

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):

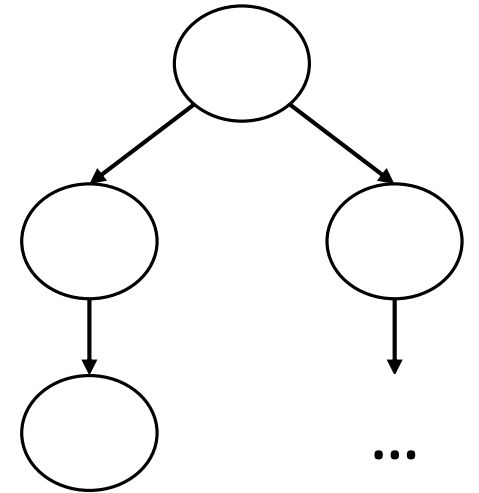
// do something with node

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

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

...

// 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

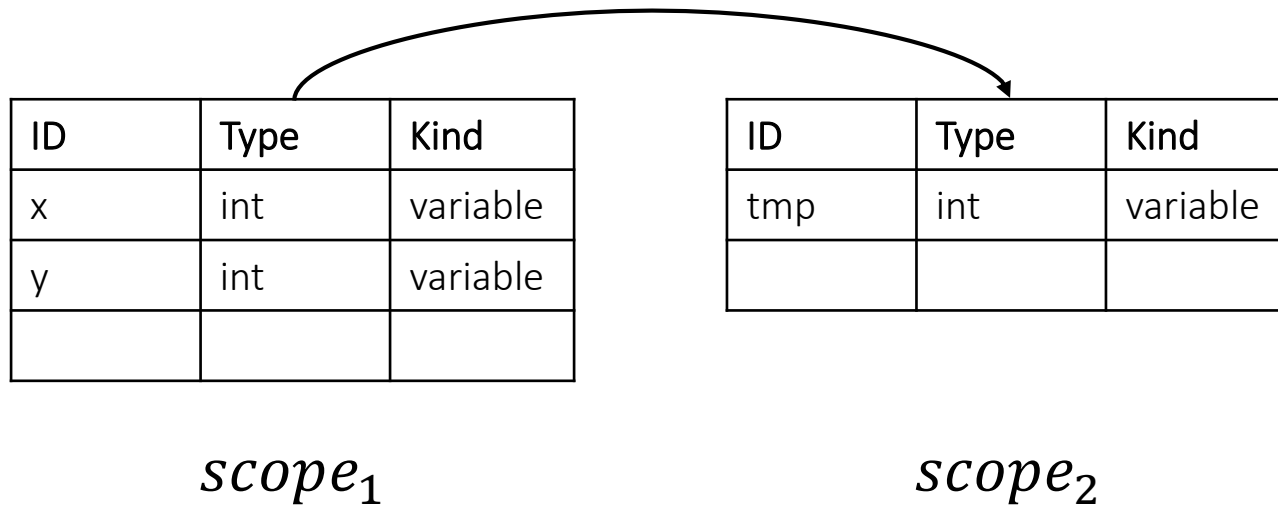


Symbol Table: Lookup

Example:

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

main scope

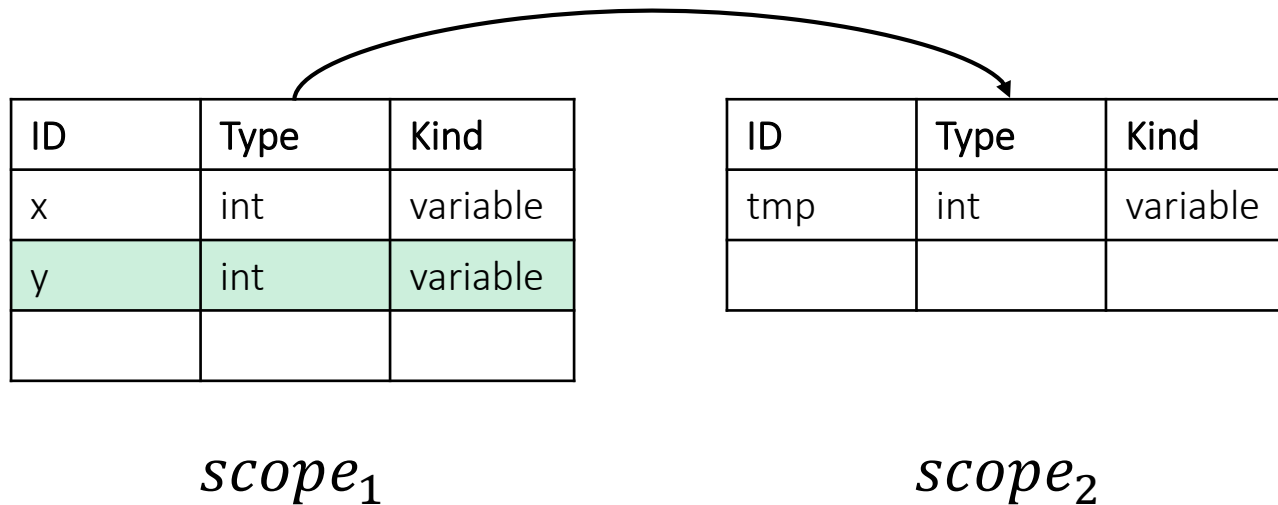


Symbol Table: Lookup

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

$scope_1$

ID	Type	Kind
tmp	int	variable

$scope_2$



Symbol Table: Exit

main scope

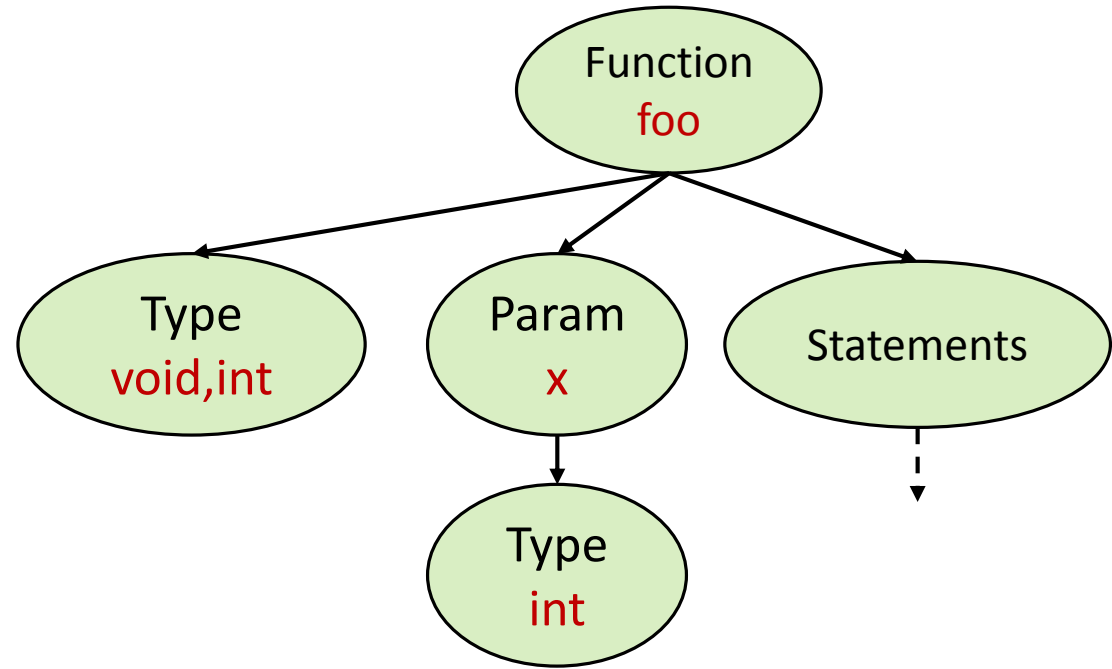
ID	Type	Kind
x	int	variable
y	int	variable

scope₁

Symbol Table Construction

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

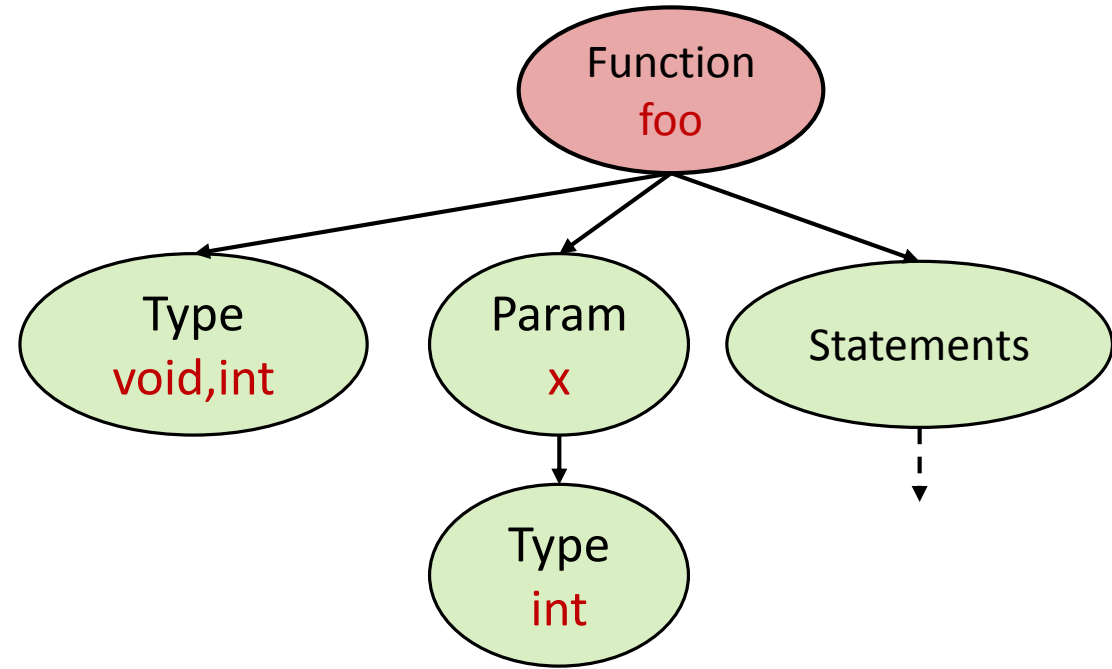

```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```





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

ID	Type	Kind
foo	void,int	function

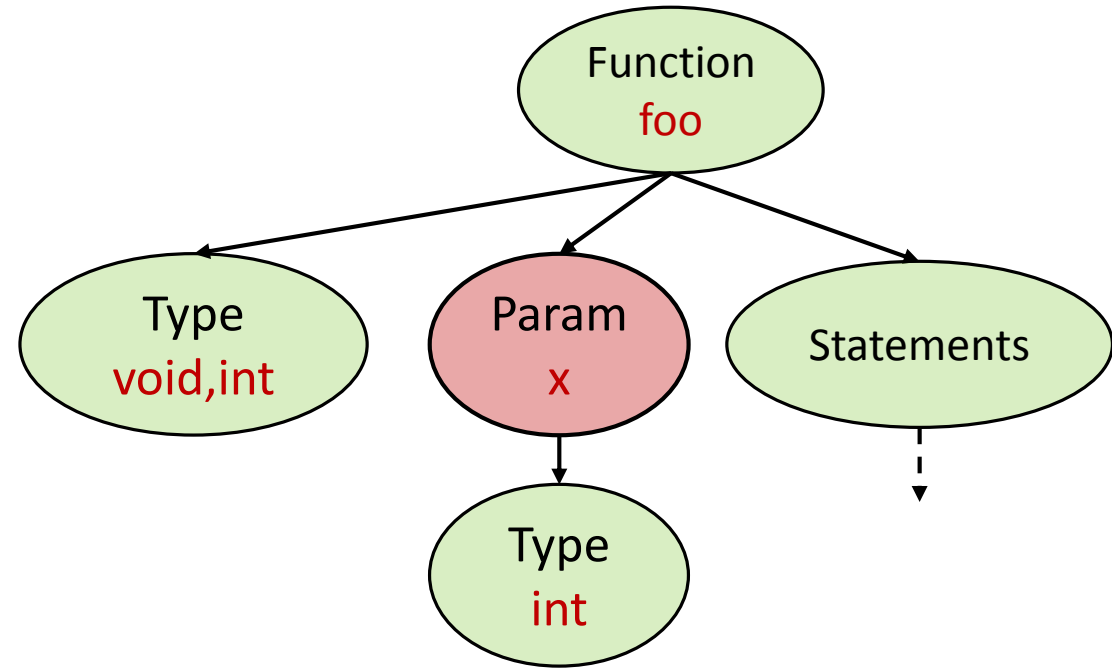




```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable

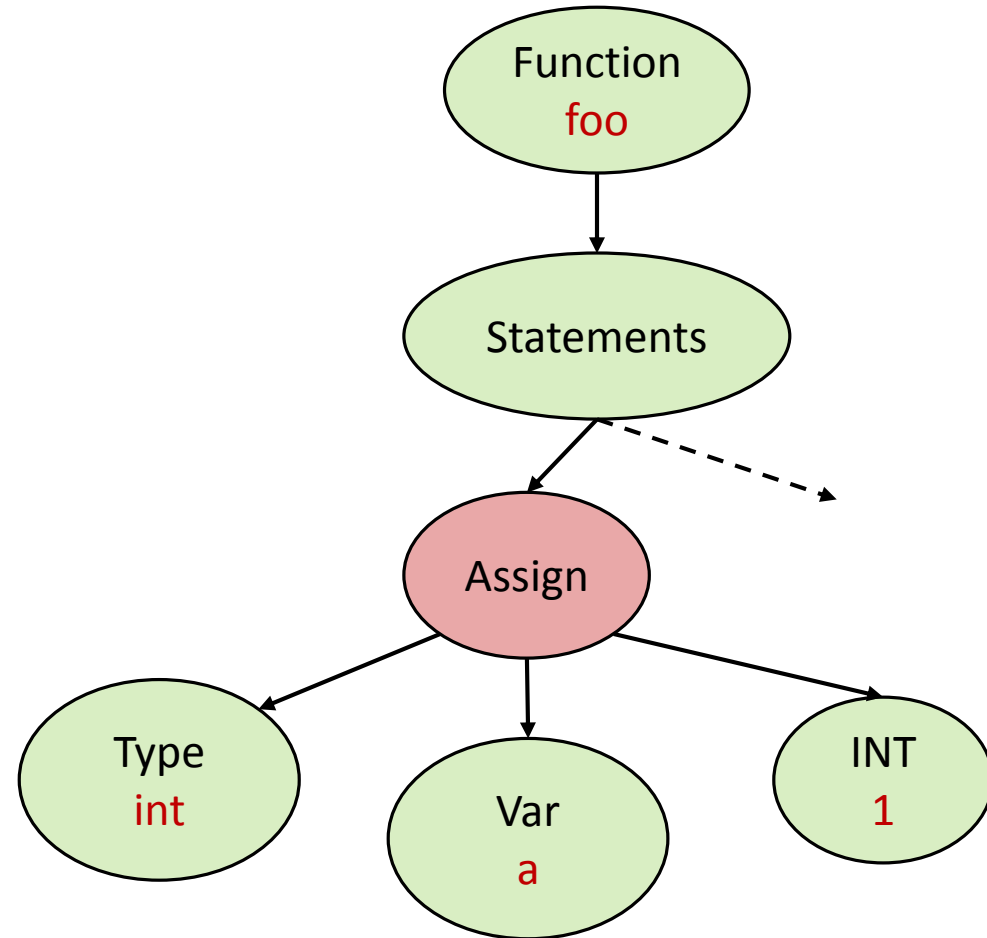




```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

ID	Type	Kind
x	int	variable
a	int	variable

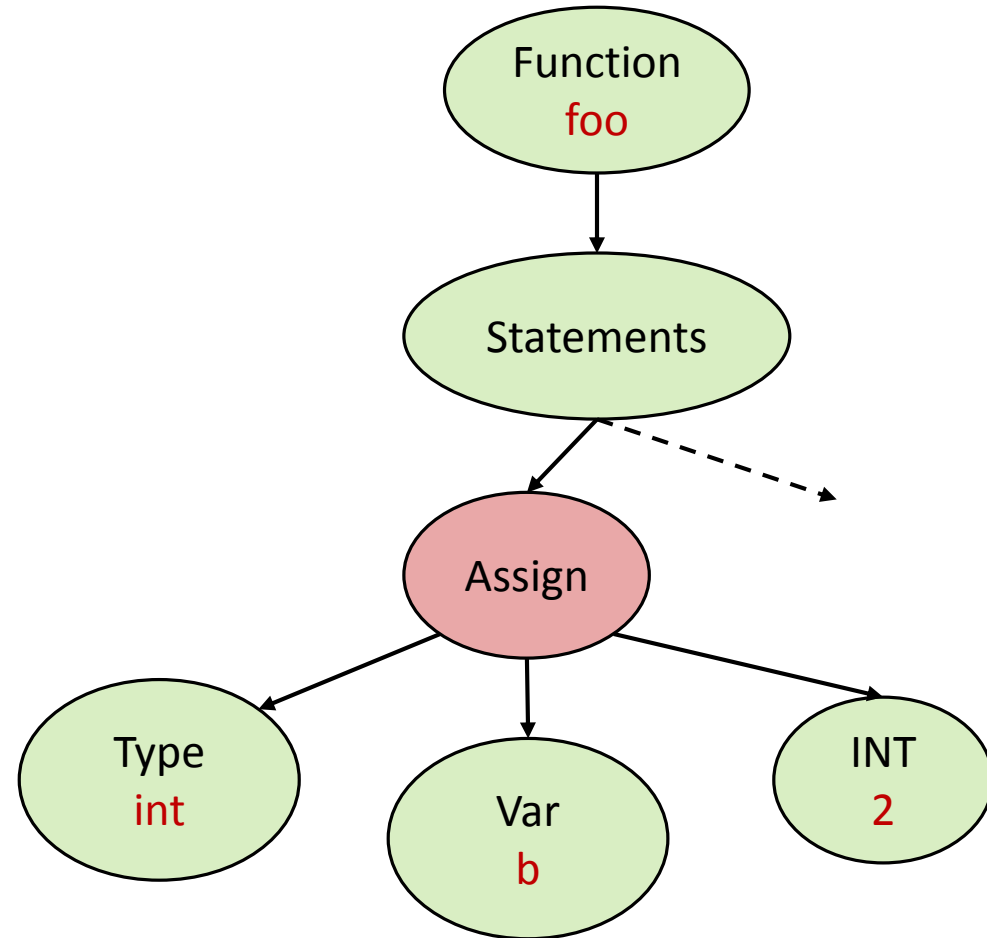




```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

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



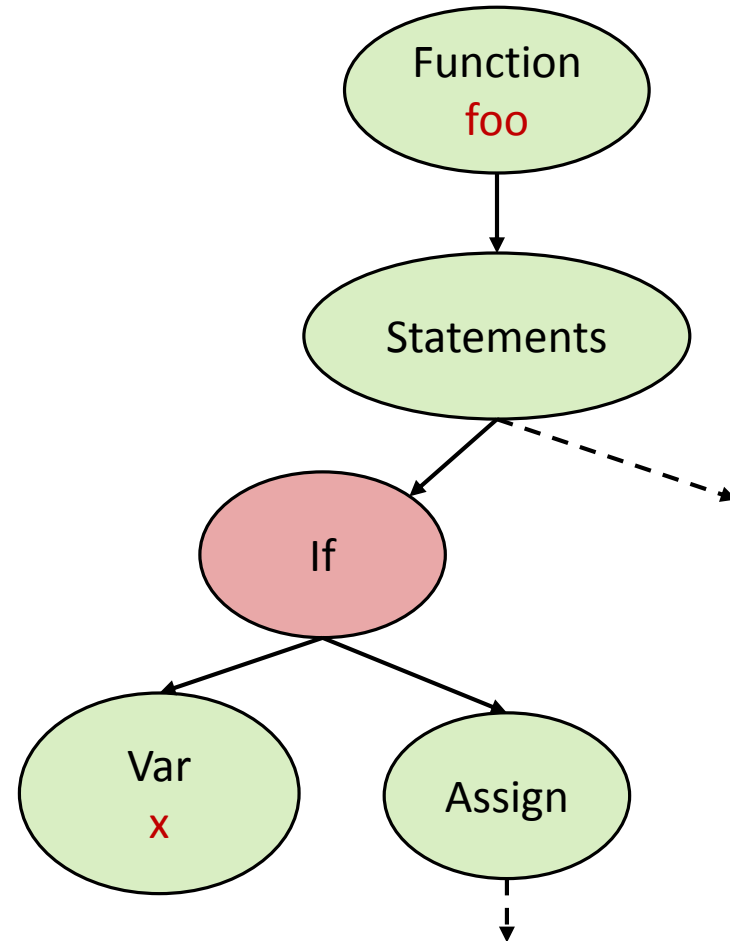


```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

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

ID	Type	Kind



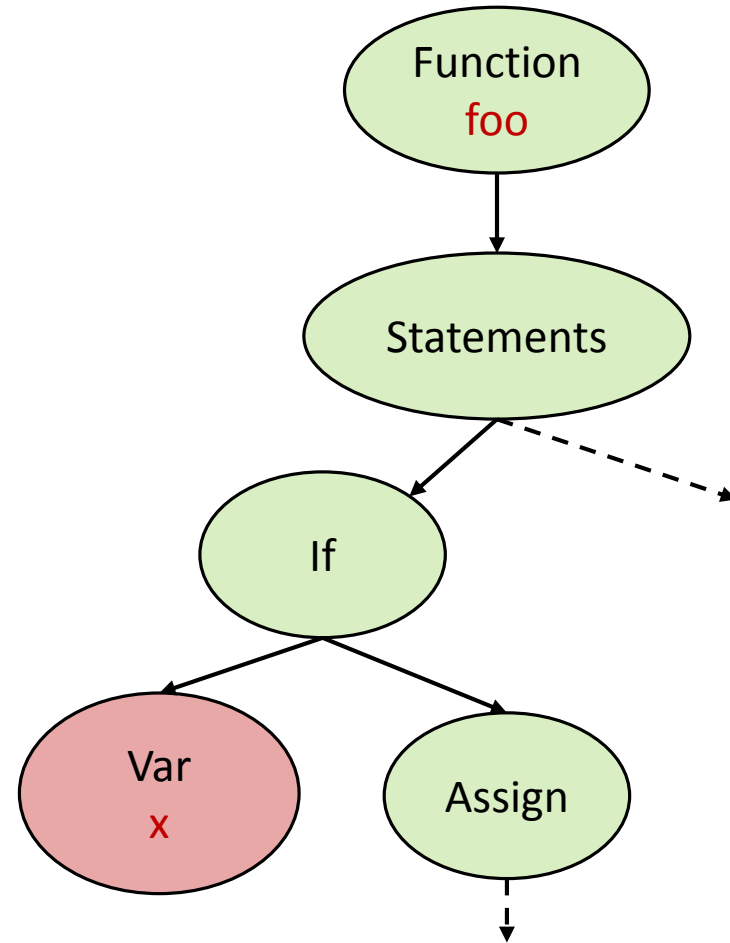


```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

ID	Type	Kind
foo	void,int	function

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

ID	Type	Kind



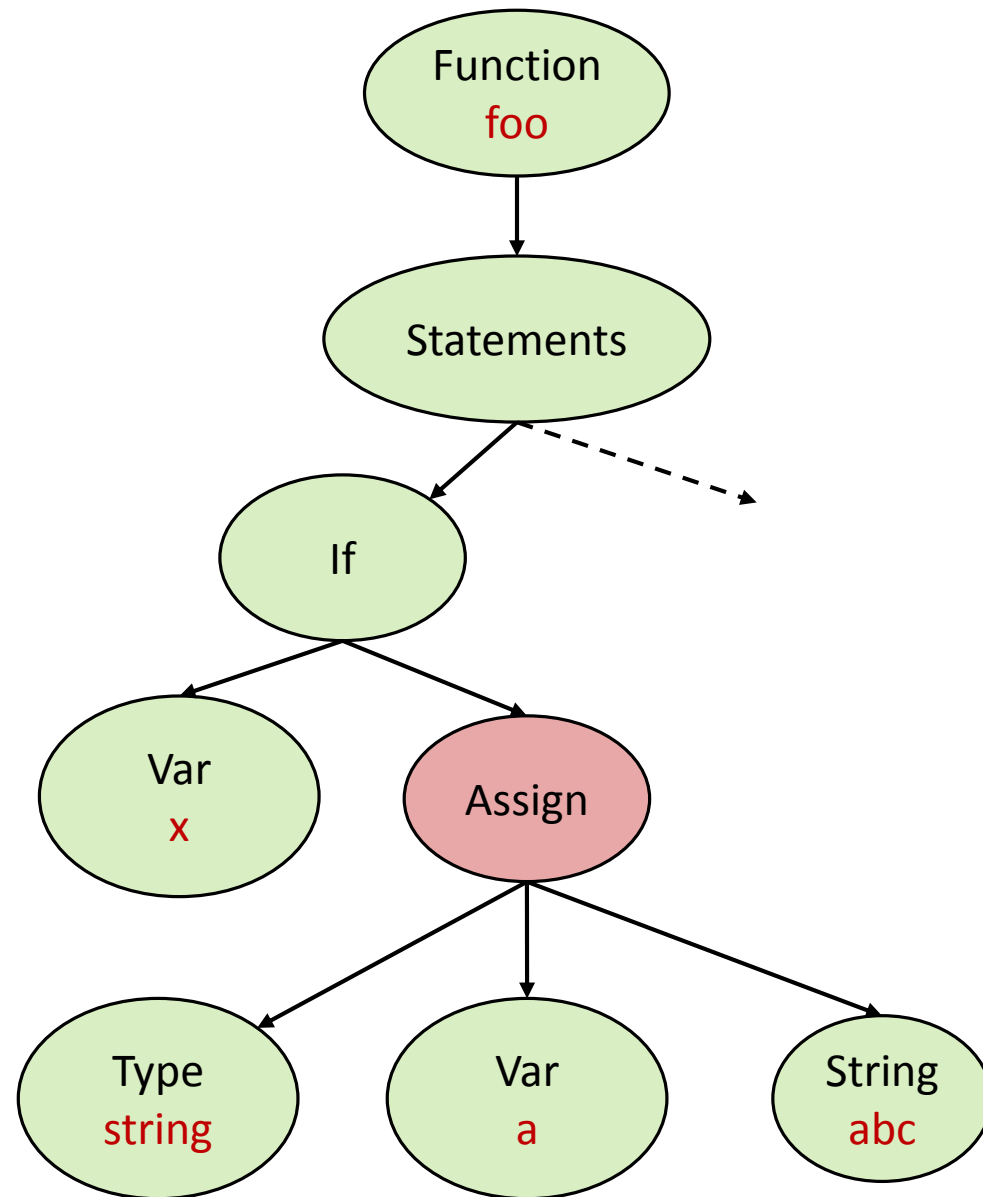


```
void foo(int x) {  
    int a = 1;  
    int b = 2;  
    if (x) {  
        string a = "abc";  
    }  
}
```

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



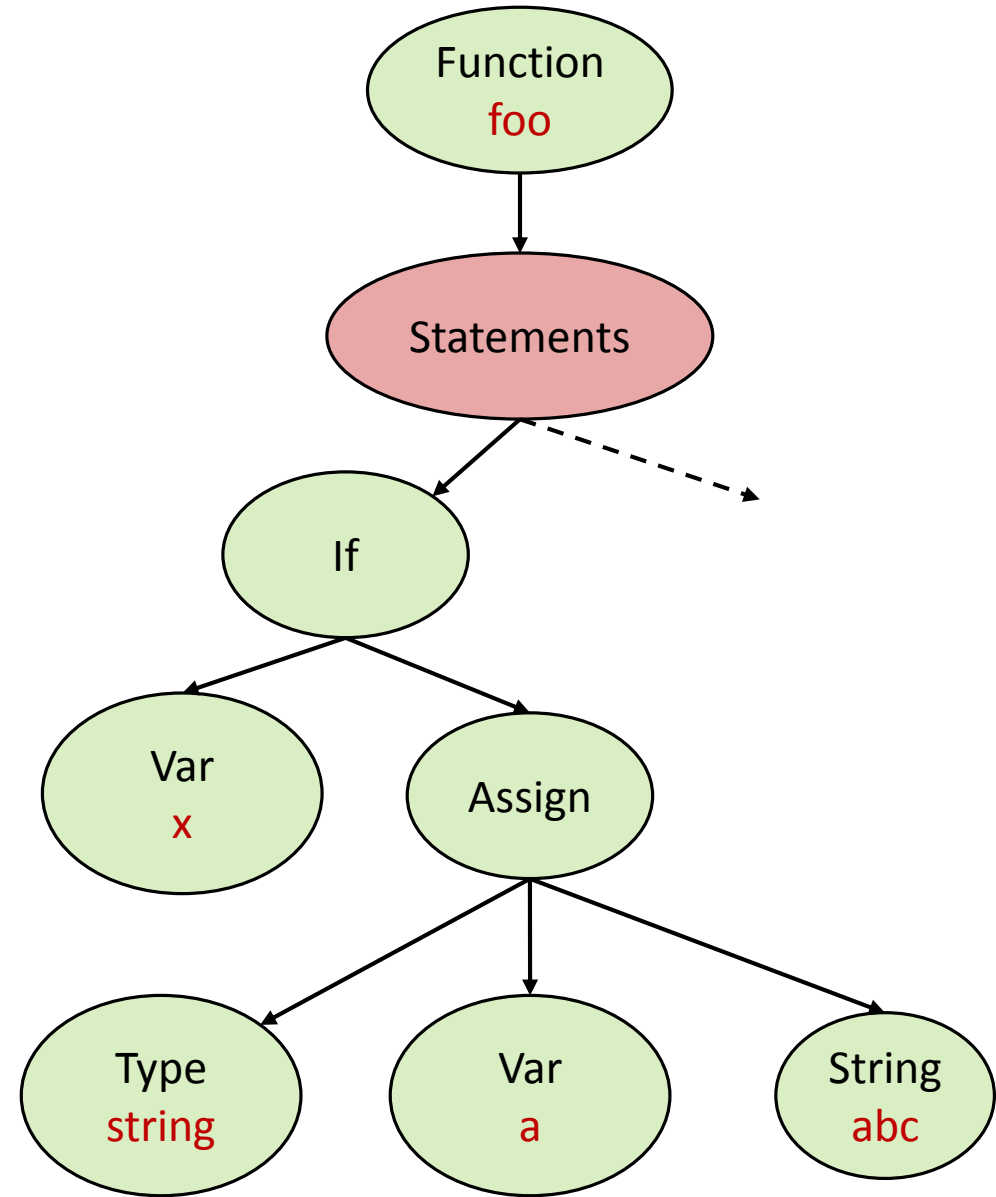

```

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

```

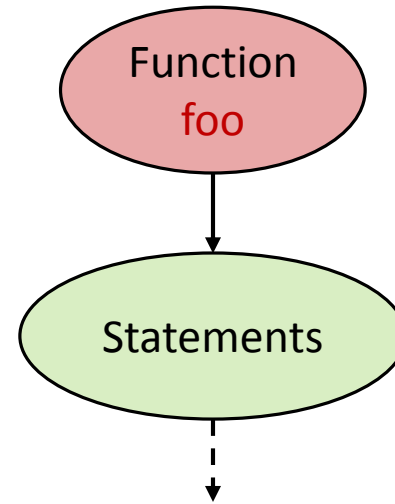
ID	Type	Kind
foo	void,int	function

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):

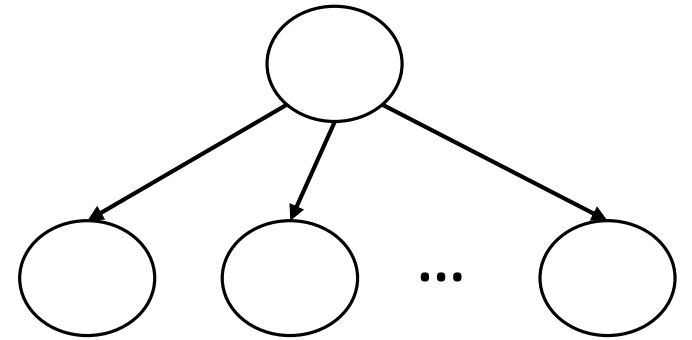
$t_1 = \text{visit}(\text{node.child}_1)$

...

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

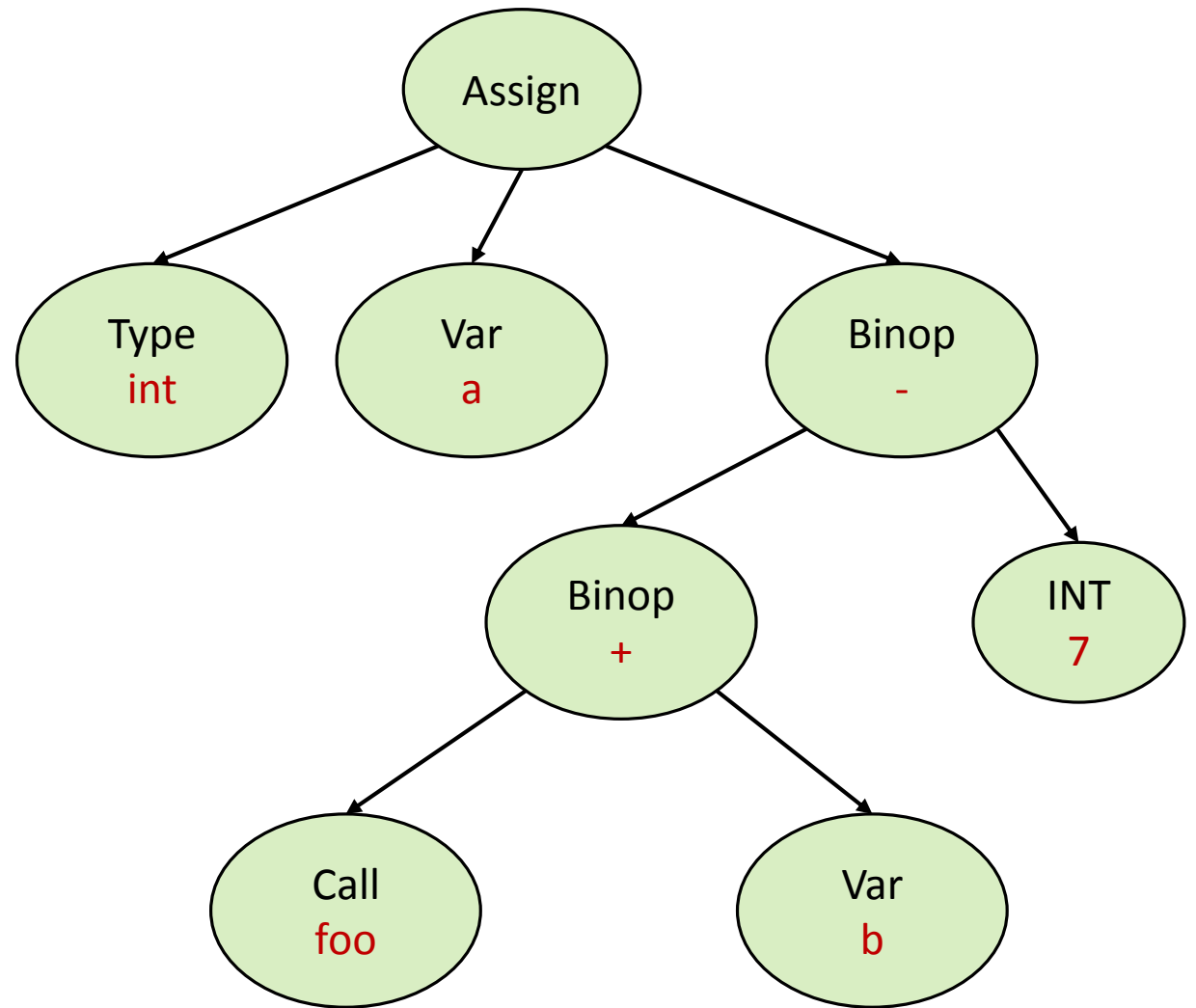
$\text{return } \underbrace{\text{compute_type}(t_1, \dots, t_n)}$

node specific



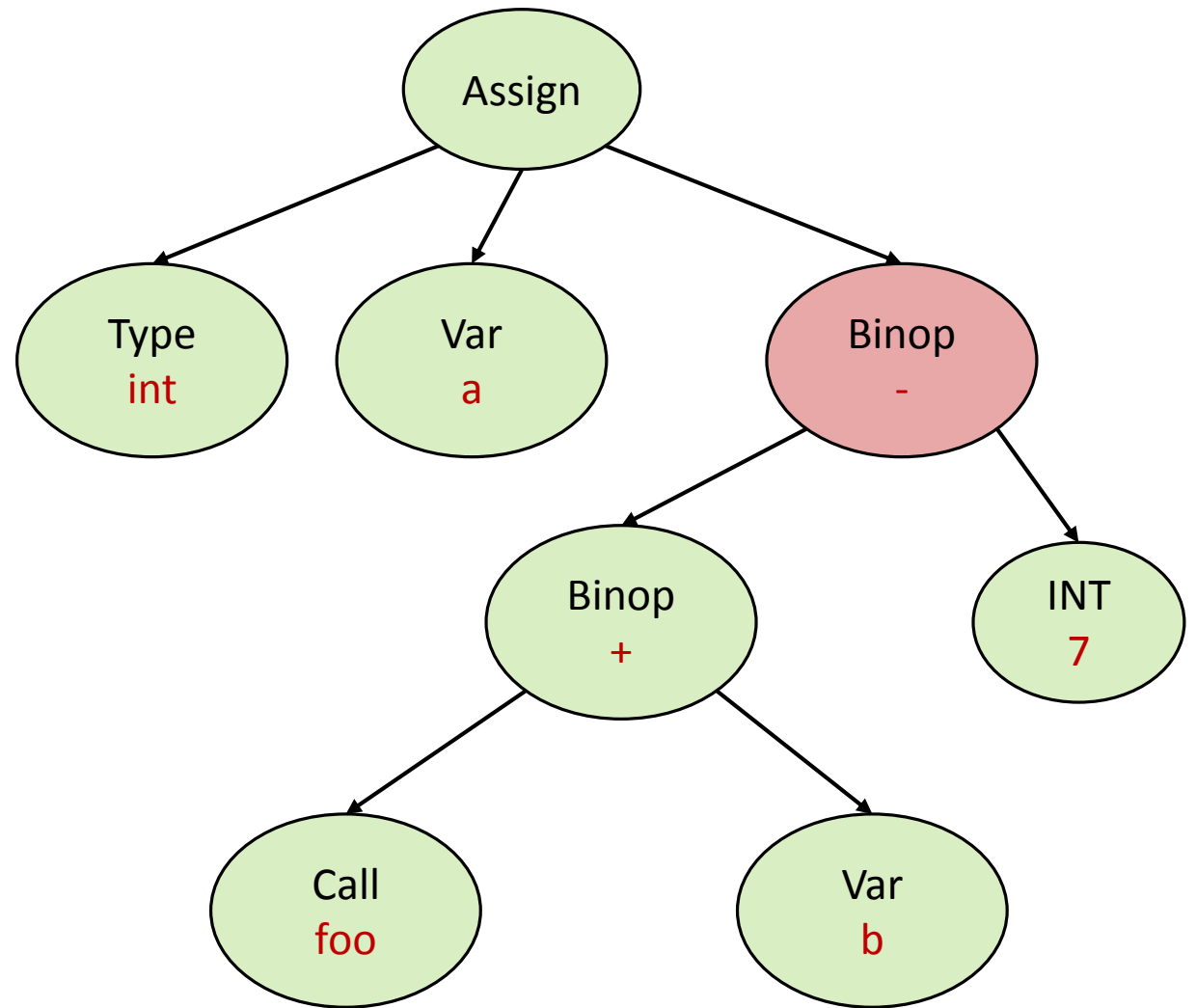
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



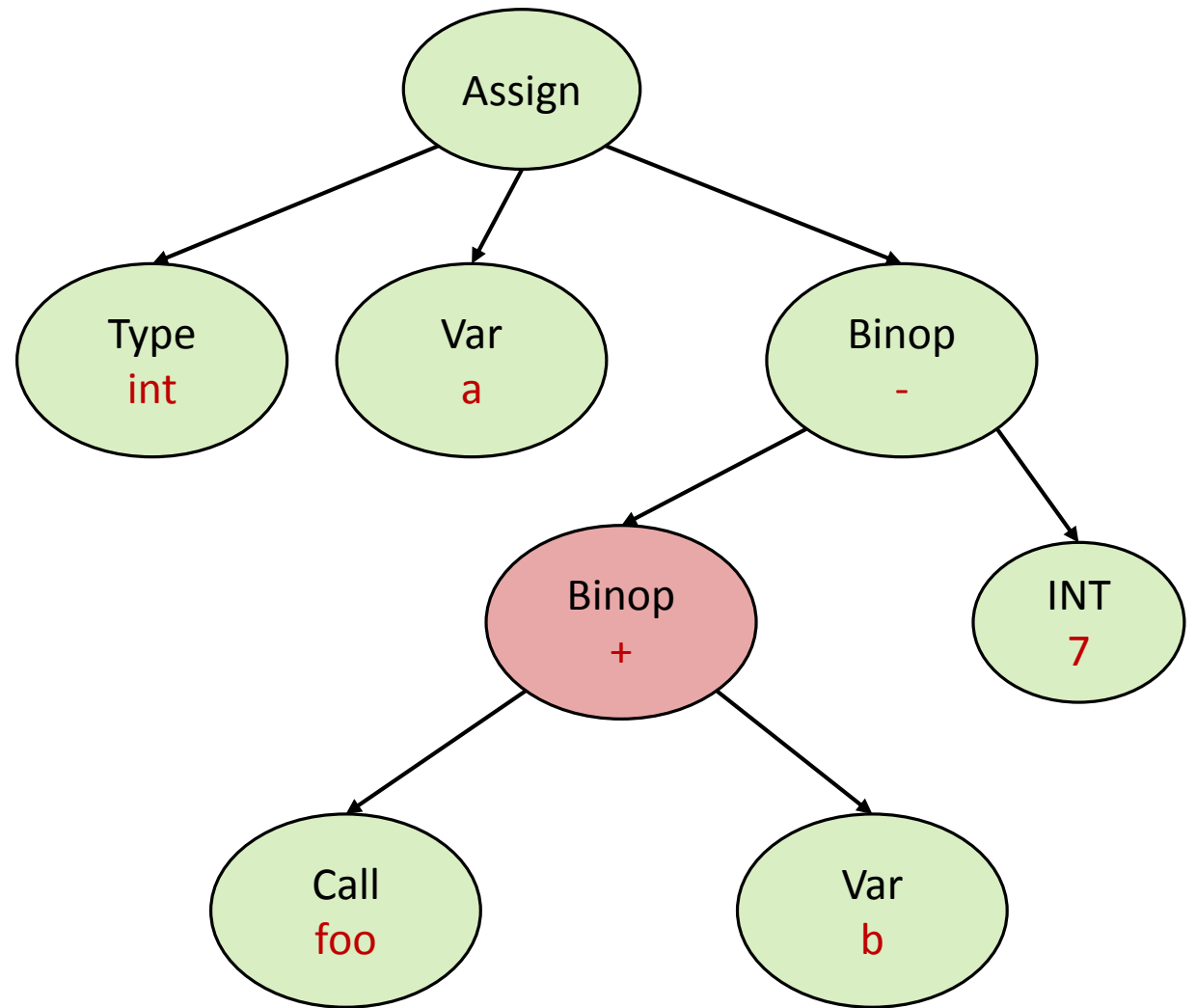
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



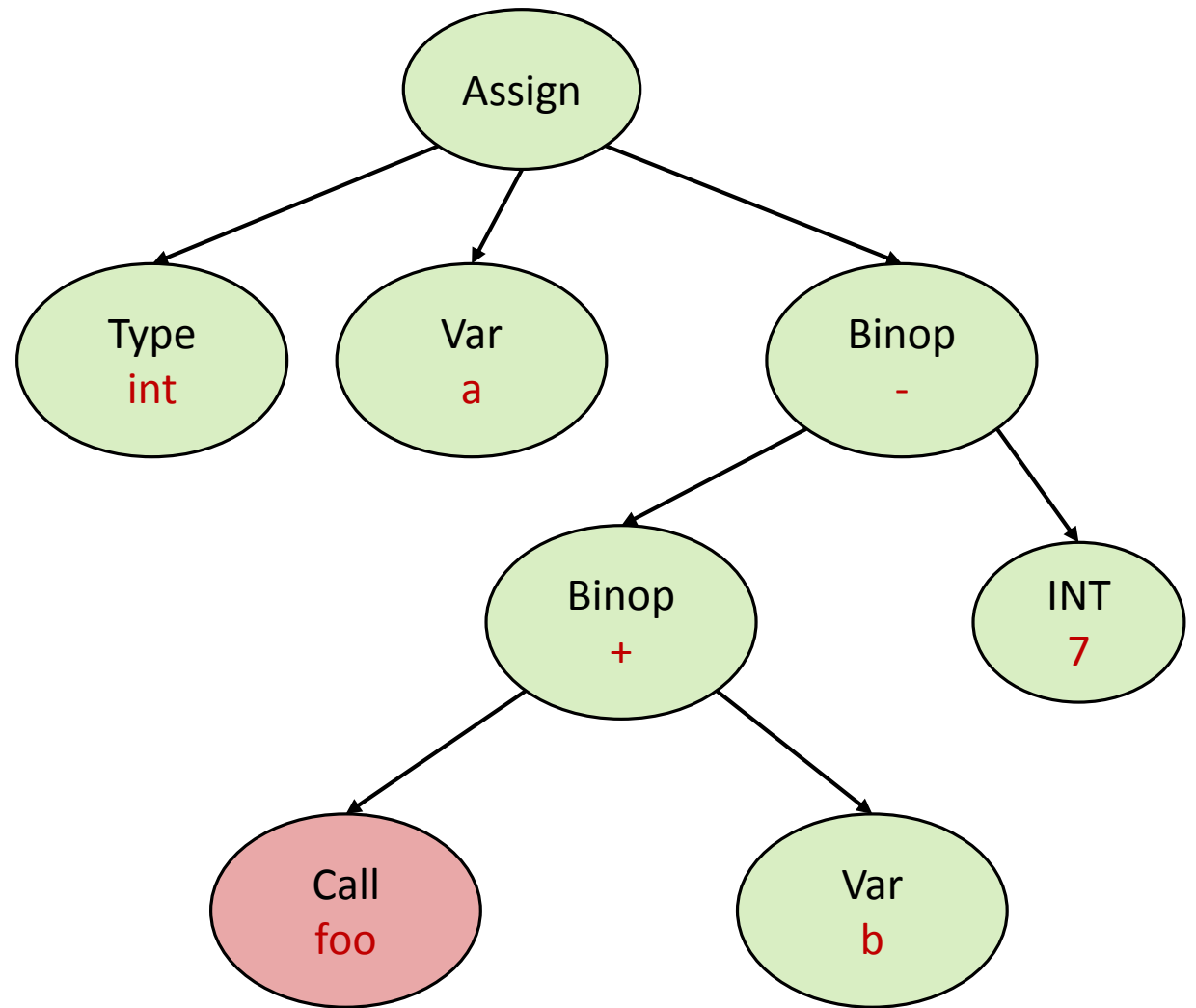
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



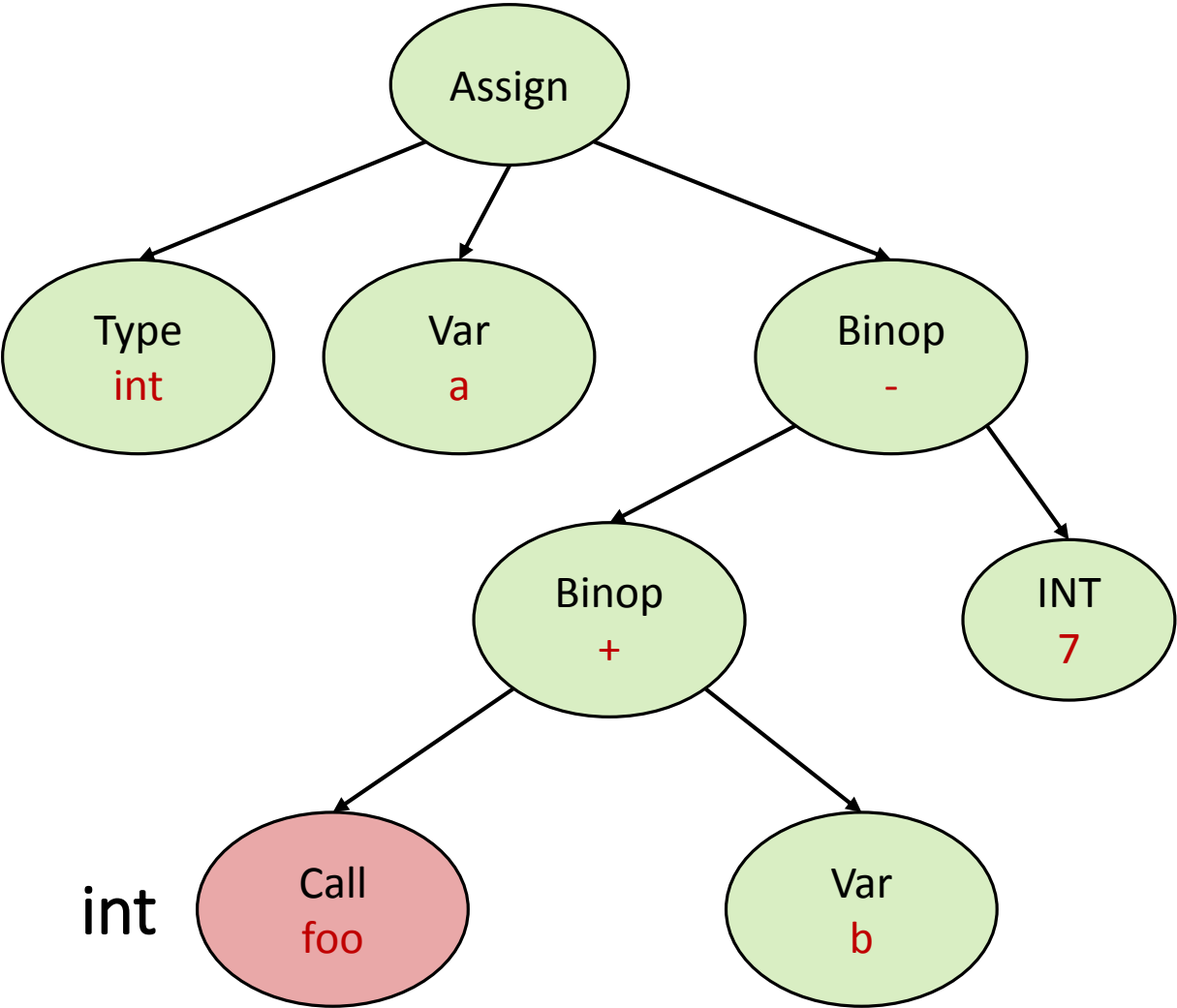

```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



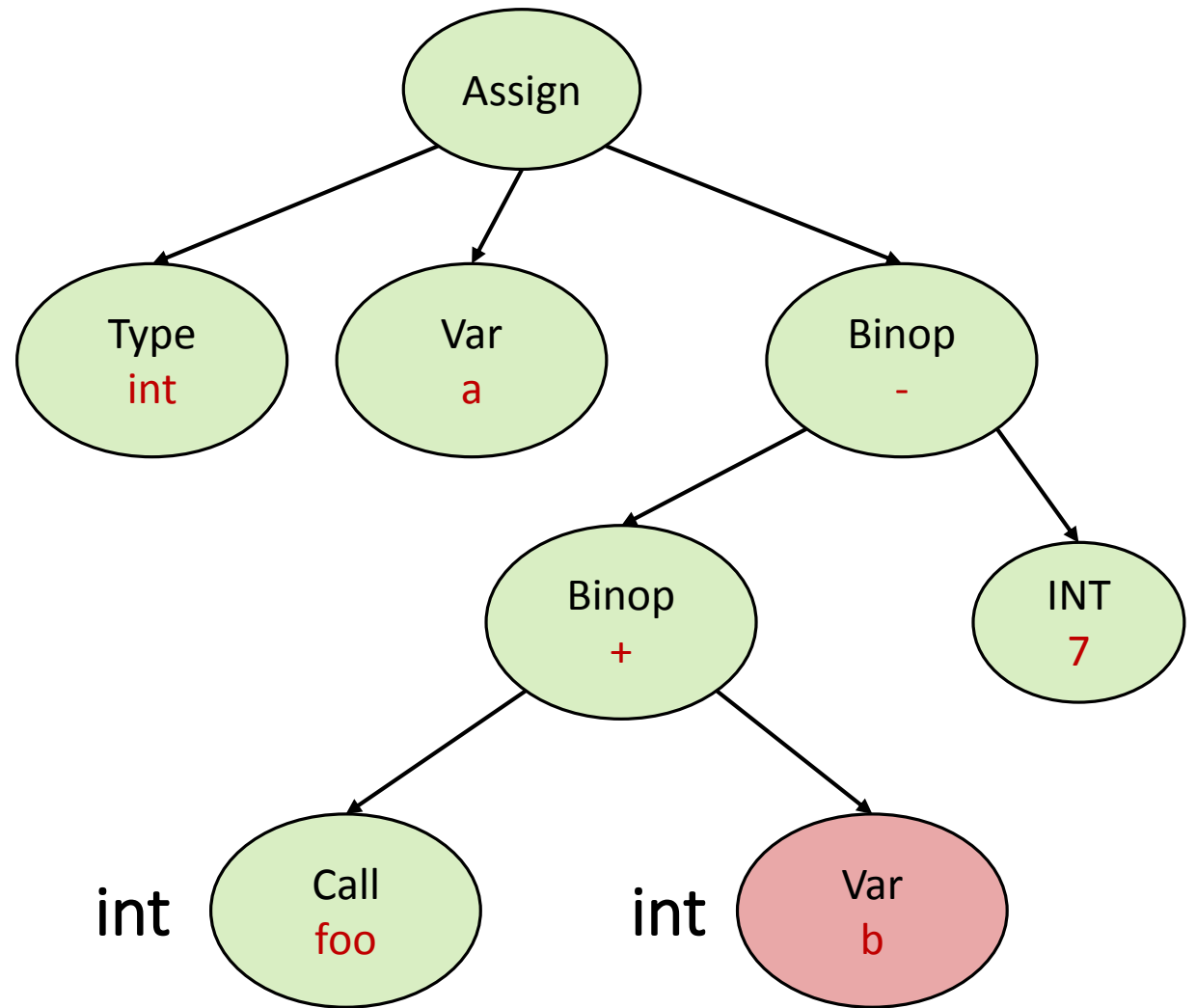
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



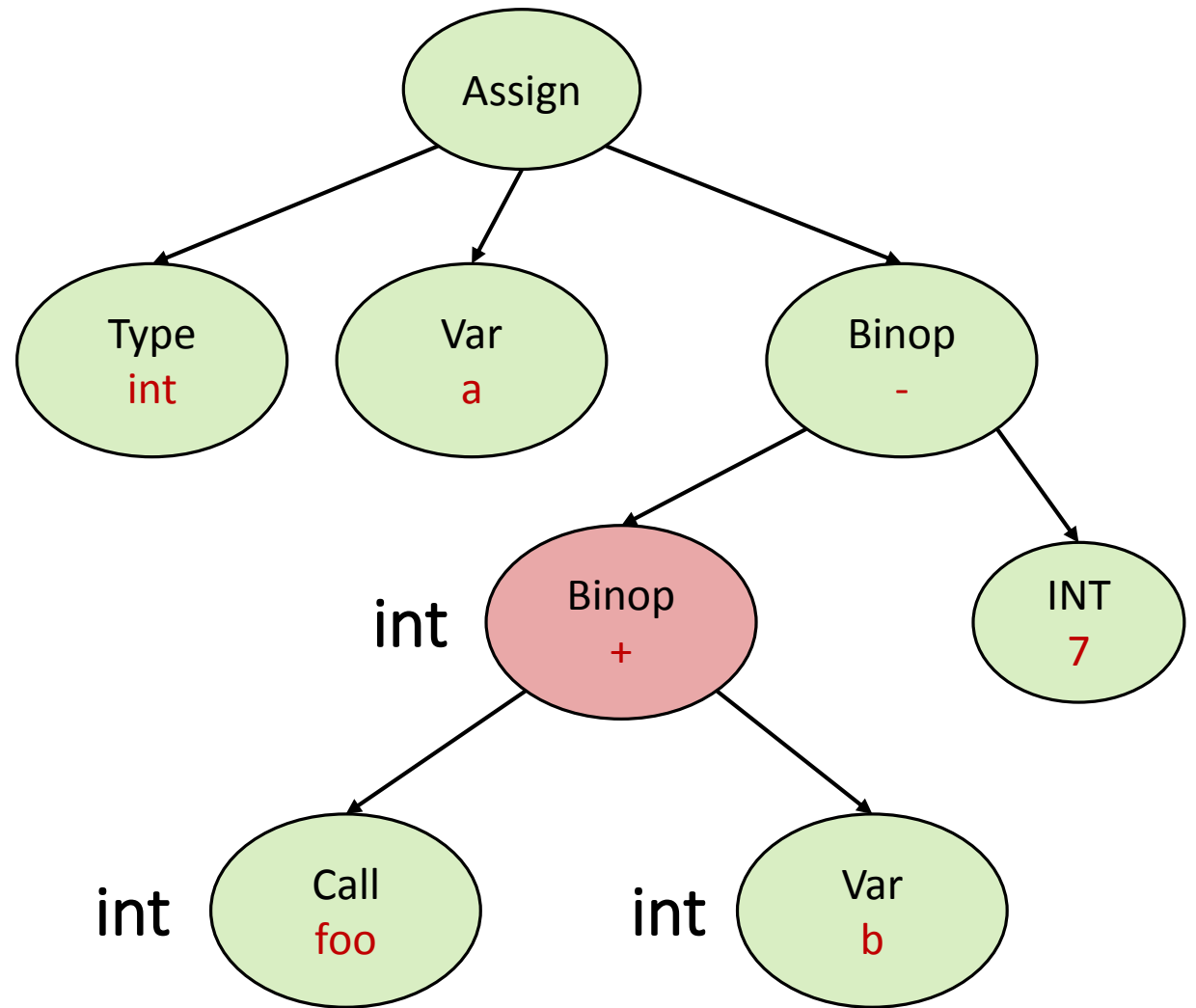
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



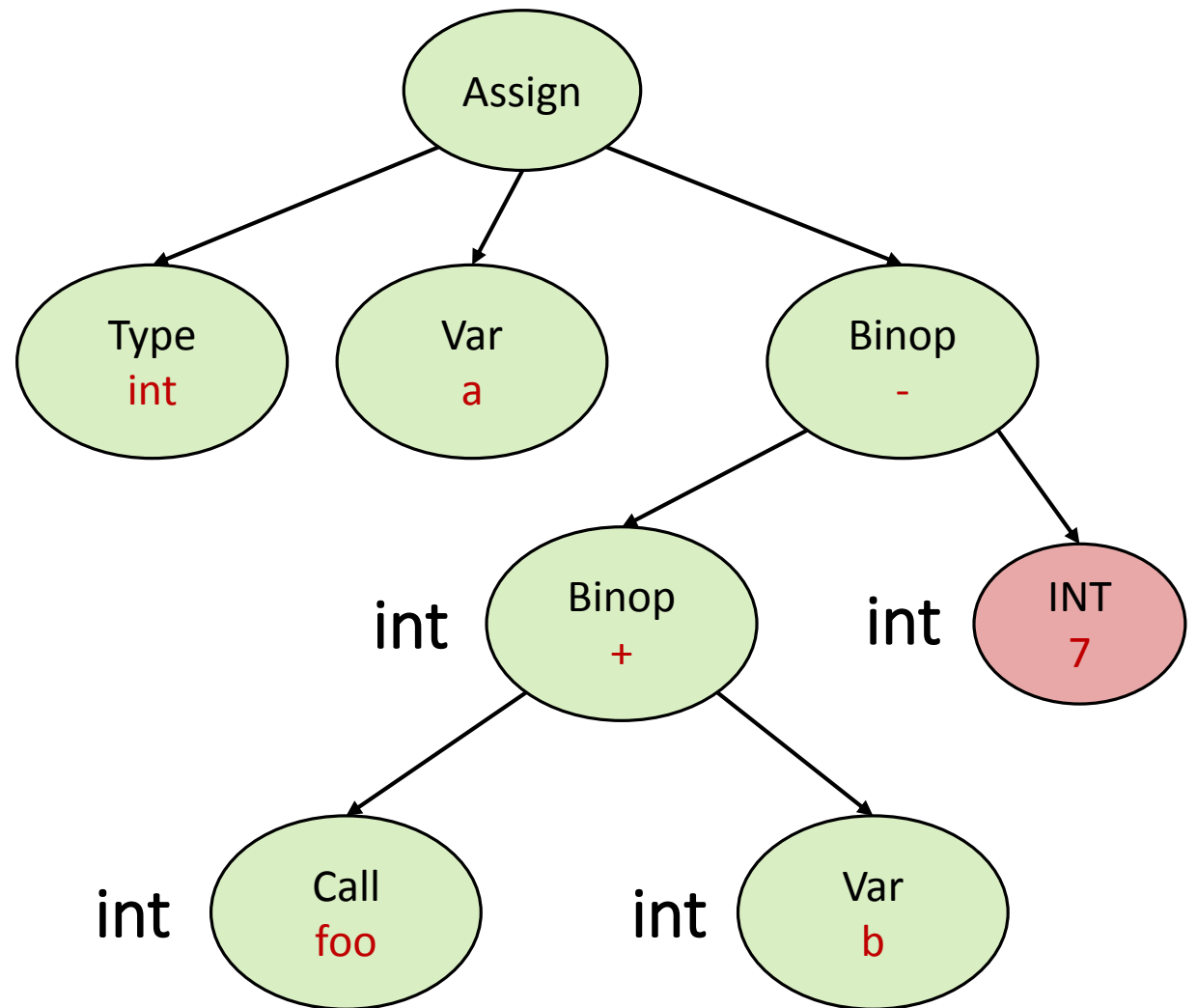
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



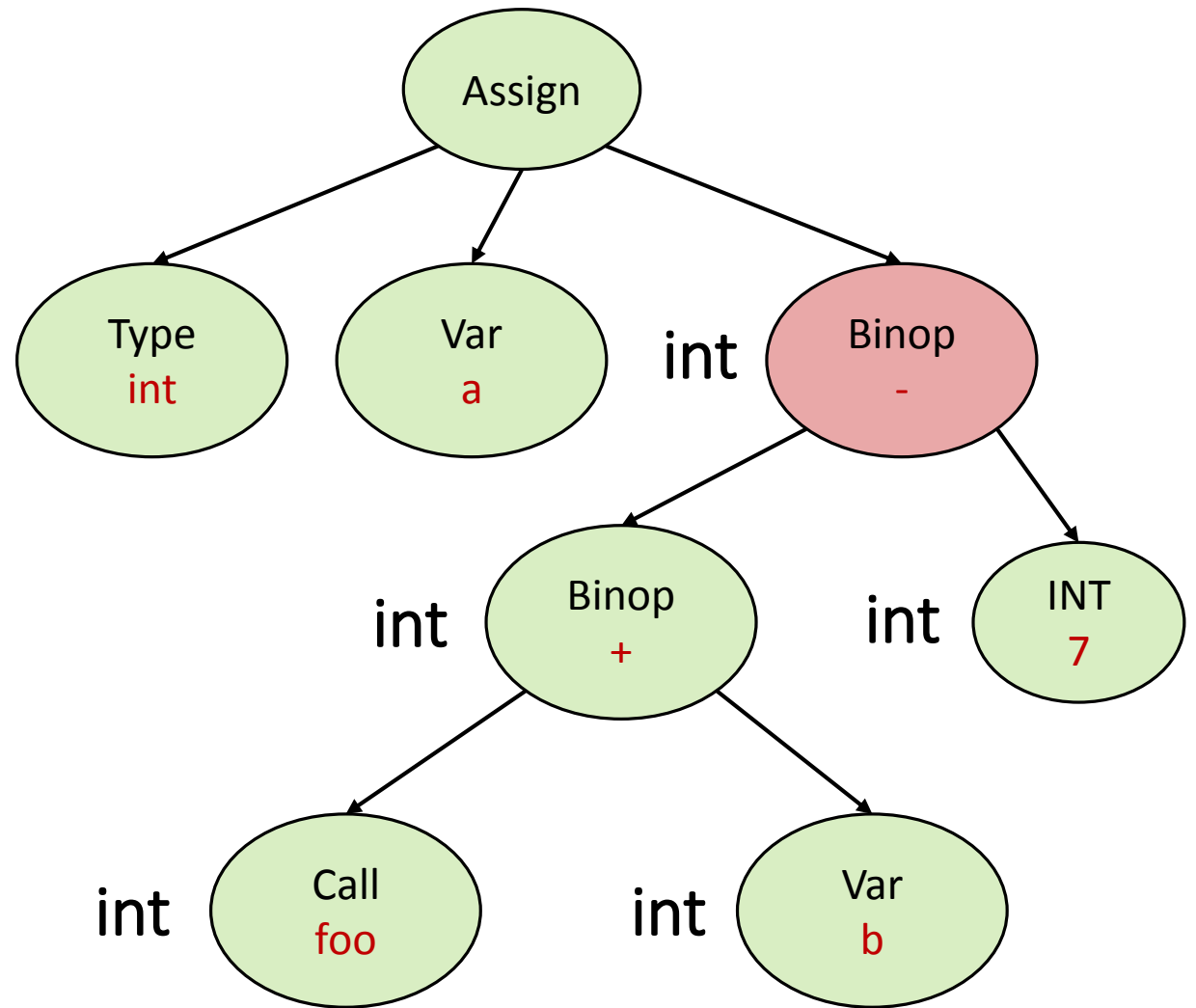
```
int a = foo() + b - 7;  
...
```

ID	Type	Kind
foo	int,void	function
b	int	variable



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

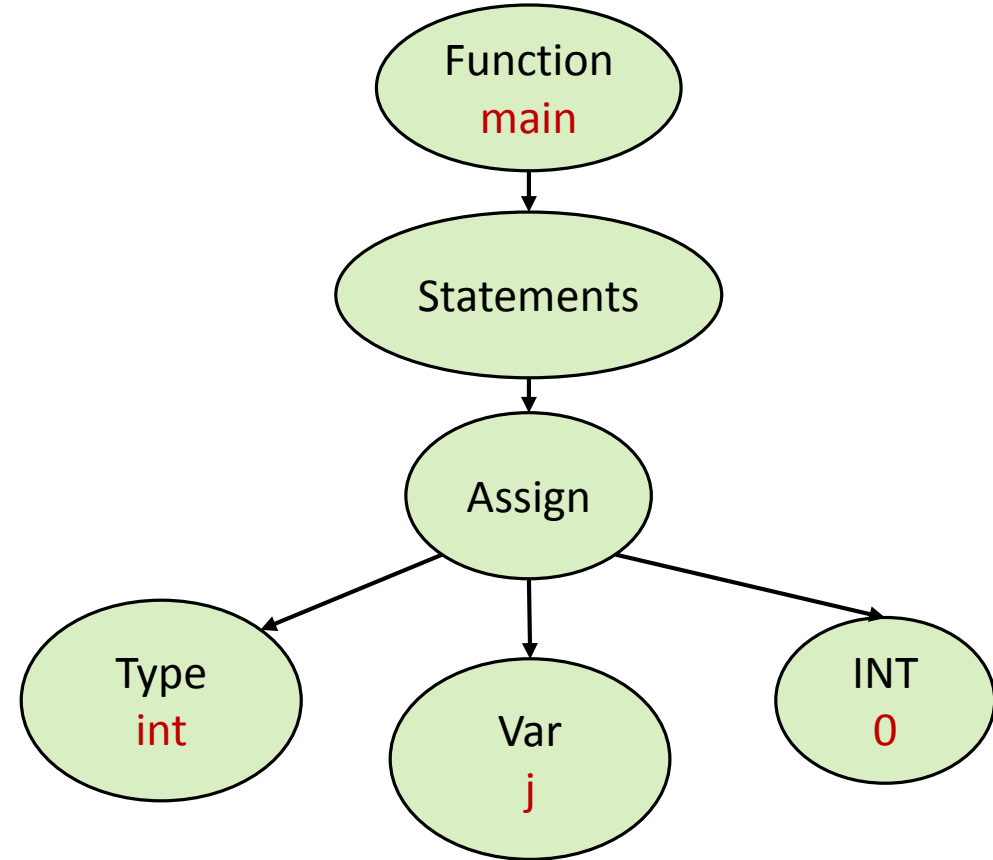
ID	Type	Kind
foo	int,void	function
b	int	variable



Examples

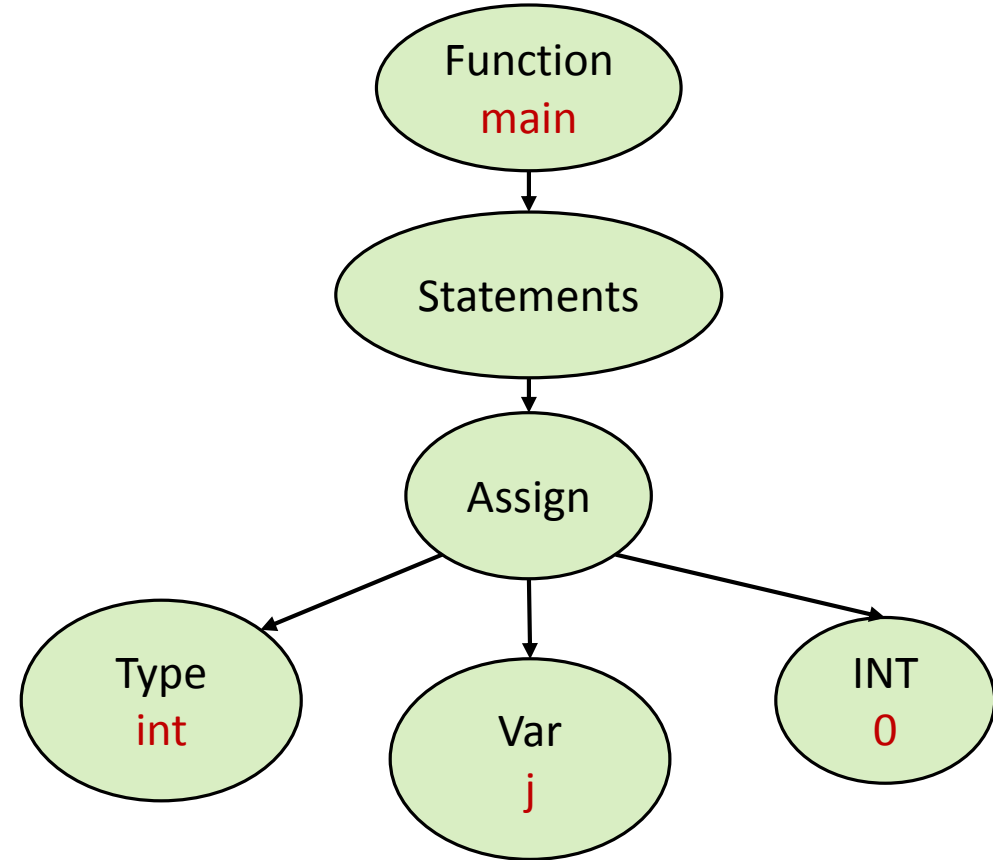
Assignments

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



Assignments

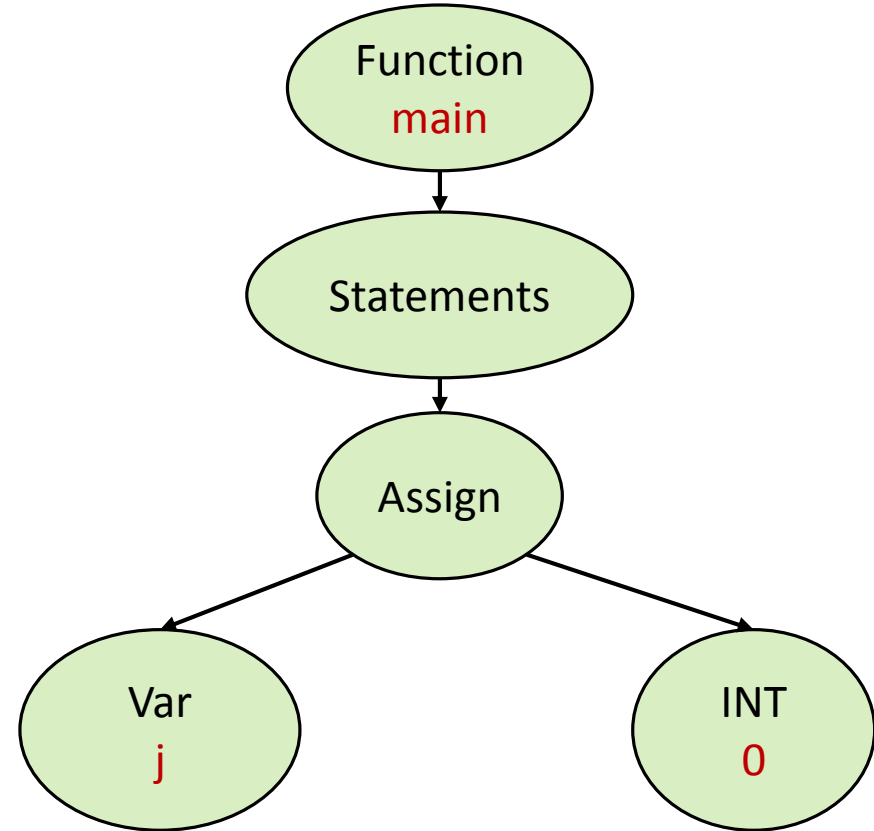
```
void main() {  
    int j = 0;  
}
```



Valid

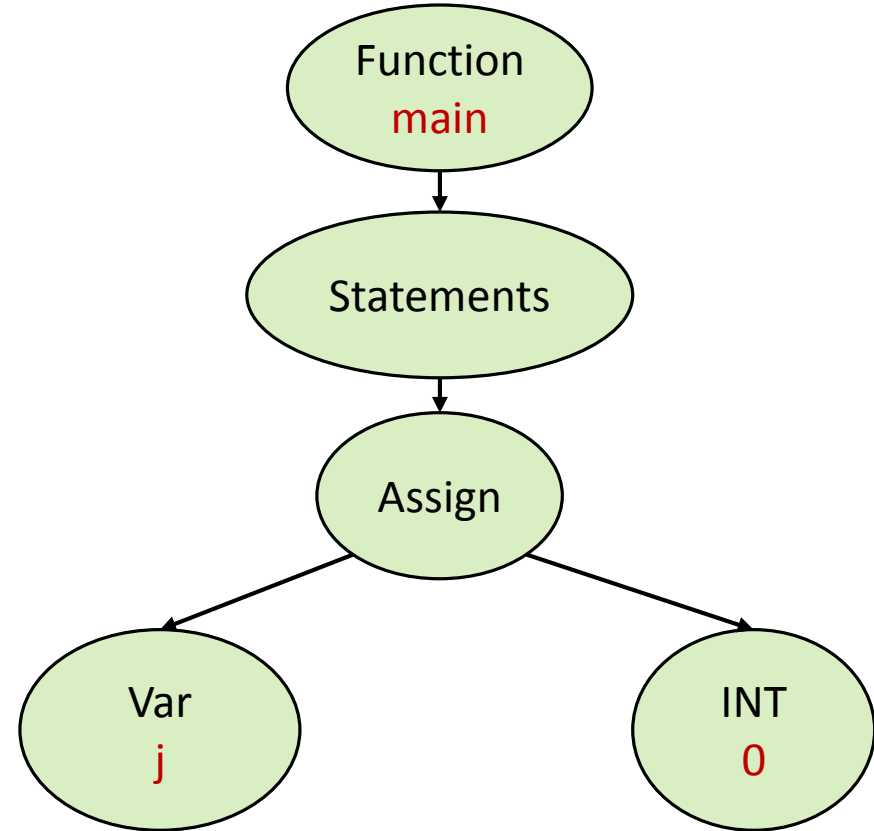
Assignments

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void main() {  
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}
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Assignments

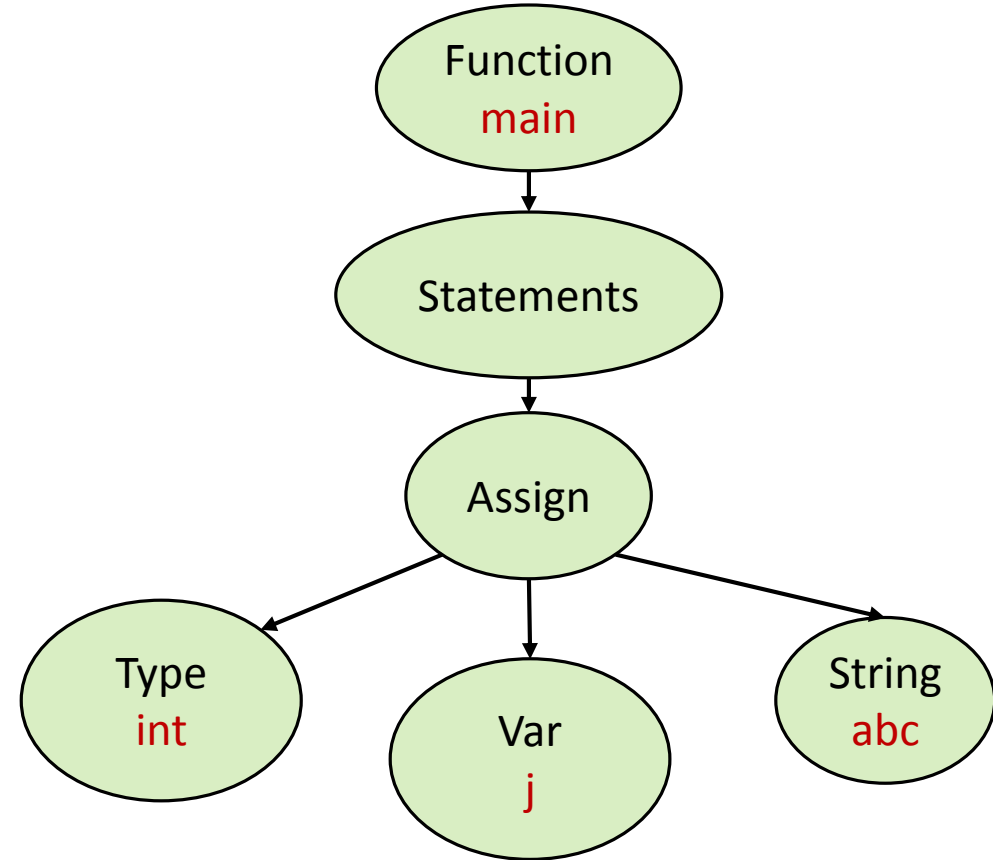
```
void main() {  
    j = 0;  
}
```



Invalid

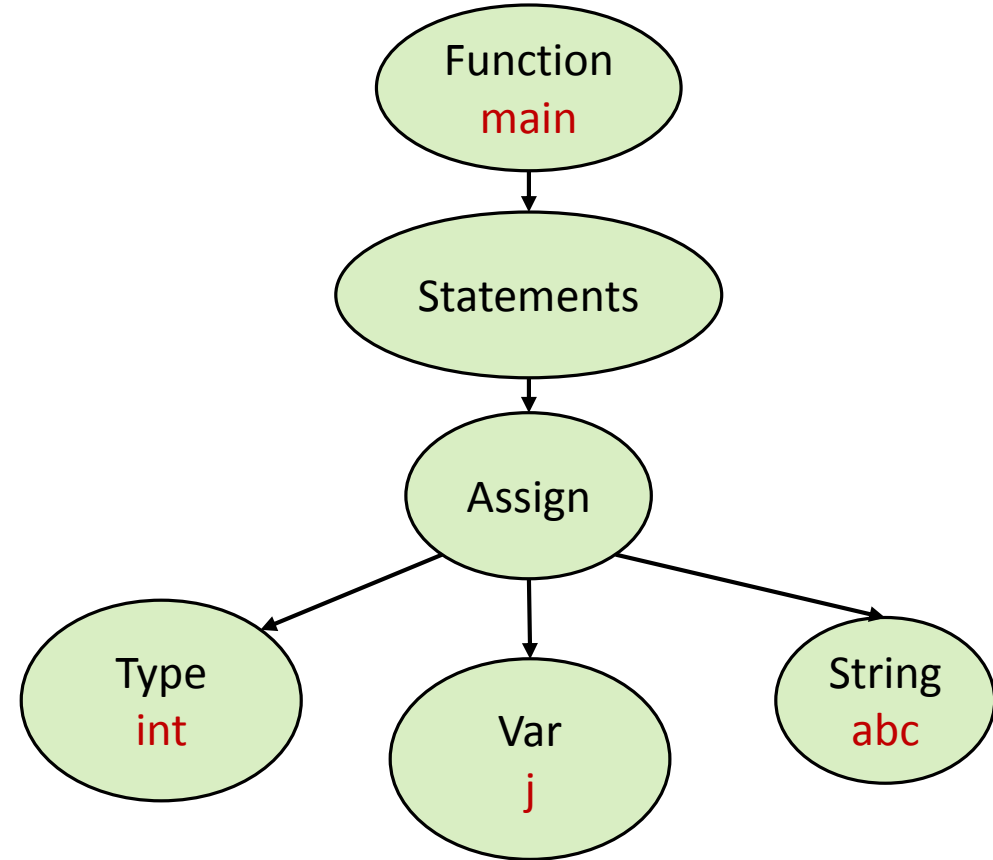
Assignments

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



Assignments

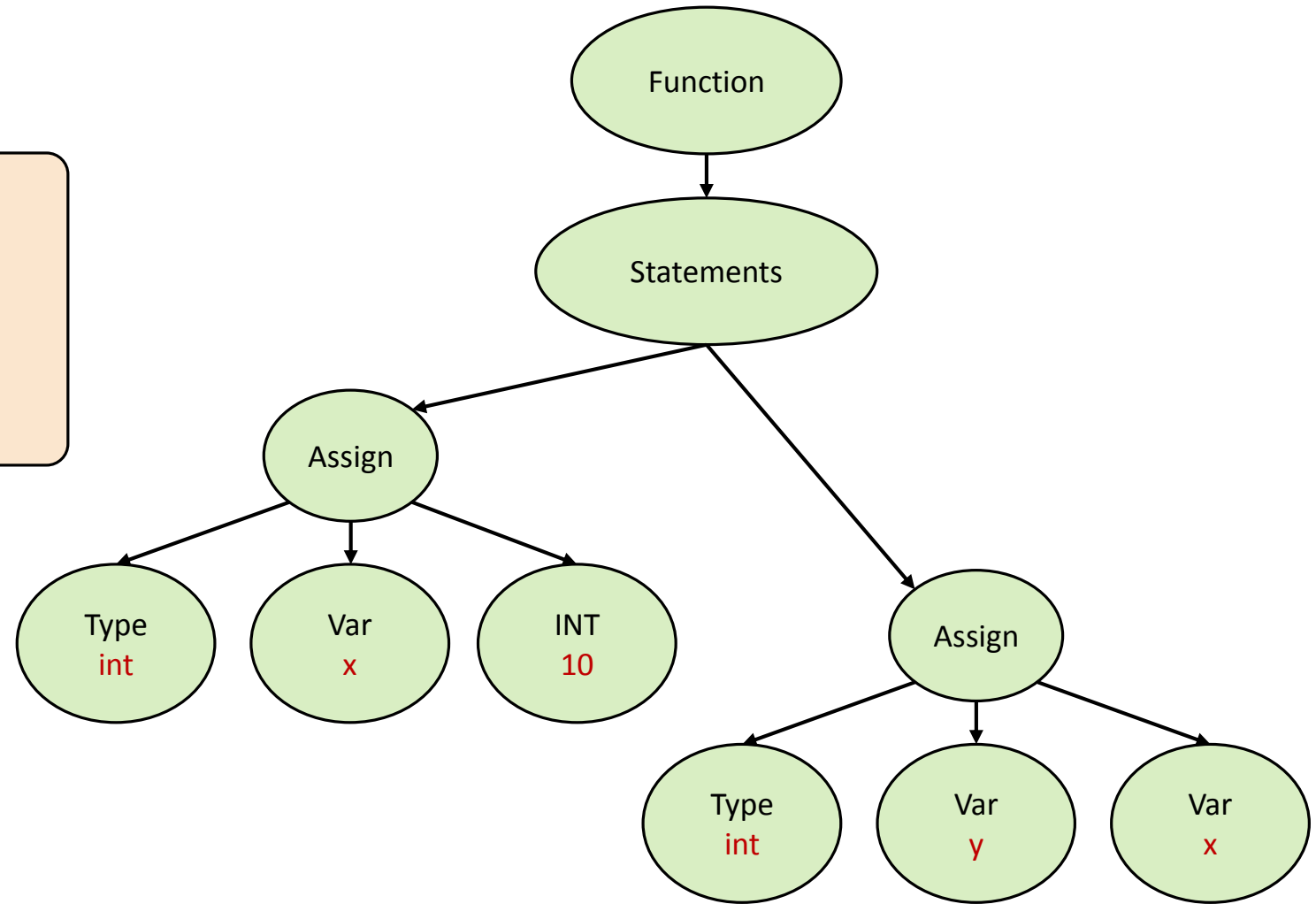
```
void main() {  
    int j = "abc";  
}
```



Invalid

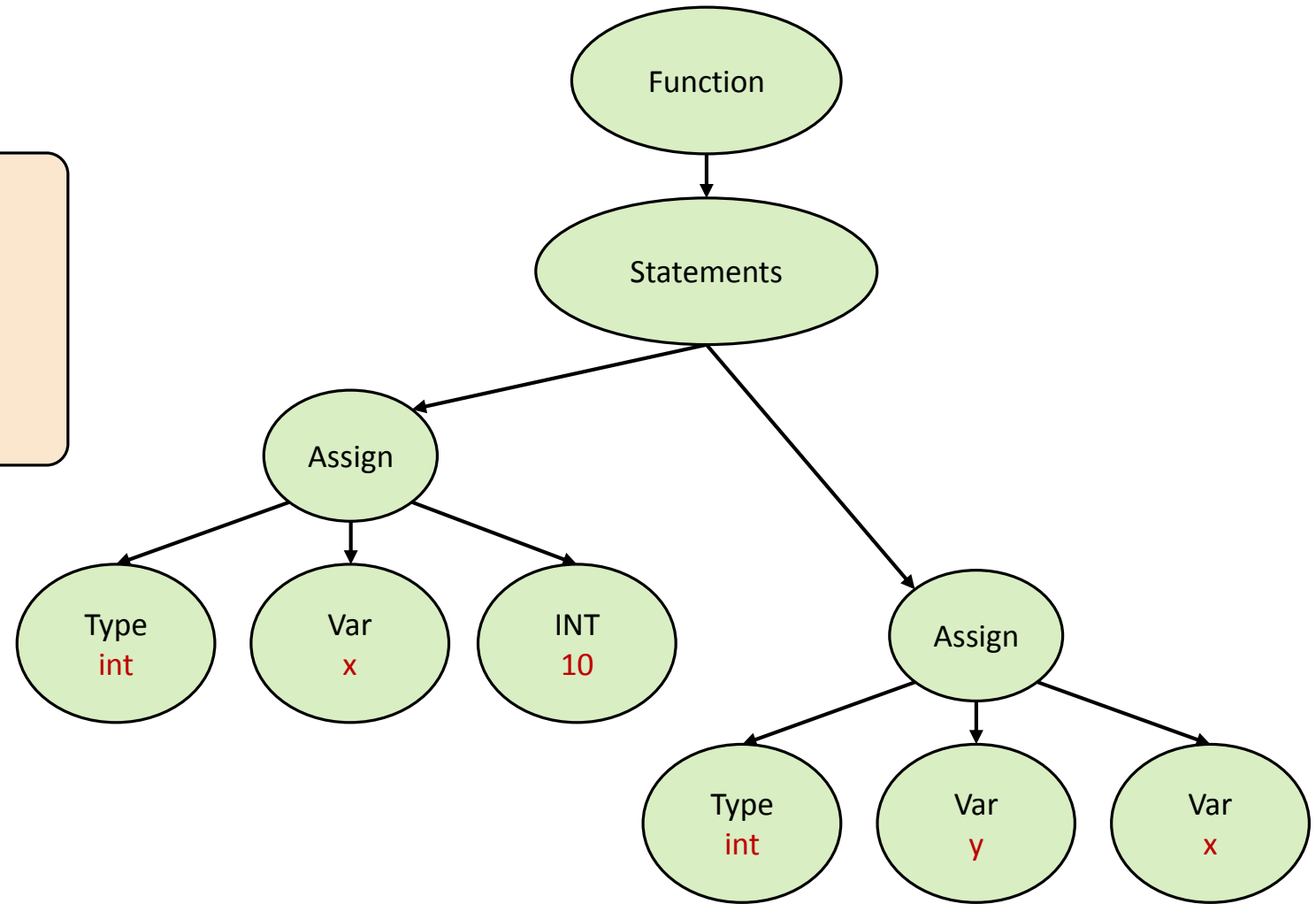
Assignments

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



Assignments

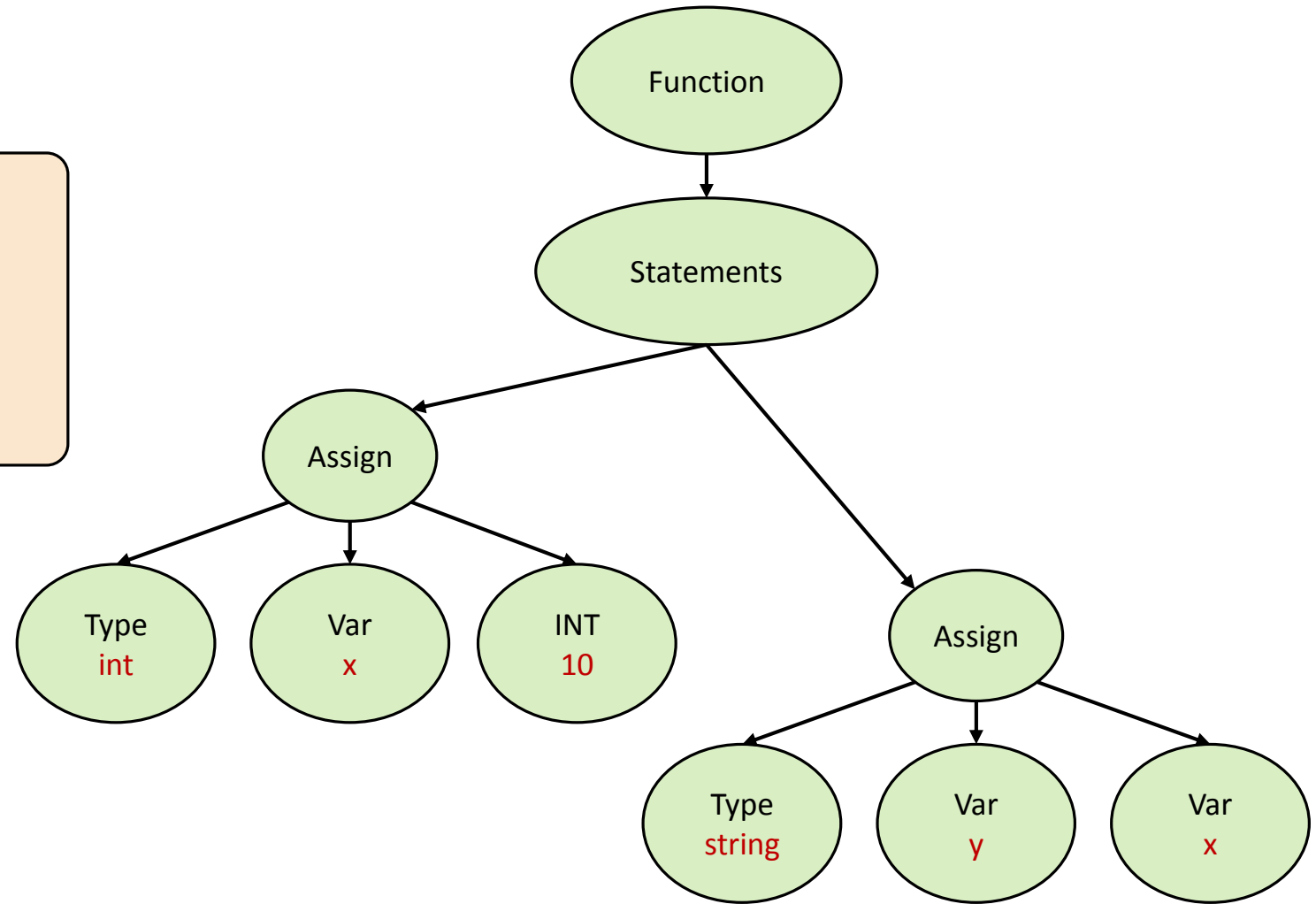
```
void main() {  
    int x = 10;  
    int y = x;  
}
```



Valid

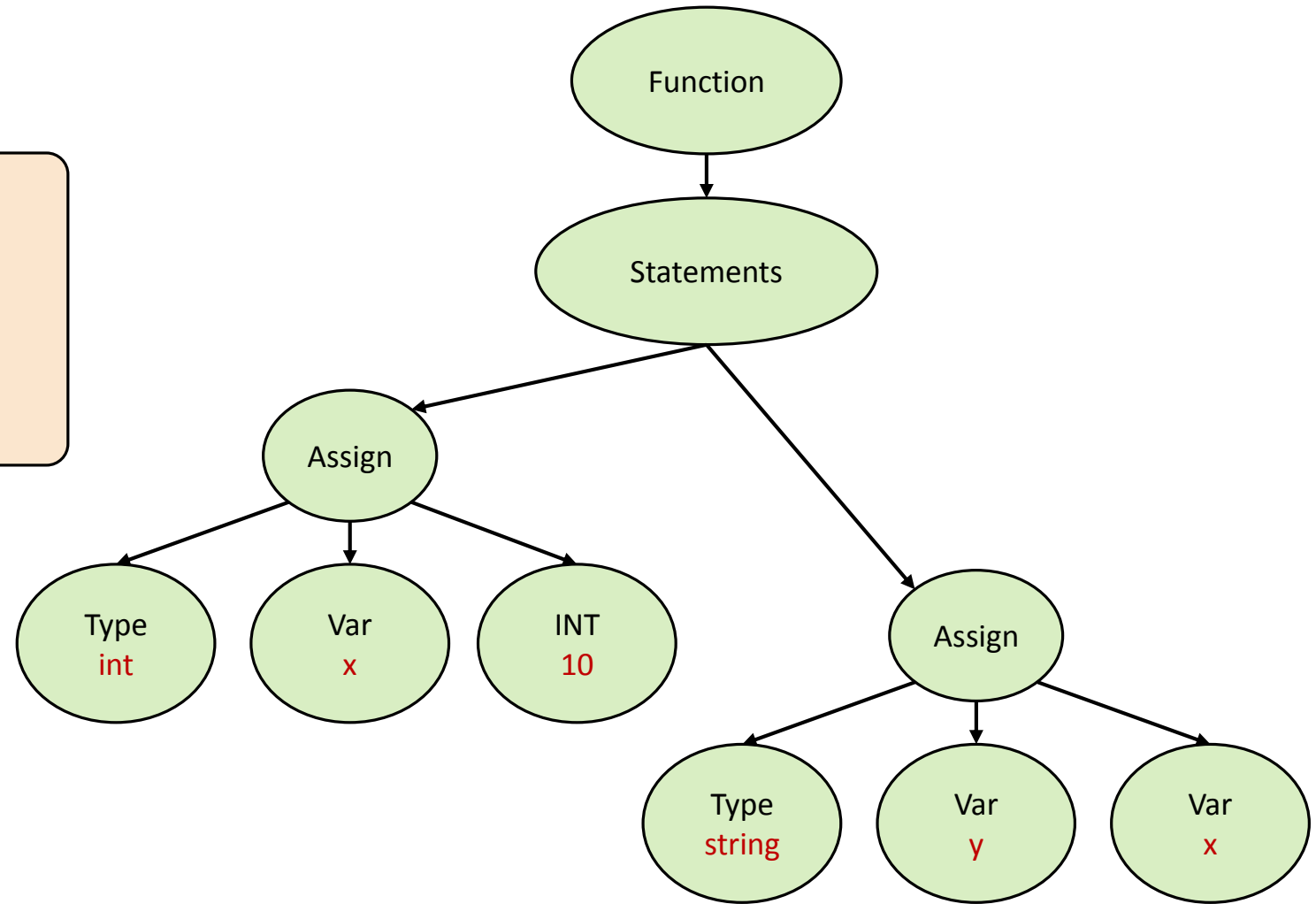
Assignments

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



Assignments

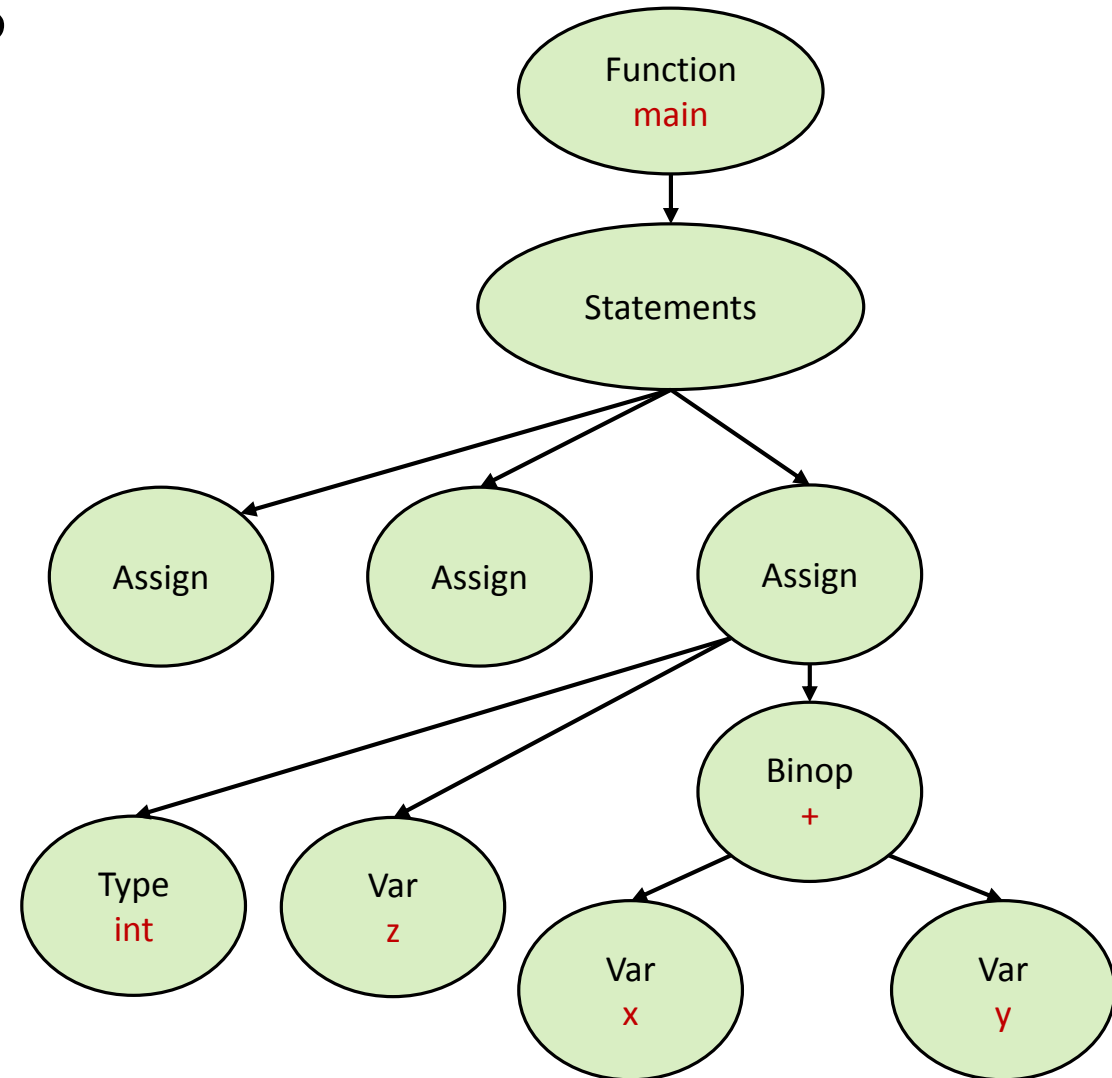
```
void main() {  
    int x = 10;  
    string y = x;  
}
```



Invalid

Binary Operations

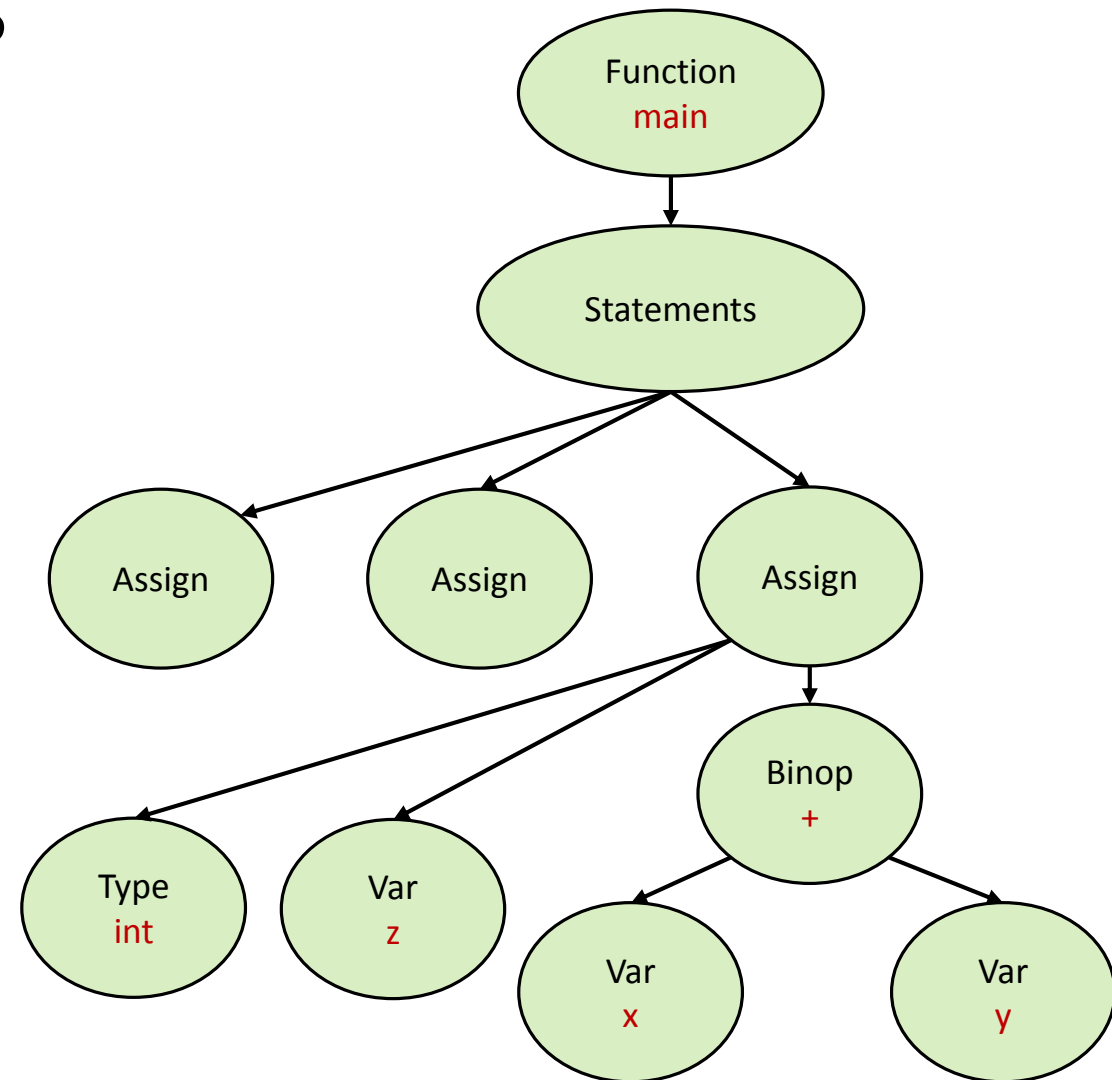
```
void main() {  
    int x = 1;  
    int y = 2;  
    int z = x + y;  
}
```



Binary Operations

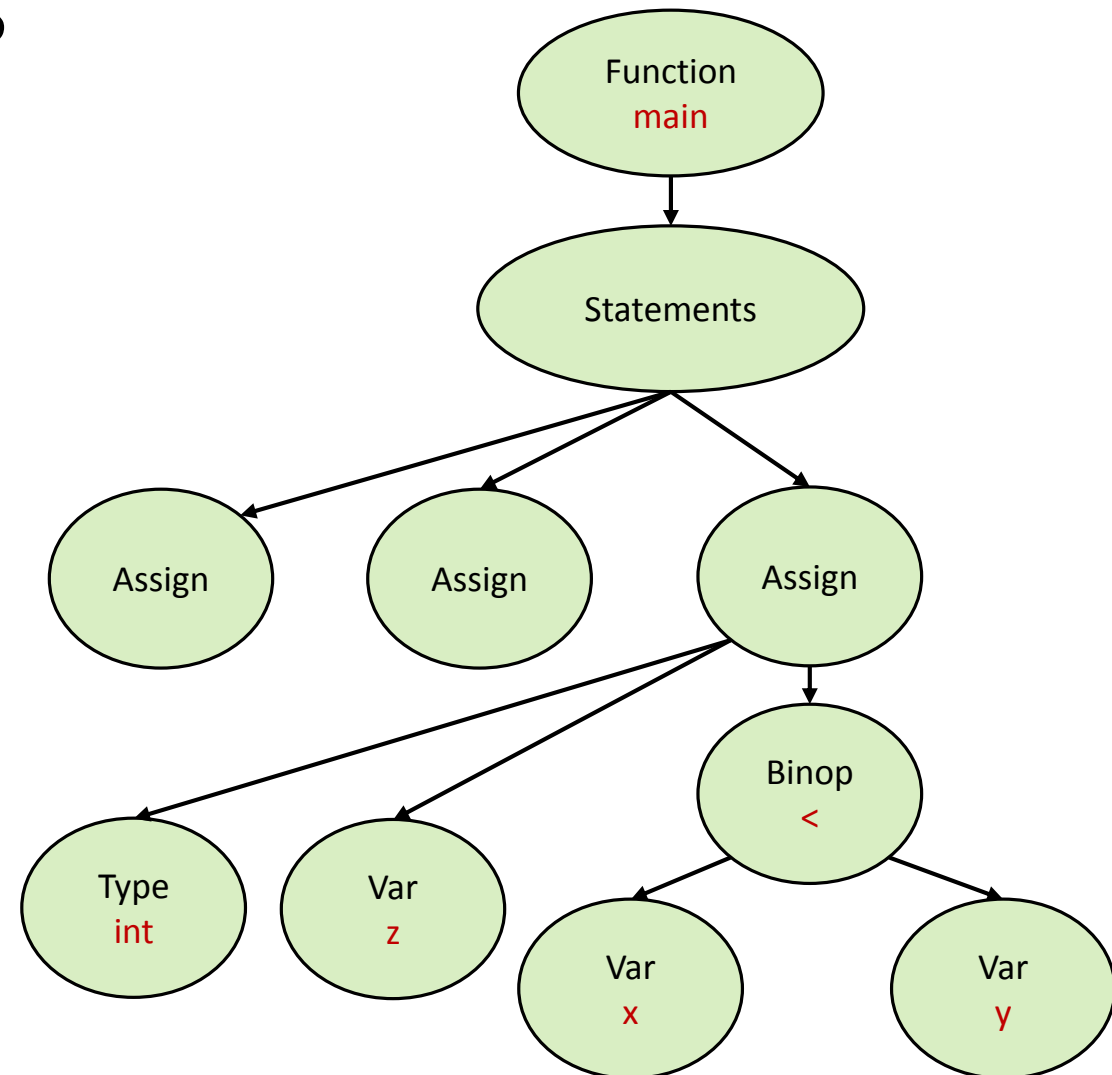
```
void main() {  
    int x = 1;  
    int y = 2;  
    int z = x + y;  
}
```

Valid



Binary Operations

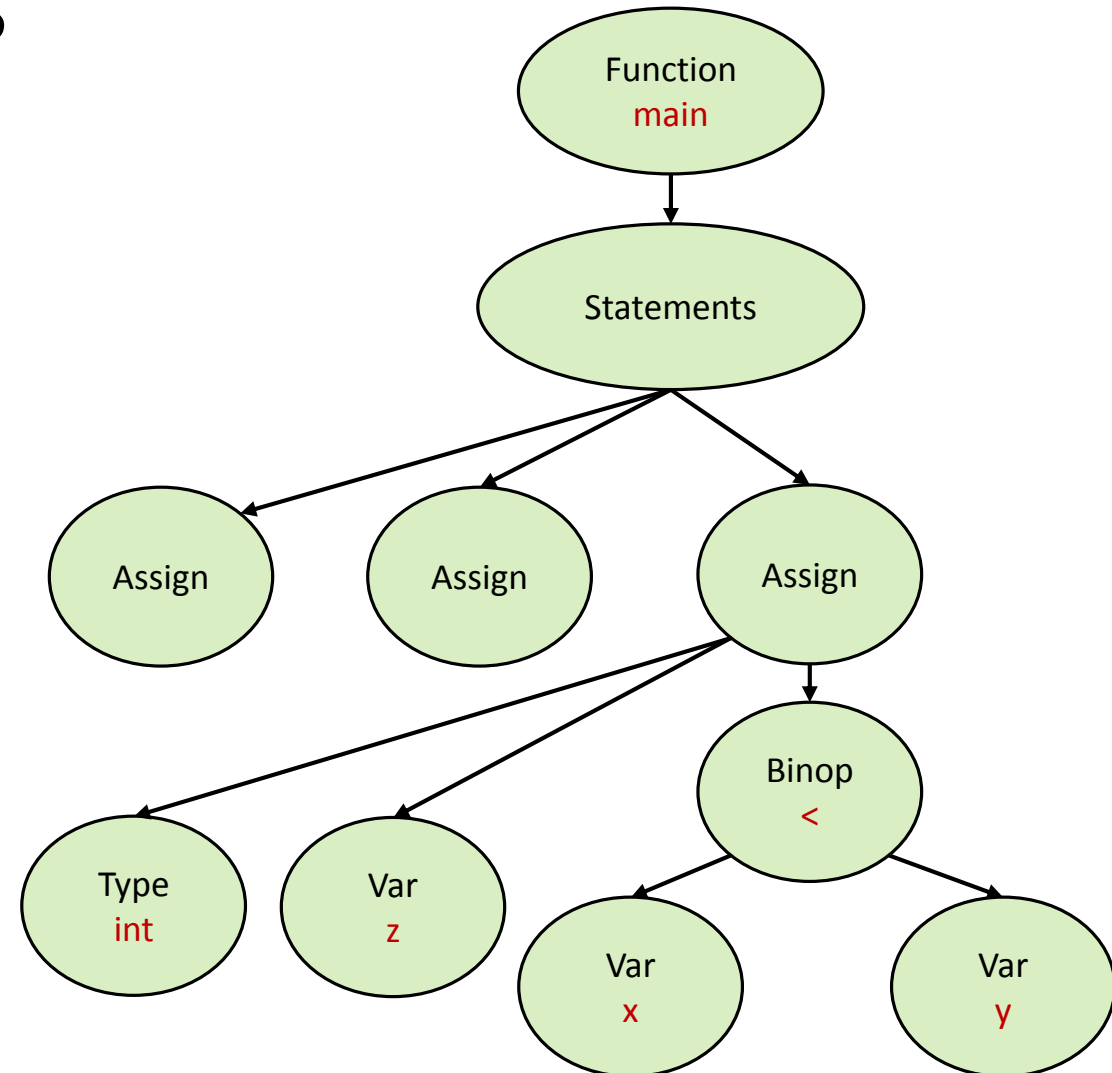
```
void main() {  
    int x = 1;  
    string y = "A";  
    int z = x < y;  
}
```



Binary Operations

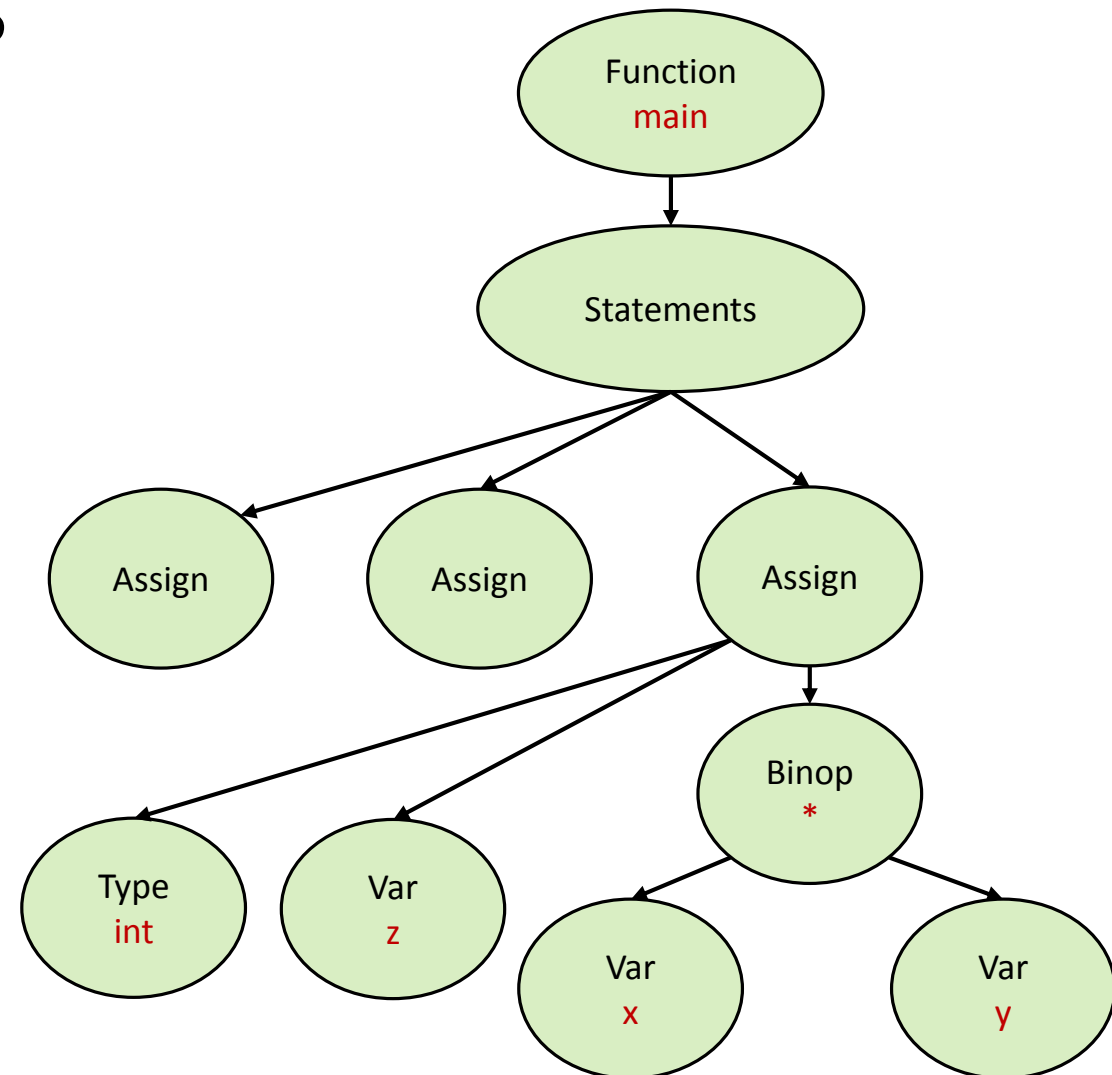
```
void main() {  
    int x = 1;  
    string y = "A";  
    int z = x < y;  
}
```

Invalid



Binary Operations

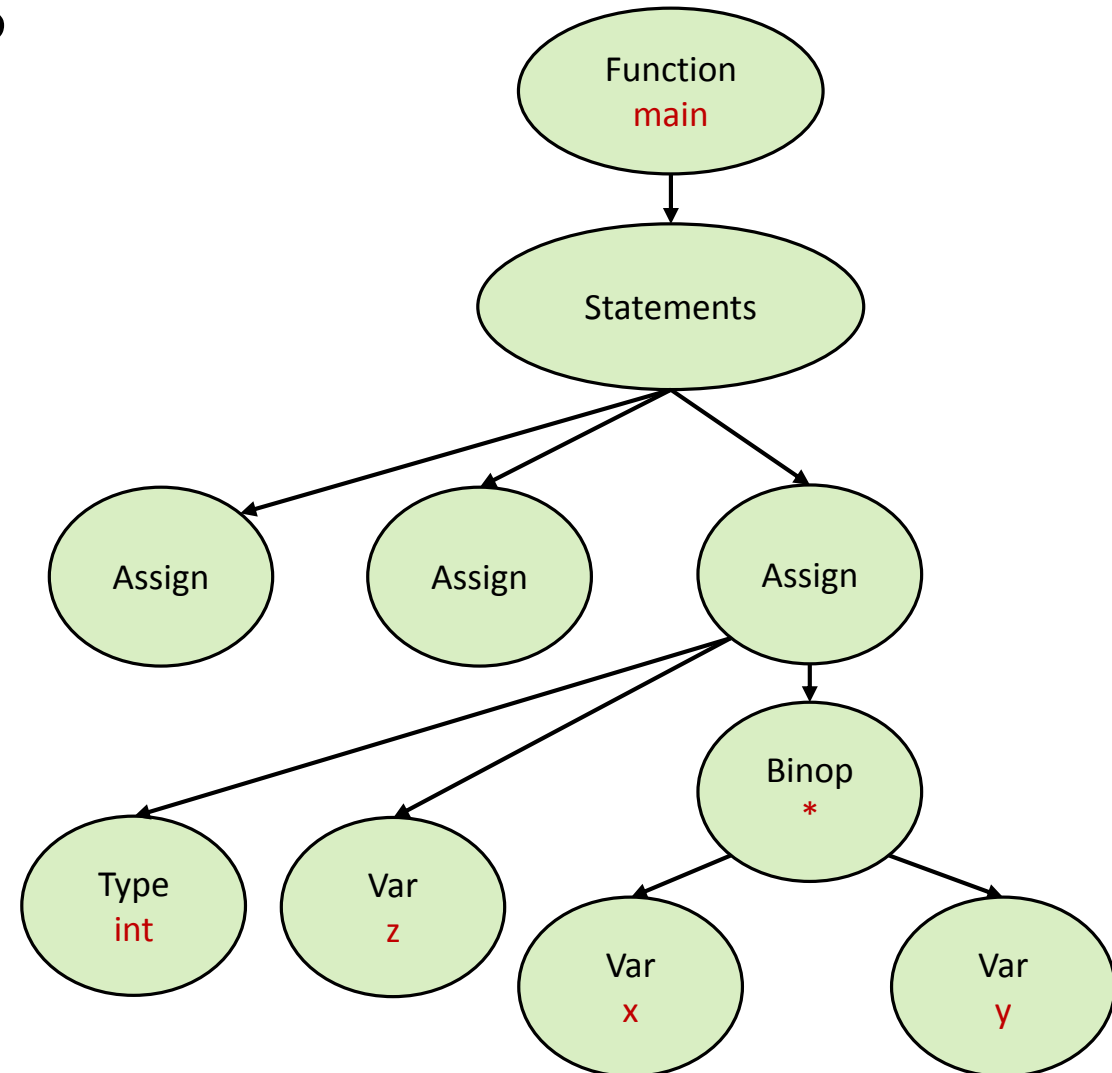
```
void main() {  
    string x = "A";  
    string y = "B";  
    string z = x * y;  
}
```



Binary Operations

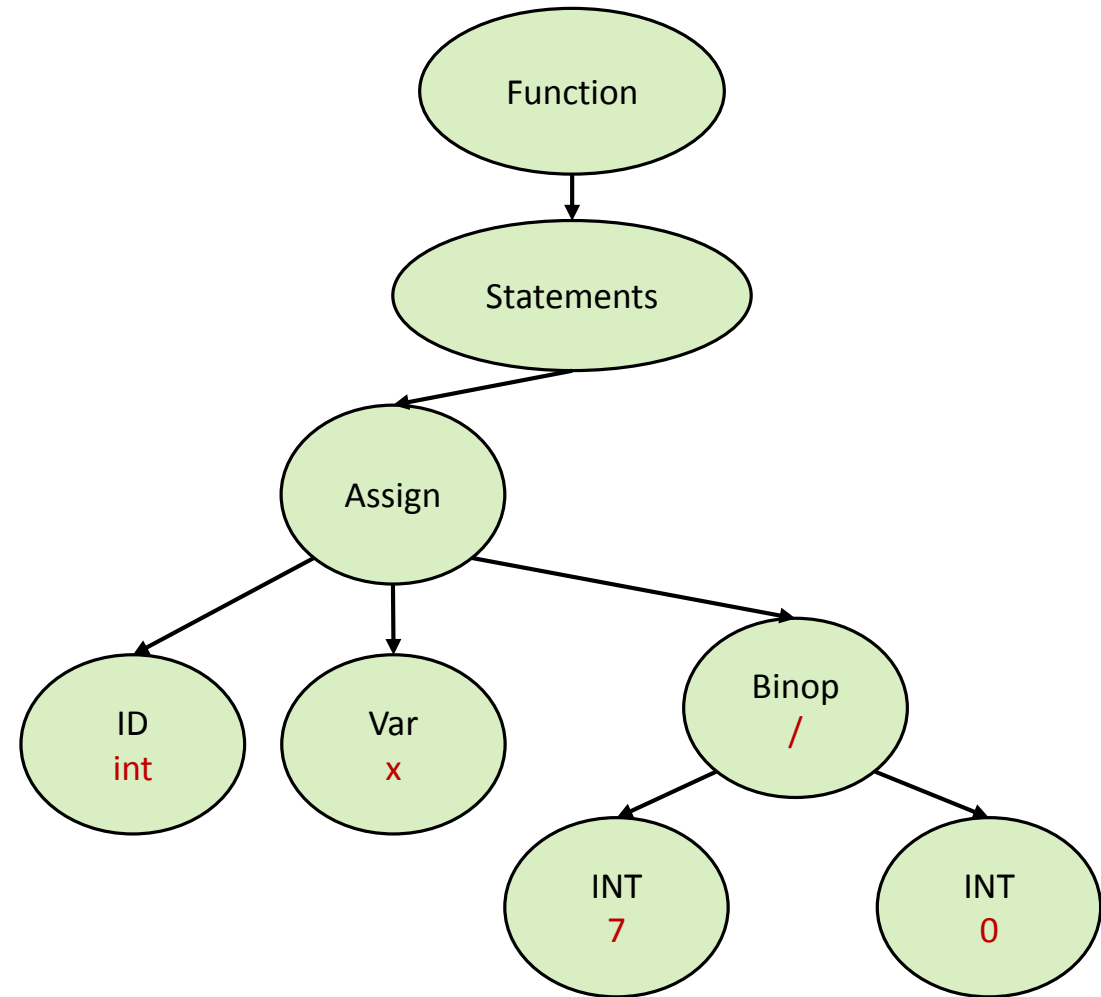
```
void main() {  
    string x = "A";  
    string y = "B";  
    string z = x * y;  
}
```

Invalid



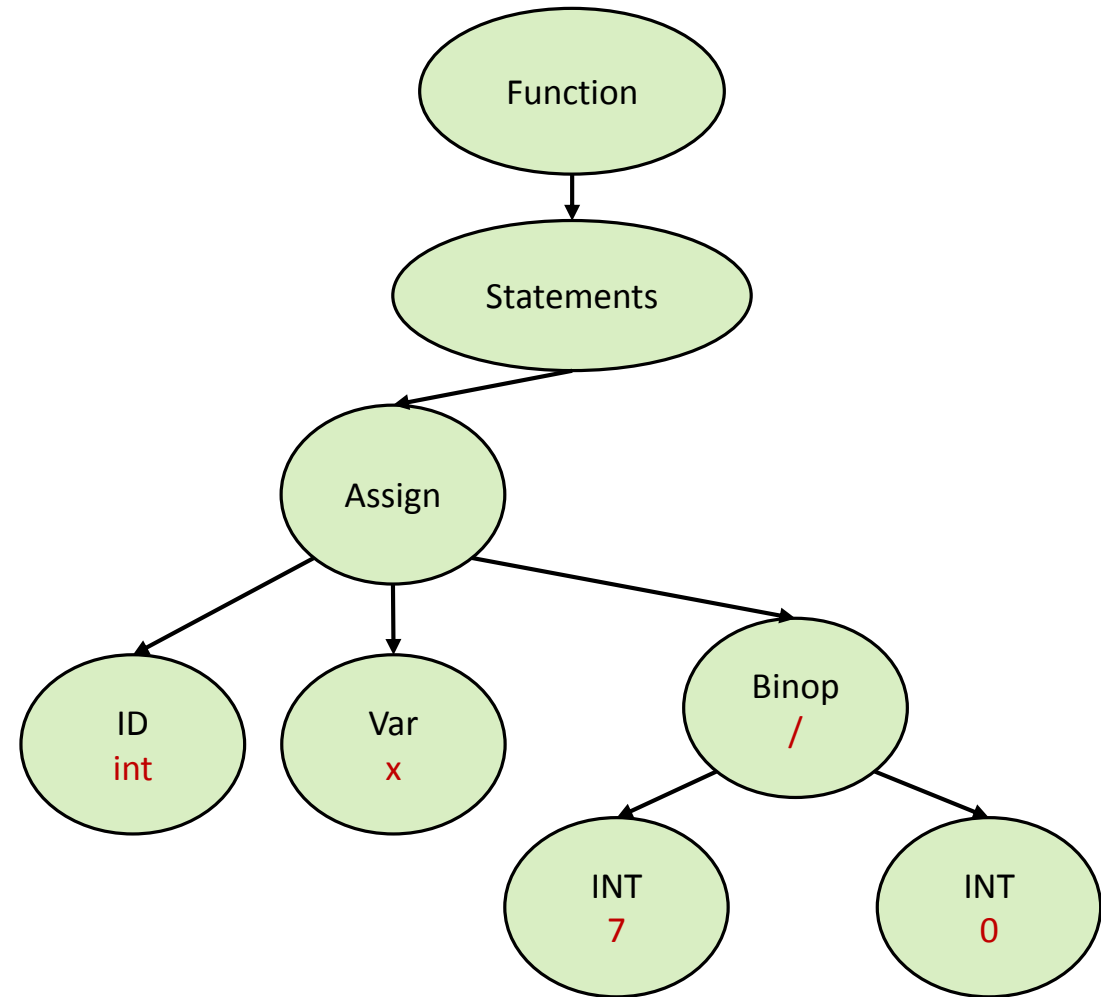
Binary Operations

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



Binary Operations

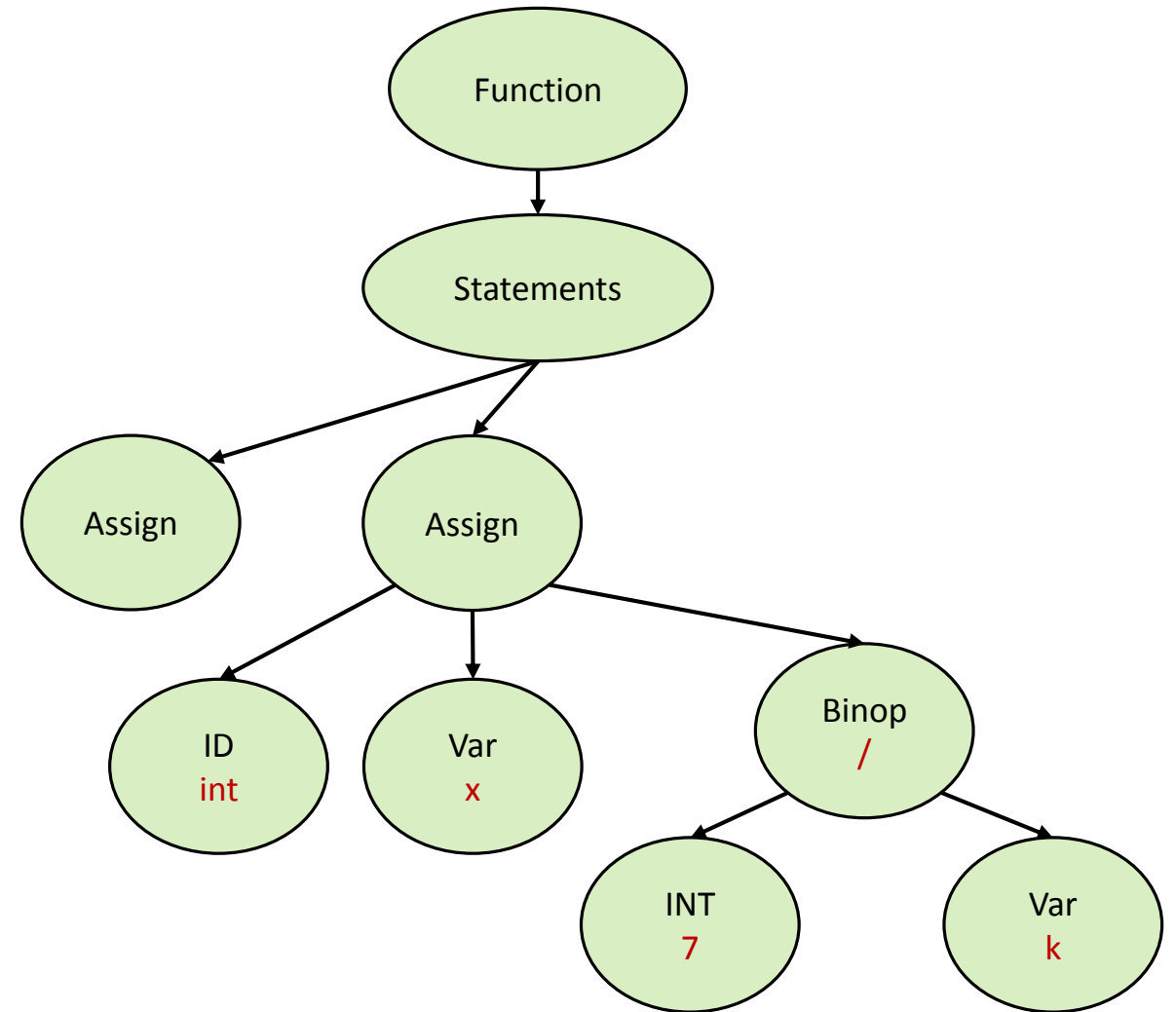
```
void main() {  
    int x = 7 / 0;  
}
```



Invalid

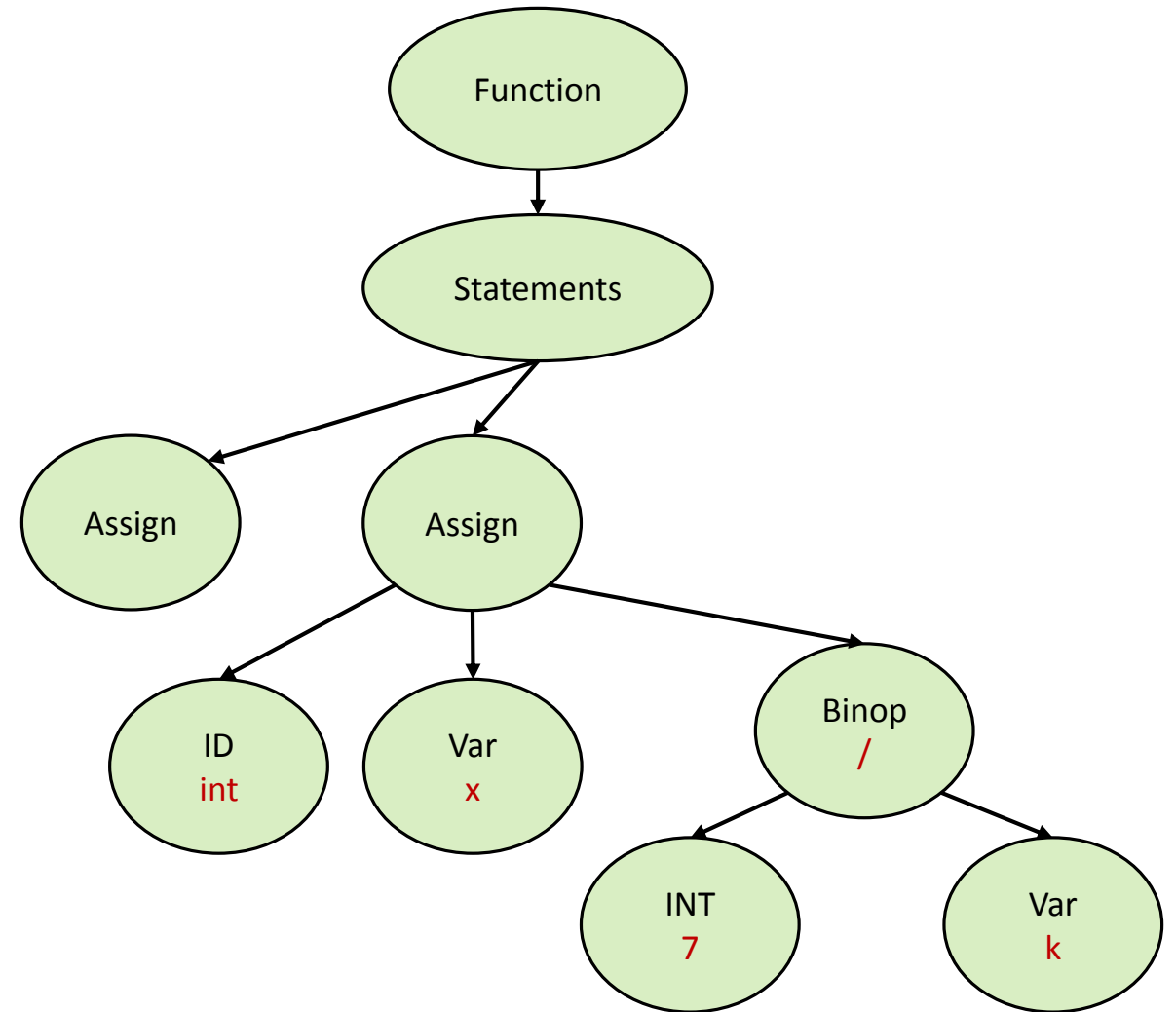
Binary Operations

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



Binary Operations

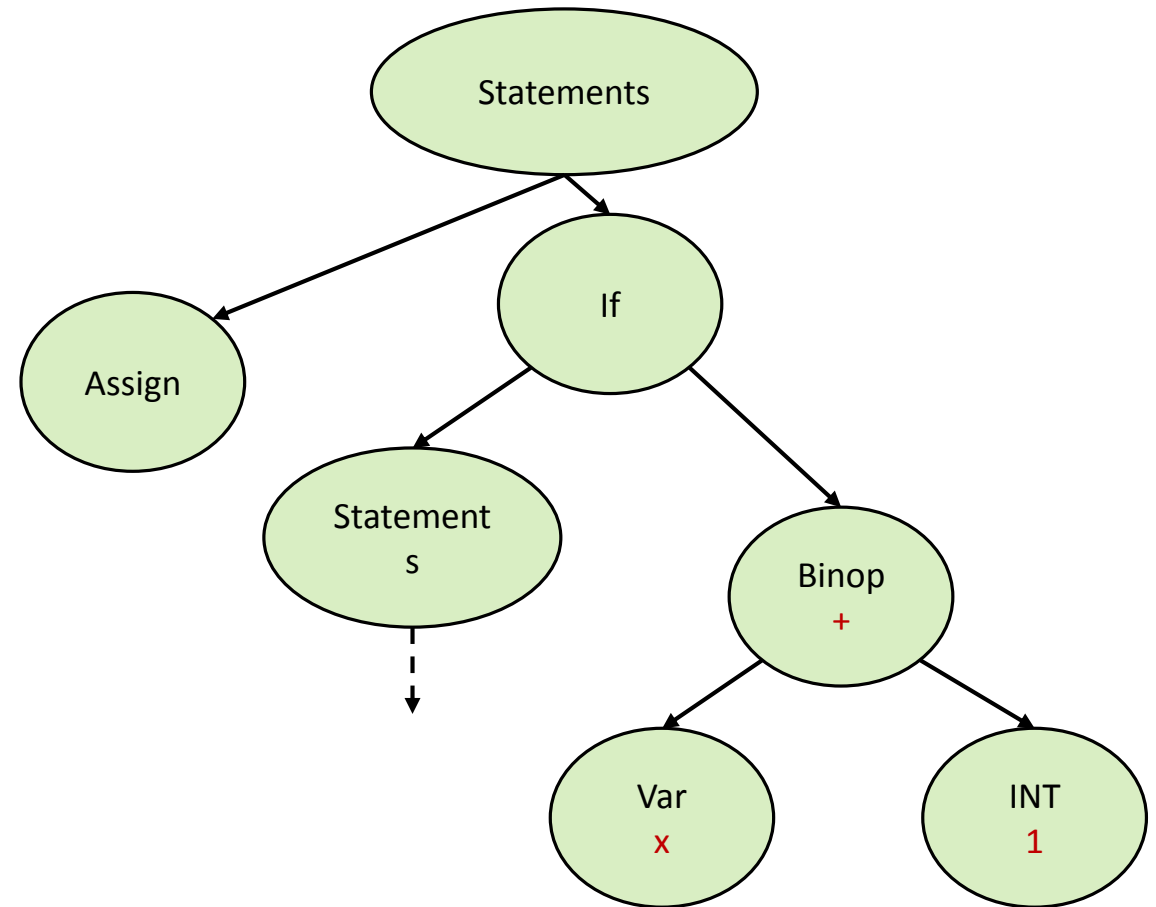
```
void main() {  
    int k = 0;  
    int x = 7 / k;  
}
```



Depends

If, While, ...

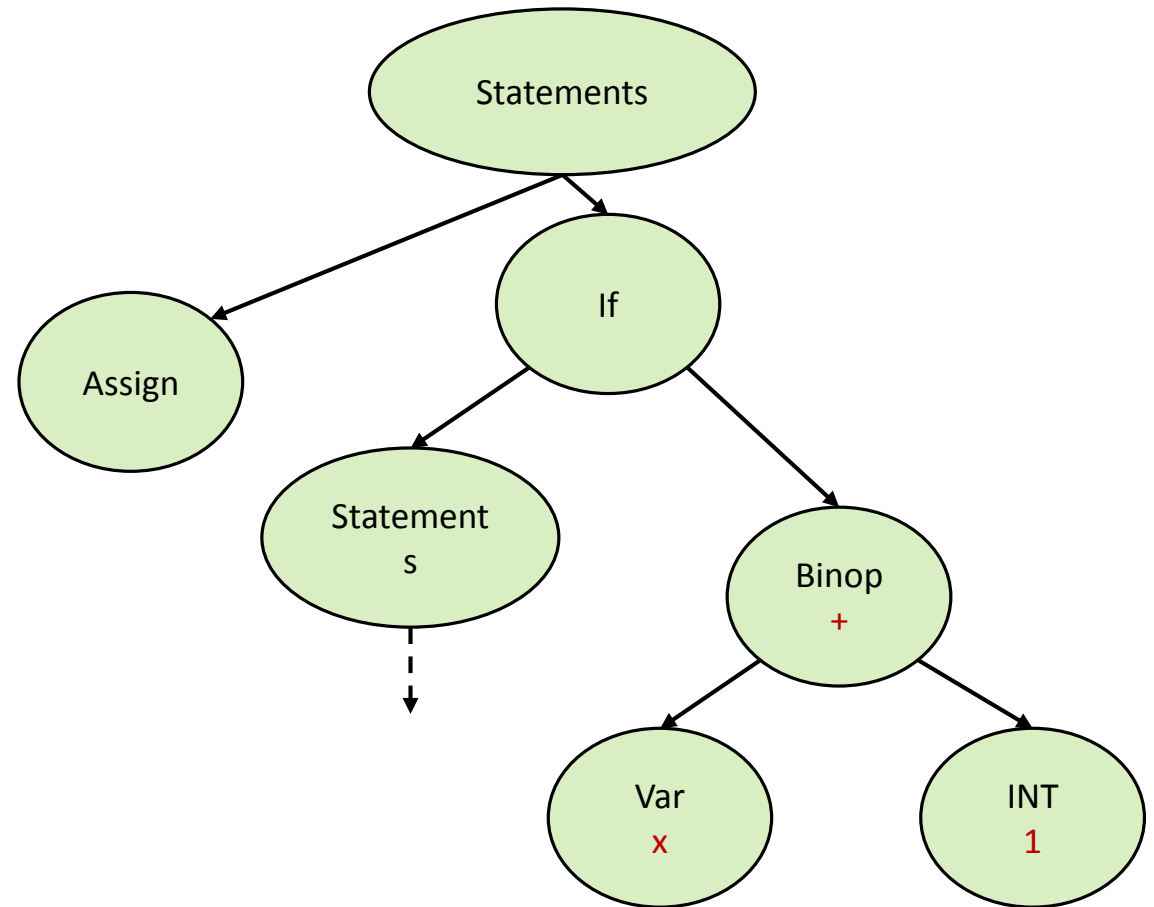
```
void main() {  
    int x = 1;  
    if (x + 1) {  
        int z = 2;  
    }  
}
```



If, While, ...

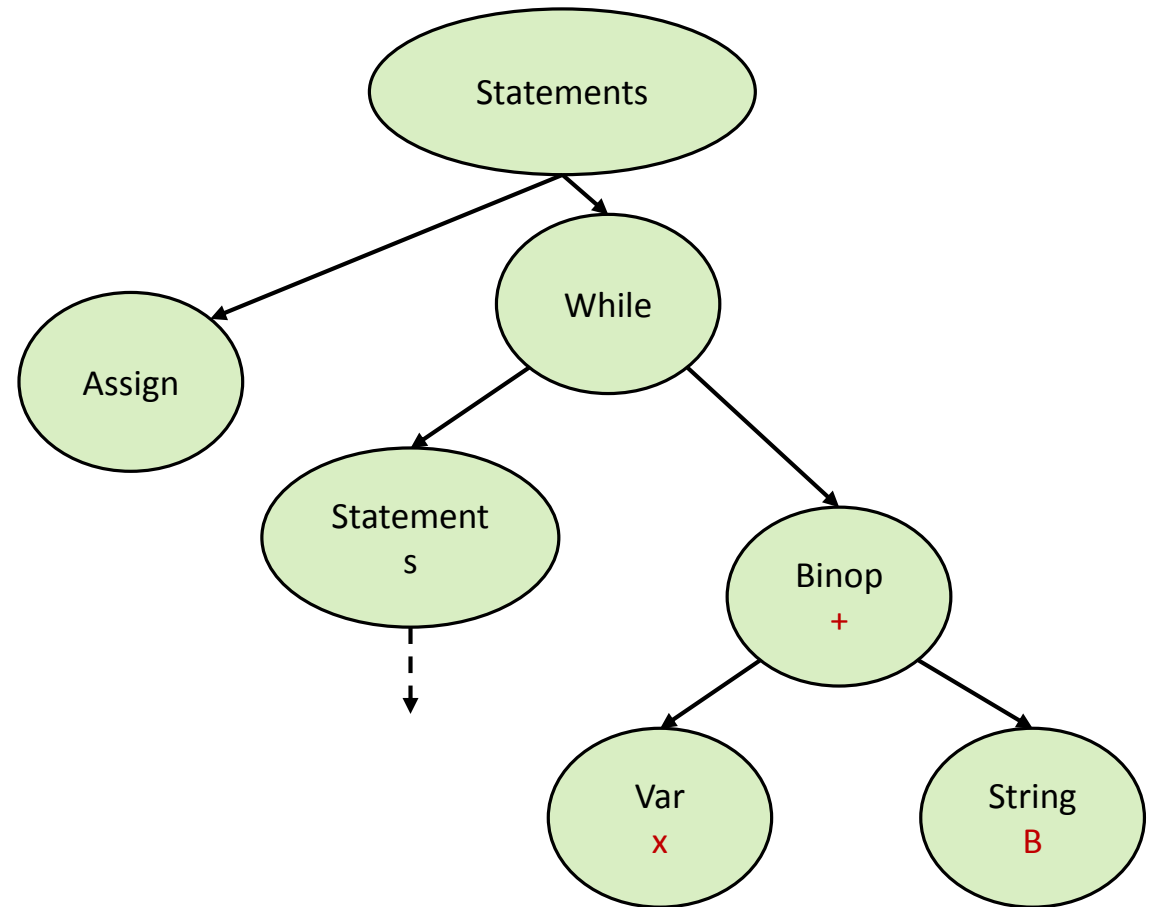
```
void main() {  
    int x = 1;  
    if (x + 1) {  
        int z = 2;  
    }  
}
```

Valid



If, While, ...

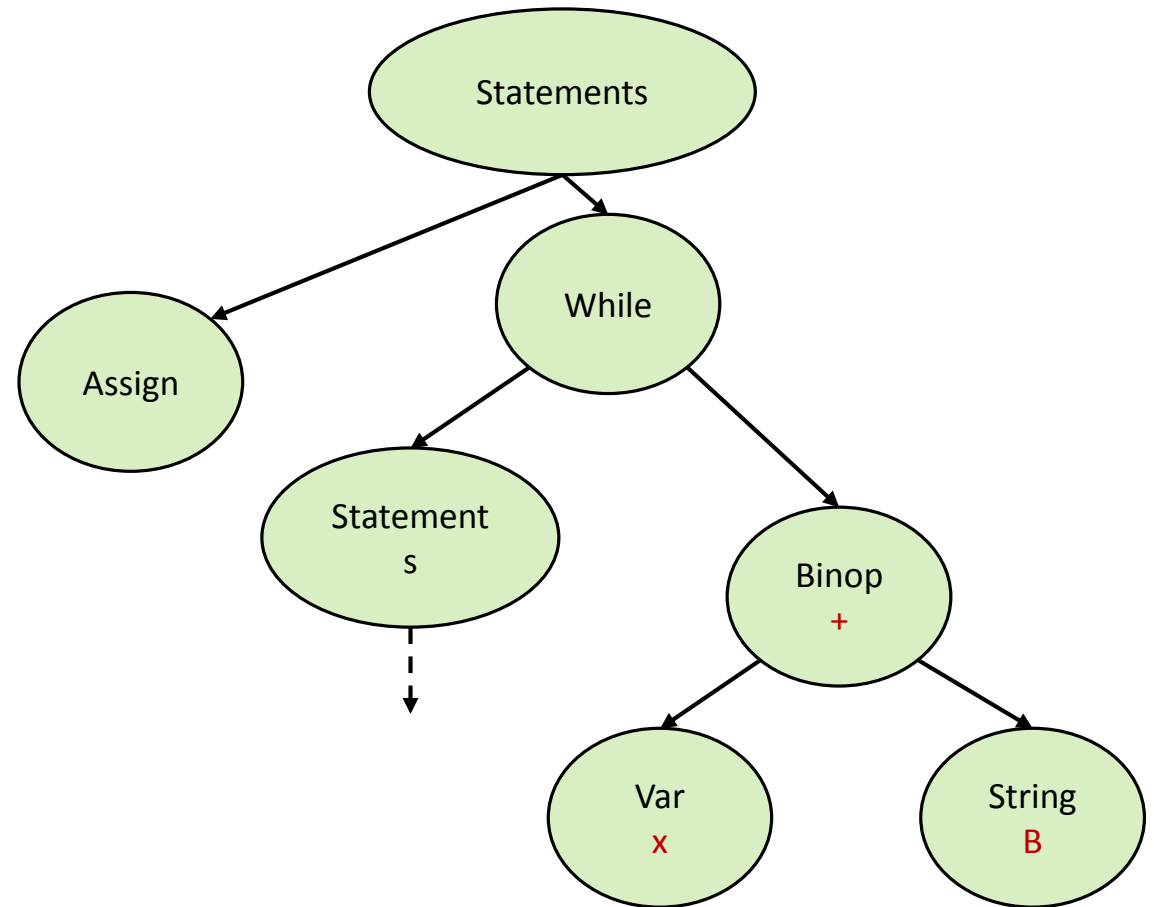
```
void main() {  
    string x = "A";  
    while (x + "B") {  
        int z = 2;  
    }  
}
```



If, While, ...

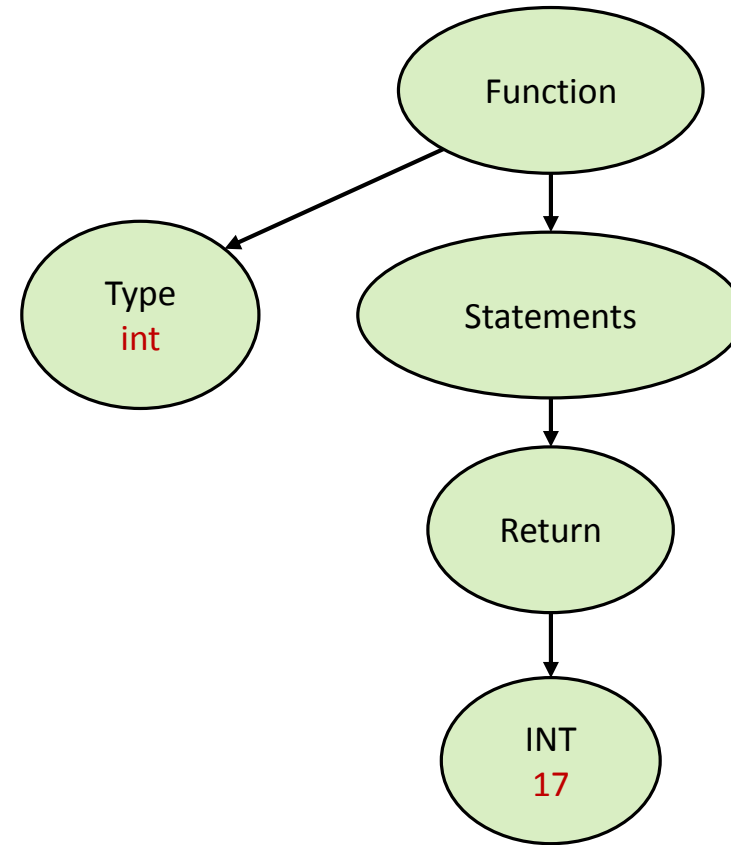
```
void main() {  
    string x = "A";  
    while (x + "B") {  
        int z = 2;  
    }  
}
```

Invalid



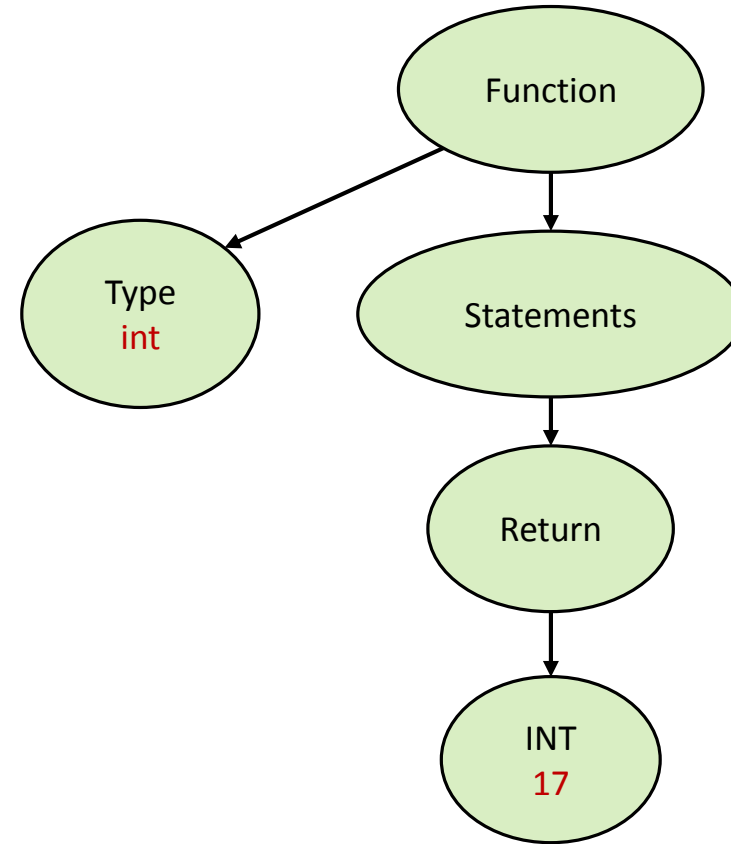
Return Statement

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



Return Statement

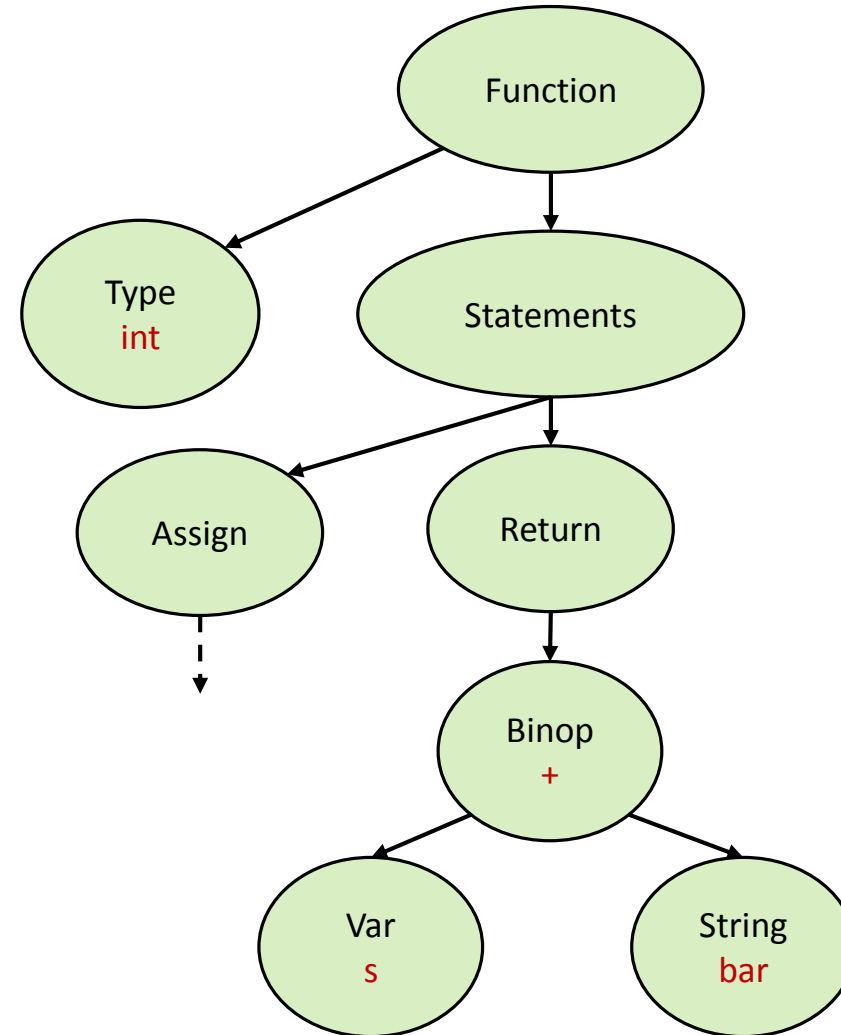
```
int main() {  
    return 17;  
}
```



Valid

Return Statement

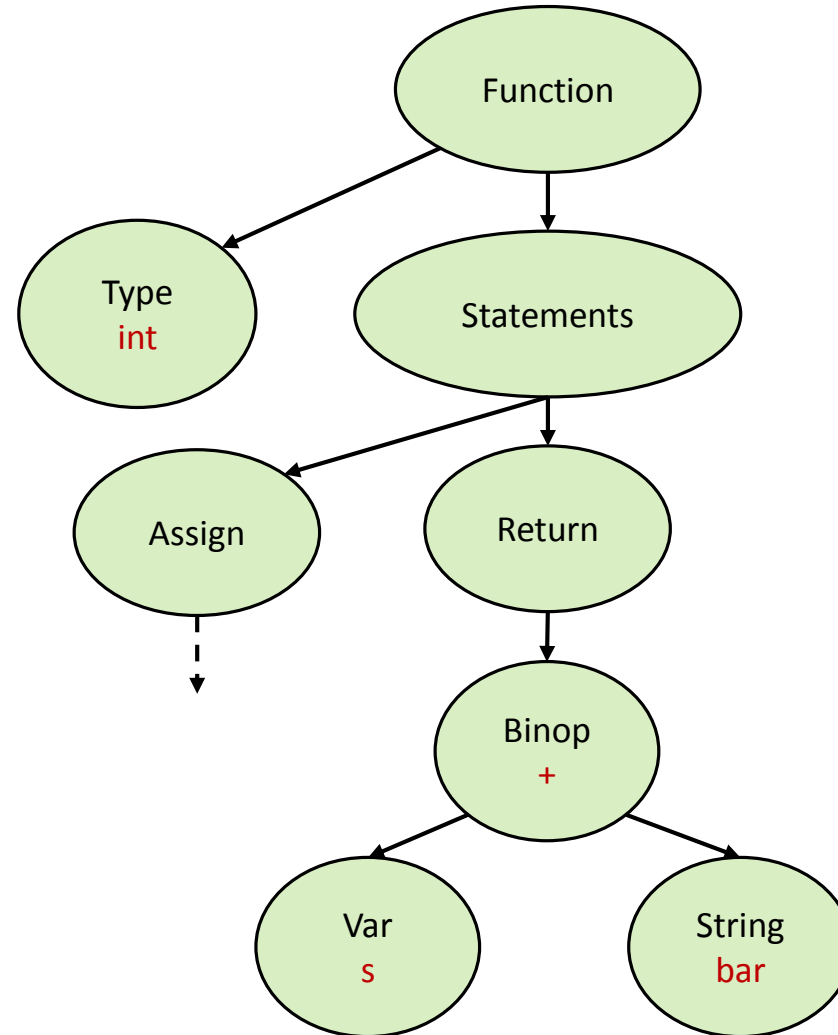
```
int main() {  
    string s = "foo"  
    return s + "bar";  
}
```



Return Statement

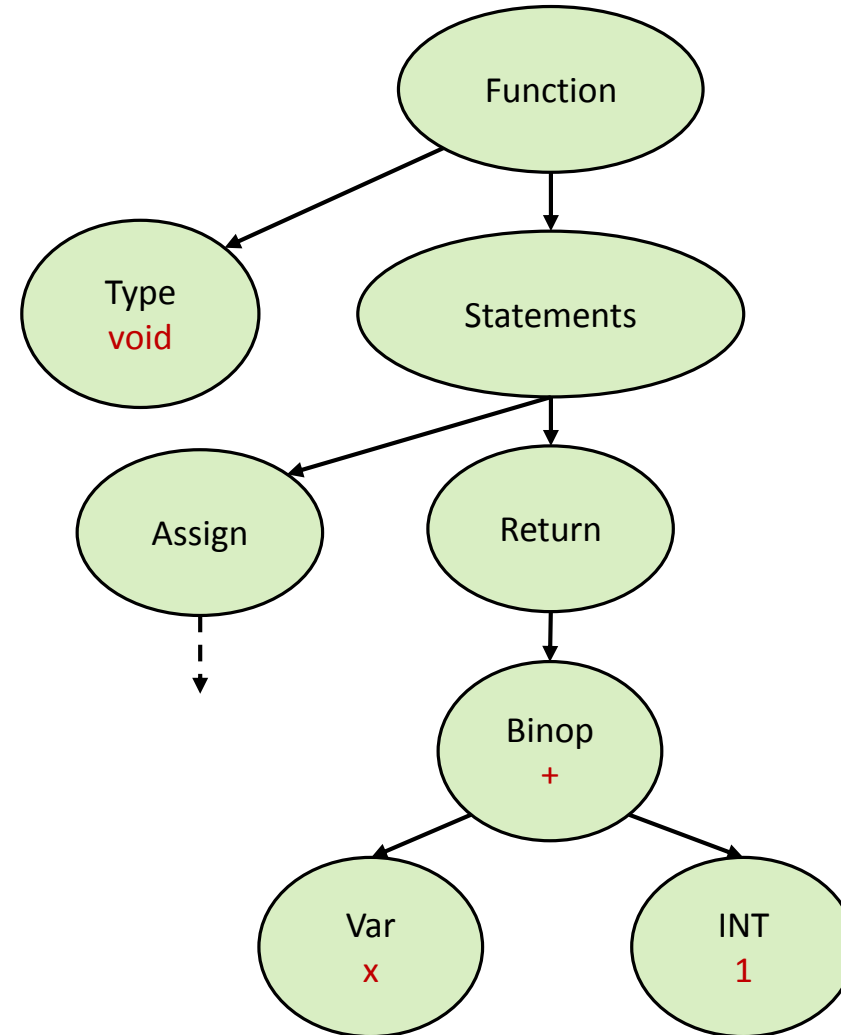
```
int main() {  
    string s = "foo"  
    return s + "bar";  
}
```

Invalid



Return Statement

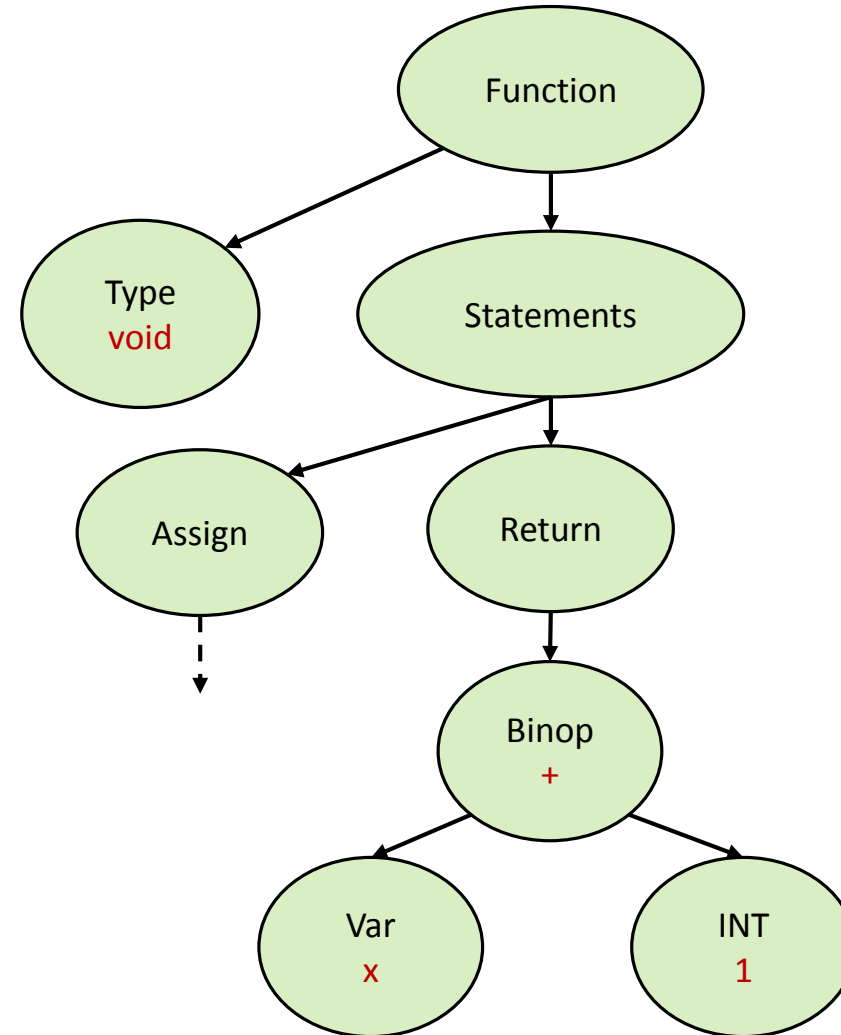
```
void main() {  
    int x = 1;  
    return x + 1;  
}
```



Return Statement

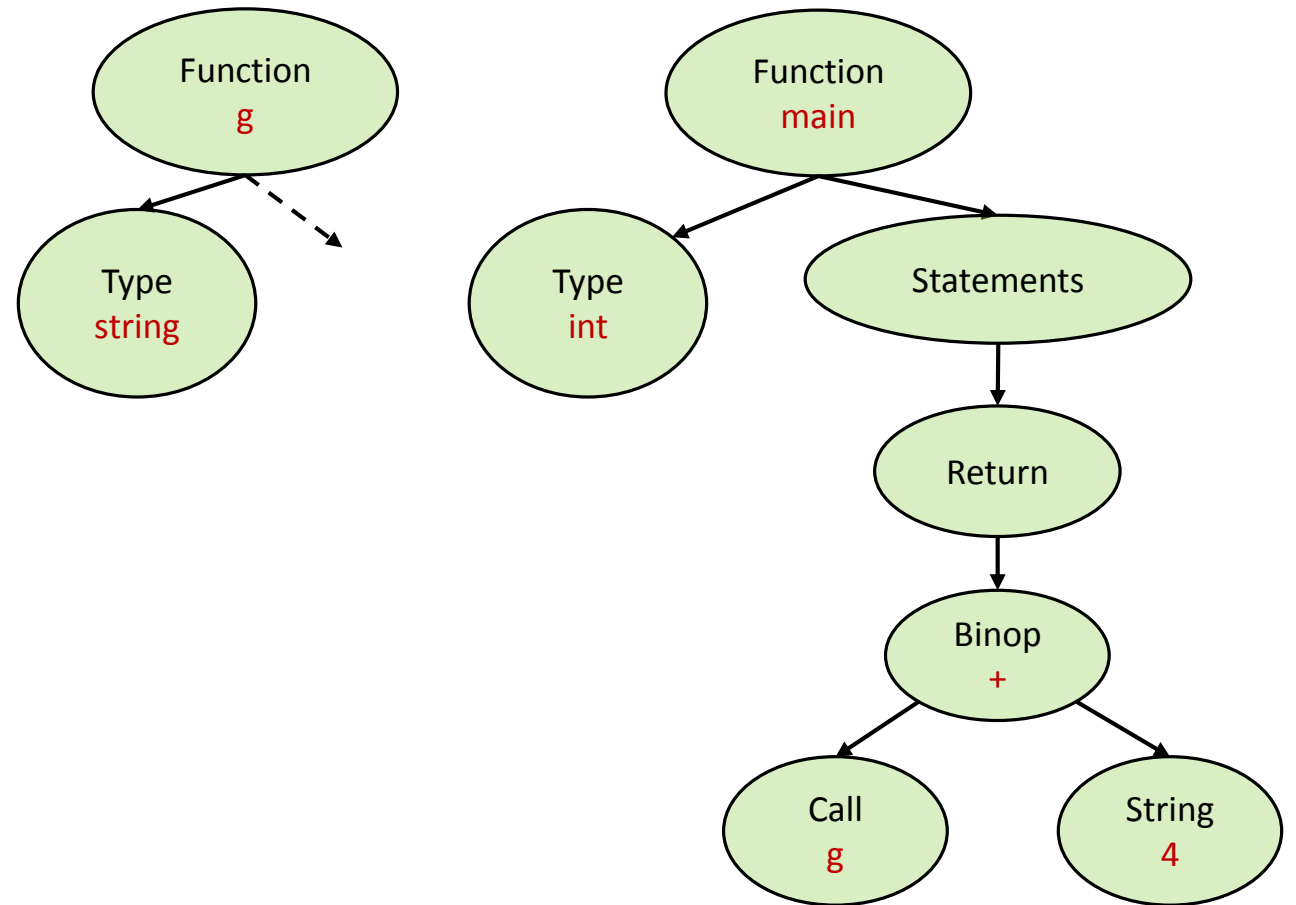
```
void main() {  
    int x = 1;  
    return x + 1;  
}
```

Invalid



Return Statement

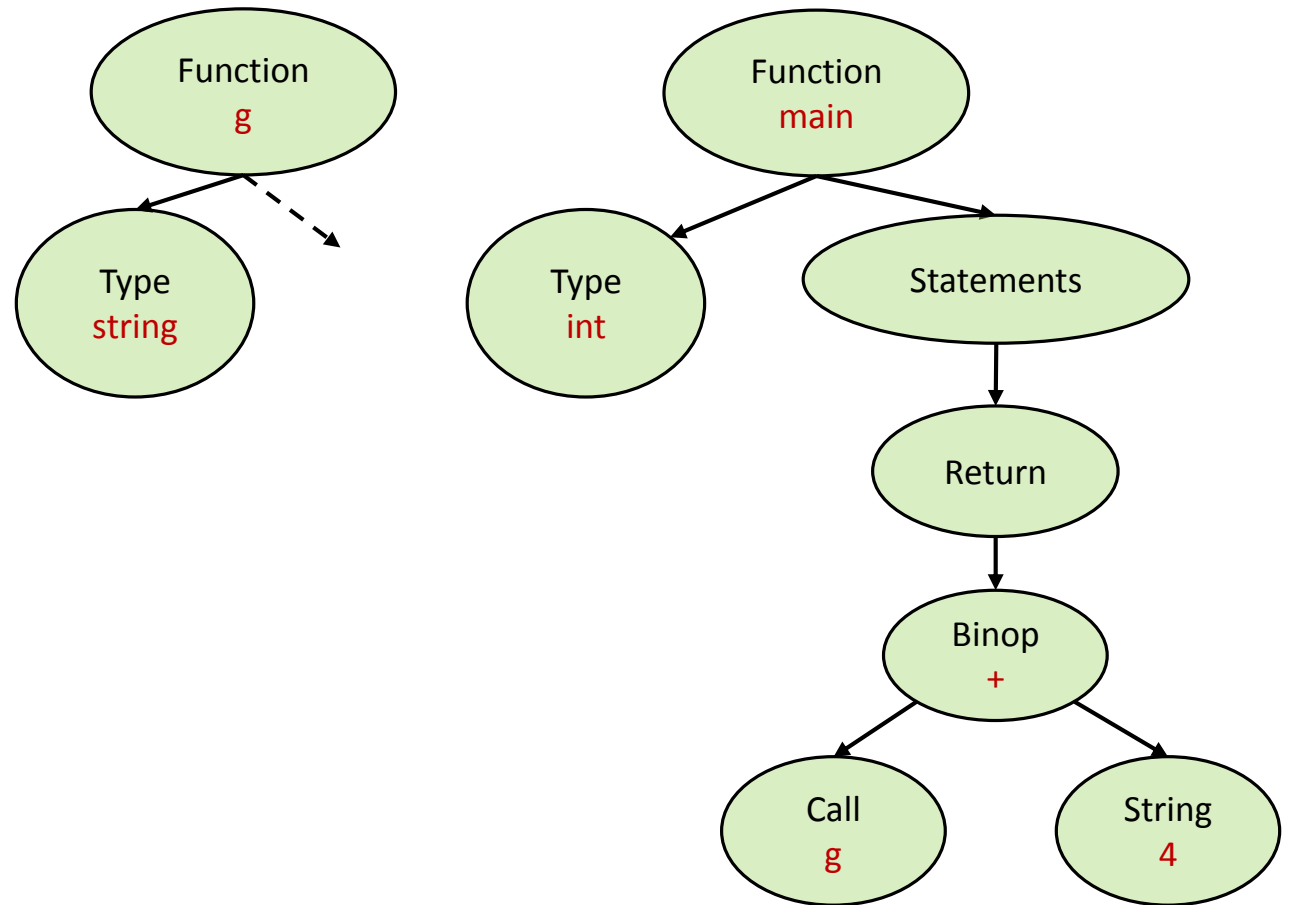
```
string g() {  
    return "123";  
}  
int main() {  
    return g() + "4";  
}
```



Return Statement

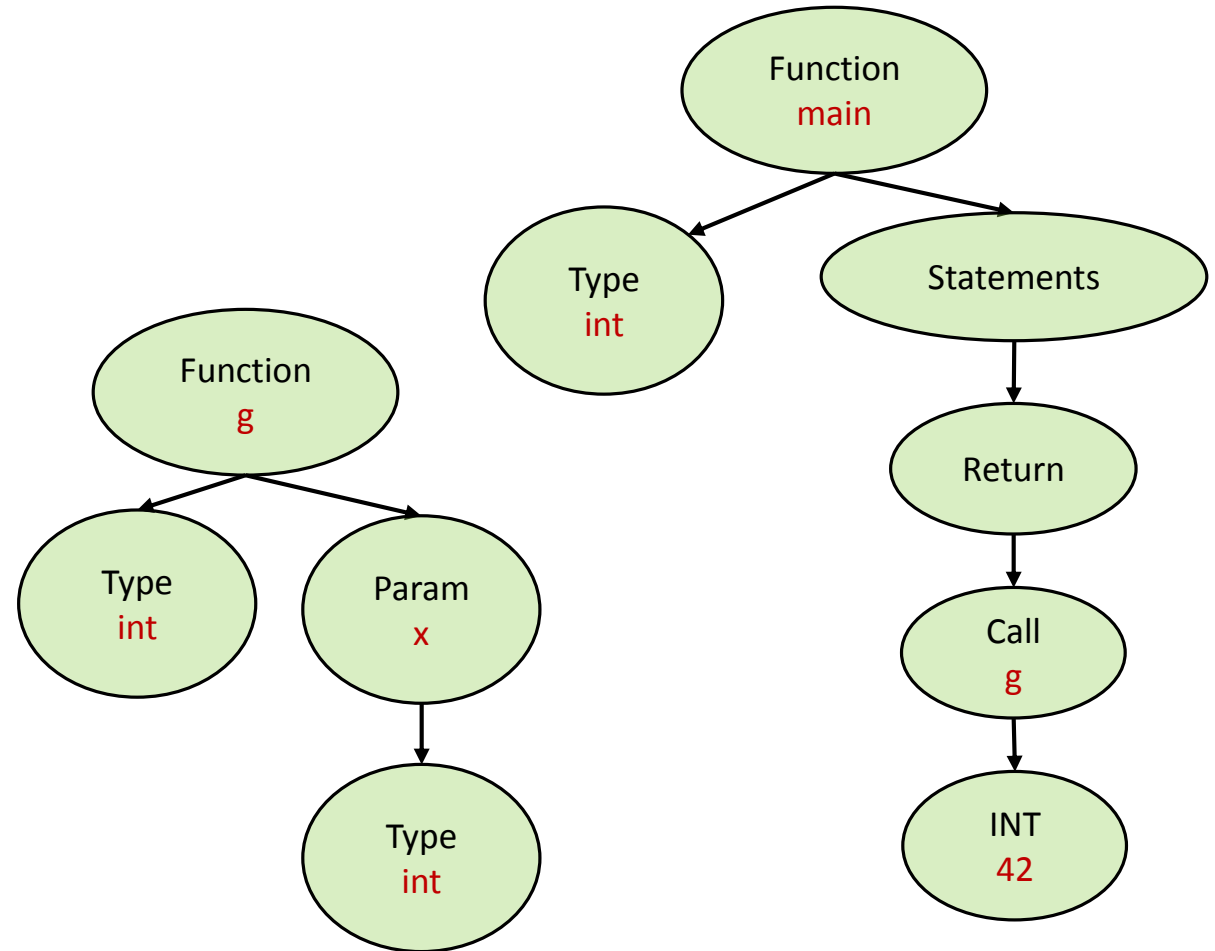
```
string g() {  
    return "123";  
}  
int main() {  
    return g() + "4";  
}
```

Invalid



Function Calls

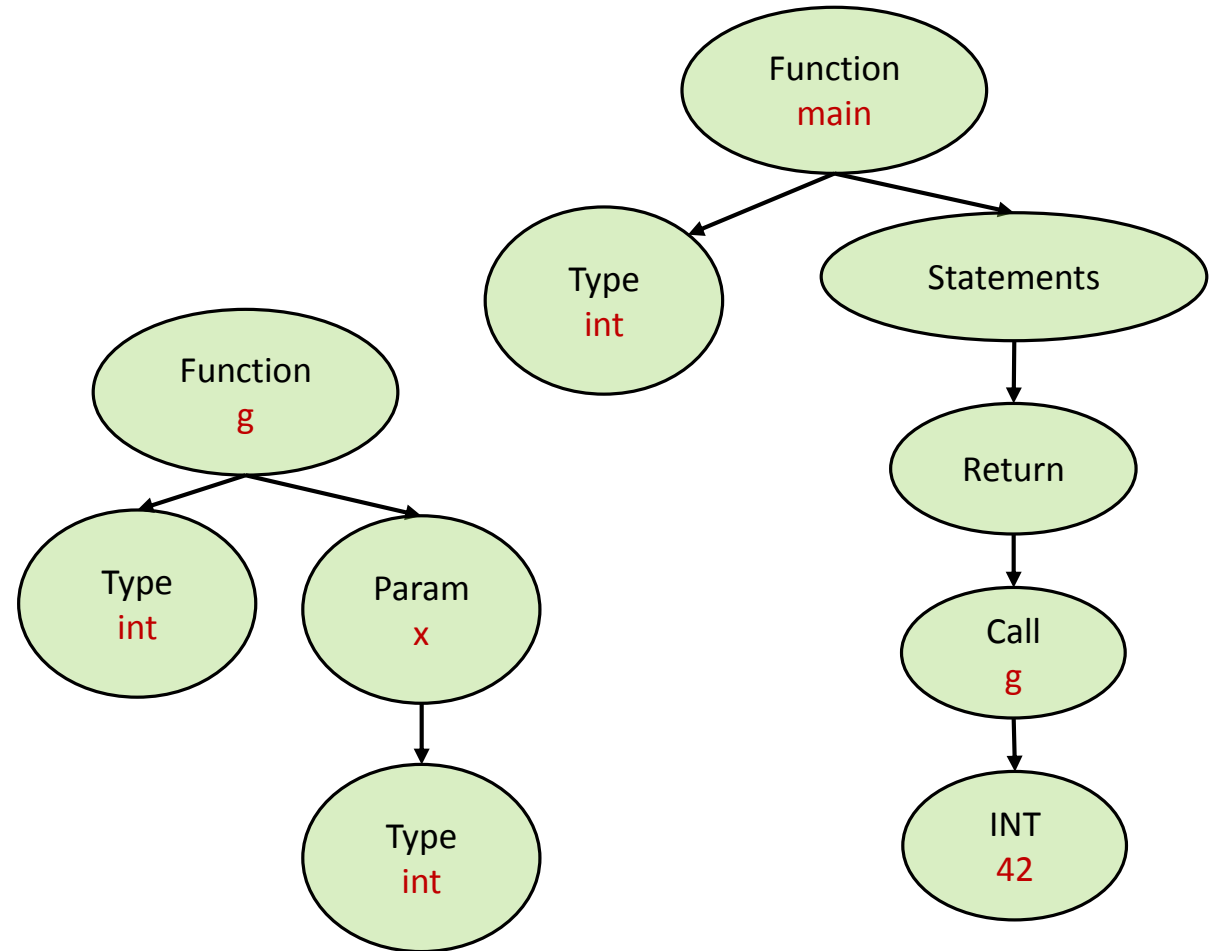
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    return g(42);  
}
```



Function Calls

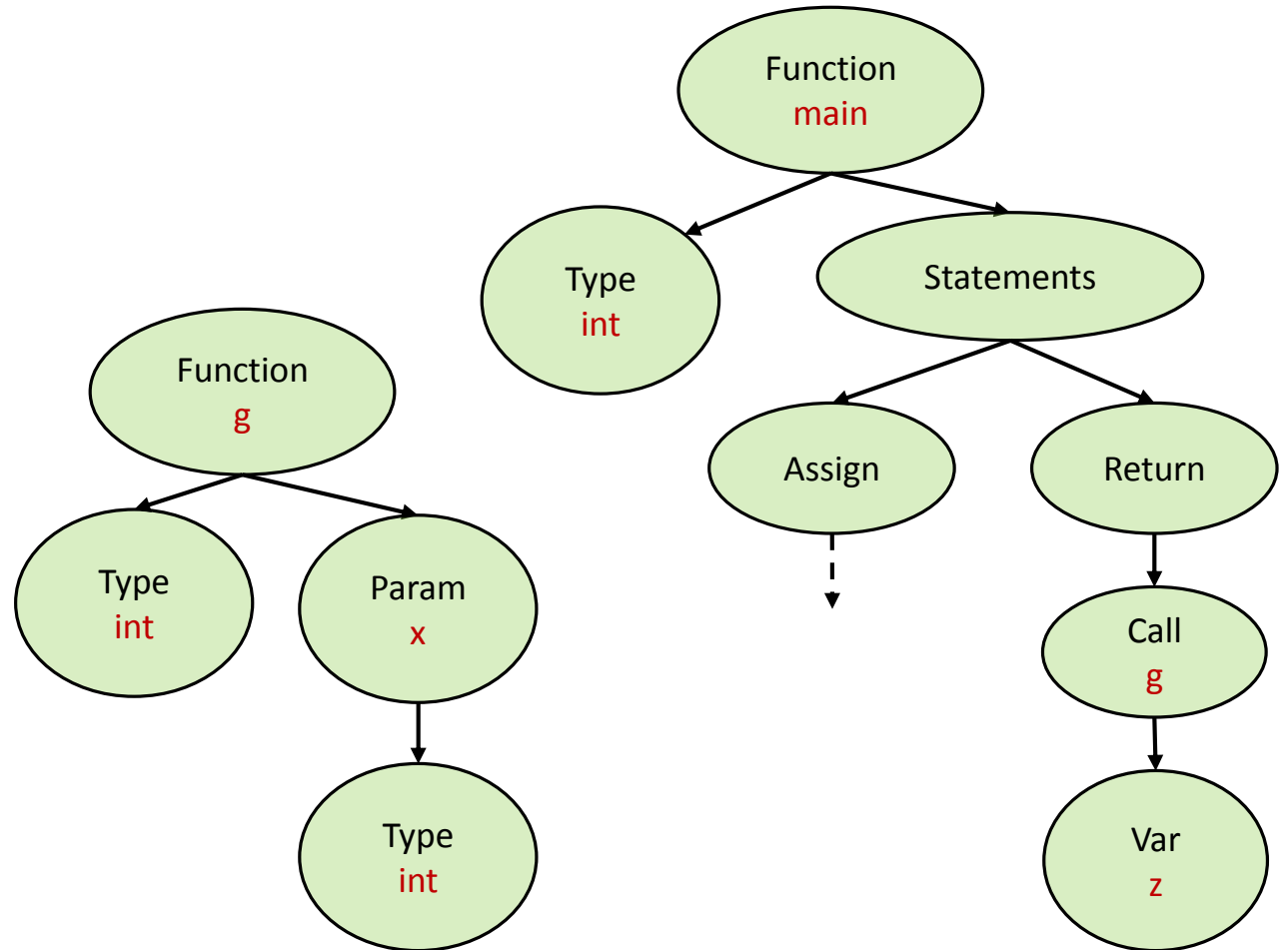
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    return g(42);  
}
```

Valid



Function Calls

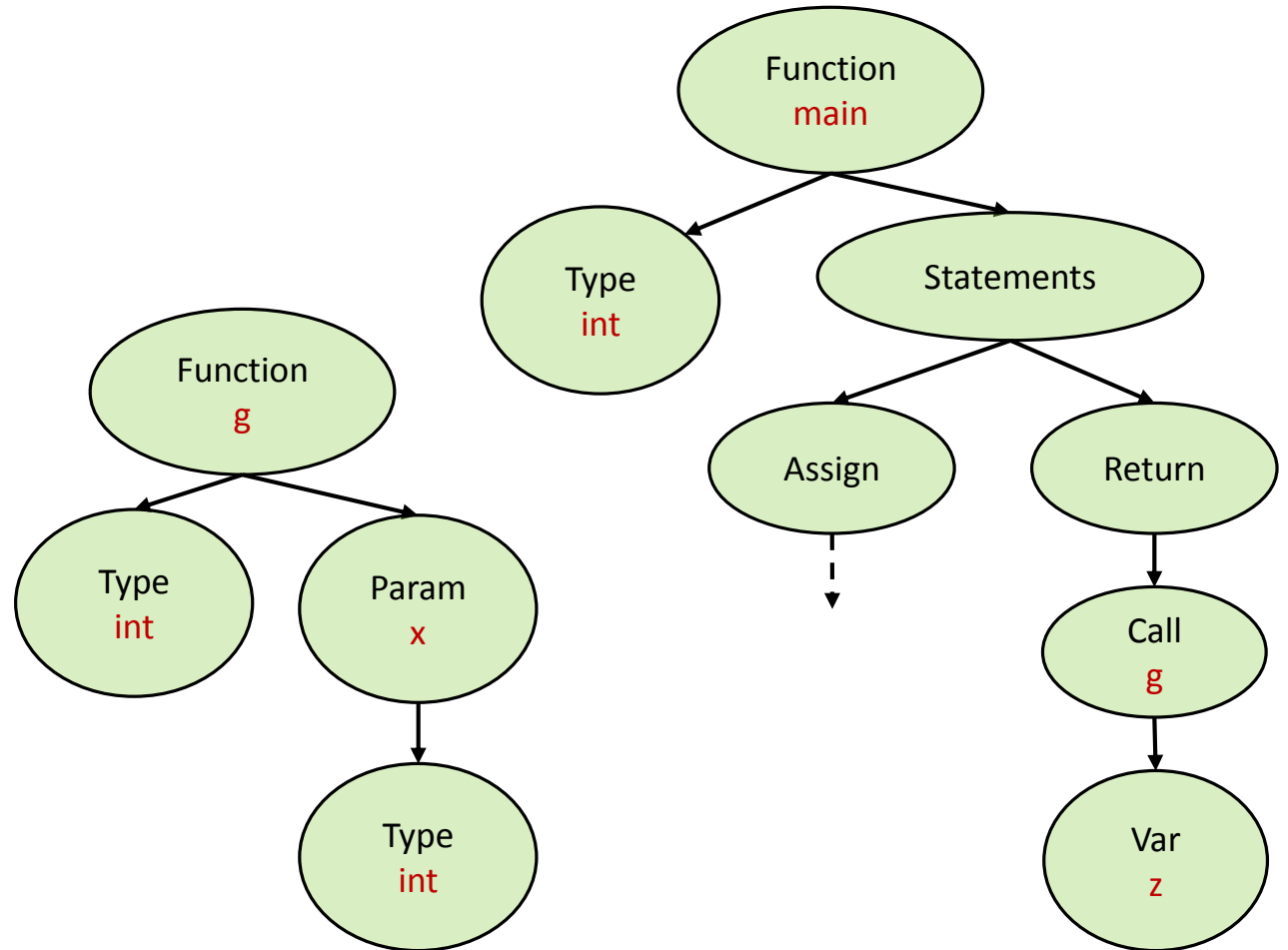
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    string z = "..."  
    return g(z);  
}
```



Function Calls

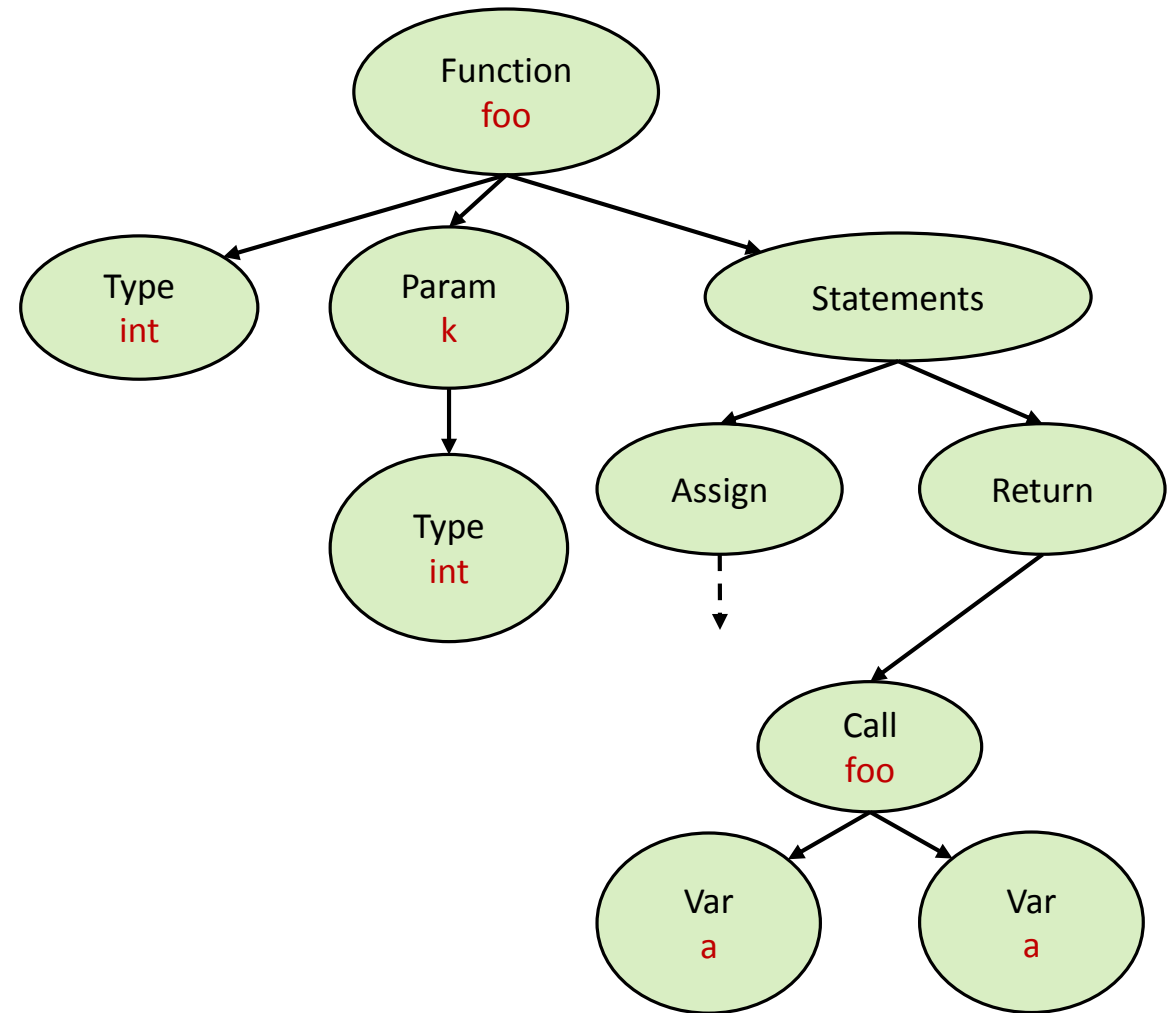
```
int g(int x) {  
    return x + 1;  
}  
int main() {  
    string z = "..."  
    return g(z);  
}
```

Invalid



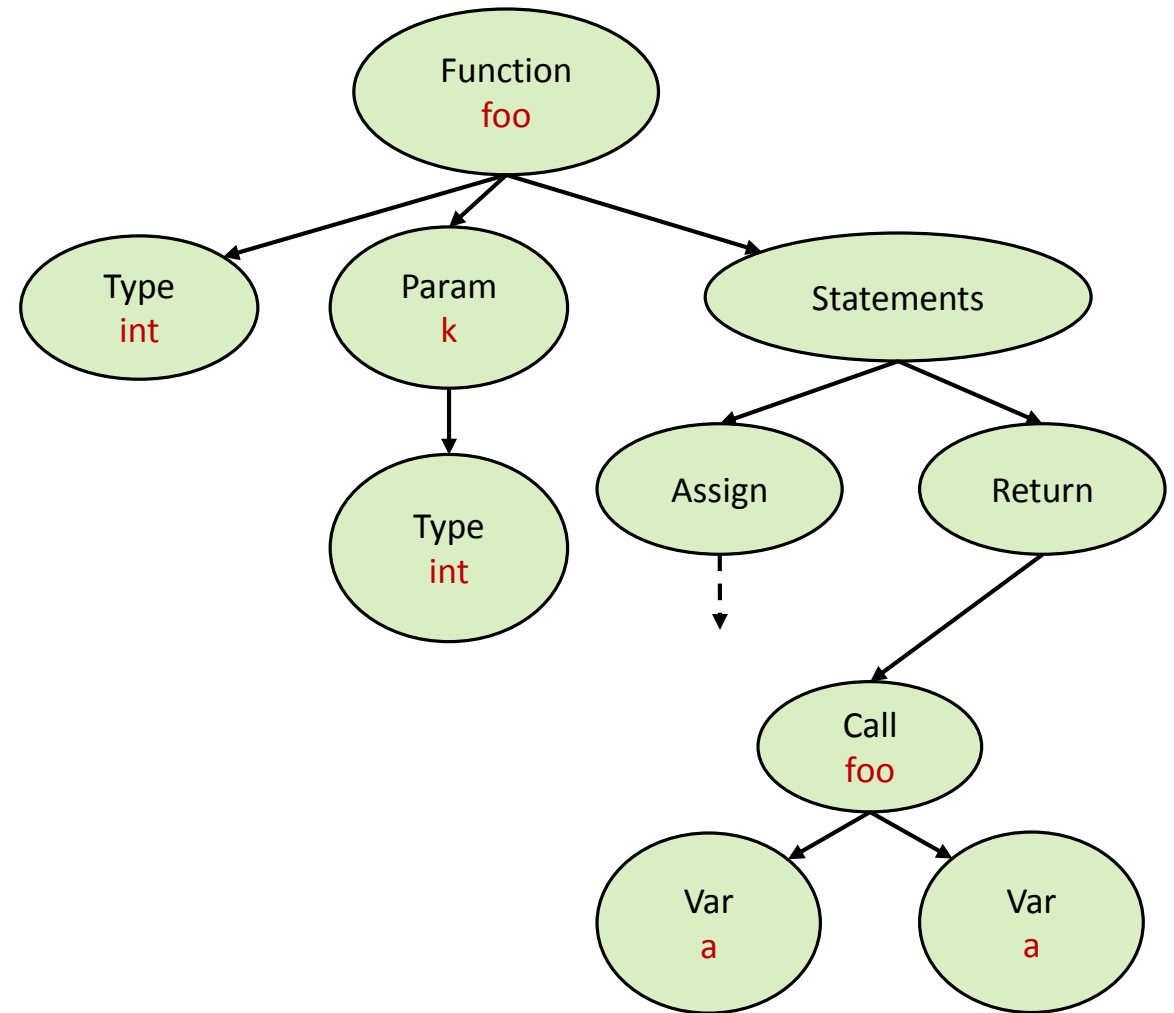
Function Calls

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



Function Calls

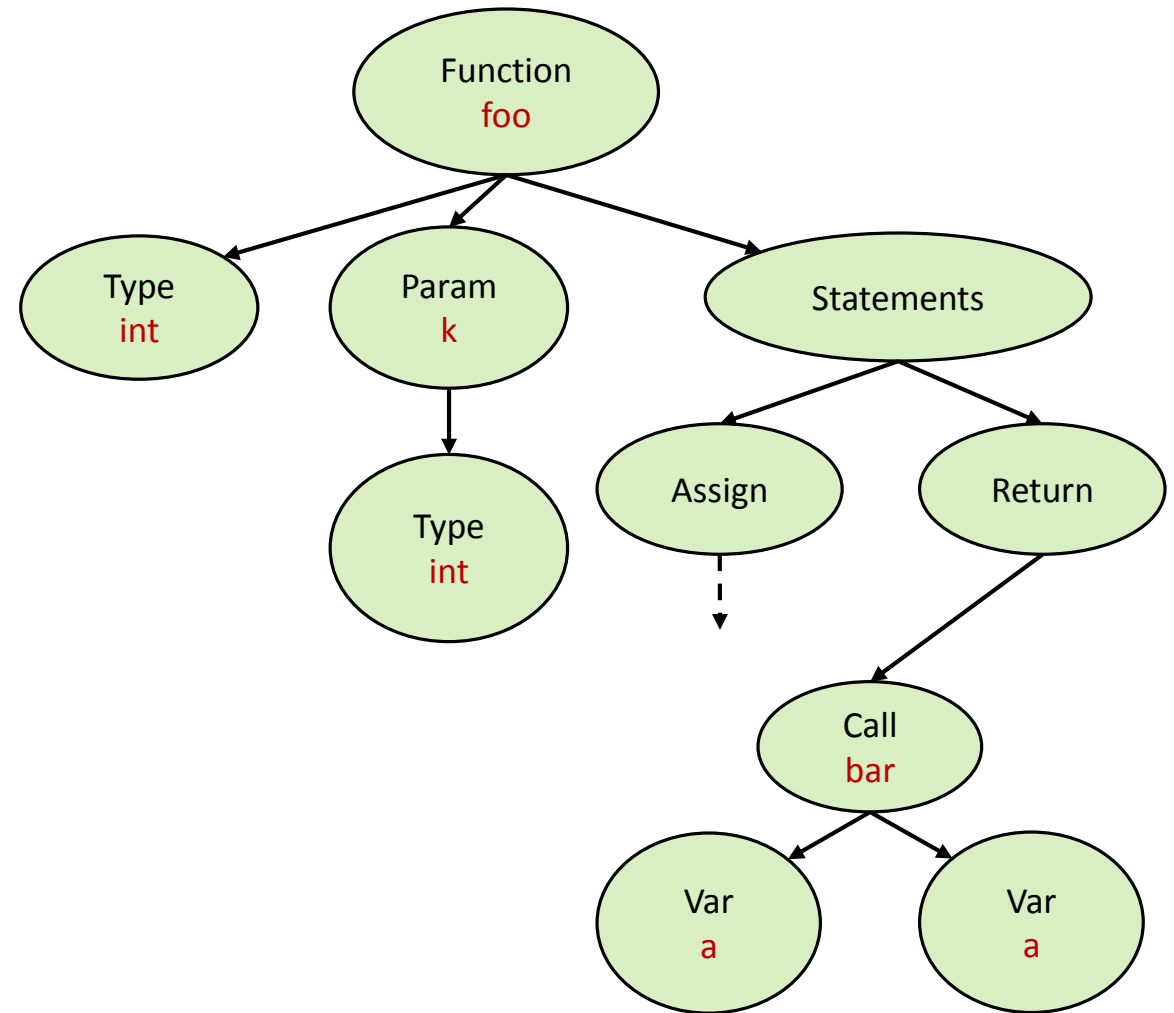
```
int foo(int k) {  
    int a = k * 10;  
    return foo(a, a);  
}
```



Invalid

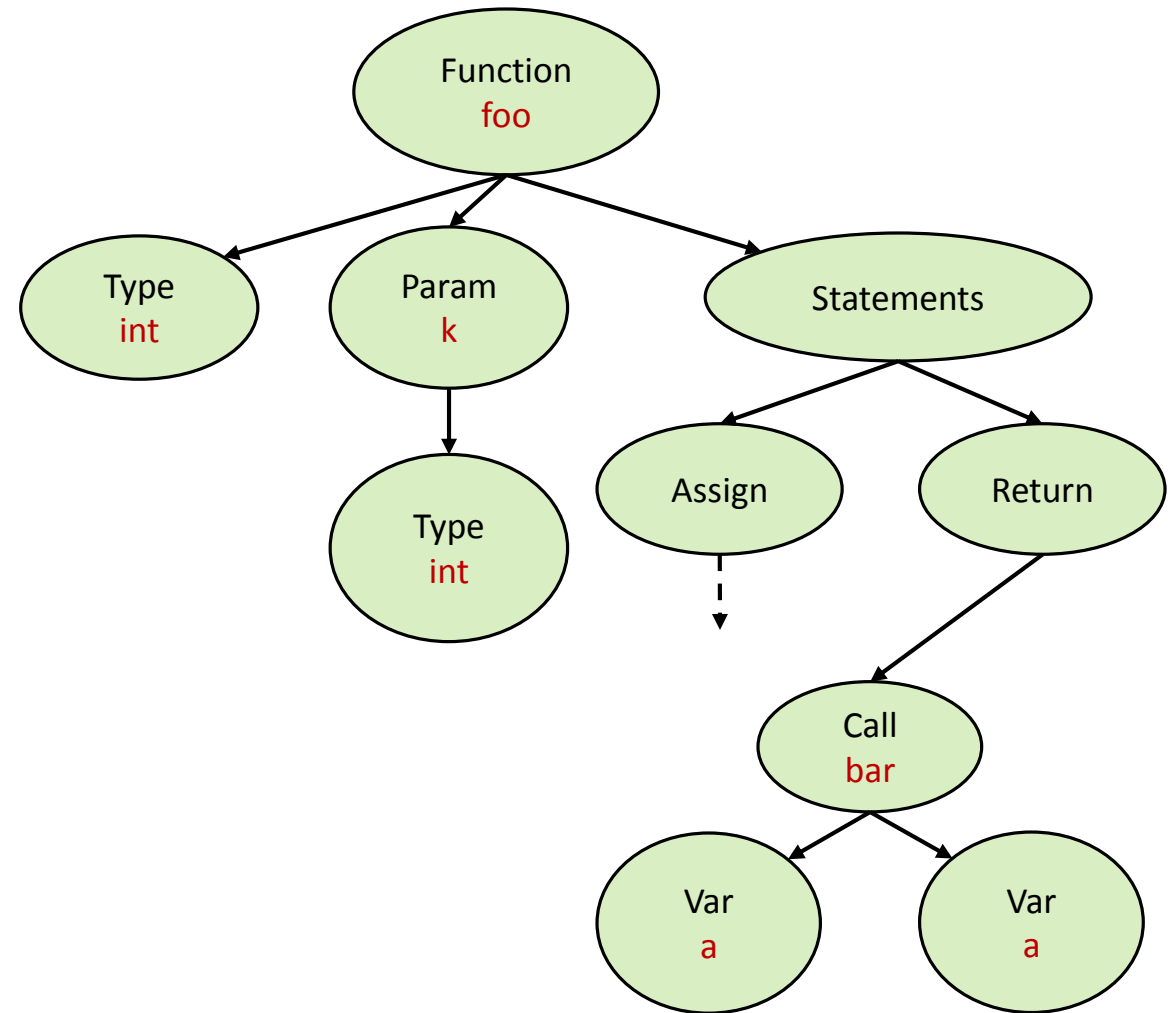
Function Calls

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



Function Calls

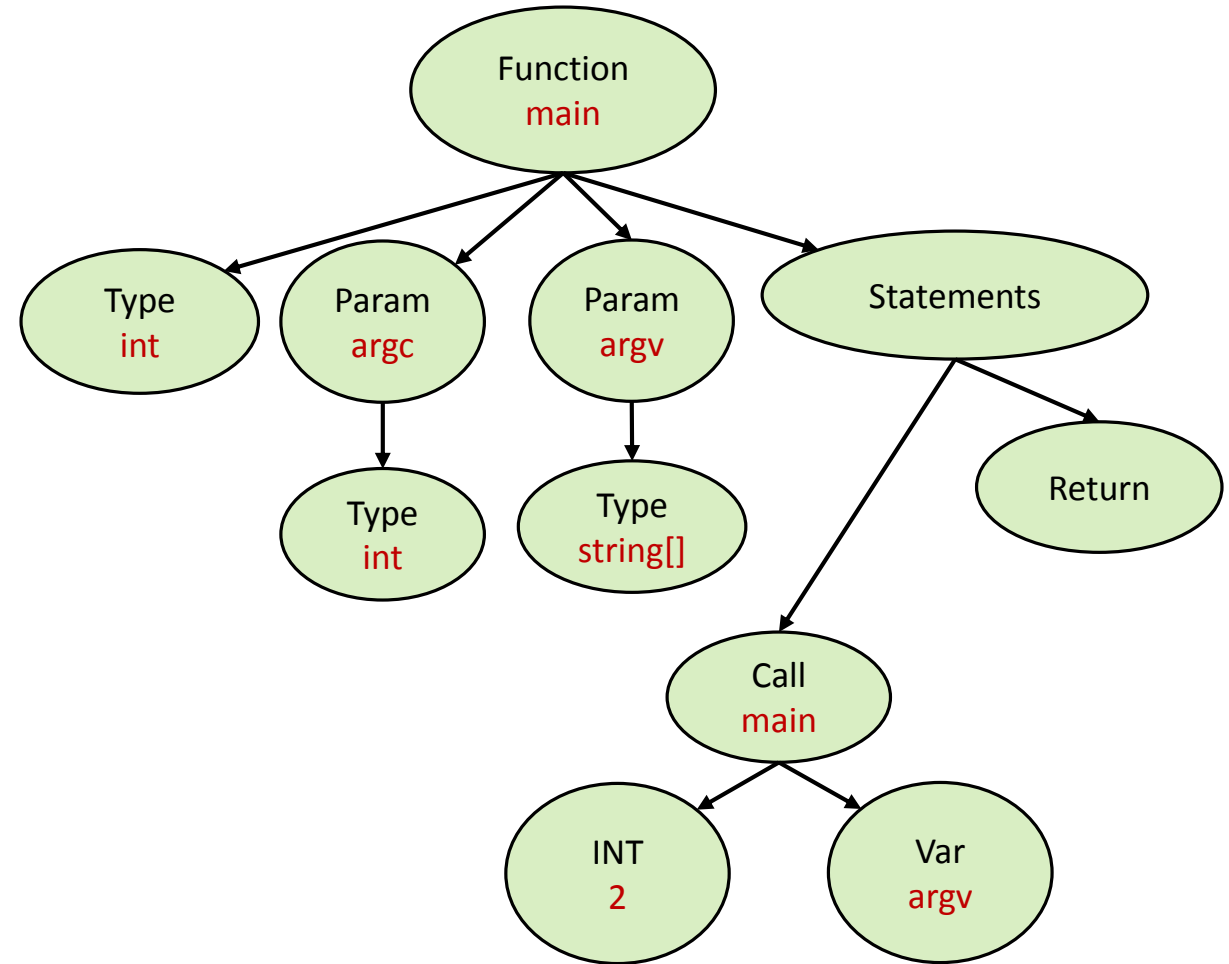
```
int foo(int k) {  
    int a = k * 10;  
    return bar(a, a);  
}
```



Invalid

Function Calls

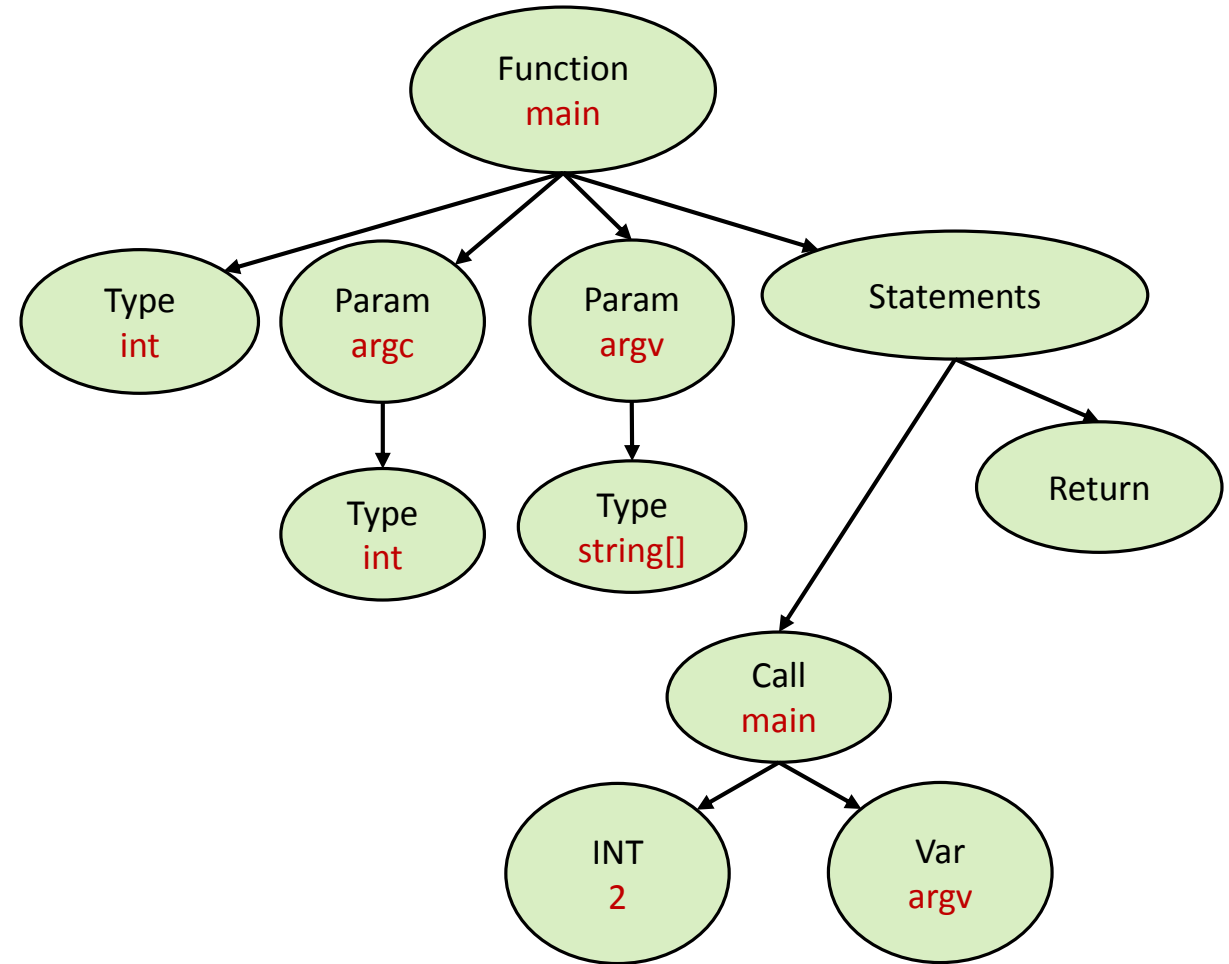
```
int main(int argc,  
          string argv[]){  
    main(2, argv);  
    return 0;  
}
```



Function Calls

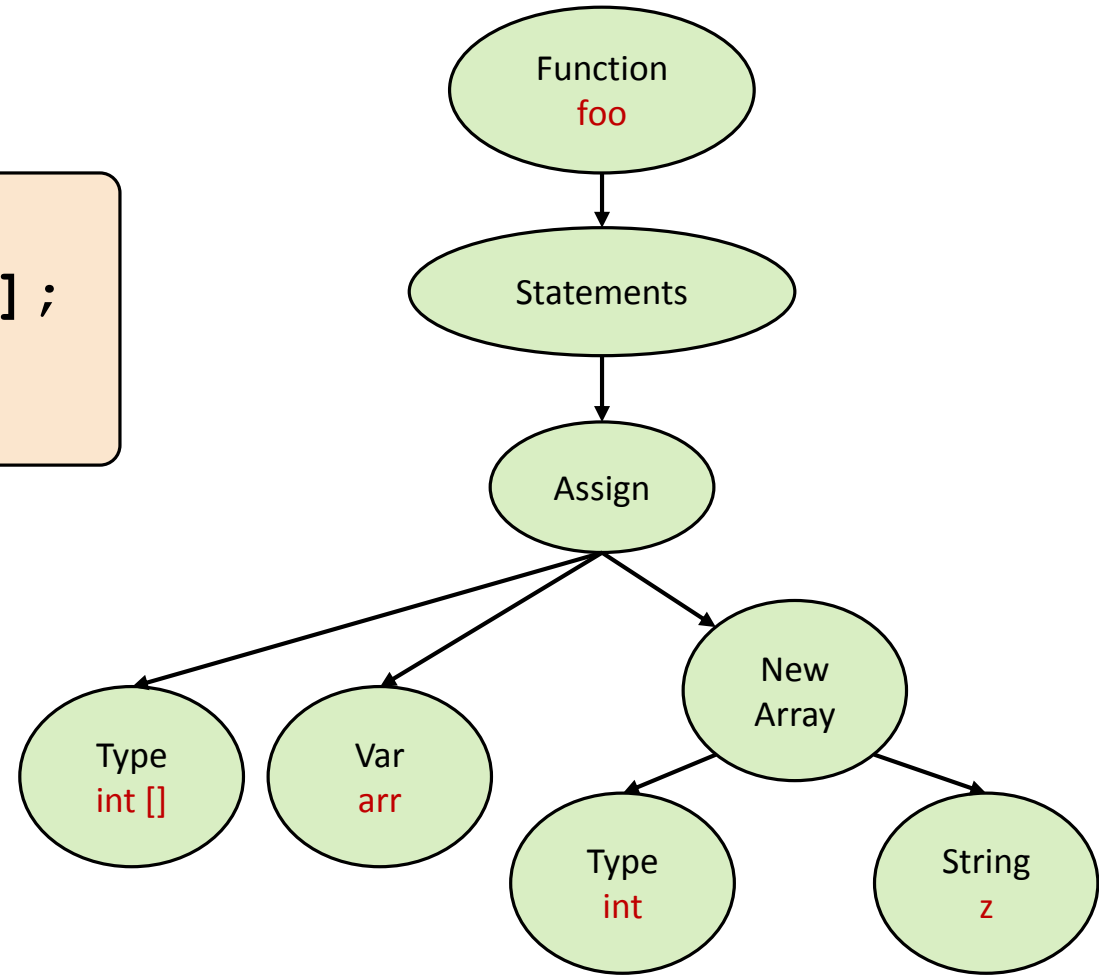
```
int main(int argc,  
          string argv[]){  
    main(2, argv);  
    return 0;  
}
```

Valid



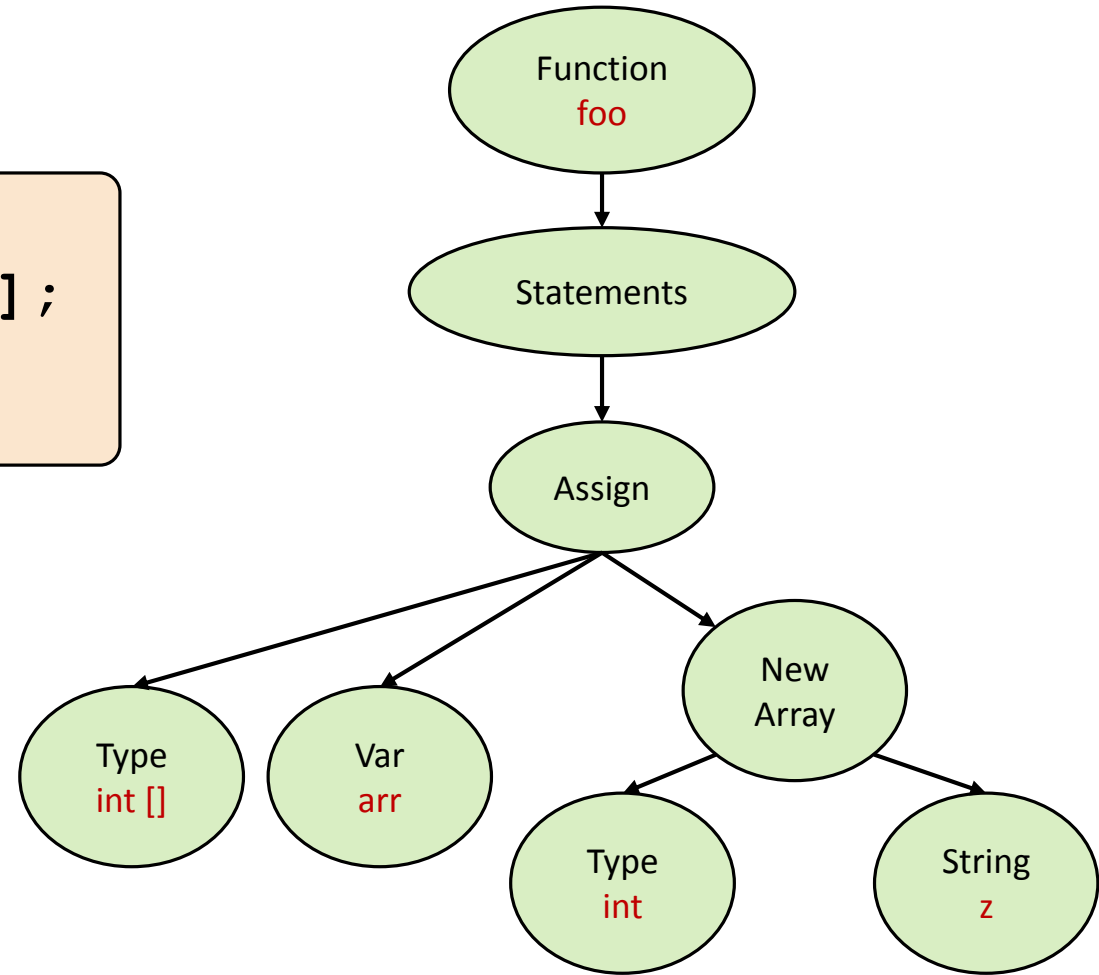
Arrays

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



Arrays

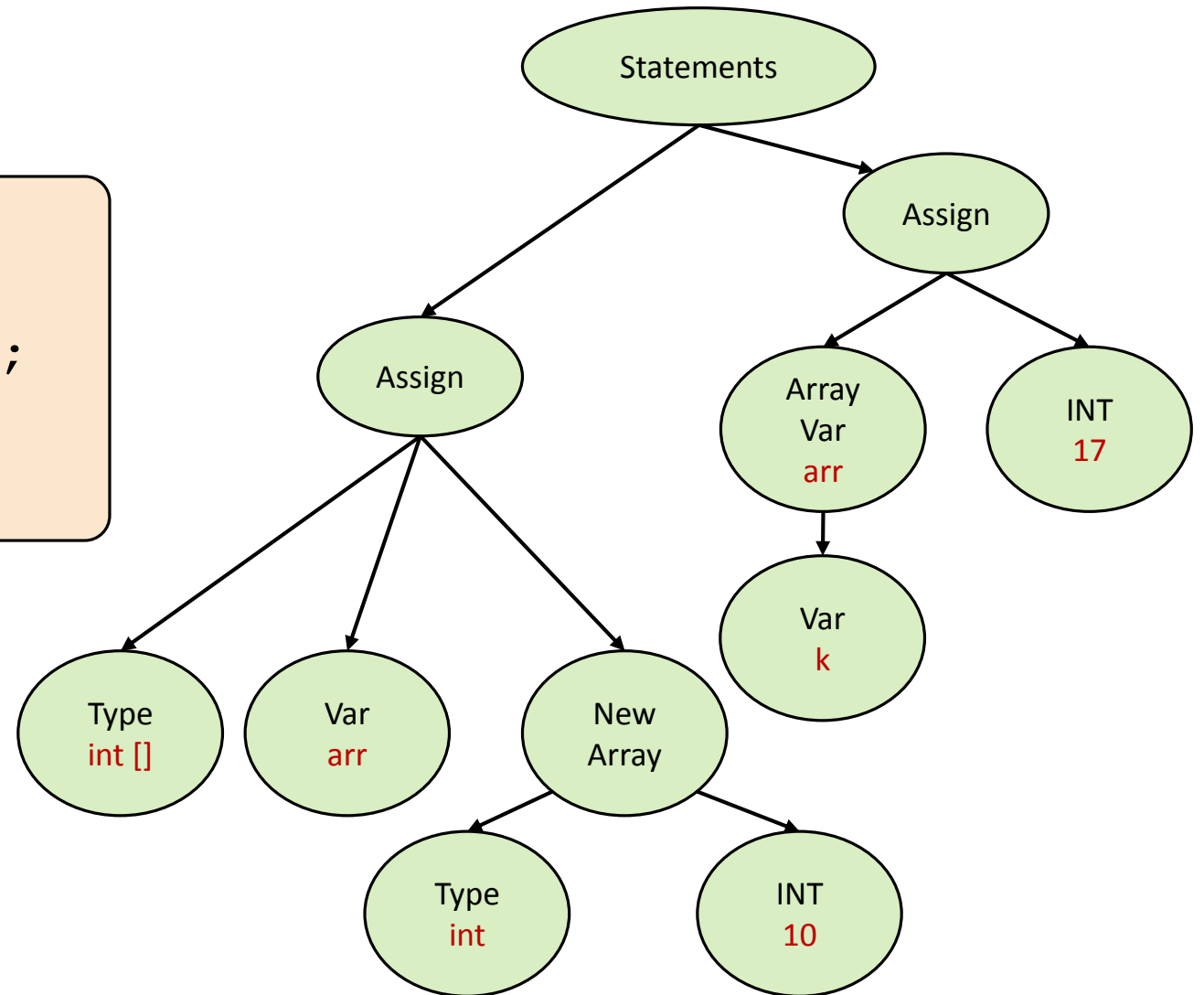
```
void foo(void) {  
    int[] arr = new int["z"];  
}
```



Invalid

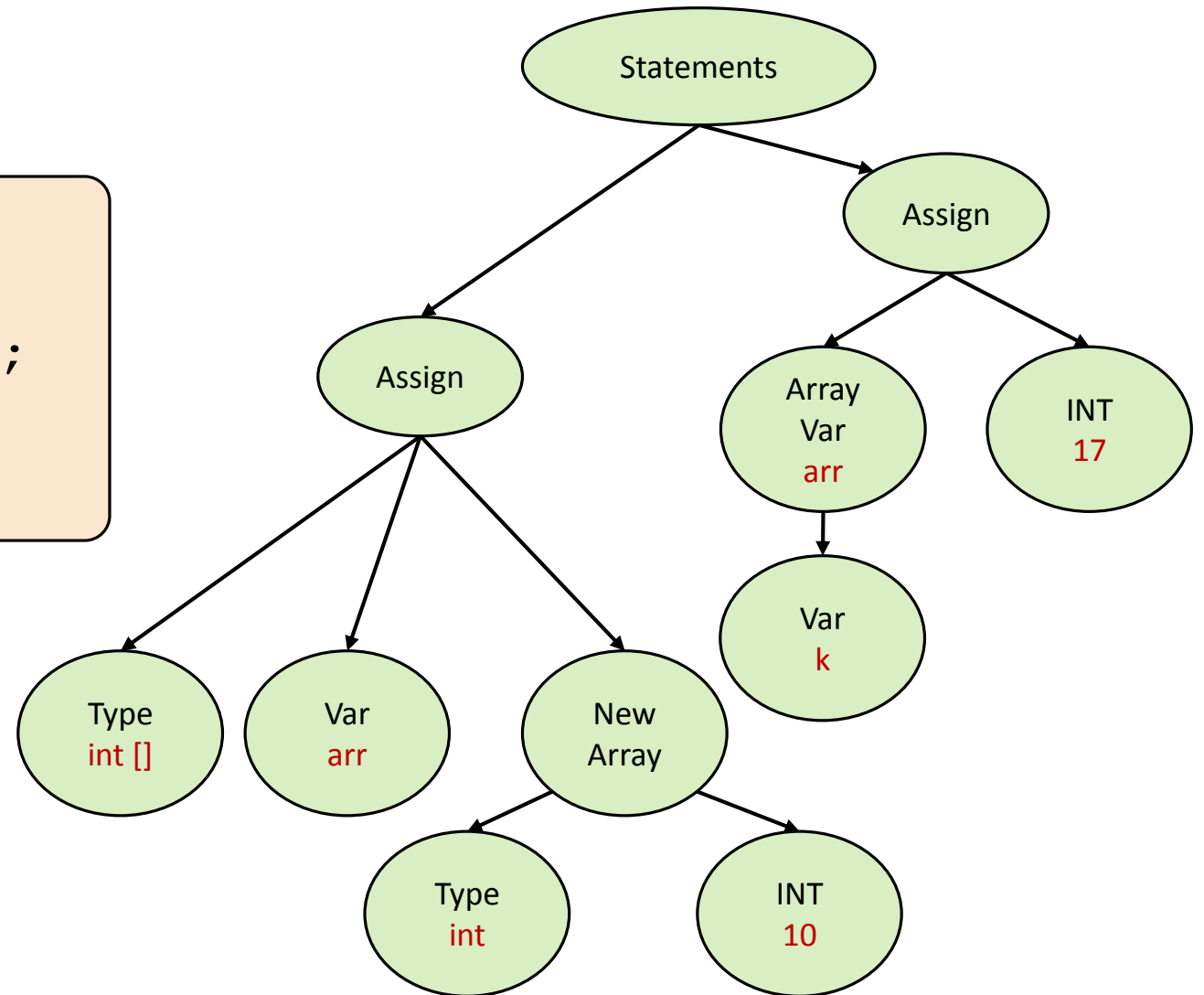
Arrays

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



Arrays

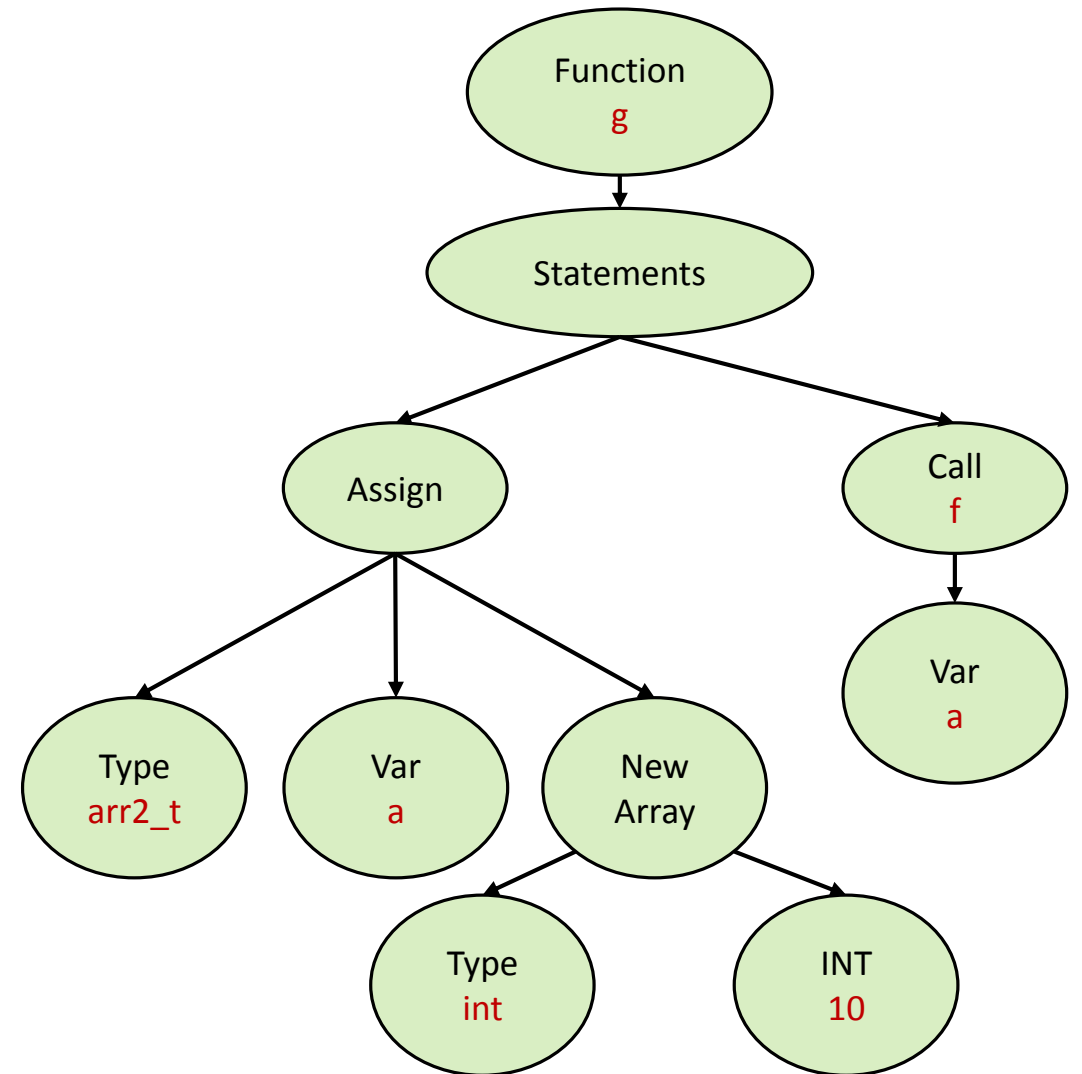
```
void foo(int d) {  
    int k = 3;  
    int[] arr = new int[10];  
    arr[k] = 17;  
}
```



Valid

Arrays

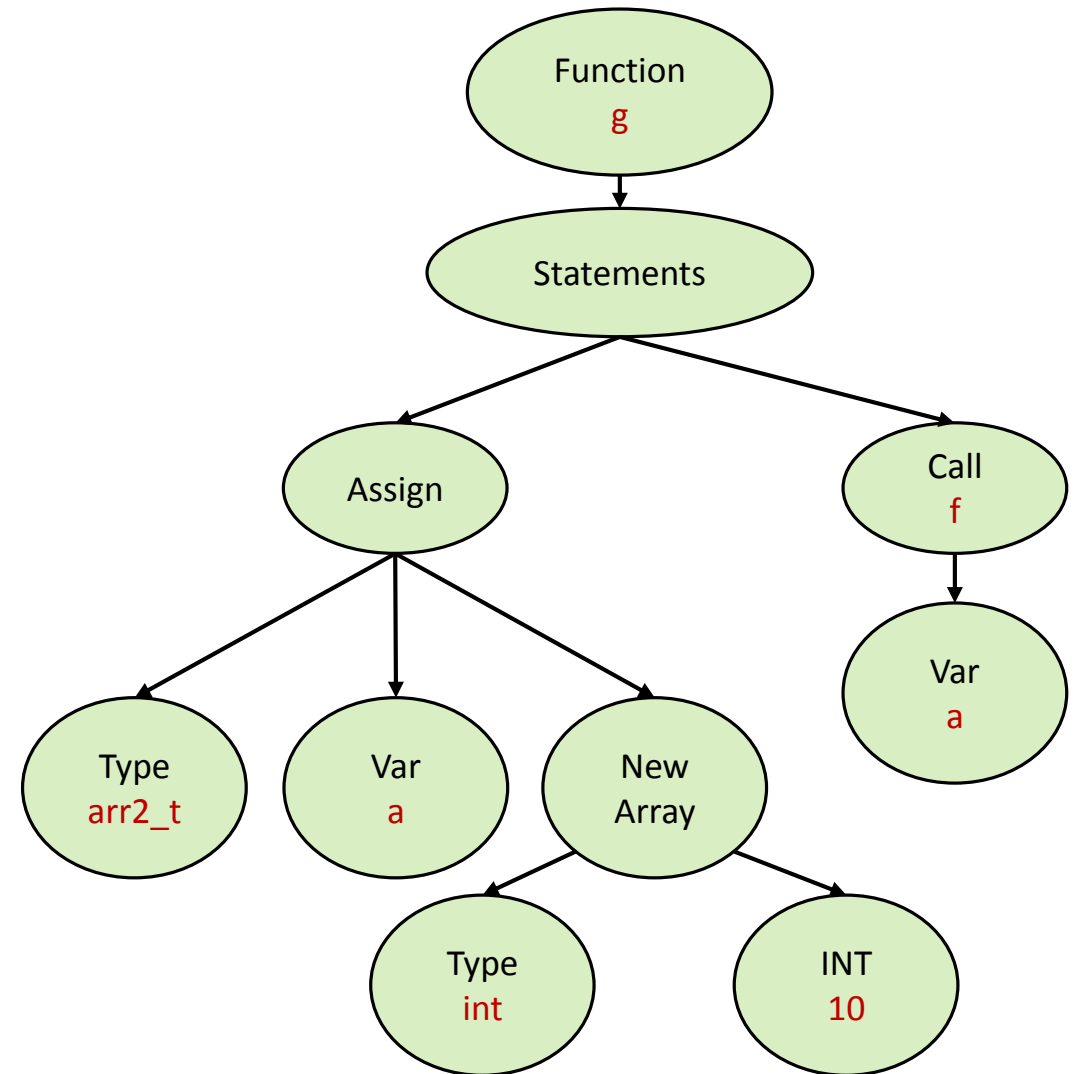
```
typedef int arr1_t[];  
typedef int arr2_t[];  
void f(arr1_t a) { }  
void g() {  
    arr2_t a = new int[10];  
    f(a);  
}
```



Arrays

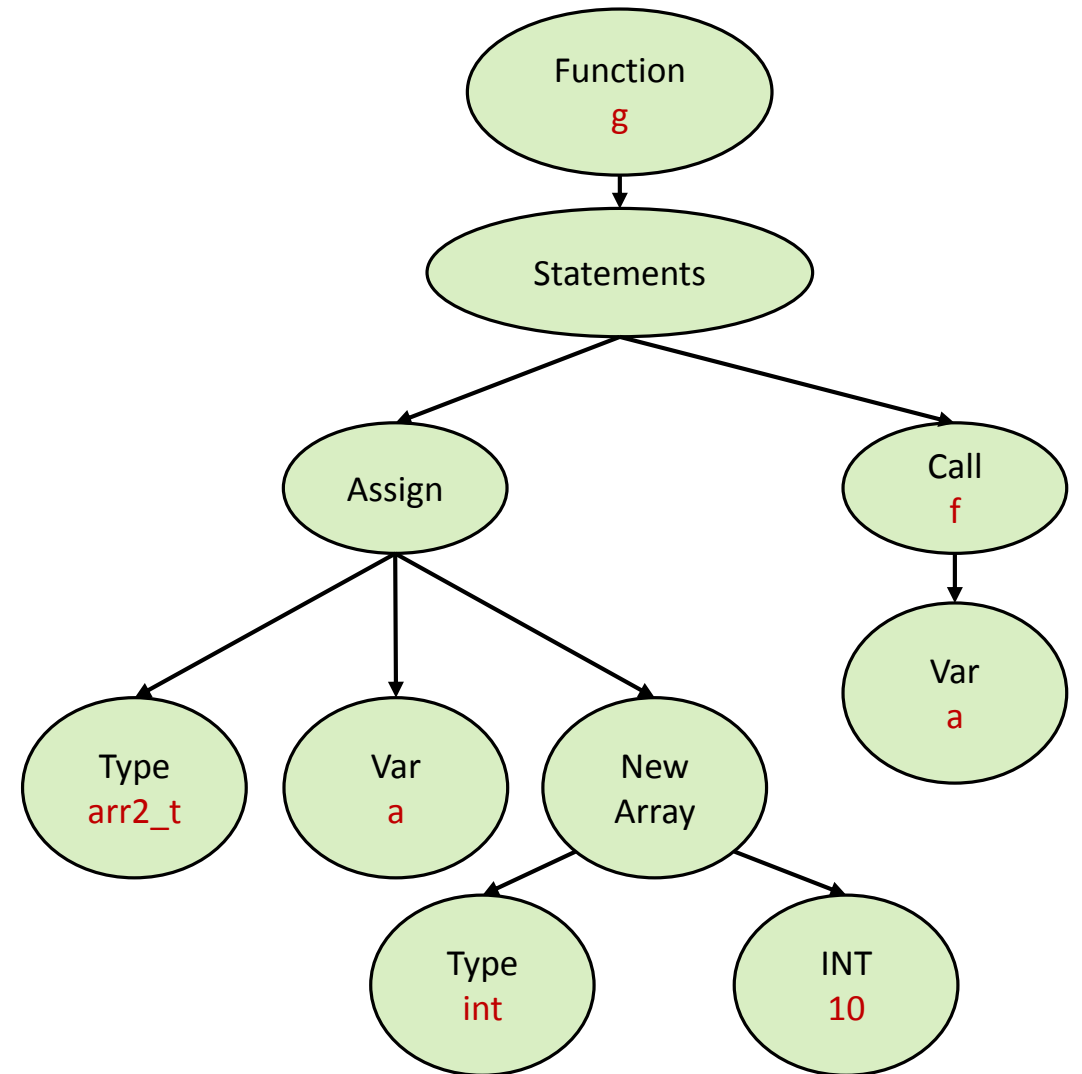
```
typedef int arr1_t[];  
typedef int arr2_t[];  
void f(arr1_t a) { }  
void g() {  
    arr2_t a = new int[10];  
    f(a);  
}
```

Invalid



Arrays

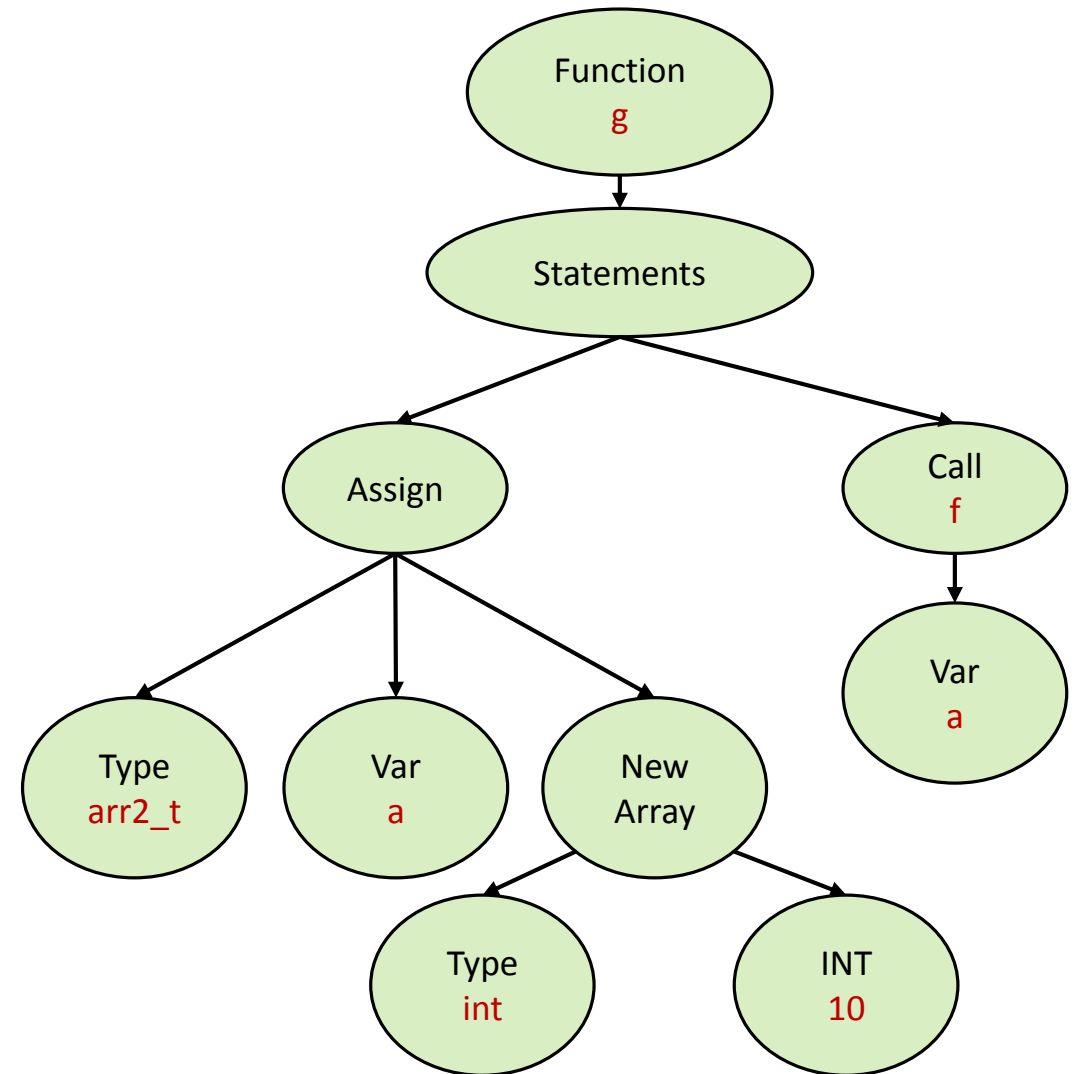
```
typedef int arr1_t[];  
typedef int arr2_t[];  
void f(arr1_t a) { }  
void g() {  
    arr2_t a = new int[10];  
    f(a);  
}
```



Arrays

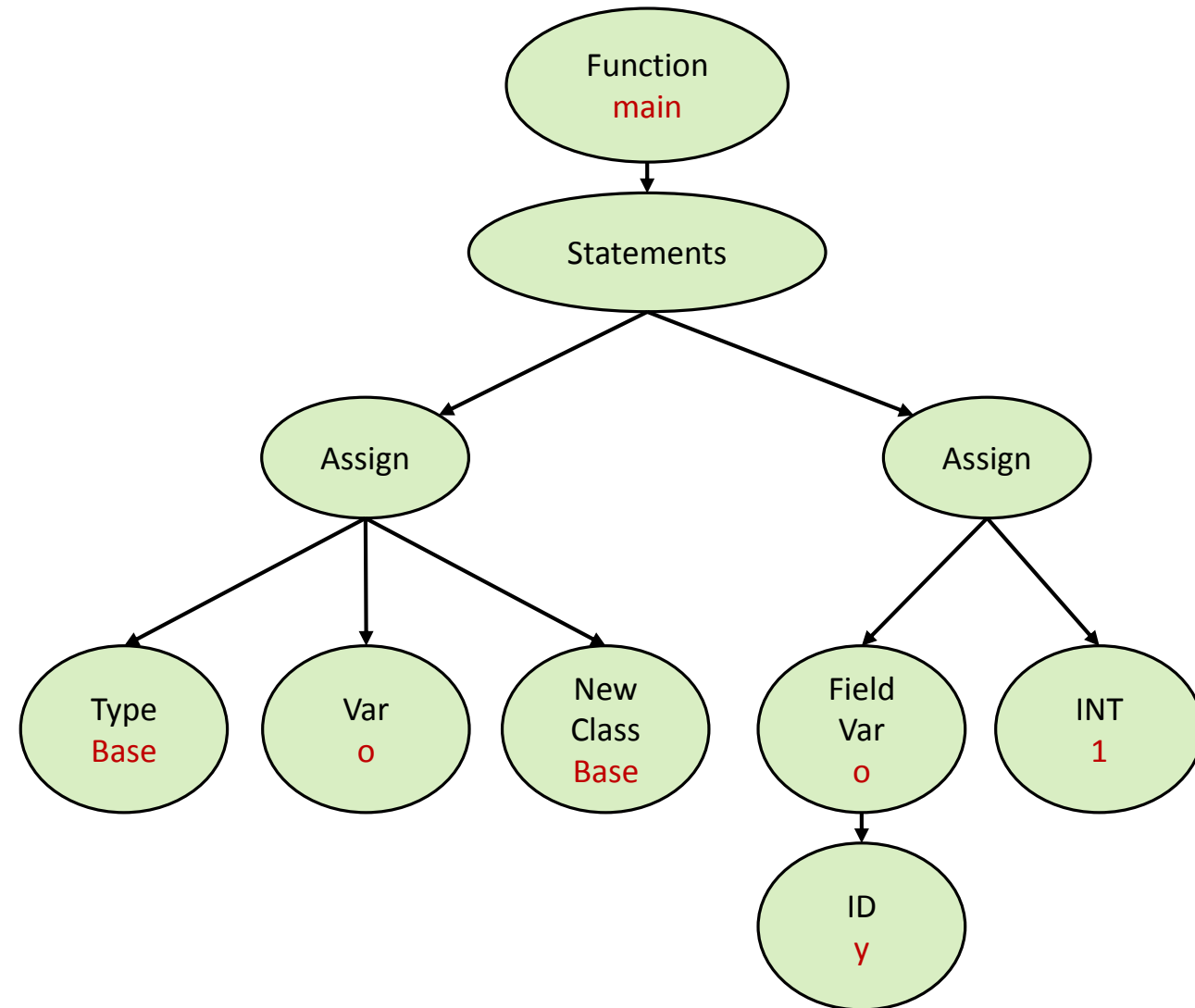
```
typedef int arr1_t[];  
typedef int arr2_t[];  
void f(arr1_t a) { }  
void g() {  
    arr2_t a = new int[10];  
    f(a);  
}
```

Invalid



Classes

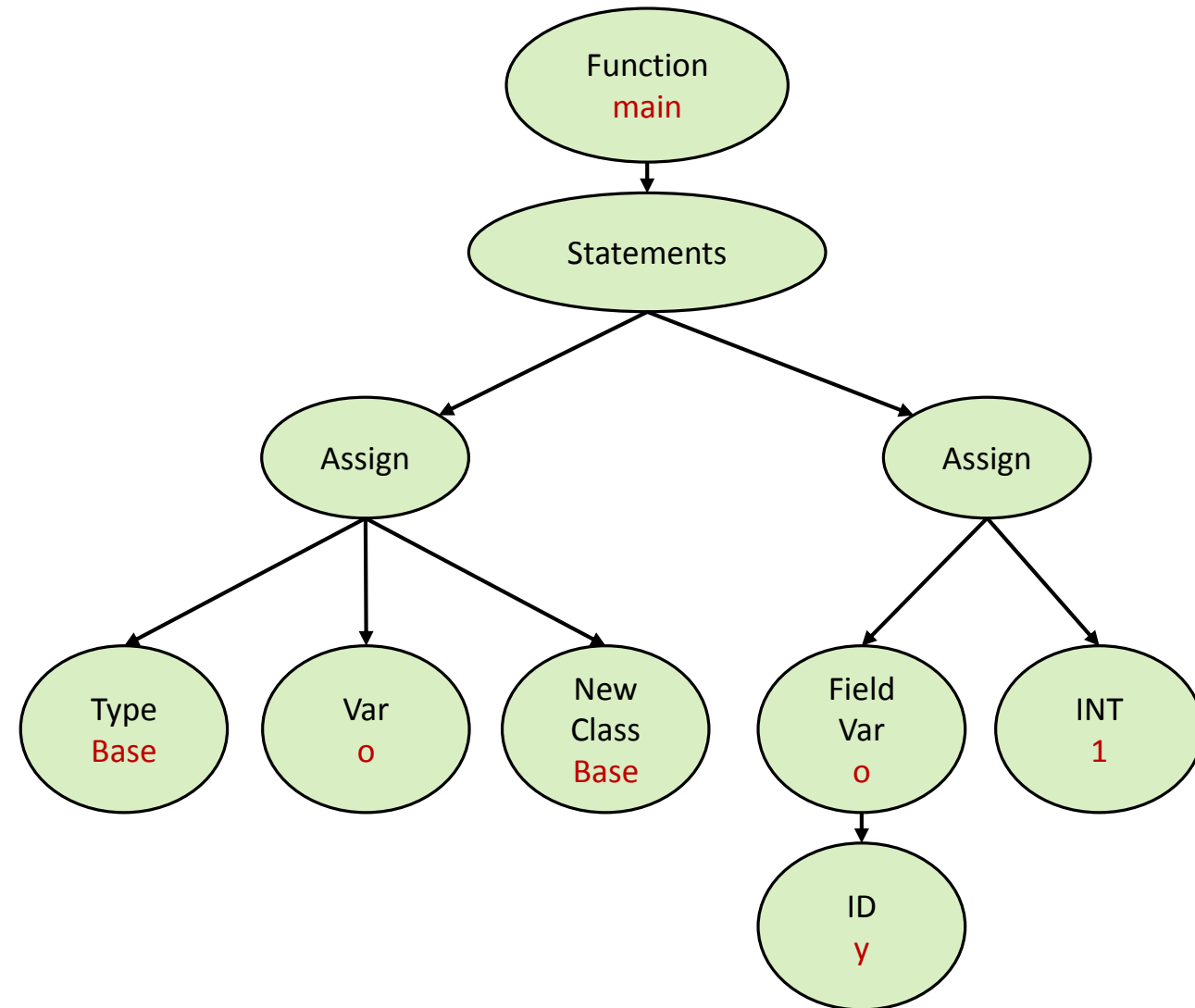
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```



Classes

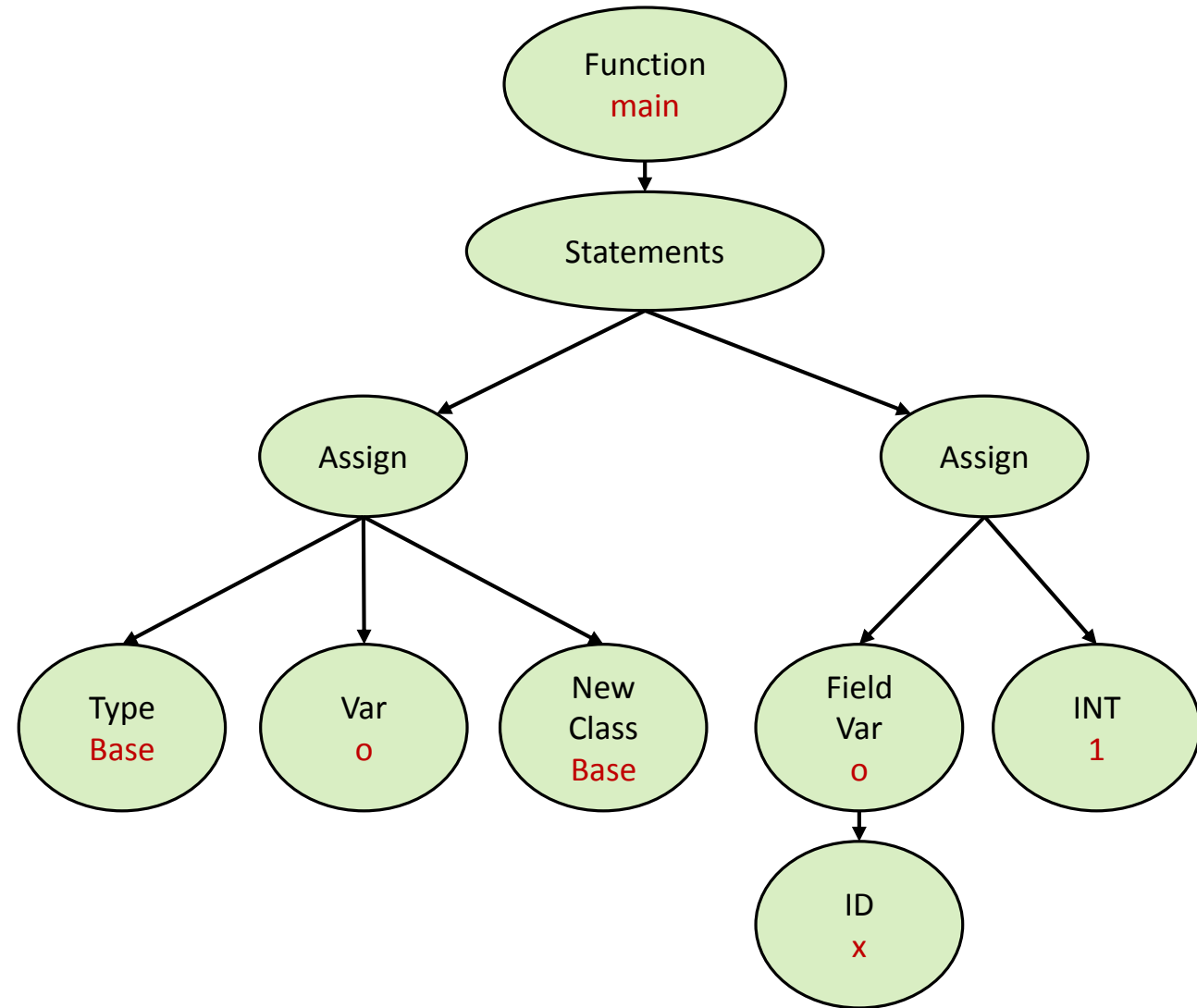
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.y = 1;  
}
```

Invalid



Classes

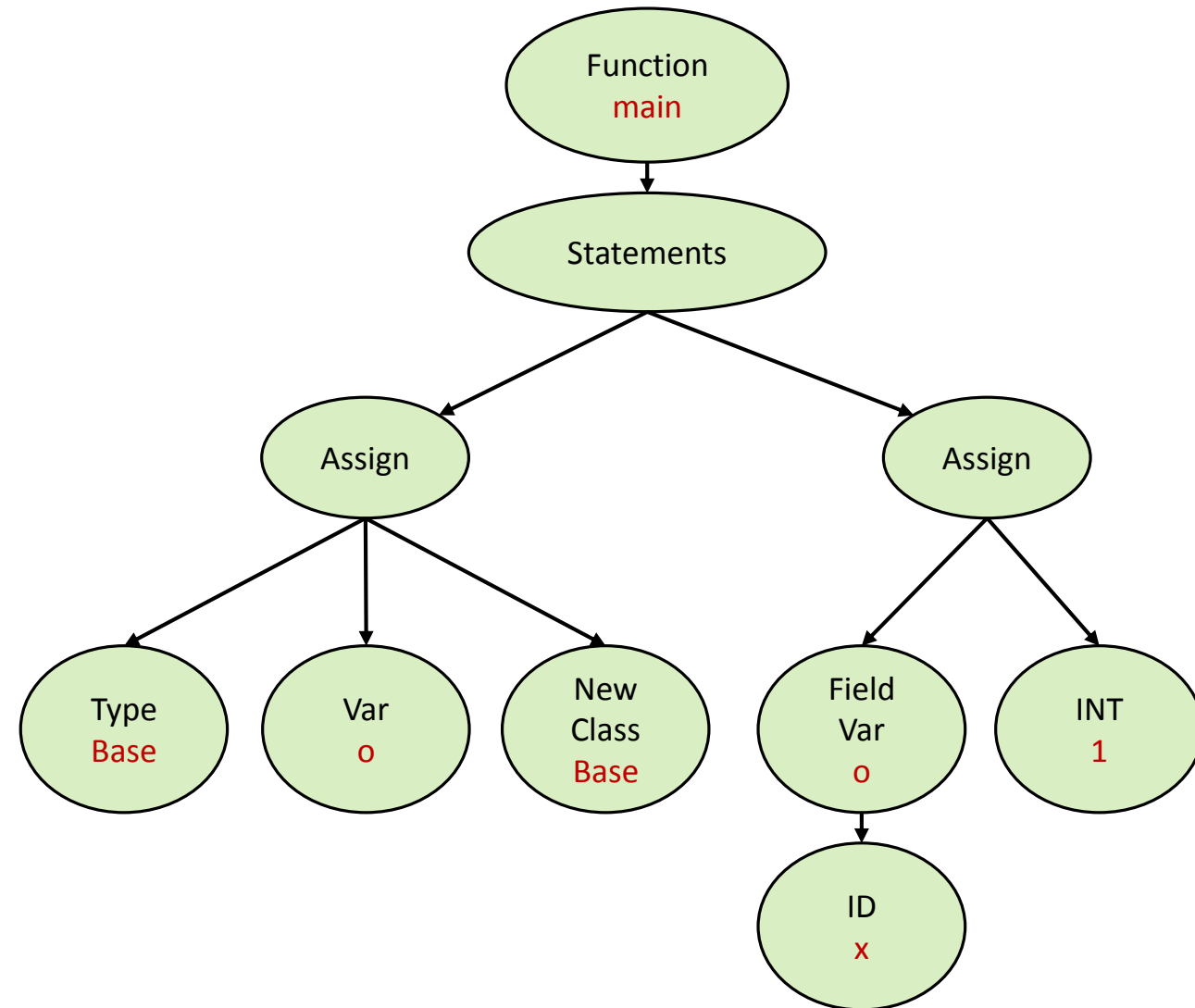
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.x = 1;  
}
```



Classes

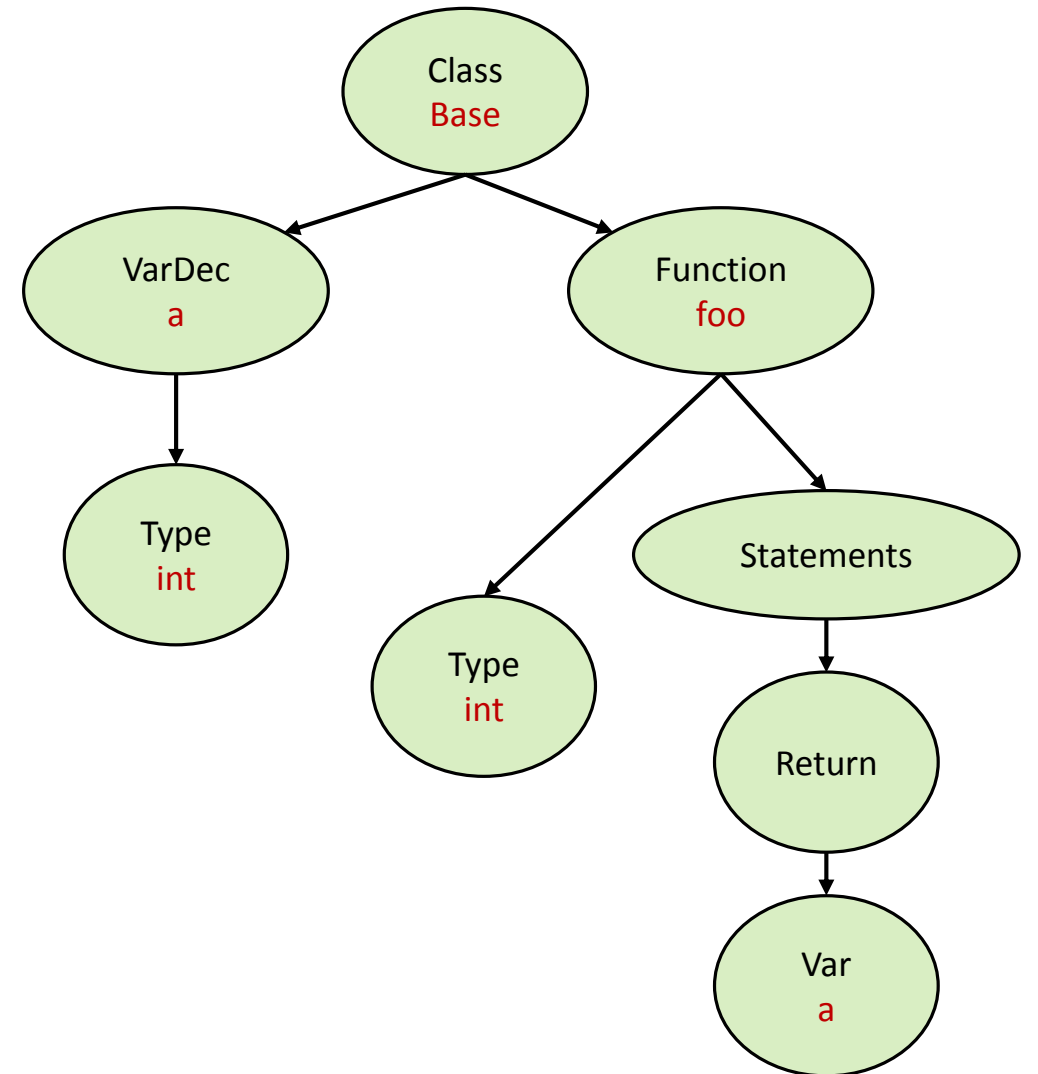
```
class Base {  
    int x;  
}  
void main() {  
    Base o = new Base;  
    o.x = 1;  
}
```

Valid



Classes

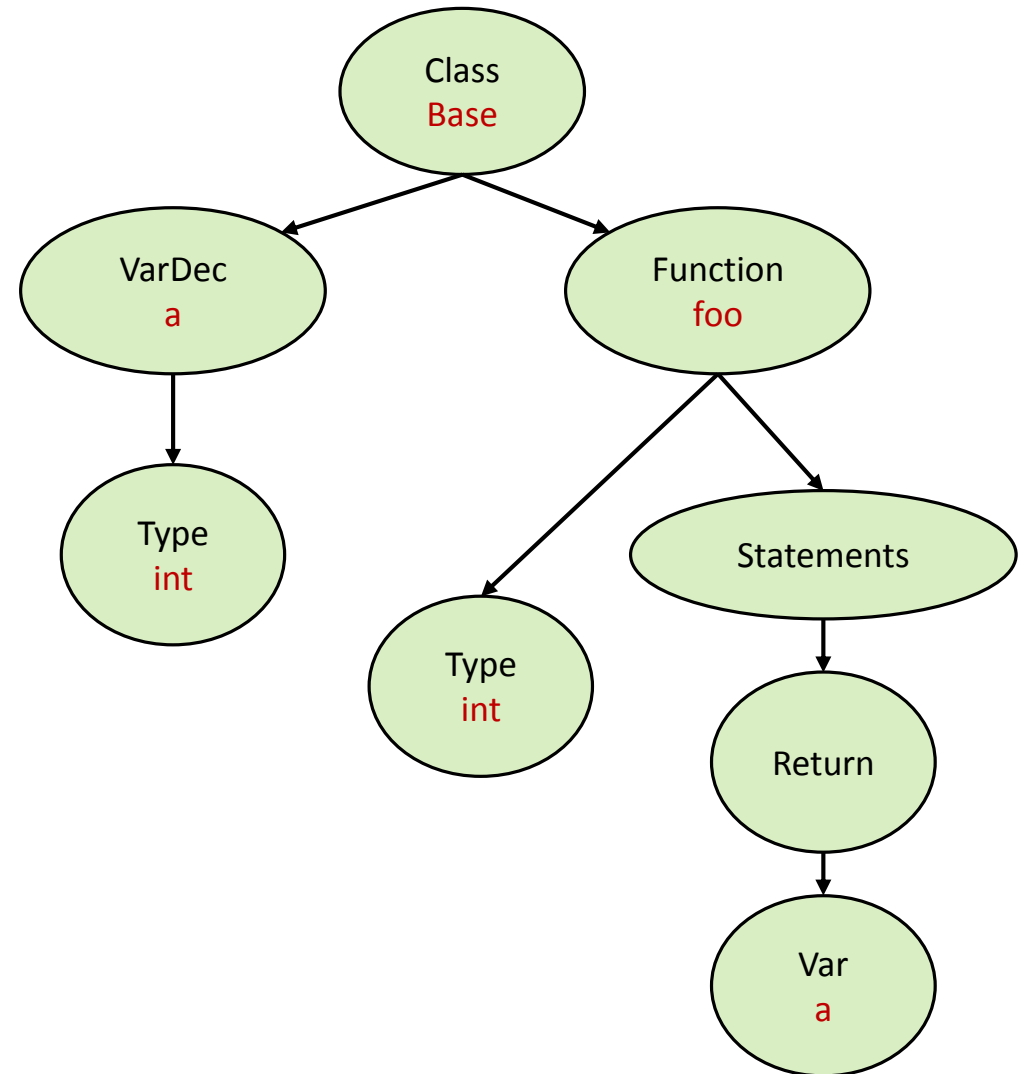
```
class Base {  
  int a;  
  int foo() {  
    return a;  
  }  
}
```



Classes

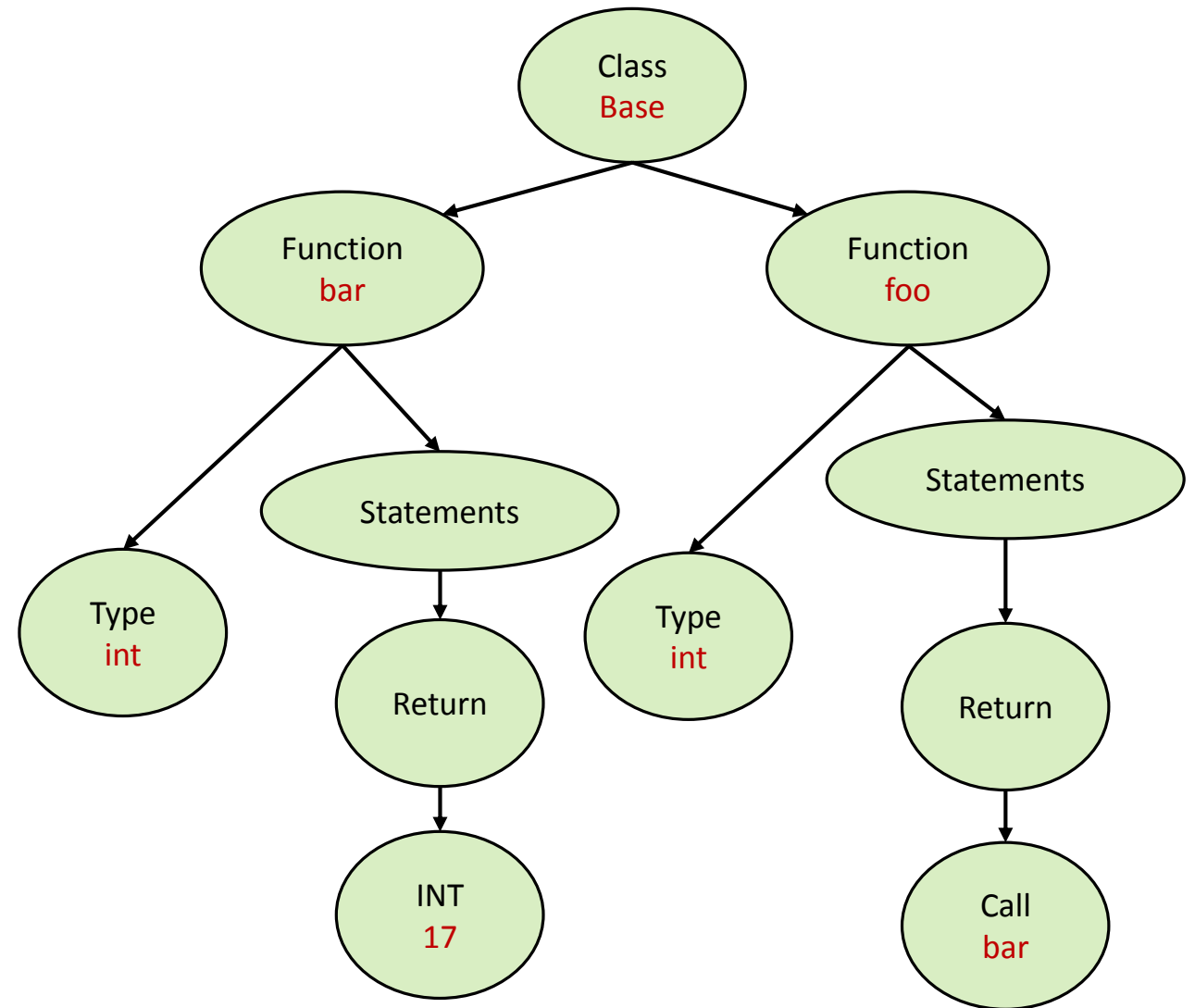
```
class Base {  
  int a;  
  int foo() {  
    return a;  
  }  
}
```

Valid



Classes

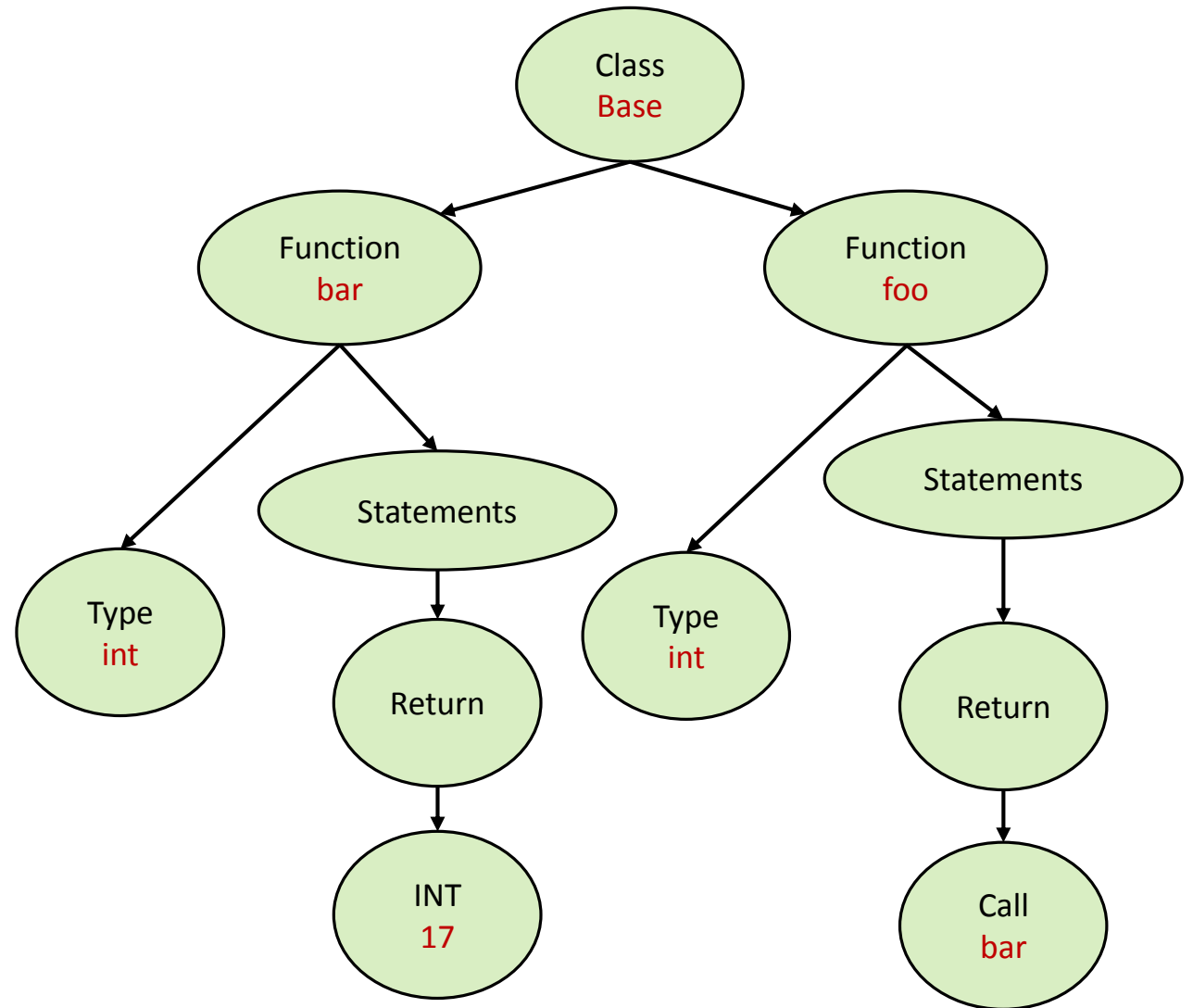
```
class Base {  
    int bar() {  
        return 17;  
    }  
    int foo() {  
        return bar();  
    }  
}
```



Classes

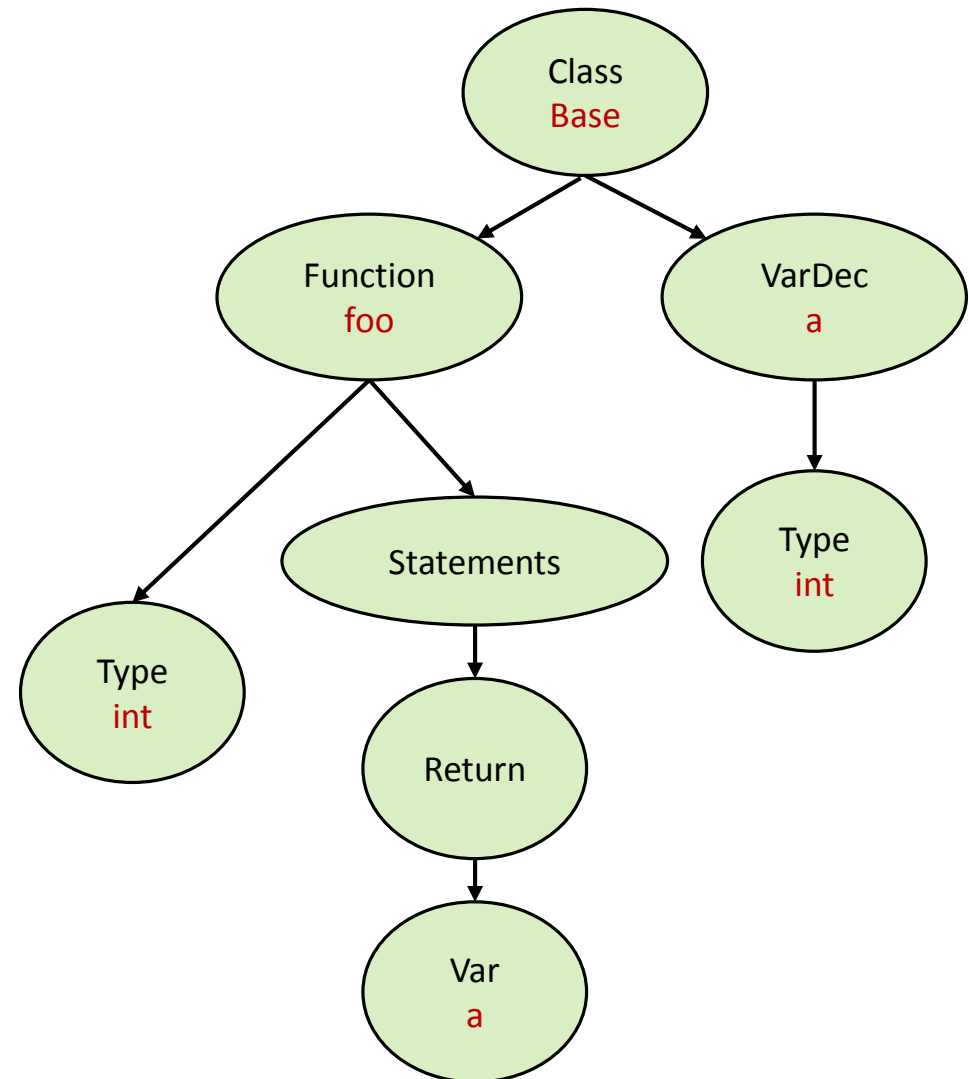
```
class Base {  
  int bar() {  
    return 17;  
  }  
  int foo() {  
    return bar();  
  }  
}
```

Valid



Classes

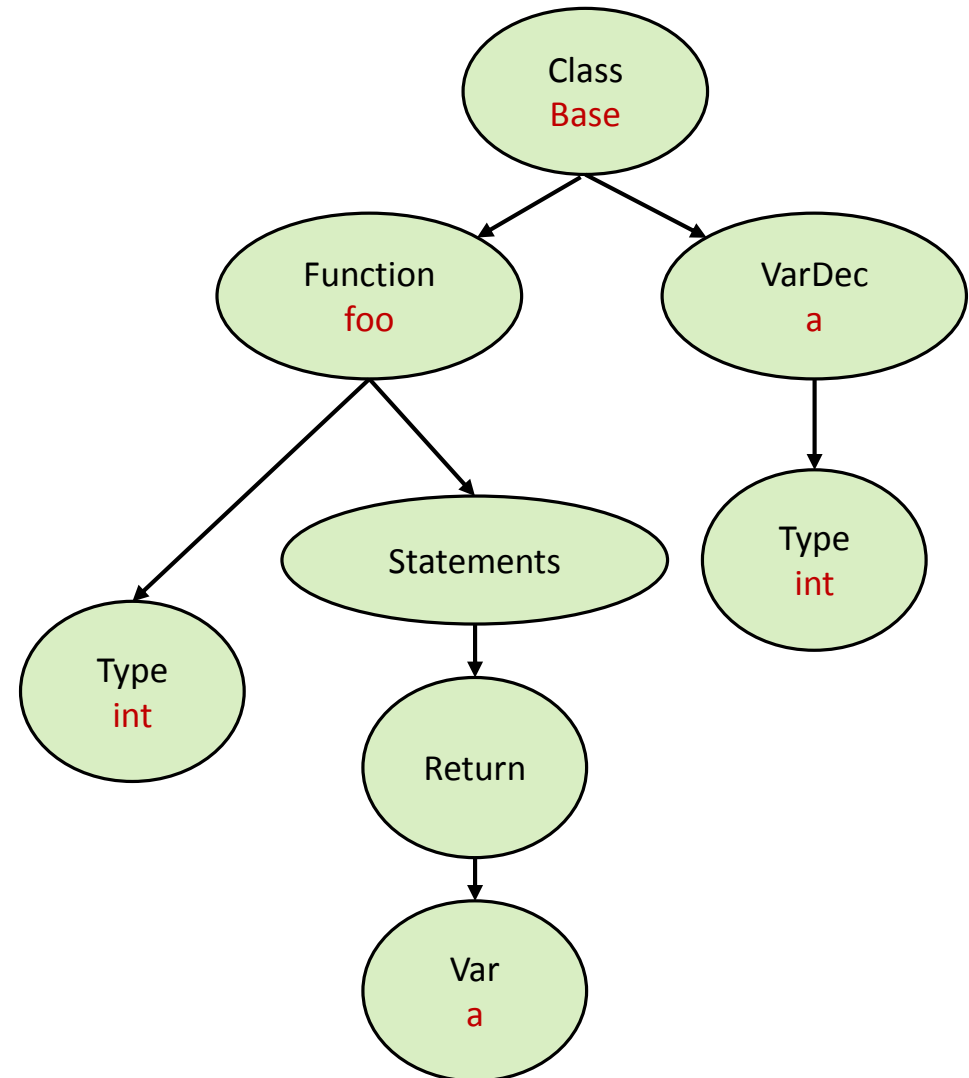
```
class Base {  
  int foo() {  
    return a;  
  }  
  int a;  
}
```



Classes

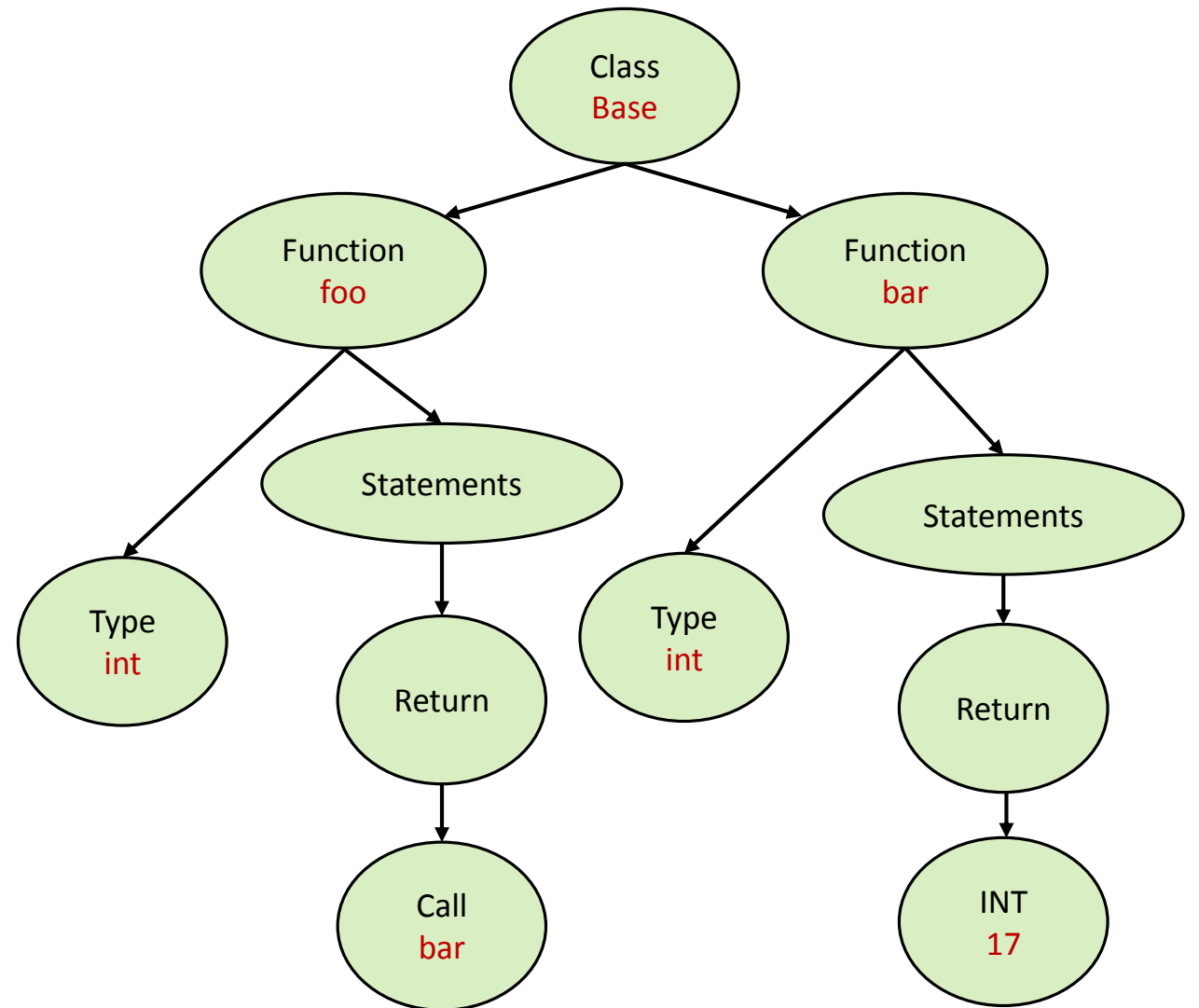
```
class Base {  
  int foo() {  
    return a;  
  }  
  int a;  
}
```

Invalid



Classes

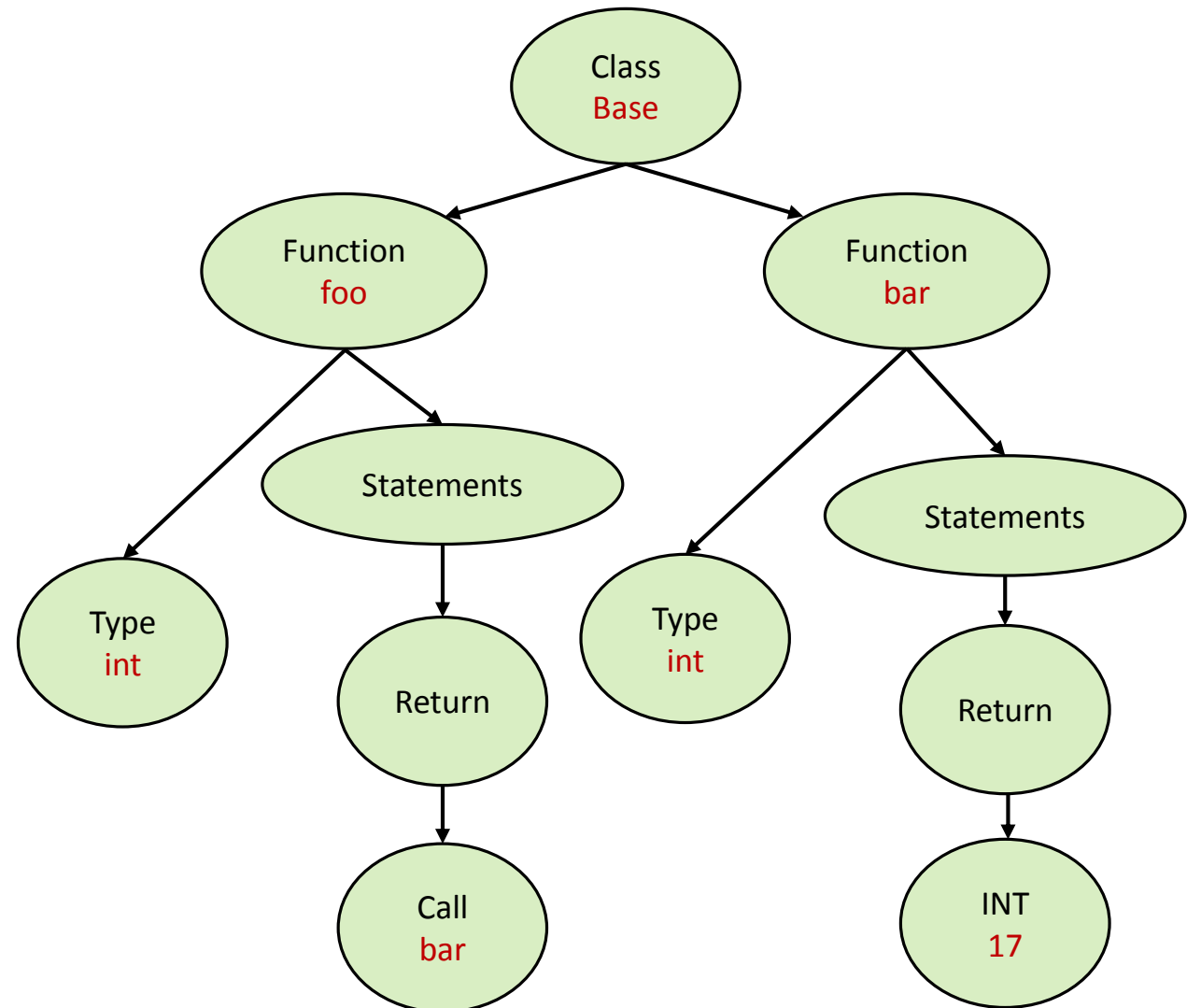
```
class Base {  
    int foo() {  
        return bar();  
    }  
    int bar() {  
        return 17;  
    }  
}
```



Classes

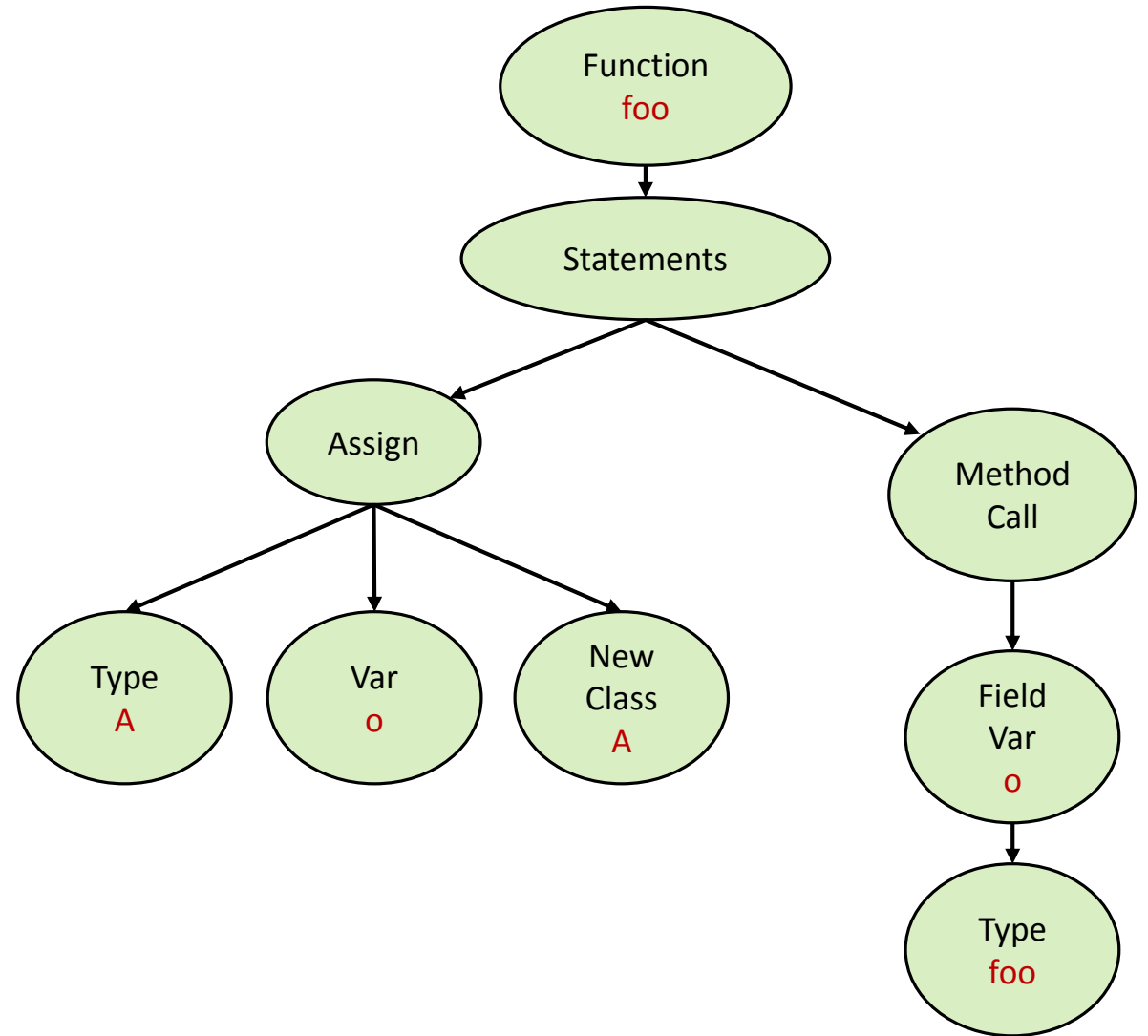
```
class Base {  
    int foo() {  
        return bar();  
    }  
    int bar() {  
        return 17;  
    }  
}
```

Invalid



Classes

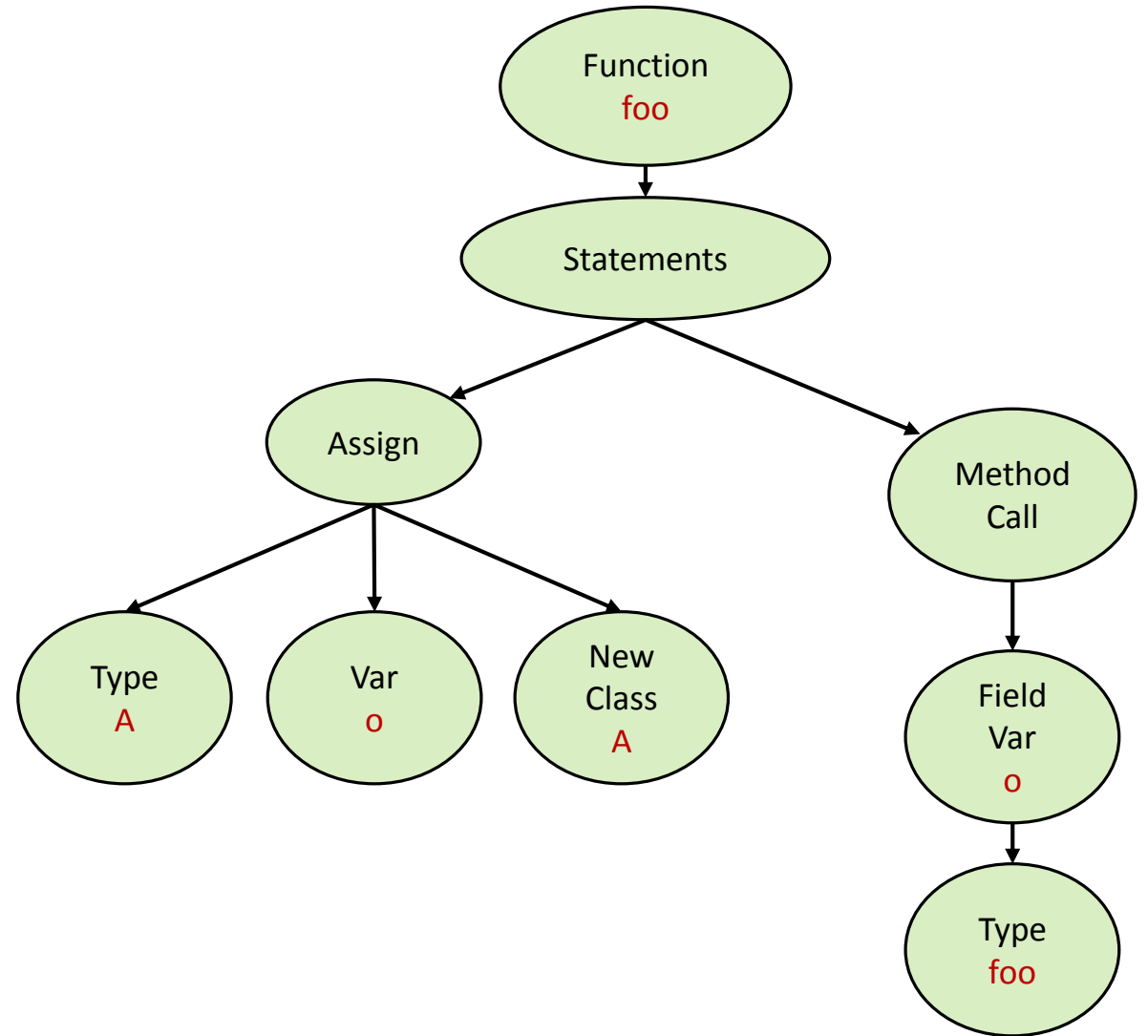
```
class A {  
  void foo() {  
    A o = new A;  
    o.foo();  
  }  
}
```



Classes

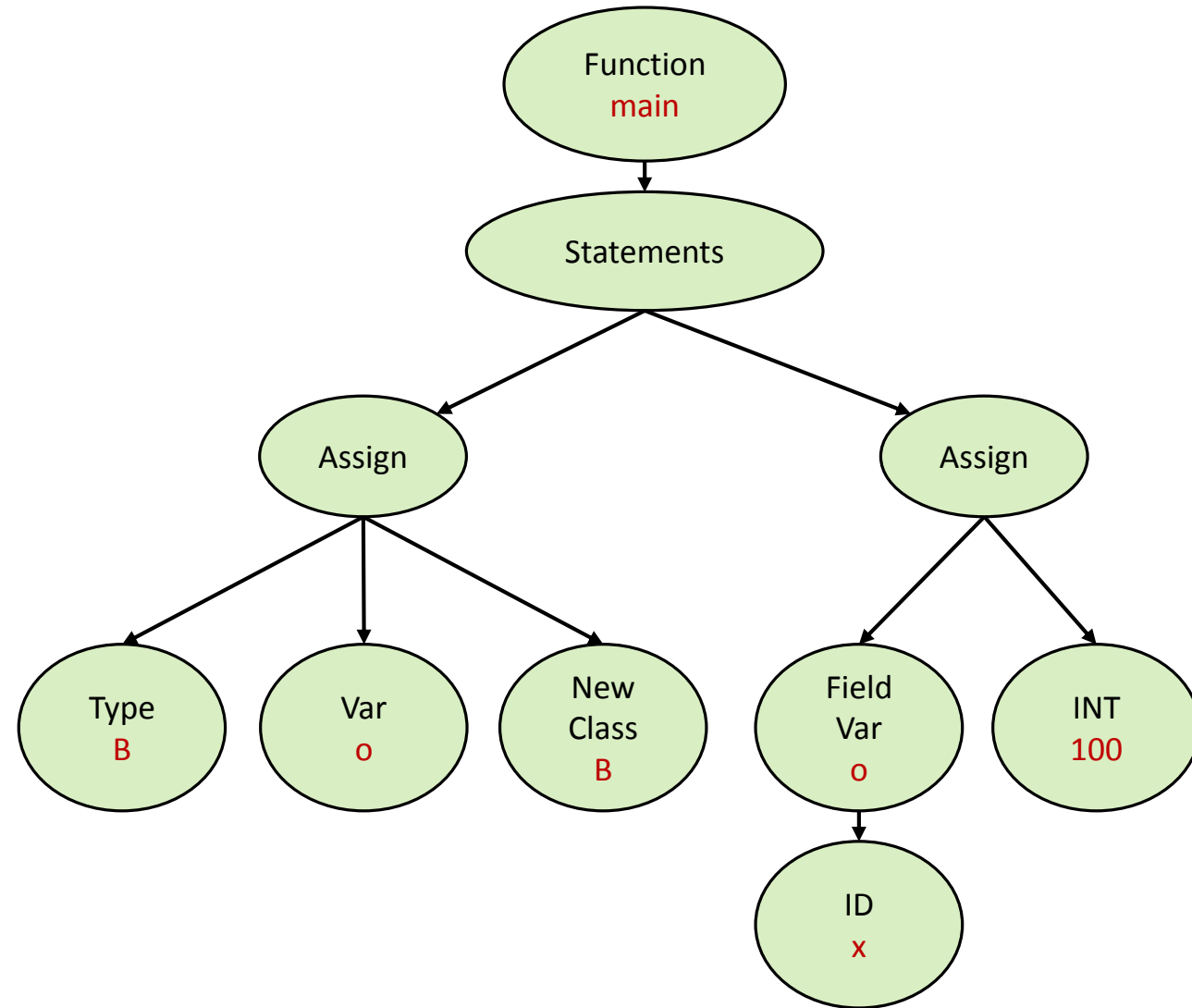
```
class A {  
  void foo() {  
    A o = new A;  
    o.foo();  
  }  
}
```

Valid



Inheritance

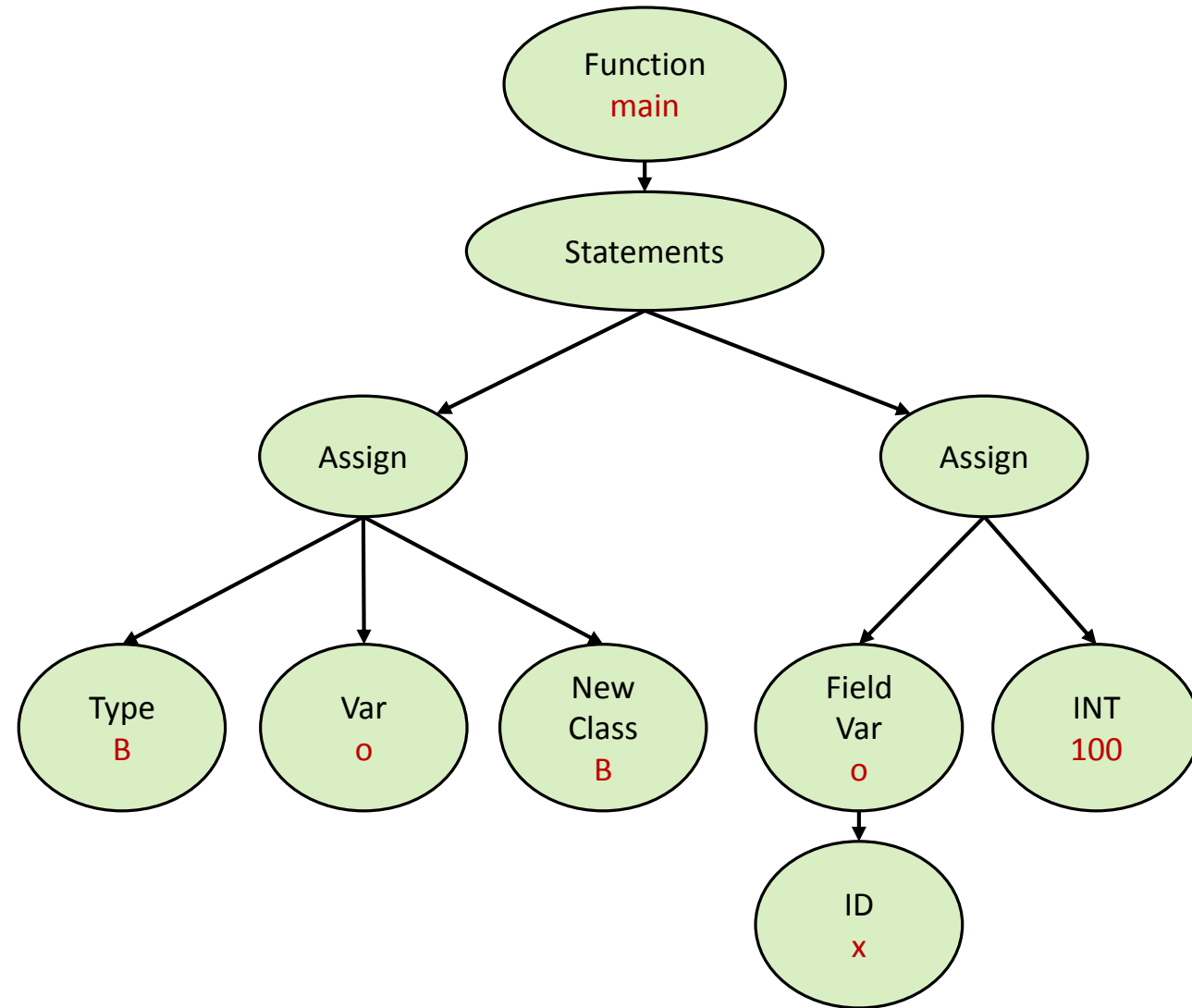
```
class A {  
    int x;  
}  
class B extends A { }  
void main() {  
    B o = new B;  
    o.x = 100;  
}
```



Inheritance

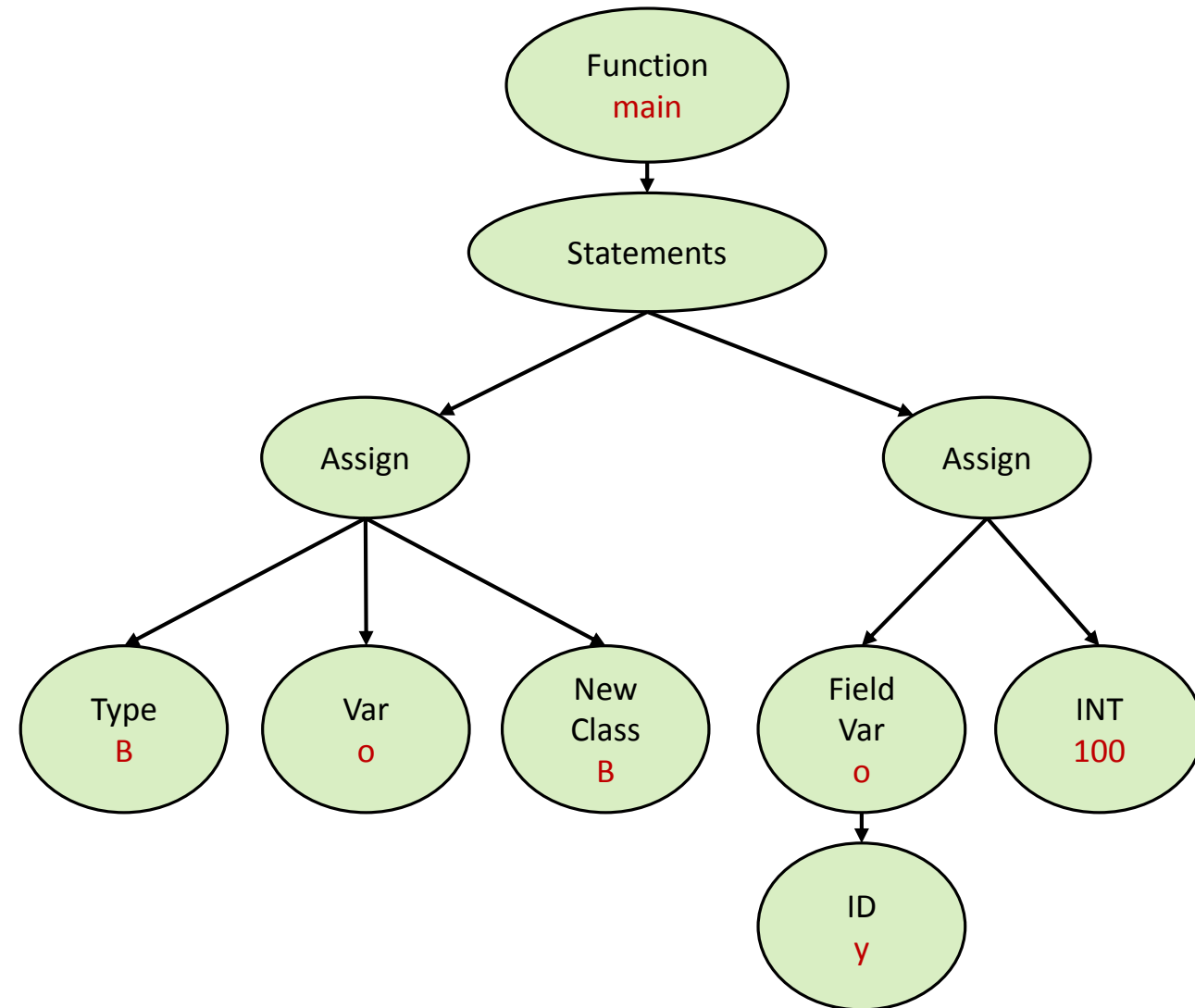
```
class A {  
    int x;  
}  
class B extends A { }  
void main() {  
    B o = new B;  
    o.x = 100;  
}
```

Valid



Inheritance

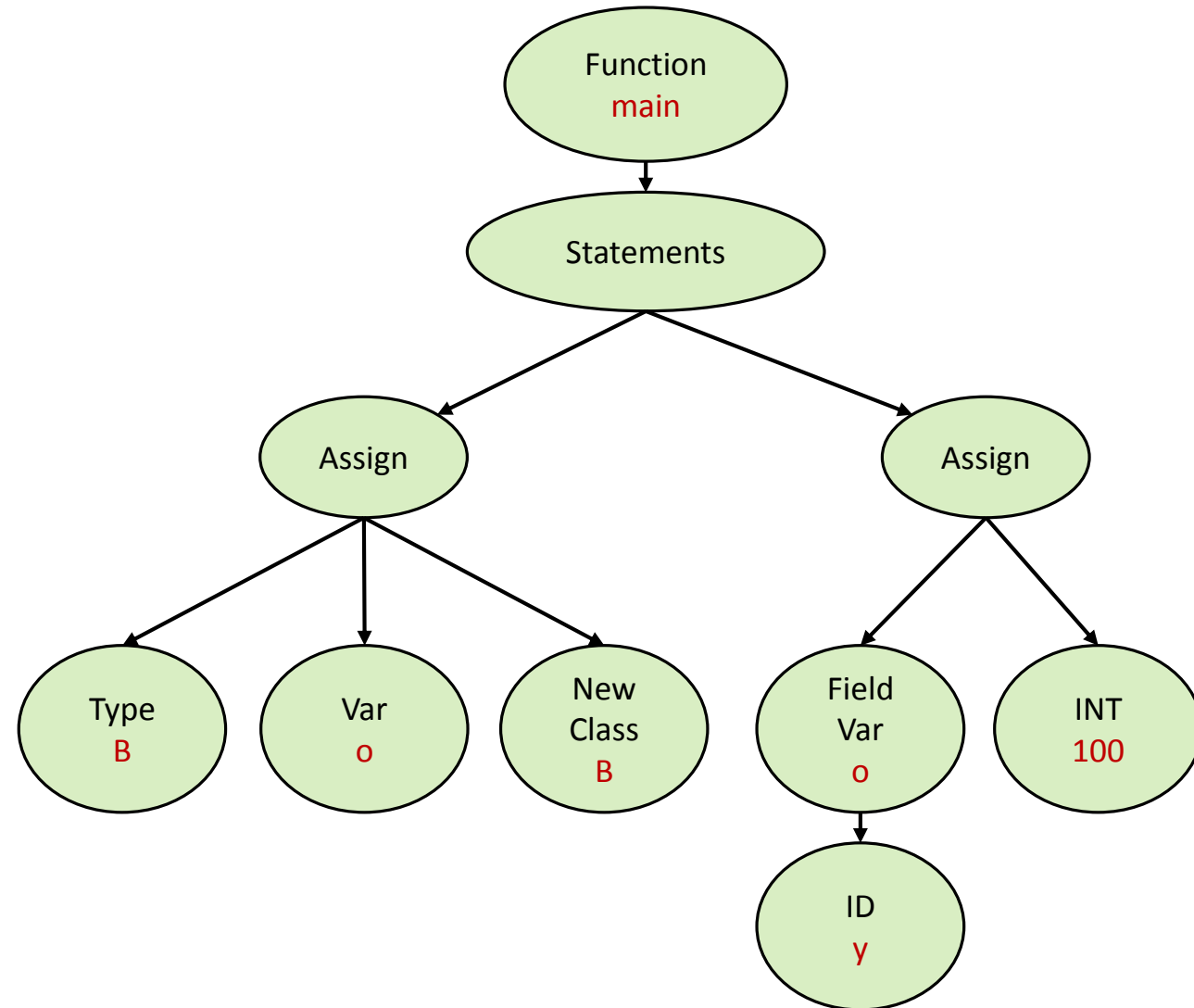
```
class A {  
    int x;  
}  
class B extends A { }  
void main() {  
    B o = new B;  
    o.y = 100;  
}
```



Inheritance

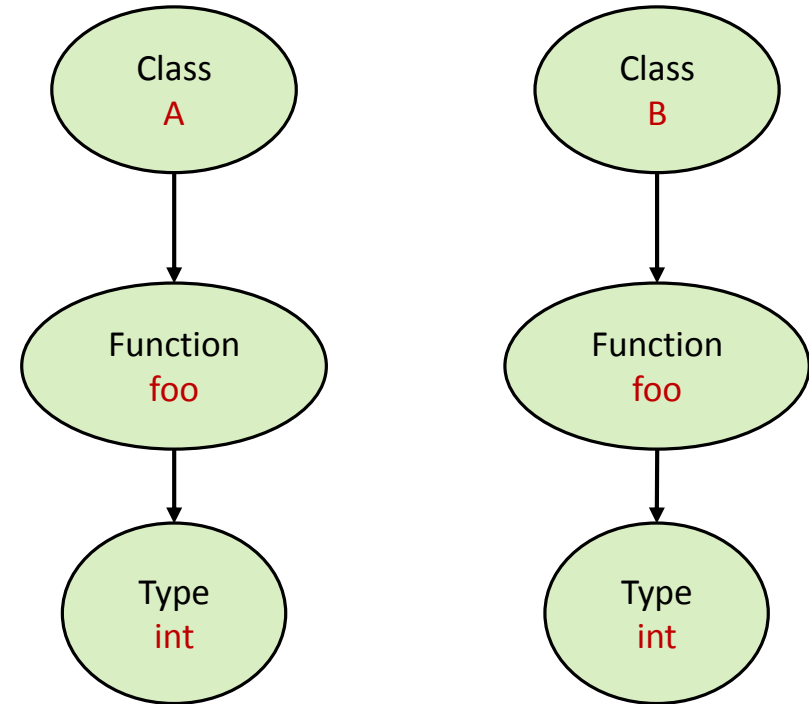
```
class A {  
    int x;  
}  
class B extends A {  
    void main() {  
        B o = new B;  
        o.y = 100;  
    }  
}
```

Invalid



Inheritance

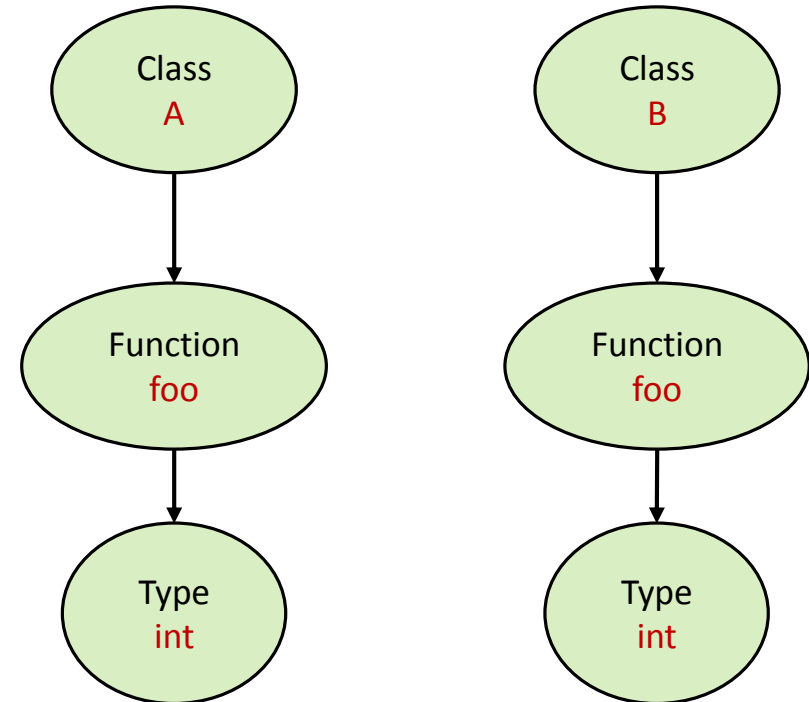
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo() {  
        return 18;  
    }  
}
```



Inheritance

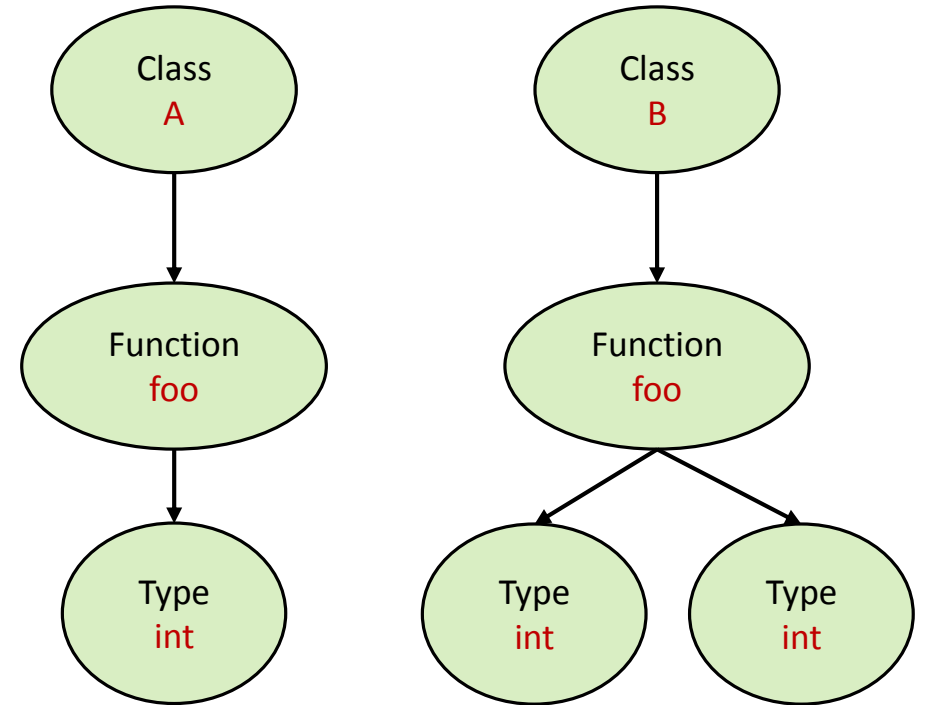
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo() {  
        return 18;  
    }  
}
```

Valid



Inheritance

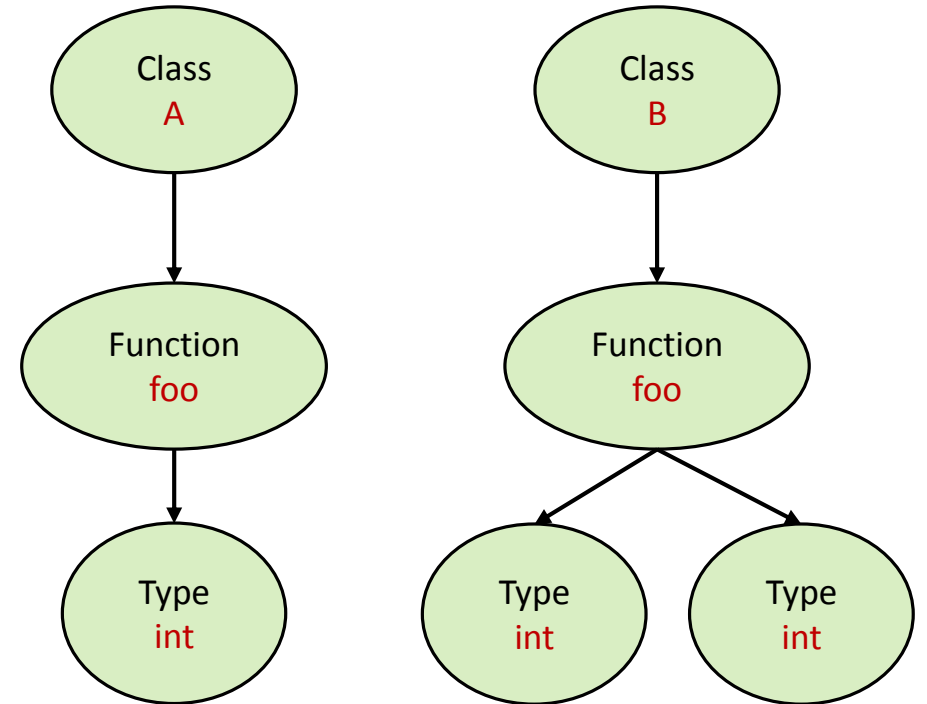
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo(int x) {  
        return x + 1;  
    }  
}
```



Inheritance

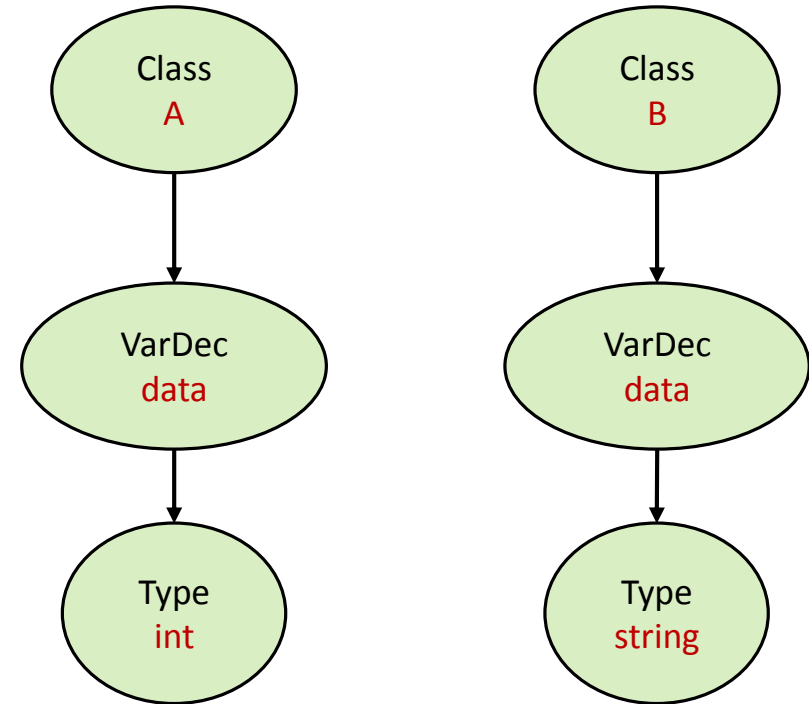
```
class A {  
    int foo() {  
        return 17;  
    }  
}  
class B extends A {  
    int foo(int x) {  
        return x + 1;  
    }  
}
```

Invalid



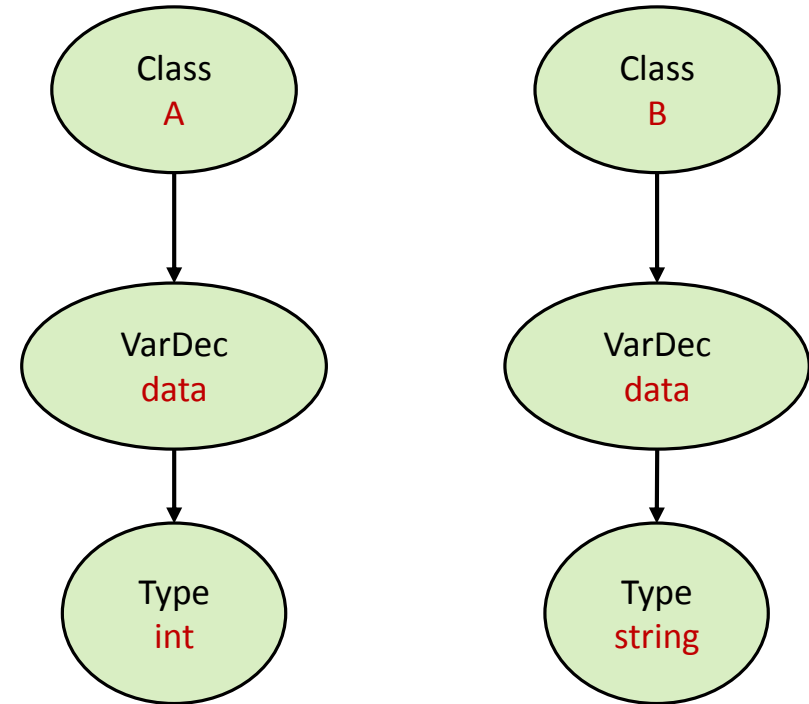
Inheritance

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



Inheritance

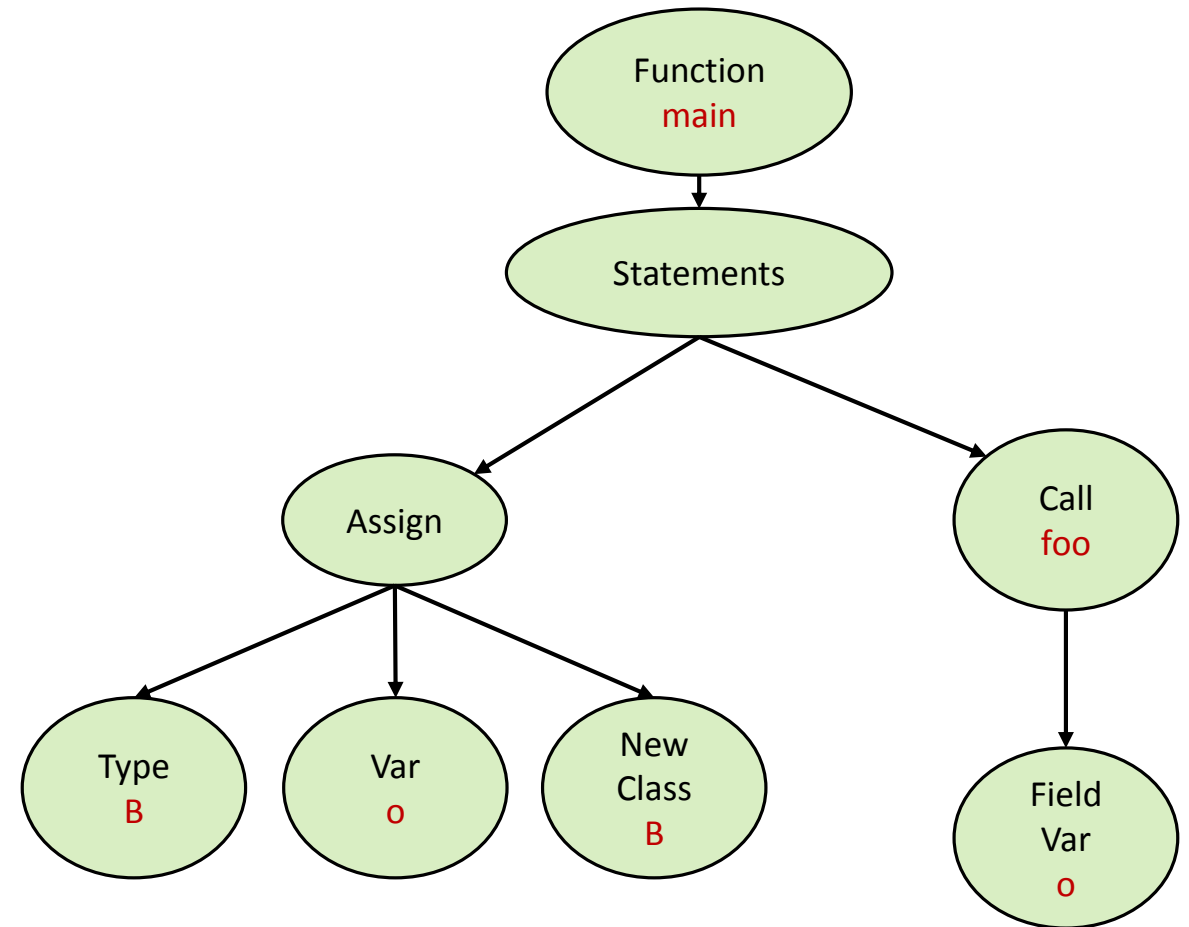
```
class A {  
    int data;  
}  
class B extends A {  
    string data;  
}
```



Invalid

Inheritance

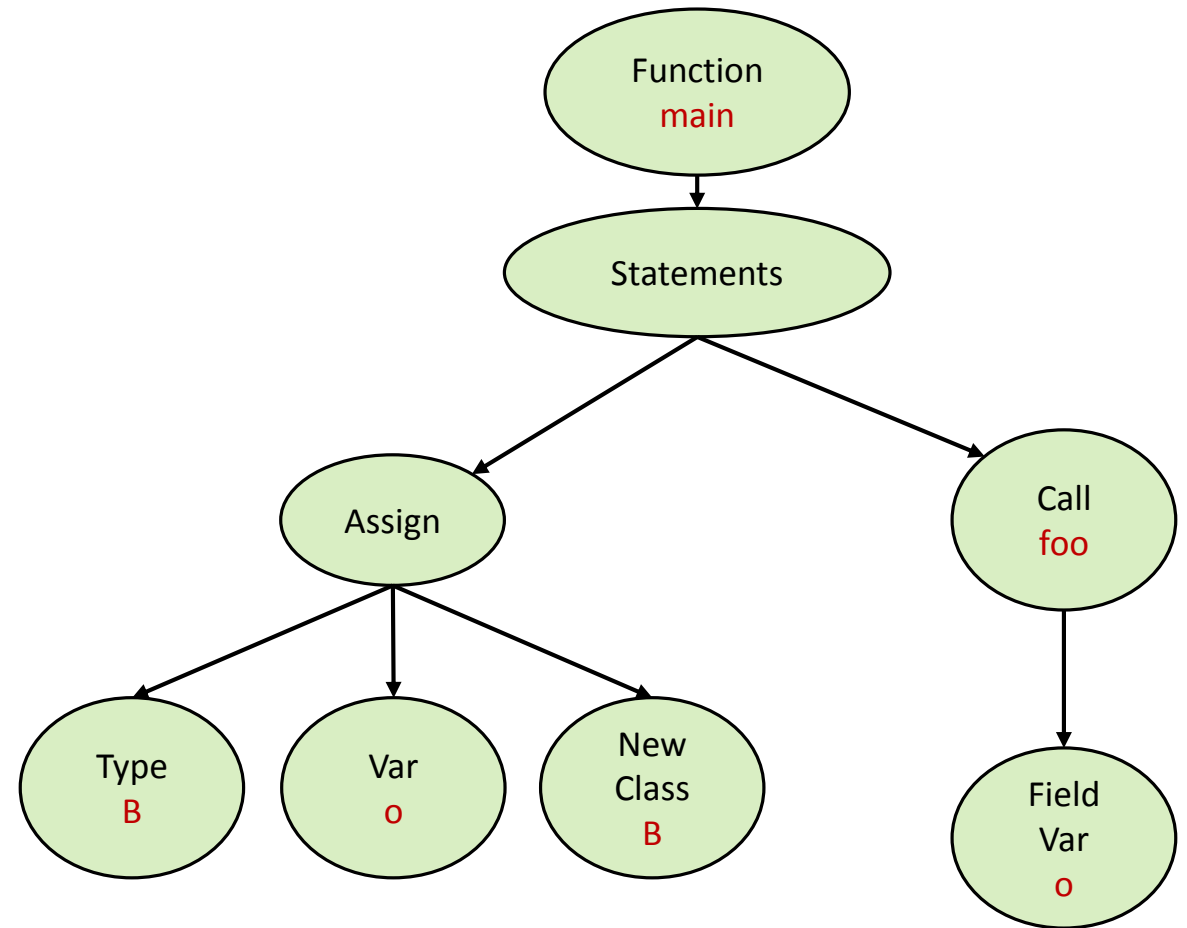
```
class A { }  
class B extends A { }  
void foo(A a) { }  
void main() {  
    B o = new B;  
    foo(o);  
}
```



Inheritance

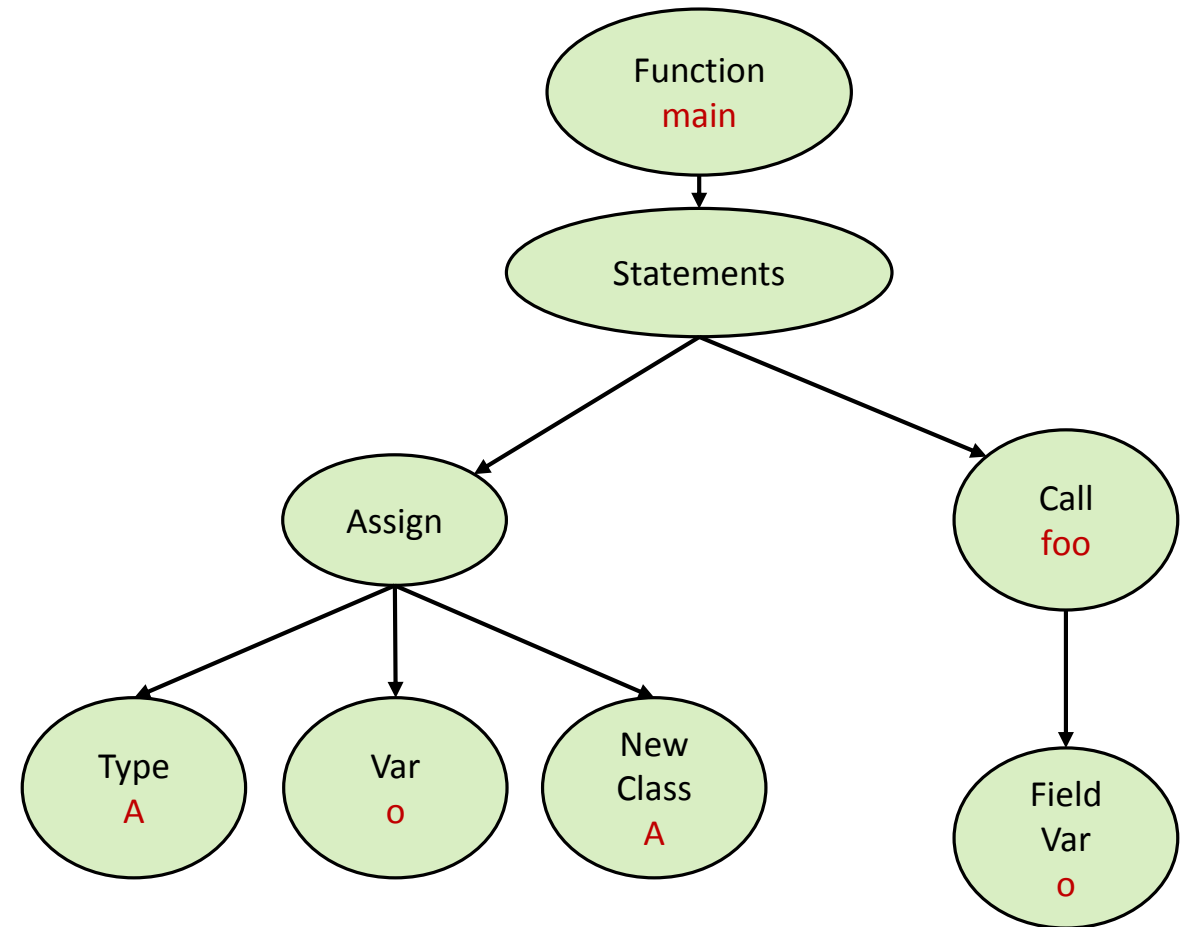
```
class A { }  
class B extends A { }  
void foo(A a) { }  
void main() {  
    B o = new B;  
    foo(o);  
}
```

Valid



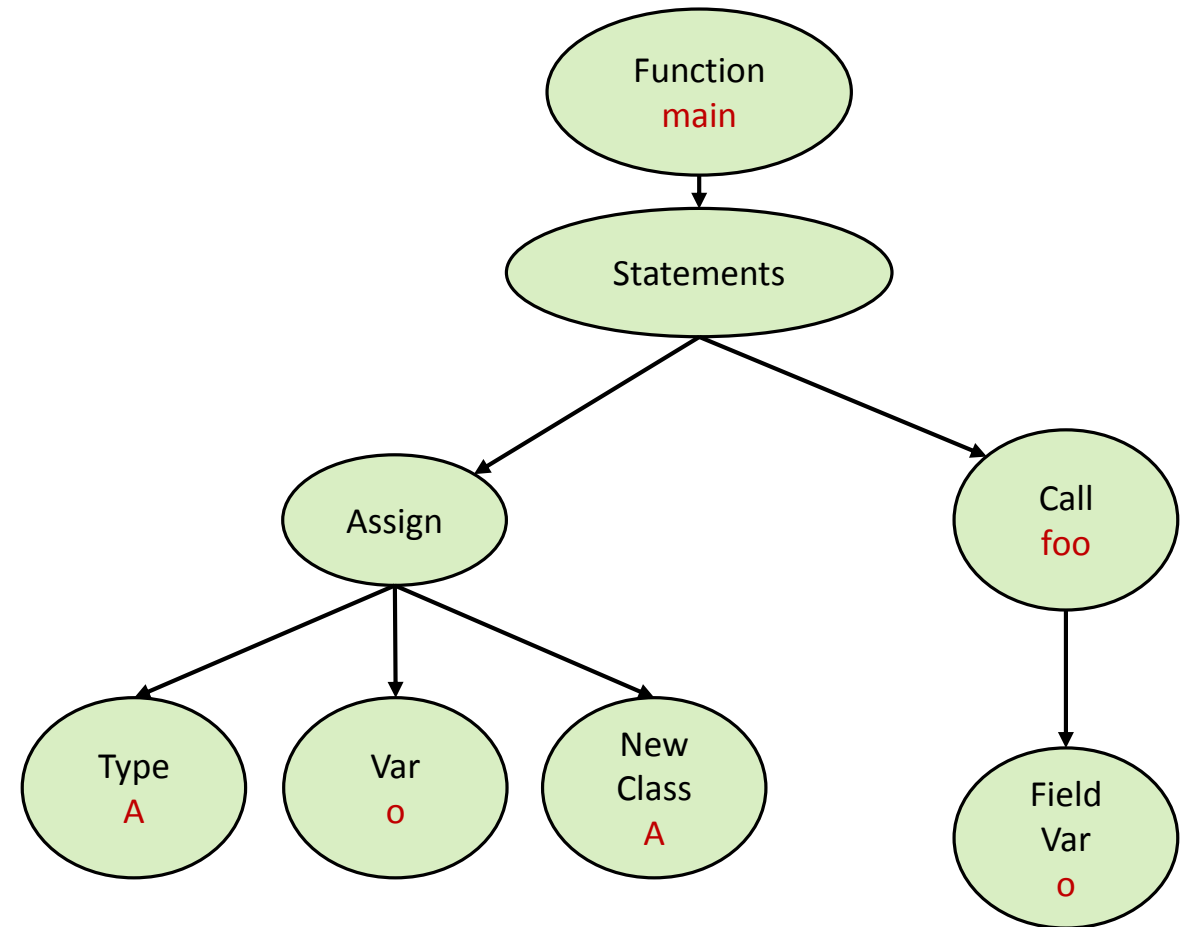
Inheritance

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



Inheritance

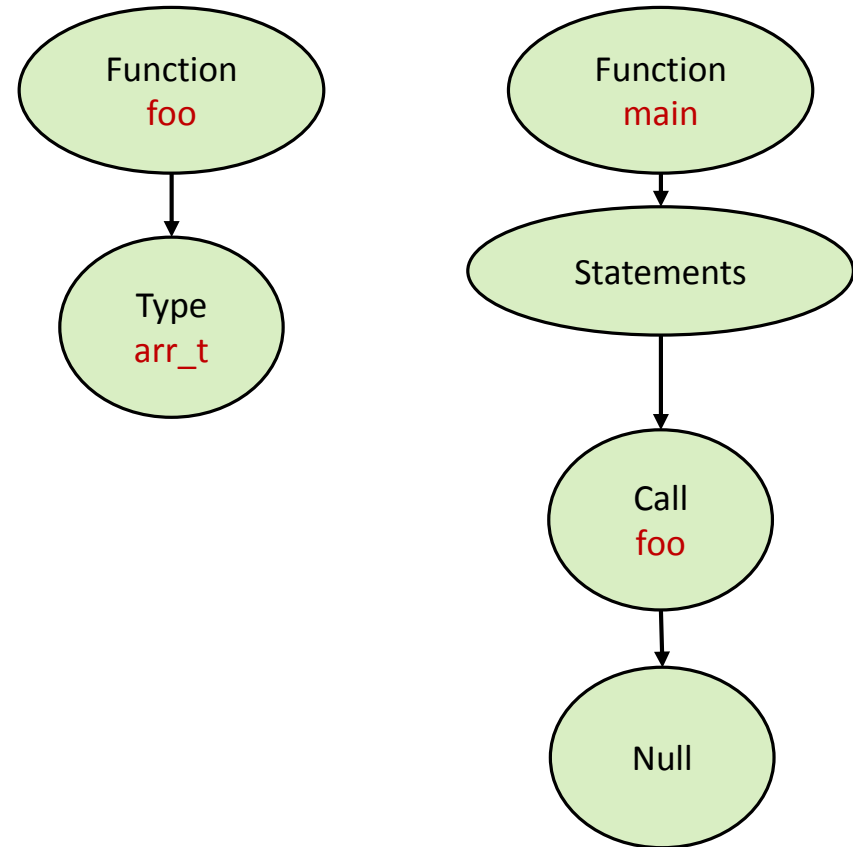
```
class A { }  
class B extends A { }  
void foo(B b) { }  
void main() {  
    A o = new A;  
    foo(o);  
}
```



Invalid

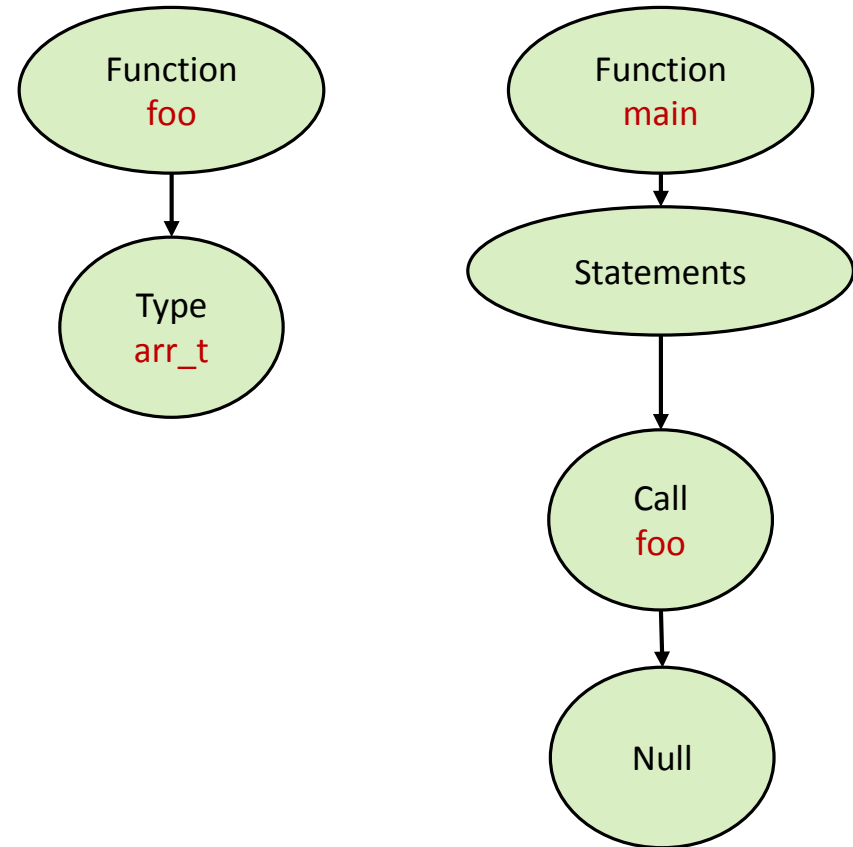
Null

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



Null

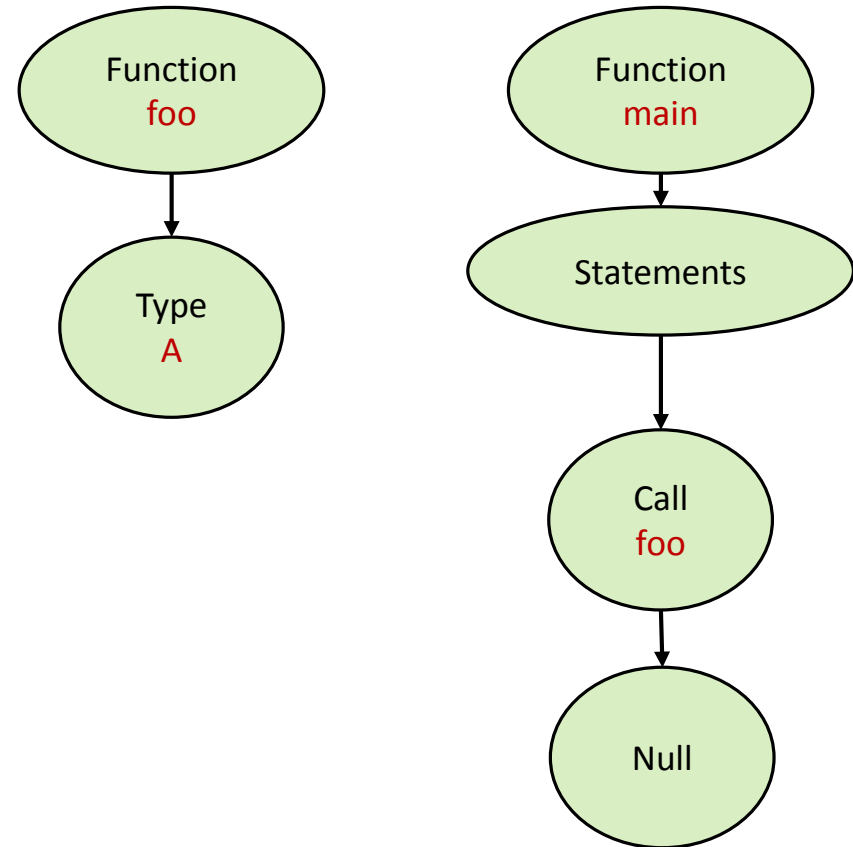
```
typedef int arr_t[];  
void foo(arr_t a) { }  
void main() {  
    foo(null);  
}
```



Valid

Null

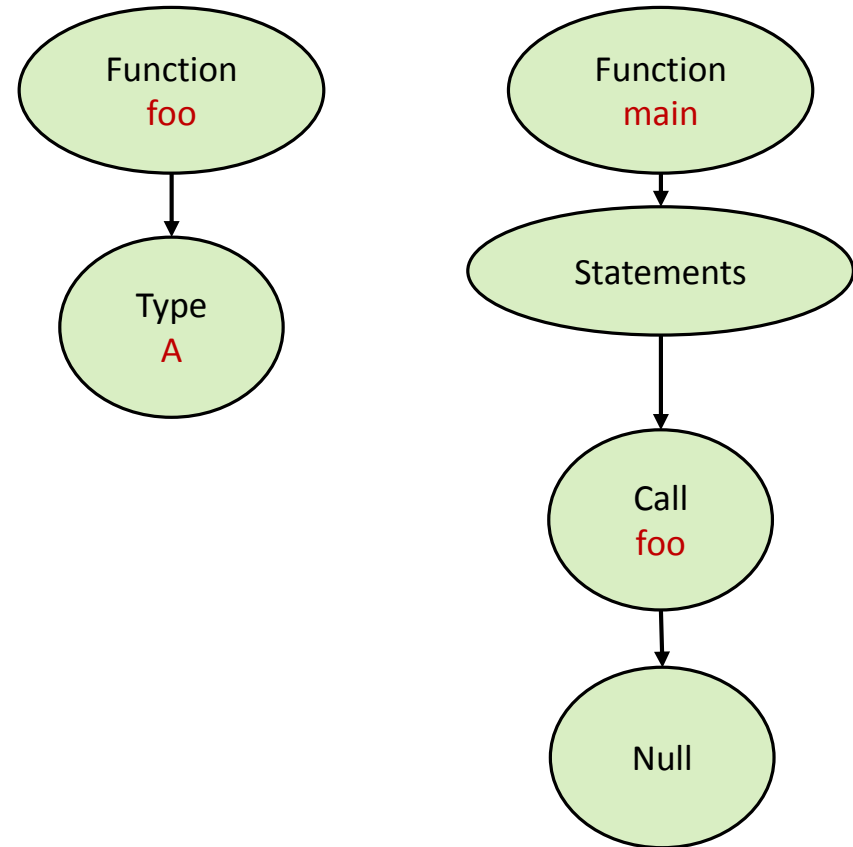
```
class A { };  
void foo(A a) { }  
void main() {  
    foo(null);  
}
```



Null

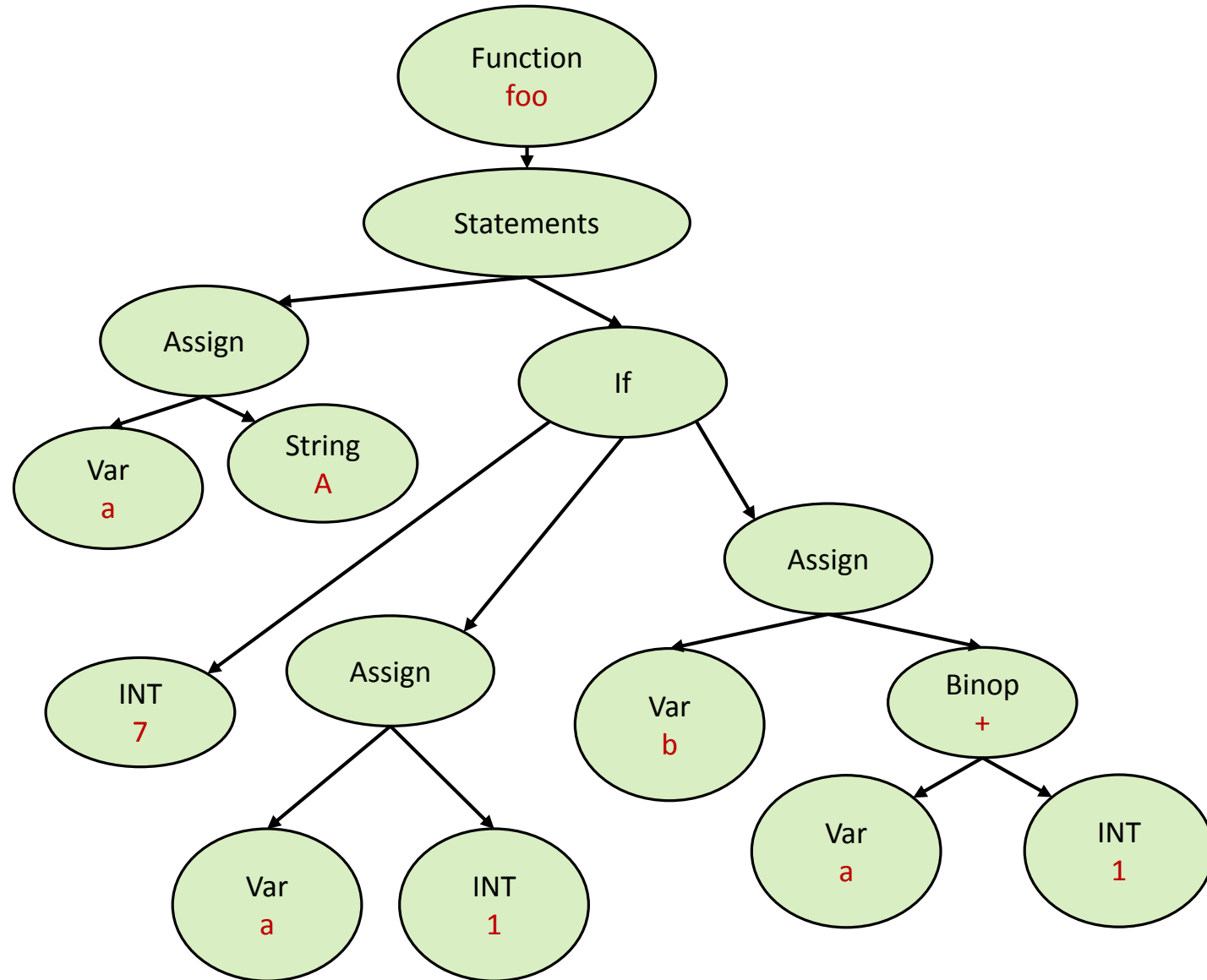
```
class A { };  
void foo(A a) { }  
void main() {  
    foo(null);  
}
```

Valid



Scopes

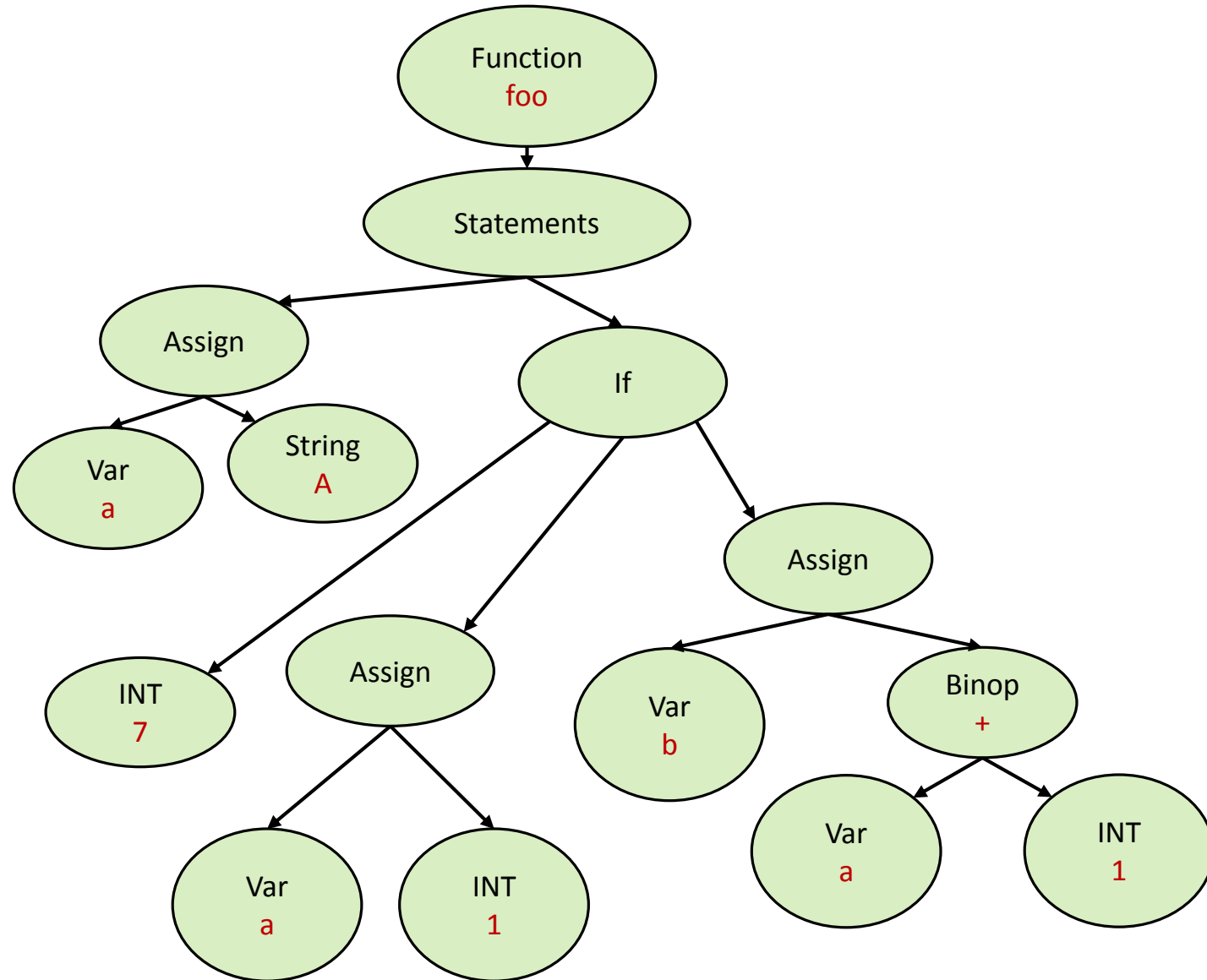
```
void foo(void) {  
  string a = "A";  
  if (7) {  
    int a = 1;  
    int b = a + 1;  
  }  
}
```



Scopes

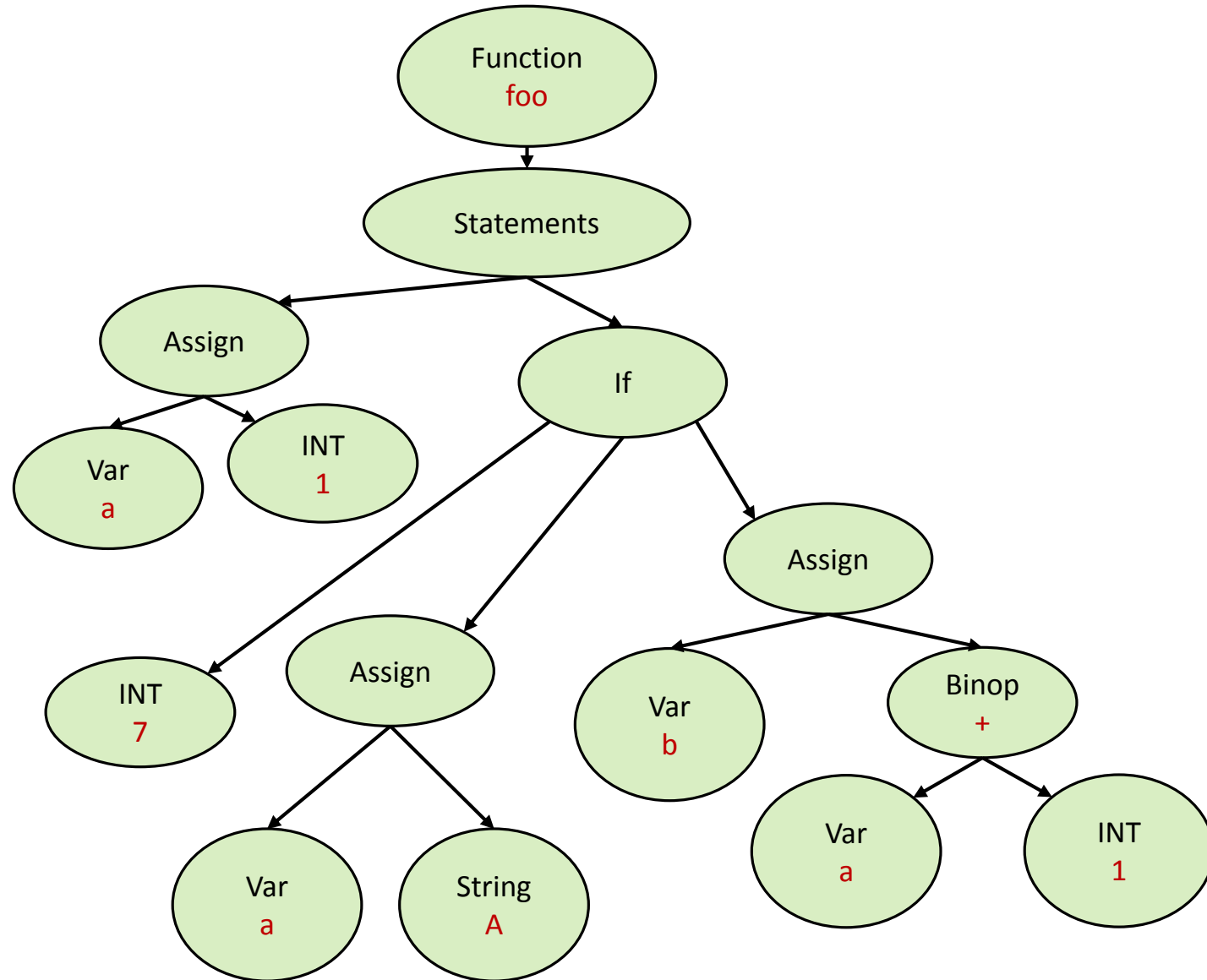
```
void foo(void) {  
  string a = "A";  
  if (7) {  
    int a = 1;  
    int b = a + 1;  
  }  
}
```

Valid



Scopes

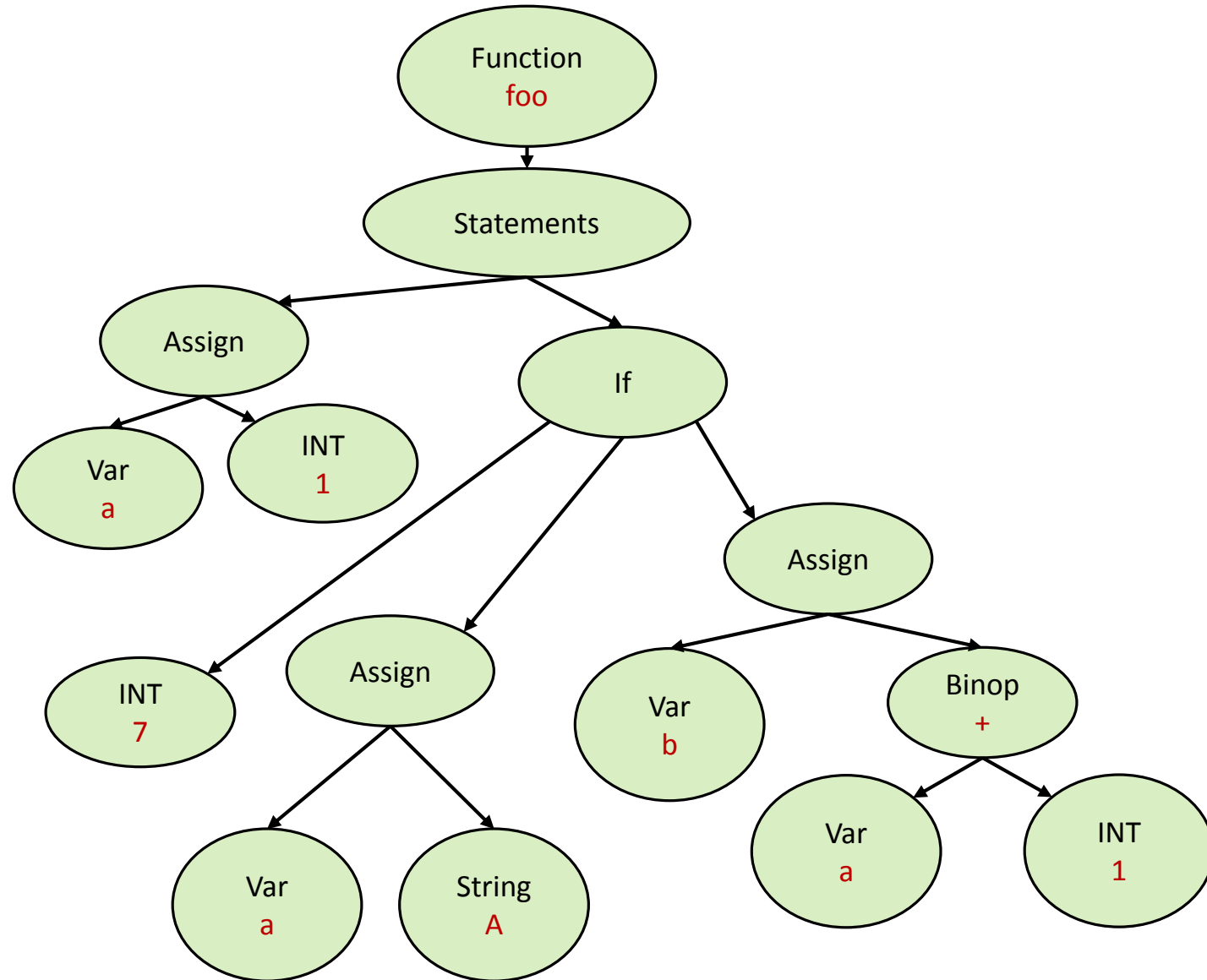
```
void foo(void) {  
  int a = 1;  
  if (7) {  
    string a = "A";  
    int b = a + 1;  
  }  
}
```



Scopes

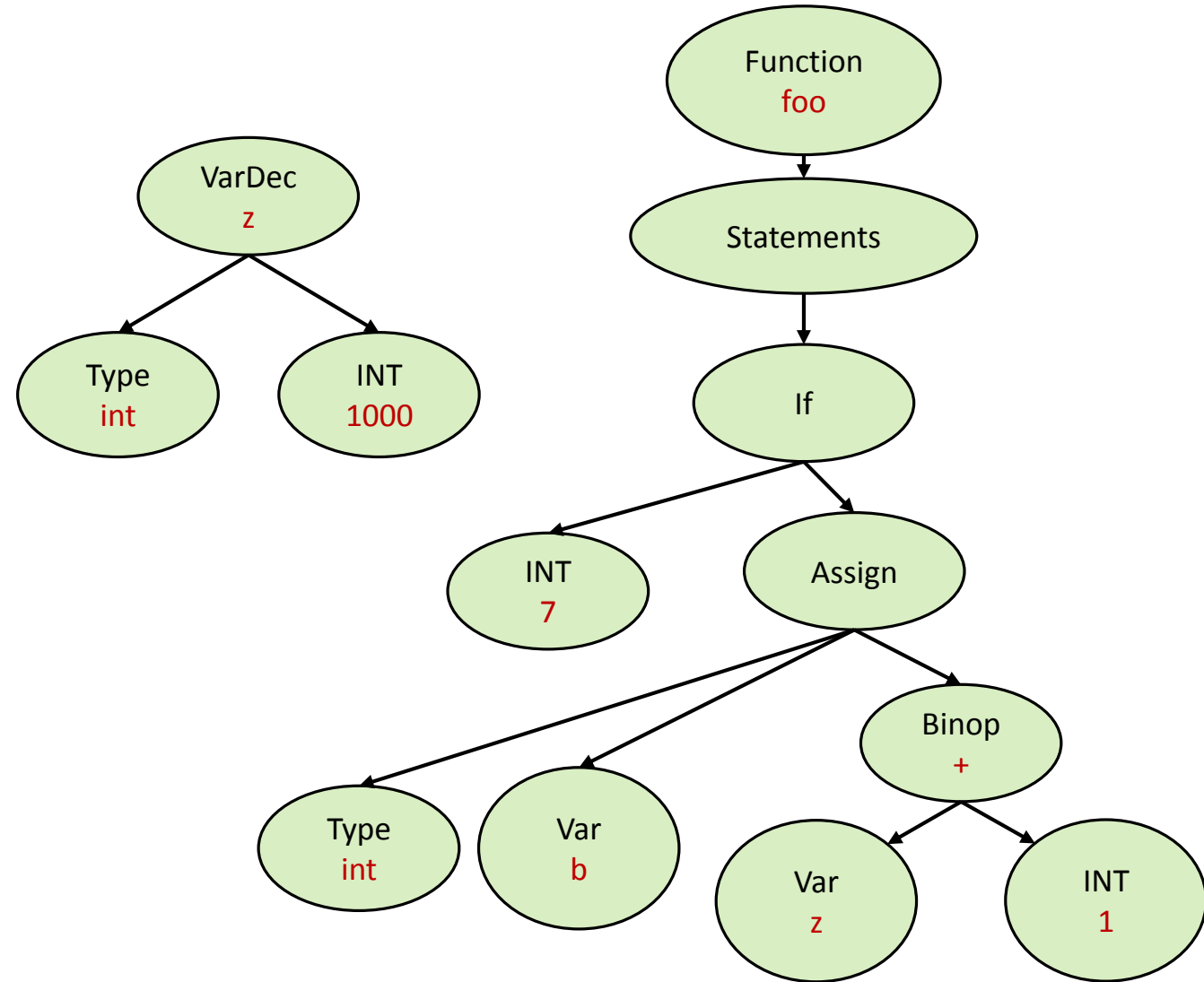
```
void foo(void) {  
  int a = 1;  
  if (7) {  
    string a = "A";  
    int b = a + 1;  
  }  
}
```

Invalid



Scopes

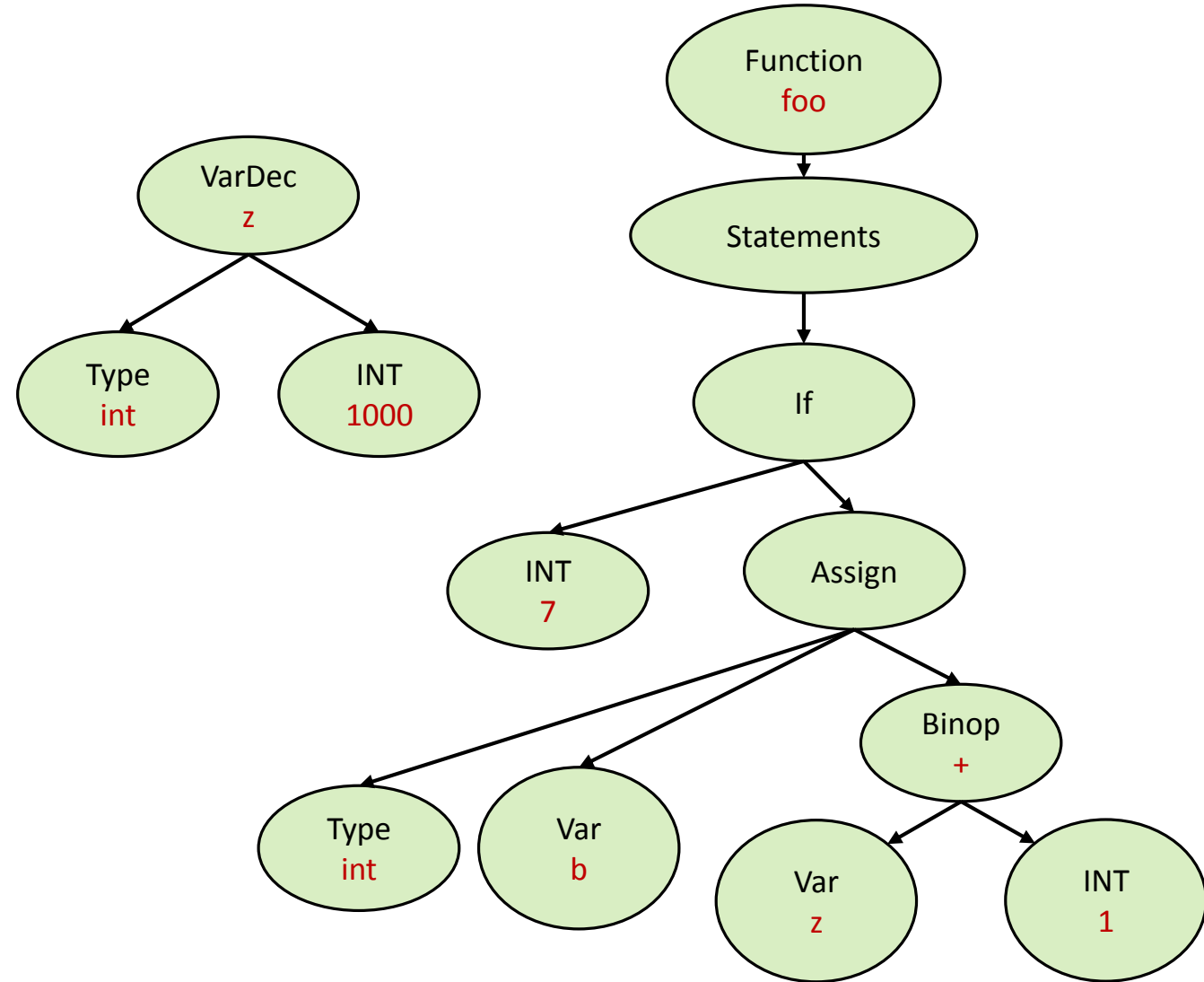
```
int z = 1000;  
void foo(int z) {  
    if (7) {  
        int b = z + 1;  
    }  
}
```



Scopes

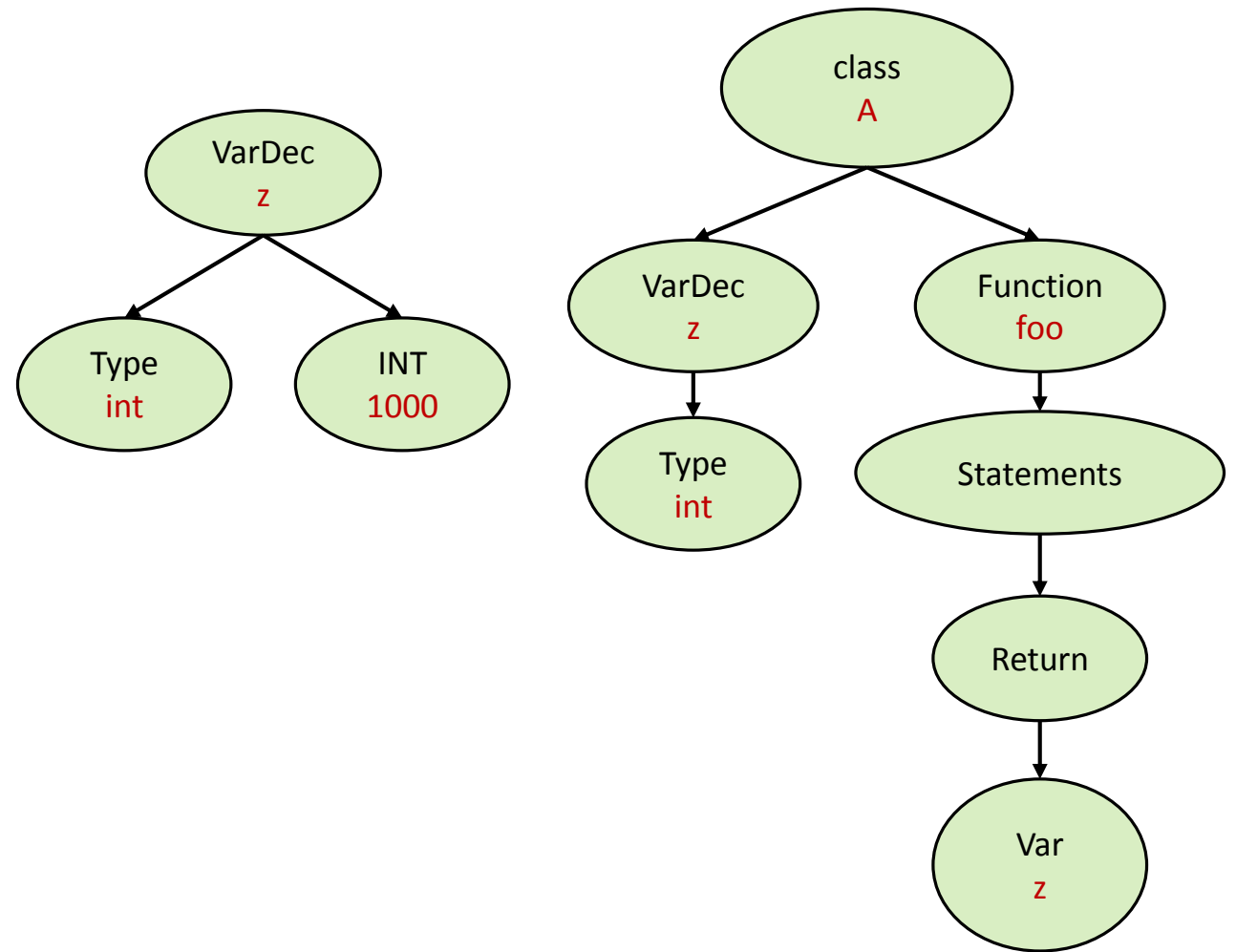
```
int z = 1000;  
void foo(int z) {  
    if (7) {  
        int b = z + 1;  
    }  
}
```

Valid



Scopes

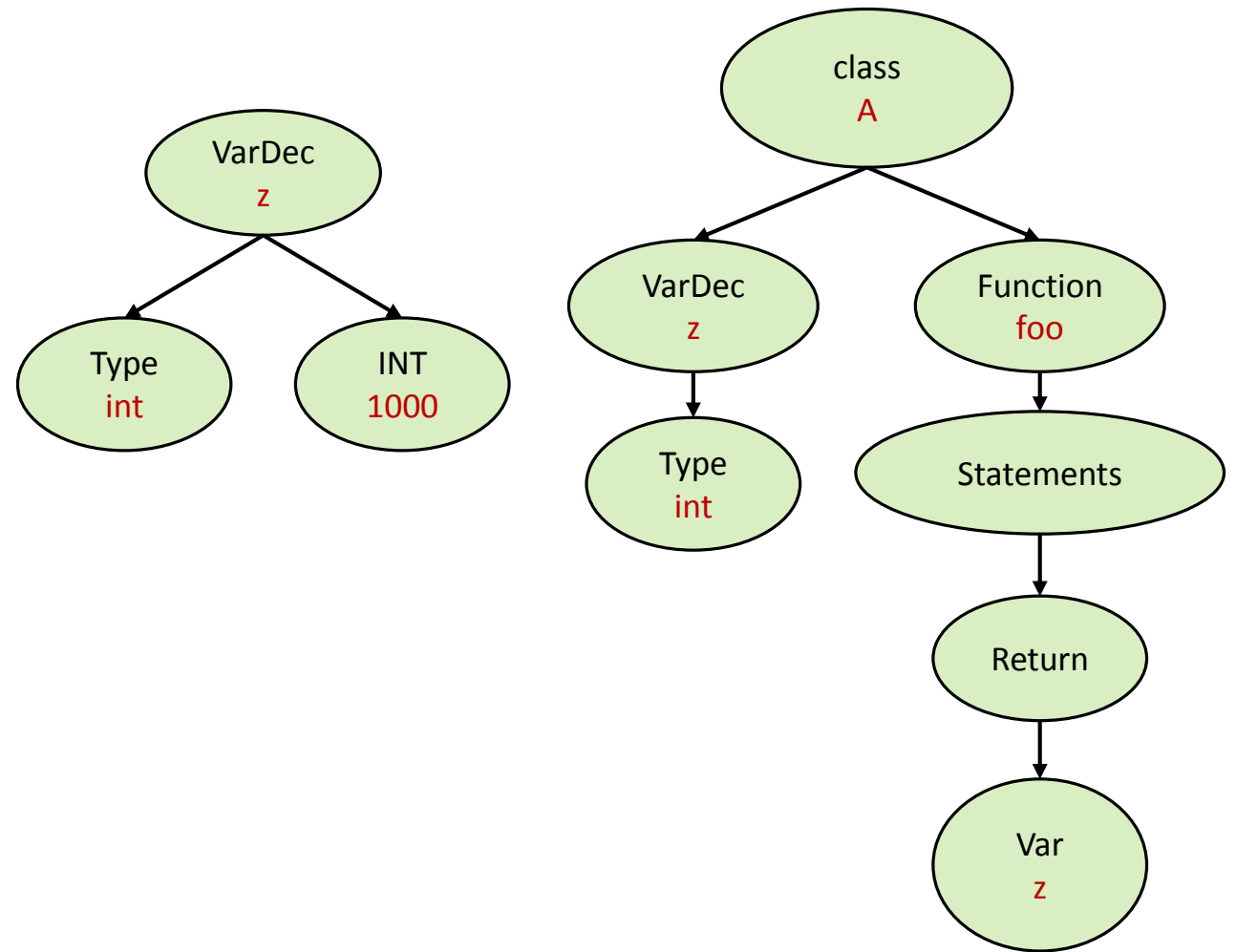
```
int z = 1000;  
class A {  
    int z;  
    int foo() {  
        return z;  
    }  
}
```



Scopes

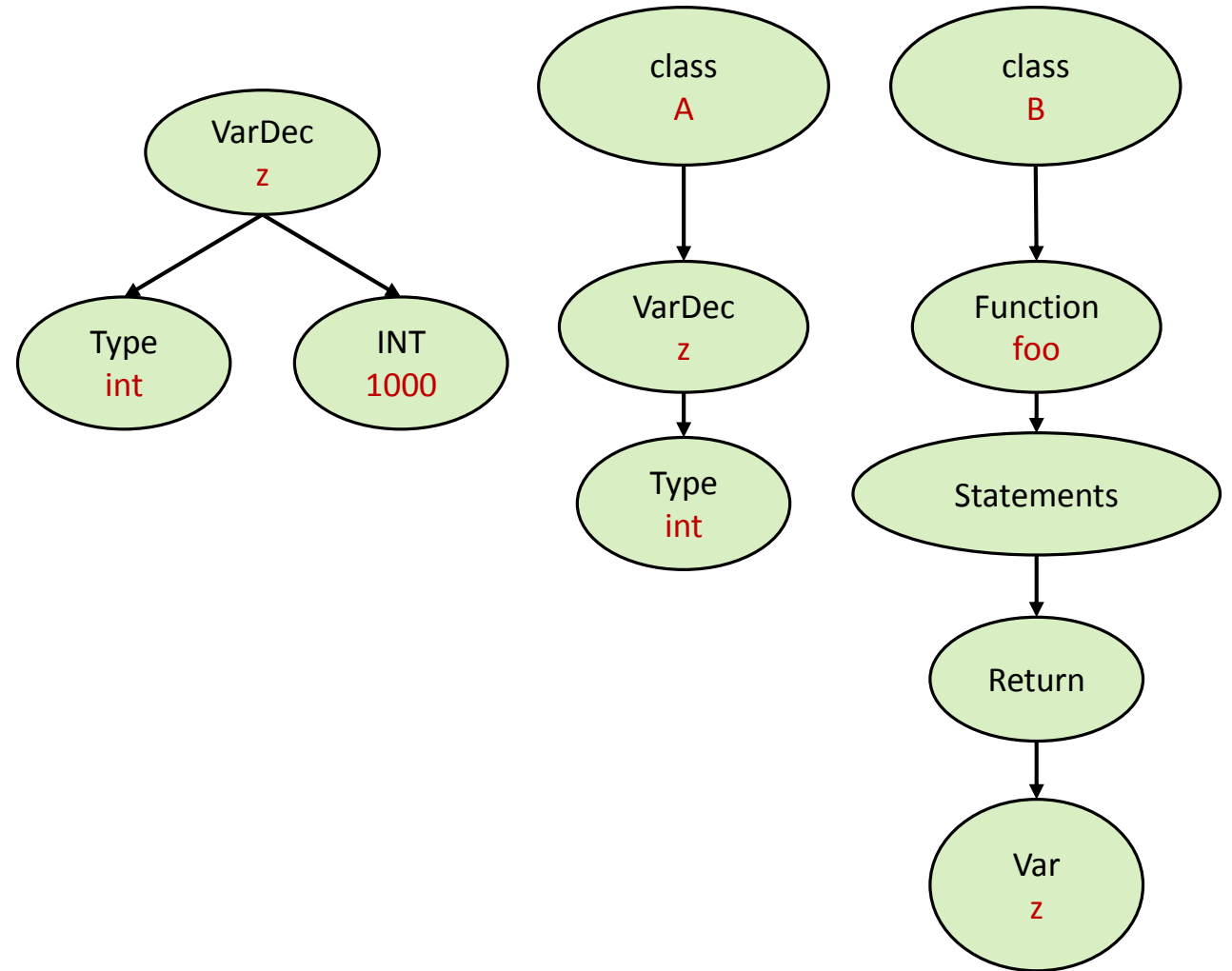
```
int z = 1000;  
class A {  
    int z;  
    int foo() {  
        return z;  
    }  
}
```

Valid



Scopes

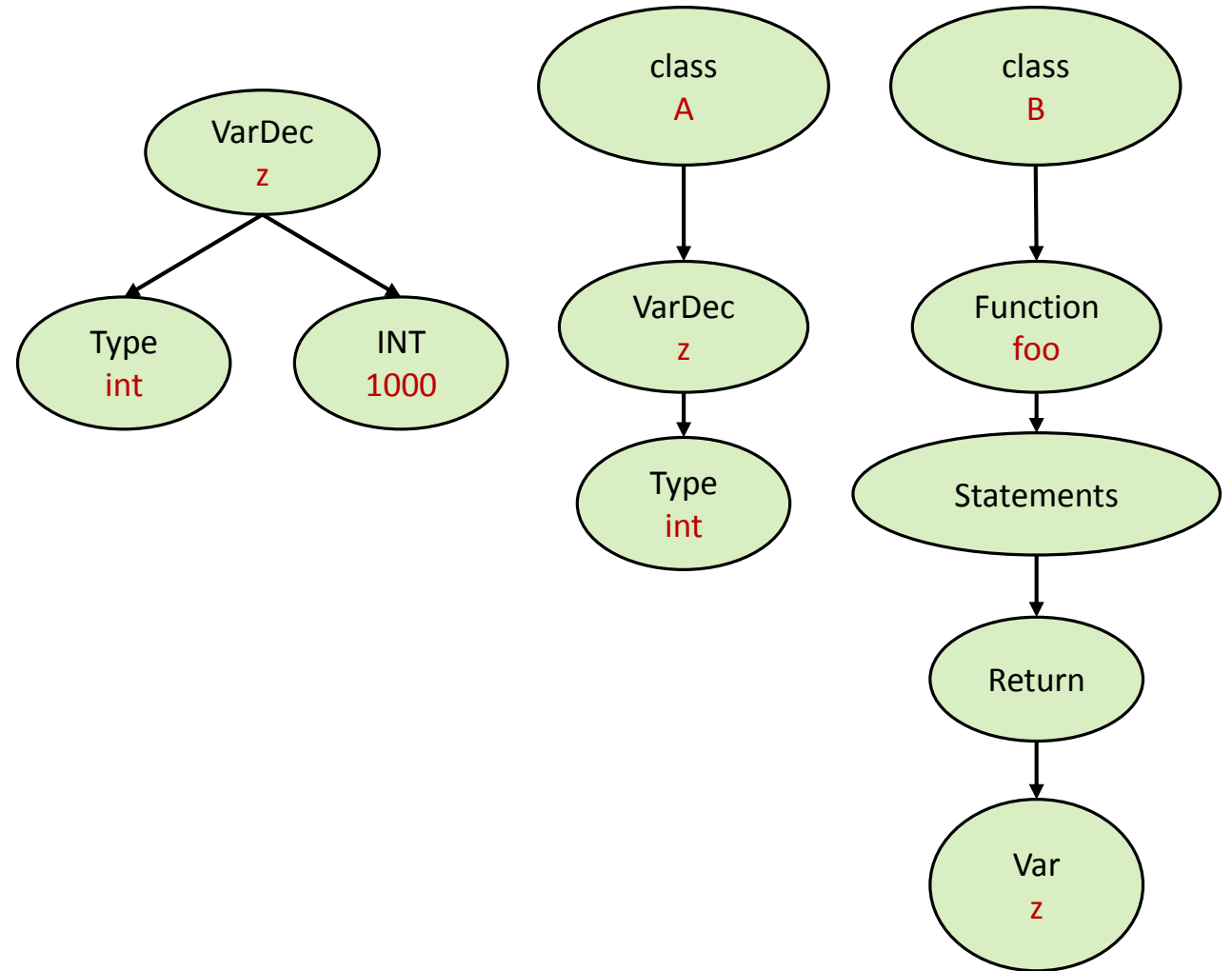
```
int z = 1000;  
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```



Scopes

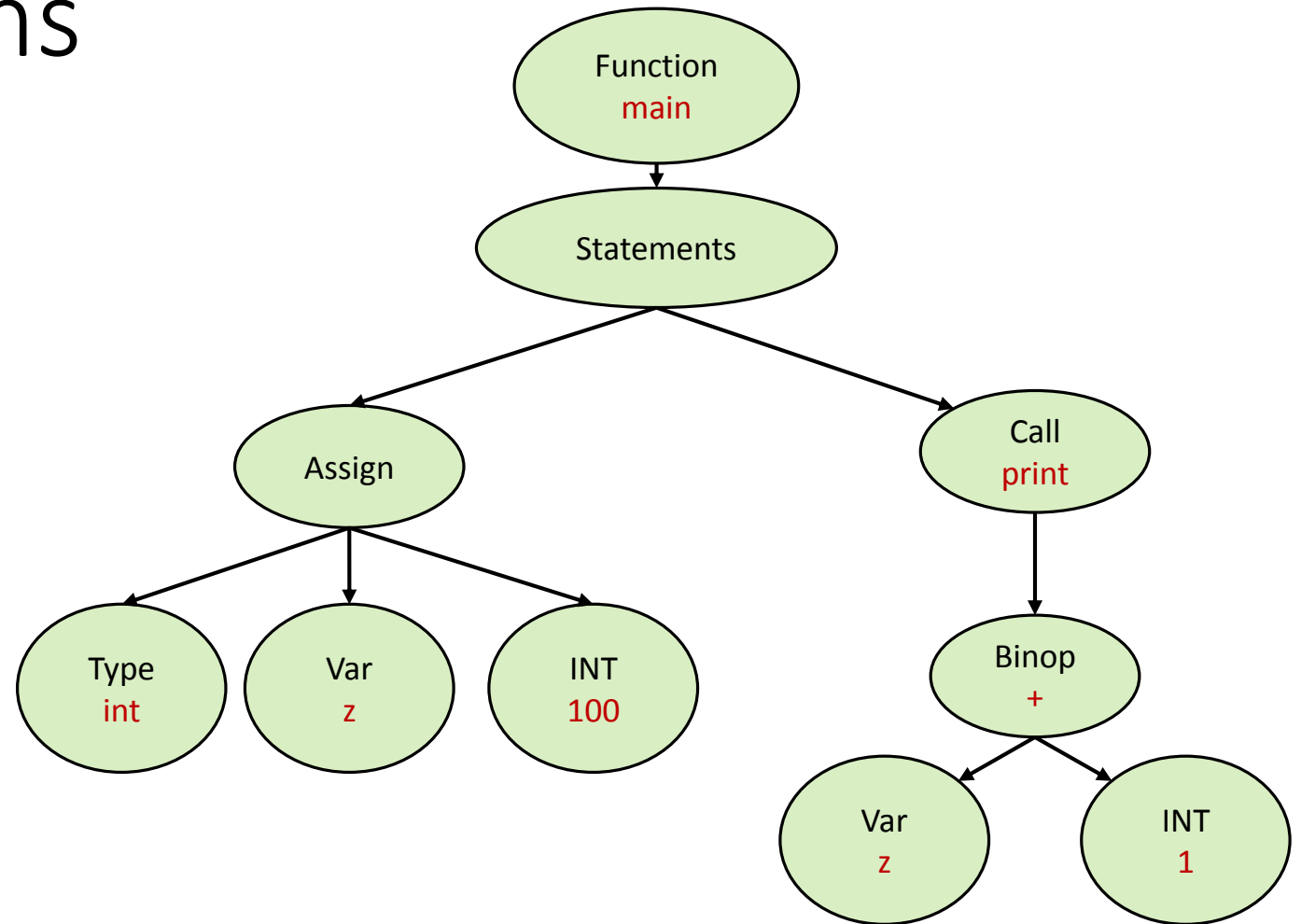
```
int z = 1000;  
class A {  
    int z;  
}  
class B extends A {  
    int foo() {  
        return z;  
    }  
}
```

Valid



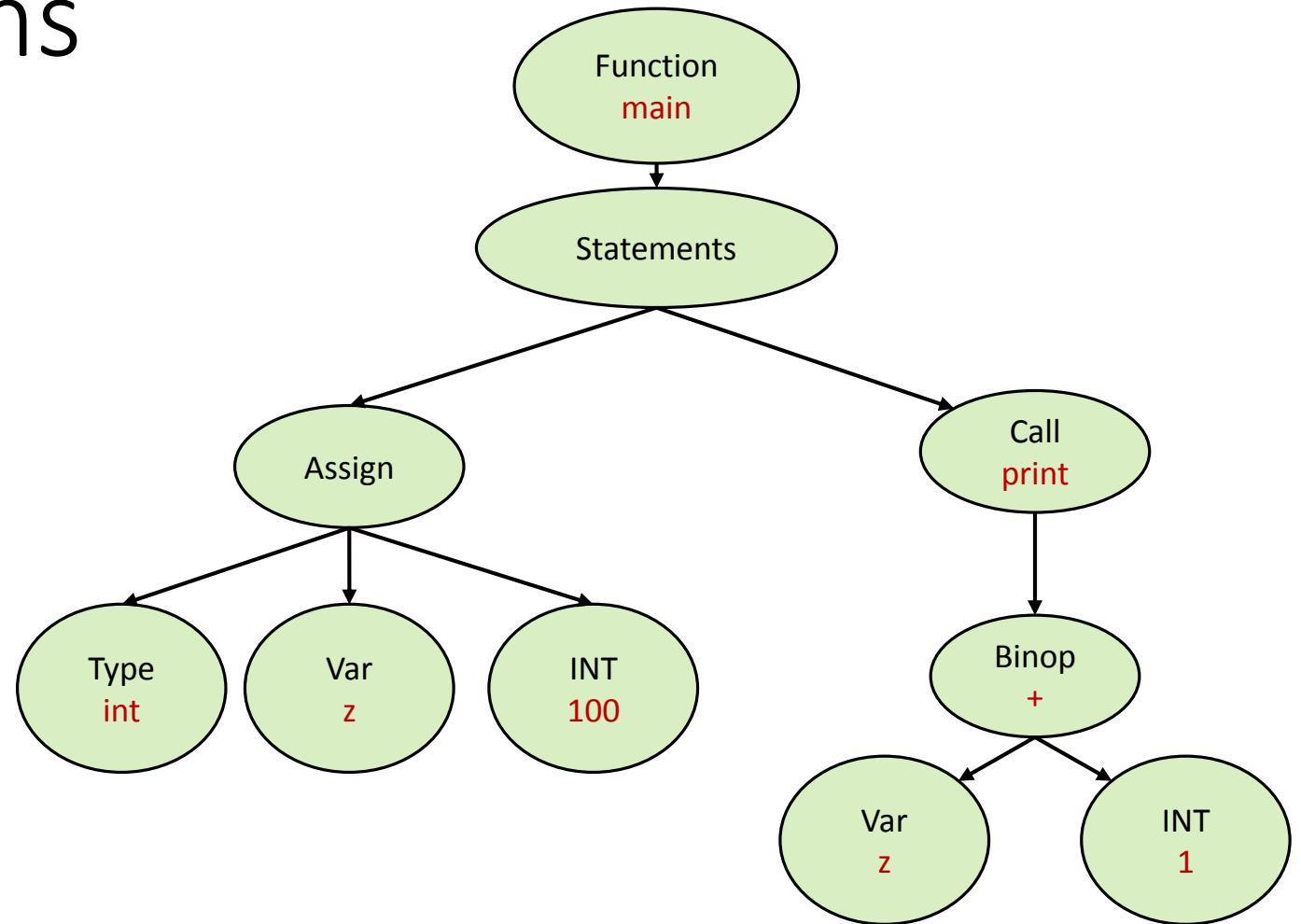
Library Functions

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



Library Functions

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



Valid

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
 - In the skeleton it's called *semantMe*
- 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  
        }  
        ...  
    }  
}
```

Implementation

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

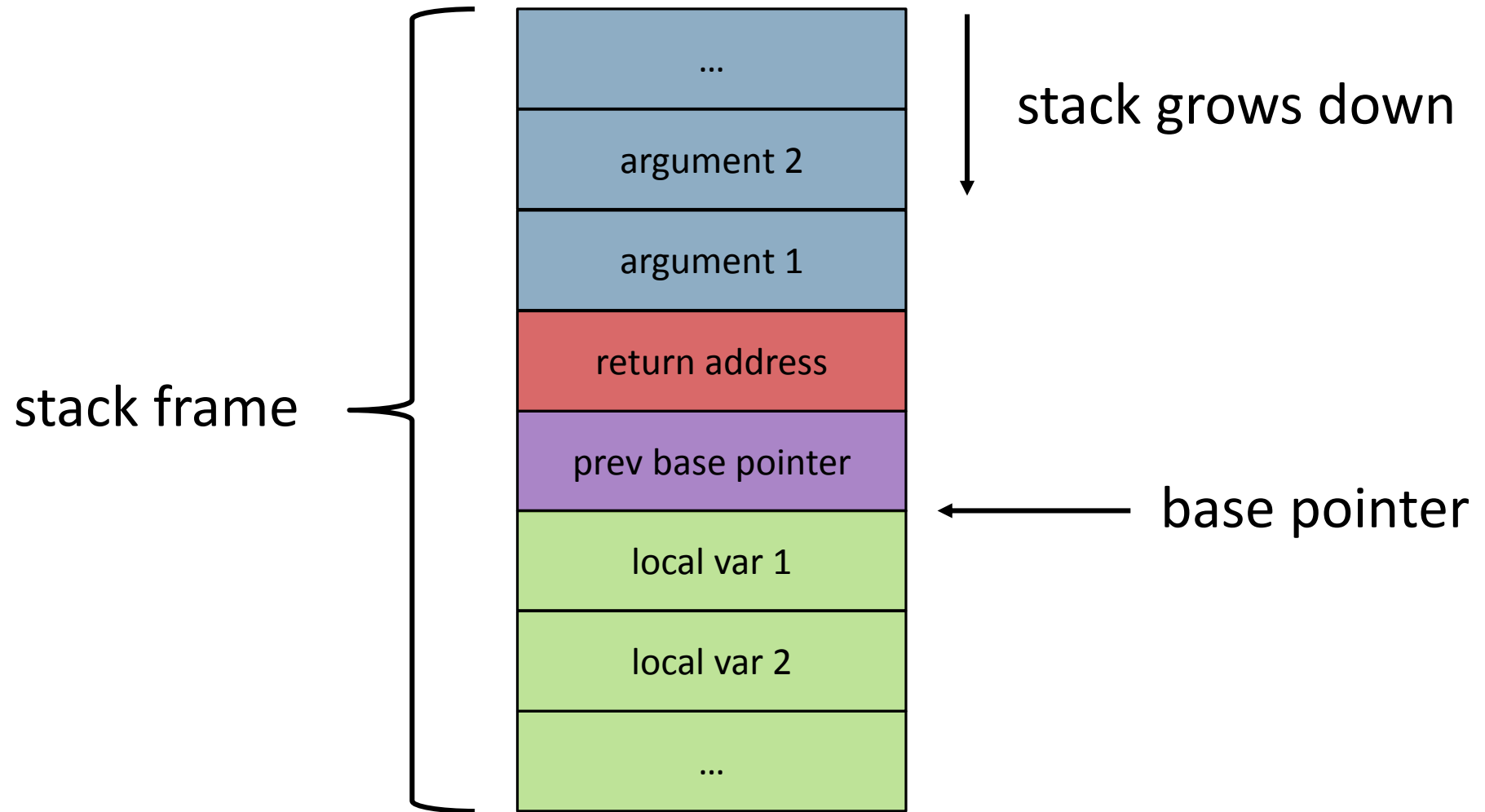

AST Annotations

AST Annotations

While analyzing the AST, we can extend it with useful information:

- Variable offsets
- Parameter offsets
- Class layout
- Type size

Stack



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

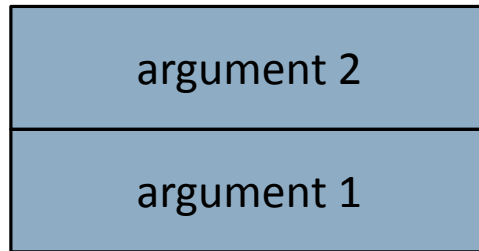
f:

```
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



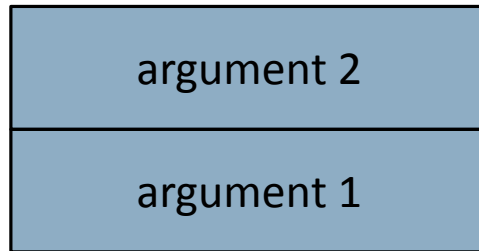
f:

```
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



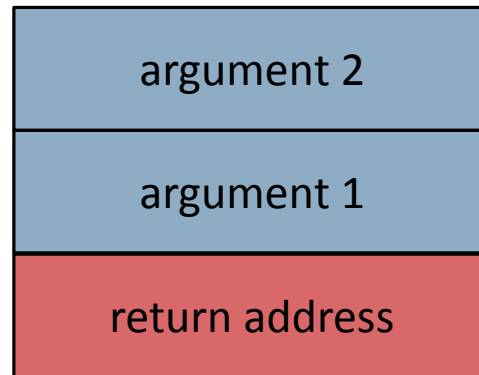
f:

```
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)

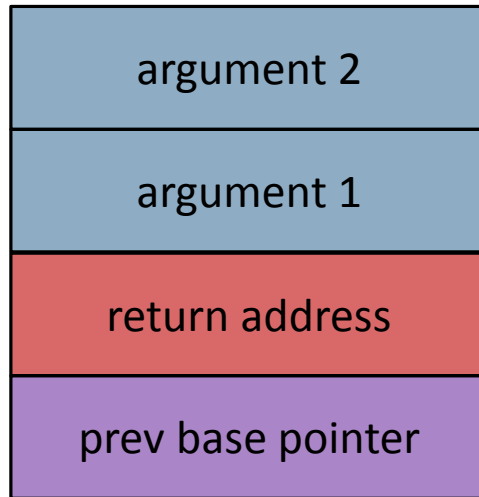
jal f

addu \$sp, \$sp, 8

move \$t0, \$v0

...

Stack



f:

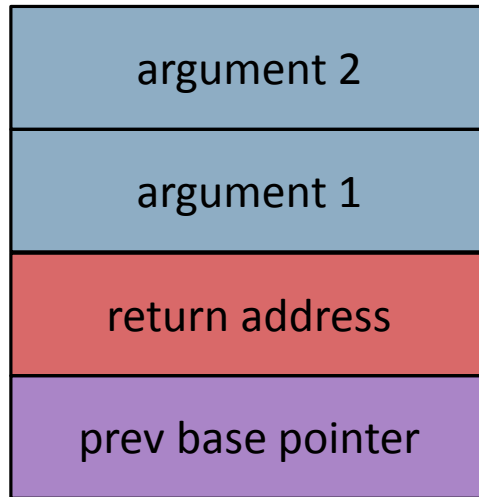
```
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

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

base pointer →



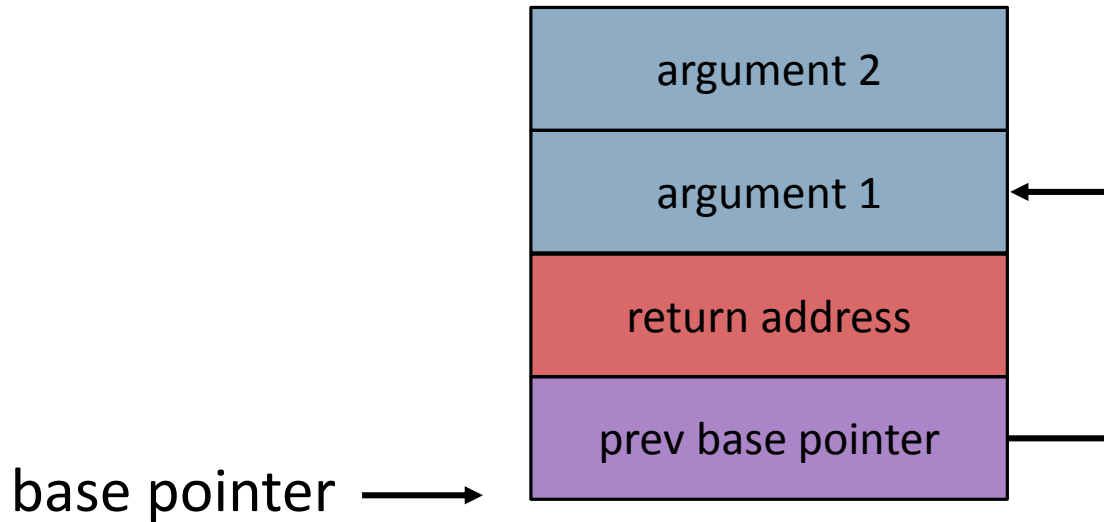
f:

```
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



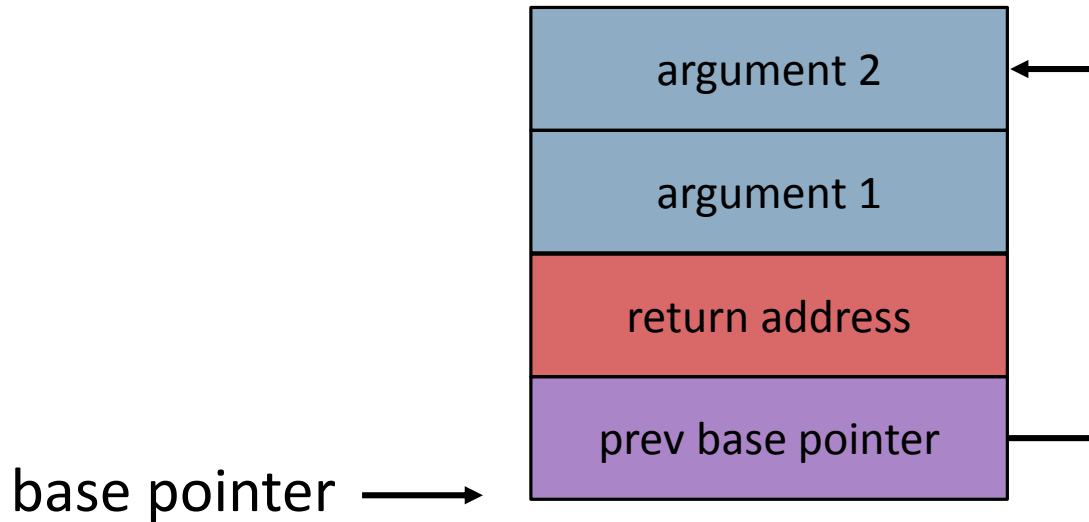
f:

```
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



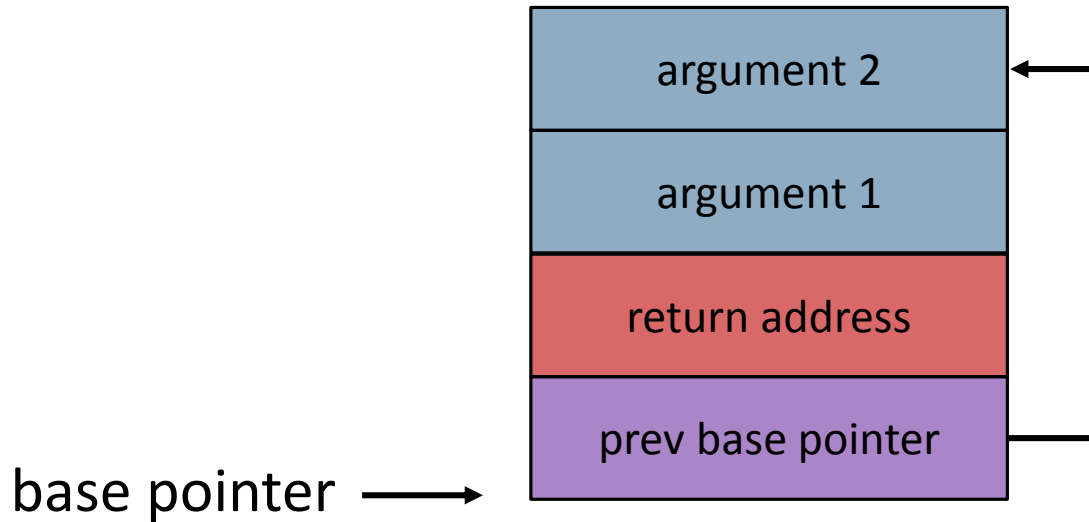
f:

```
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



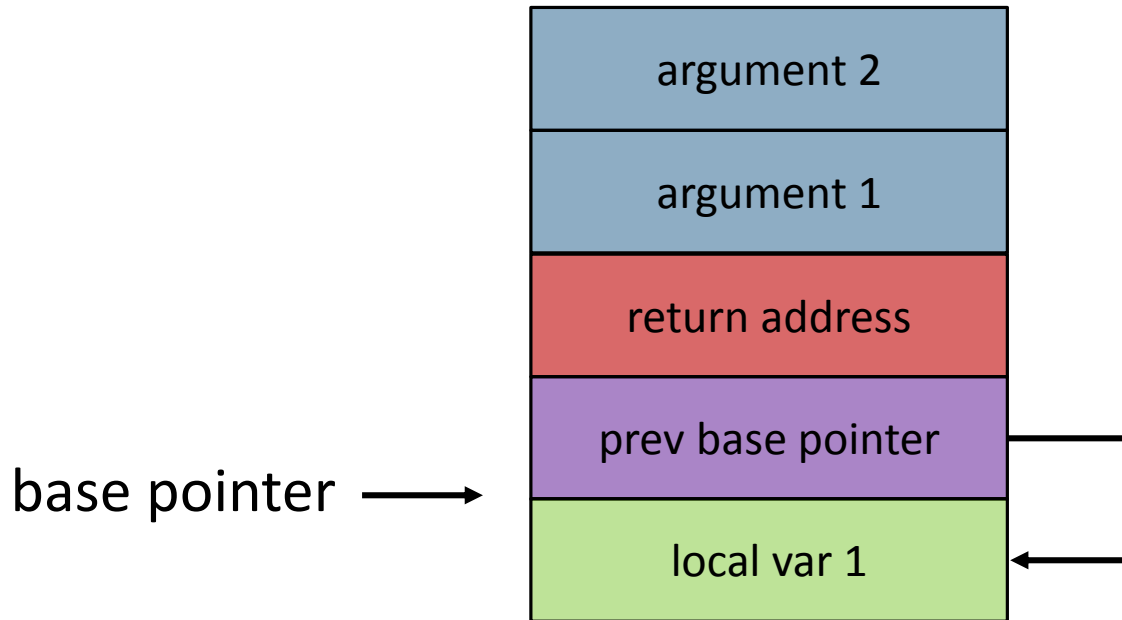
f:

```
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:

```
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
...
```

Variable Offsets

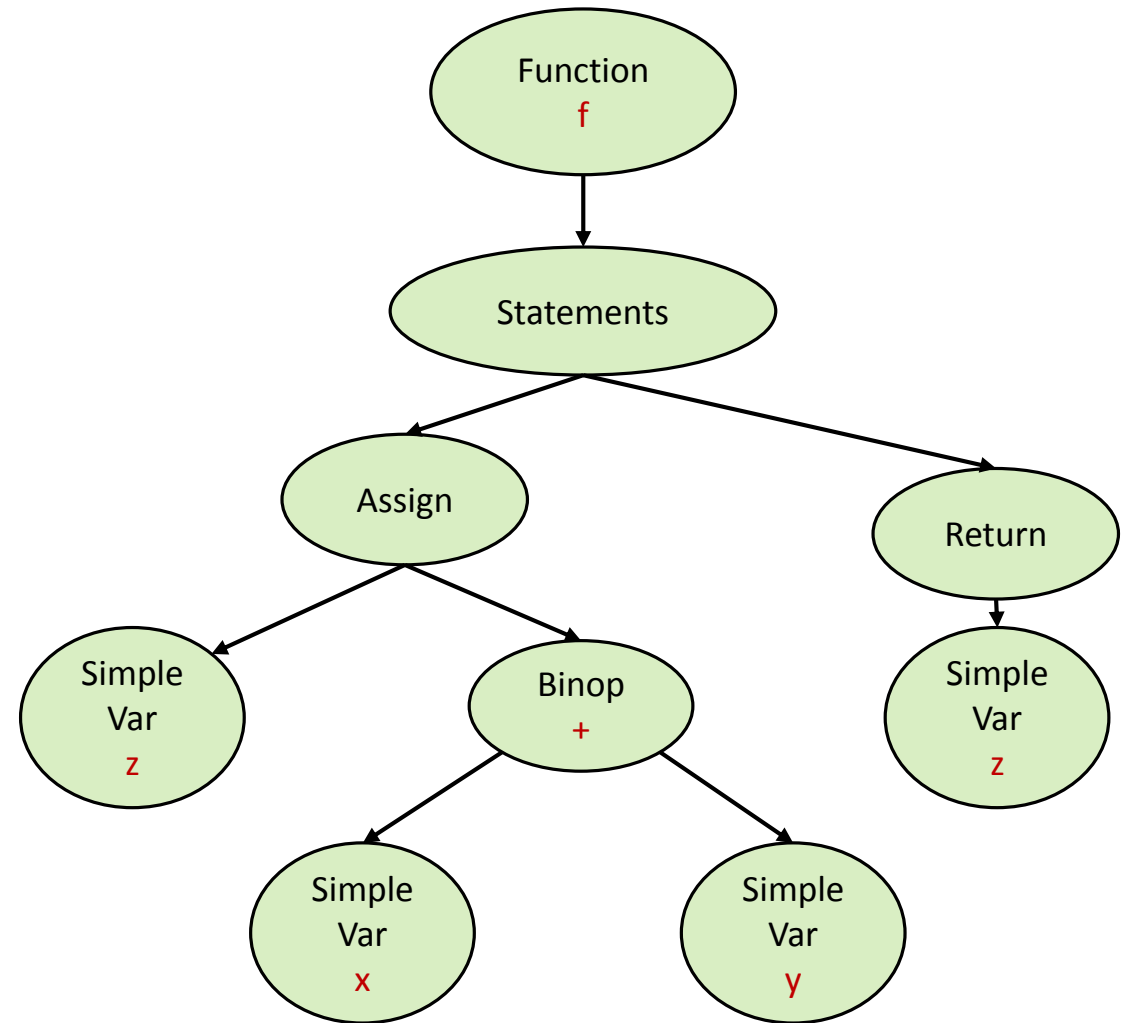
Machine code **does not** contain names of:

- Local variables
- Parameters

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

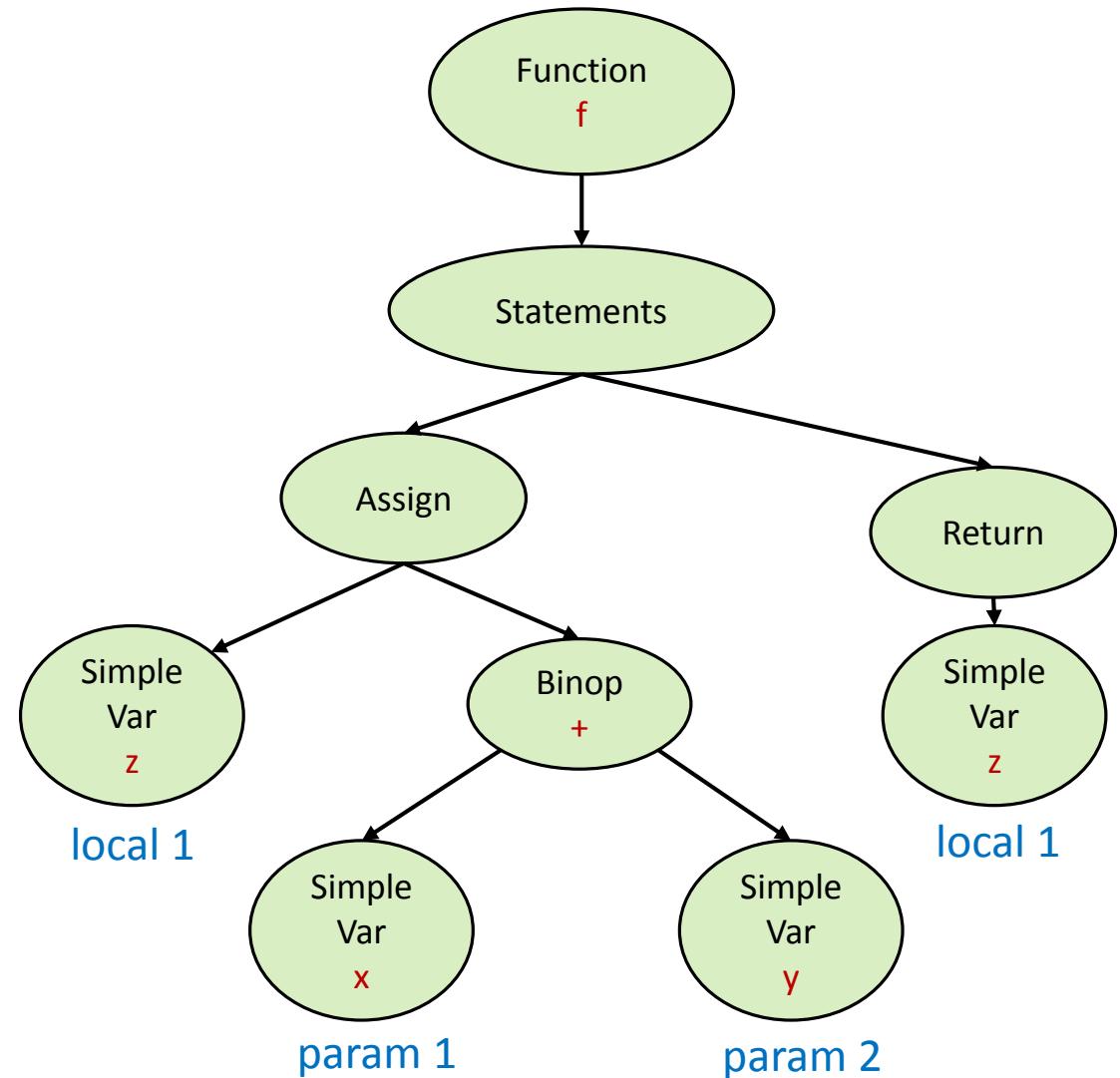
Variable Offsets

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



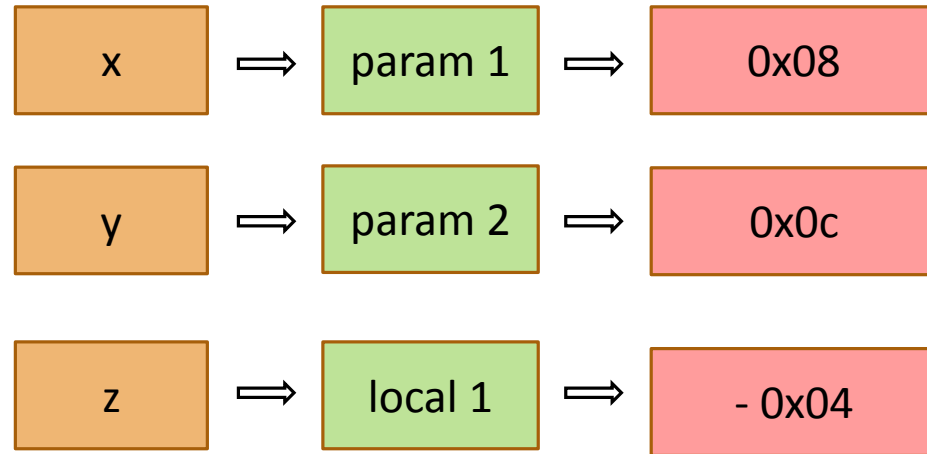
Variable Offsets

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



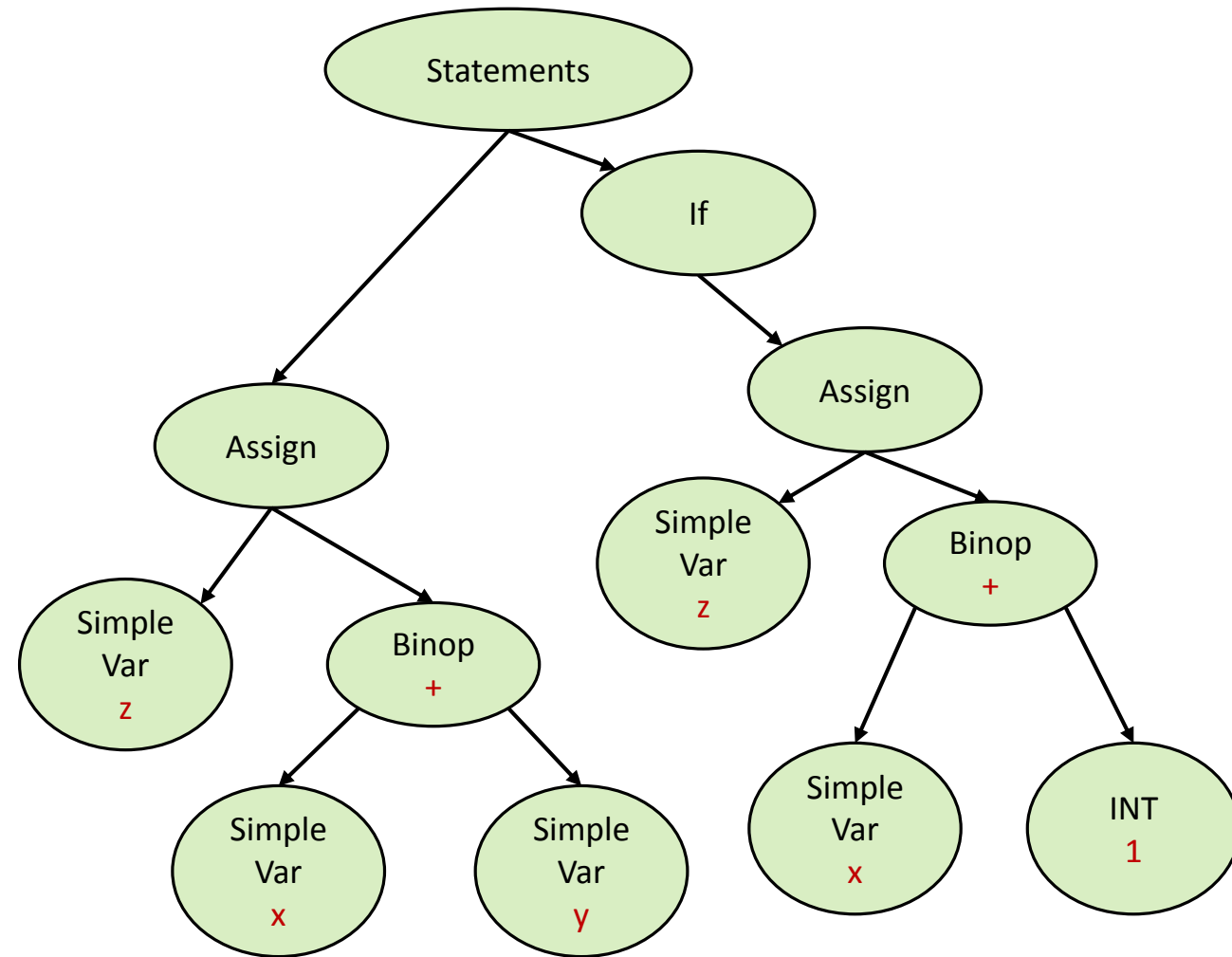
Variable Offsets

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



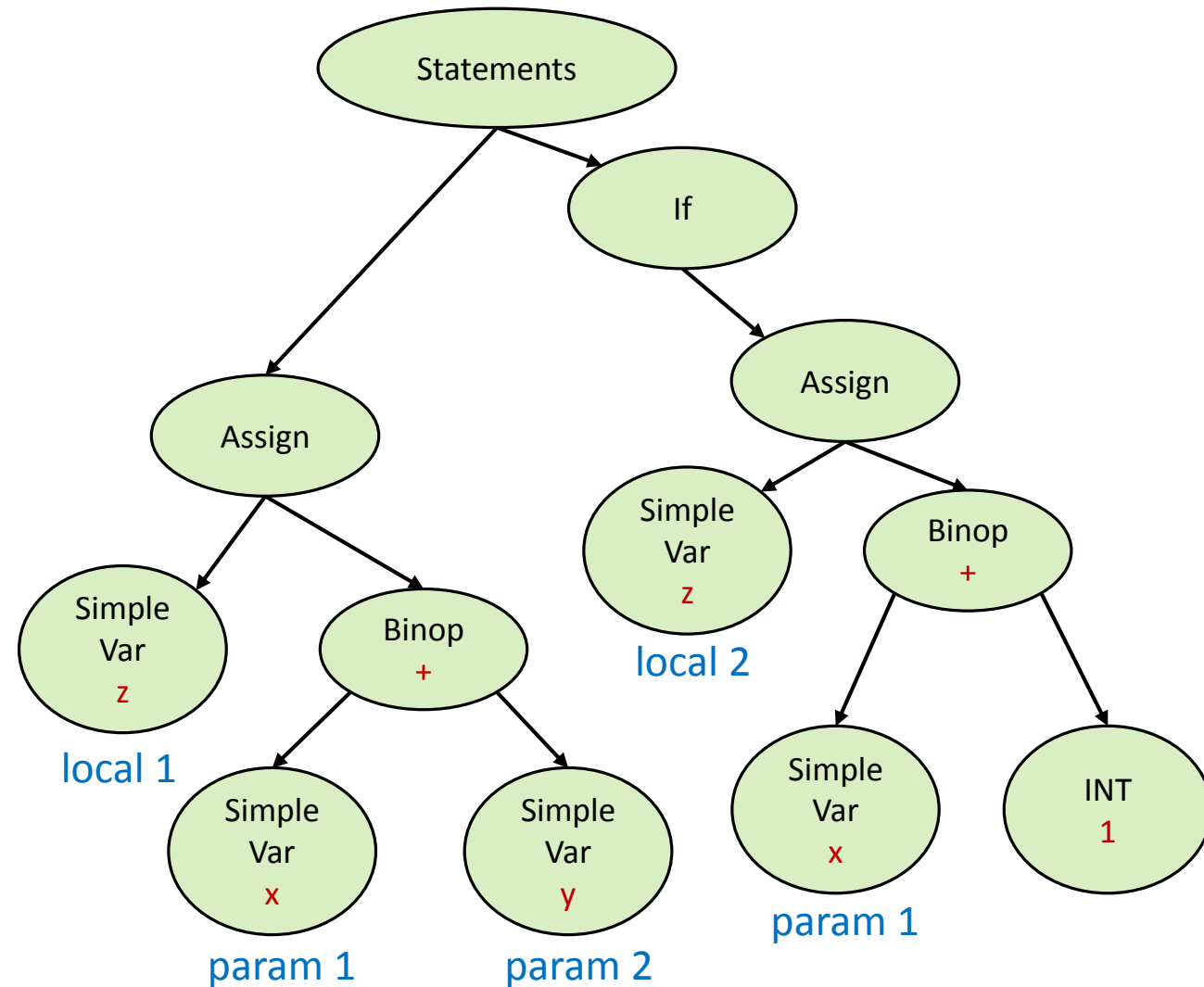
Variable Offsets

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



Variable Offsets

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



Field Offsets

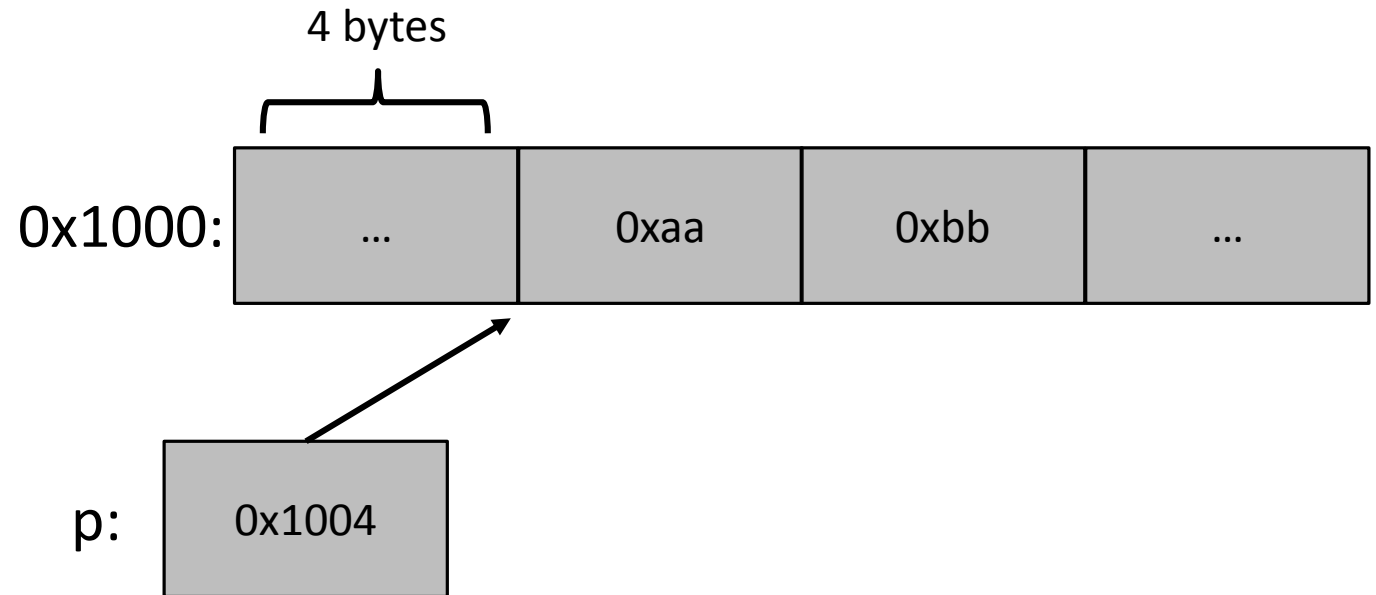
How does an object of this class look in memory?

```
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)  
lw $t1, 0xaa  
sw $t1, 0($t0)  
lw $t1, 0xbb  
sw $t1, 4($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)  
lw $t1, 0xaa  
sw $t1, 0($t0)  
lw $t1, 0xbb  
sw $t1, 4($t0)  
<epilogue>
```


Field Offsets

How does an object of this class look in memory?

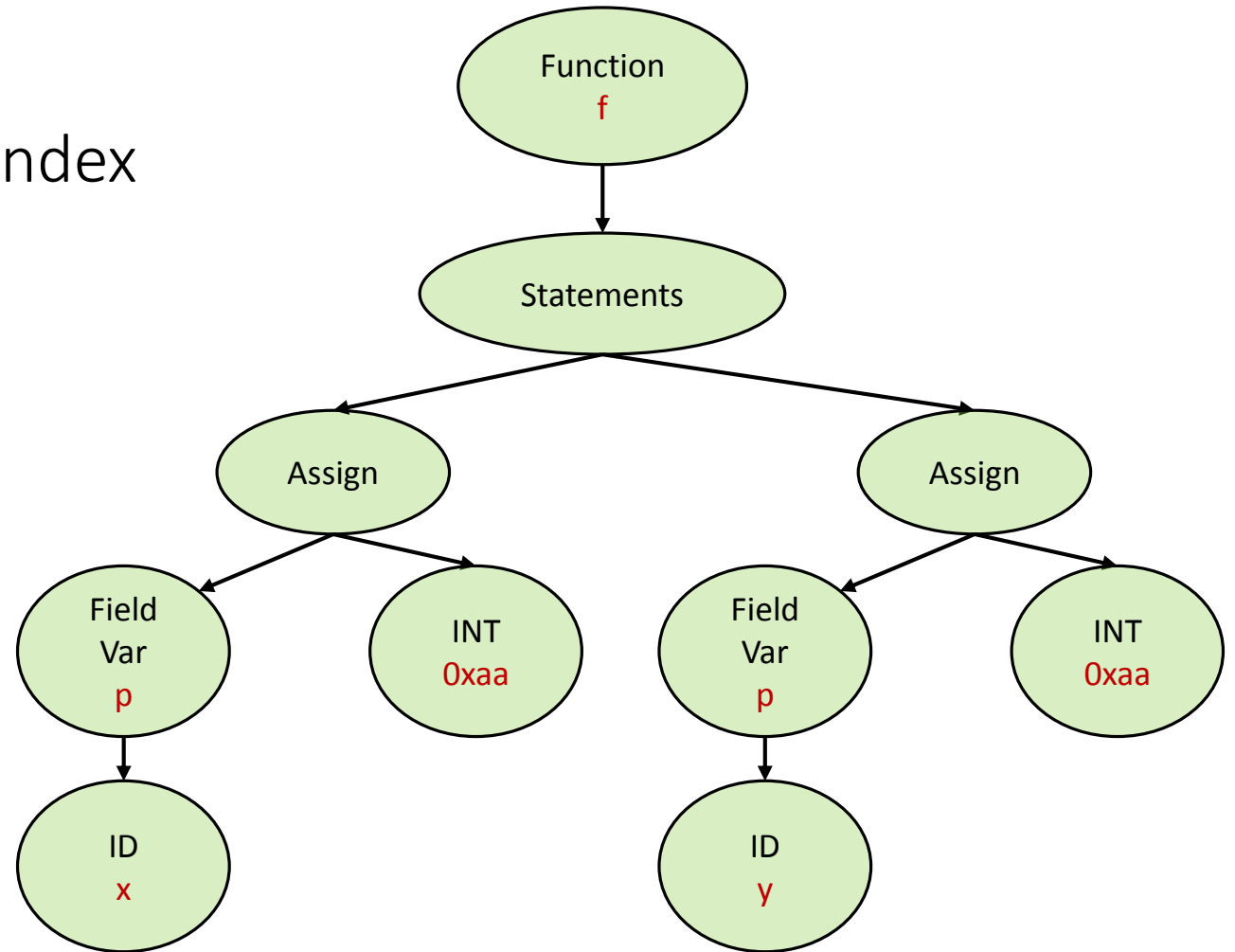
```
class Point {  
    int x;  
    int y;  
}  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```

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

Field Offsets

Each class field should have an index

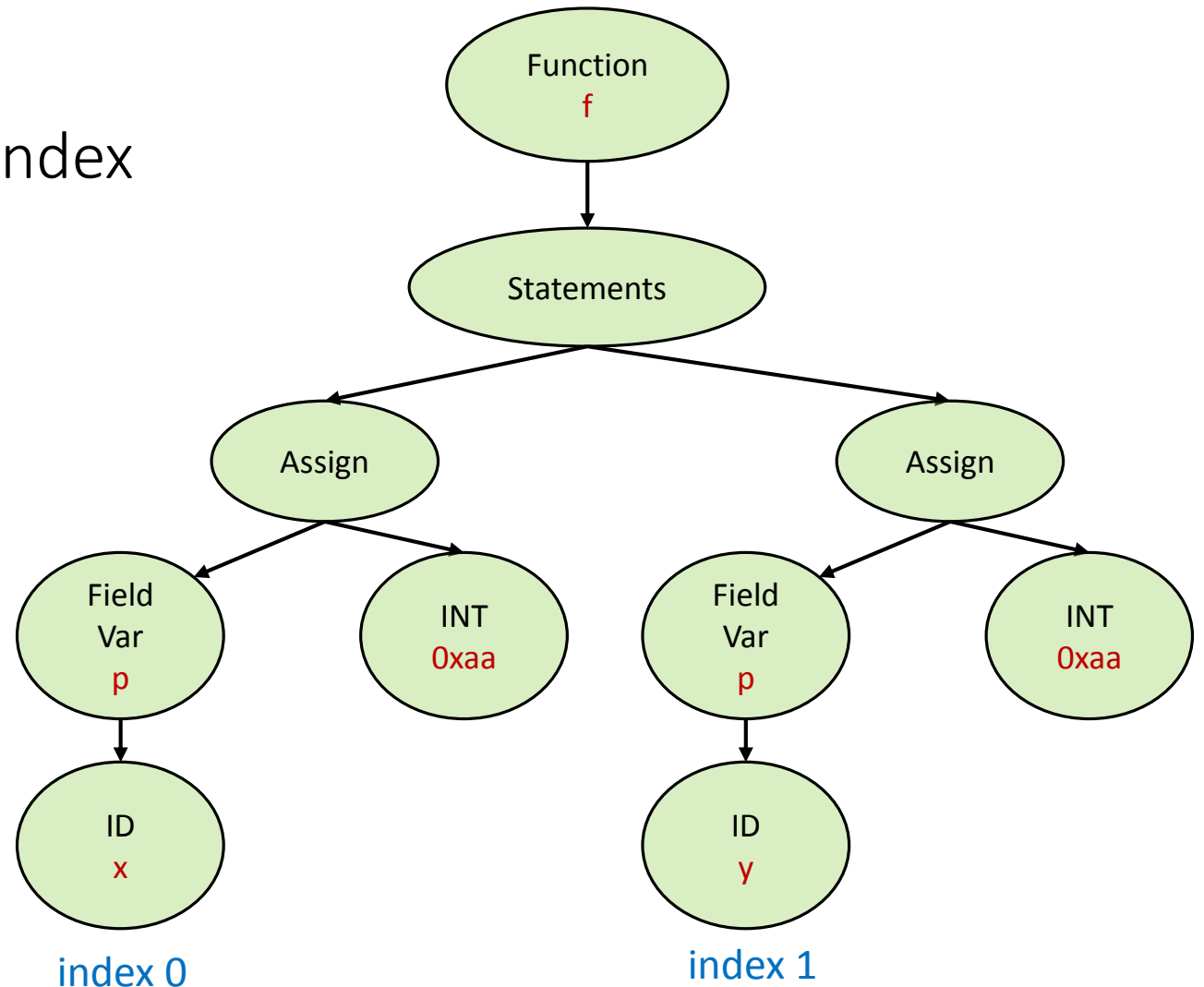
```
class Point {  
    int x;  
    int y;  
}  
void f(Point p) {  
    p.x = 0xaa;  
    p.y = 0xbb;  
}
```



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;  
}
```



Type Sizes

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

```
f:  
<prologue>  
li $t0, 8  
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, 8  
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, 12  
subu $sp, $sp, 4  
sw $t0, 0($sp)  
jal malloc  
addu $sp, $sp, 4  
sw $v0, -4($fp)  
<epilogue>
```