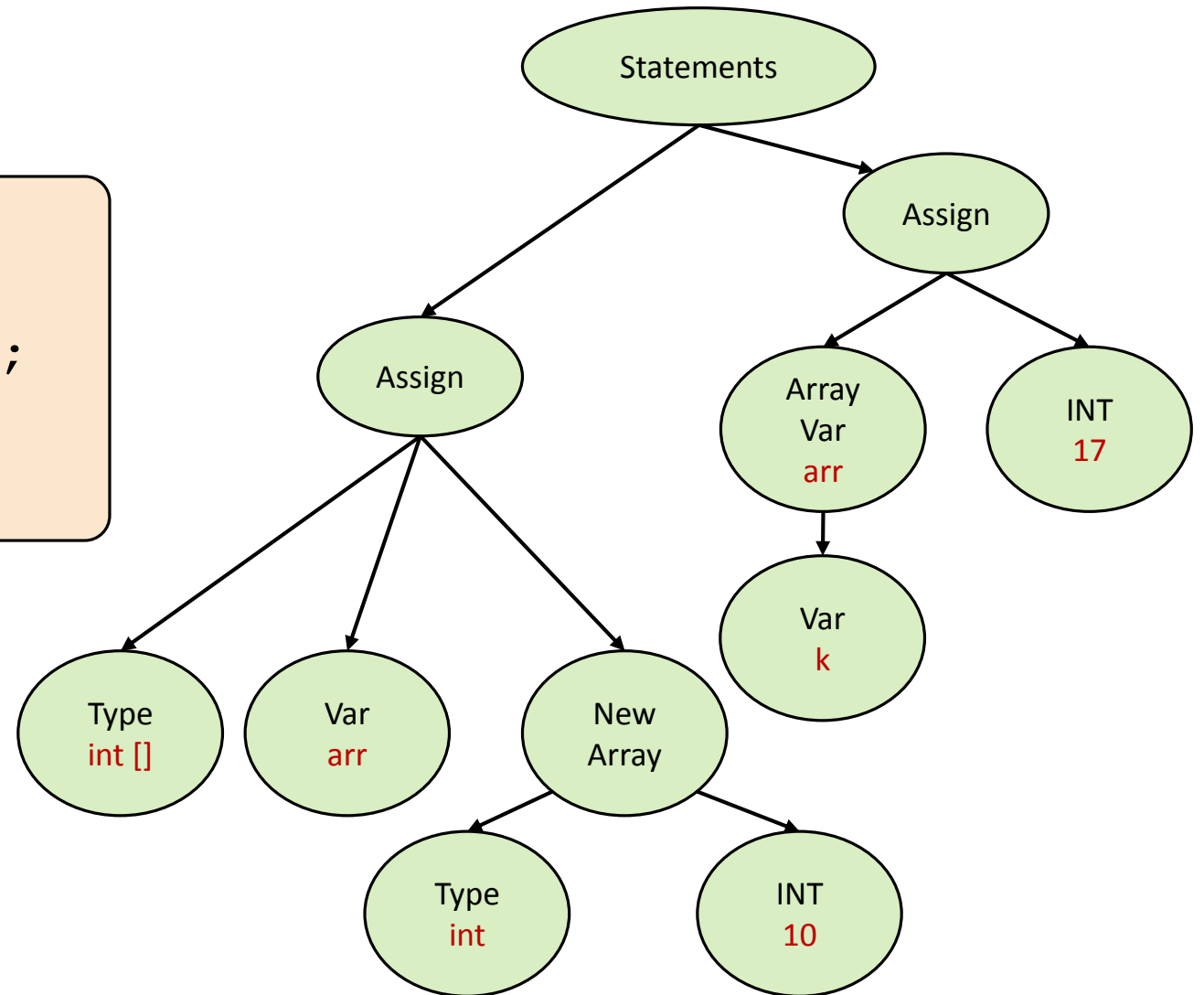
```
void foo(void) {  
    int[] arr = new int["z"];  
}
```



Invalid

Arrays

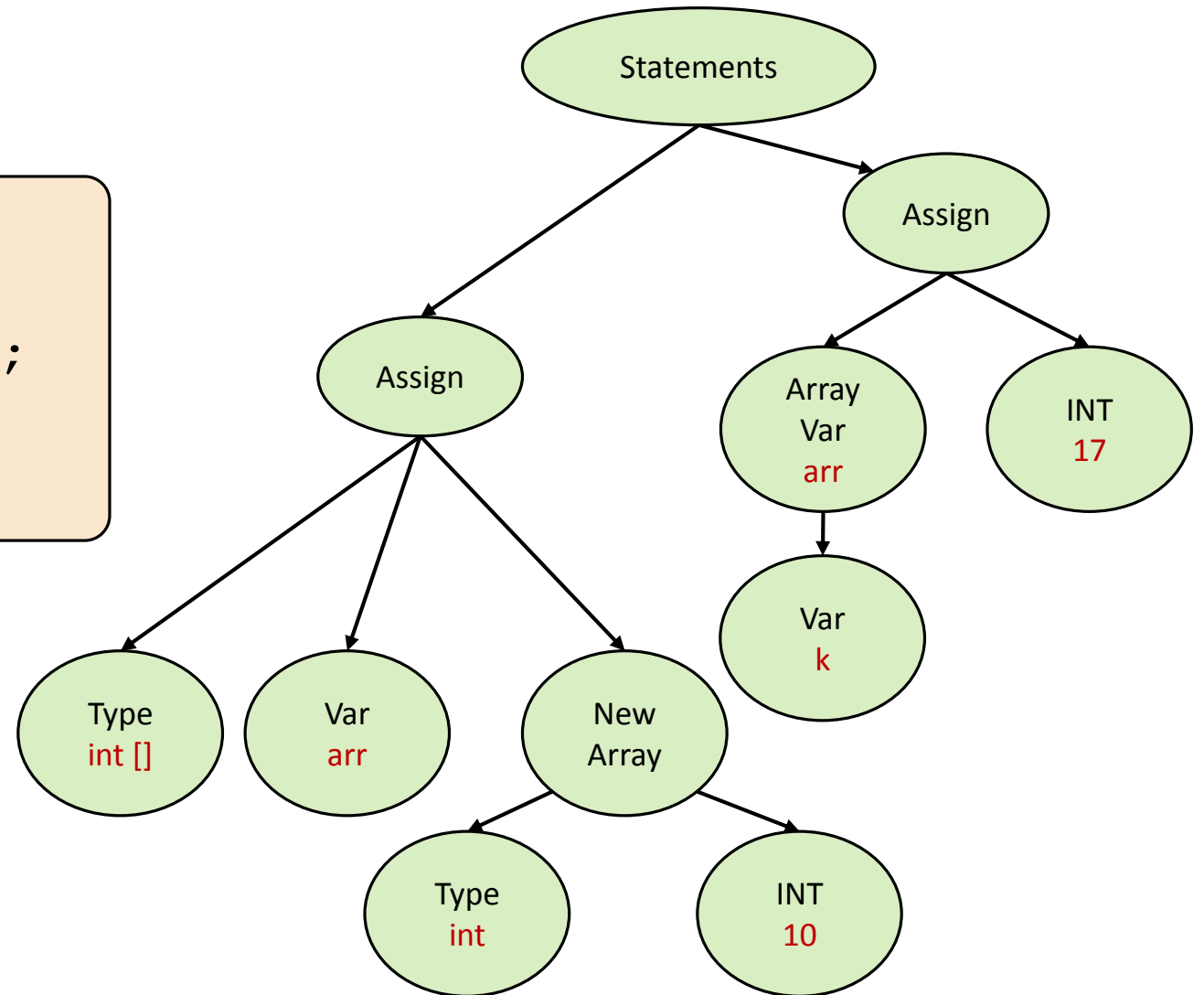
```
void foo(int d) {  
    int k = 3;  
    int[] arr = new int[10];  
    arr[k] = 17;  
}
```



Arrays

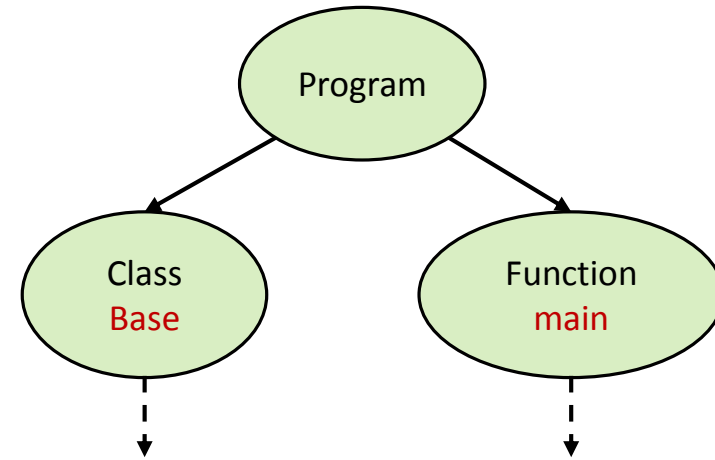
```
void foo(int d) {  
    int k = 3;  
    int[] arr = new int[10];  
    arr[k] = 17;  
}
```

Valid



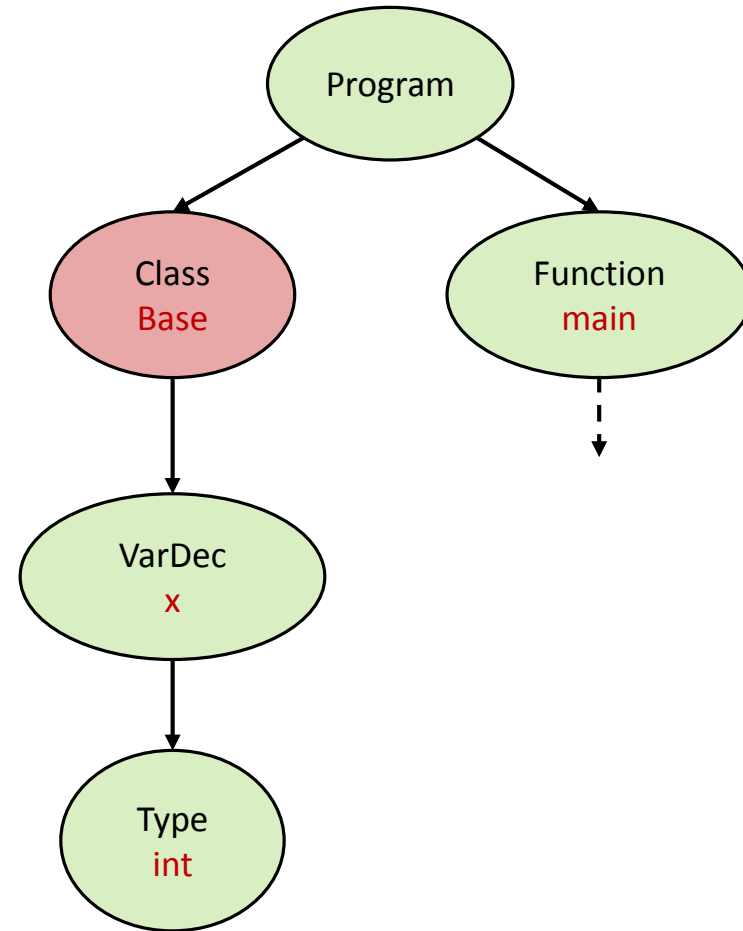
Classes

```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```



Classes

```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```



Classes

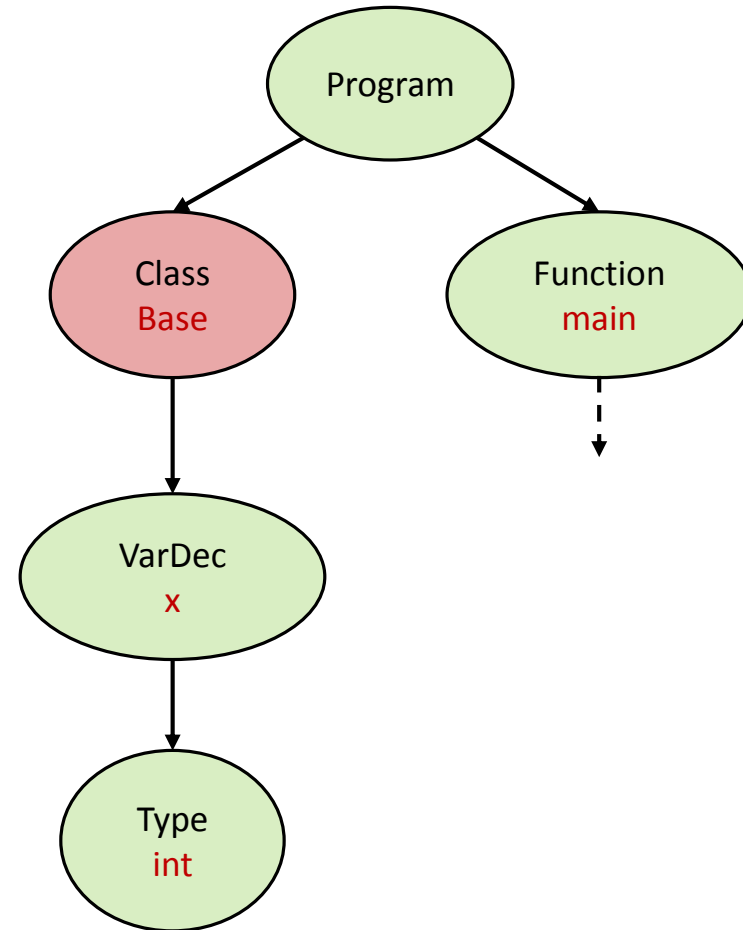
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```

ID	Type	Kind
Base	...	class

$scope_1$

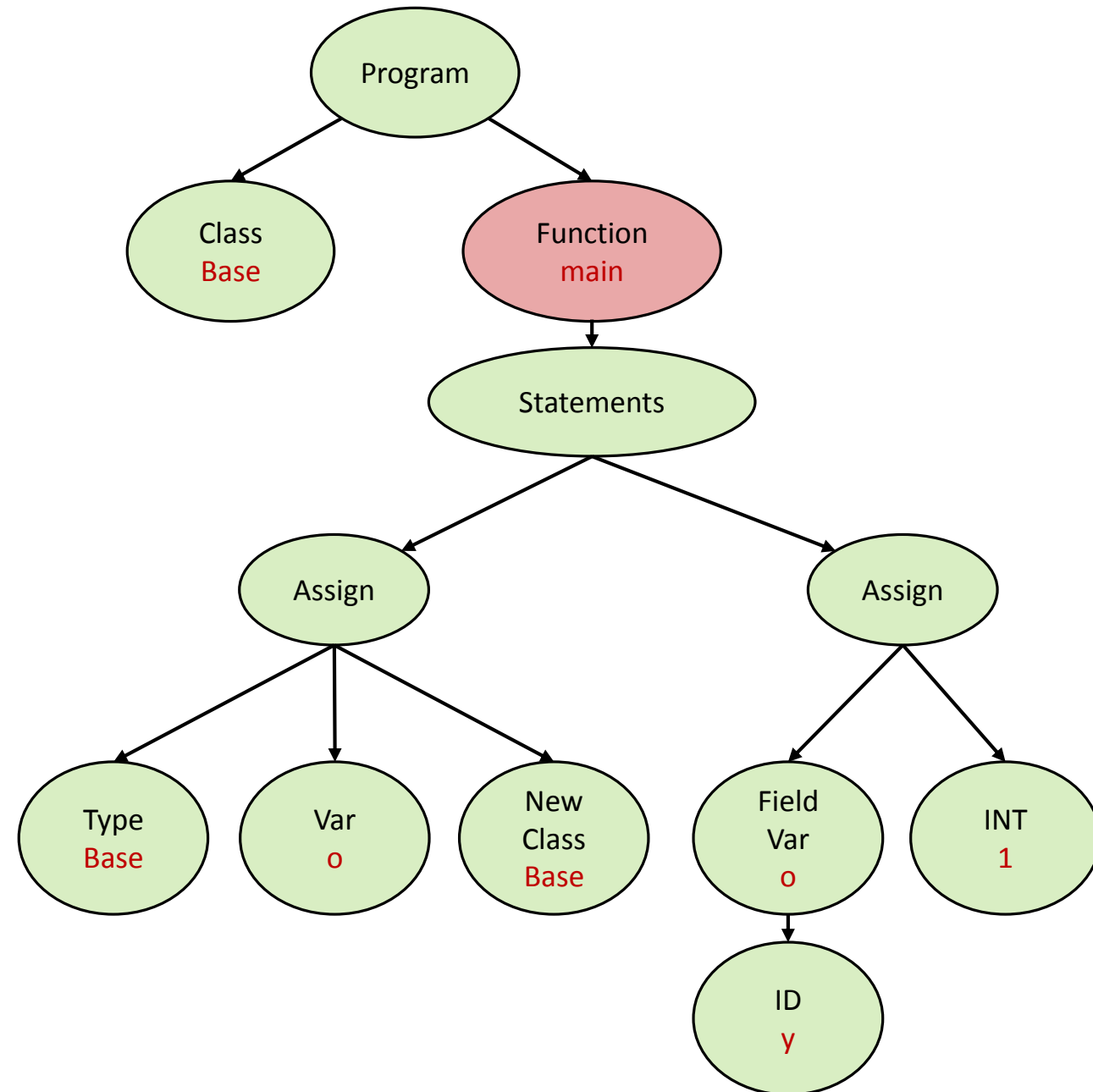
ID	Type	Kind
x	int	variable

$scope_2$



Classes

```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```



Classes

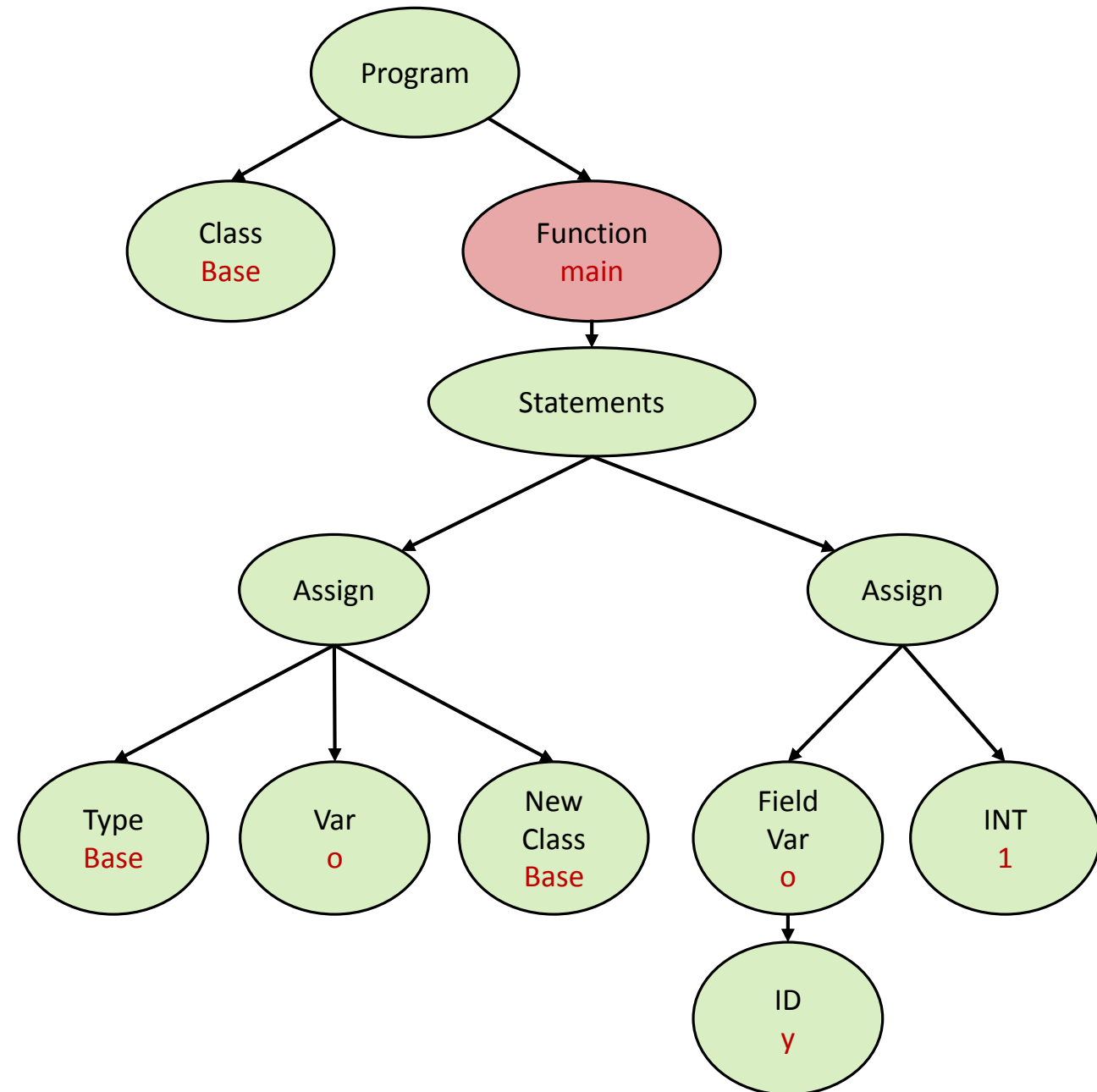
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```

ID	Type	Kind
Base	...	class
main	...	function

scope₁

ID	Type	Kind
o	Base	variable

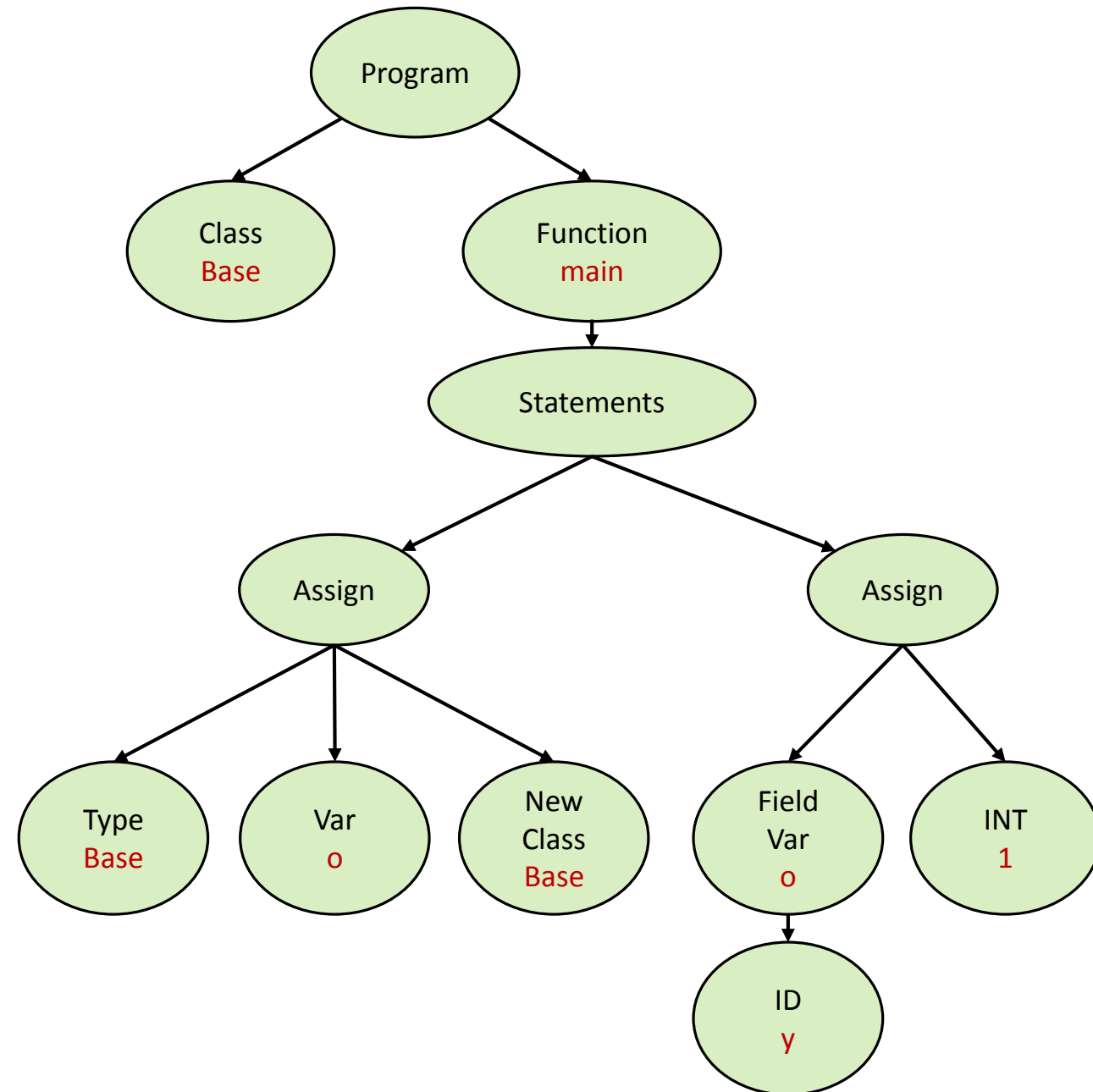
scope₂



Classes

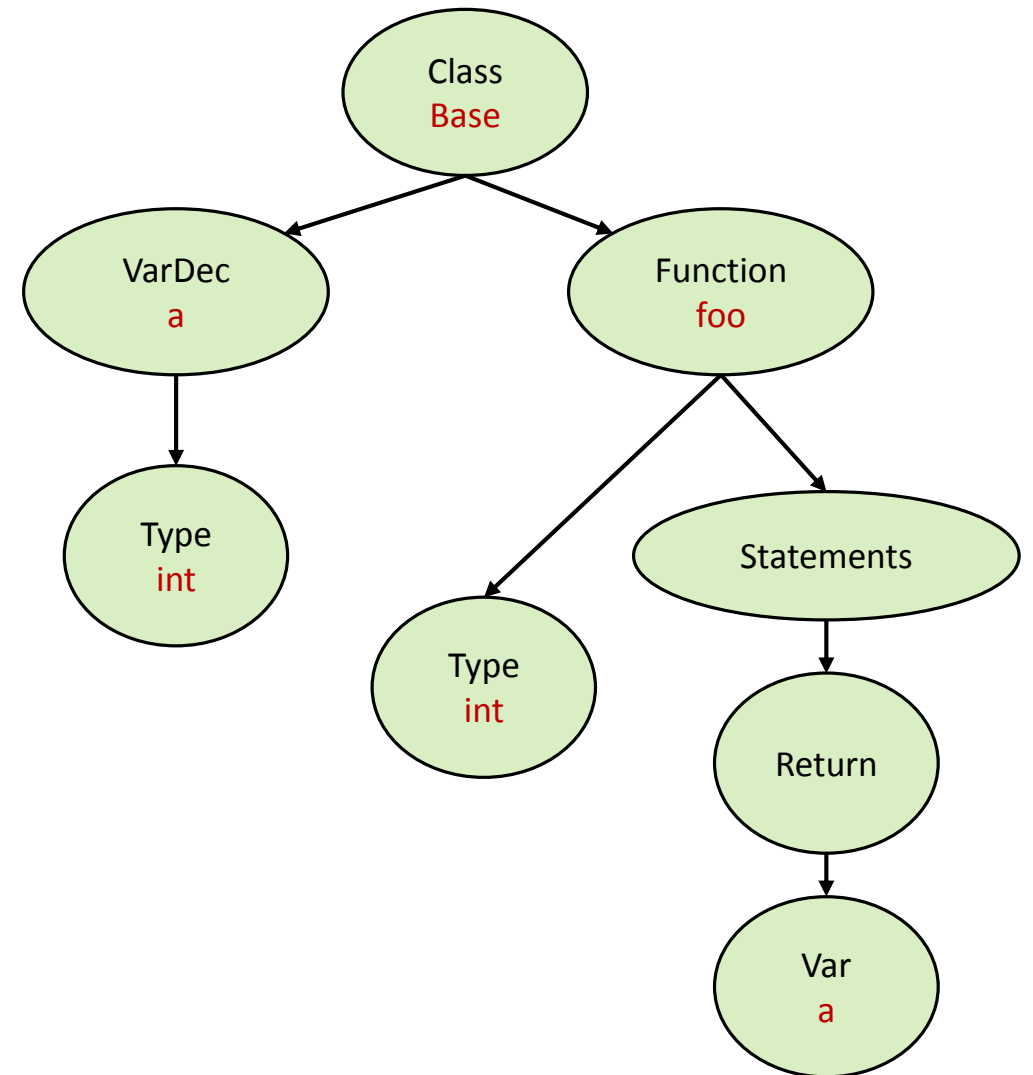
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```

Invalid



Classes

```
class Base {  
  int a;  
  int foo() {  
    return a;  
  }  
}
```



Classes

```
class Base {  
  int a;  
  int foo() {  
    return a;  
  }  
}
```

ID	Type	Kind
Base	...	class

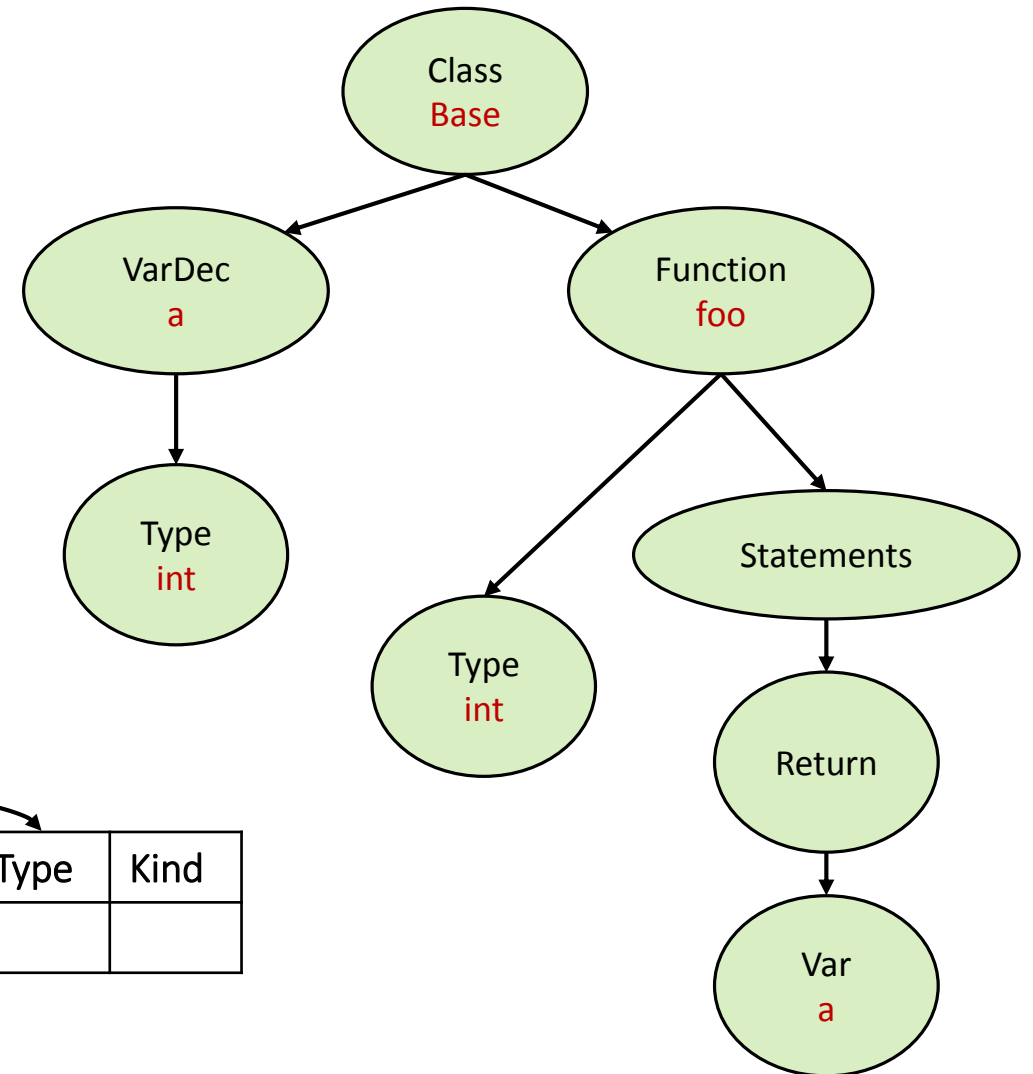
scope₁

ID	Type	Kind
a	int	variable
foo	...	function

scope₂

ID	Type	Kind

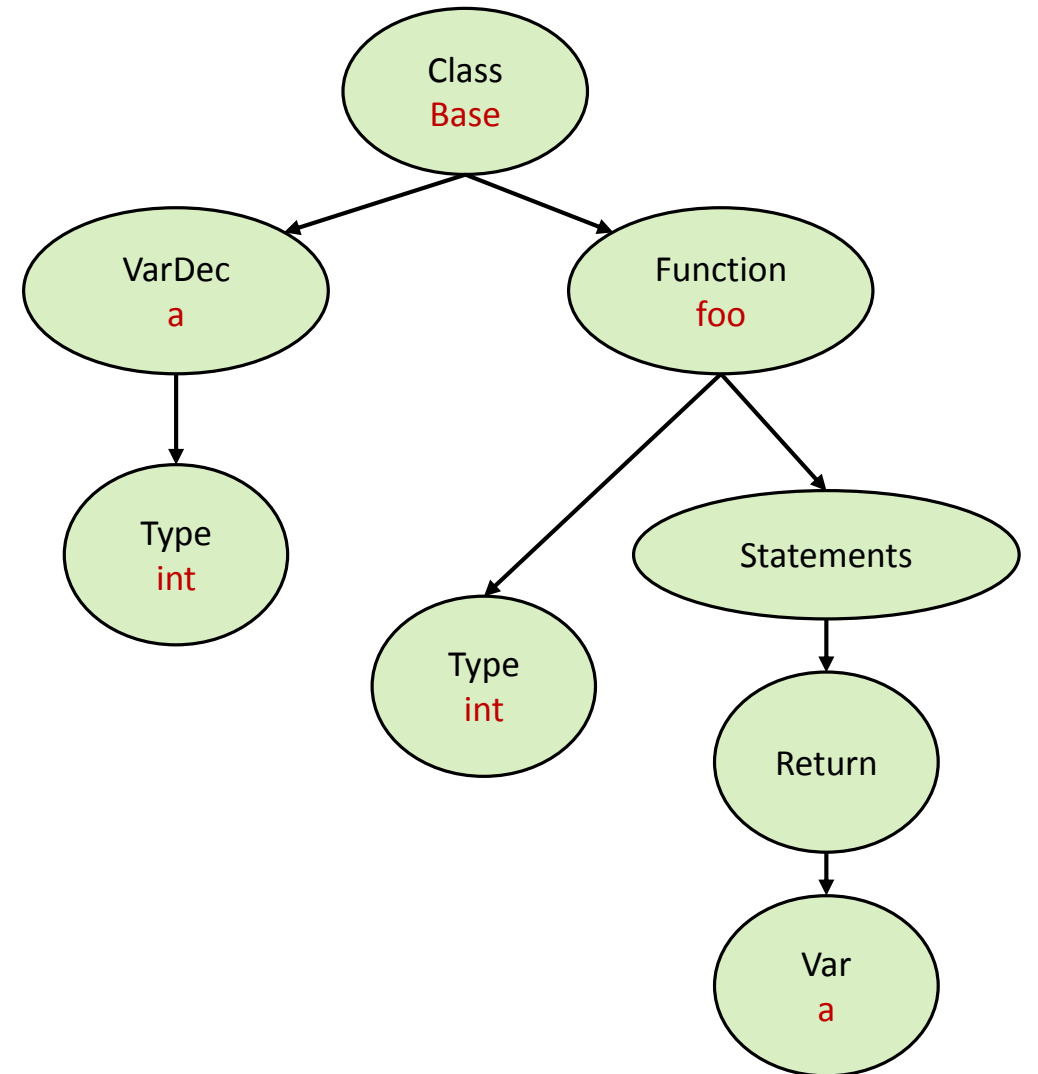
scope₃



Classes

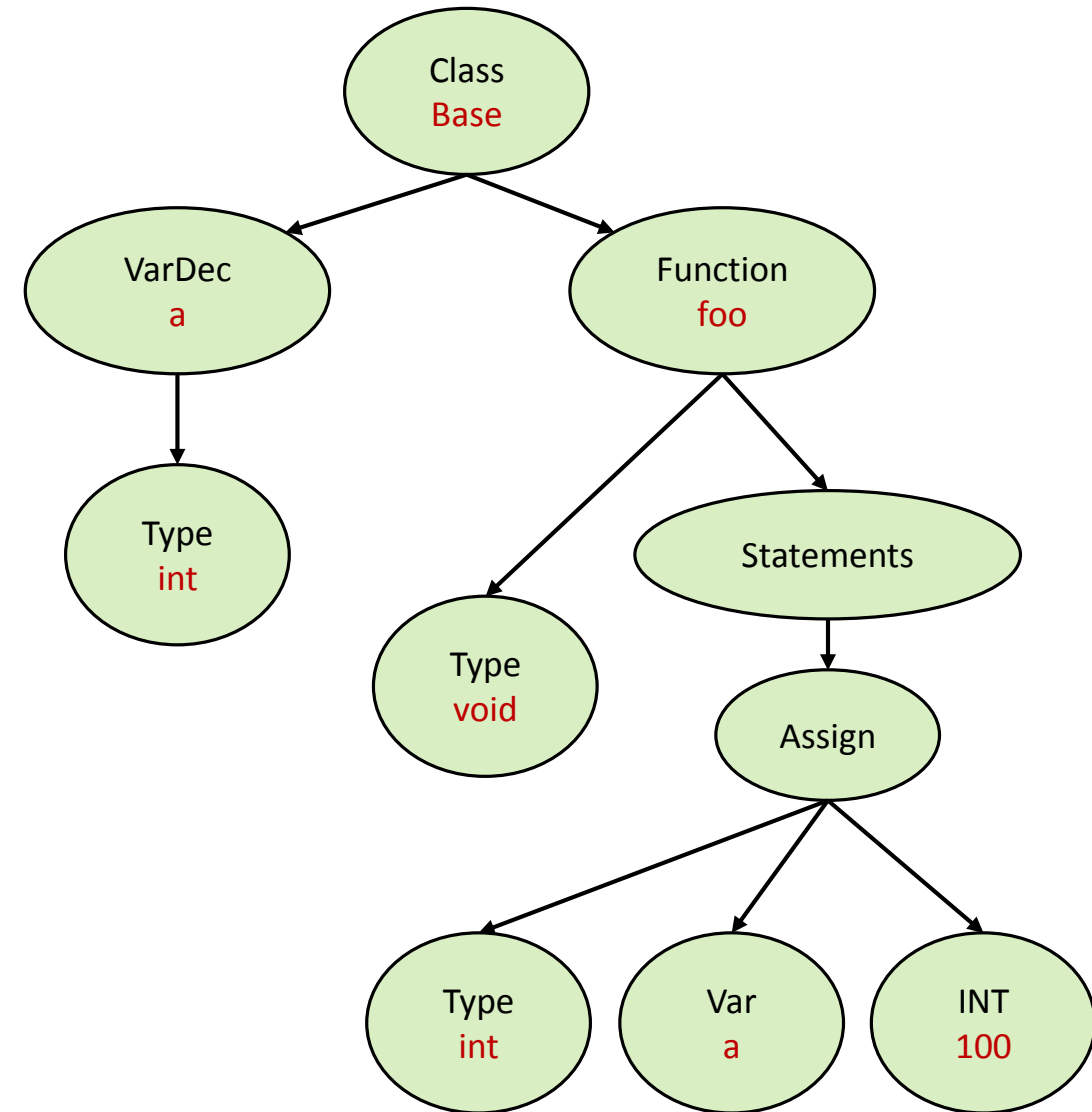
```
class Base {  
  int a;  
  int foo() {  
    return a;  
  }  
}
```

Valid



Classes

```
class Base {  
  int a;  
  void foo() {  
    int a = 100;  
  }  
}
```



Classes

```
class Base {  
  int a;  
  void foo() {  
    int a = 100;  
  }  
}
```

ID	Type	Kind
Base	...	class

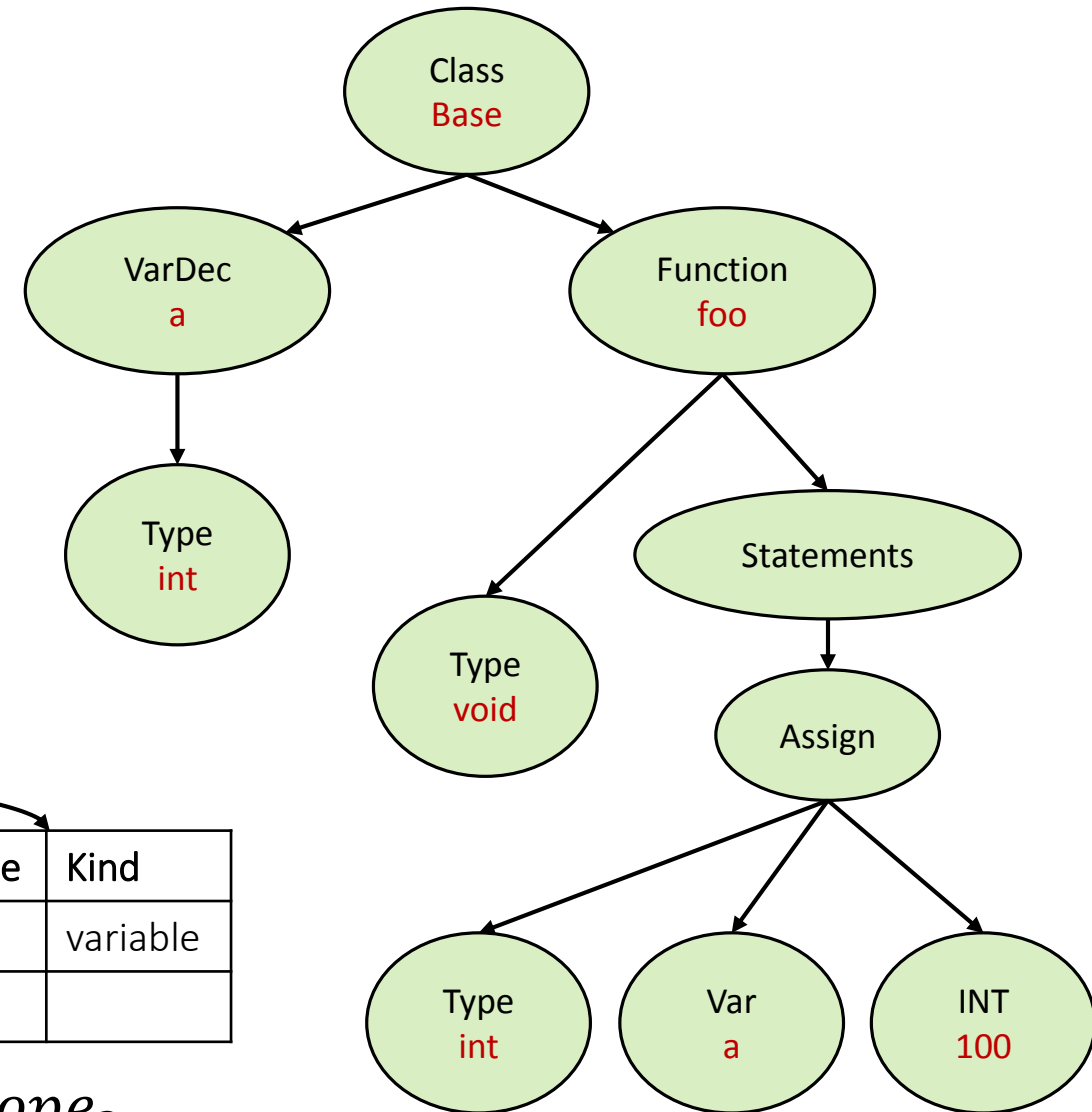
scope₁

ID	Type	Kind
a	int	variable
foo	...	function

scope₂

ID	Type	Kind
a	int	variable

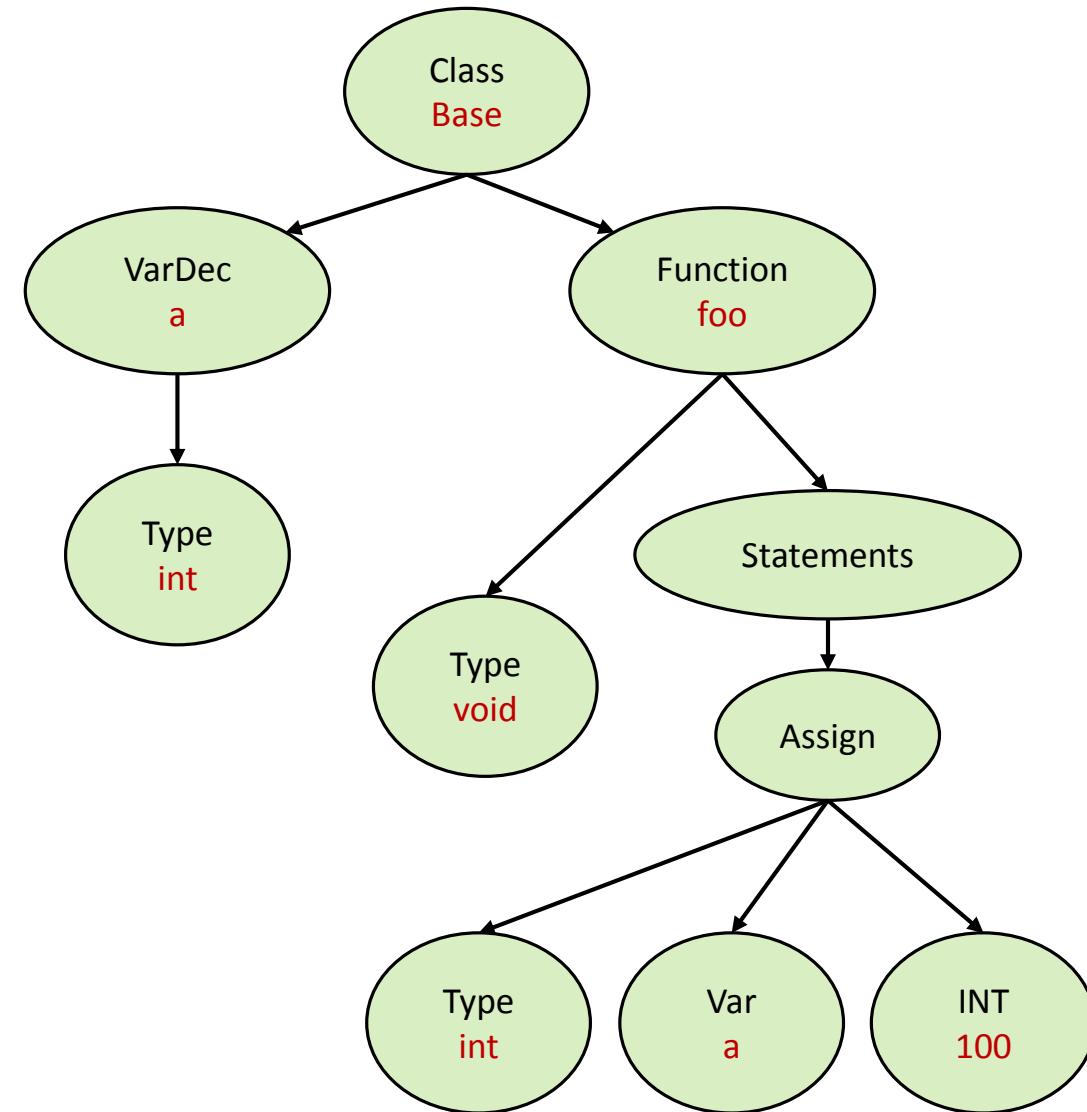
scope₃



Classes

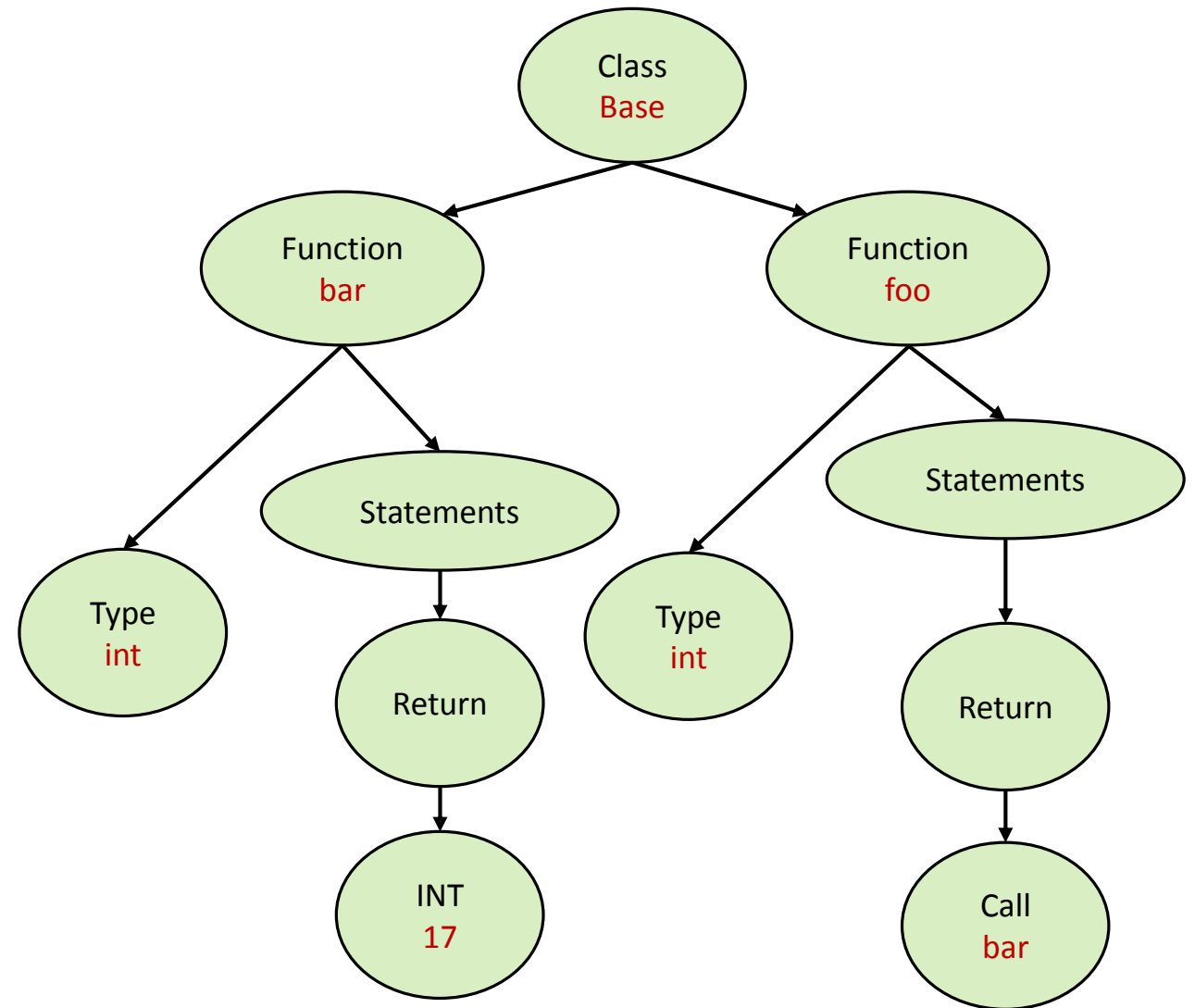
```
class Base {  
  int a;  
  void foo() {  
    int a = 100;  
  }  
}
```

Valid



Classes

```
class Base {  
    int bar() {  
        return 17;  
    }  
    int foo() {  
        return bar();  
    }  
}
```



Classes

```
class Base {  
  int bar() {  
    return 17;  
  }  
  int foo() {  
    return bar();  
  }  
}
```

ID	Type	Kind
Base	...	class

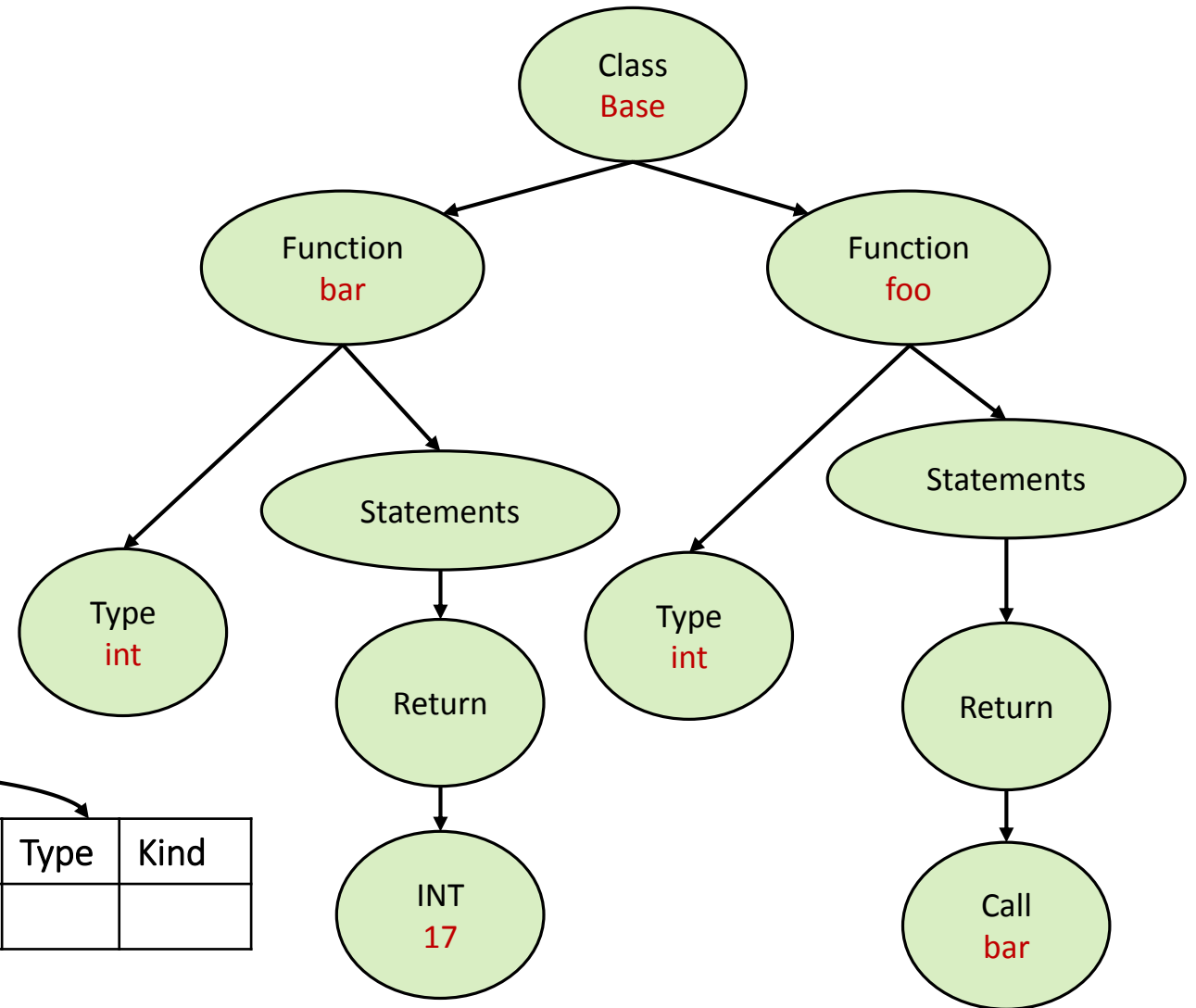
$scope_1$

ID	Type	Kind
bar	...	function

$scope_2$

ID	Type	Kind

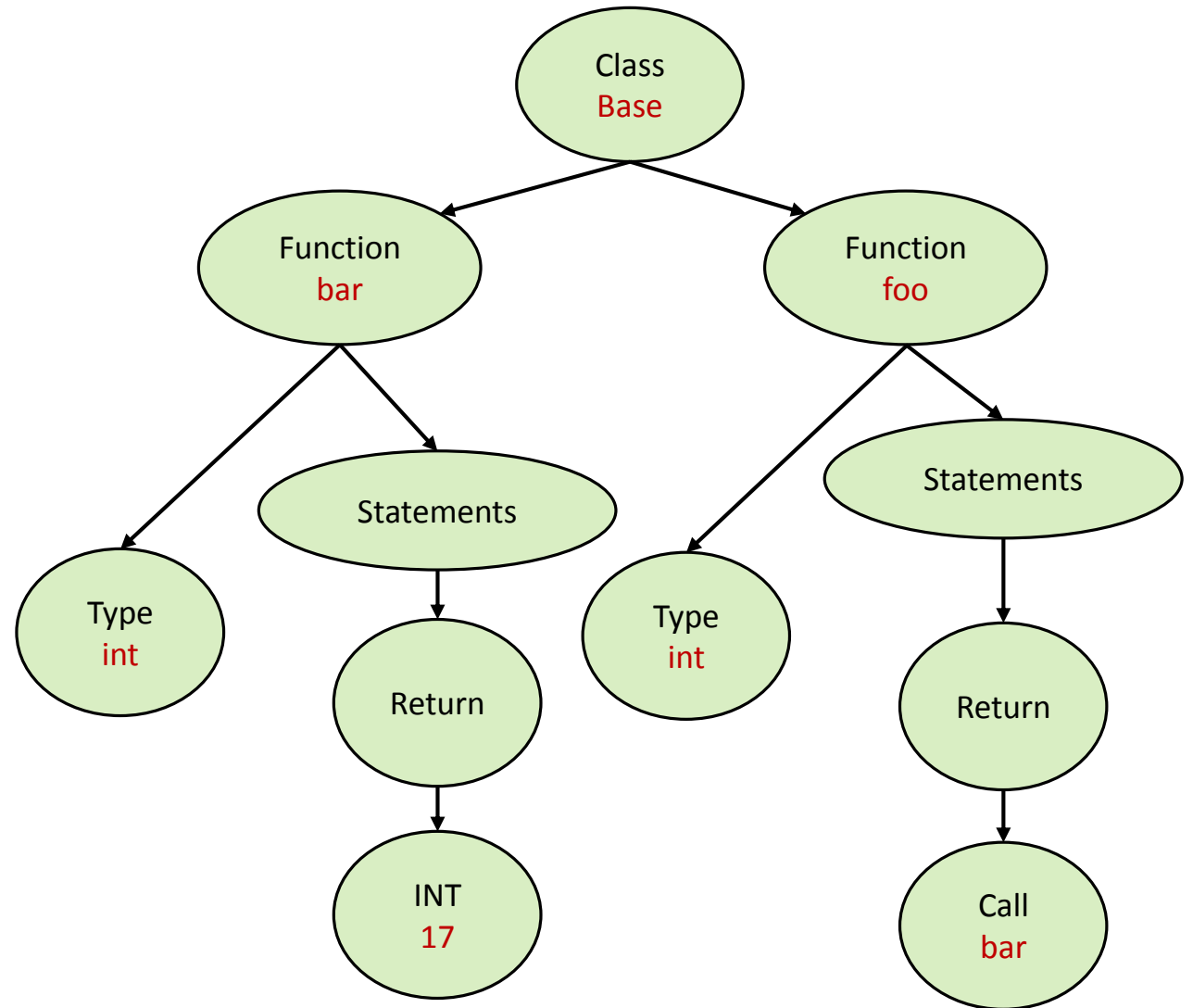
$scope_3$



Classes

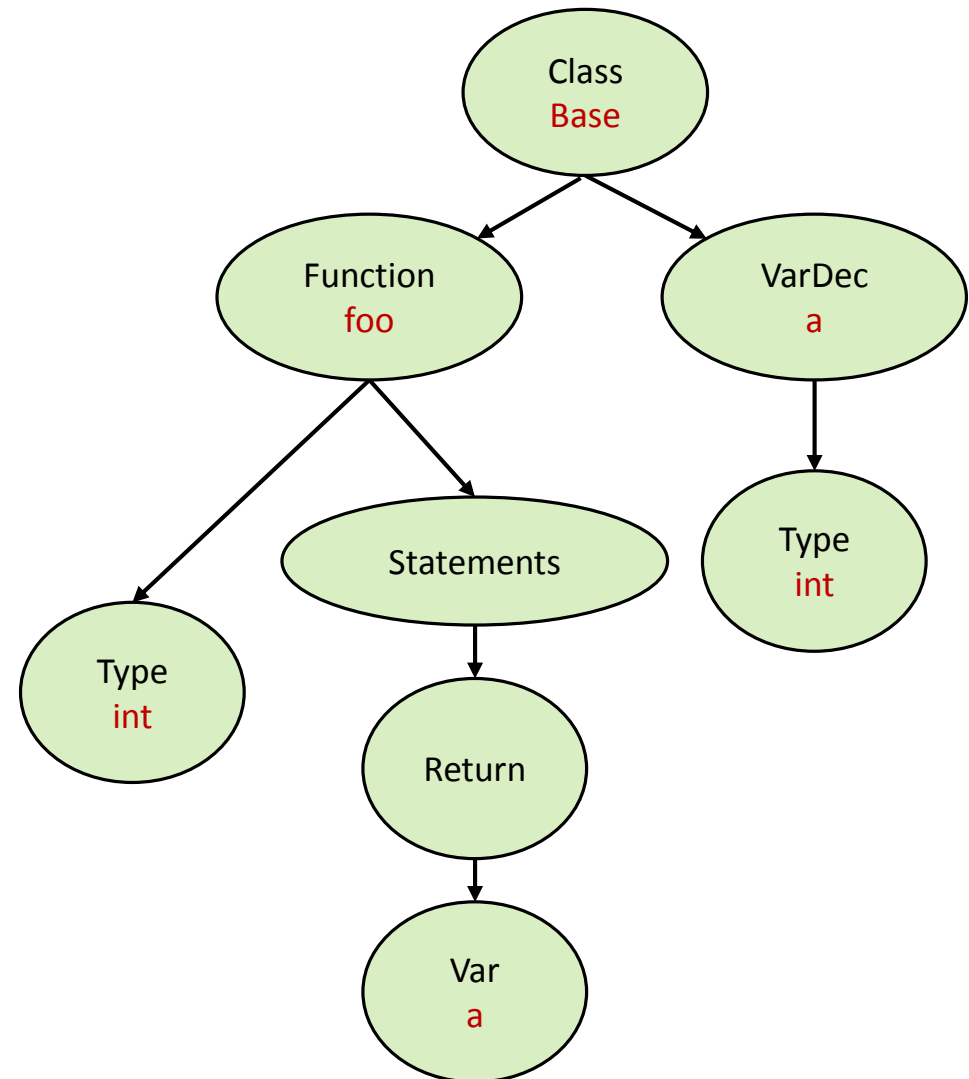
```
class Base {  
  int bar() {  
    return 17;  
  }  
  int foo() {  
    return bar();  
  }  
}
```

Valid



Classes

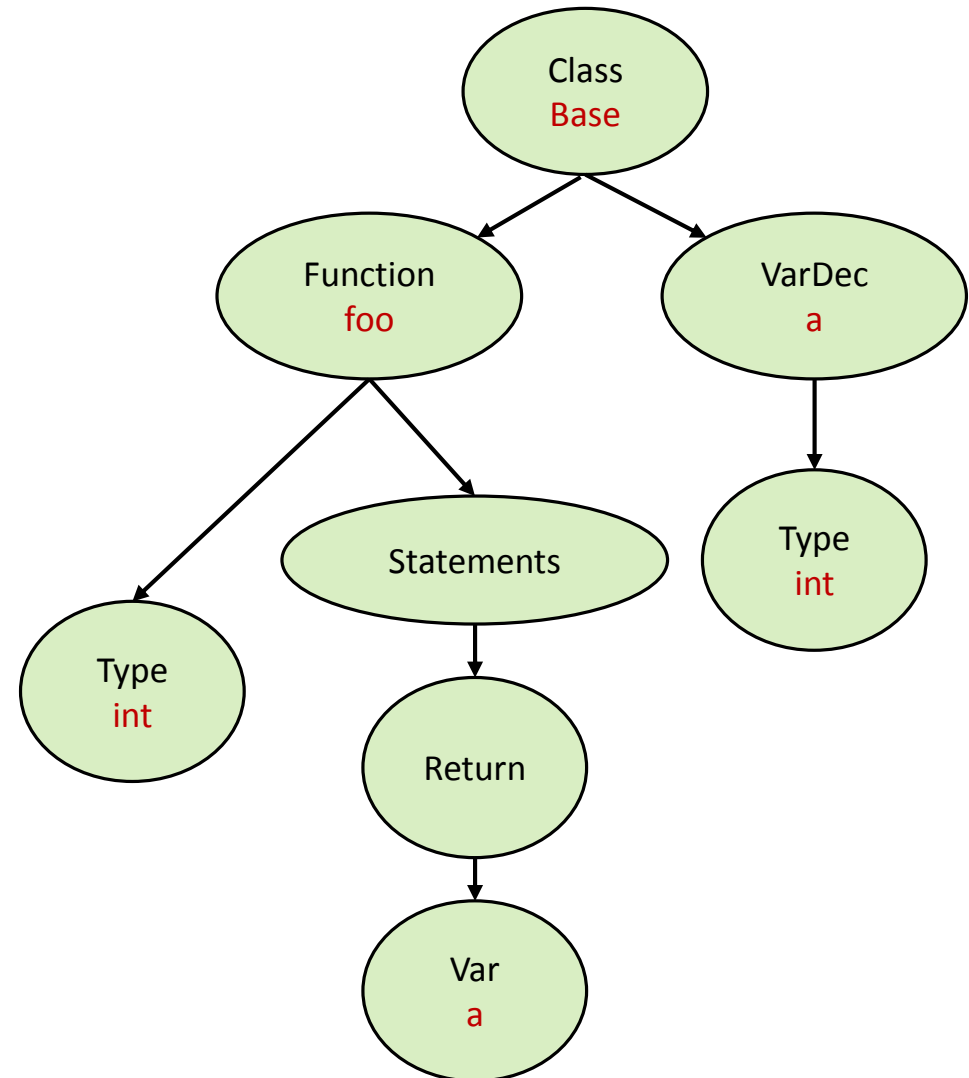
```
class Base {  
  int foo() {  
    return a;  
  }  
  int a;  
}
```



Classes

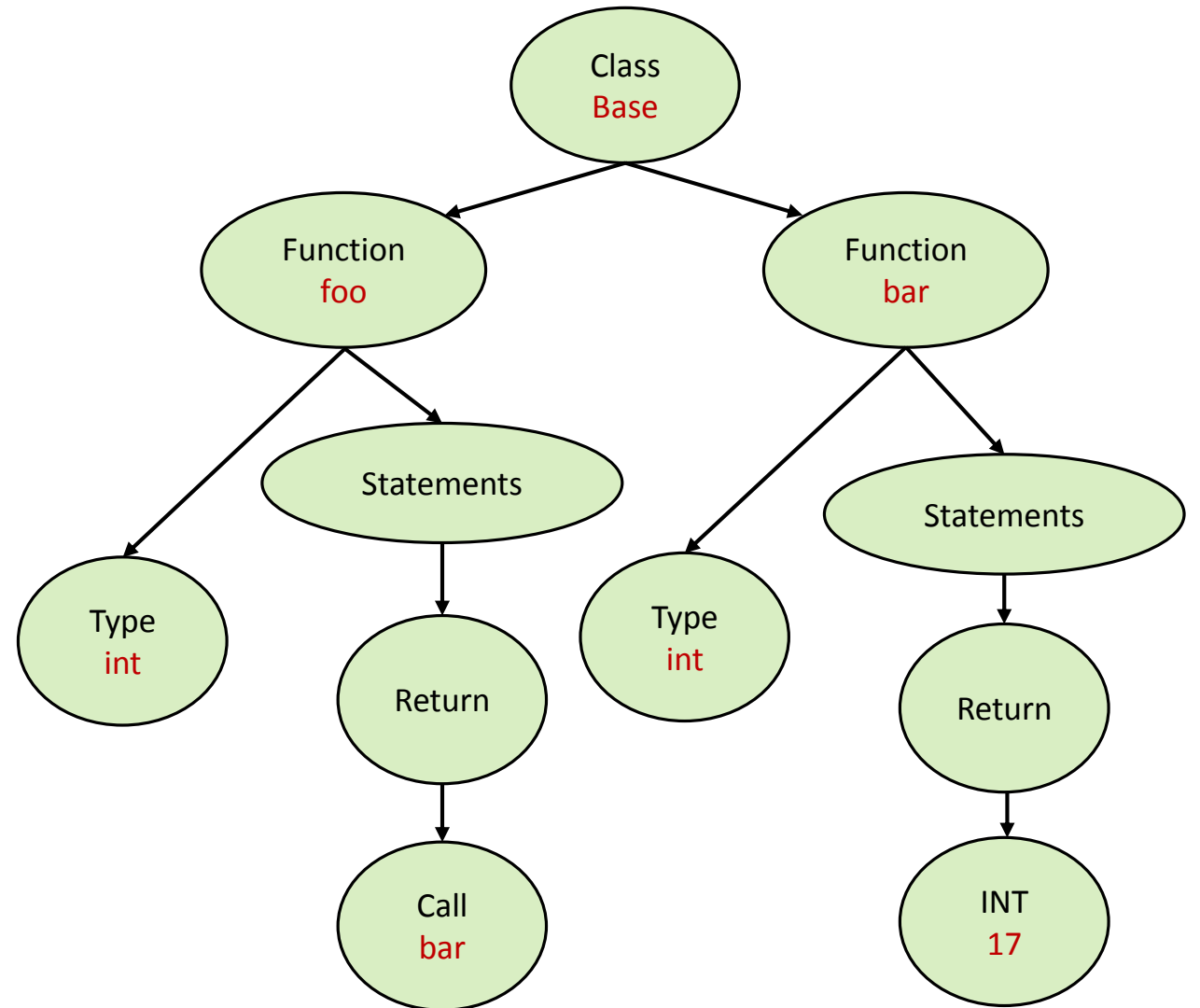
```
class Base {  
  int foo() {  
    return a;  
  }  
  int a;  
}
```

Invalid



Classes

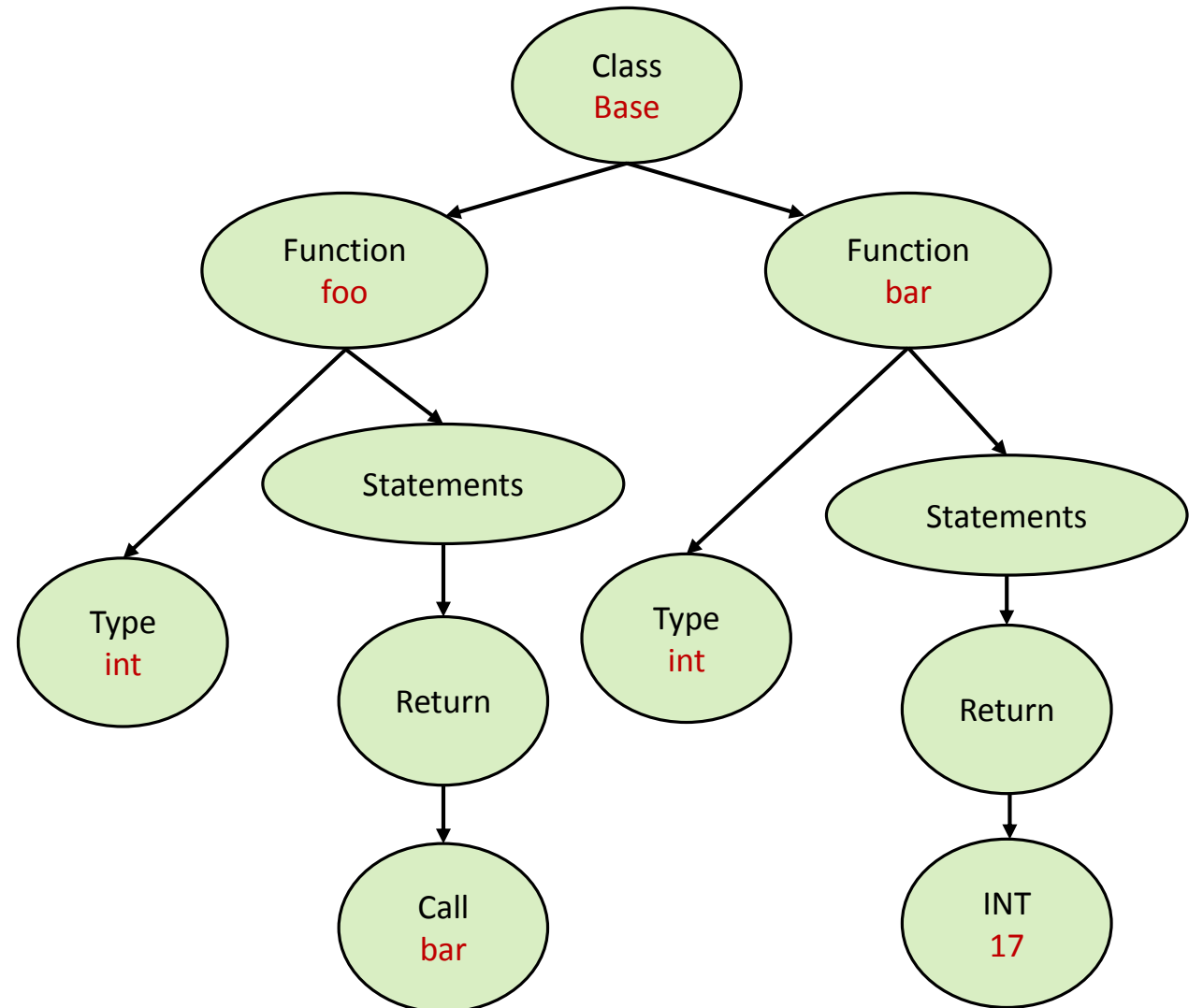
```
class Base {  
  int foo() {  
    return bar();  
  }  
  int bar() {  
    return 17;  
  }  
}
```



Classes

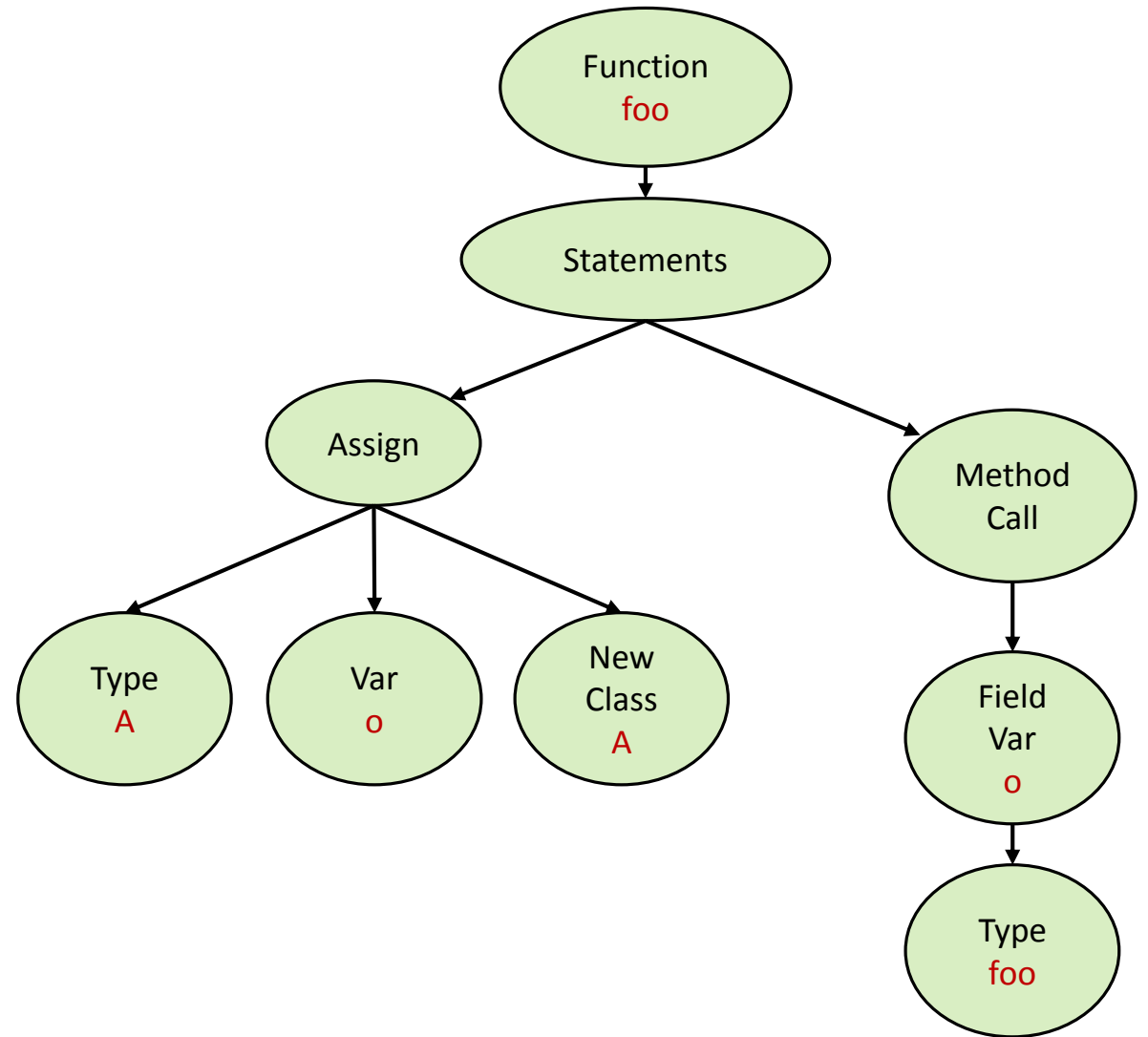
```
class Base {  
    int foo() {  
        return bar();  
    }  
    int bar() {  
        return 17;  
    }  
}
```

Invalid



Classes

```
class A {  
  void foo() {  
    A o = new A;  
    o.foo();  
  }  
}
```



Classes

```
class A {  
  void foo() {  
    A o = new A;  
    o.foo();  
  }  
}
```

ID	Type	Kind
A	...	class

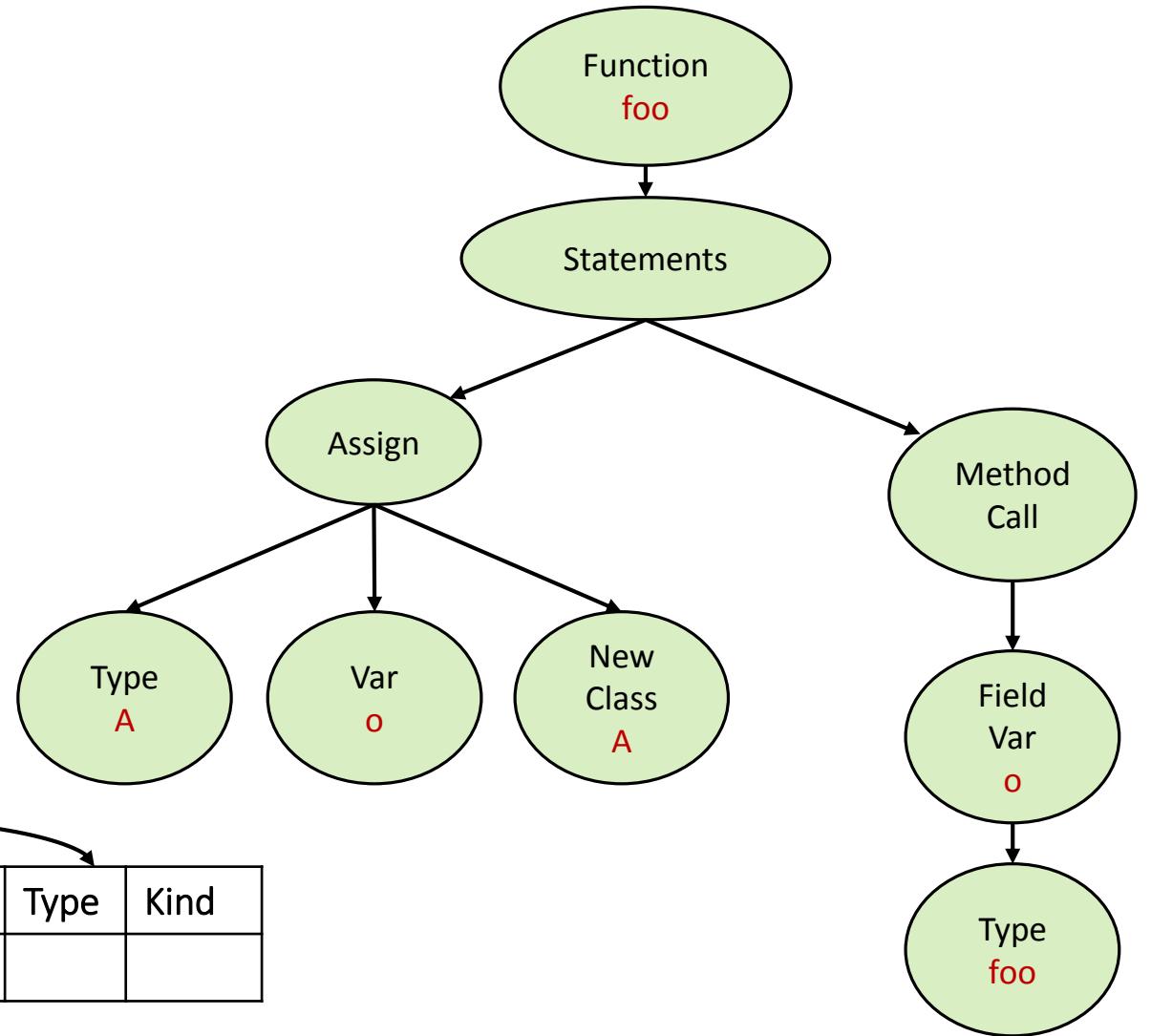
scope₁

ID	Type	Kind
foo	...	function

scope₂

ID	Type	Kind

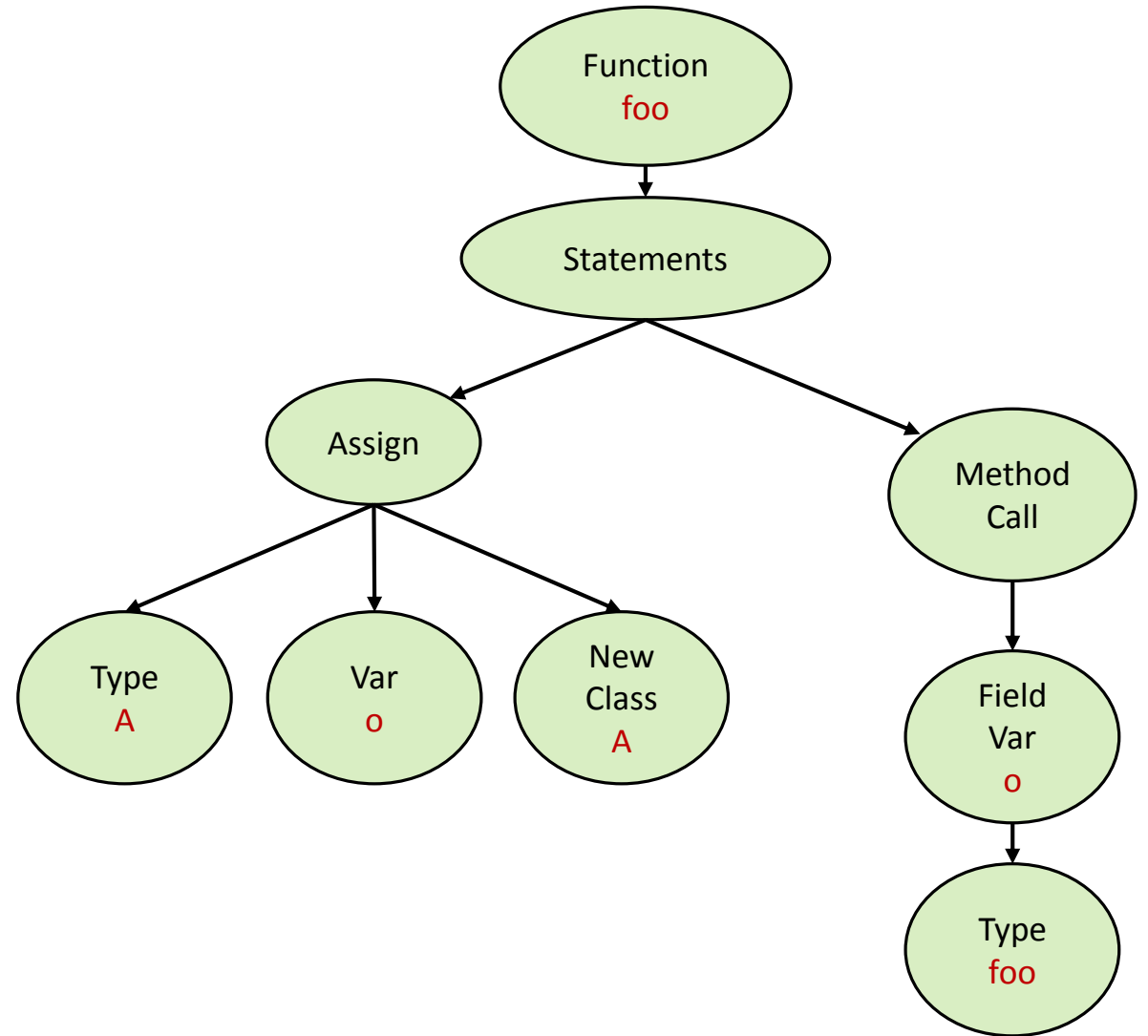
scope₃



Classes

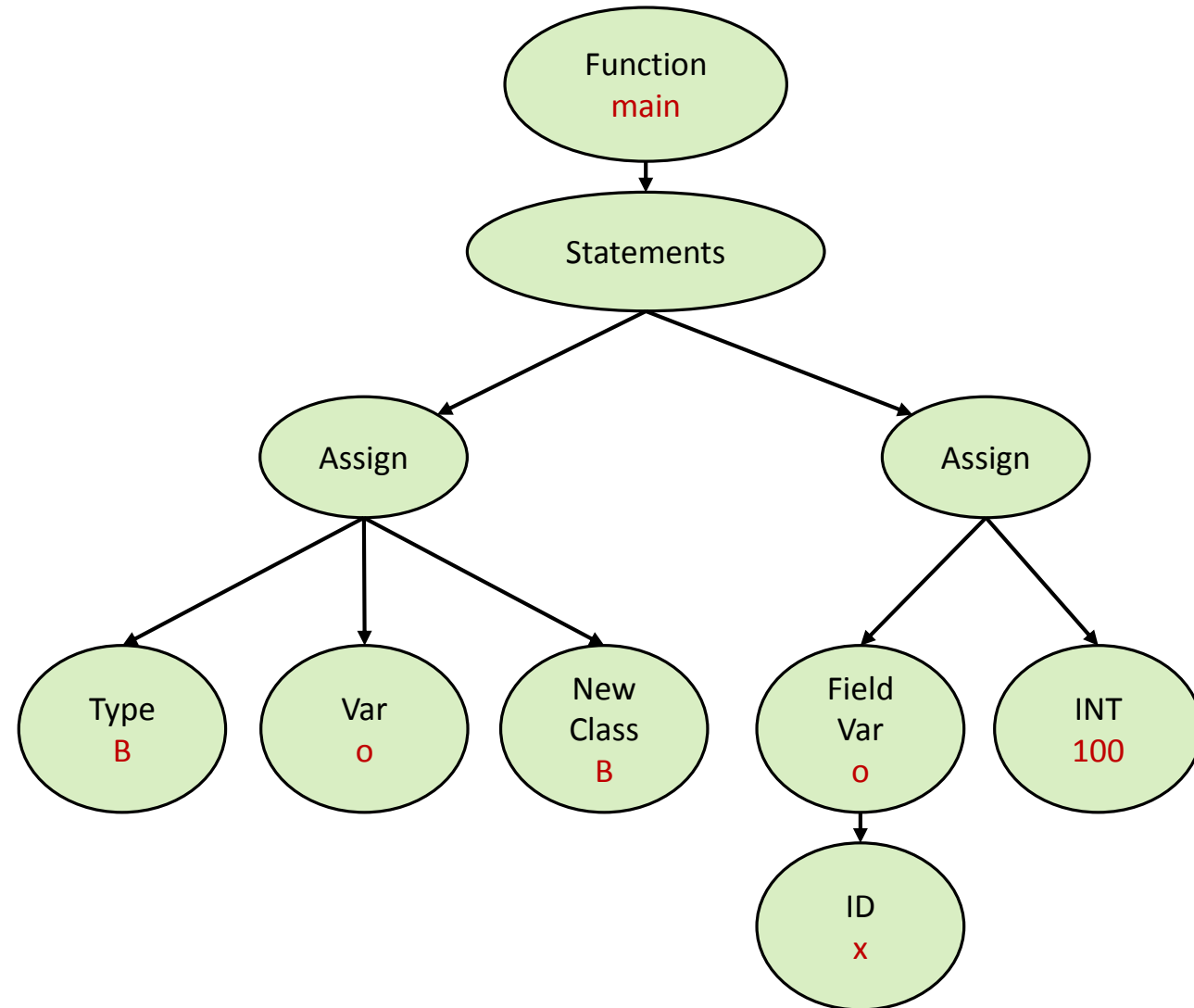
```
class A {  
  void foo() {  
    A o = new A;  
    o.foo();  
  }  
}
```

Valid



Inheritance

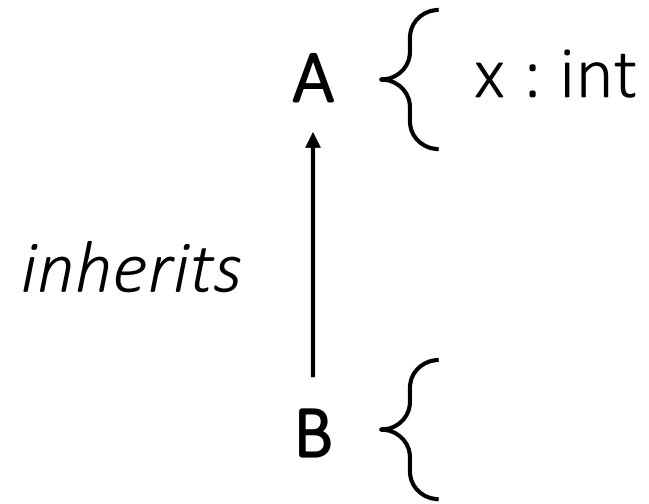
```
class A {  
    int x;  
}  
class B extends A { }  
void main() {  
    B o = new B;  
    o.x = 100;  
}
```



Inheritance

```
class A {  
    int x;  
}  
class B extends A { }  
void main() {  
    B o = new B;  
    o.x = 100;  
}
```

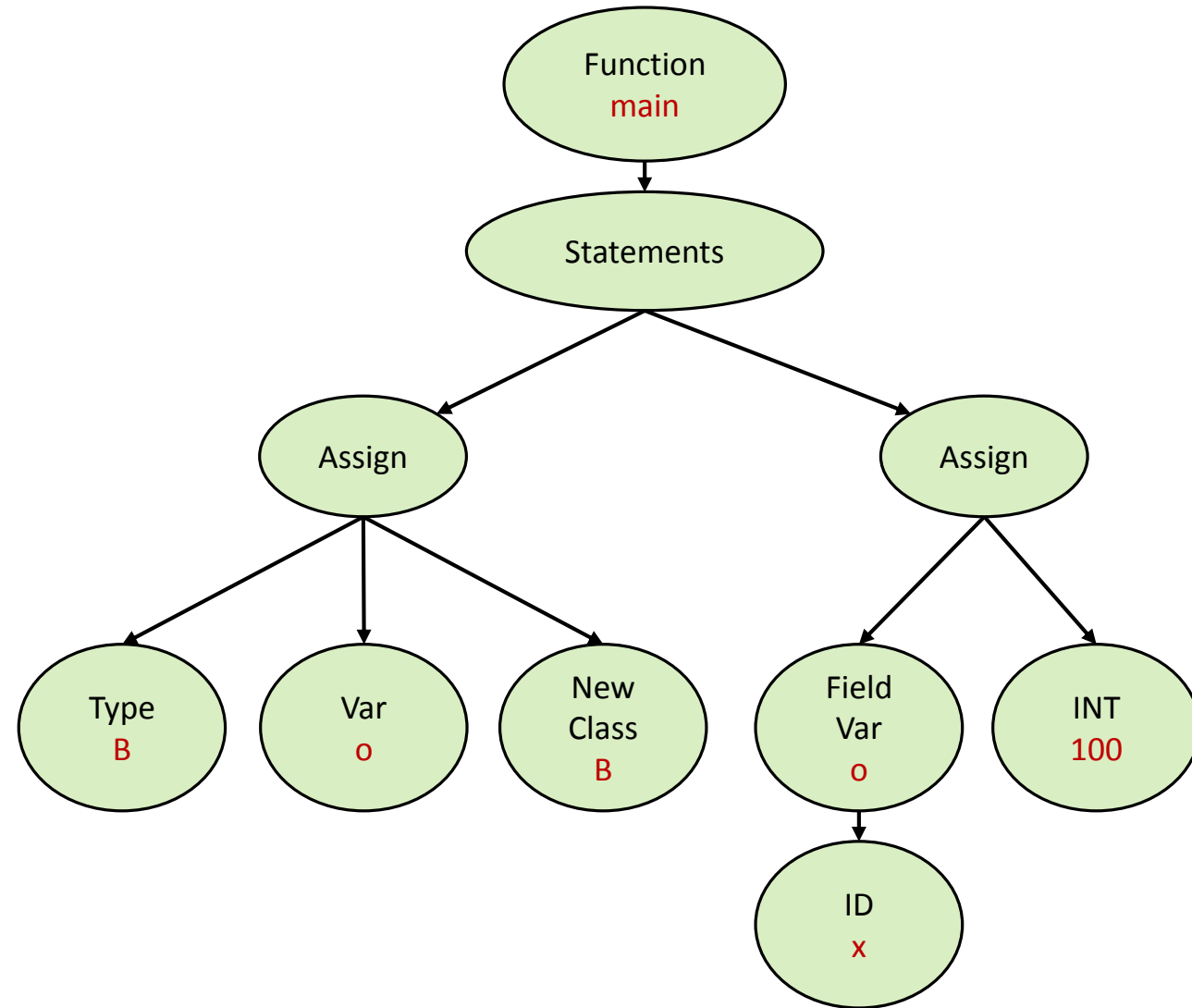
class hierarchy



Inheritance

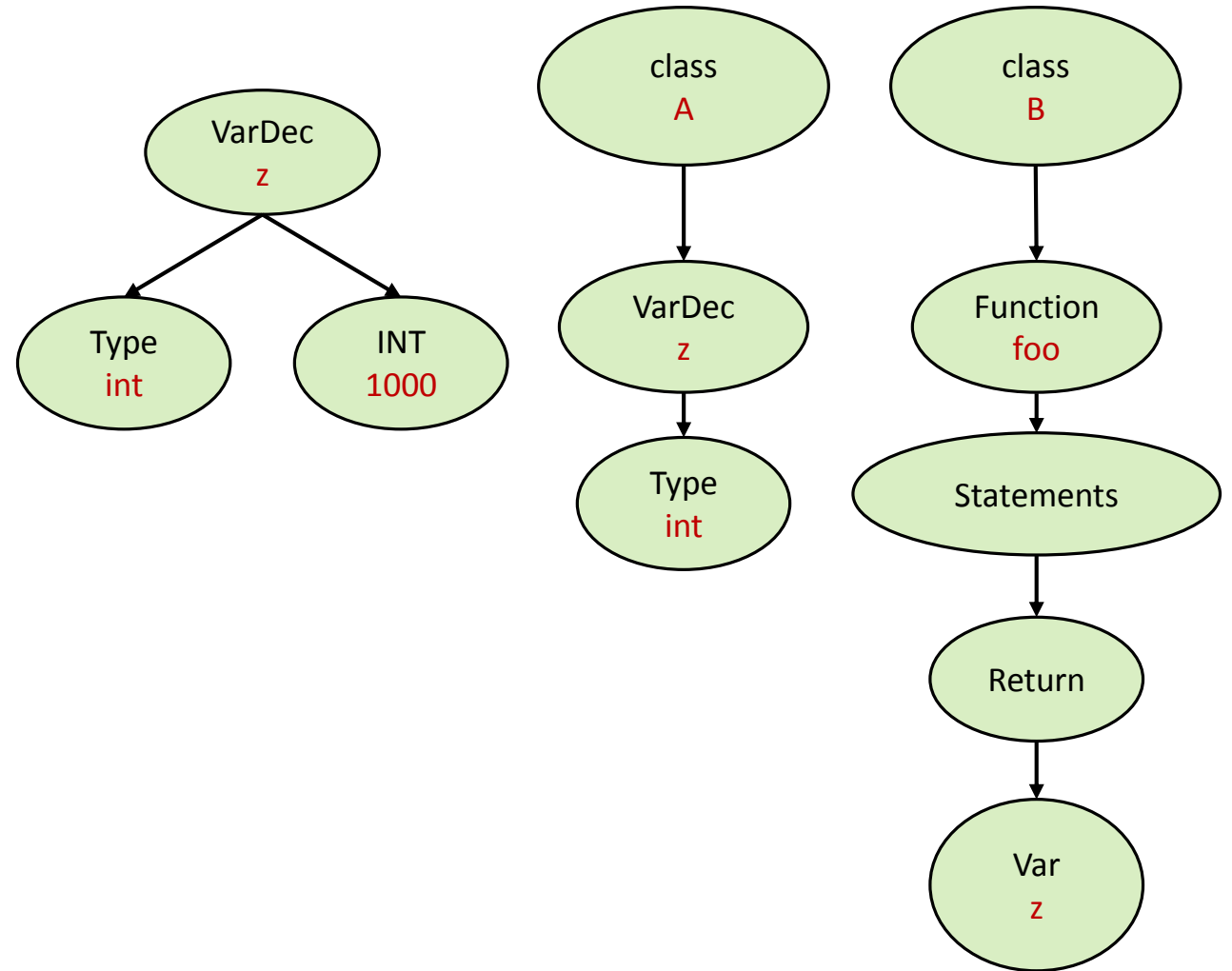
```
class A {  
    int x;  
}  
class B extends A { }  
void main() {  
    B o = new B;  
    o.x = 100;  
}
```

Valid



Inheritance

```
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```



Inheritance

```
class A {  
  int z;  
}  
class B extends A {  
  int foo() {  
    return z;  
  }  
}
```

ID	Type	Kind
A	...	class
B	...	class

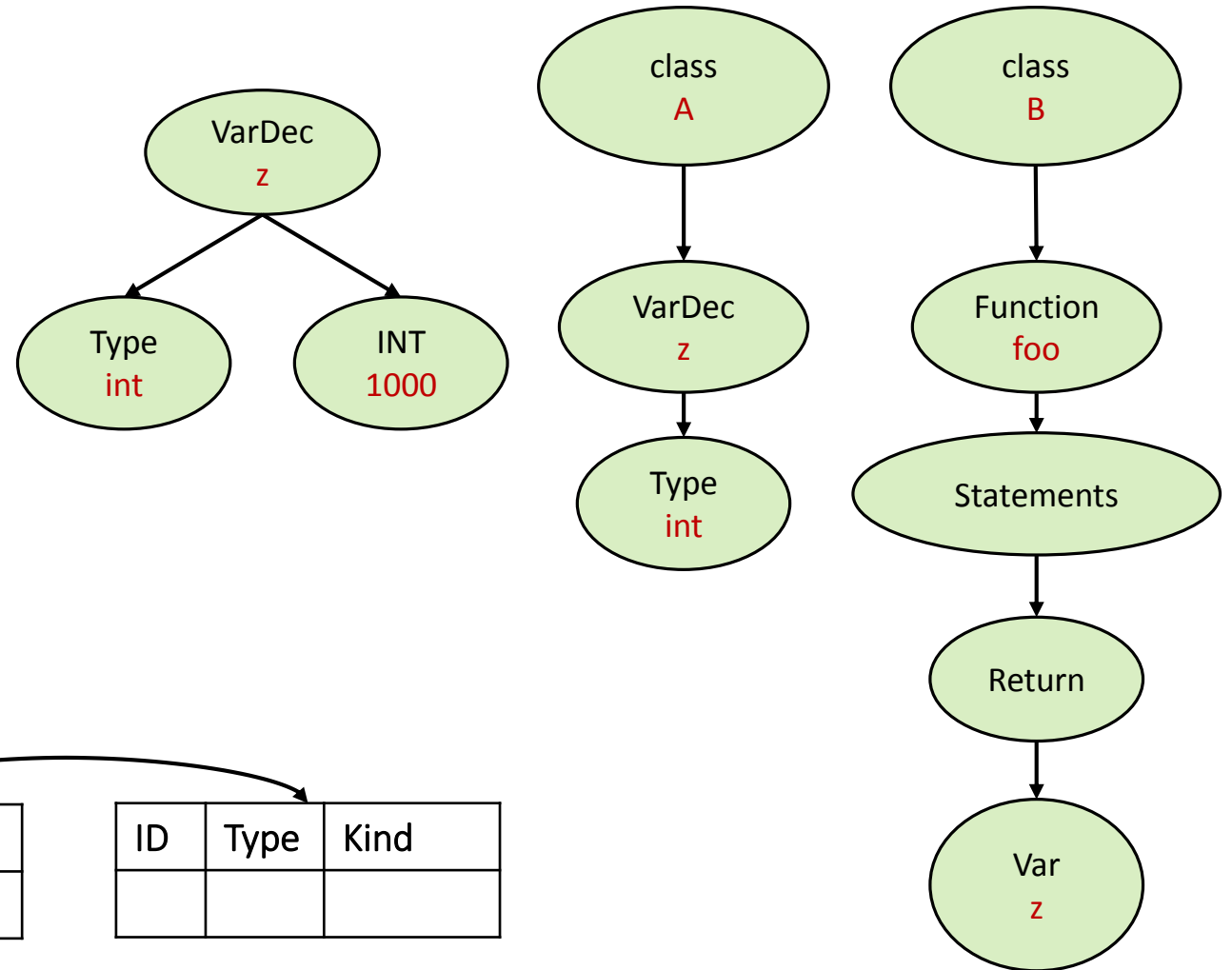
$scope_1$

ID	Type	Kind
foo	...	function

$scope_2$

ID	Type	Kind

$scope_3$



Inheritance

```
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```

ID	Type	Kind
A	...	class
B	...	class

scope₁

ID	Type	Kind
foo	...	function

scope₂
(scope of class B)

ID	Type	Kind

scope₃

Inheritance

```
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```

ID	Type	Kind
A	...	class
B	...	class

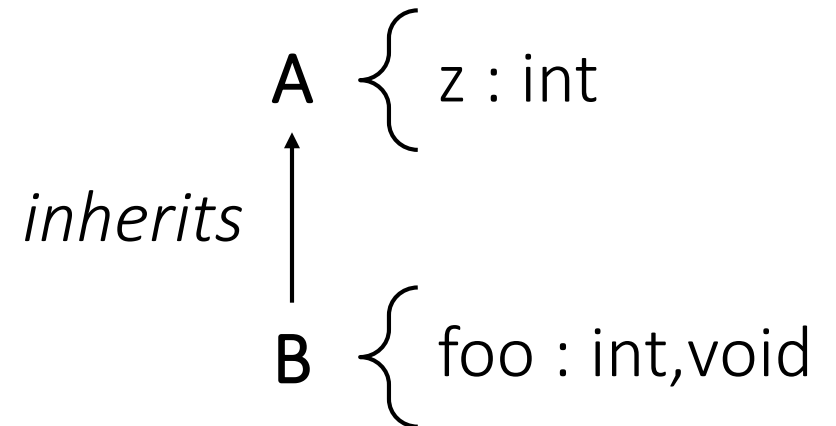
scope₁

ID	Type	Kind
foo	...	function

scope₂
(scope of class B)

ID	Type	Kind

scope₃



Inheritance

```
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```

ID	Type	Kind
A	...	class
B	...	class

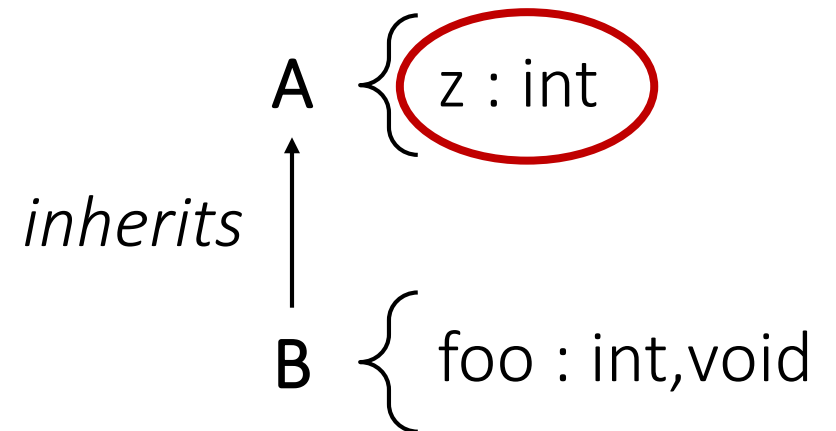
scope₁

ID	Type	Kind
foo	...	function

scope₂
(scope of class B)

ID	Type	Kind

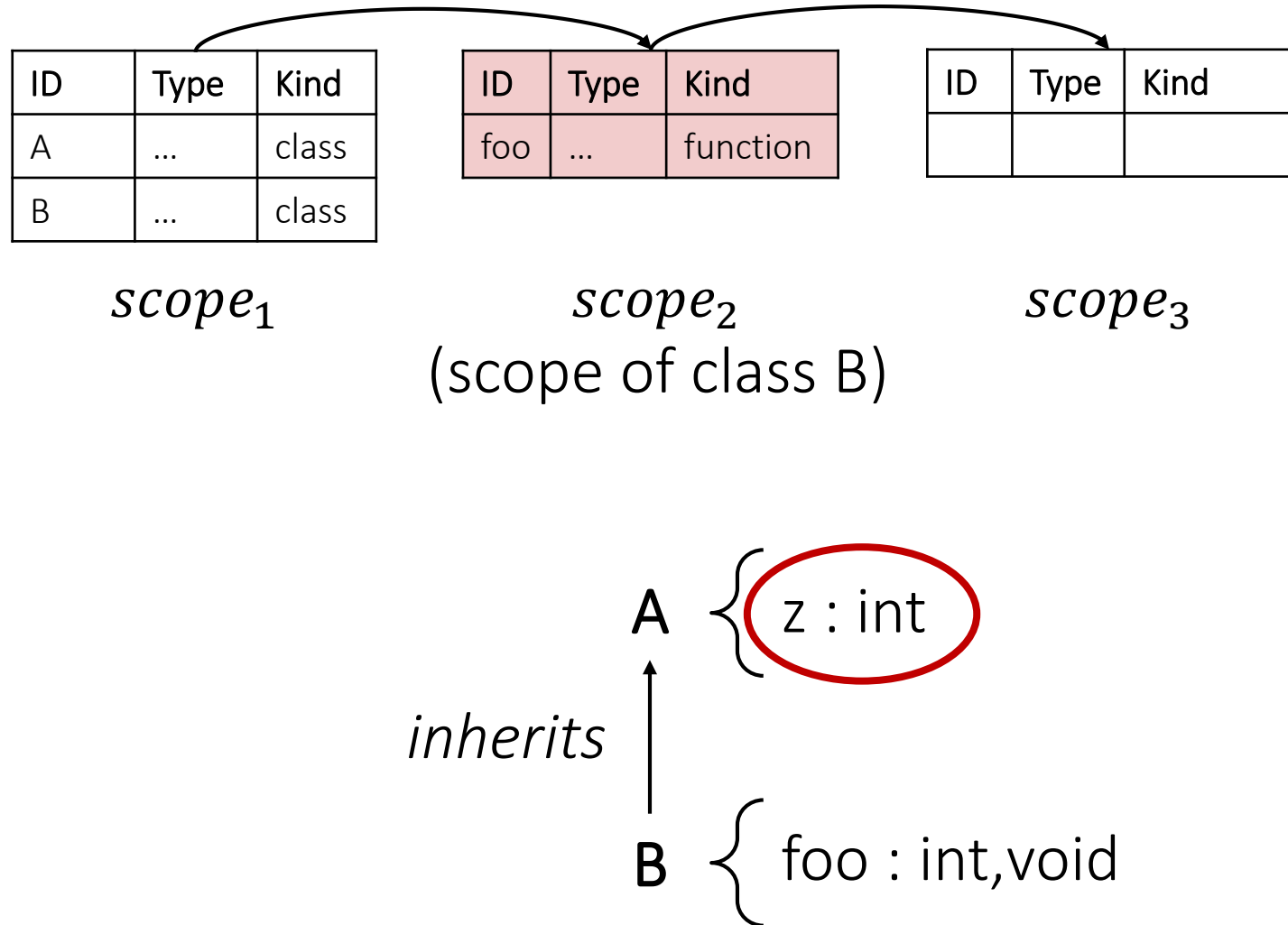
scope₃



Inheritance

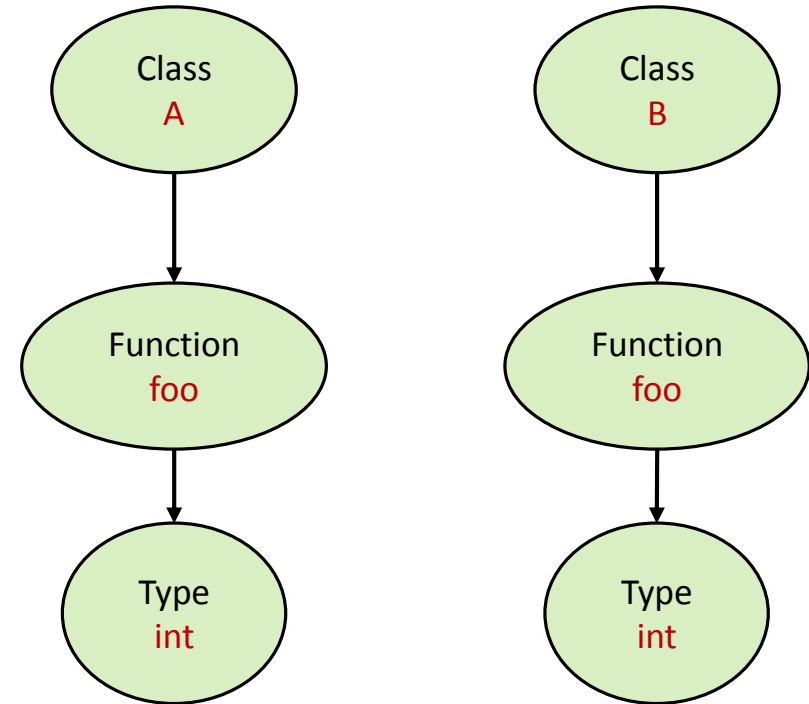
```
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```

Valid



Inheritance

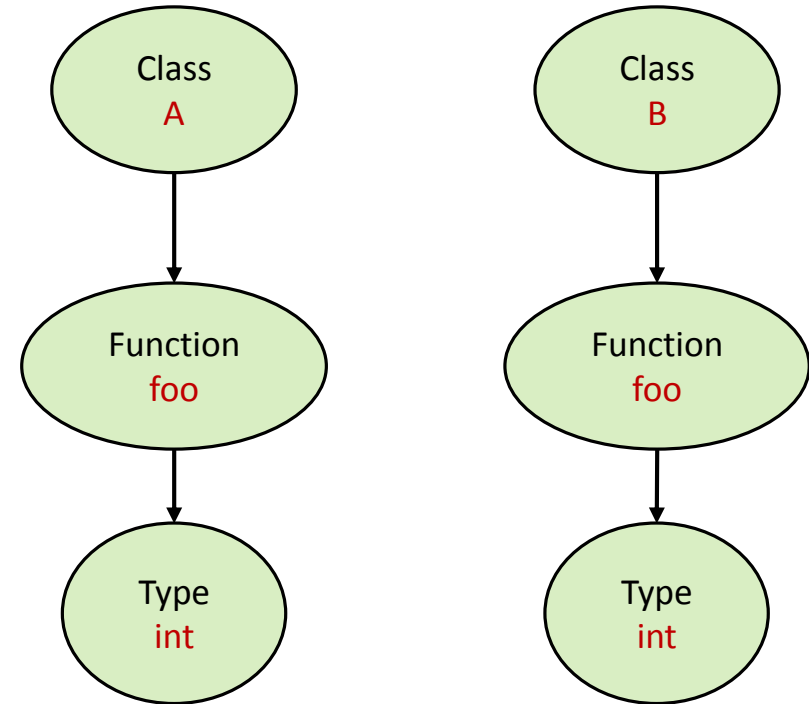
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo() {  
        return 18;  
    }  
}
```



Inheritance

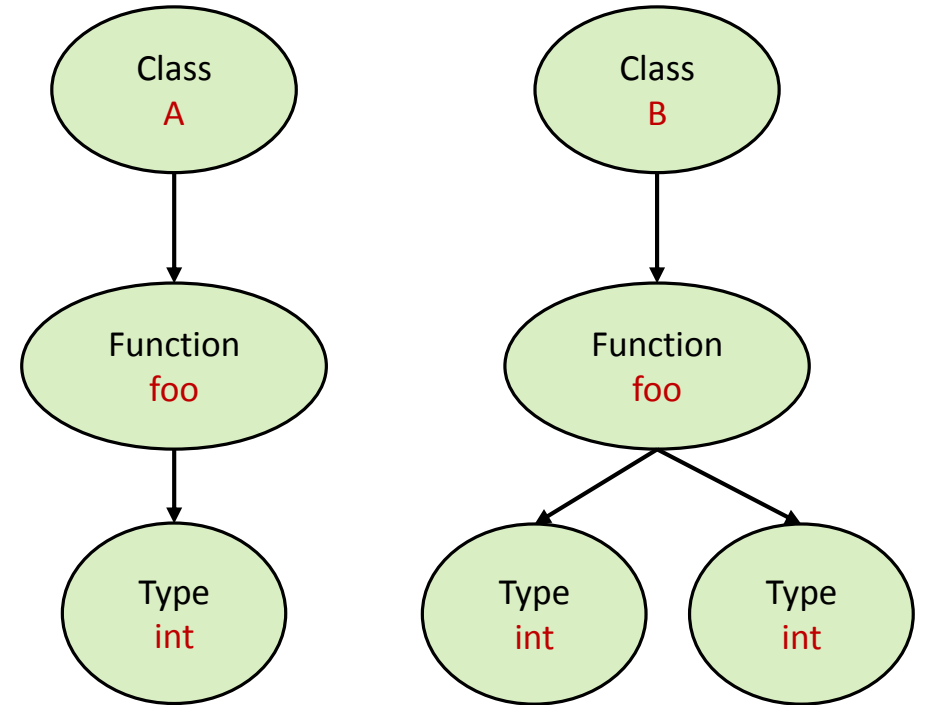
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo() {  
        return 18;  
    }  
}
```

Valid



Inheritance

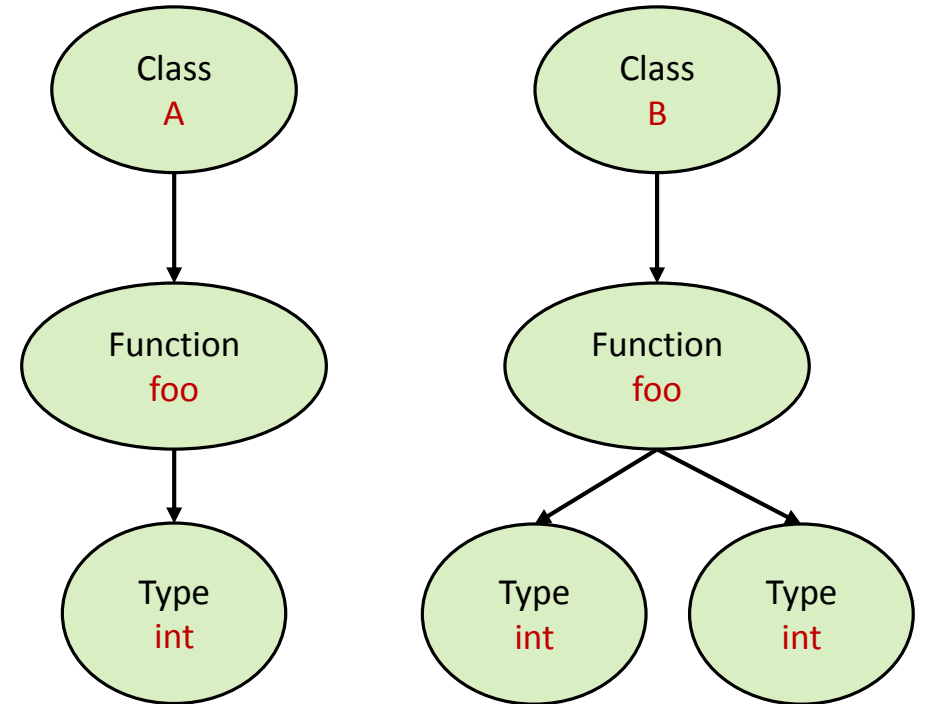
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo(int x) {  
        return x + 1;  
    }  
}
```



Inheritance

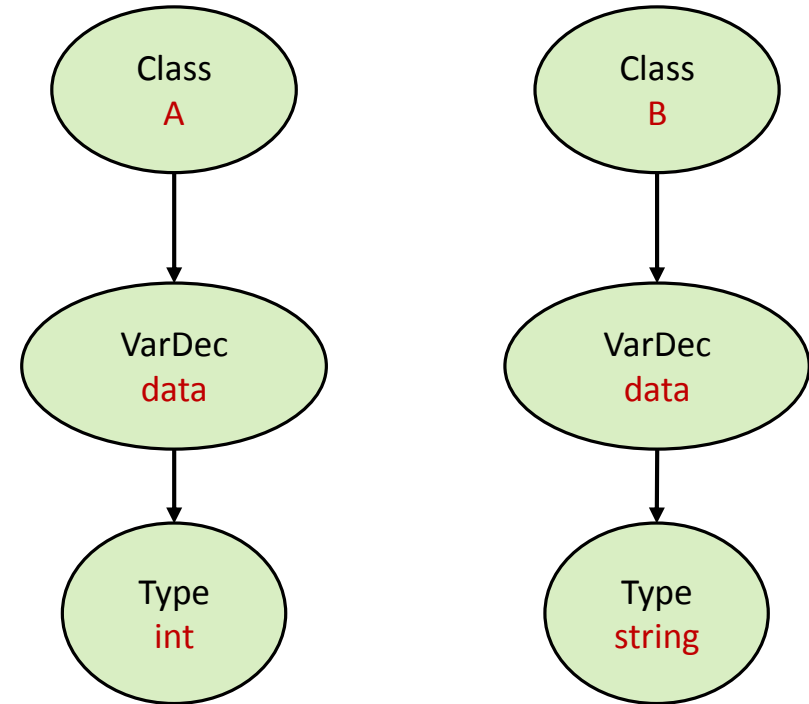
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo(int x) {  
        return x + 1;  
    }  
}
```

Invalid



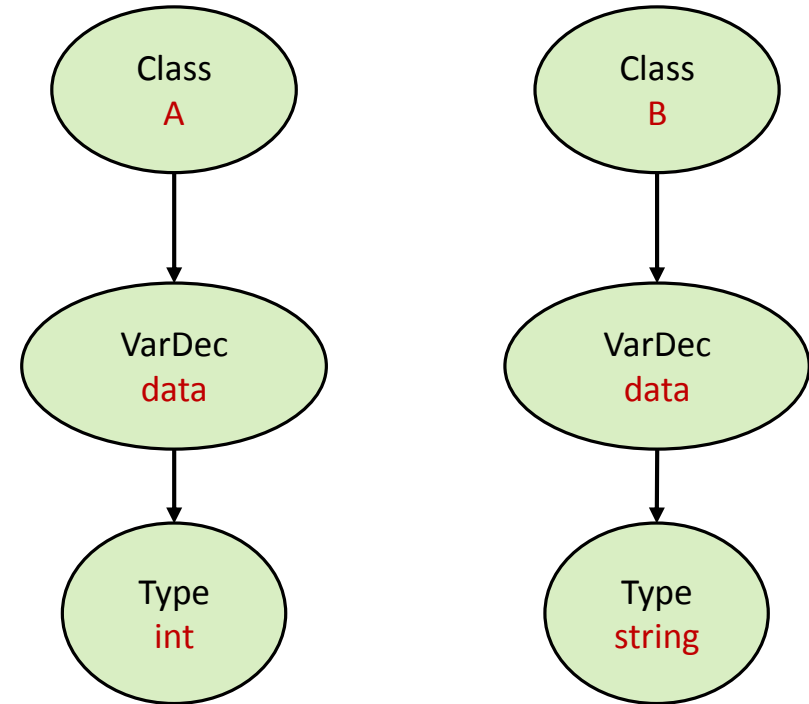
Inheritance

```
class A {  
    int data;  
}  
class B extends A {  
    string data;  
}
```



Inheritance

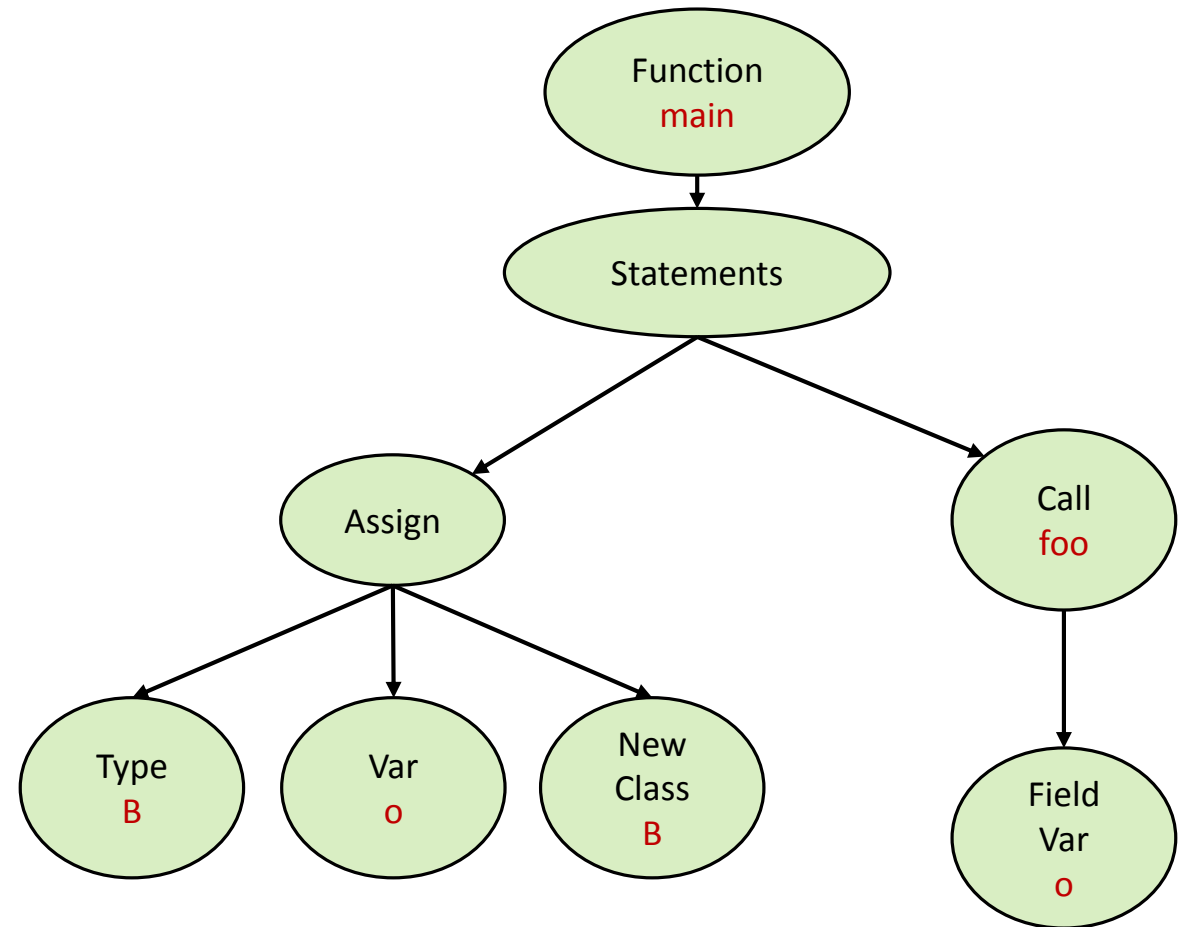
```
class A {  
    int data;  
}  
class B extends A {  
    string data;  
}
```



Invalid

Inheritance

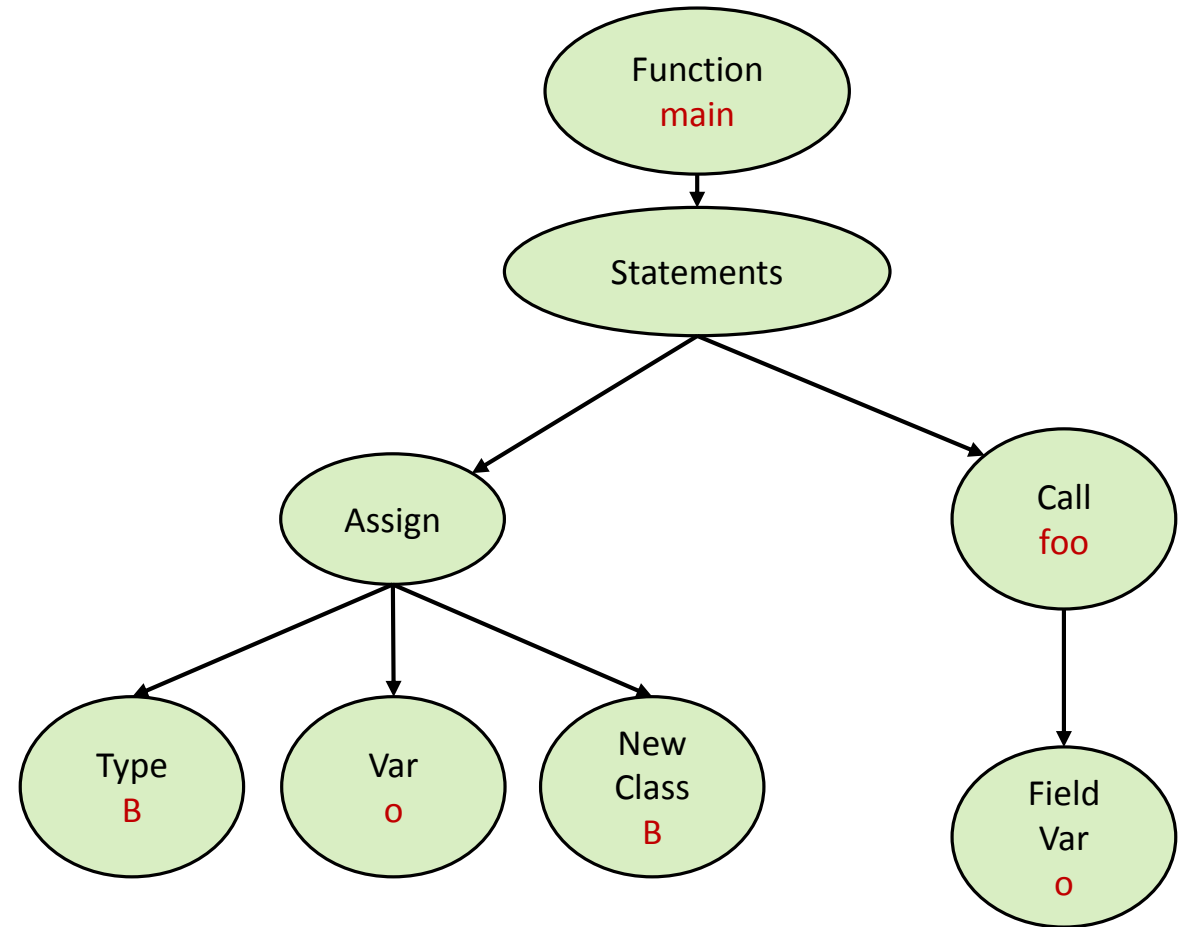
```
class A { }  
class B extends A { }  
void foo(A a) { }  
void main() {  
    B o = new B;  
    foo(o);  
}
```



Inheritance

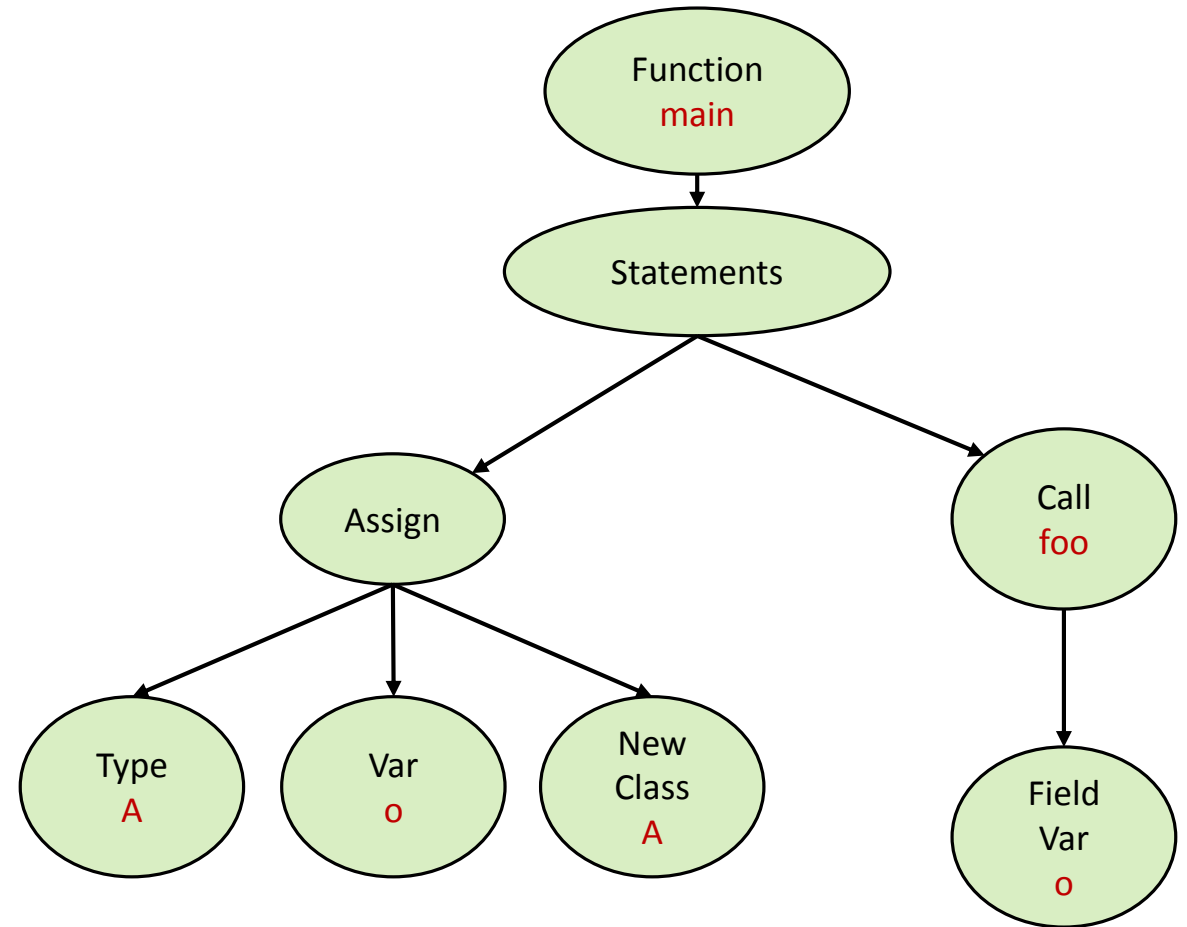
```
class A { }  
class B extends A { }  
void foo(A a) { }  
void main() {  
    B o = new B;  
    foo(o);  
}
```

Valid



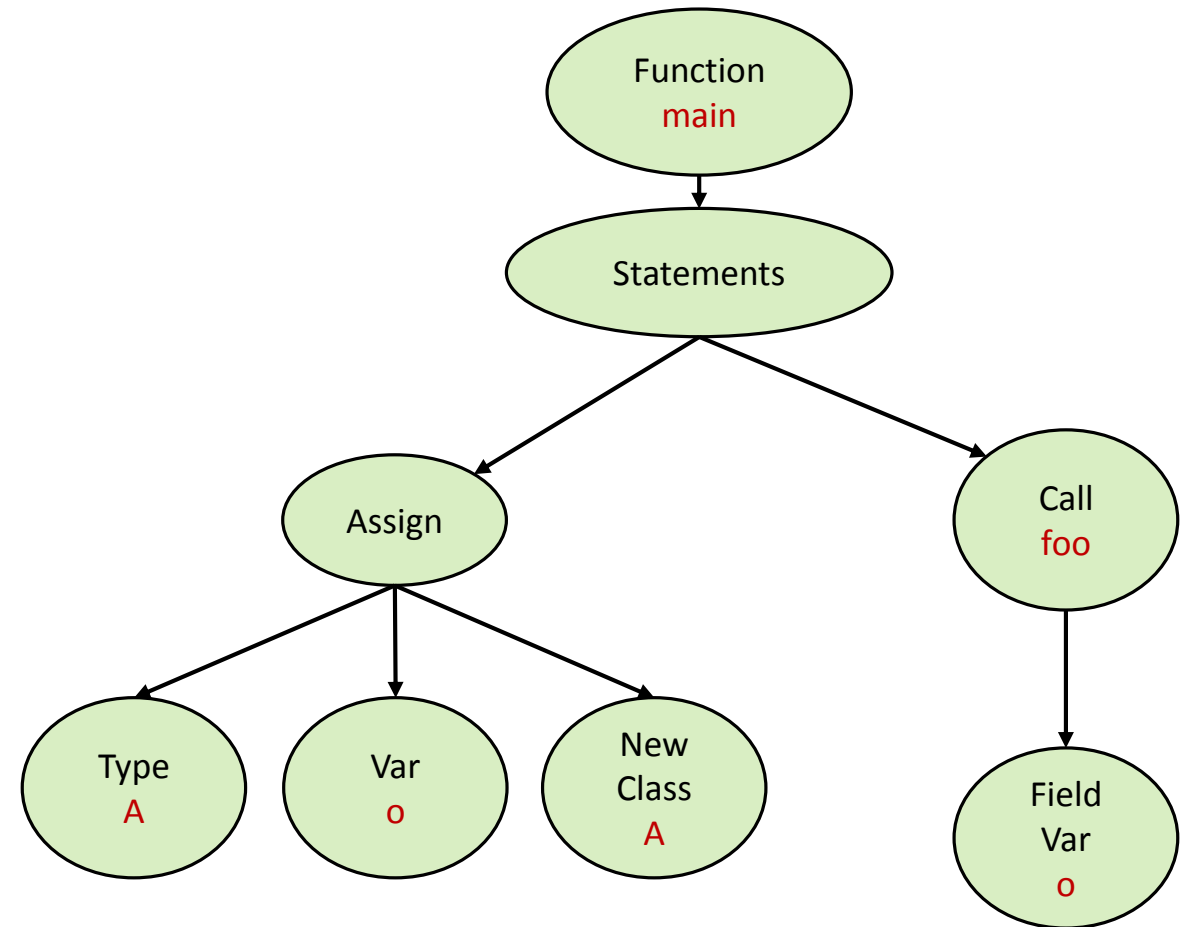
Inheritance

```
class A { }  
class B extends A { }  
void foo(B b) { }  
void main() {  
    A o = new A;  
    foo(o);  
}
```



Inheritance

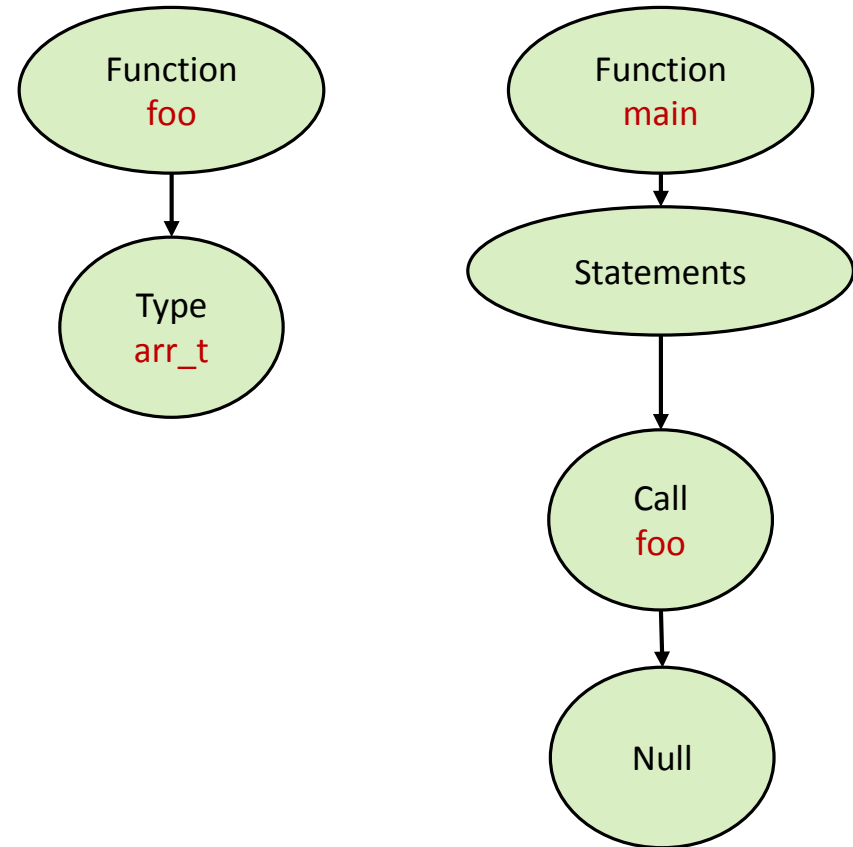
```
class A { }  
class B extends A { }  
void foo(B b) { }  
void main() {  
    A o = new A;  
    foo(o);  
}
```



Invalid

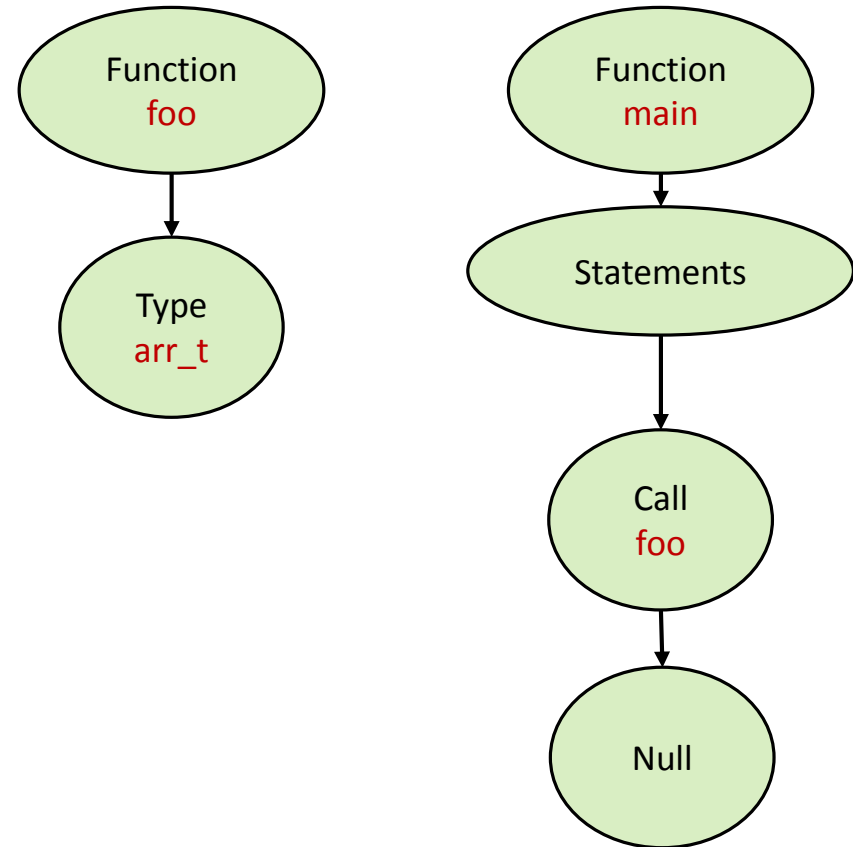
Null

```
typedef int arr_t[];  
void foo(arr_t a) { }  
void main() {  
    foo(null);  
}
```



Null

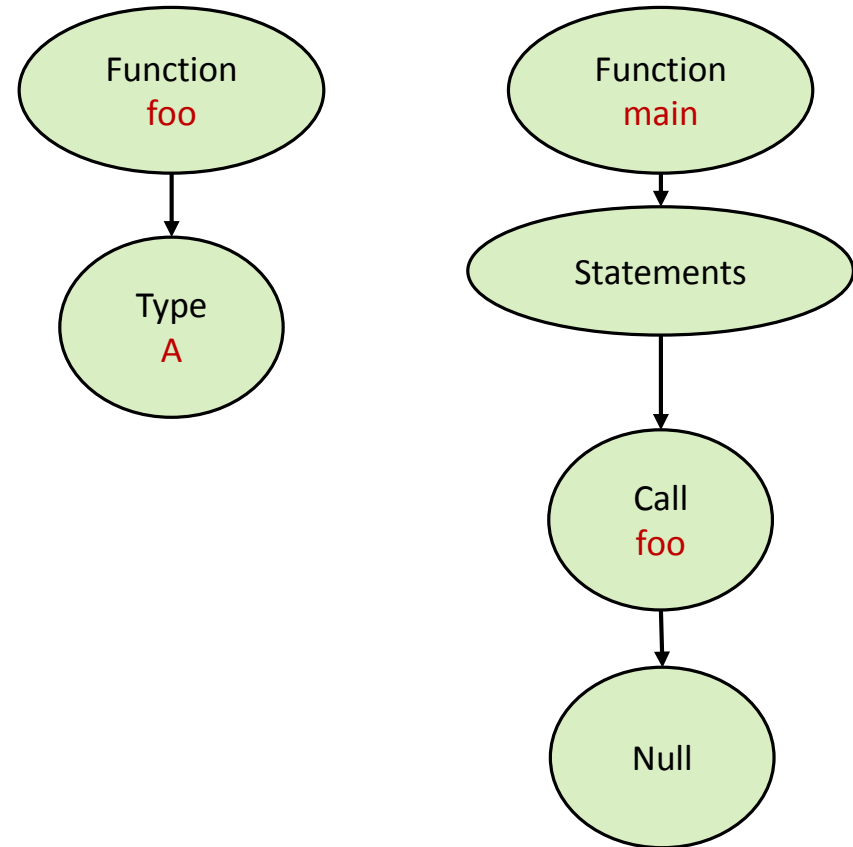
```
typedef int arr_t[];  
void foo(arr_t a) { }  
void main() {  
    foo(null);  
}
```



Valid

Null

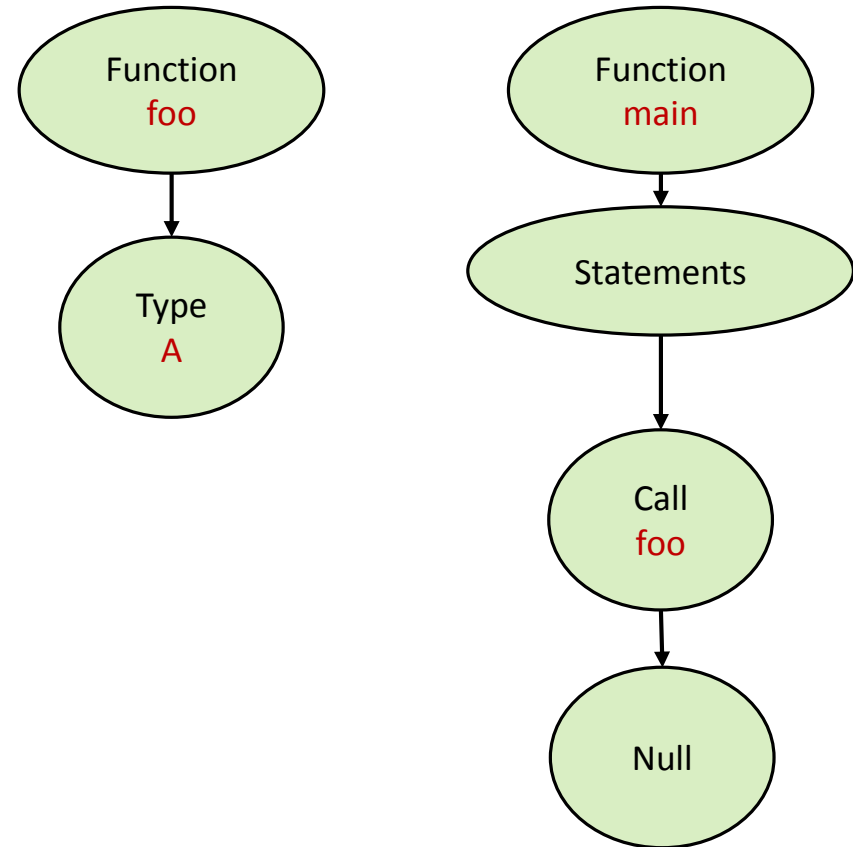
```
class A { };  
void foo(A a) { }  
void main() {  
    foo(null);  
}
```



Null

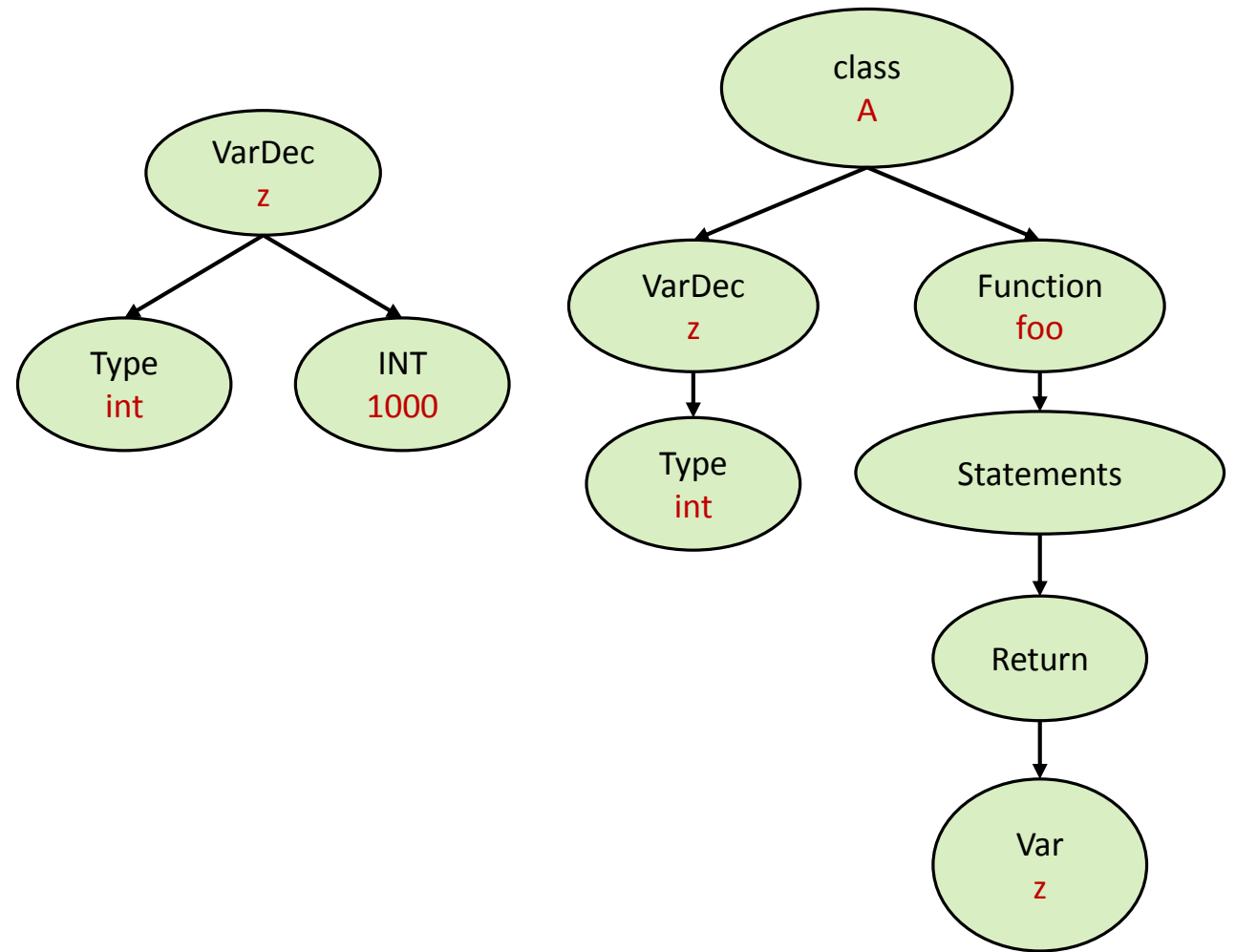
```
class A { };  
void foo(A a) { }  
void main() {  
    foo(null);  
}
```

Valid



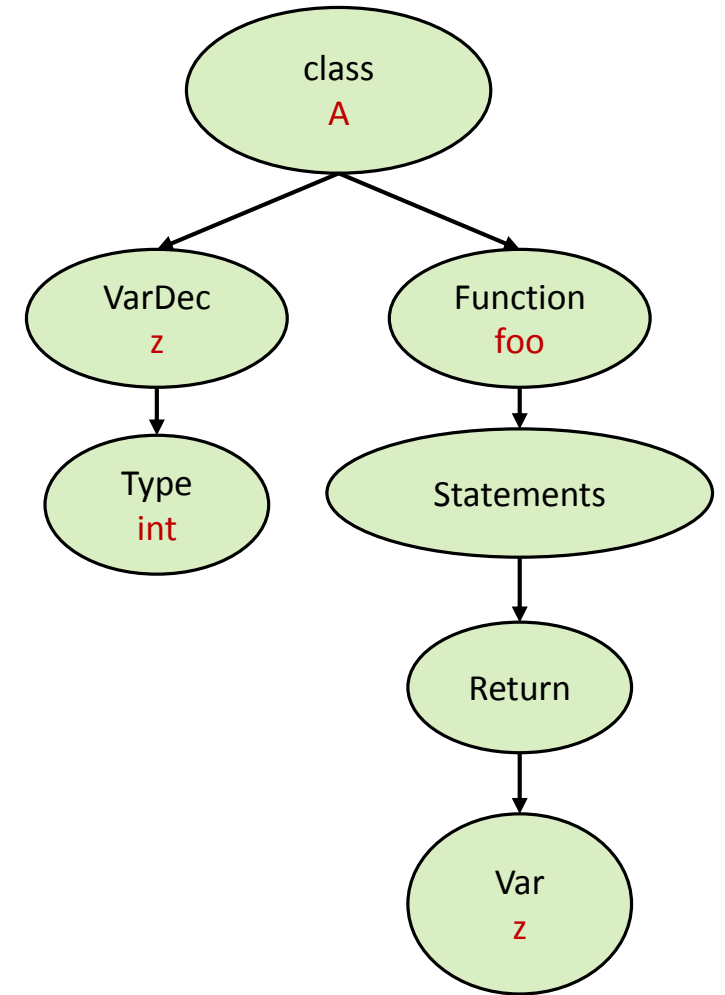
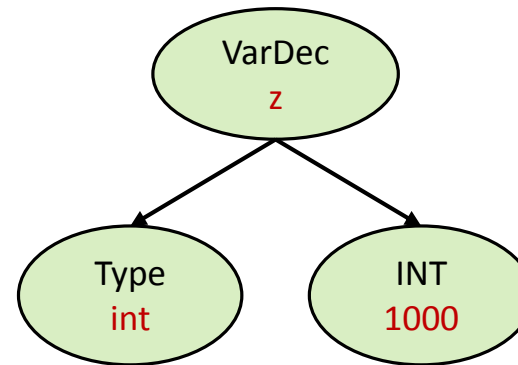
Scopes

```
int z = 1000;  
class A {  
  int z;  
  int foo() {  
    return z;  
  }  
}
```



Scopes

```
int z = 1000;  
class A {  
    int z;  
    int foo() {  
        return z;  
    }  
}
```



ID	Type	Kind
z	int	variable
A	...	class

scope₁

ID	Type	Kind
z	int	variable
foo	...	function

scope₂

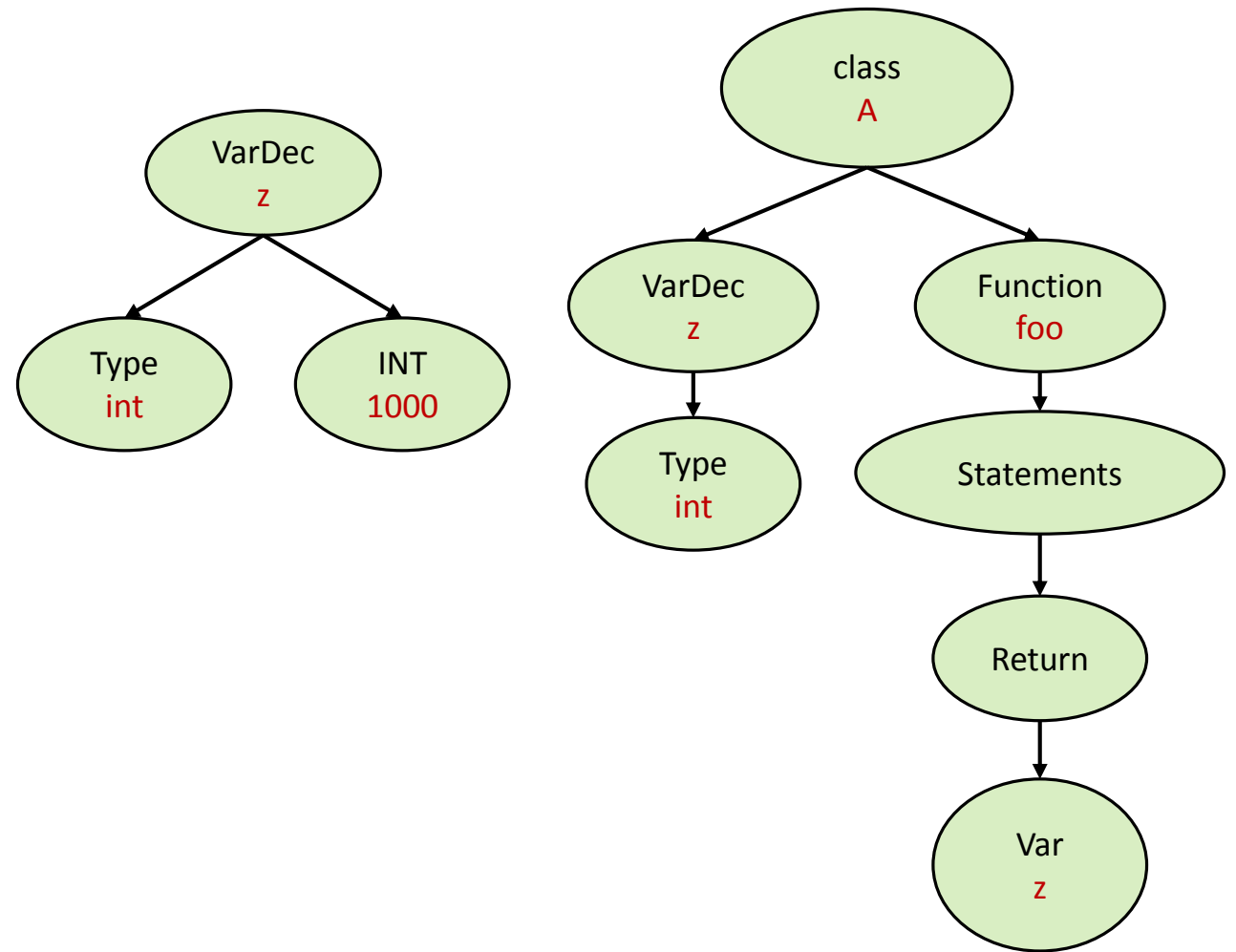
ID	Type	Kind

scope₃

Scopes

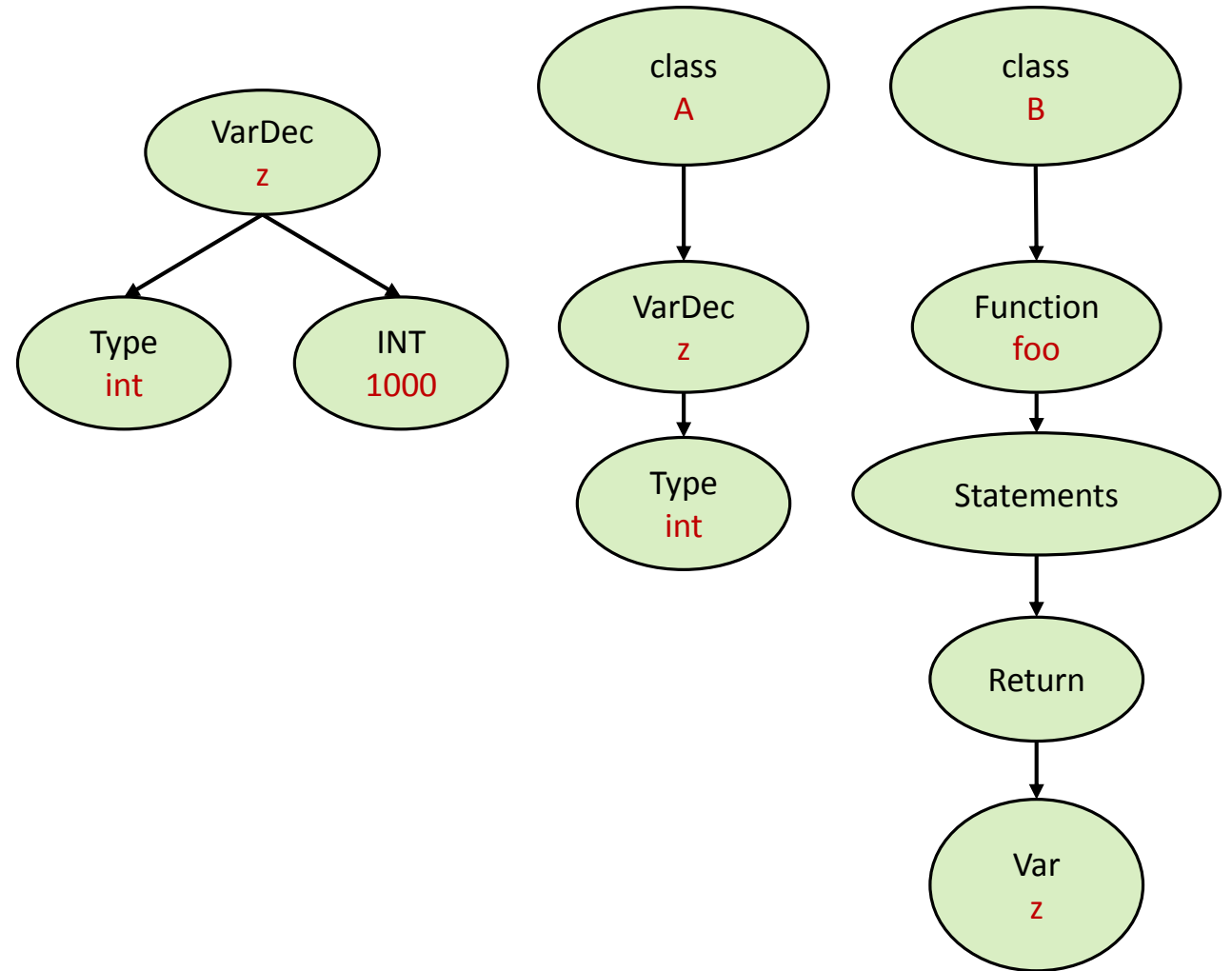
```
int z = 1000;  
class A {  
  int z;  
  int foo() {  
    return z;  
  }  
}
```

Valid



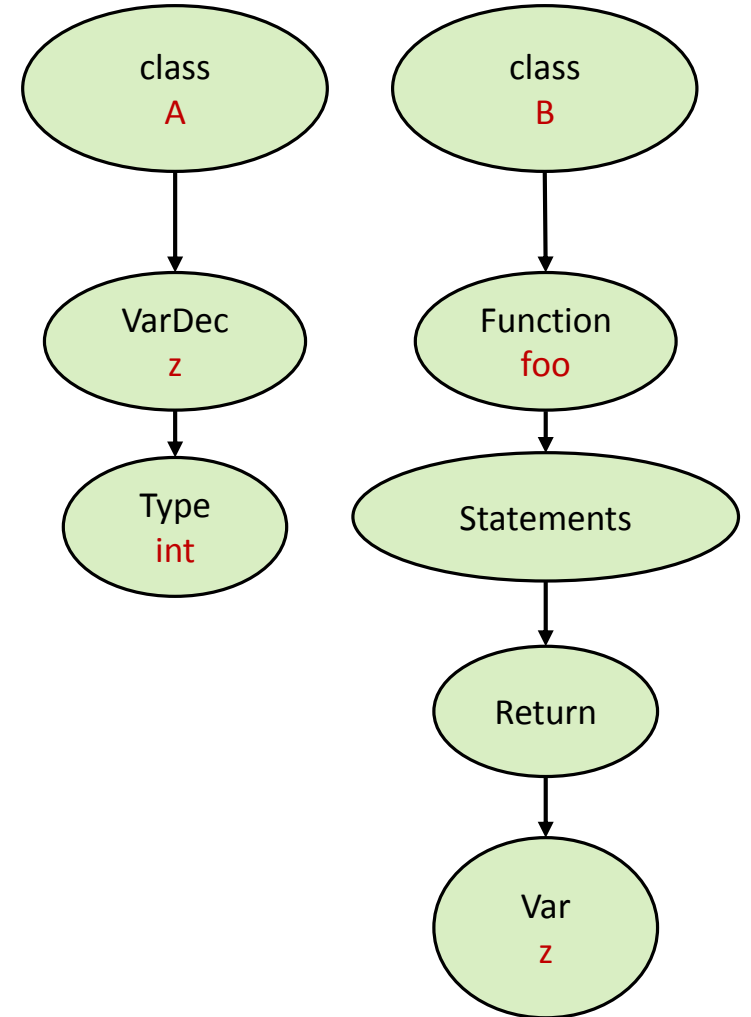
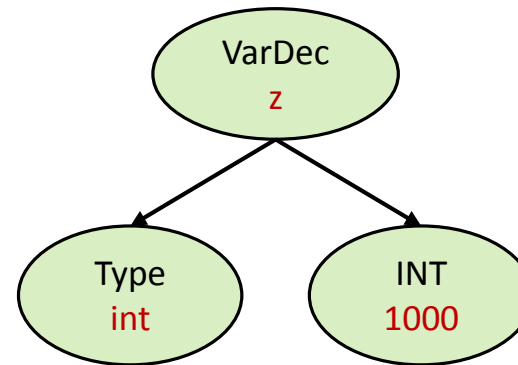
Scopes

```
int z = 1000;  
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```



Scopes

```
int z = 1000;  
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```



ID	Type	Kind
z	int	variable
A	...	class
B	...	class

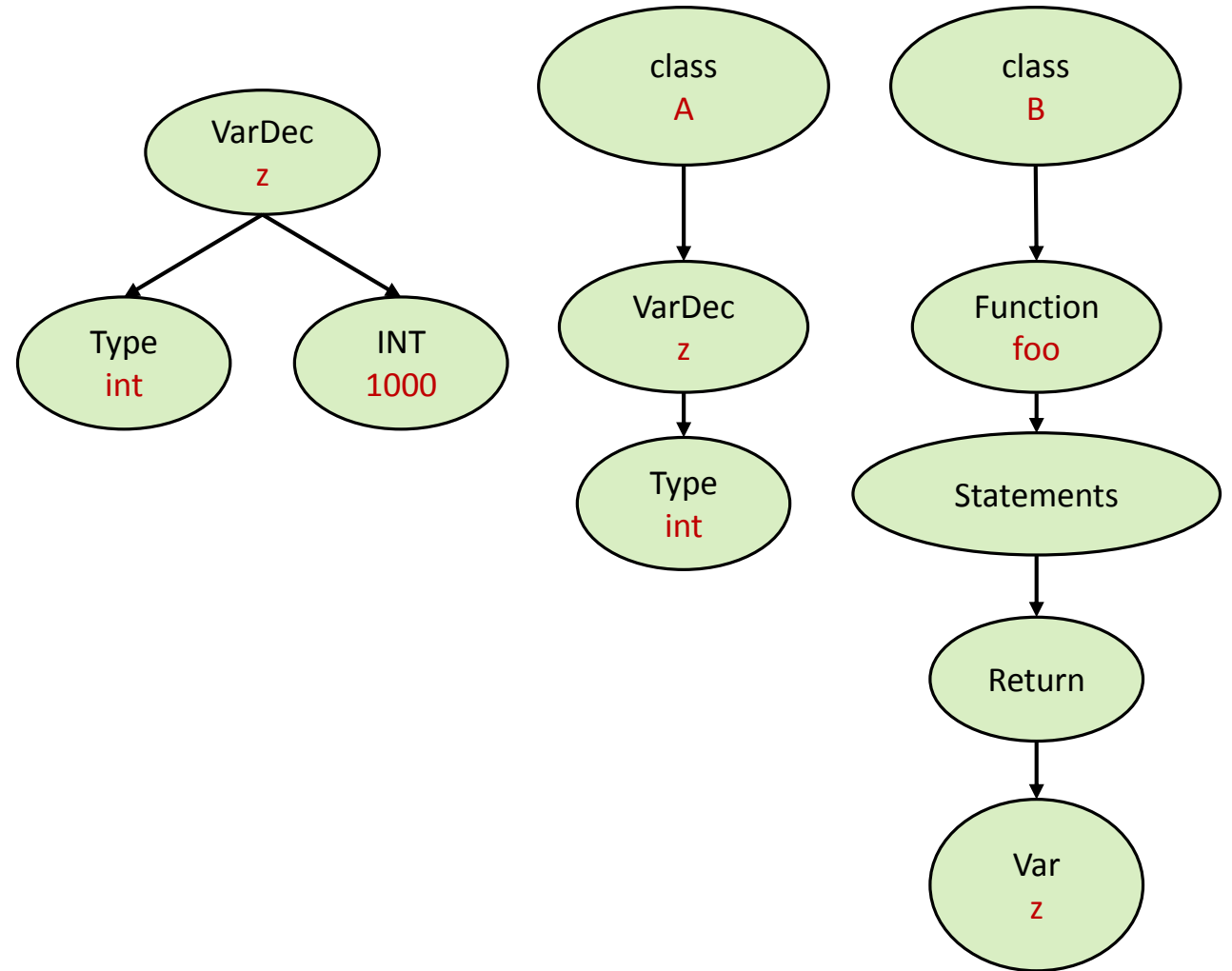
ID	Type	Kind
foo	...	function

ID	Type	Kind

Scopes

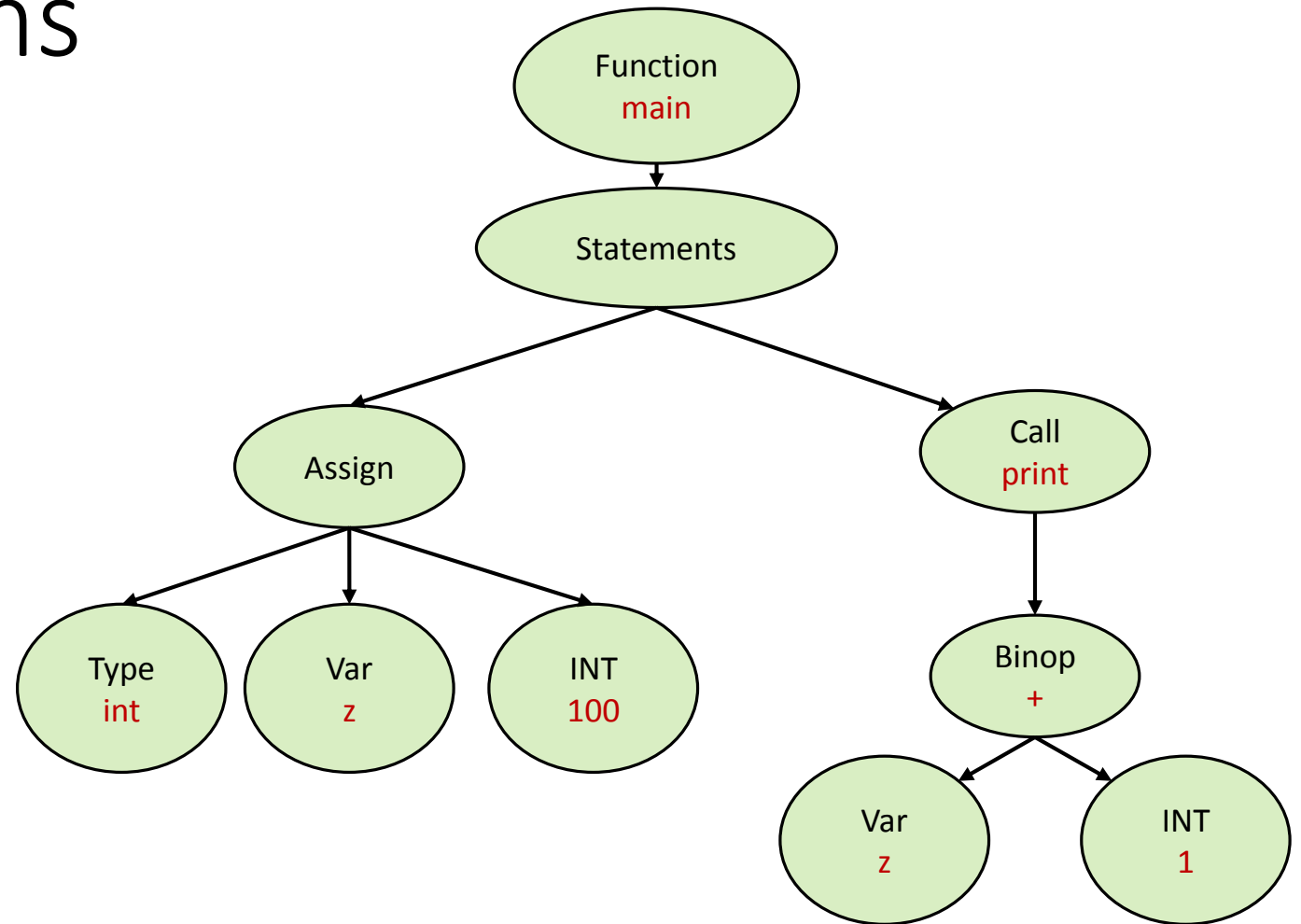
```
int z = 1000;  
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```

Valid



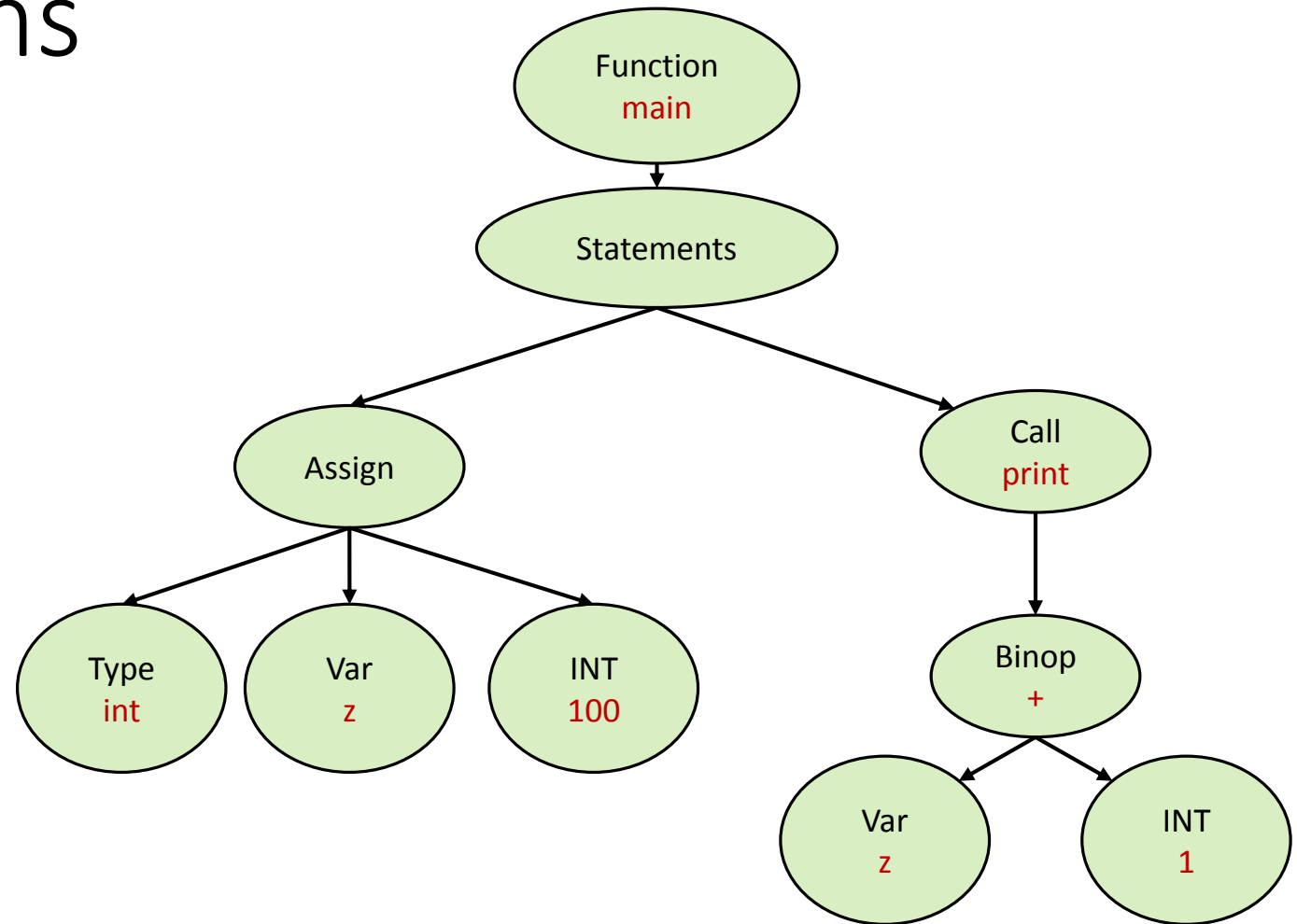
Library Functions

```
void main() {  
    int z = 100;  
    print(z + 1);  
}
```



Library Functions

```
void main() {  
    int z = 100;  
    print(z + 1);  
}
```



Valid

Exam Question

We extend the language with automatic type inference:

- Can use **auto** when the declaration has an initial value

Describe the changes required in:

- Lexical analysis
- Syntactic analysis
- Semantic analysis

```
auto i := 8 + 100;  
auto s := "1234";  
class A {}  
A a := new A;  
auto b := a;
```

Implementation

The AST is traversed in a top-down manner:

- Each AST node class, has a **visit** API
 - Performs the relevant semantic checks
 - May call the visitors of the node's children
- The traversal starts from the root node

Implementation

```
class ASTExpBinOp {
    public ASTExp left;
    public ASTExp right;
    ...
    public Type visit() {
        Type t1 = left.visit();
        Type t2 = right.visit();
        if (t1 != t2) {
            // error
        }

        // return the corresponding type
    }
}
```

Implementation

```
class ASTStatmentList {  
    public ASTStatement head;  
    public ASTStatmentList tail;  
    ...  
    public Type visit() {  
        if (head)  
            head.visit();  
        if (tail)  
            tail.visit();  
        return null;  
    }  
}
```

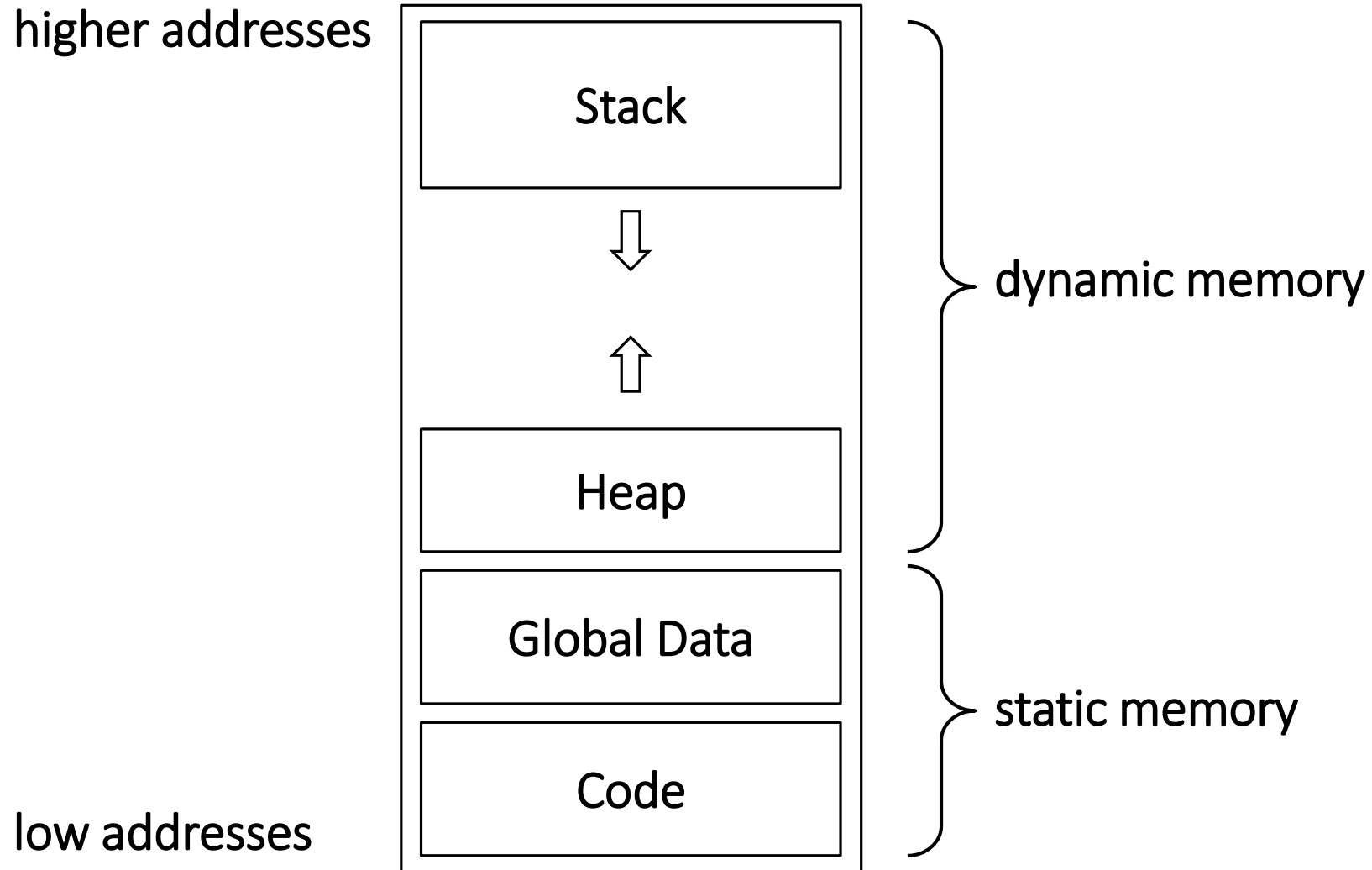
AST Annotations

AST Annotations

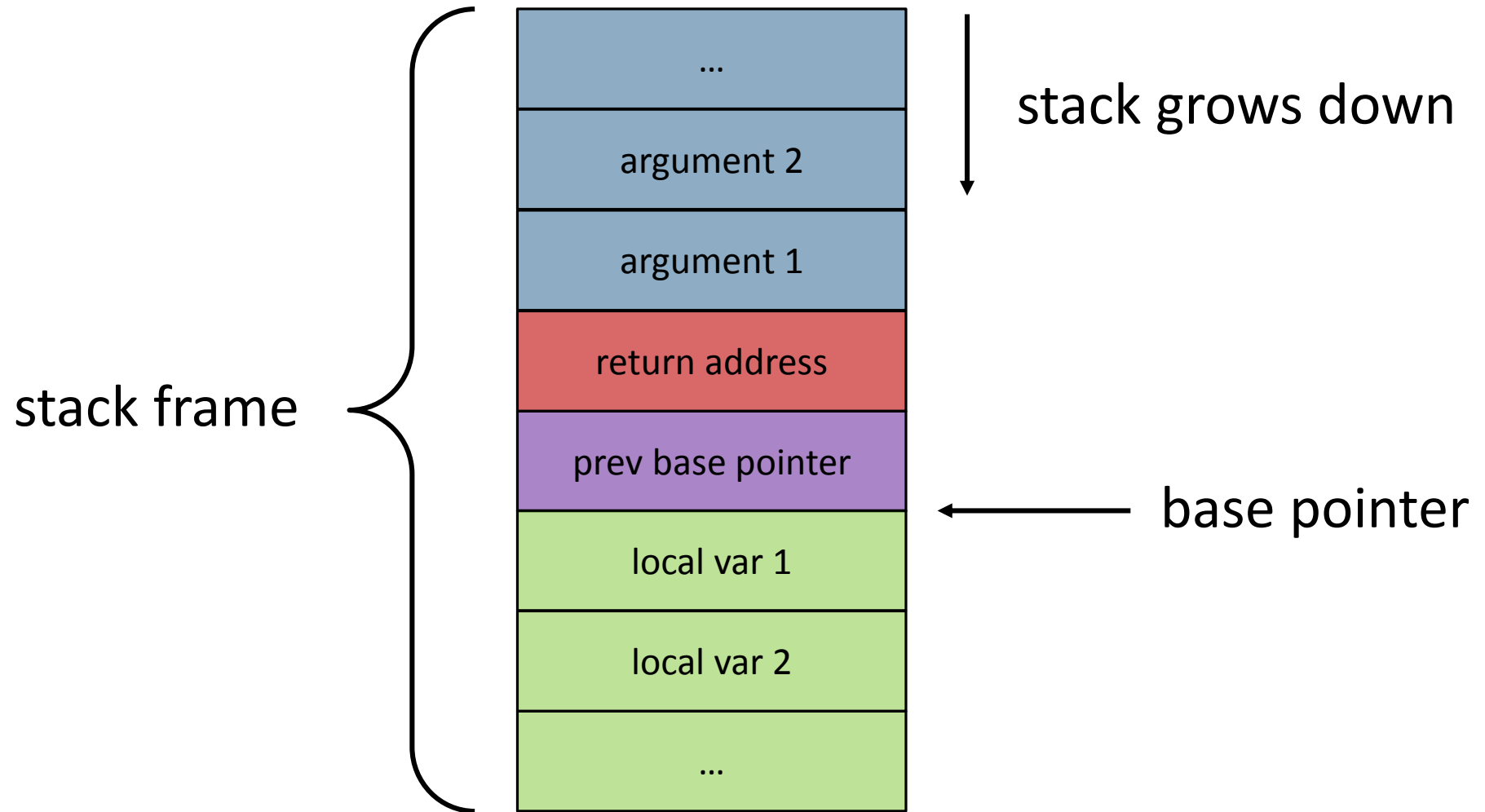
Annotate the AST with information needed for **code generation**:

- Variable offsets
- Parameter offsets
- Class layouts
- Type sizes

Runtime Memory Layout



Stack



MIPS: Instructions Set

MIPS has 32 registers:

- t0, ..., t9 (general purpose)
- a0, a1, a2, a3 (arguments)
- v0 (return value)
- sp (stack pointer)
- fp (frame pointer)
- ra (return address)
- ...

MIPS: Instructions Set

Setting registers values:

- li
- move

```
li $t0, 3  
move $t1, $t2
```

MIPS: Instructions Set

Arithmetic instructions operate on registers and constants:

- add, sub, ...

```
add $t2, $t0, $t1  
sub $t3, t1, 7
```

MIPS: Instructions Set

Read from memory:

- lw

```
lw $t0, 0($t1)
```

```
lw $t0, 12($t1)
```

```
lw $t0, -8($t1)
```

MIPS: Instructions Set

Write from memory:

- lw

```
sw $t0,0($t1)
```

```
sw $t0,12($t1)
```

```
sw $t0,-8($t1)
```

MIPS: Instructions Set

Branches:

- jal?

jal ...

Stack

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}  
int g() {  
    int x = f(10, 20)  
}
```

f:

```
subu $sp, $sp, 4  
sw $ra, 0($sp)  
subu $sp, $sp, 4  
sw $fp, 0($sp)  
move $fp, $sp  
sub $sp, $sp, 16  
lw $t0, 8($fp)  
lw $t1, 12($fp)  
add $t2, $t0, $t1  
sw $t2, -4($fp)  
lw $v0, -4($fp)  
move $sp, $fp  
lw $fp, 0($sp)  
lw $ra, 4($sp)  
addu $sp, $sp, 8  
jr $ra
```

g:

```
...  
li $t0, 20  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
li $t0, 10  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
jal f  
addu $sp, $sp, 8  
move $t0, $v0  
...
```

Stack

argument 2

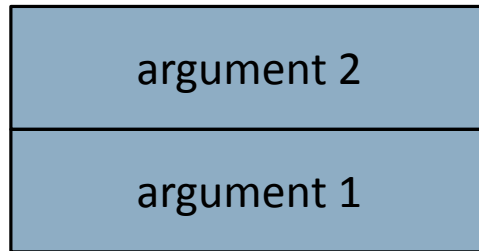
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



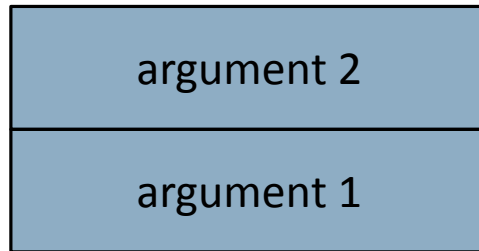
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



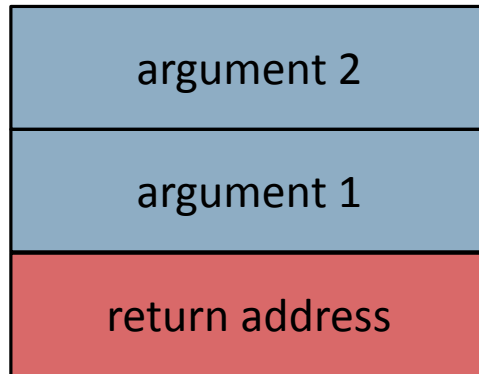
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



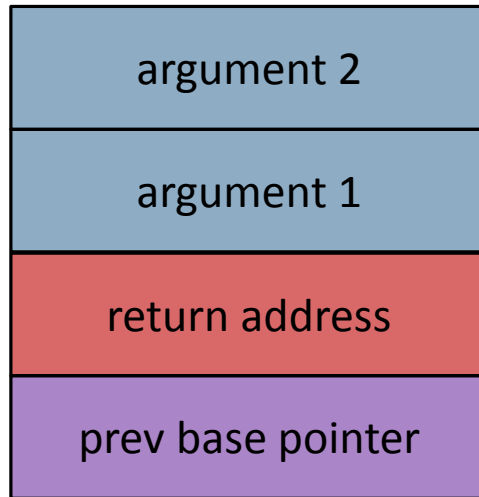
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



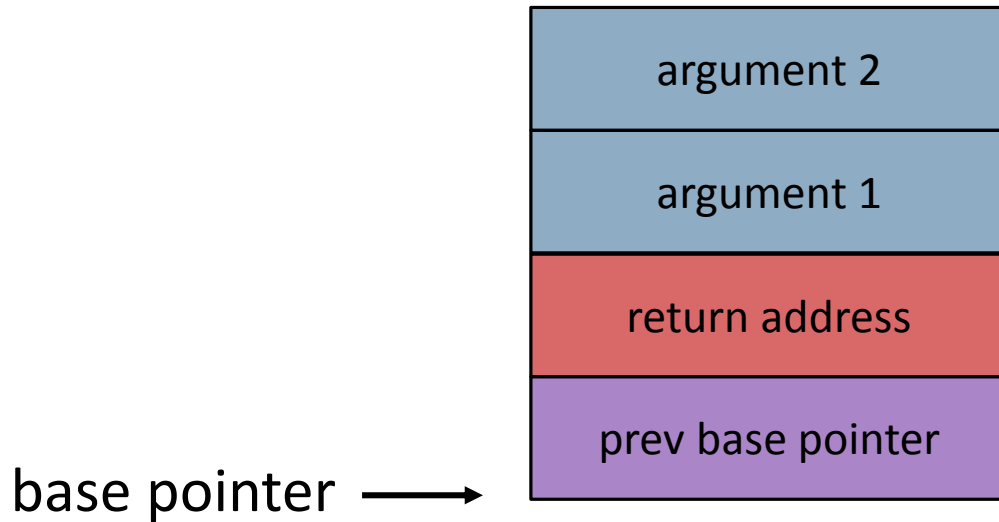
f:

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subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
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lw $t0, 8($fp)
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sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



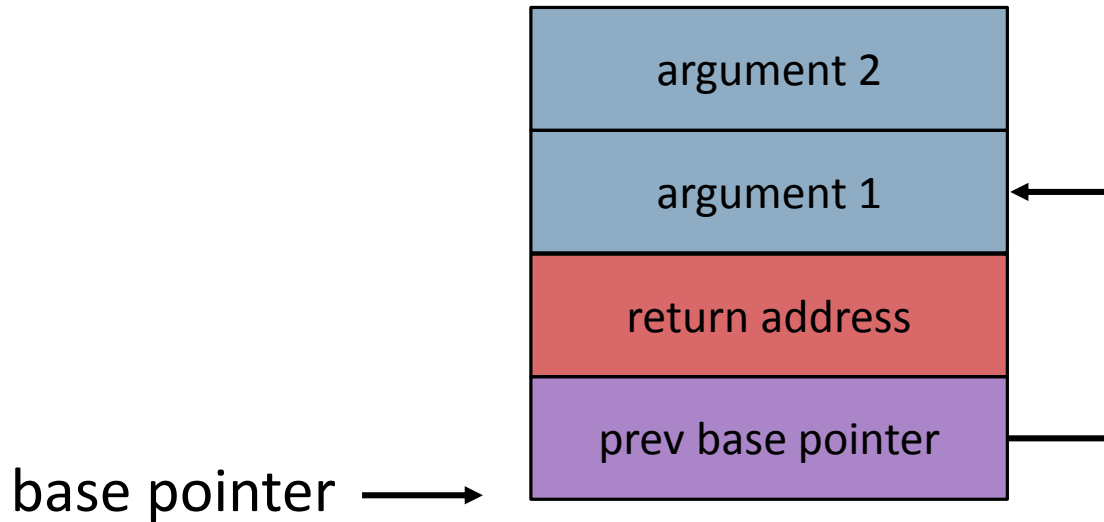
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



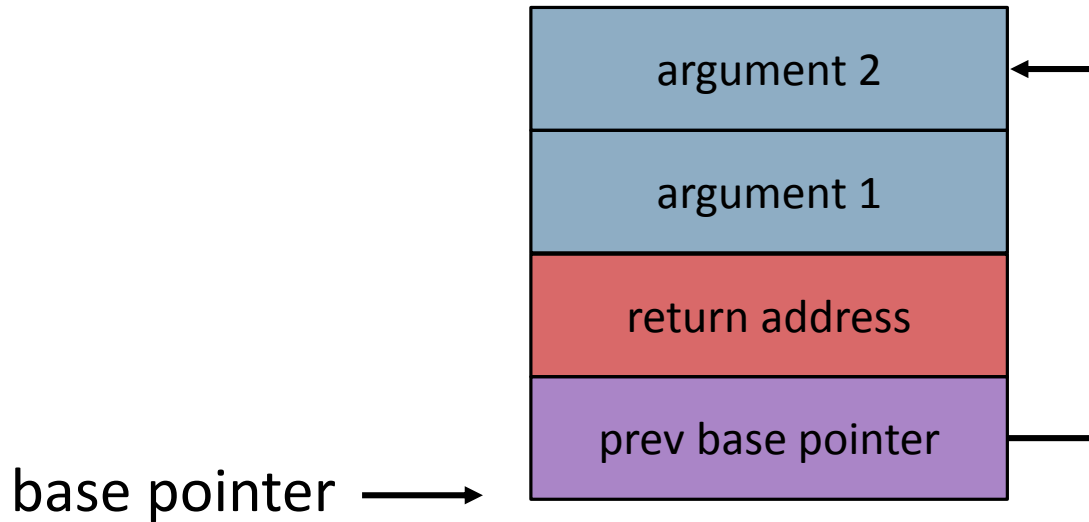
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
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add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```


Stack



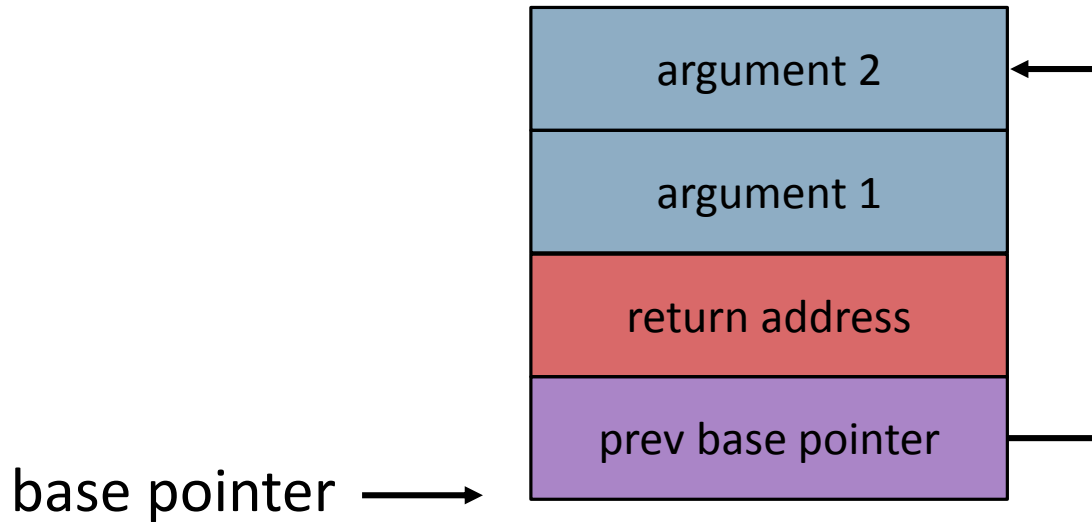
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```
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sw $fp, 0($sp)
move $fp, $sp
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lw $t0, 8($fp)
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add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
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subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



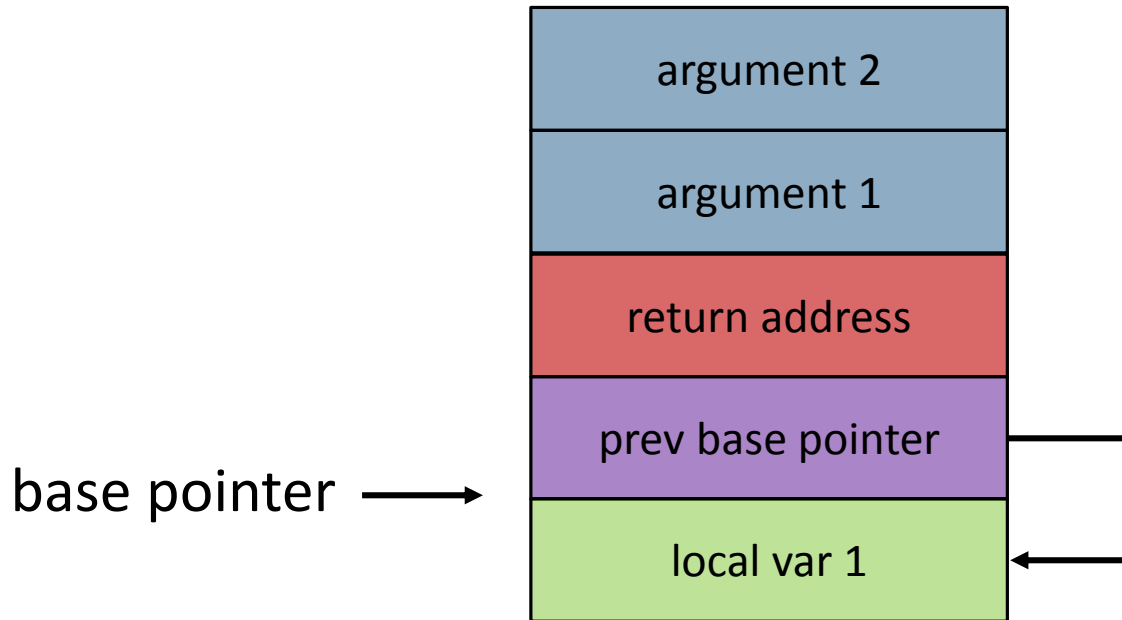
f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
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move $sp, $fp
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lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack



f:

```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
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sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

g:

```
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Variable Offsets

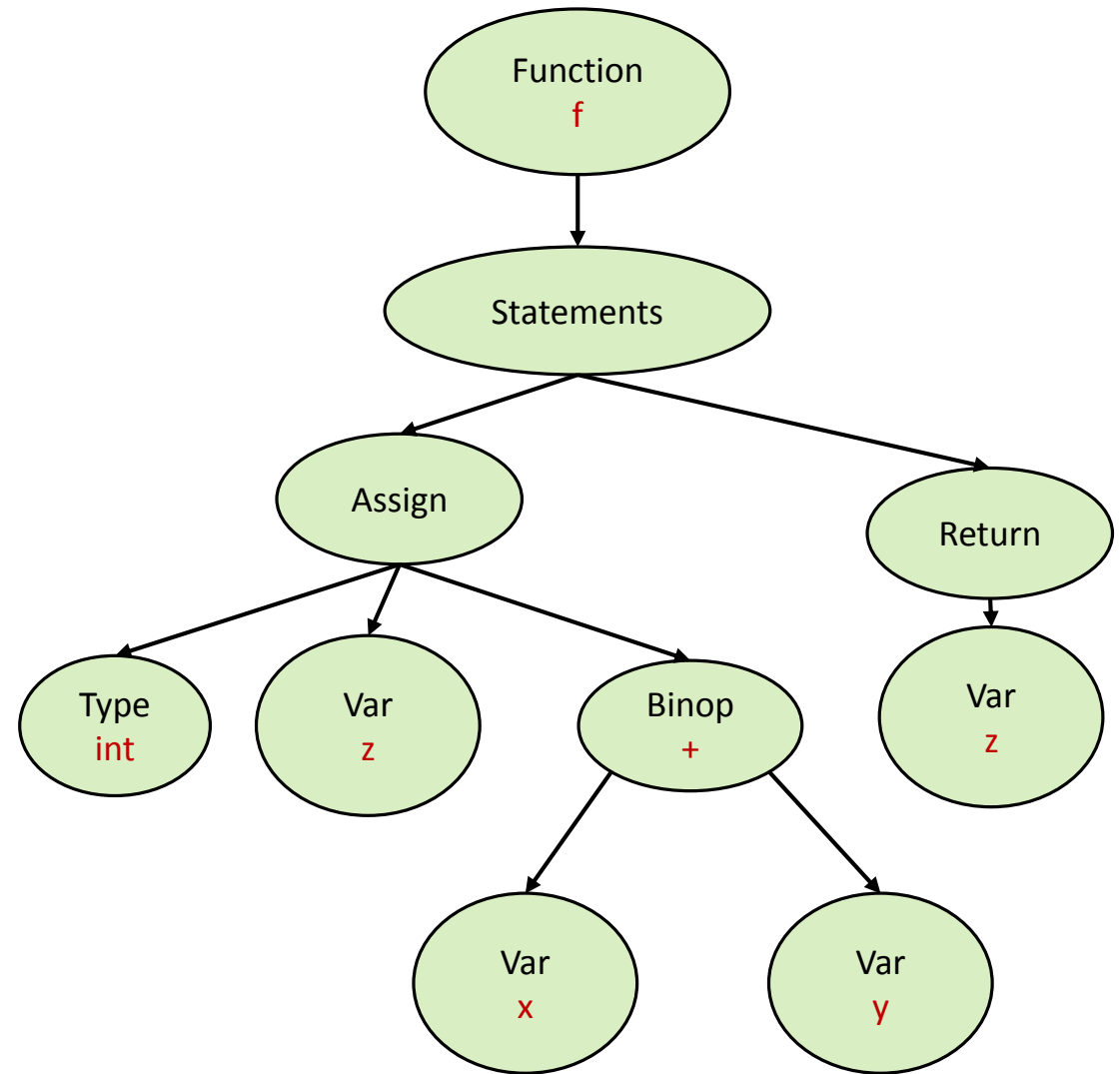
Machine code **does not** contain names of:

- Local variables
- Parameters

Instead, we use offsets **relatively** to the **stack base pointer**

Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

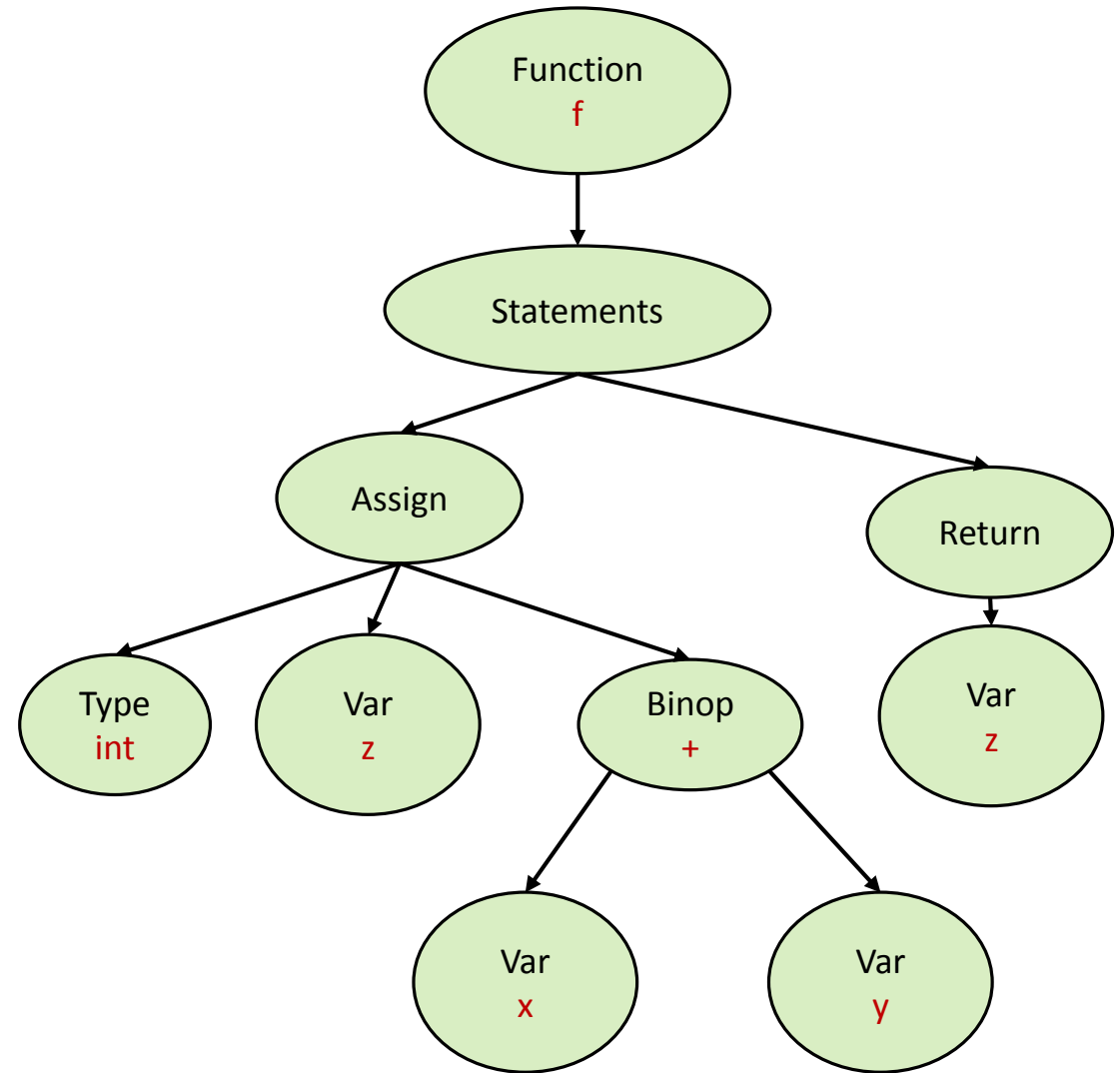


Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

$scope_1$



Variable Offsets

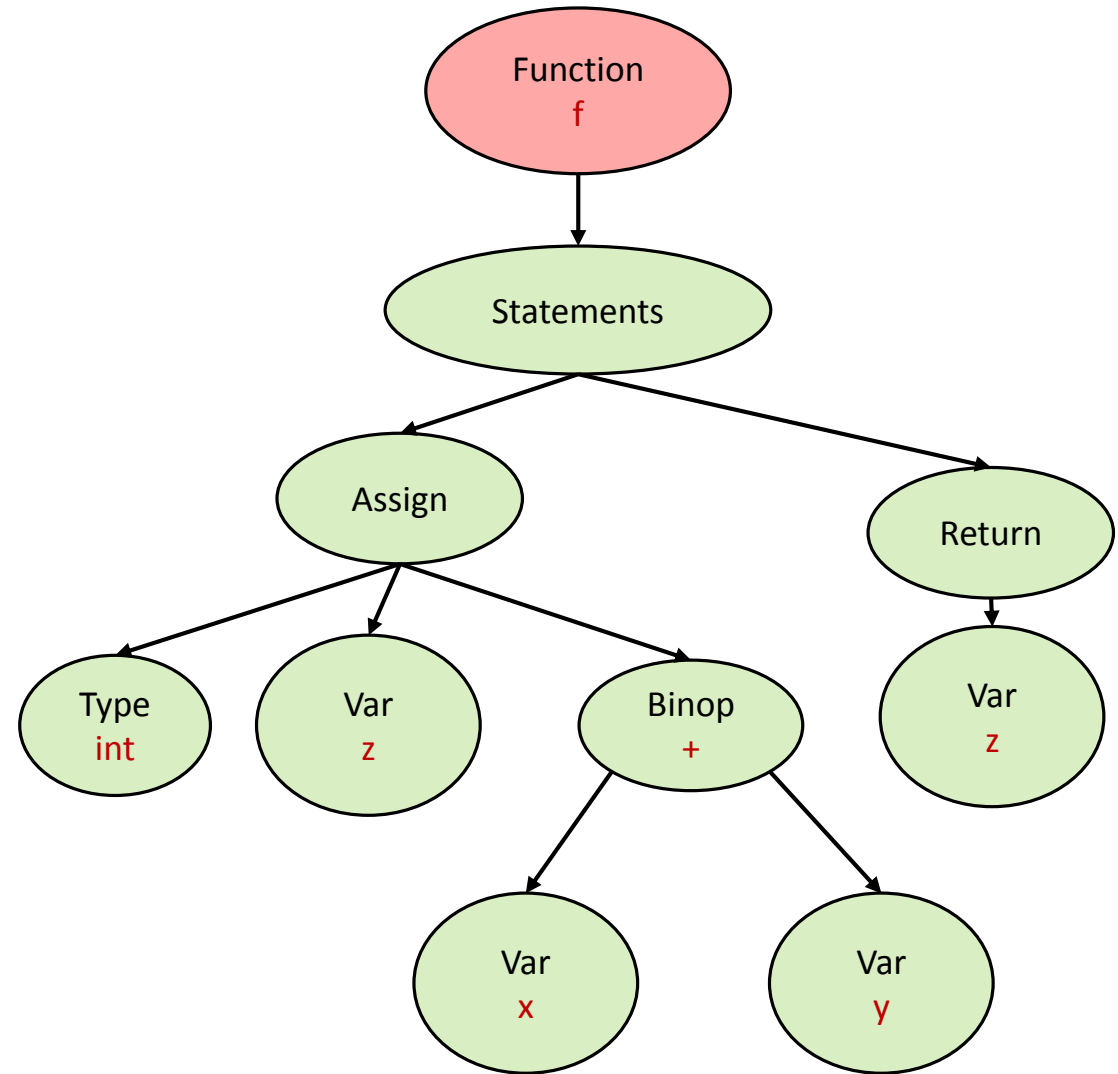
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

ID	Type	Kind

$scope_1$

$scope_2$



Variable Offsets

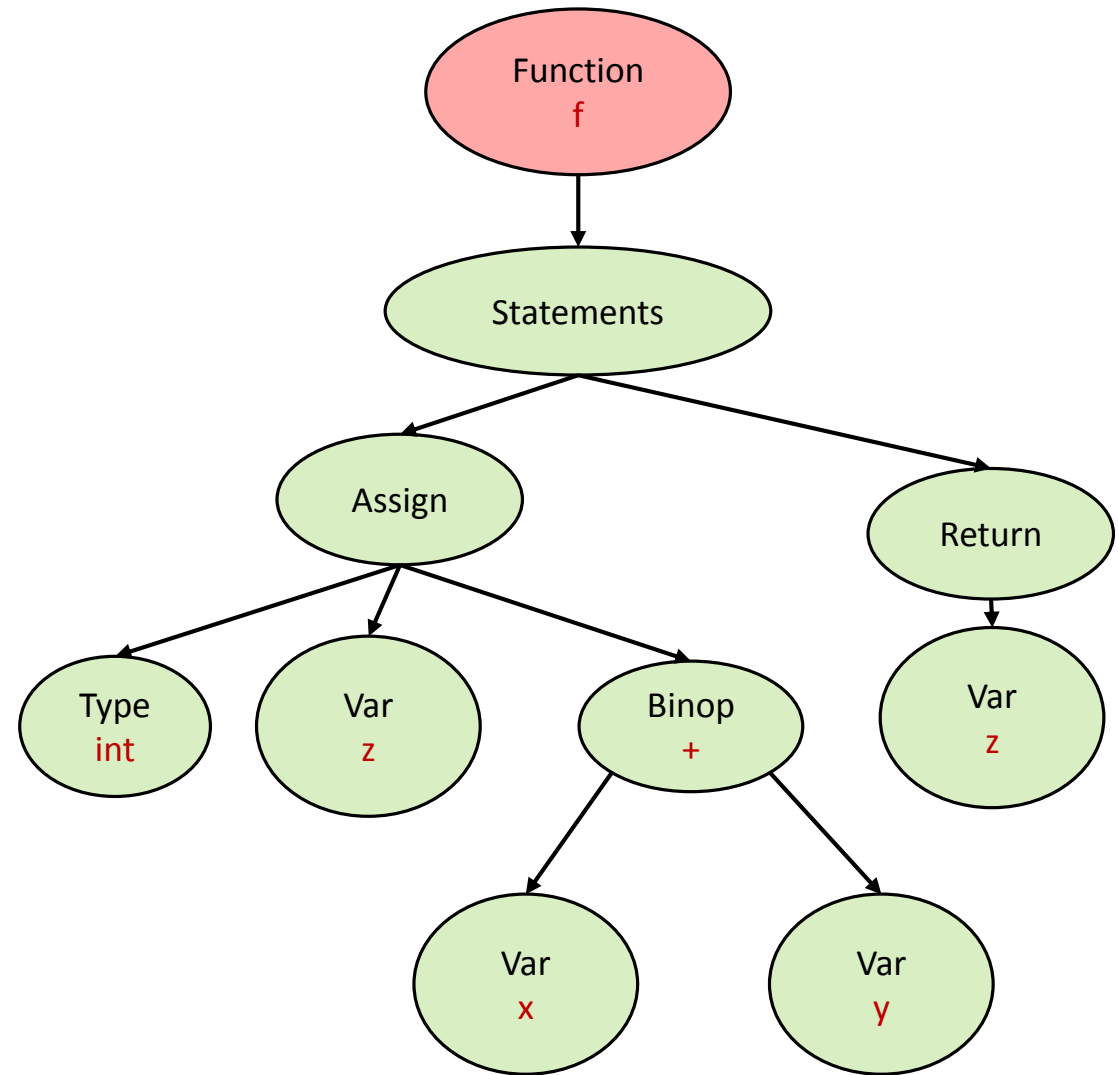
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

ID	Type	Kind
x	int	variable

$scope_1$

$scope_2$



Variable Offsets

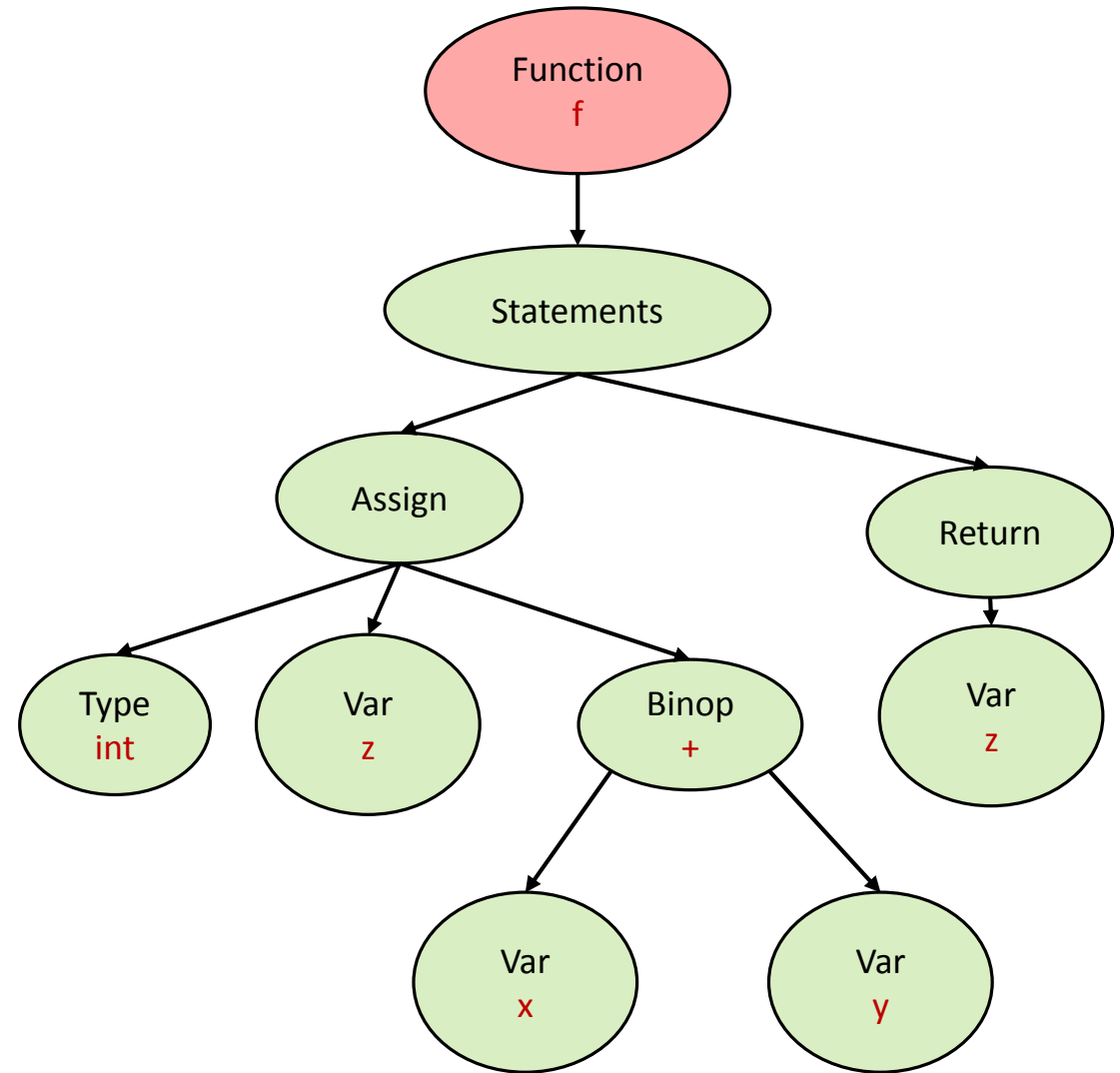
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

scope₁

ID	Type	Kind
x	int	variable
y	int	variable

scope₂



Variable Offsets

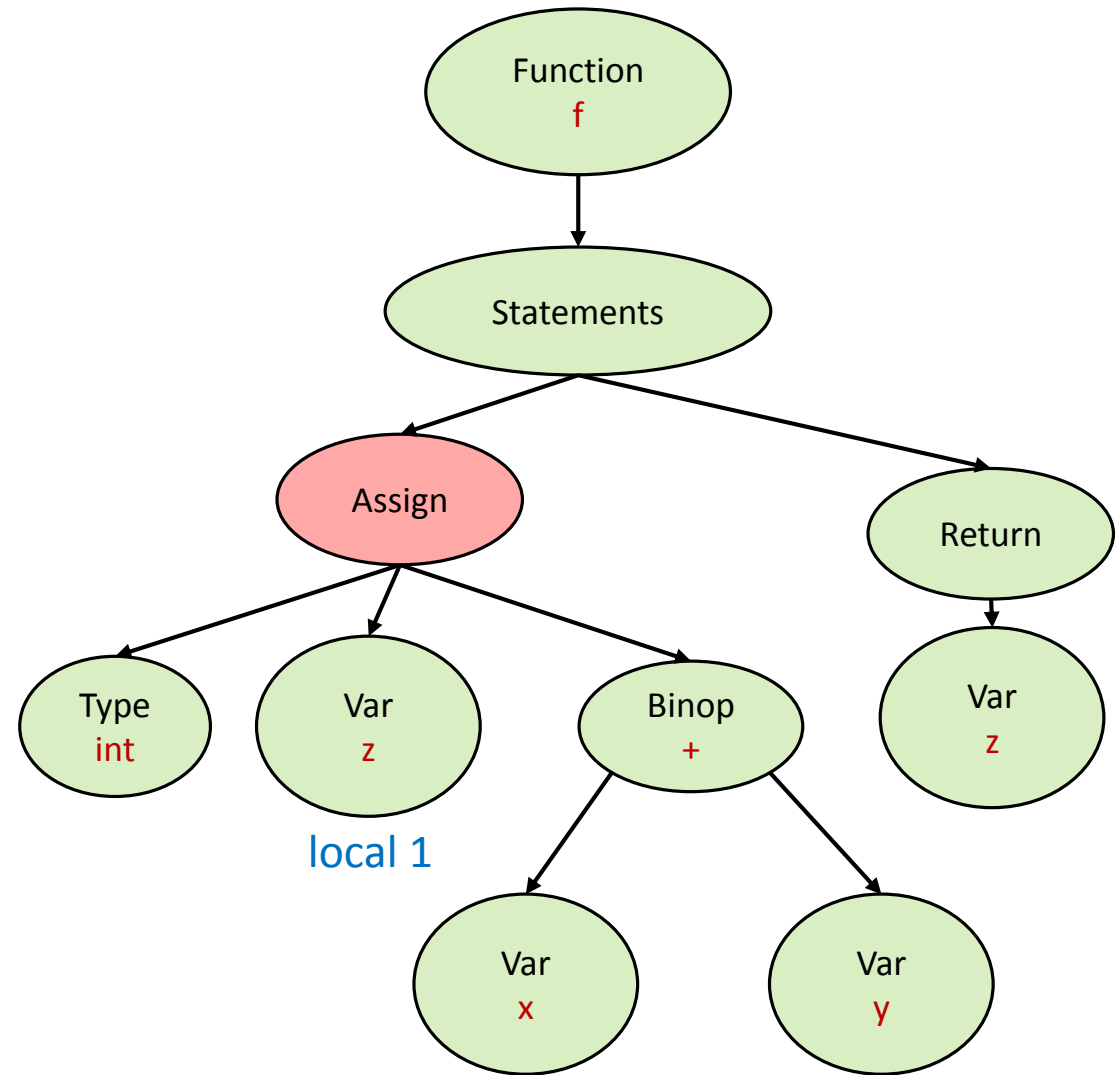
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

scope₁

ID	Type	Kind
x	int	variable
y	int	variable
z	int	variable

scope₂



Variable Offsets

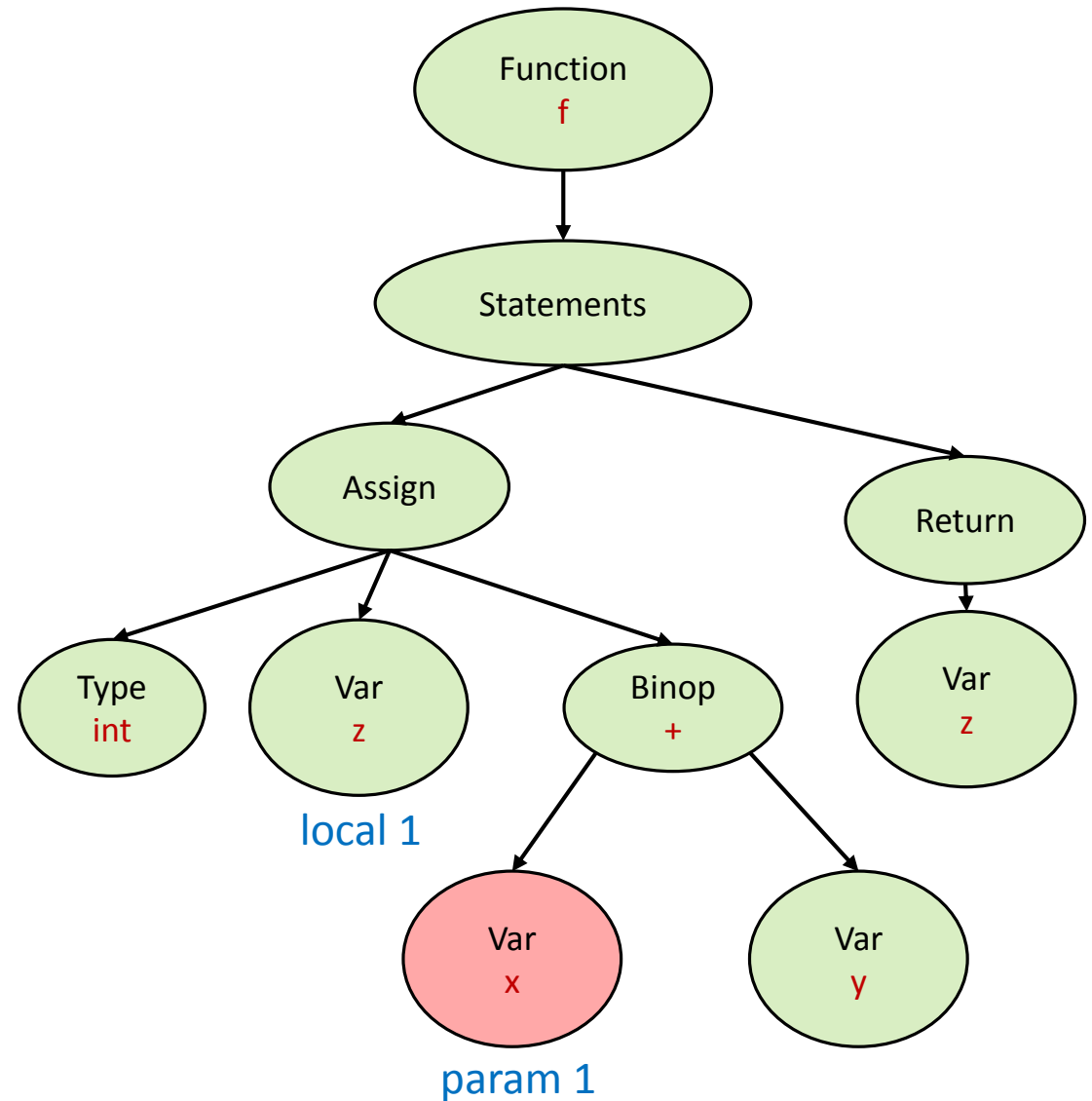
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

scope₁

ID	Type	Kind
x	int	variable
y	int	variable
z	int	variable

scope₂



Variable Offsets

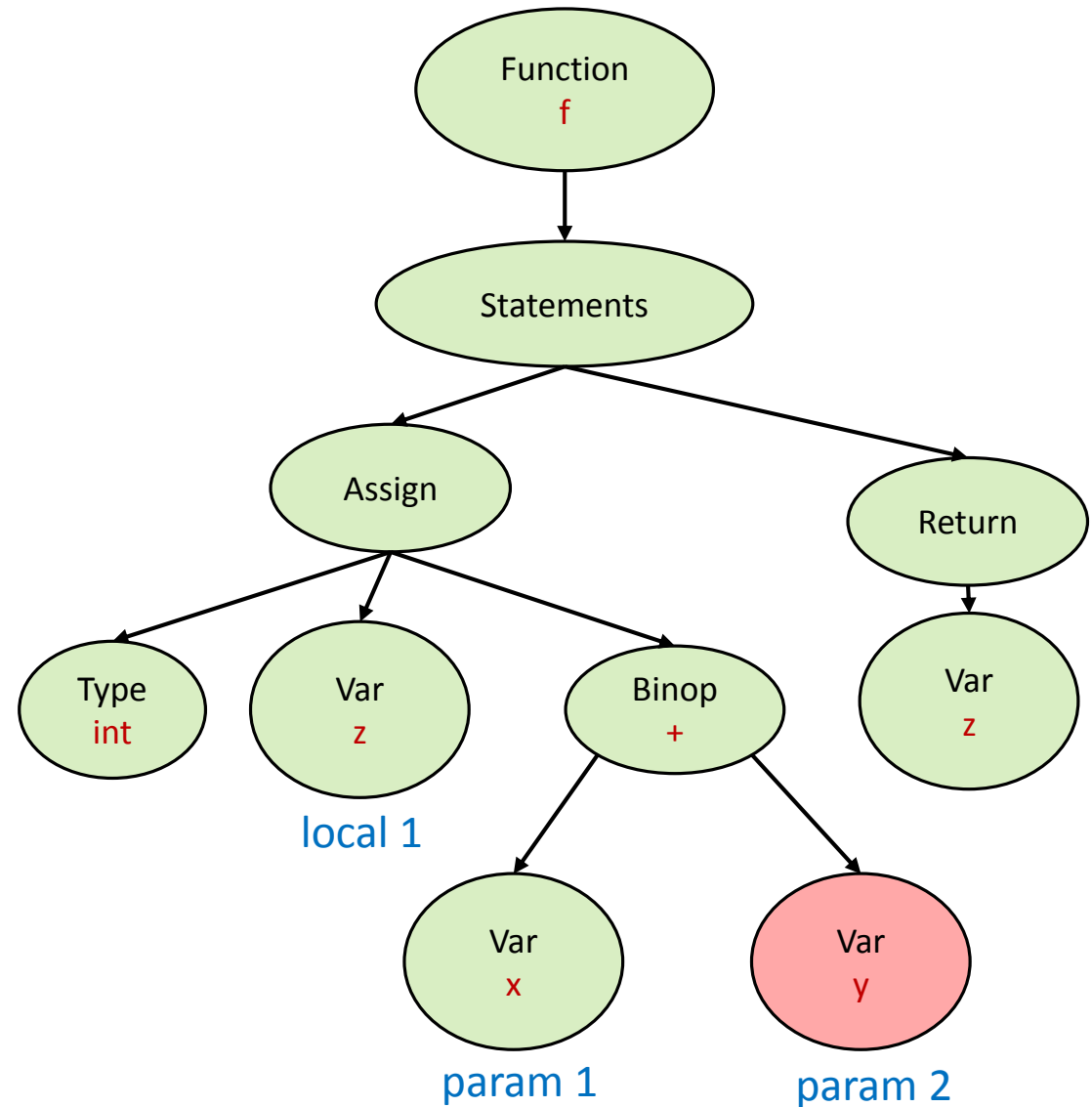
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

scope₁

ID	Type	Kind
x	int	variable
y	int	variable
z	int	variable

scope₂



Variable Offsets

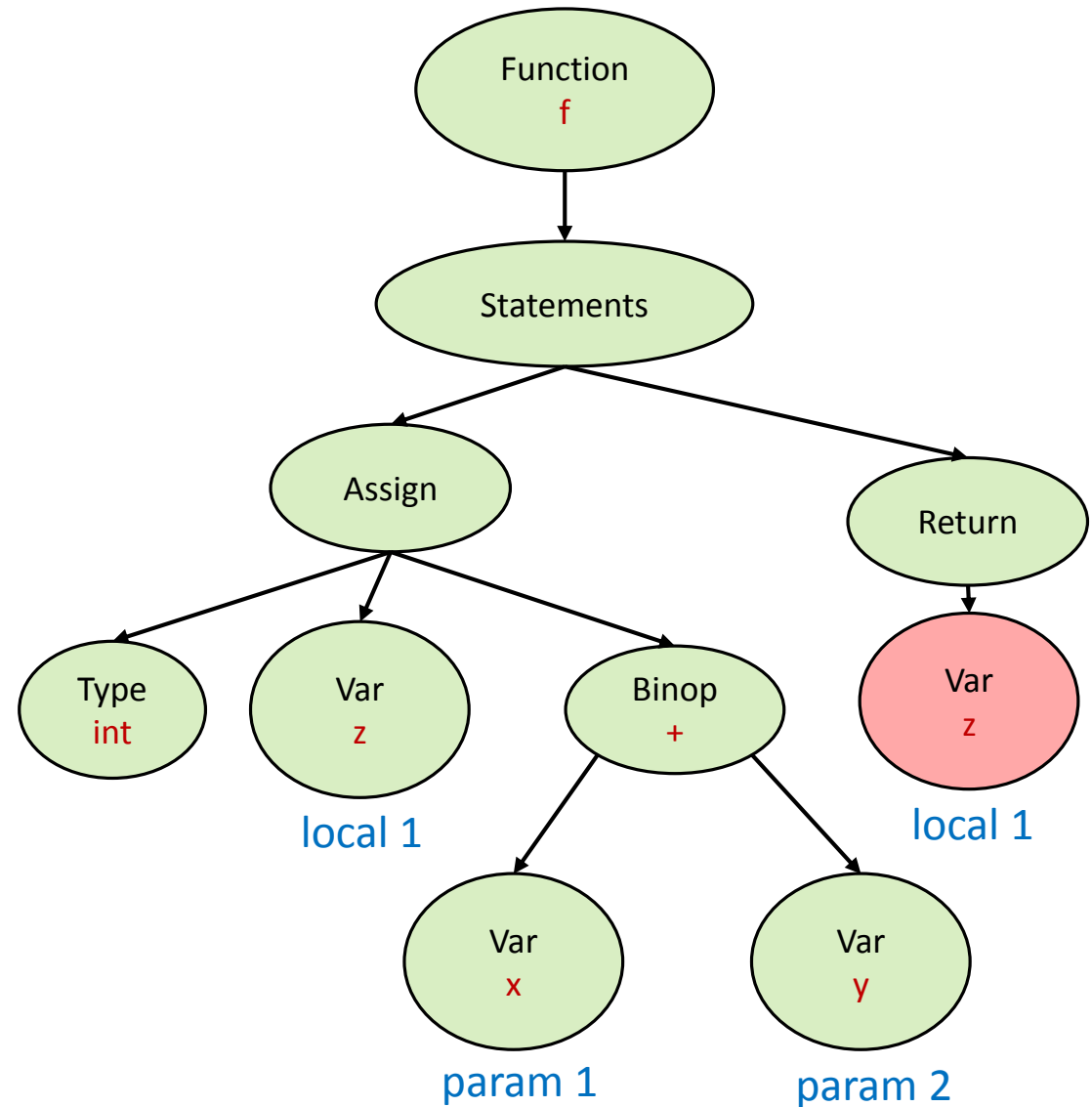
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

*scope*₁

ID	Type	Kind
x	int	variable
y	int	variable
z	int	variable

*scope*₂



Variable Offsets

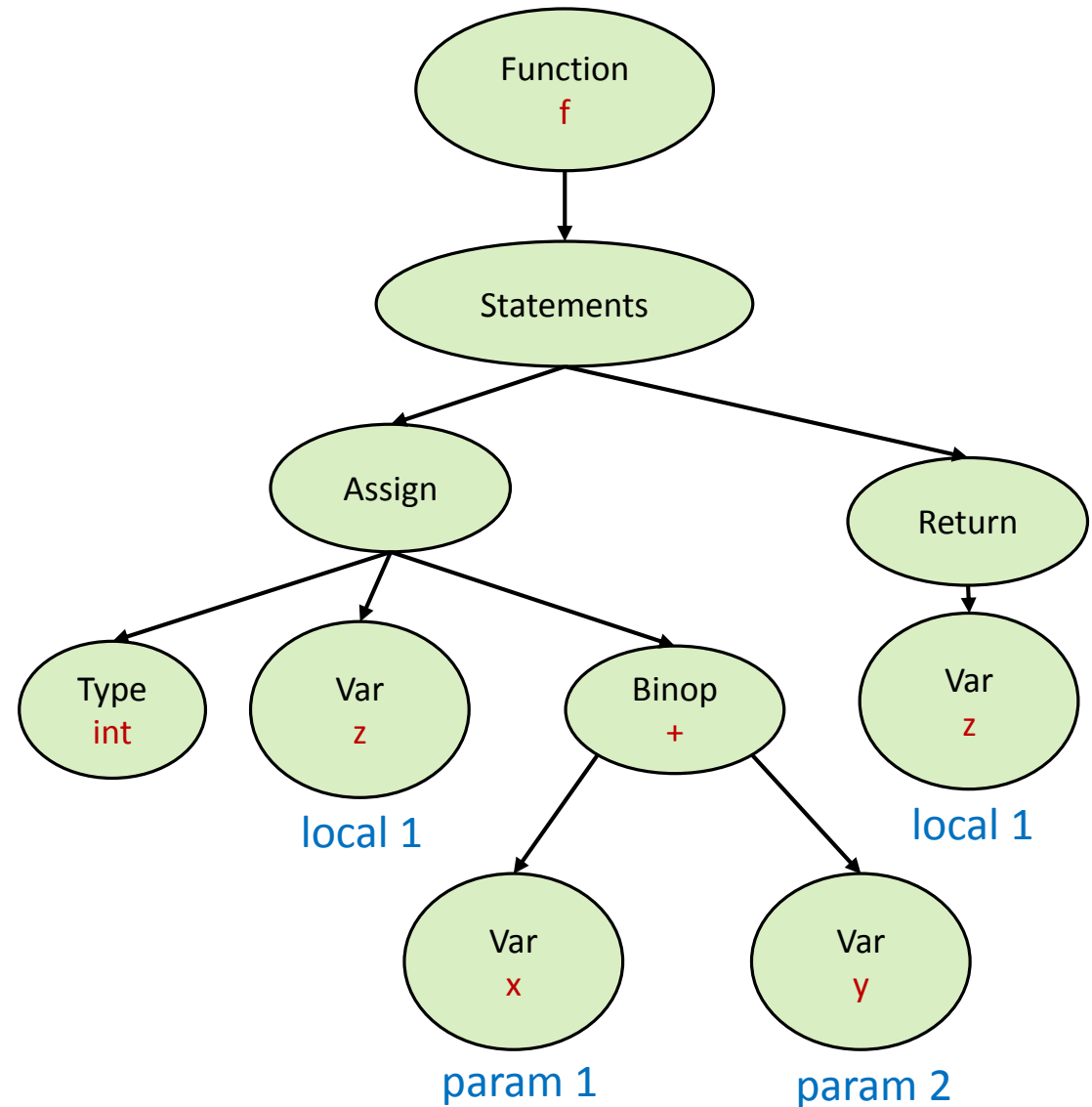
```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

ID	Type	Kind
f	...	function

scope₁

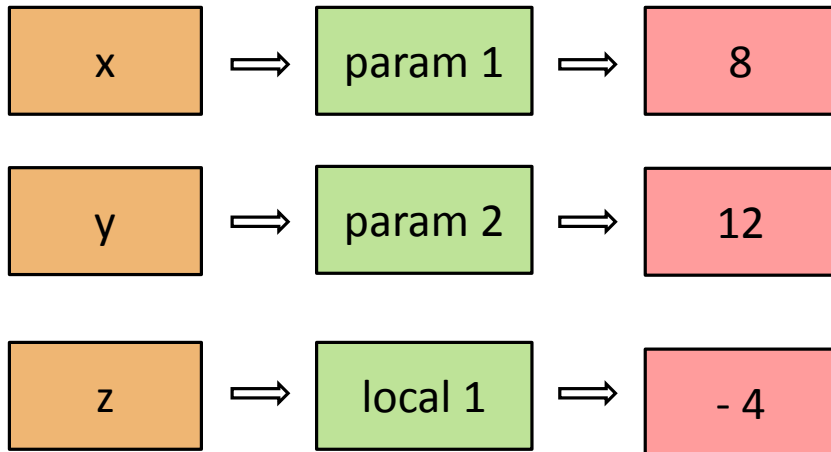
ID	Type	Kind
x	int	variable
y	int	variable
z	int	variable

scope₂



Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```



Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

f:

...

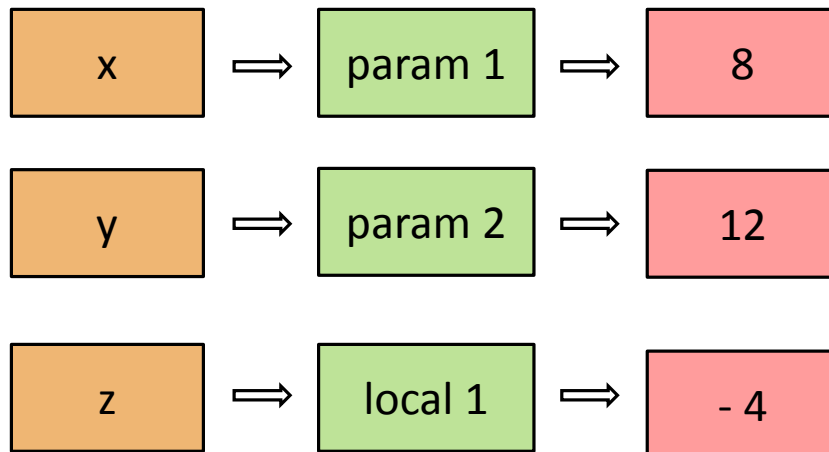
lw \$t0, 8(\$fp)

lw \$t1, 12(\$fp)

add \$t2, \$t0, \$t1

sw \$t2, -4(\$fp)

...



Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

f:

...

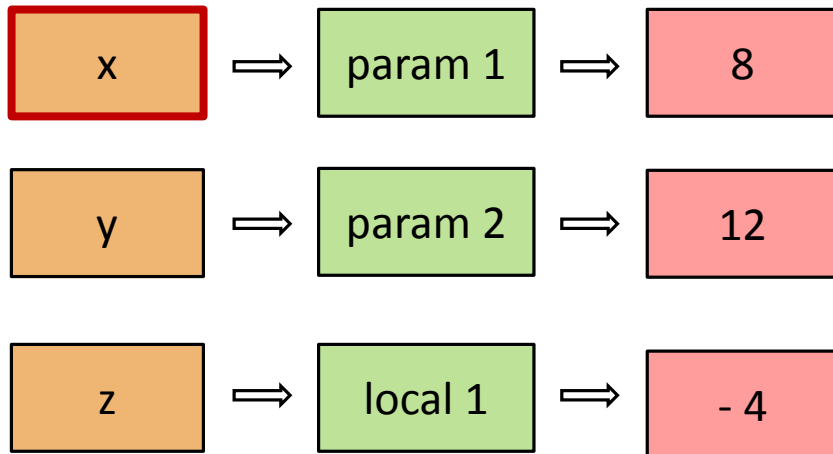
lw \$t0, 8(\$fp)

lw \$t1, 12(\$fp)

add \$t2, \$t0, \$t1

sw \$t2, -4(\$fp)

...



Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

f:

...

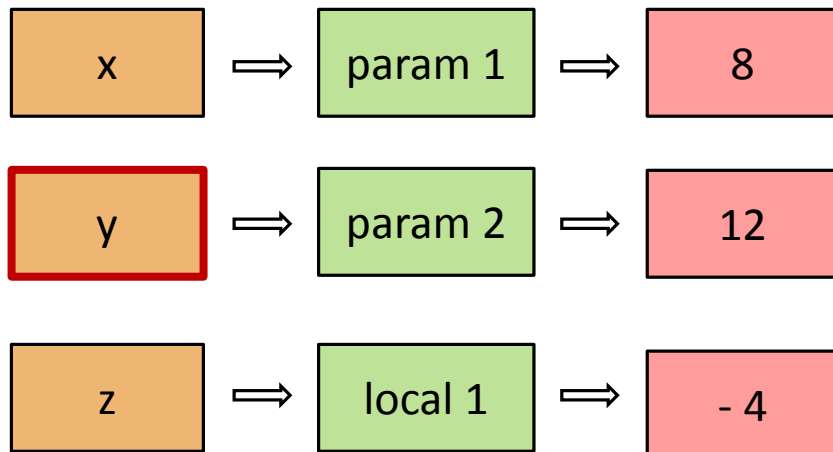
lw \$t0, 8(\$fp)

lw \$t1, 12(\$fp)

add \$t2, \$t0, \$t1

sw \$t2, -4(\$fp)

...



Variable Offsets

```
int f(int x, int y) {  
    int z = x + y;  
    return z;  
}
```

f:

...

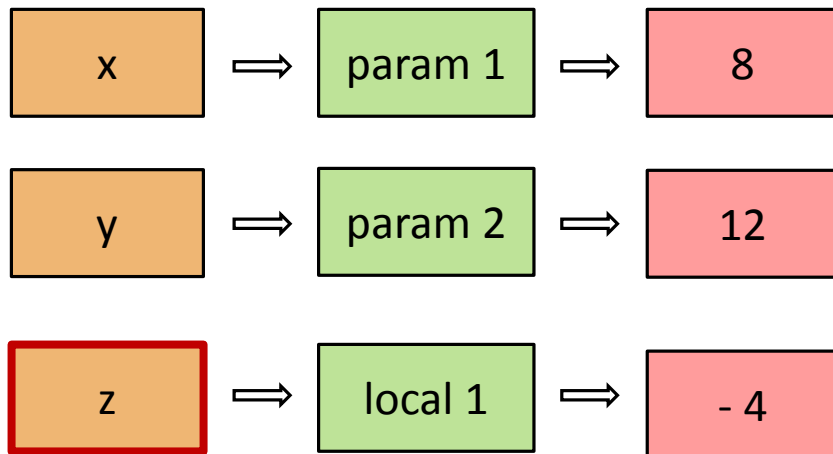
lw \$t0, 8(\$fp)

lw \$t1, 12(\$fp)

add \$t2, \$t0, \$t1

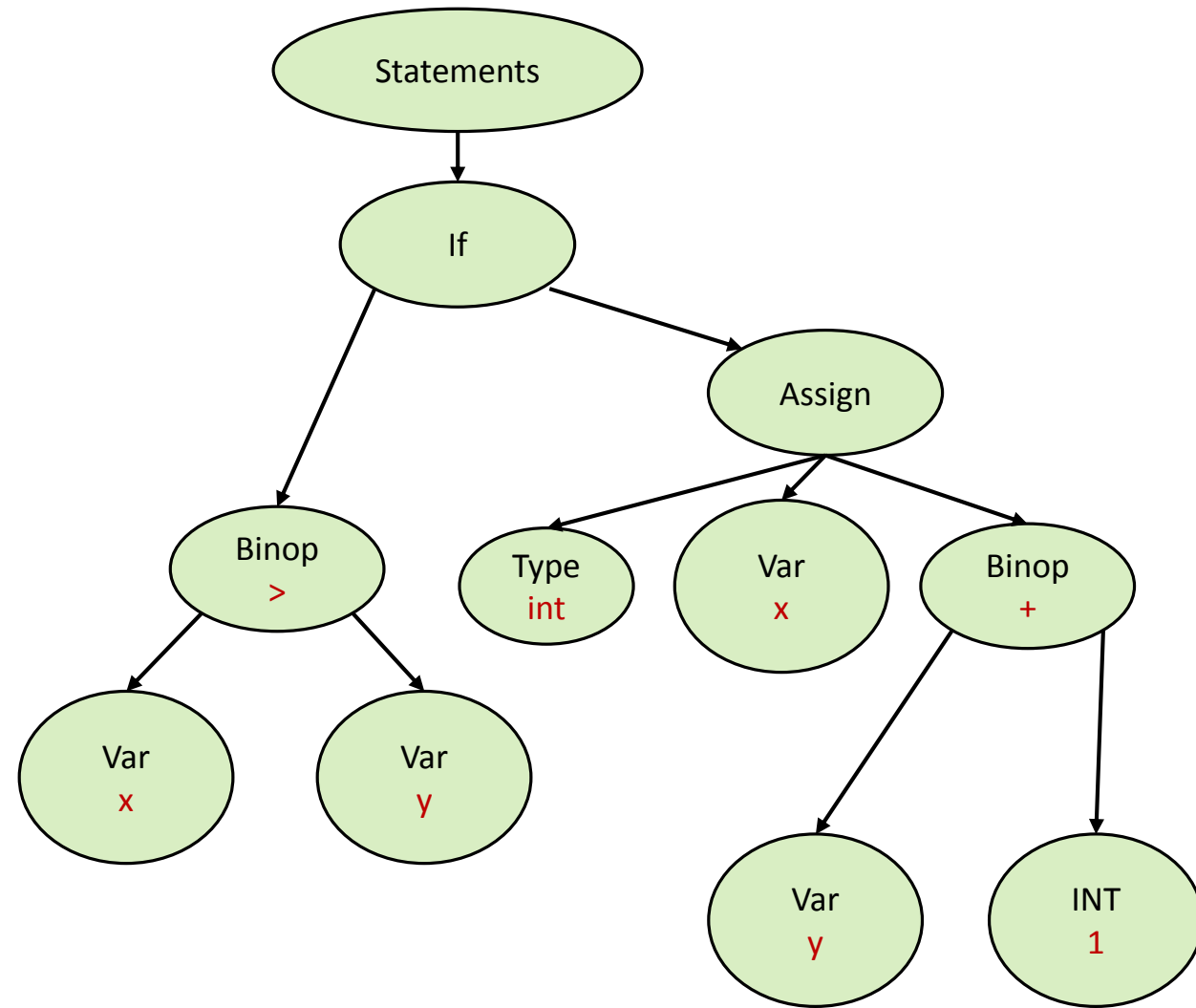
sw \$t2, -4(\$fp)

...



Variable Offsets

```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```



Variable Offsets

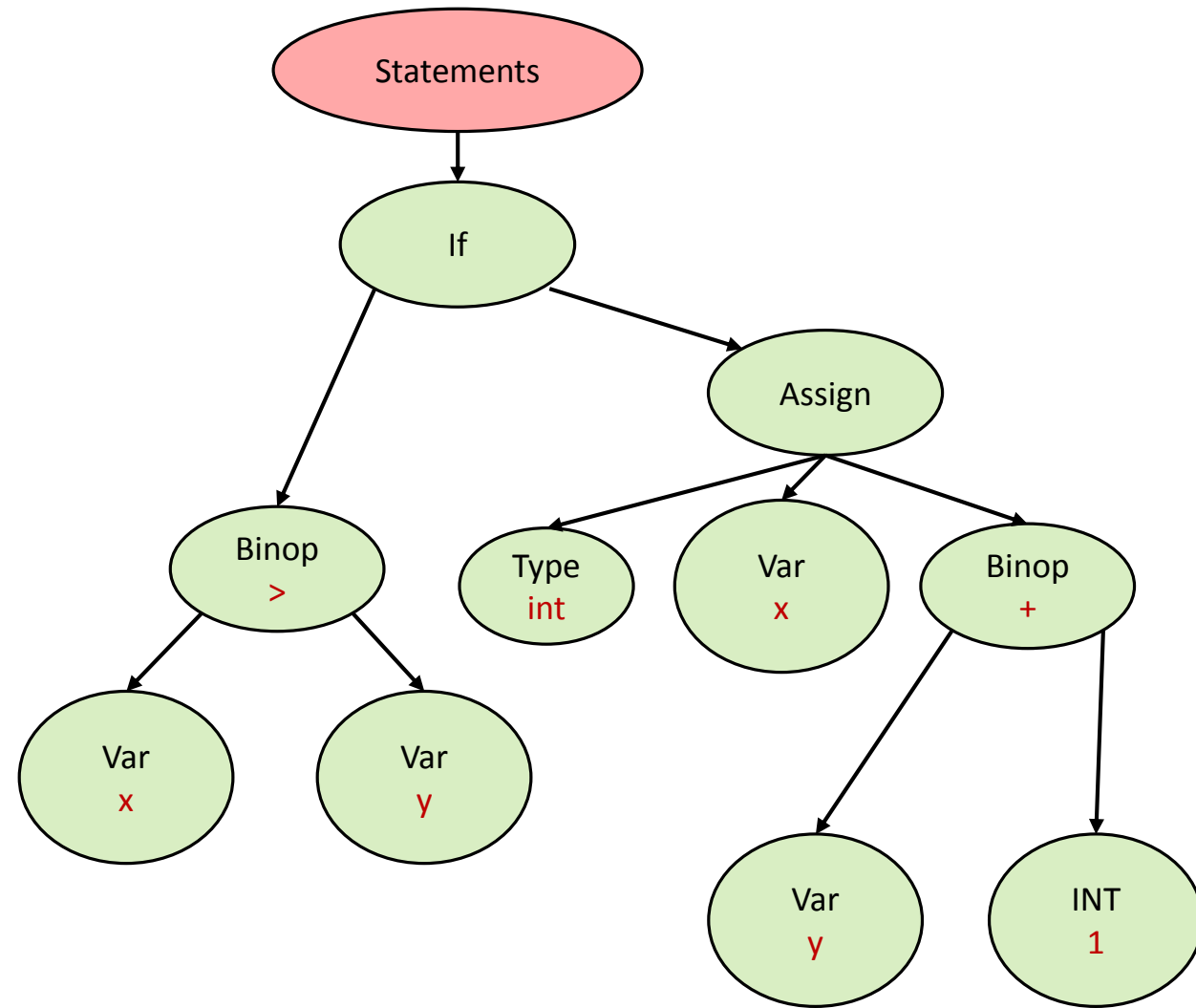
```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```

ID	Type	Kind
...

ID	Type	Kind
x	int	variable
y	int	variable

scope₁

scope₂



Variable Offsets

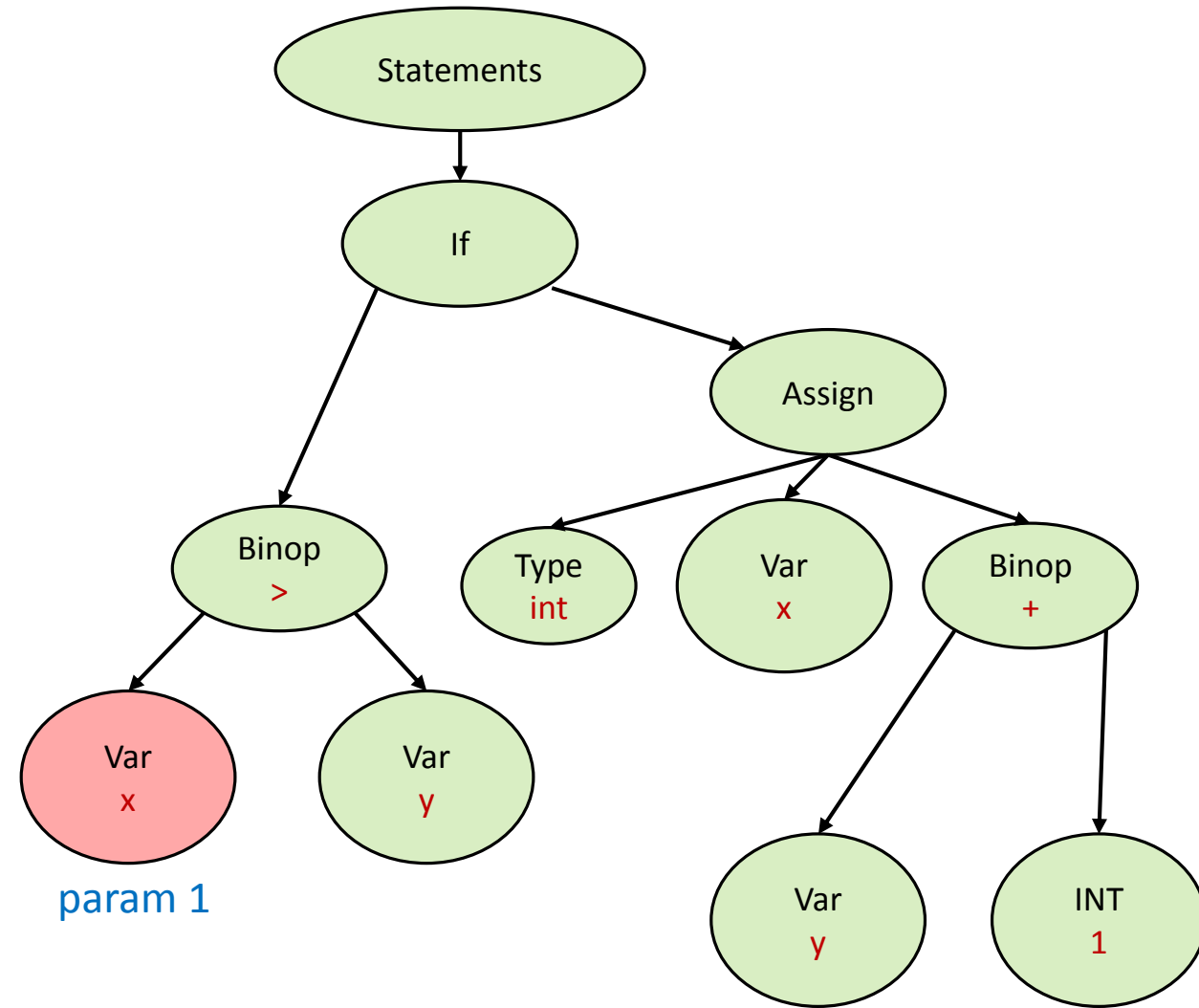
```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```

ID	Type	Kind
...

ID	Type	Kind
x	int	variable
y	int	variable

scope₁

scope₂



Variable Offsets

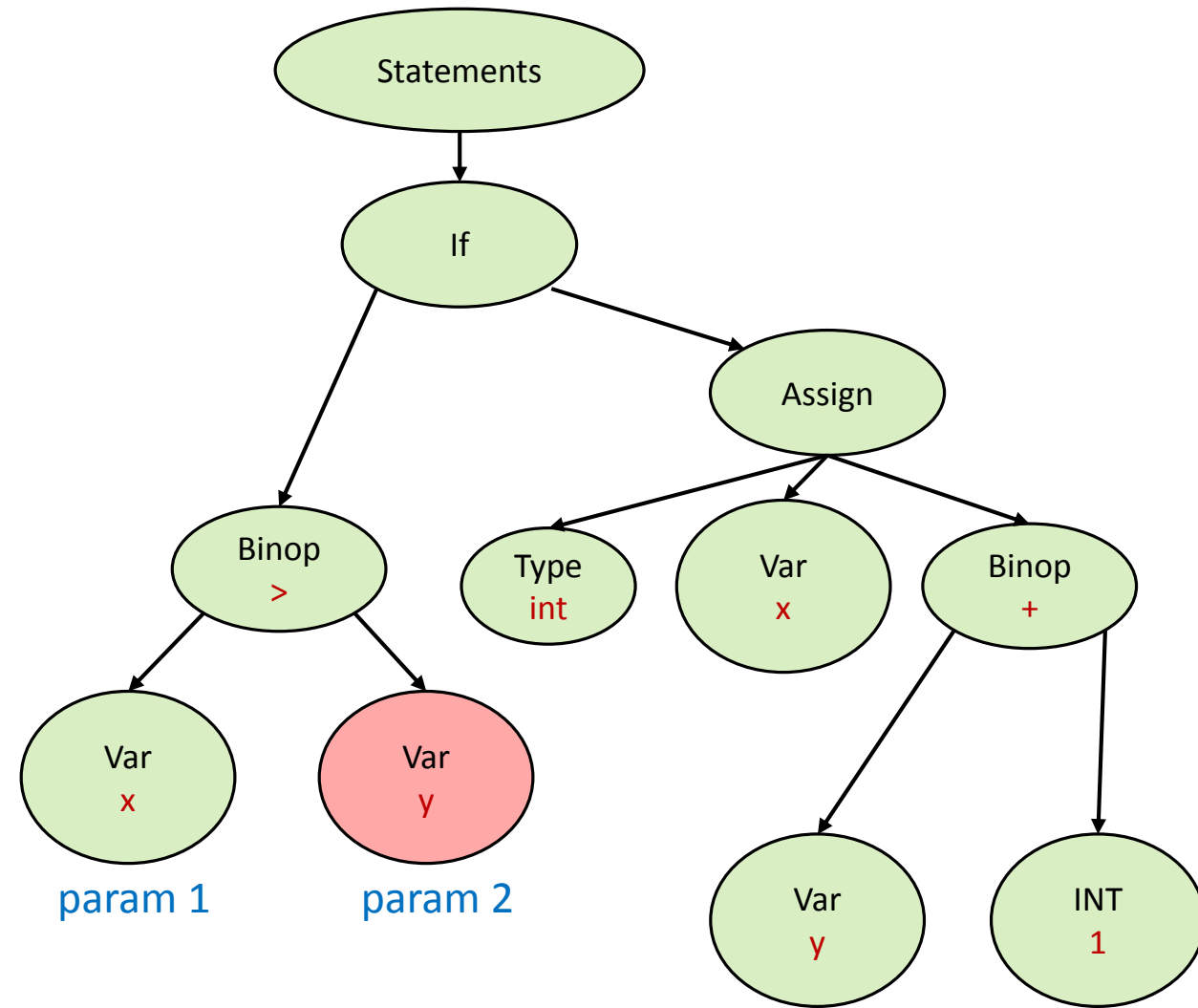
```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```

ID	Type	Kind
...

ID	Type	Kind
x	int	variable
y	int	variable

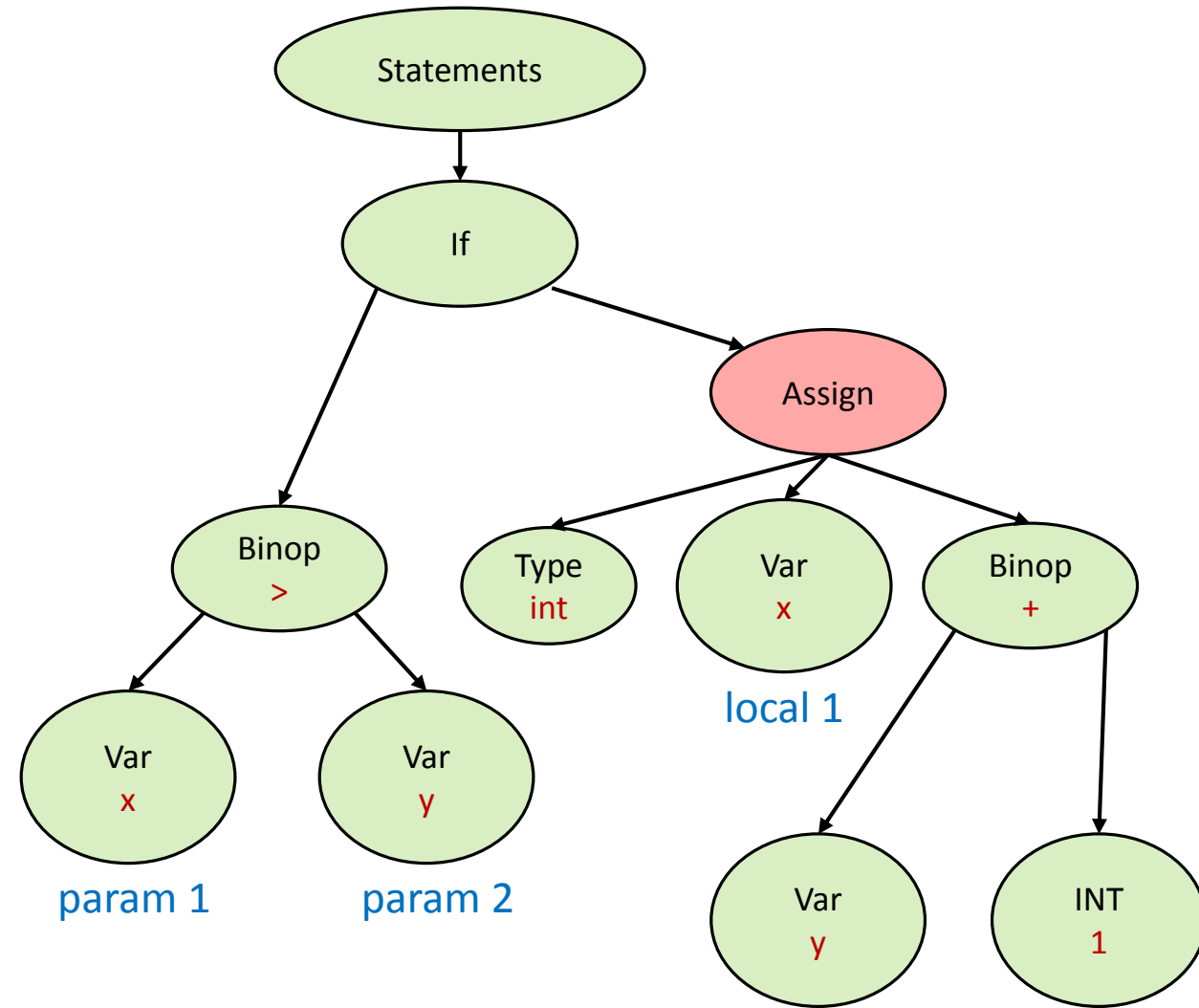
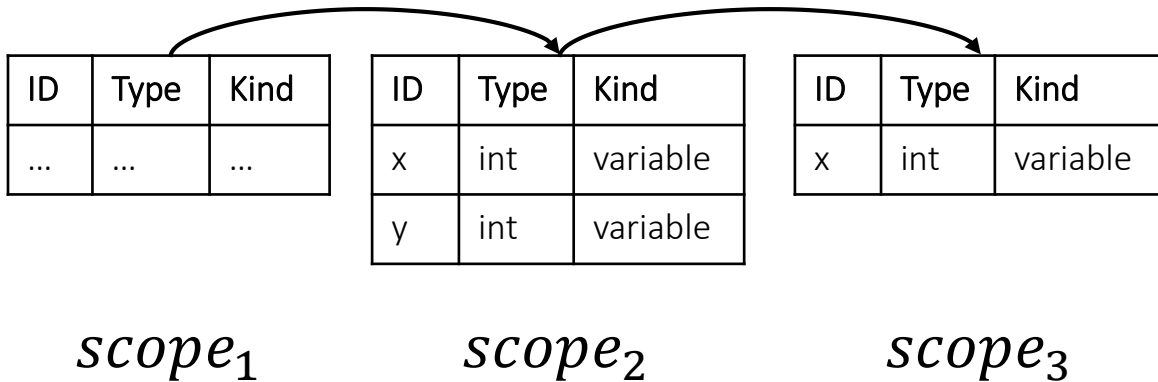
scope₁

scope₂



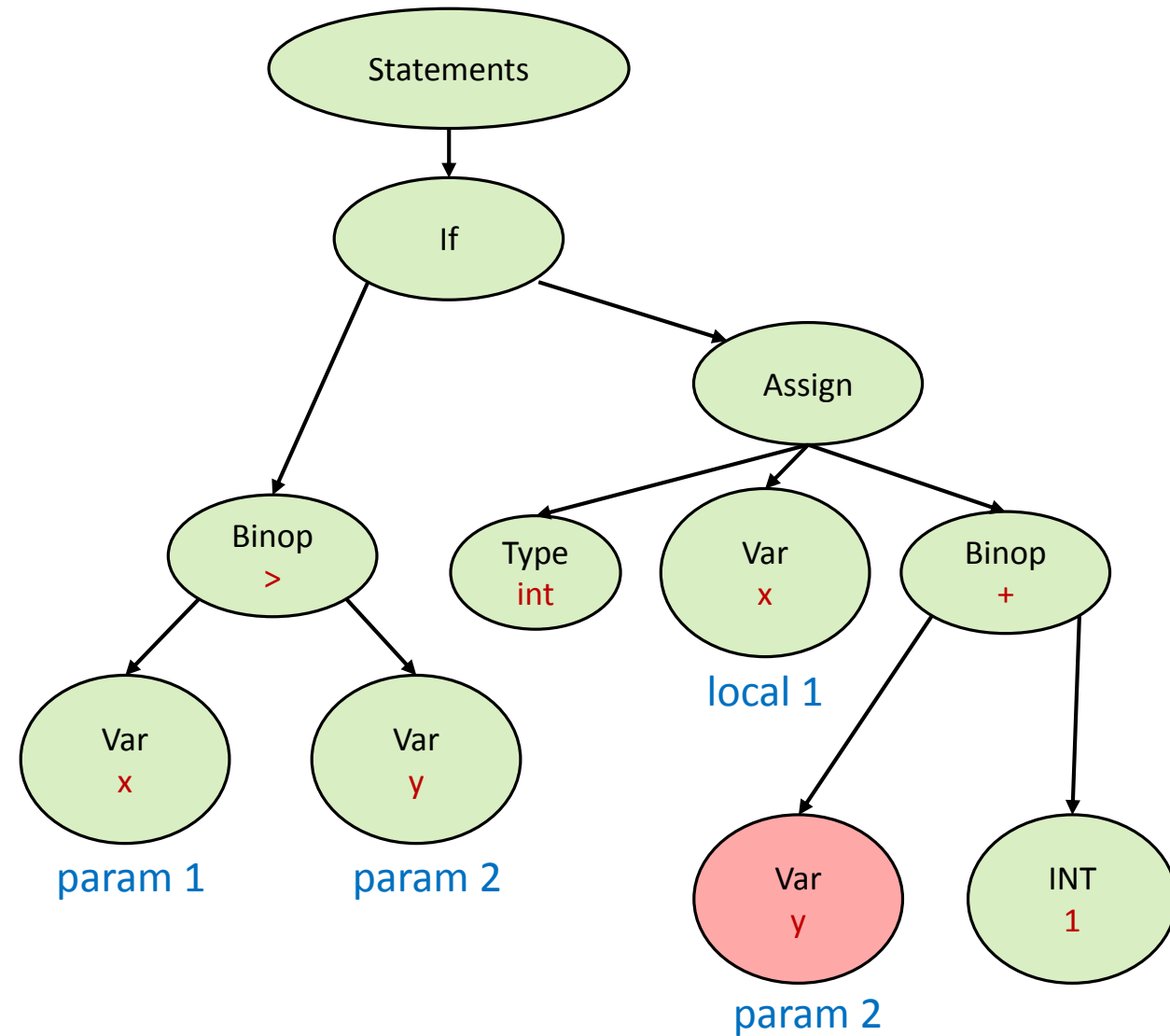
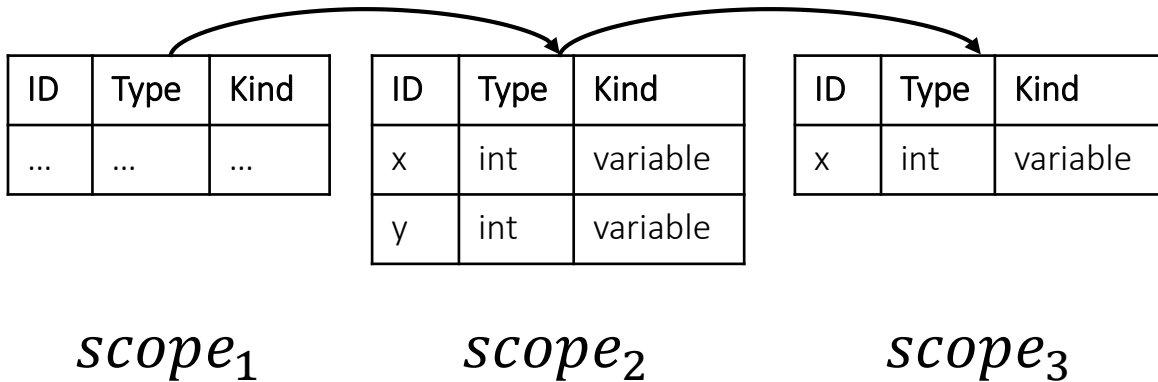
Variable Offsets

```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```



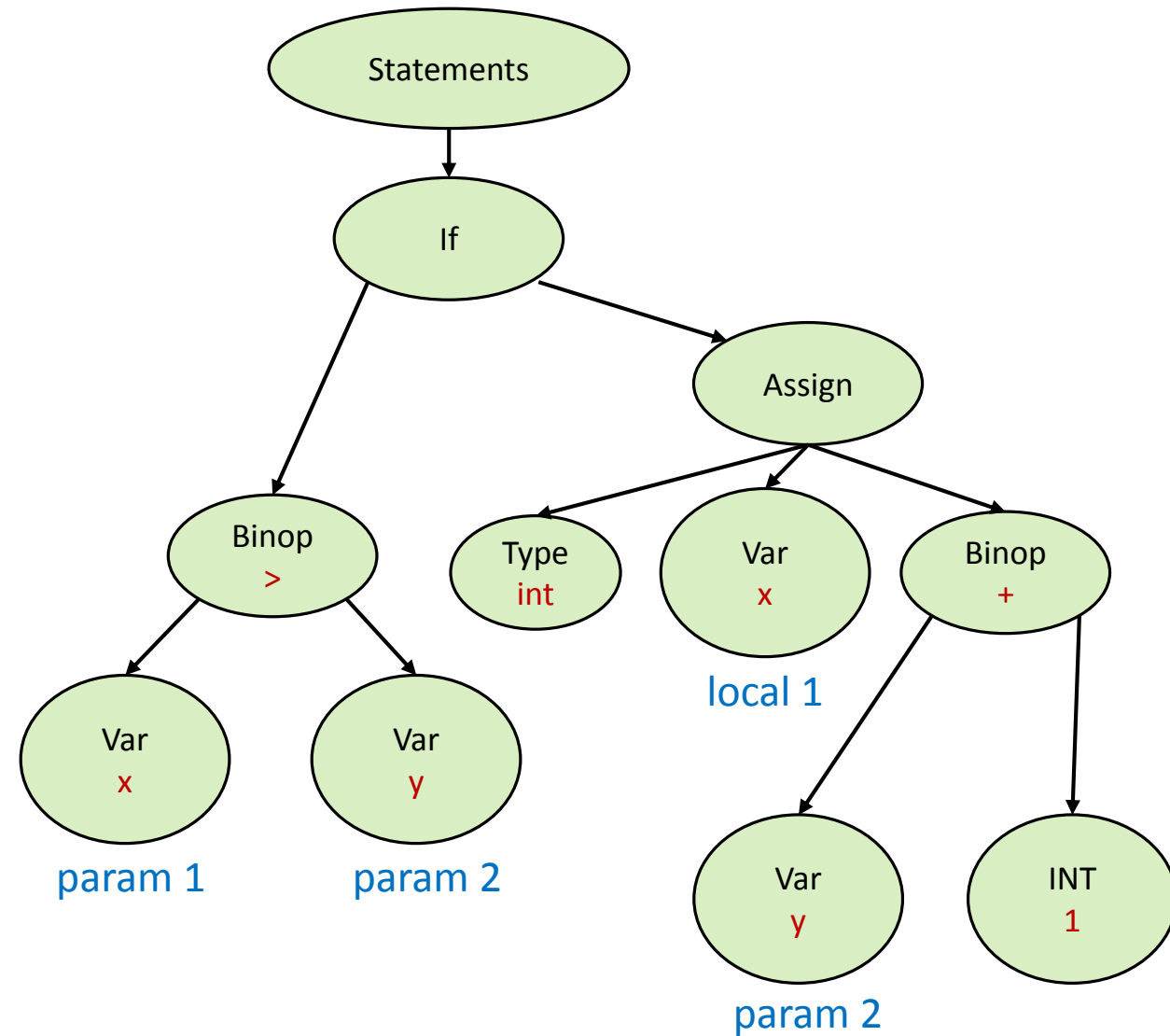
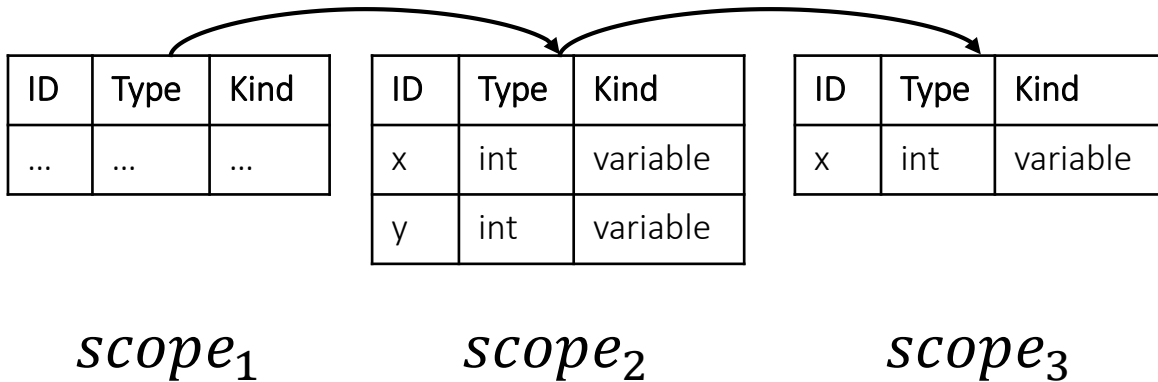
Variable Offsets

```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```



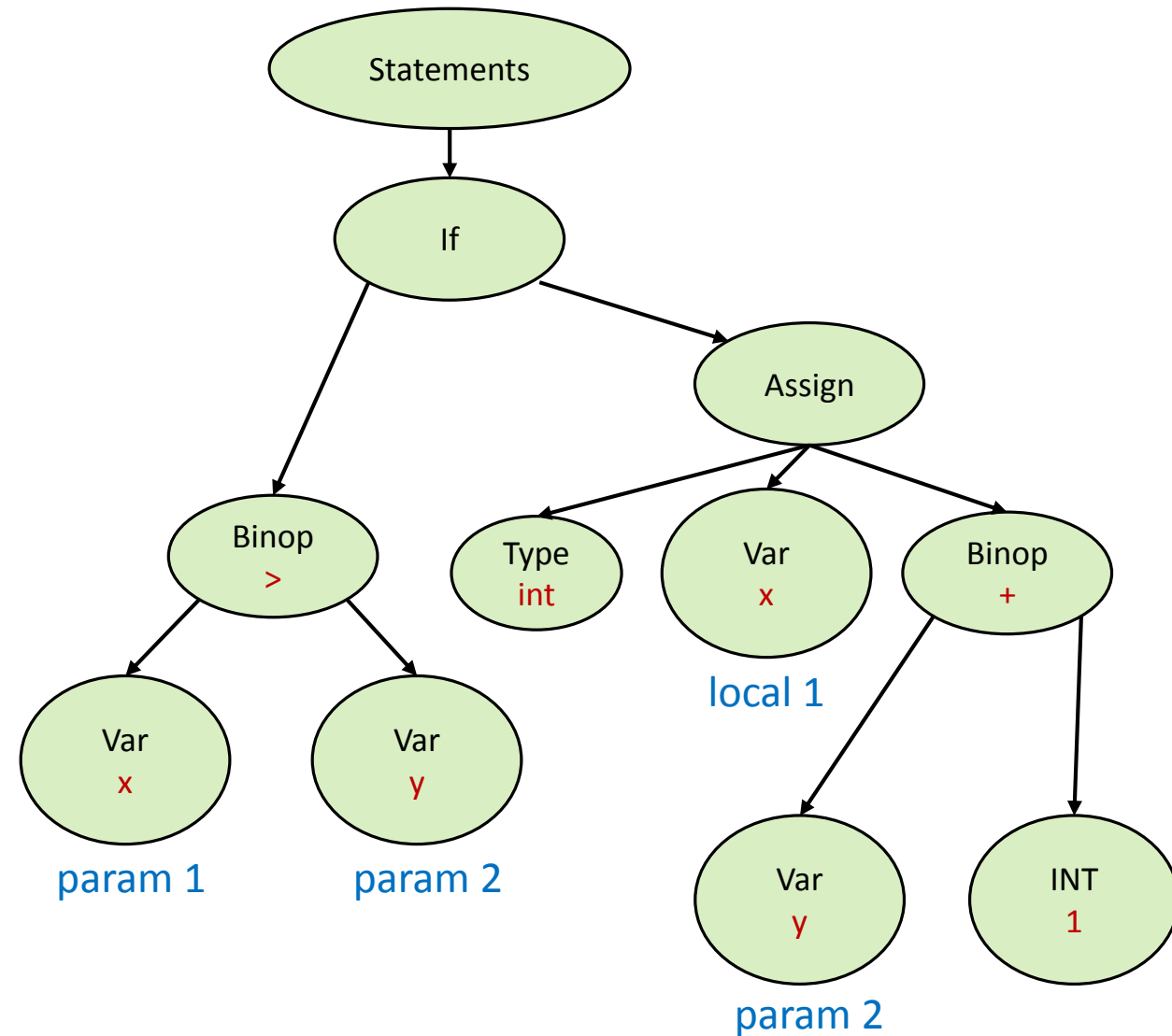
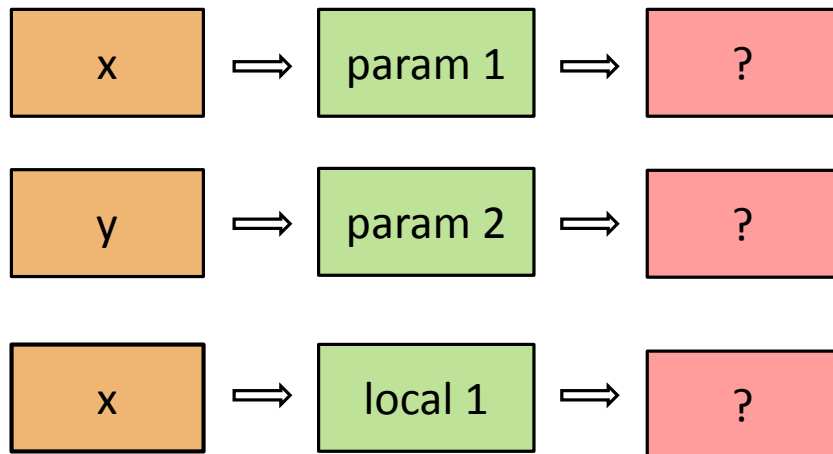
Variable Offsets

```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```



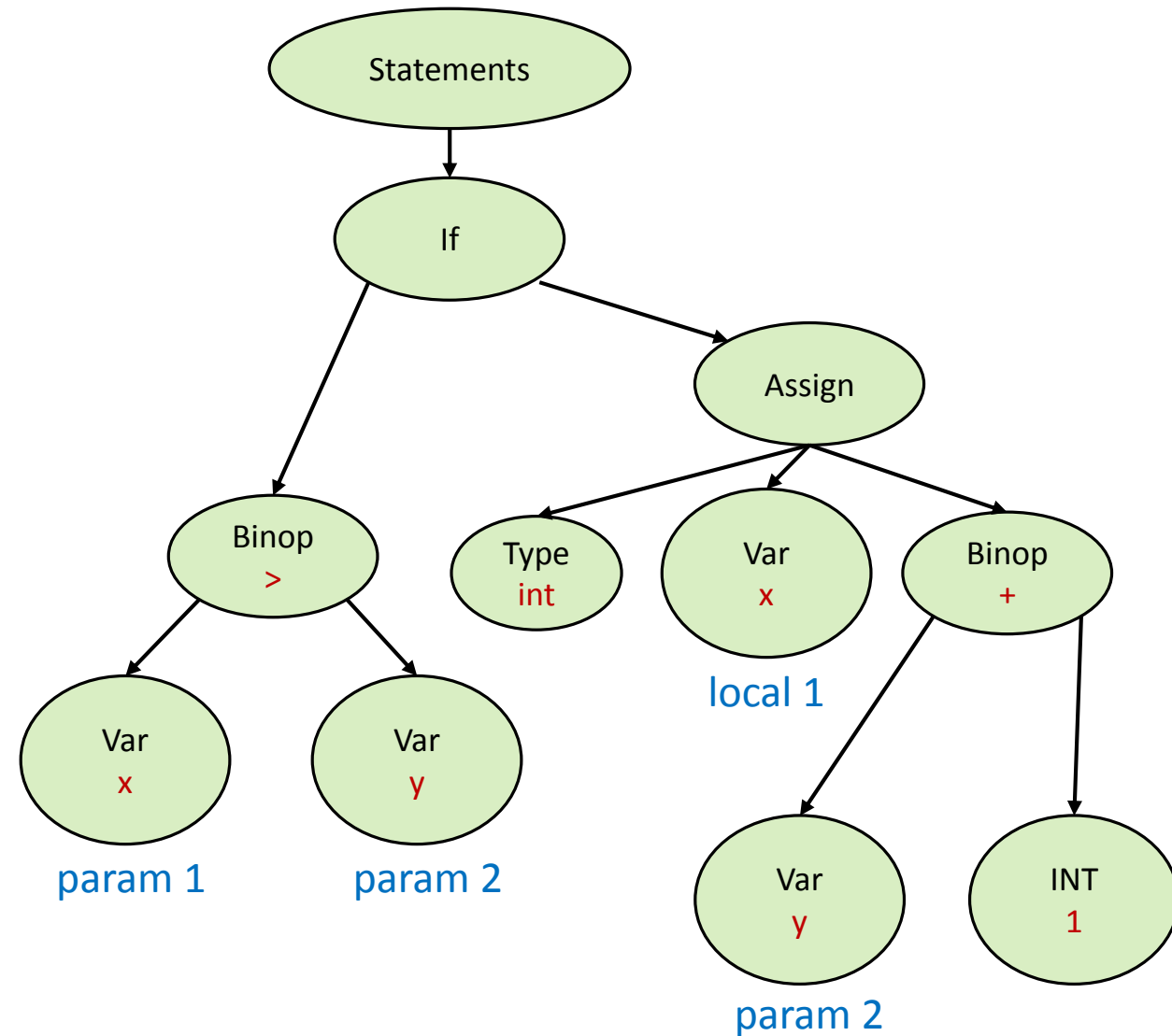
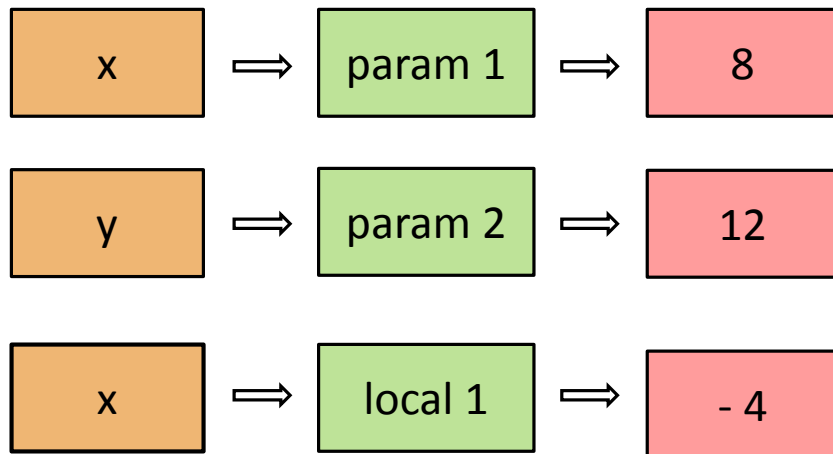
Variable Offsets

```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```



Variable Offsets

```
void f(int x, int y) {  
    if (x > y) {  
        int x = y + 1;  
    }  
}
```



Storing Values

In our language, values can be stored in 32-bit registers:

- type **int** (4 bytes)
- type **string** (4 bytes pointer)
- arrays (4 bytes pointer)
- classes (4 bytes pointer)

Field Offsets

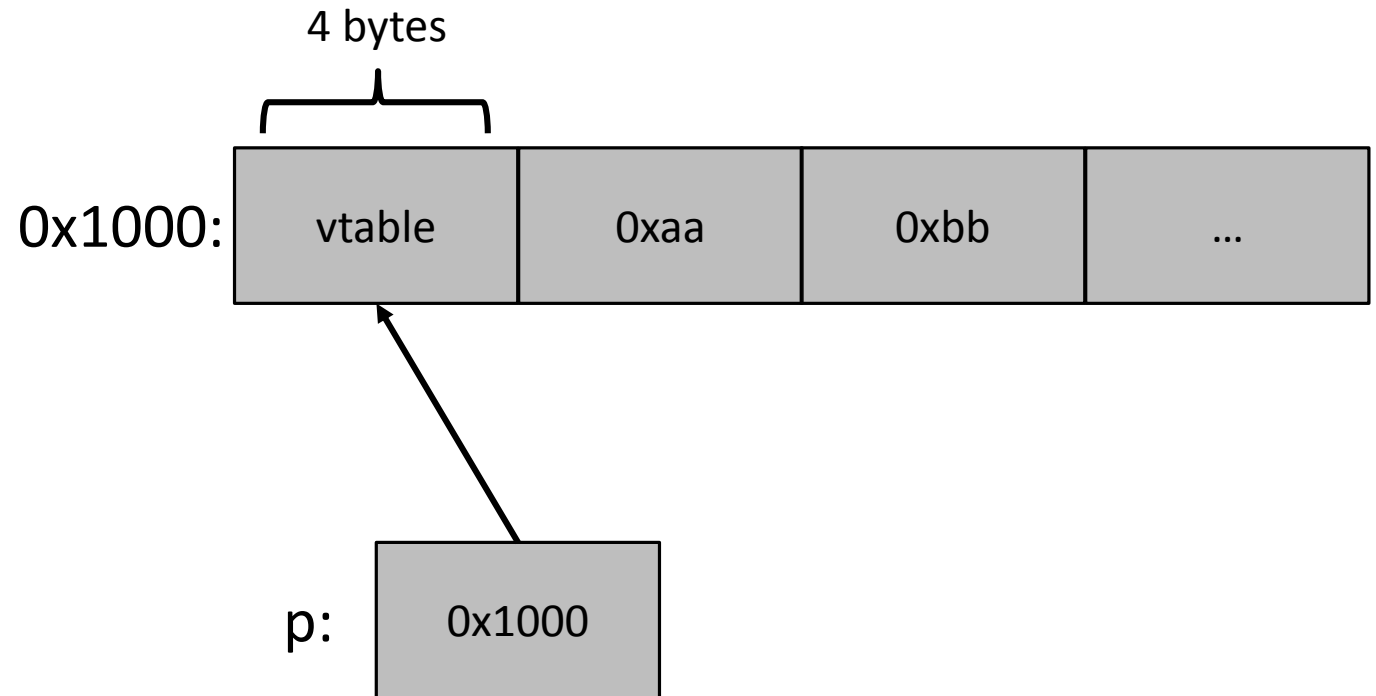
How does an object of this class look in memory?

```
class Point {  
    int x;  
    int y;  
}  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

Field Offsets

How does an object of this class look in memory?

```
class Point {  
    int x;  
    int y;  
}  
  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```



Field Offsets

How does an object of this class look in memory?

```
class Point {  
    int x;  
    int y;  
}  
  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

```
f:  
<prologue>  
lw $t0, 8($fp)  
li $t1, 0xaa  
sw $t1, 4($t0)  
li $t1, 0xbb  
sw $t1, 8($t0)  
<epilogue>
```


Field Offsets

How does an object of this class look in memory?

```
class Point {  
    int x;  
    int y;  
}  
  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

```
f:  
<prologue>  
lw $t0, 8($fp)  
li $t1, 0xaa  
sw $t1, 4($t0)  
li $t1, 0xbb  
sw $t1, 8($t0)  
<epilogue>
```

Field Offsets

How does an object of this class look in memory?

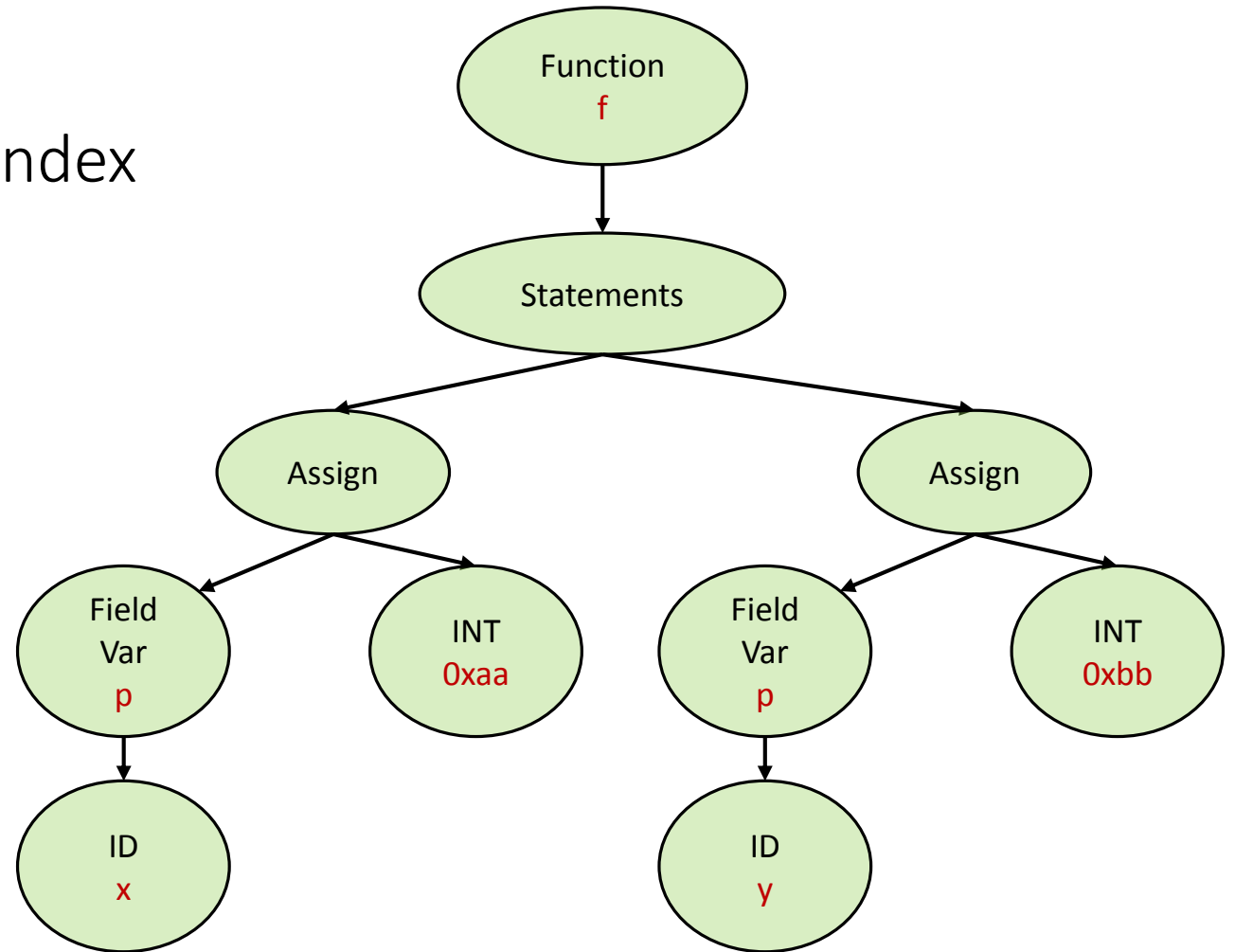
```
class Point {  
    int x;  
    int y;  
}  
  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

```
f:  
<prologue>  
lw $t0, 8($fp)  
li $t1, 0xaa  
sw $t1, 4($t0)  
li $t1, 0xbb  
sw $t1, 8($t0)  
<epilogue>
```

Field Offsets

Each class field should have an index

```
class Point {  
    int x;  
    int y;  
}  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```



Field Offsets

Each class field should have an index

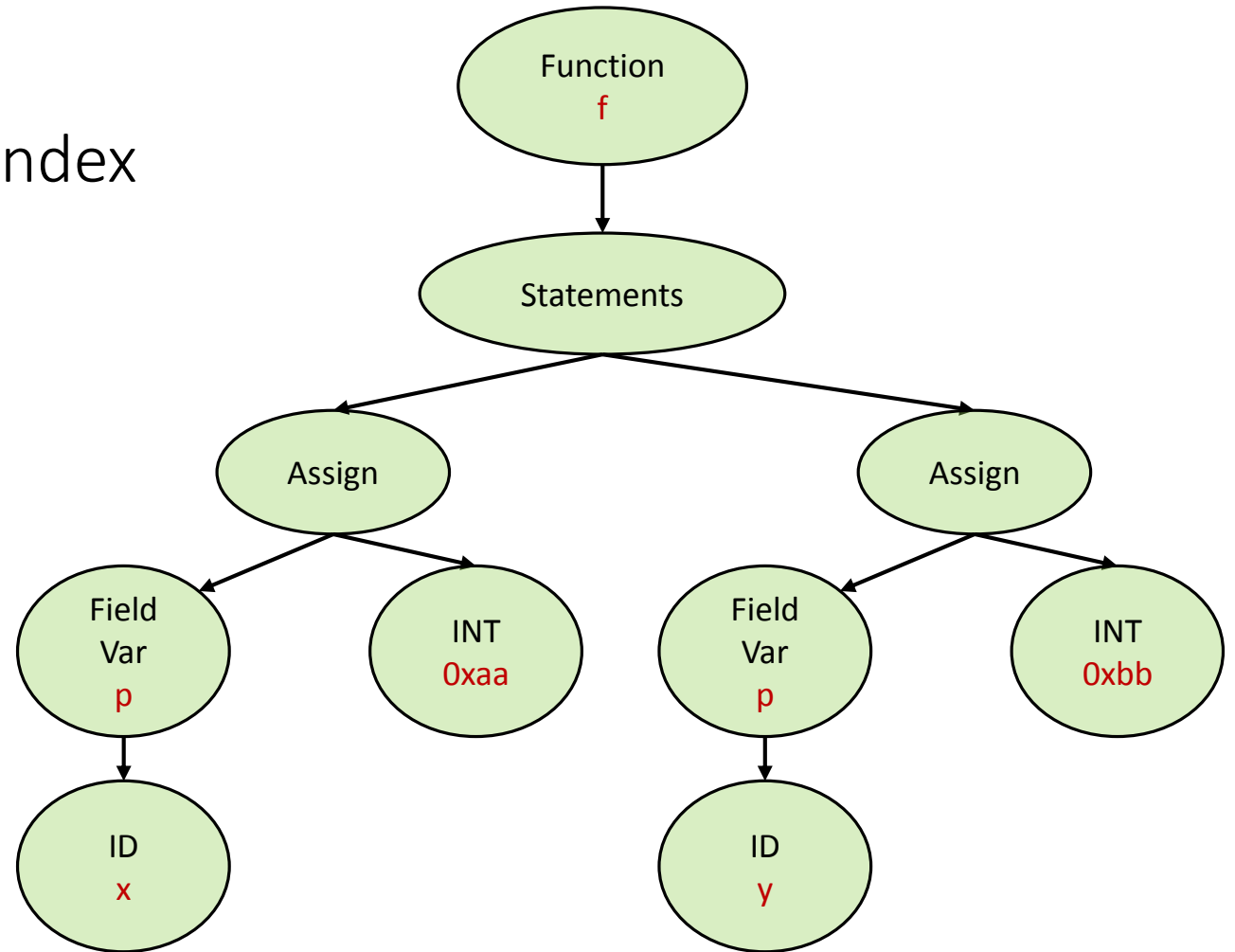
```
class Point {  
    int x;  
    int y;  
}  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

ID	Type	Kind
...

$scope_1$

ID	Type	Kind
p	Point	variable

$scope_2$



Field Offsets

Each class field should have an index

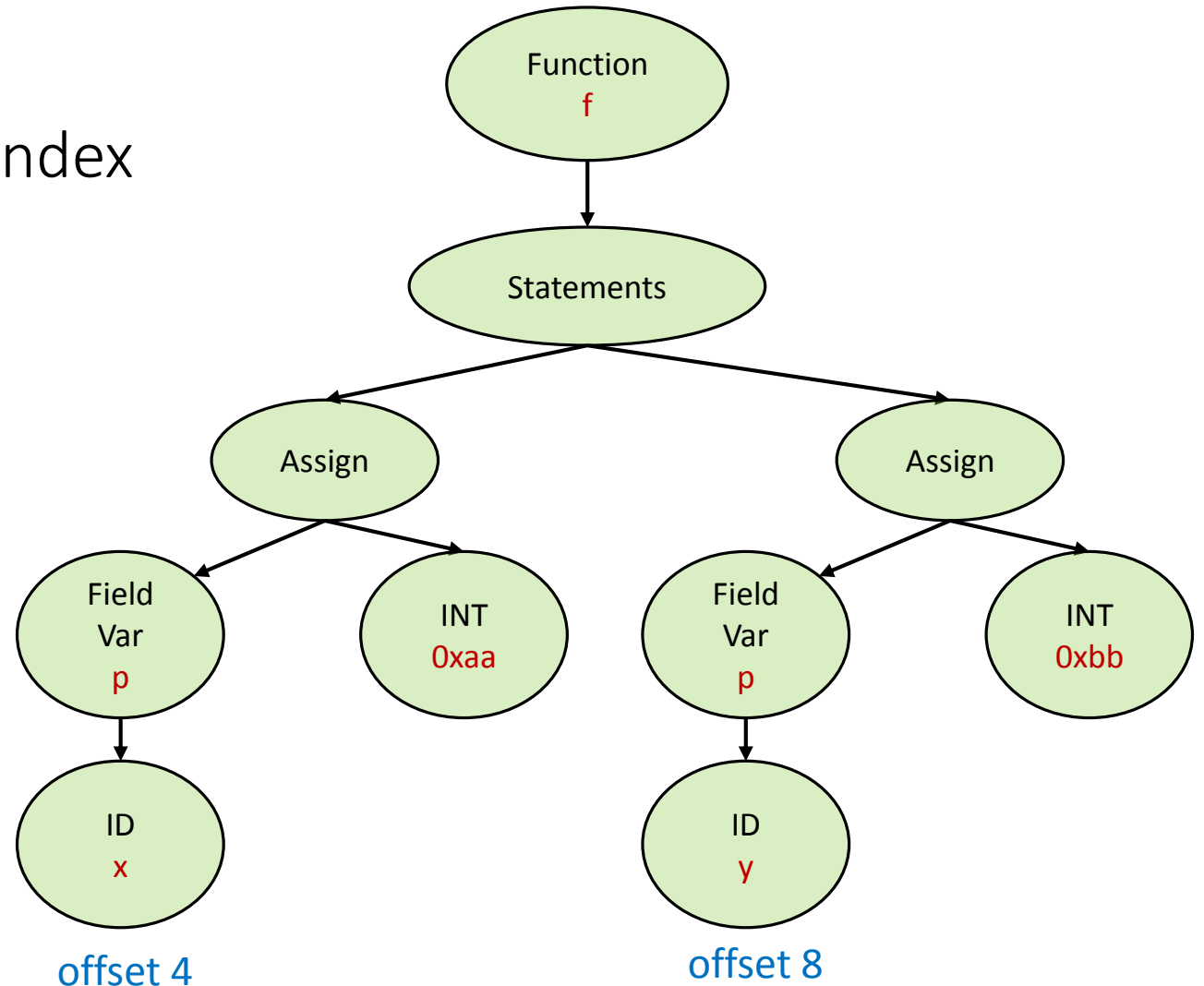
```
class Point {  
    int x;  
    int y;  
}  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

ID	Type	Kind
...

$scope_1$

ID	Type	Kind
p	Point	variable

$scope_2$



Type Sizes

```
class Point {  
    int x;  
    int y;  
}  
void f() {  
    Point p = new Point;  
}
```

```
f:  
<prologue>  
li $t0, 12  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
jal malloc  
addu $sp, $sp, 4  
sw $v0, -4($fp)  
<epilogue>
```

Type Sizes

```
class Point {  
    int x;  
    int y;  
}  
void f() {  
    Point p = new Point;  
}
```

```
f:  
<prologue>  
li $t0, 12  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
jal malloc  
addu $sp, $sp, 4  
sw $v0, -4($fp)  
<epilogue>
```

Type Sizes

```
class Point {  
    int x;  
    int y;  
    string name;  
}  
void f() {  
    Point p = new Point;  
}
```

```
f:  
<prologue>  
li $t0, ?  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
jal malloc  
addu $sp, $sp, 4  
sw $v0, -4($fp)  
<epilogue>
```


Type Sizes

```
class Point {  
    int x;  
    int y;  
    string name;  
}  
void f() {  
    Point p = new Point;  
}
```

```
f:  
<prologue>  
li $t0, 16  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
jal malloc  
addu $sp, $sp, 4  
sw $v0, -4($fp)  
<epilogue>
```