Semantic Analysis

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Semantic Analysis

Perform various checks:

- Type checking
  - 1 + “1”
- Scopes
  - Undefined variables
- Other
  - Division by zero
  - Visibility semantics in classes (public, private, …)

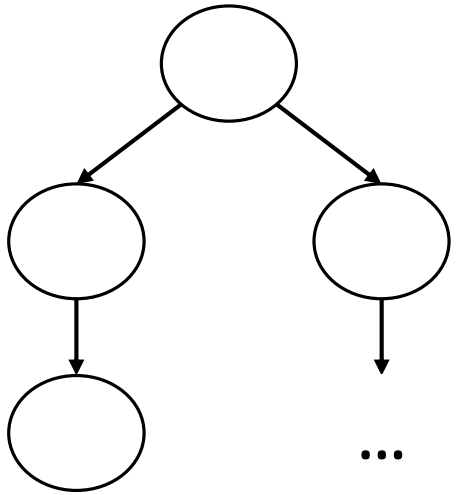
Visitor Design Pattern

Perform computations over tree-like data structures

$visit(node)$:

// do something with node

$r_1 = visit(node.child_1)$
$r_2 = visit(node.child_2)$
…
// do something with $r_1, r_2, \ldots$



Visitor Design Pattern: Example

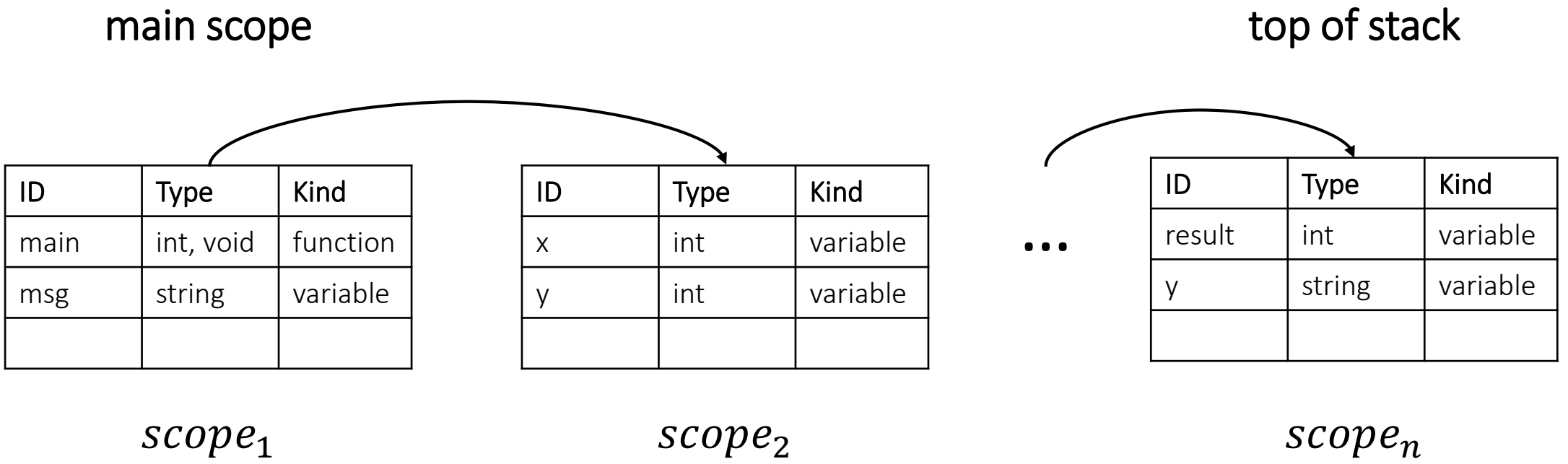
Printing the AST

$visit(node)$:
    $print(node)$
    $for\ child\ in\ node.children$:
        $visit(child)$

Symbol Table

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

Symbol Table



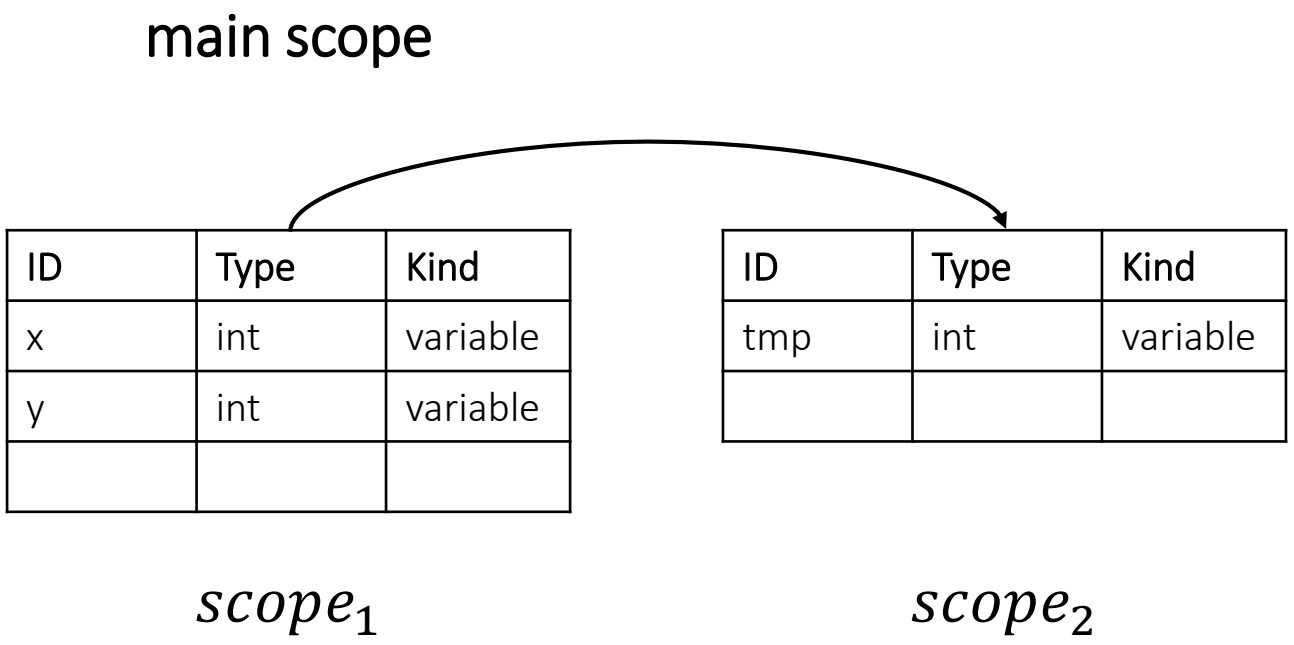
Symbol Table Operations

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

Symbol Table: Insert

Example:

- Insert(z, int, variable)

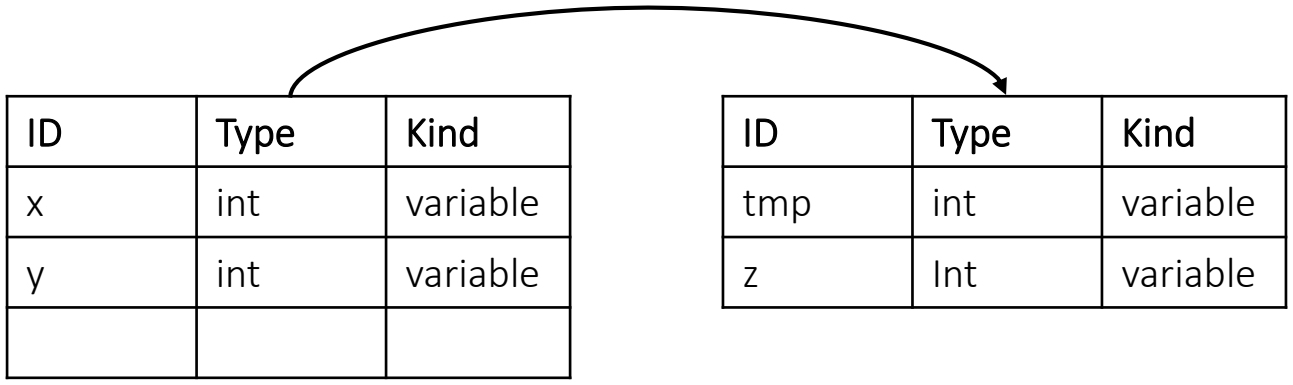


Symbol Table: Insert

Example:

- Insert(z, int, variable)

main scope



ID	Type	Kind
x	int	variable
y	int	variable

$scope_1$

ID	Type	Kind
tmp	int	variable
z	Int	variable

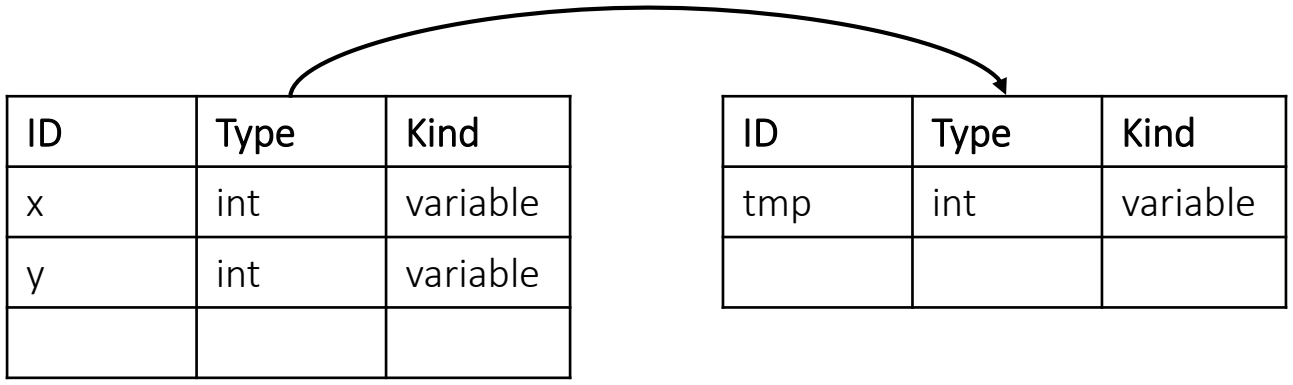
$scope_2$

Symbol Table: Lookup

Example:

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

main scope



ID	Type	Kind
x	int	variable
y	int	variable

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Symbol Table: Lookup

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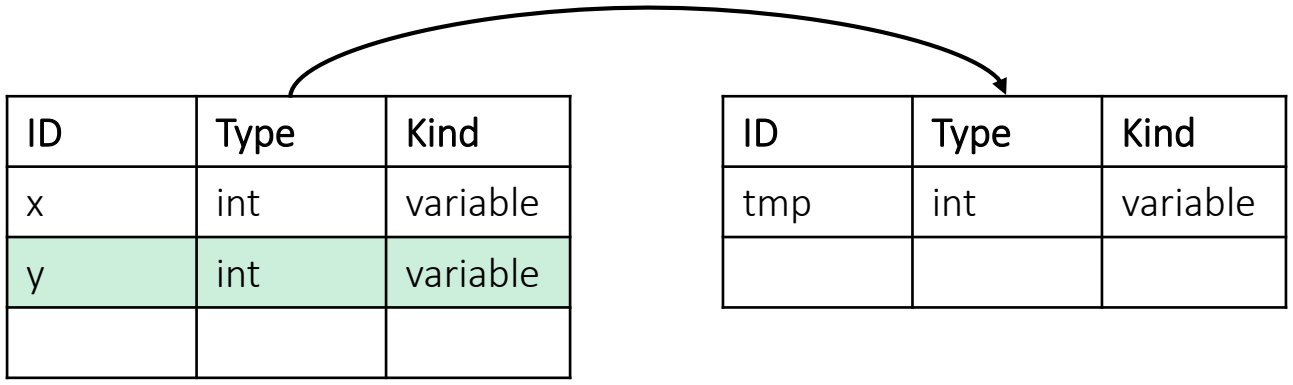


ID	Type	Kind
x	int	variable
y	int	variable

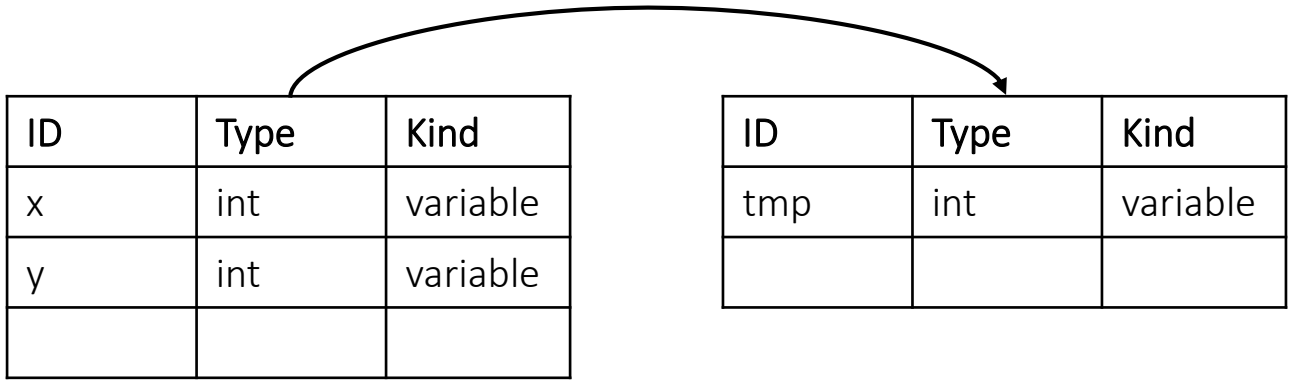
$scope_1$

ID	Type	Kind
tmp	int	variable

$scope_2$

Symbol Table: Enter

main scope



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$scope_1$

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Symbol Table: Enter

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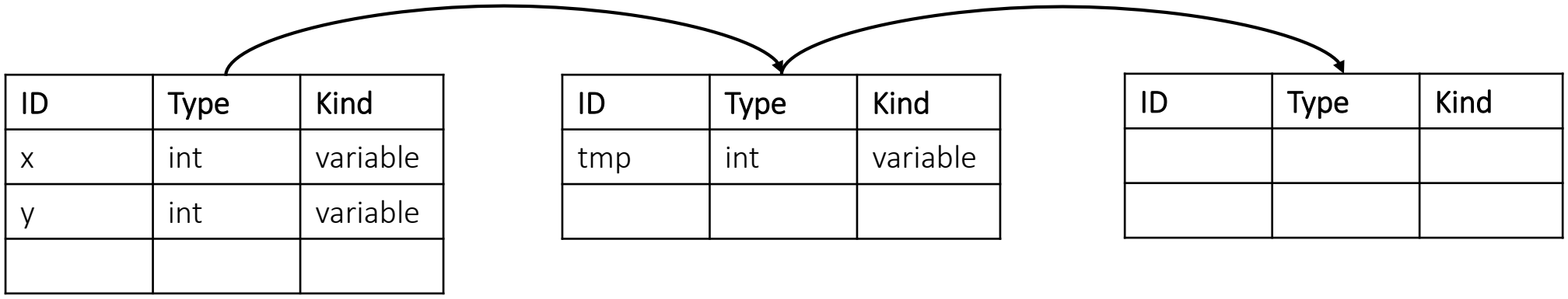

ID	Type	Kind
x	int	variable
y	int	variable

ID	Type	Kind
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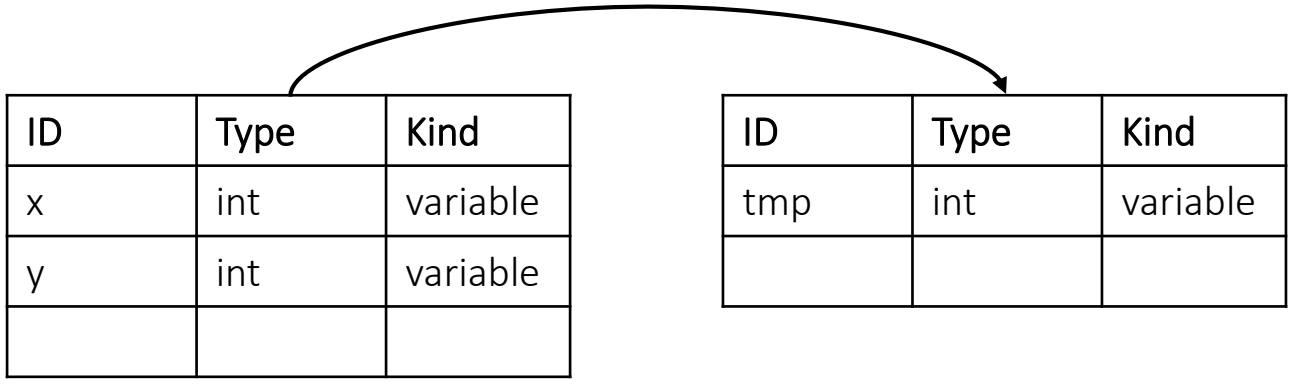
ID	Type	Kind

$scope_1$ $scope_2$ $scope_3$

Symbol Table: Exit

main scope



ID	Type	Kind
x	int	variable
y	int	variable

ID	Type	Kind
tmp	int	variable

$scope_1$ $scope_2$

Symbol Table: Exit

main scope

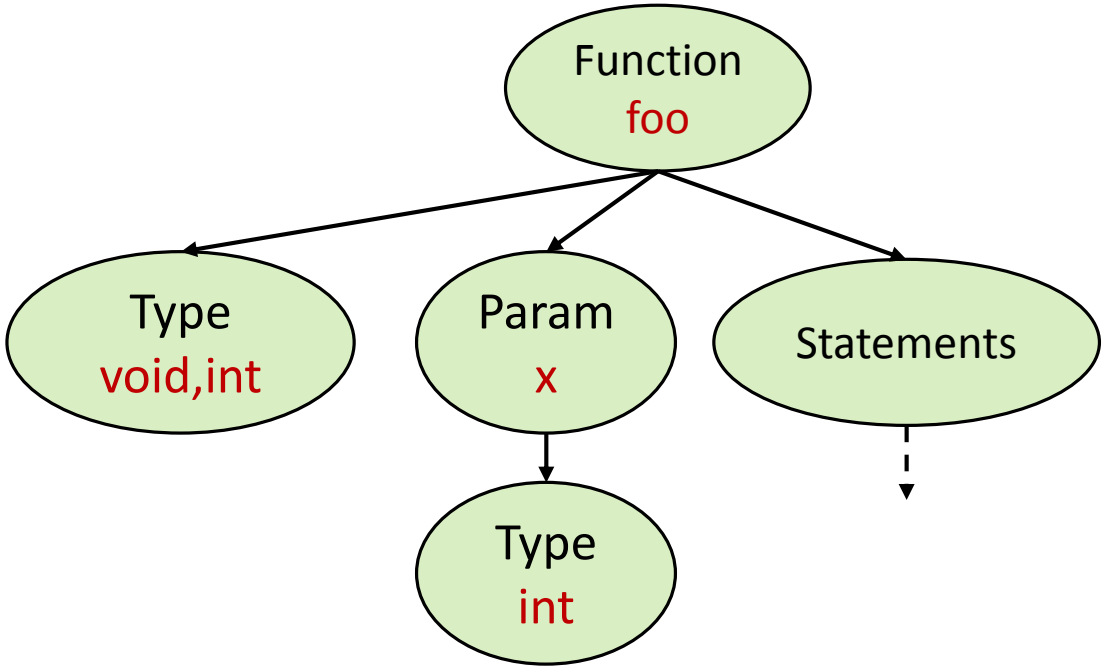
ID	Type	Kind
x	int	variable
y	int	variable

$scope_1$

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";
  }
}
```



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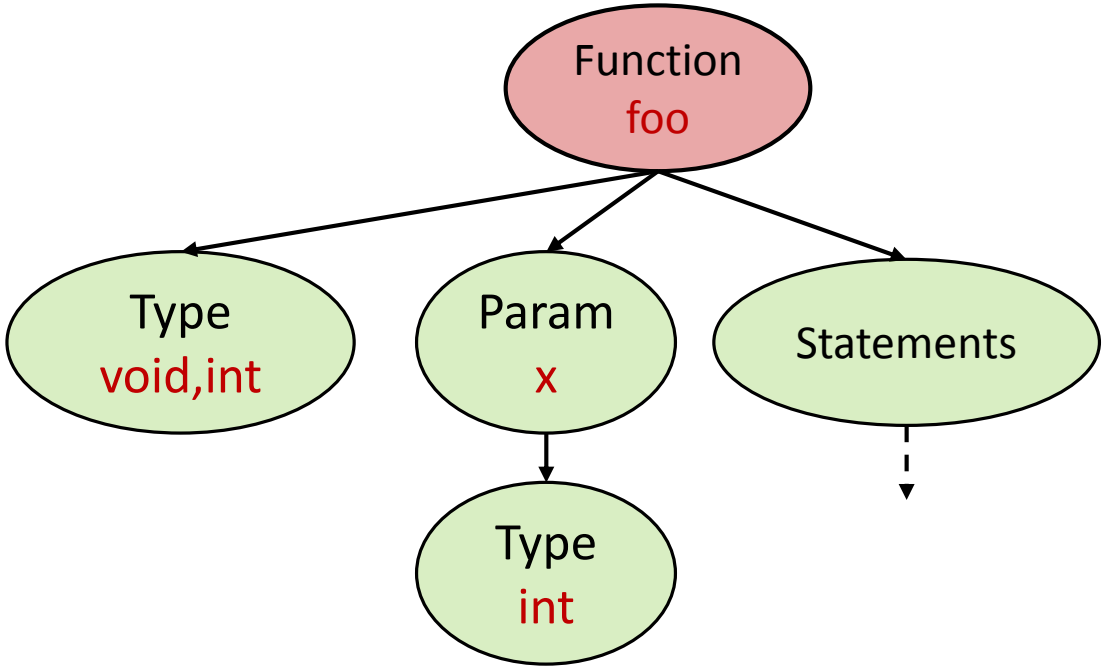

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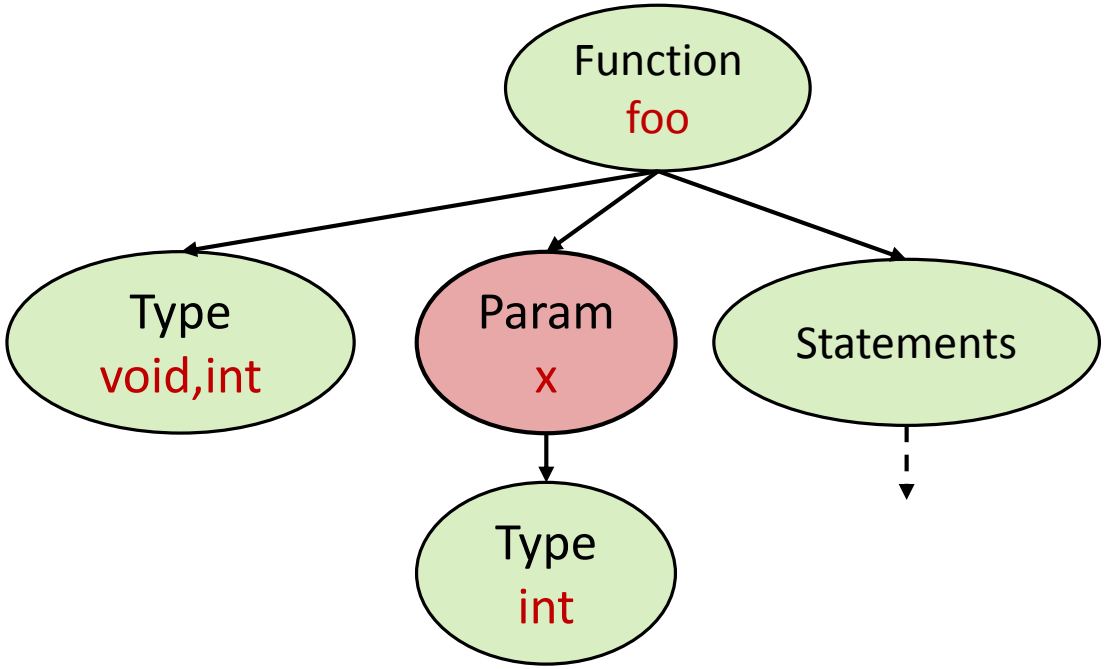

ID	Type	Kind
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ID	Type	Kind
x	int	variable

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  int a = 1;
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```

ID	Type	Kind
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ID	Type	Kind
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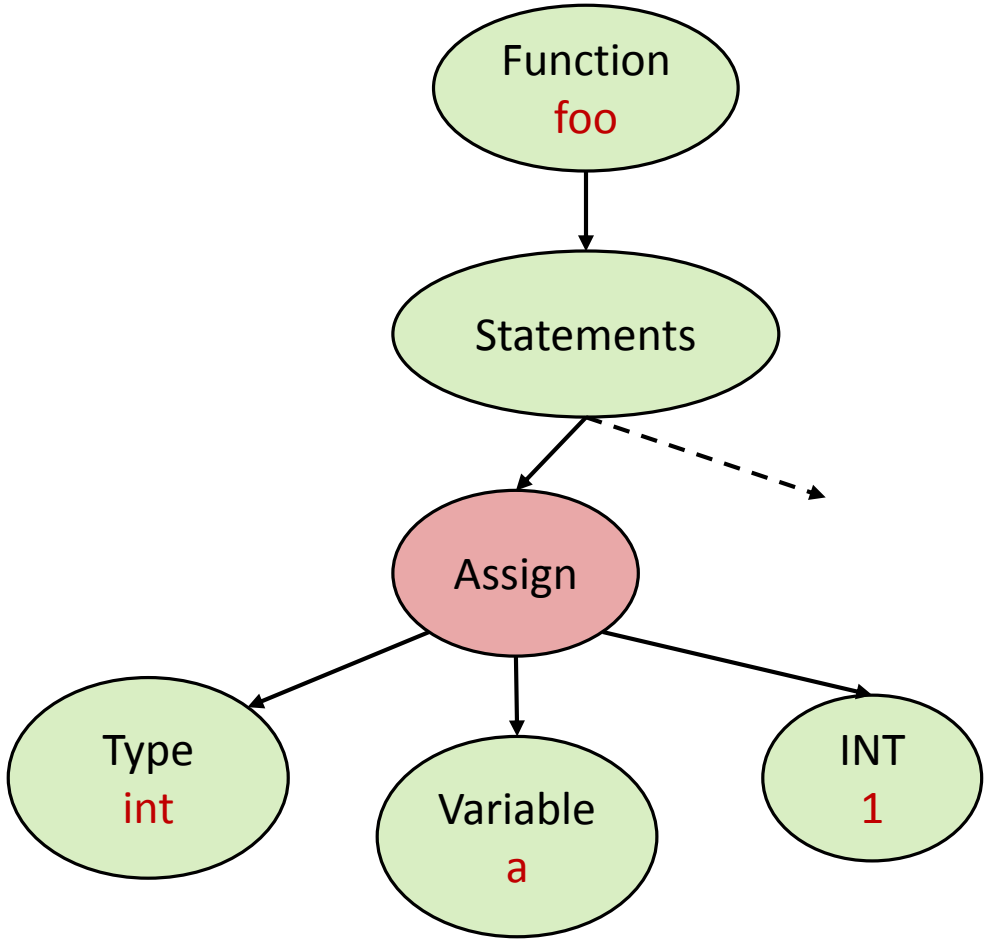
a	int	variable



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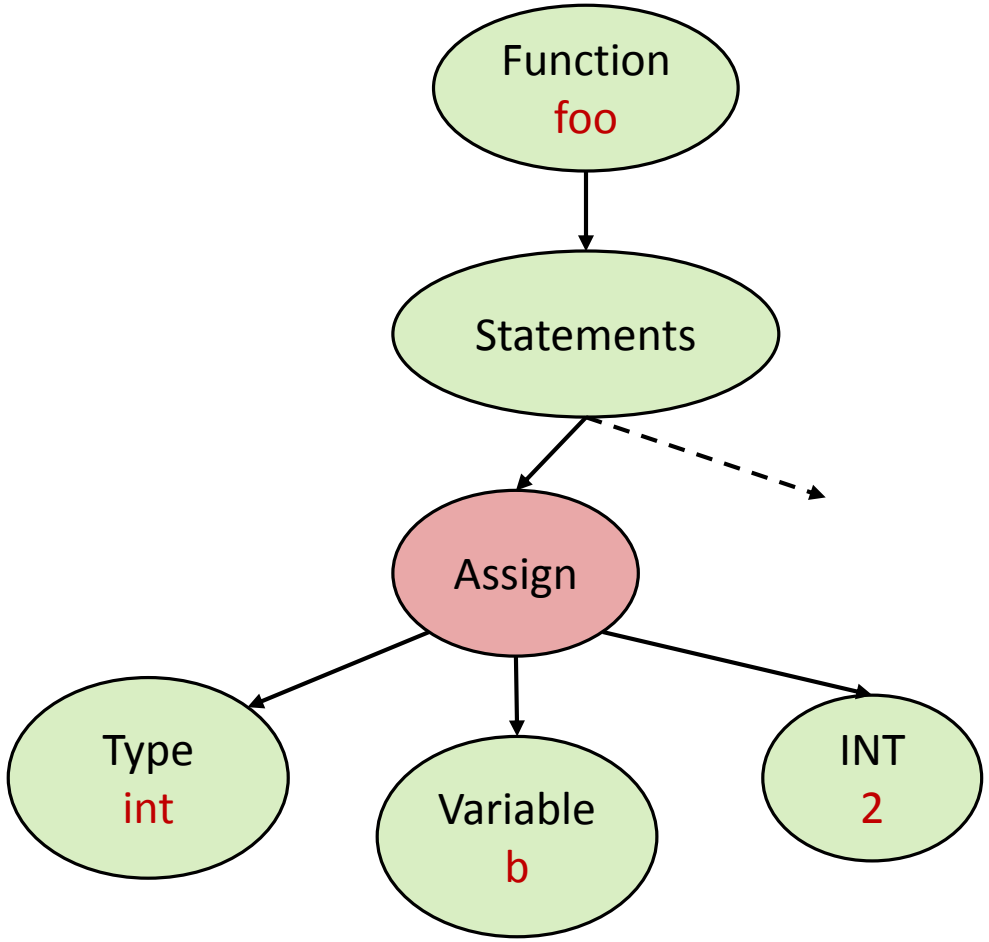
ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable



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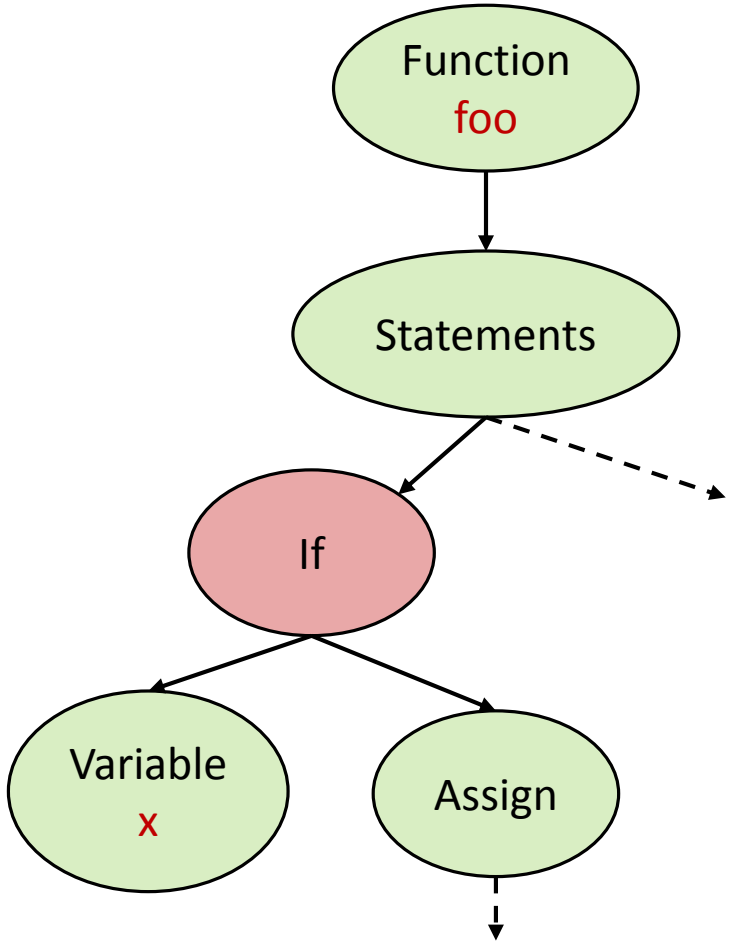

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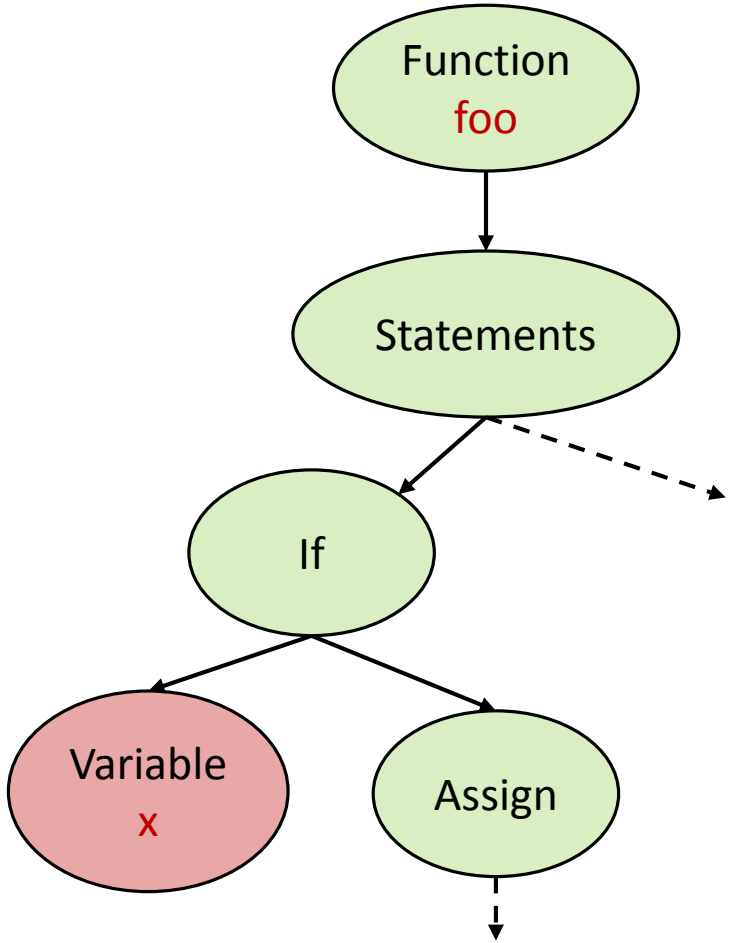

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ID	Type	Kind
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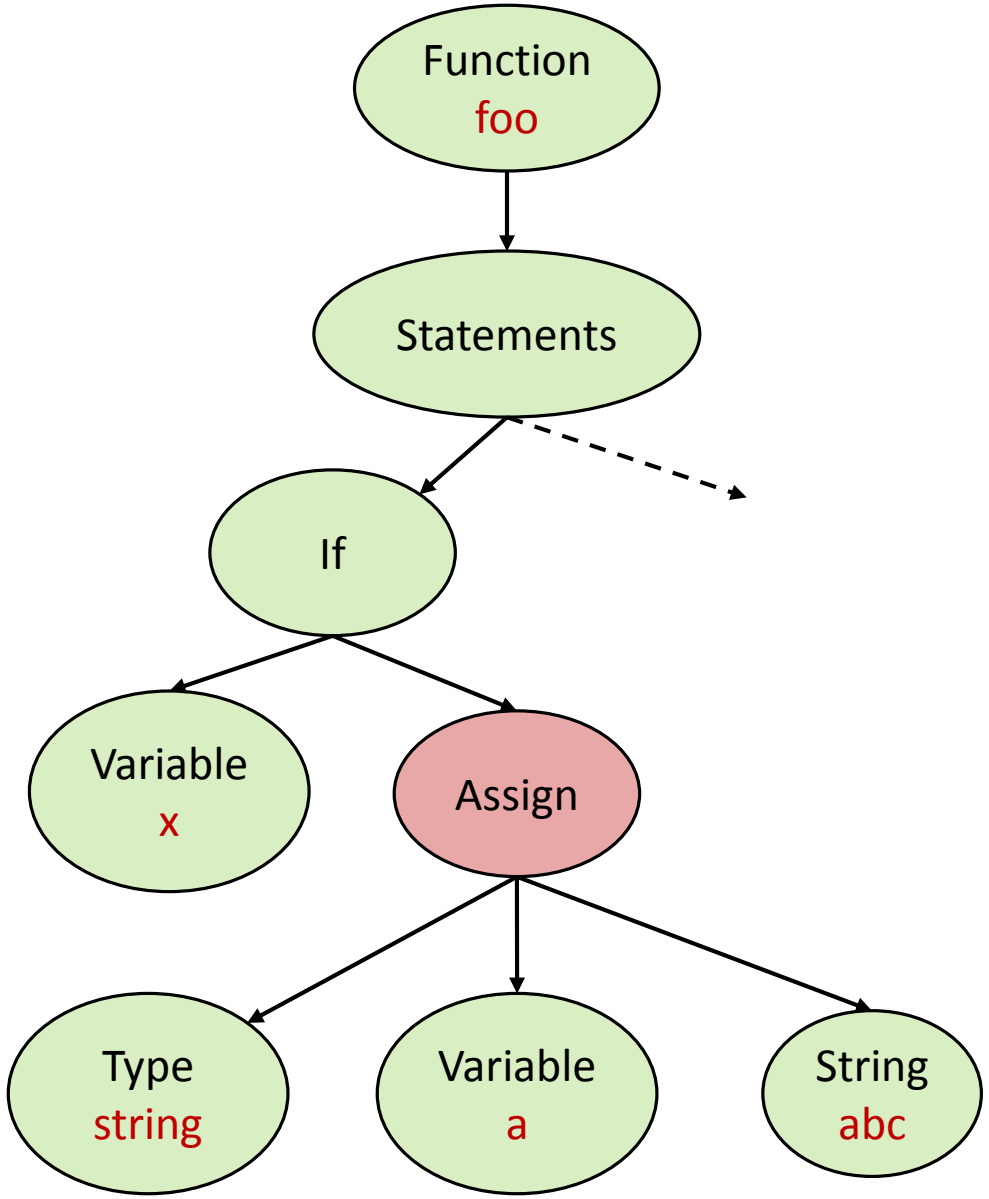
ID	Type	Kind
x	int	variable
a	int	variable
b	int	variable

ID	Type	Kind
a	string	variable



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foo	void,int	function

ID	Type	Kind
x	int	variable
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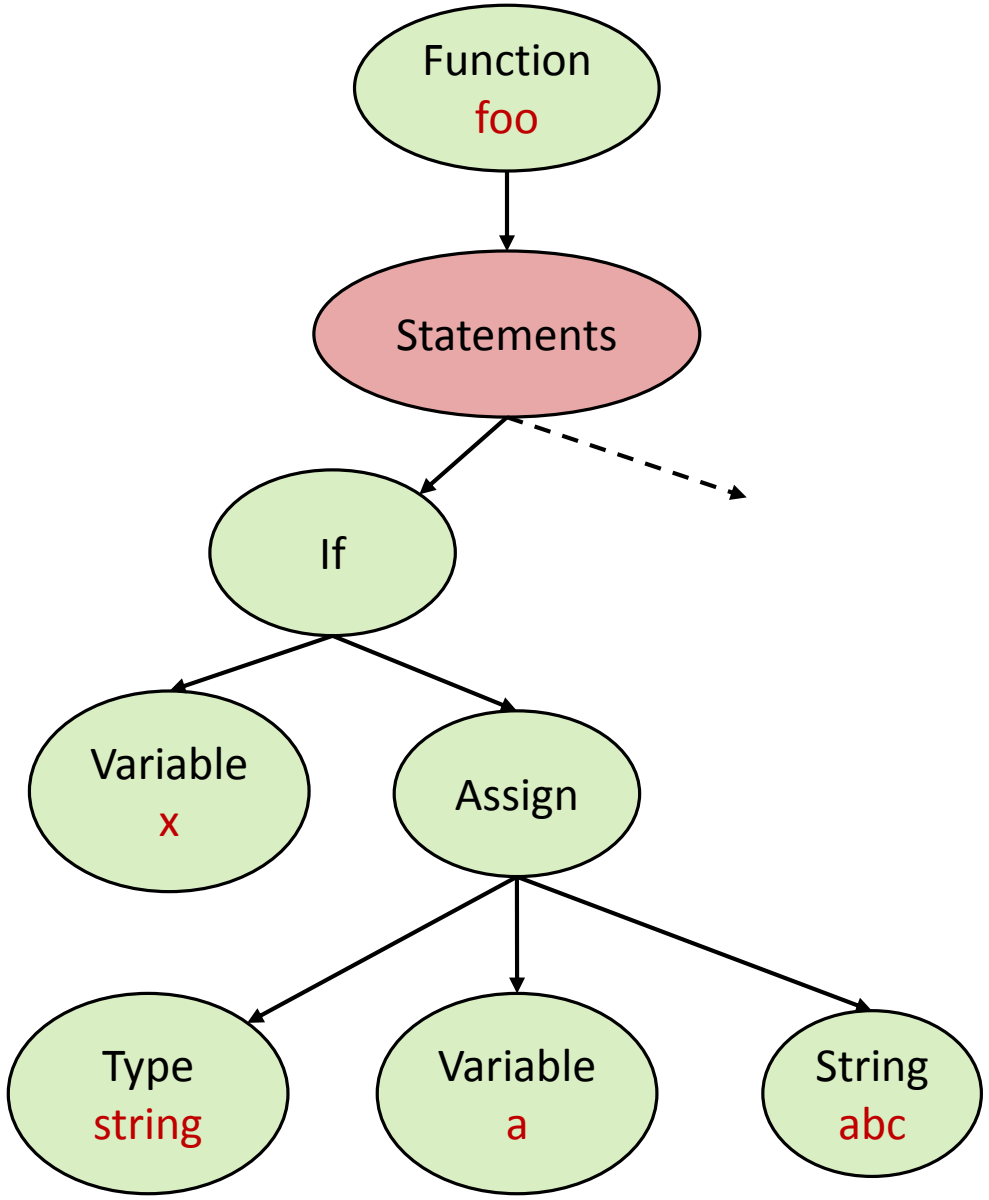

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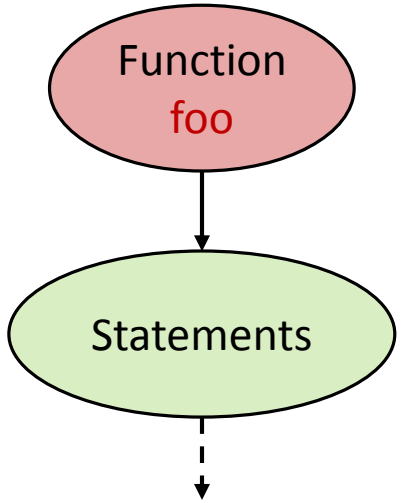

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}
```

Type Checking

Goals:

- Type correctness of expressions
- Compute type of expressions

Performed using:

- AST visitor
- Symbol table

Type Checking

Basic algorithm:

$visit(node)$:

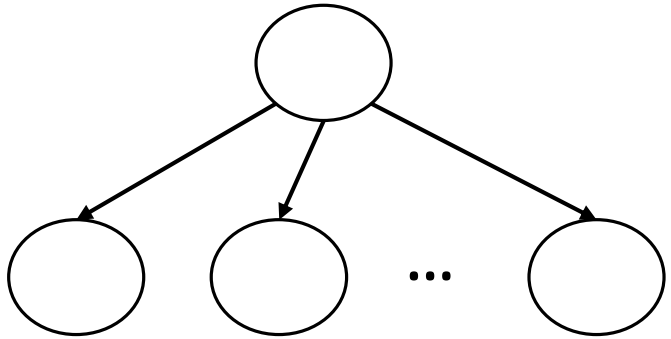
$\mathrm{t}_1 = visit(node.child_1)$

…

$\mathrm{t}_\mathrm{n} = visit(node.child_n)$

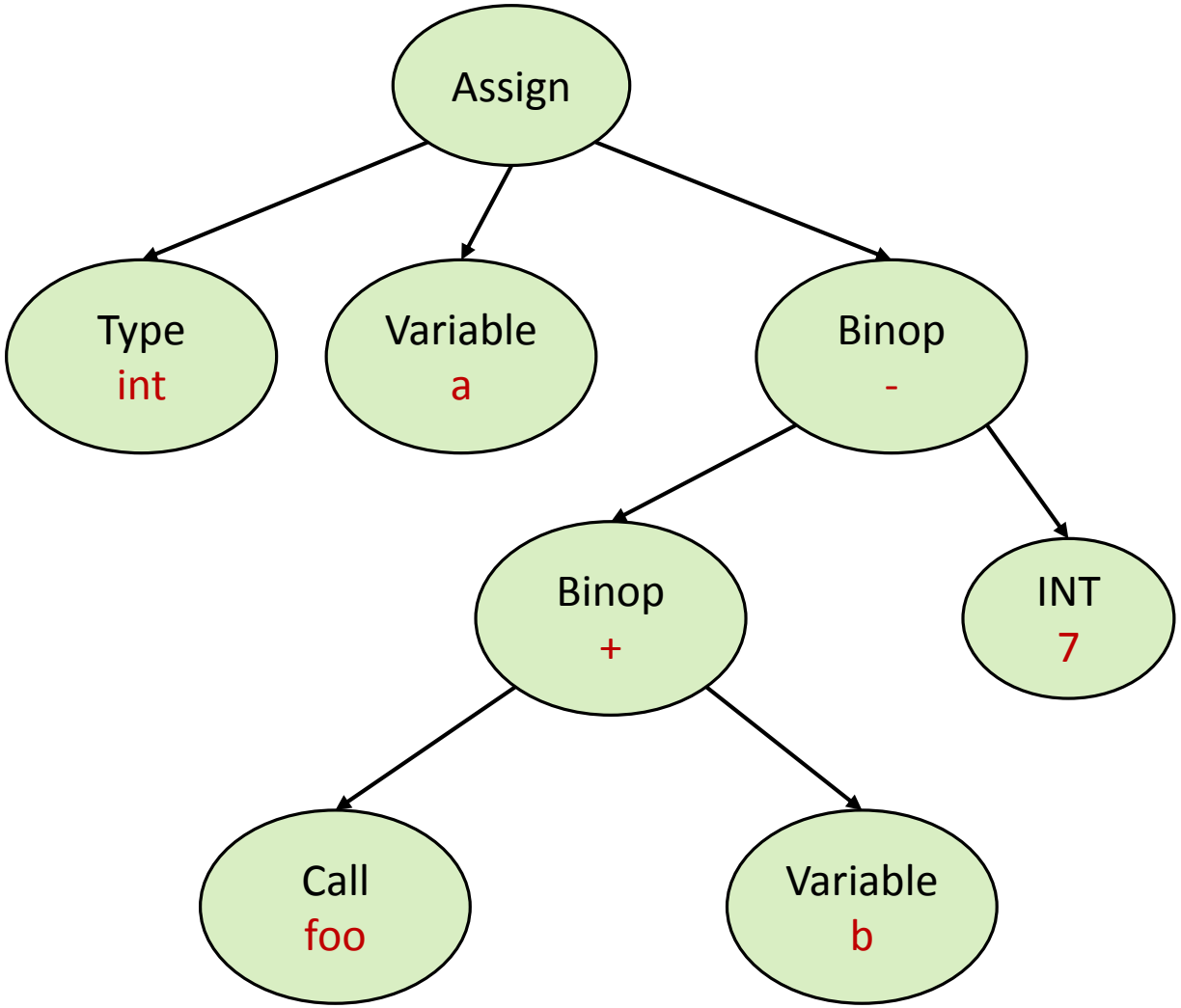
$return \underbrace{compute\_type(t_1, \ldots, t_n)}$

node specific



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

ID	Type	Kind
foo	int,void	function
b	int	variable



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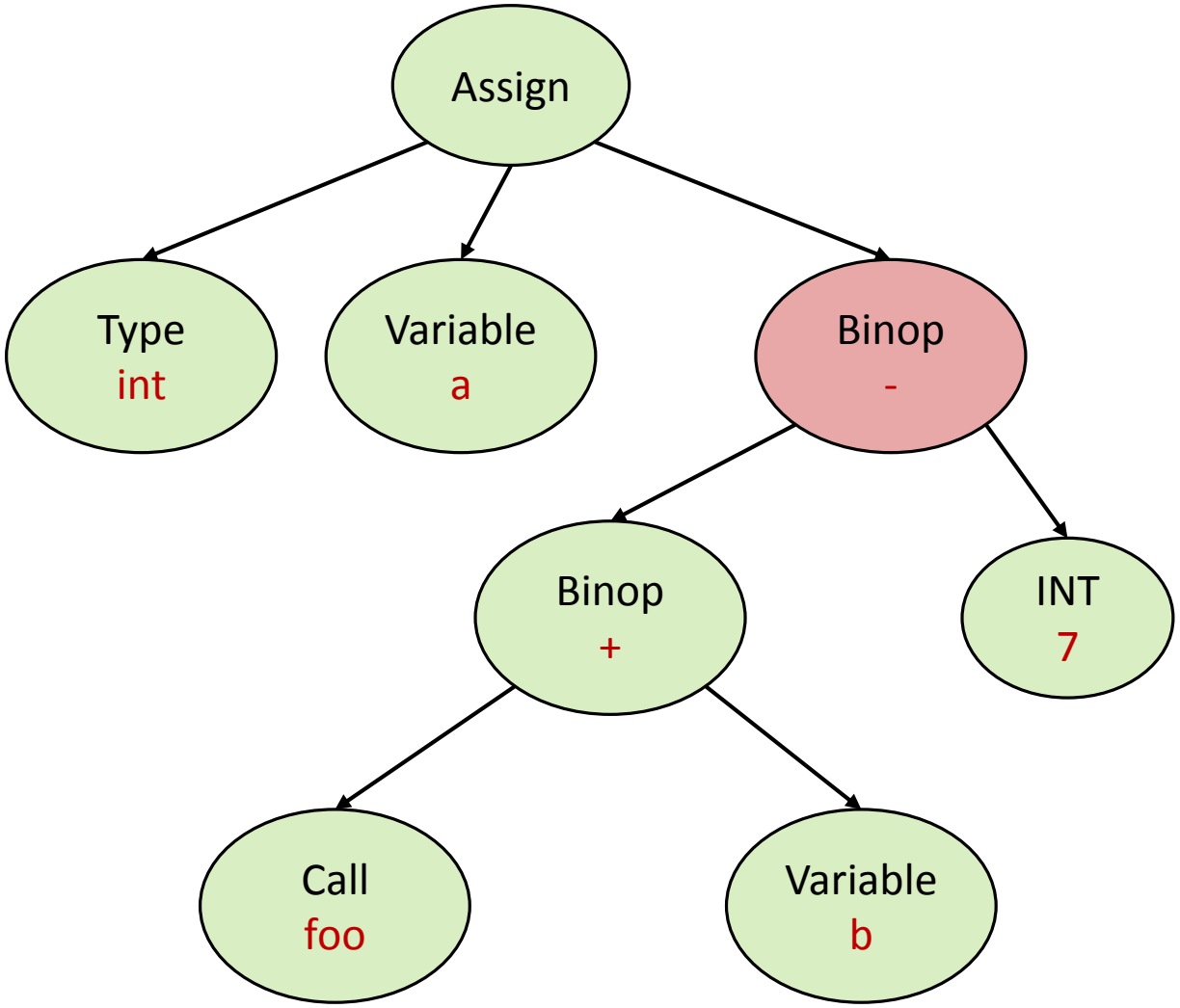

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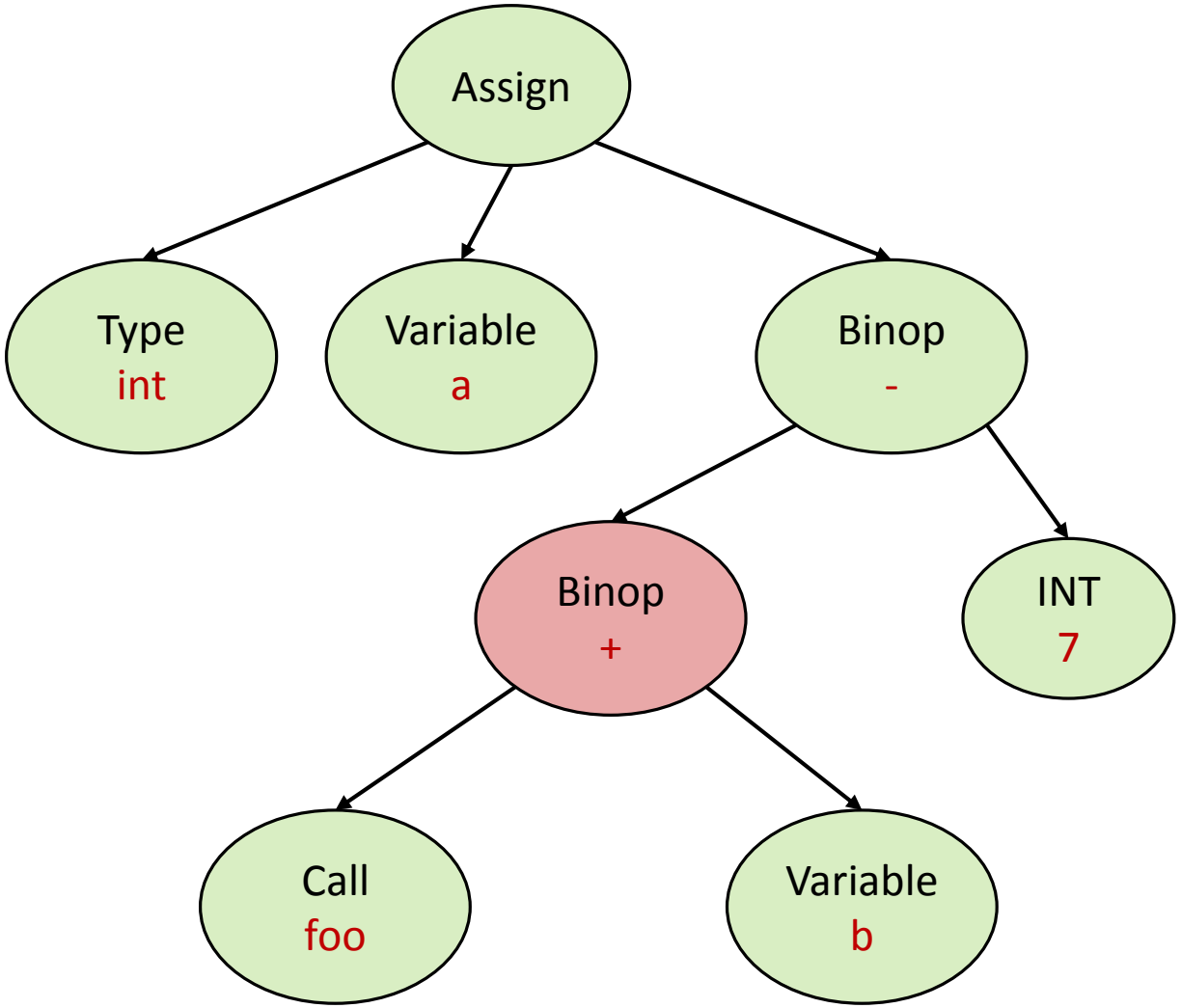

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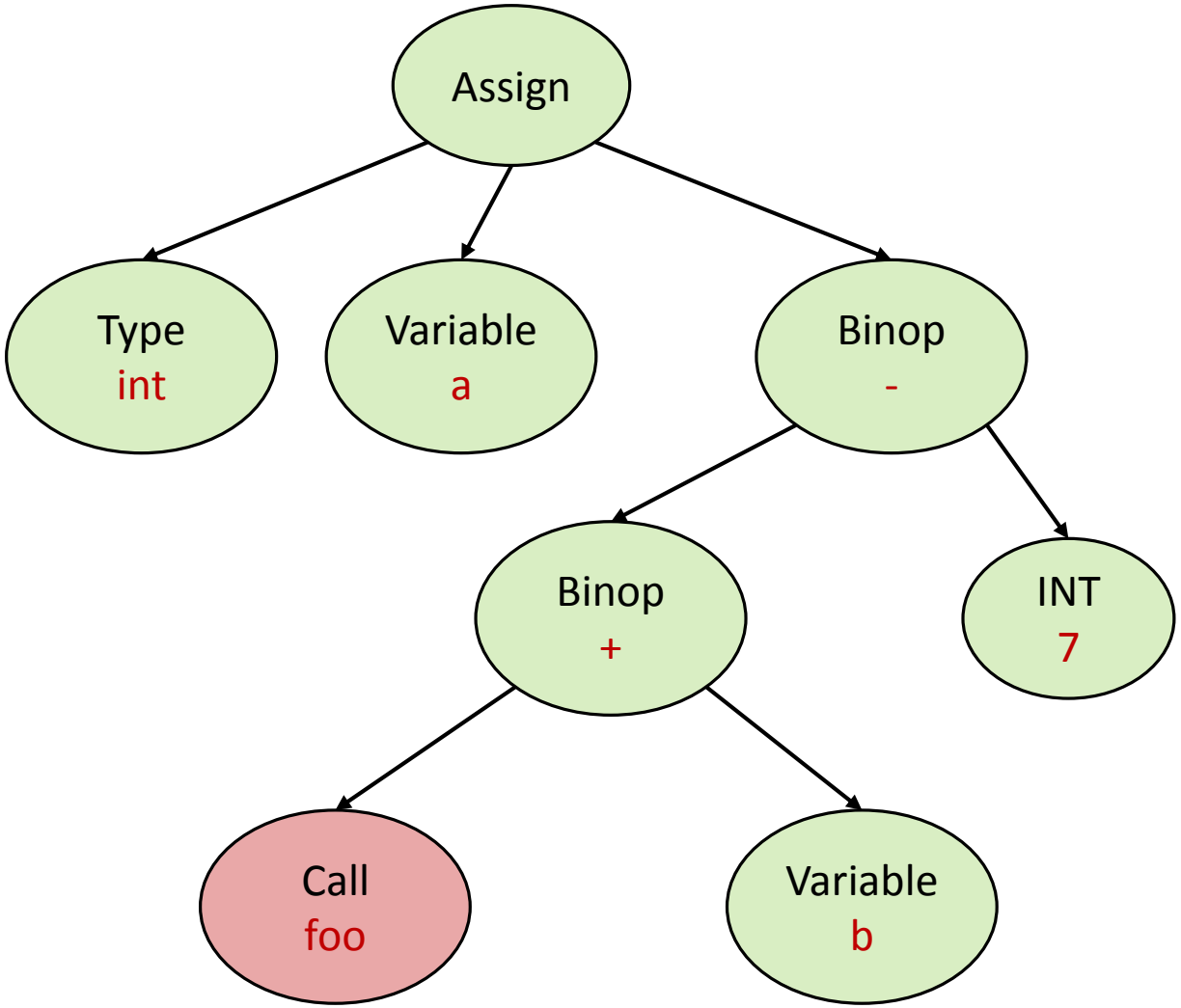

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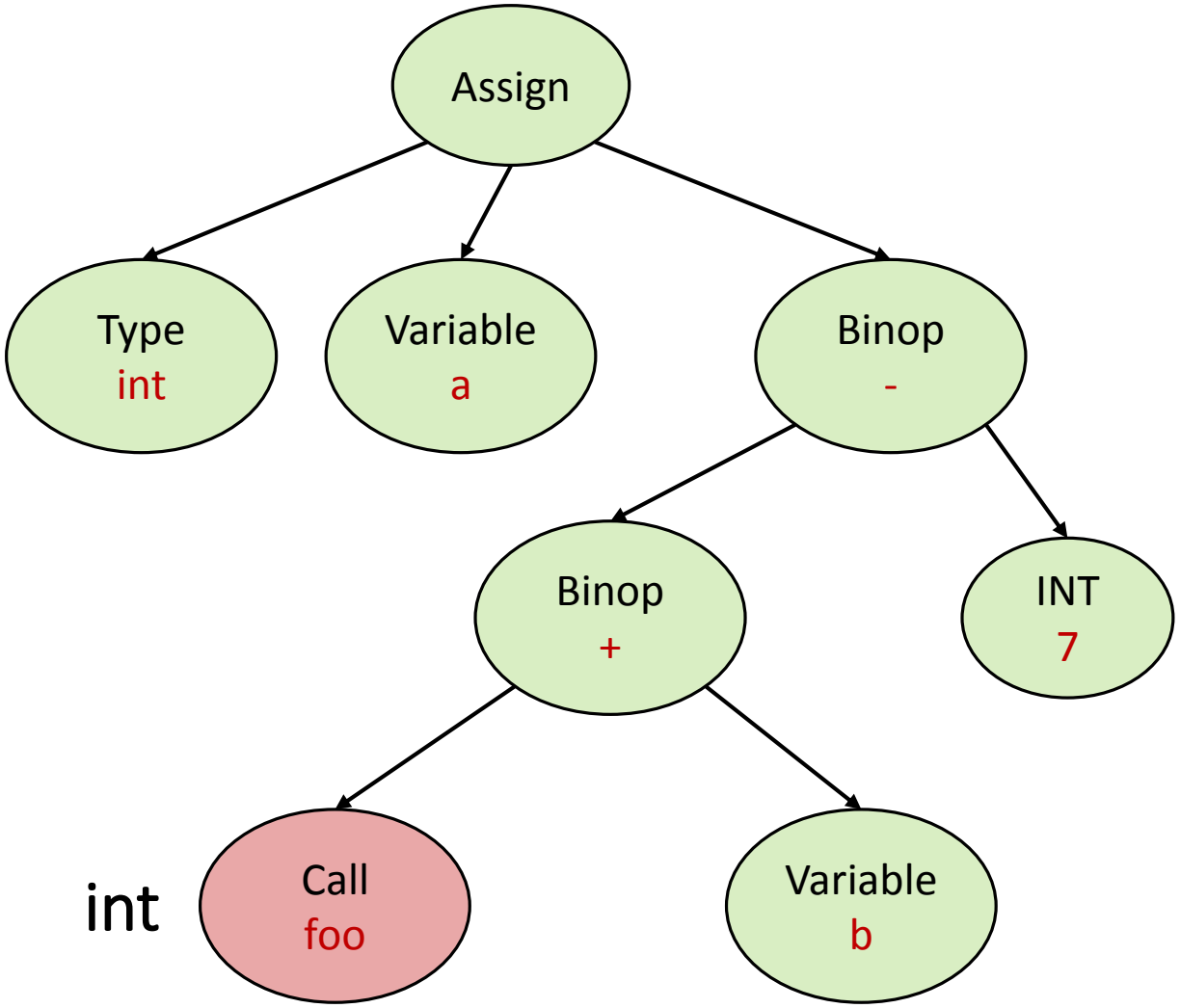

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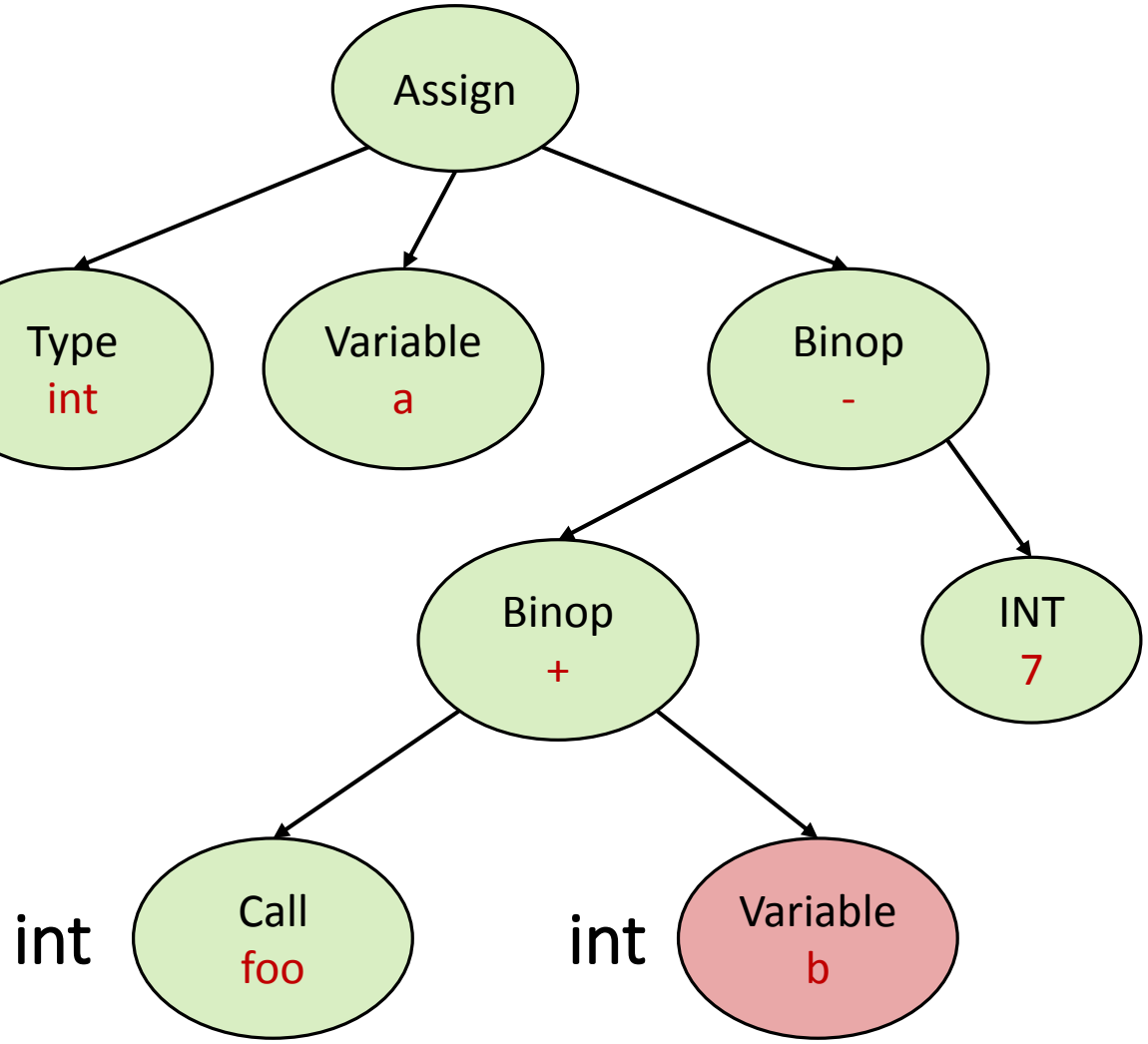

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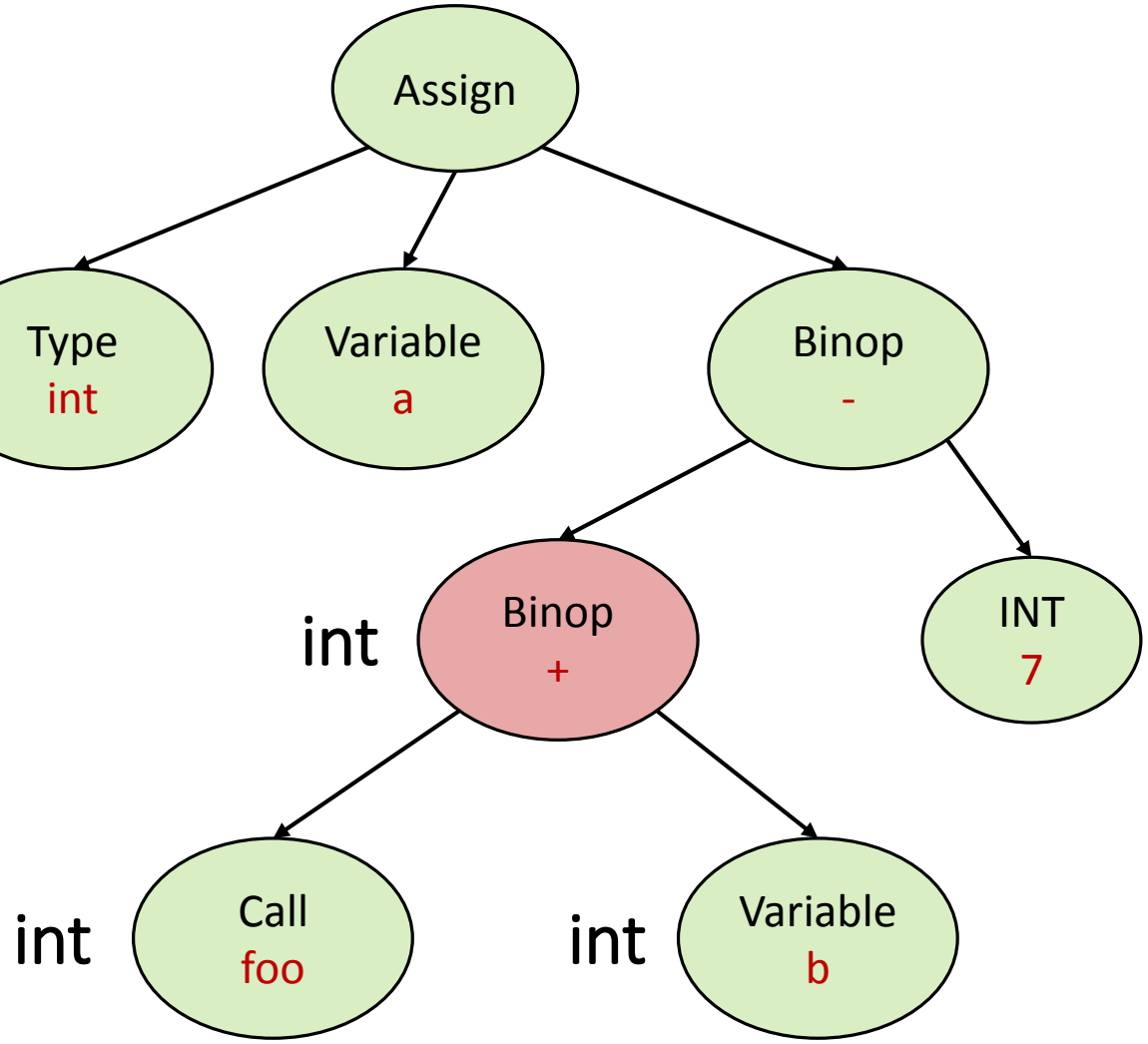

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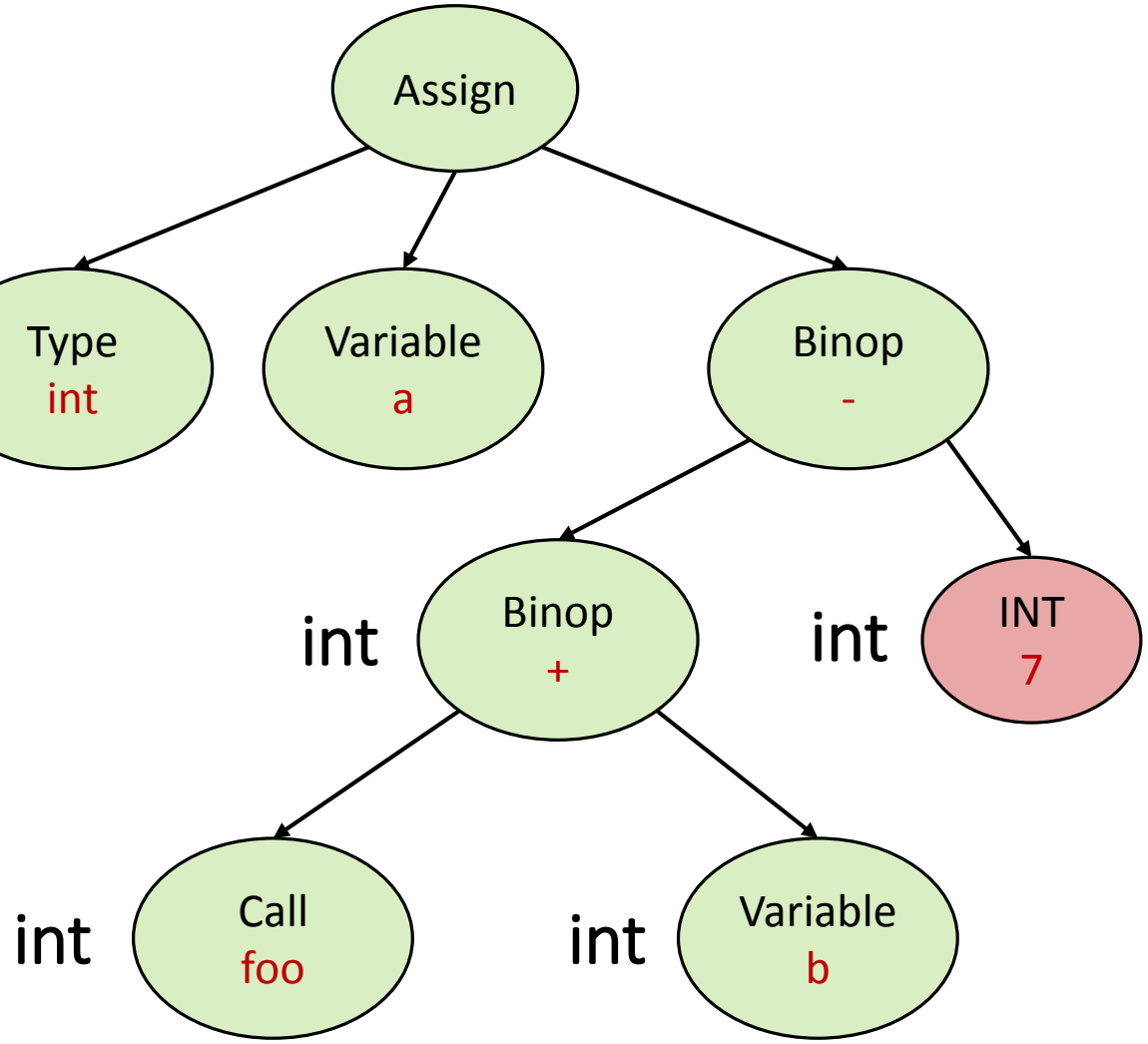

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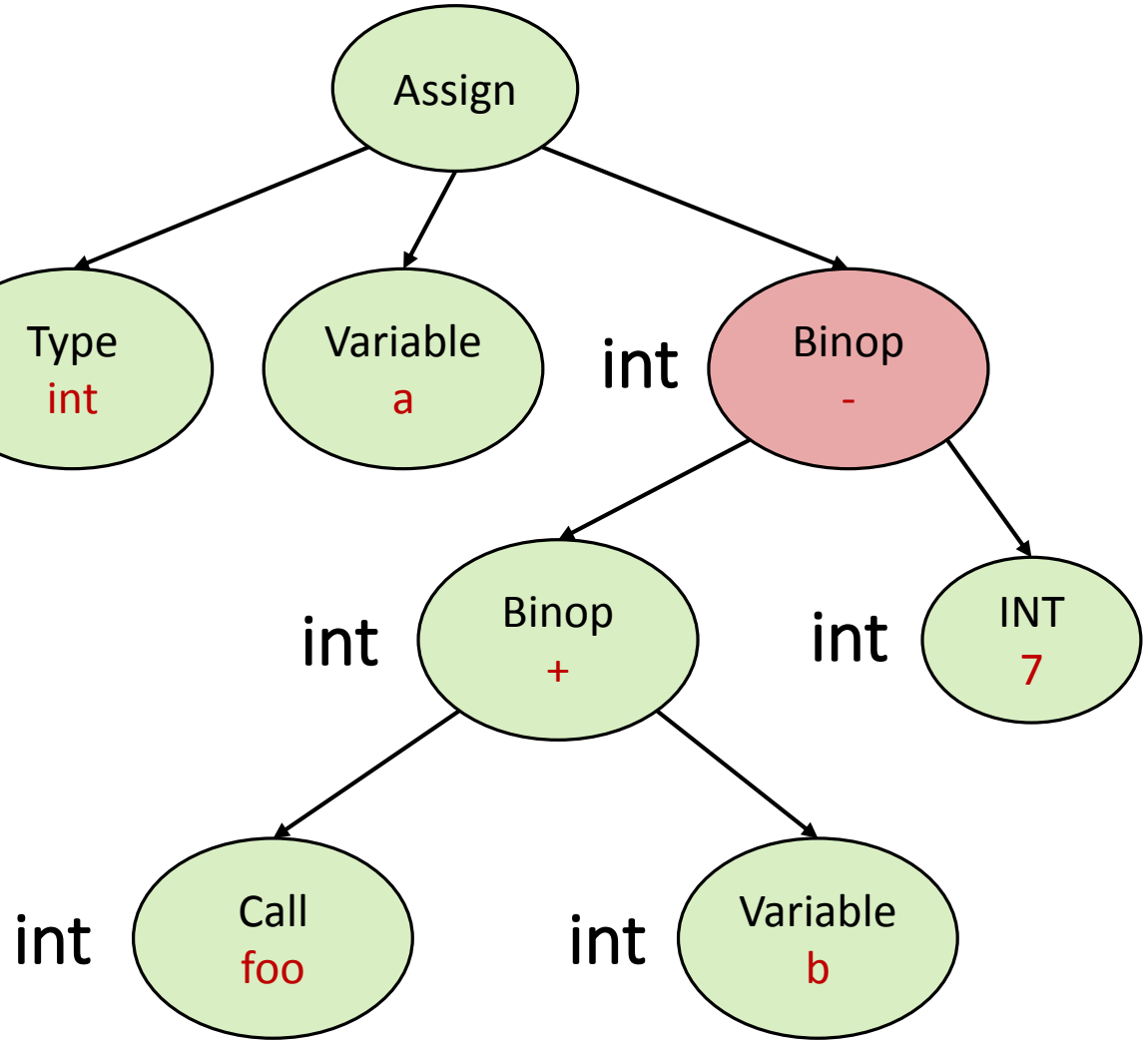
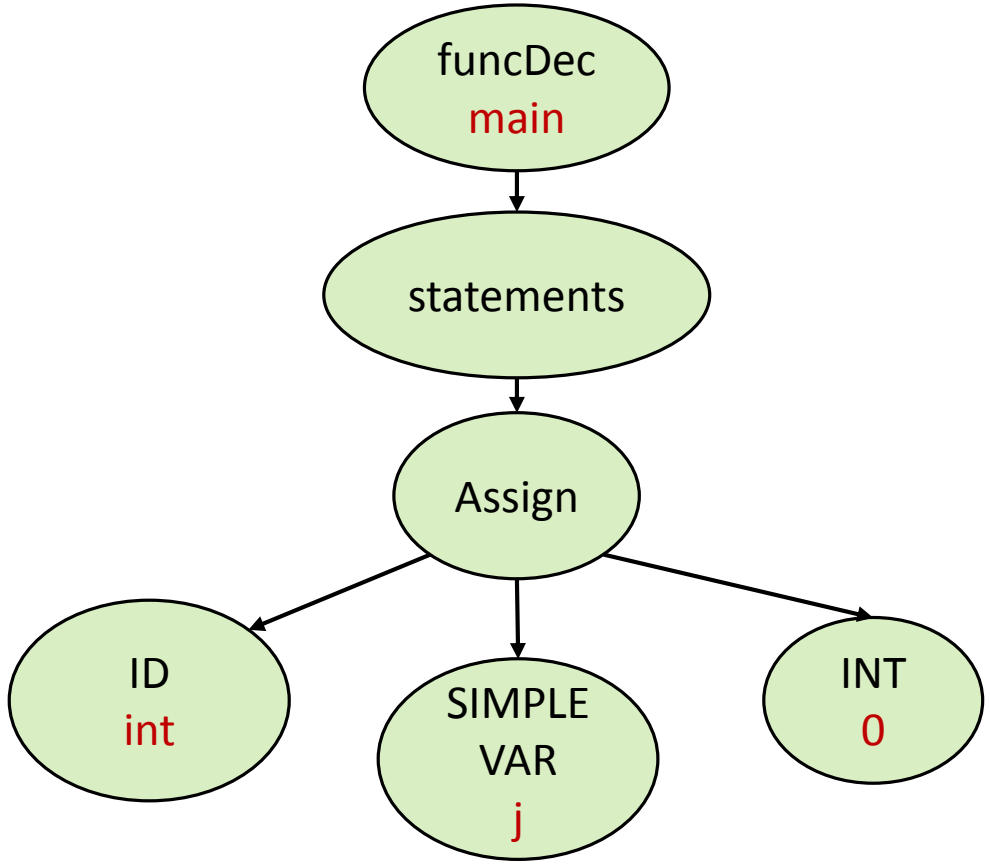


Examples

Assignments

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



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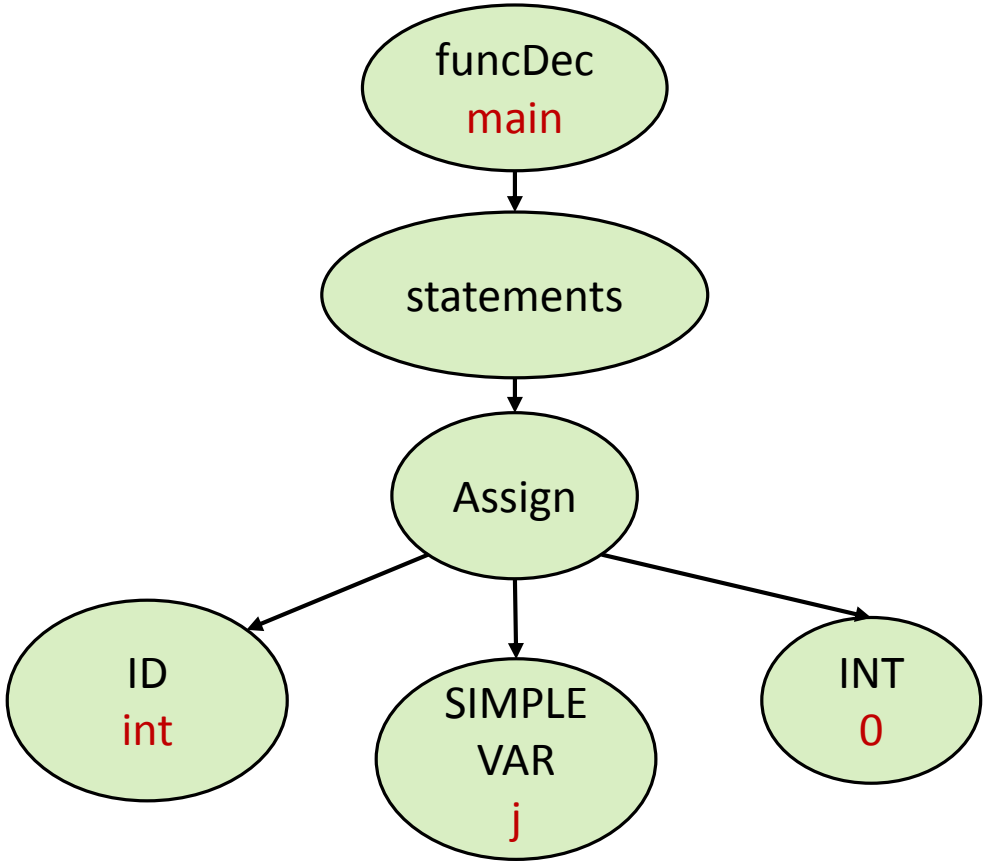
Valid



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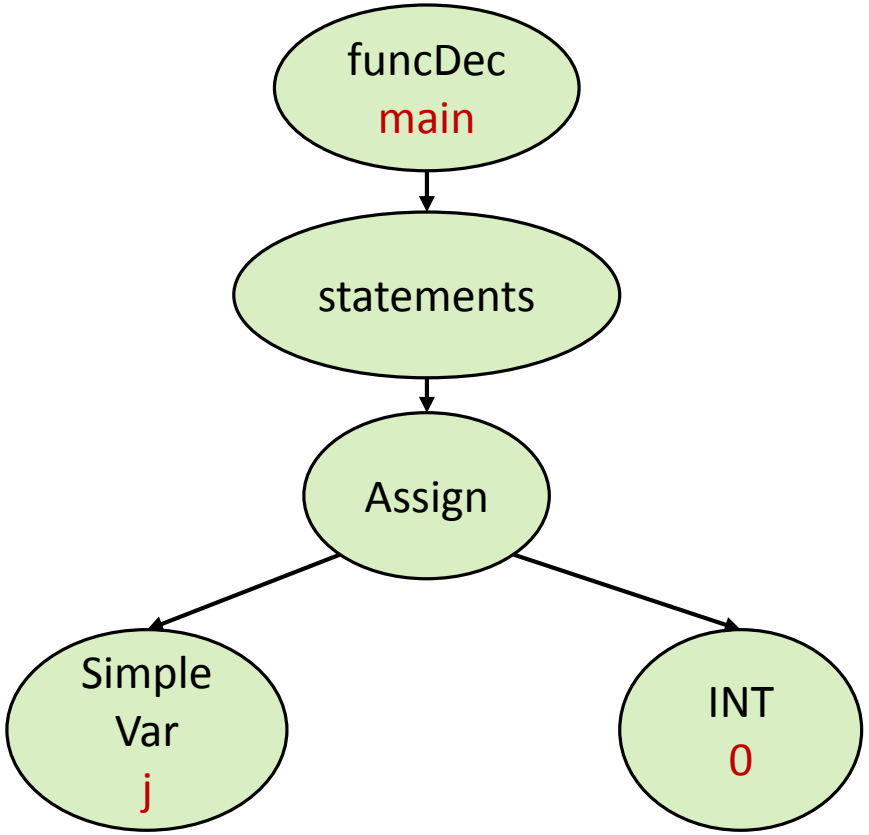

Assignments

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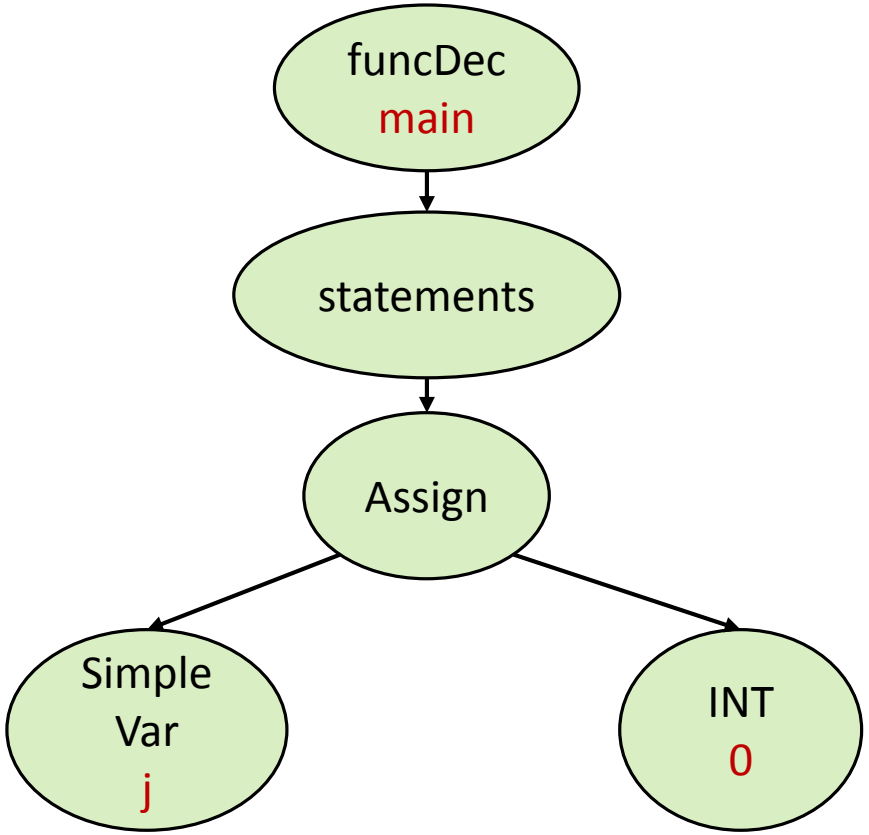
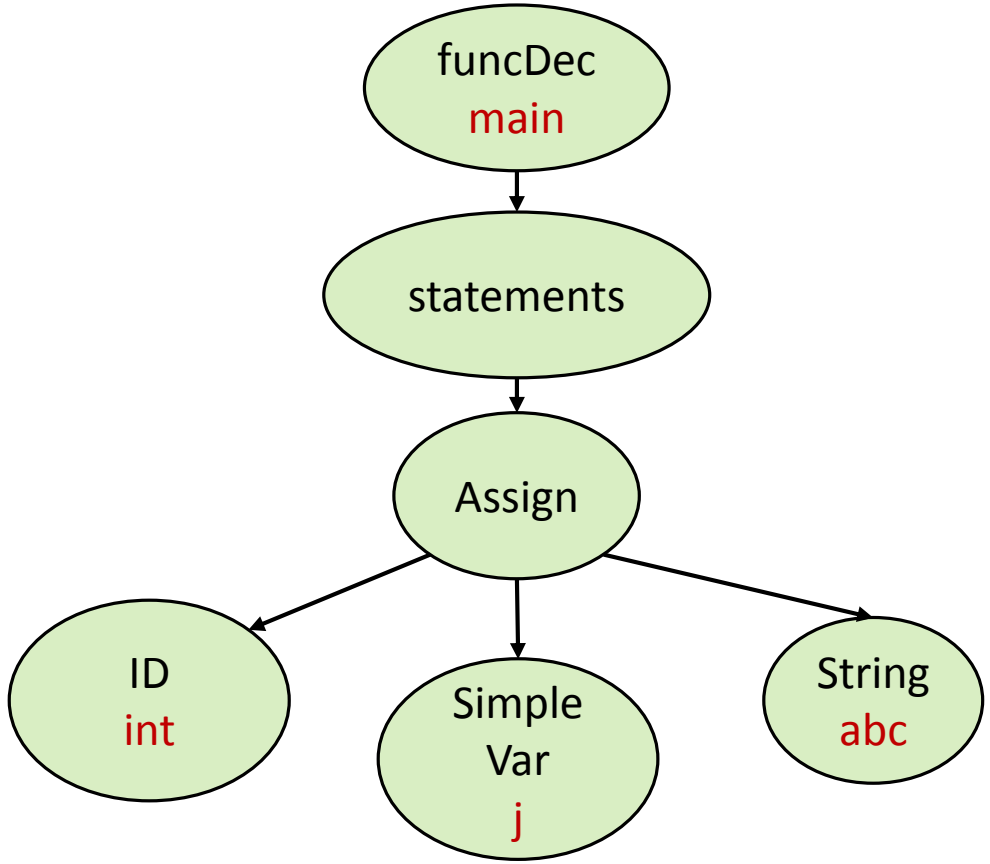
Invalid



Assignments

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



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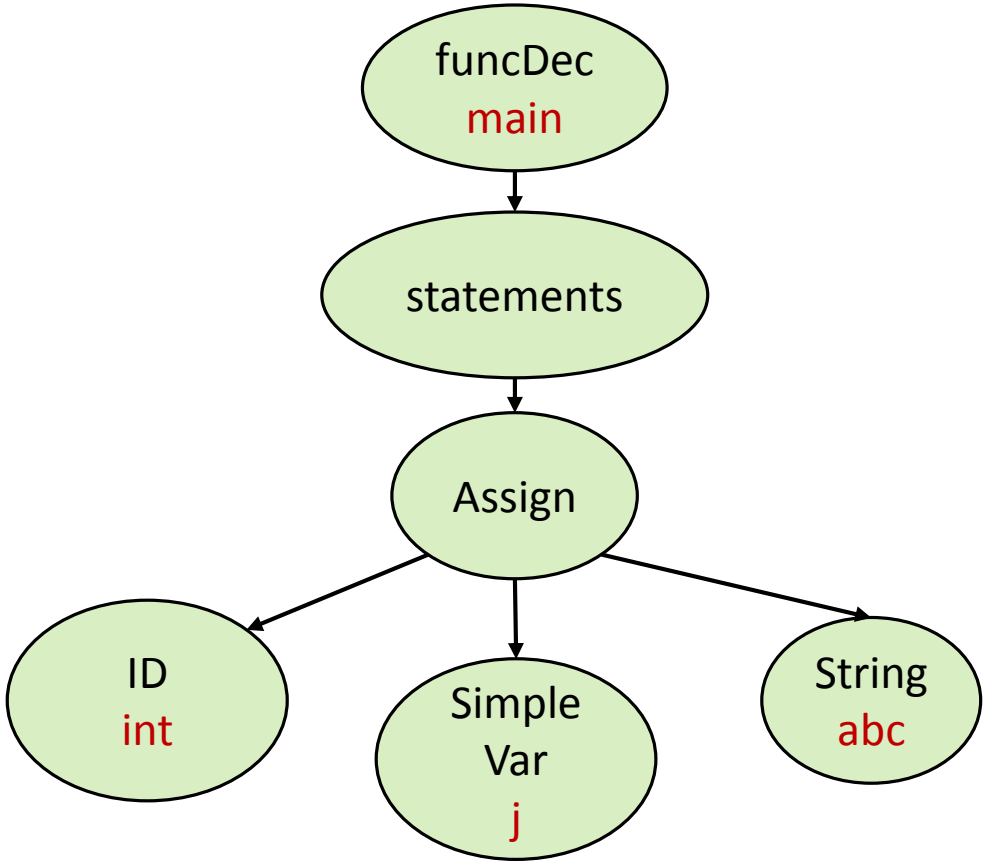

Assignments

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

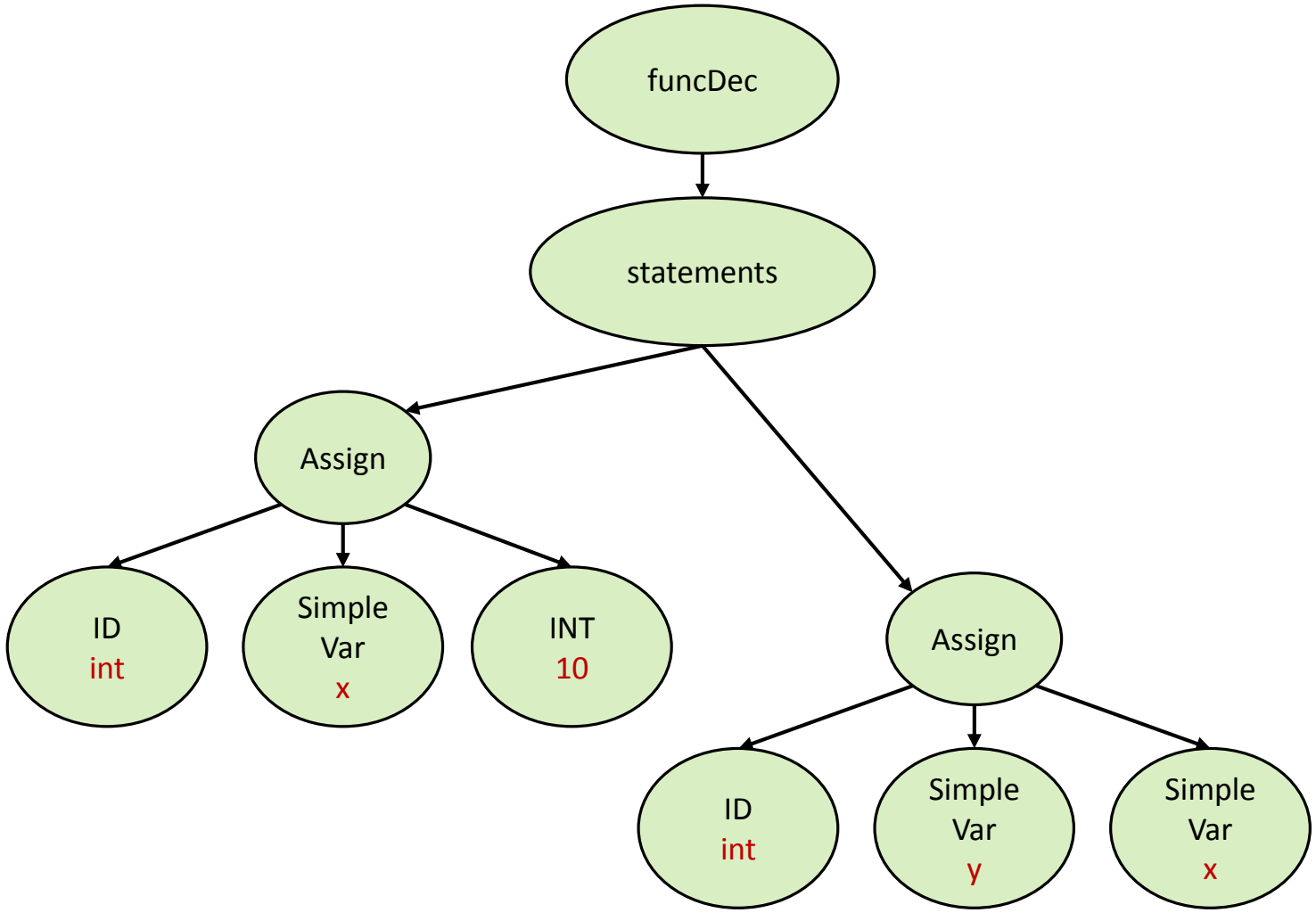

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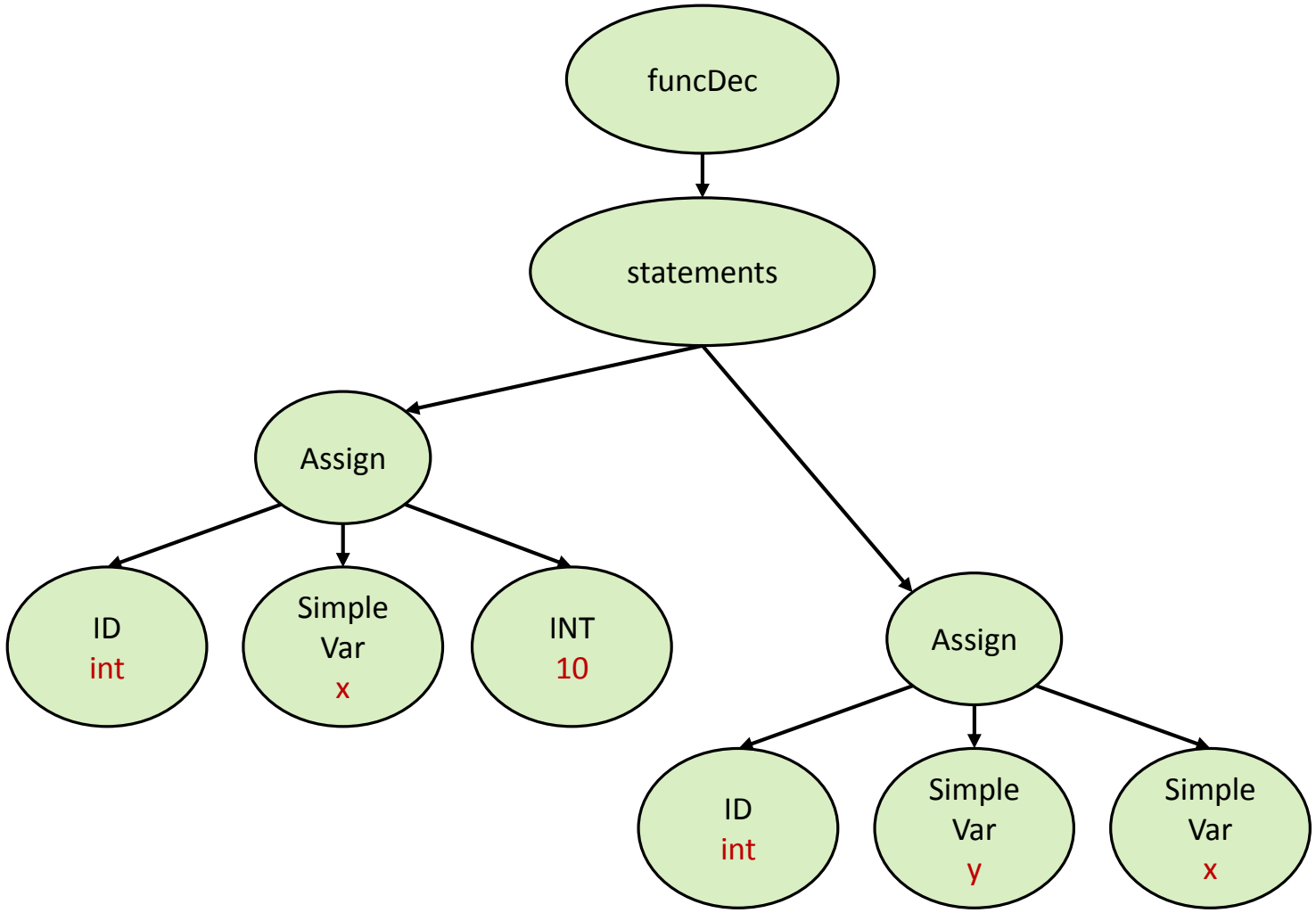

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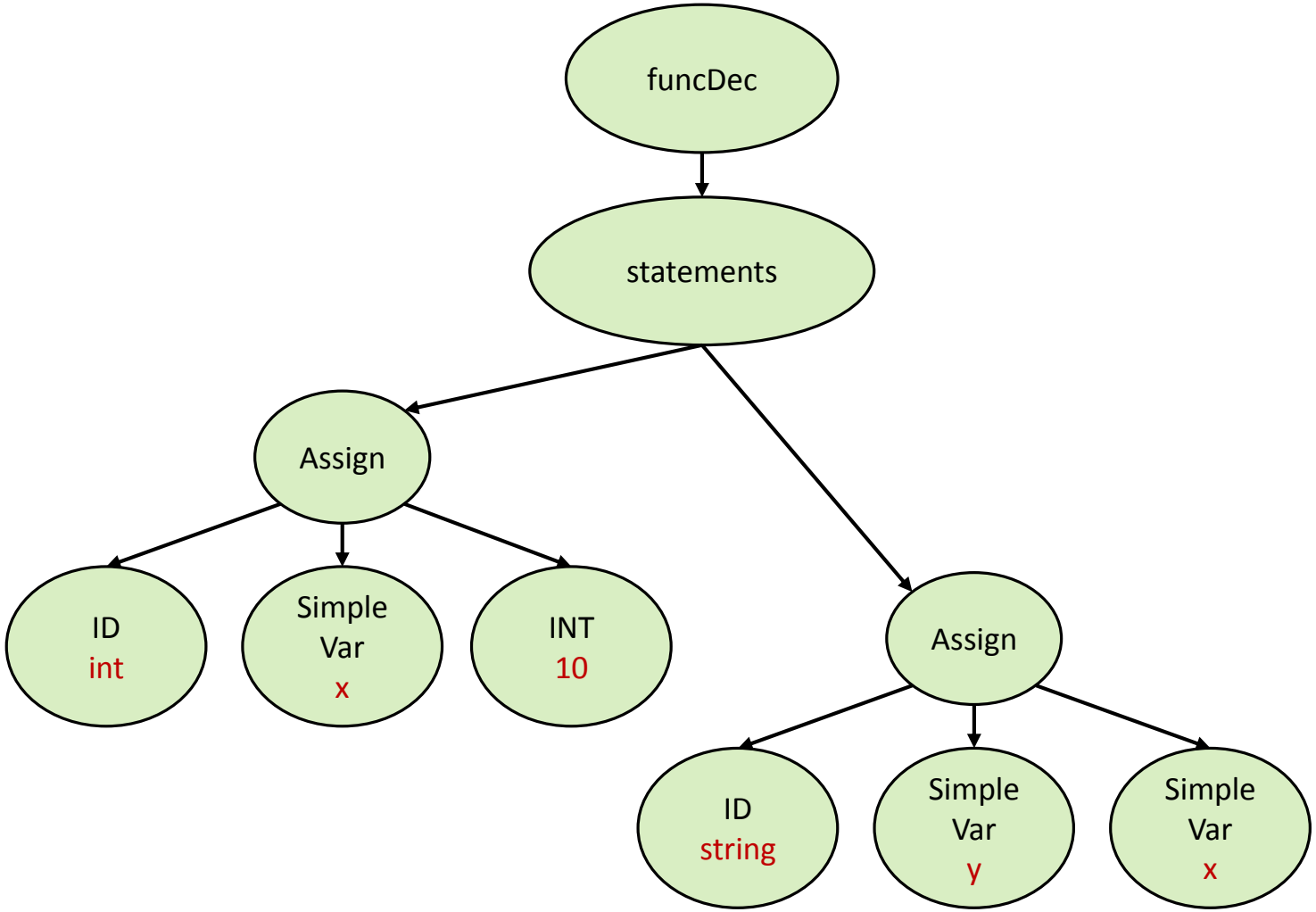
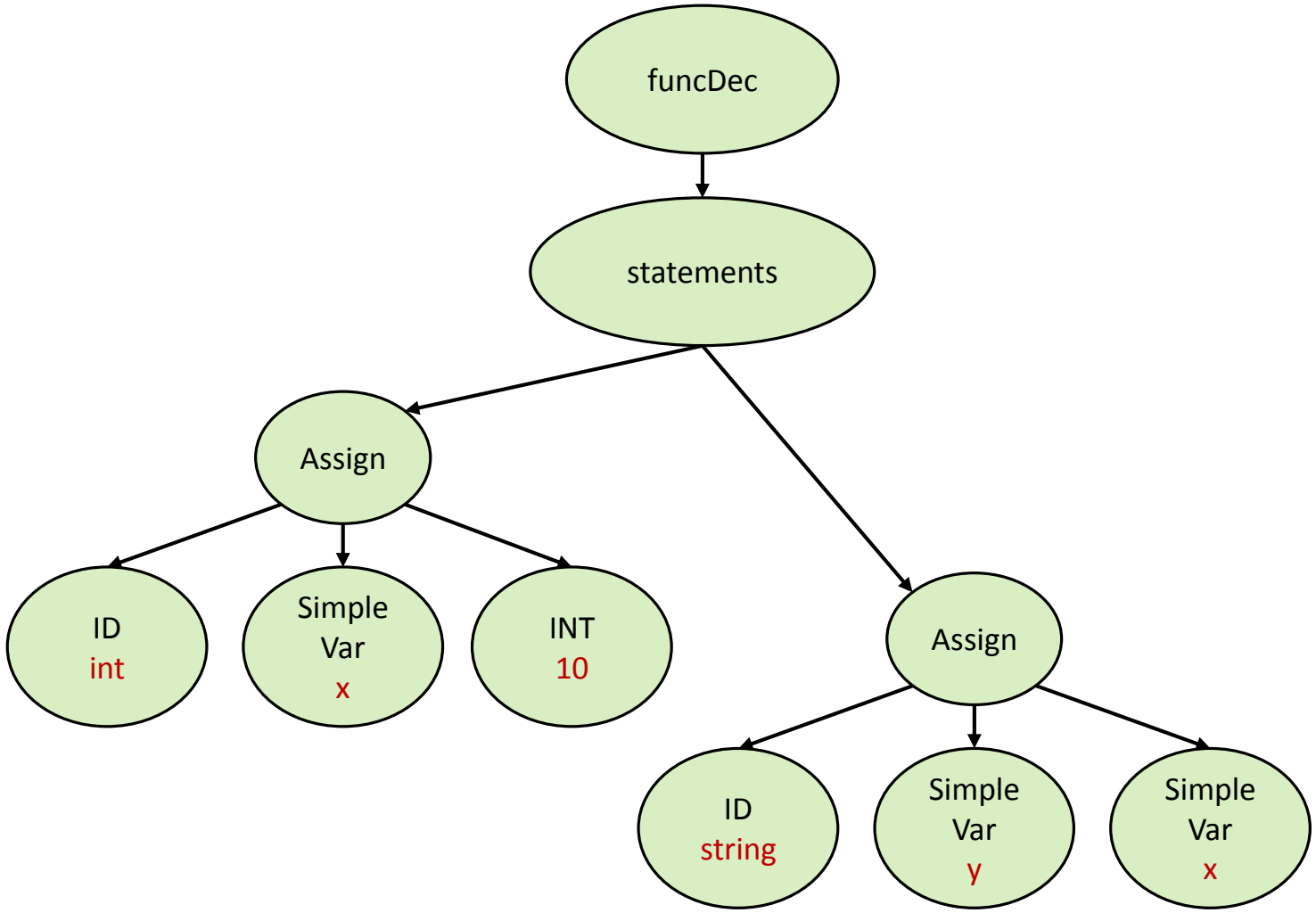
}
```



Assignments

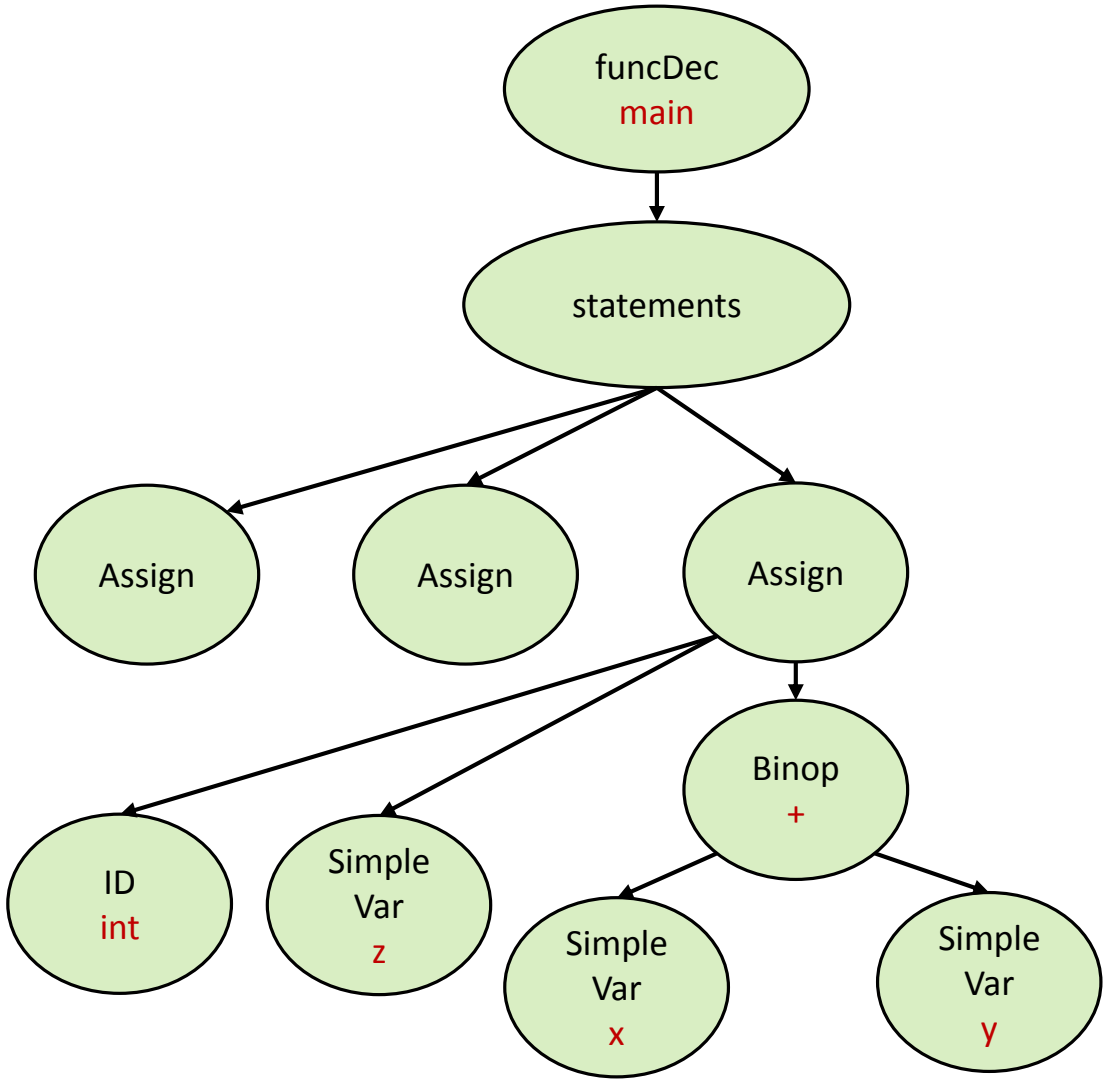
```
void main() {
   int x = 10;
   string y = x;
}
```

Invalid



Binary Operations

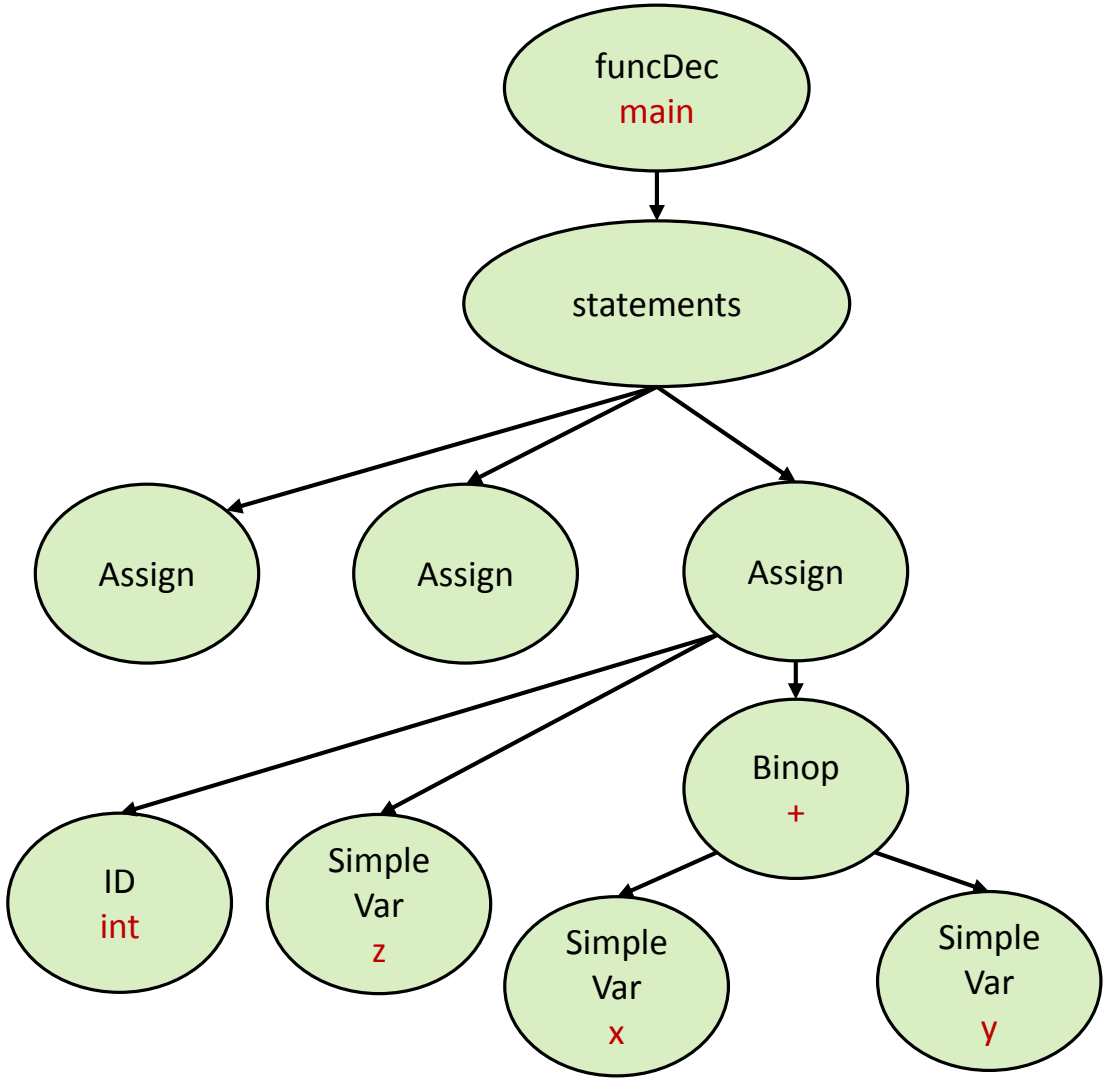
```
void main() {
   int x = 1;
   int y = 2;
   int z = x + y;
}
```



Binary Operations

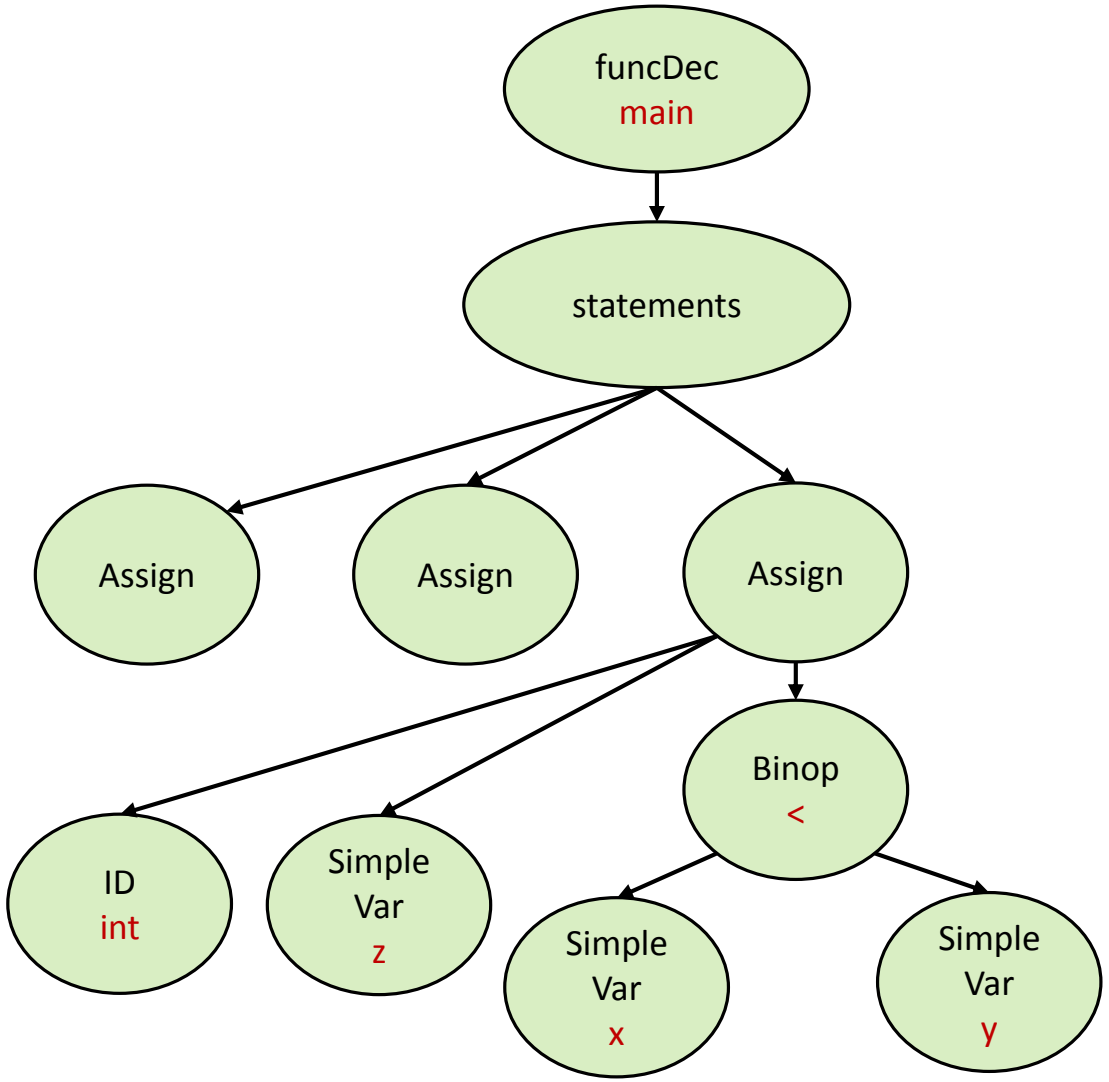
```
void main() {
   int x = 1;
   int y = 2;
   int z = x + y;
}
```

Valid



Binary Operations

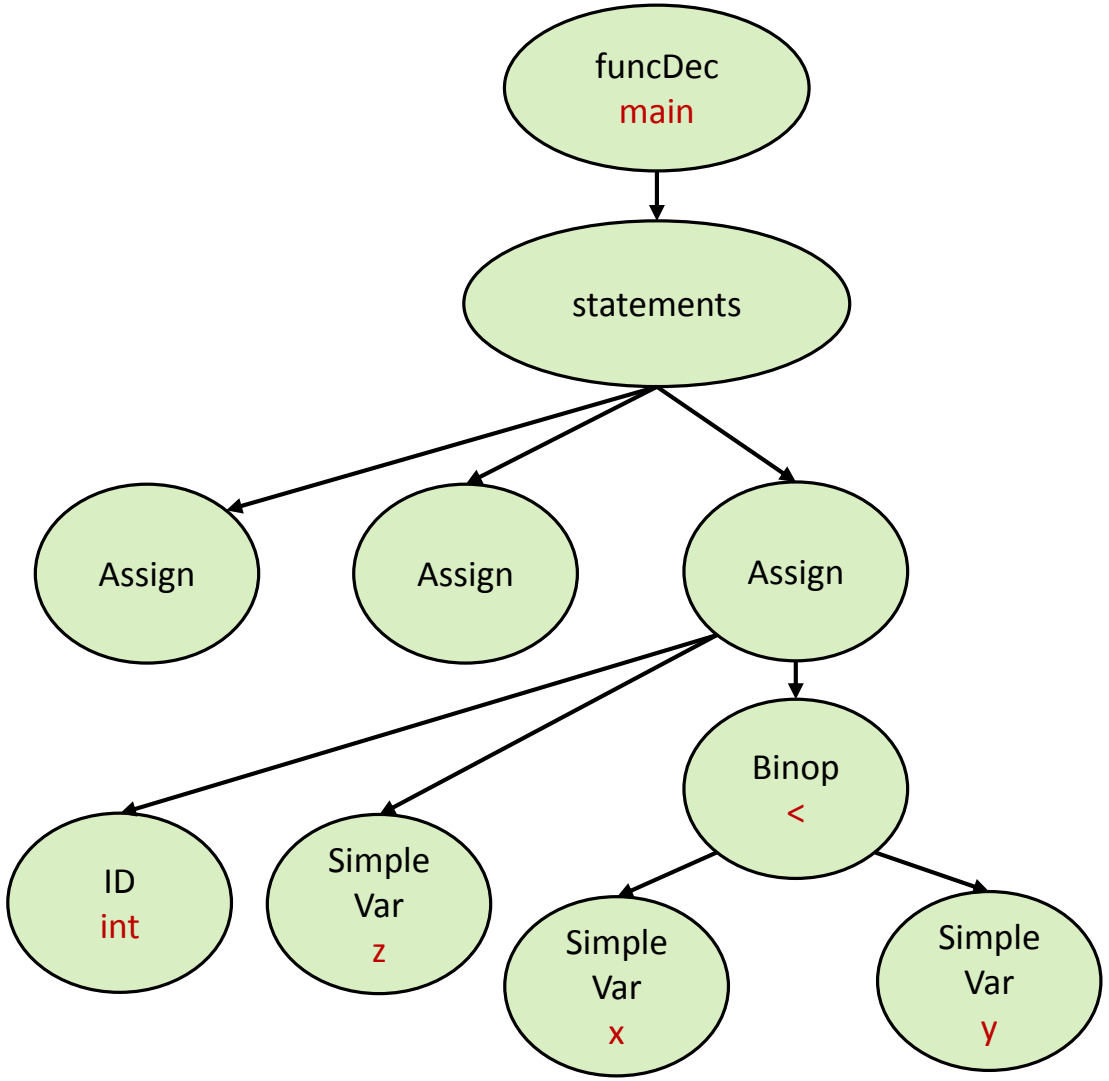
```
void main() {
   int x = 1;
   string y = "A";
   int z = x < y;
}
```



Binary Operations

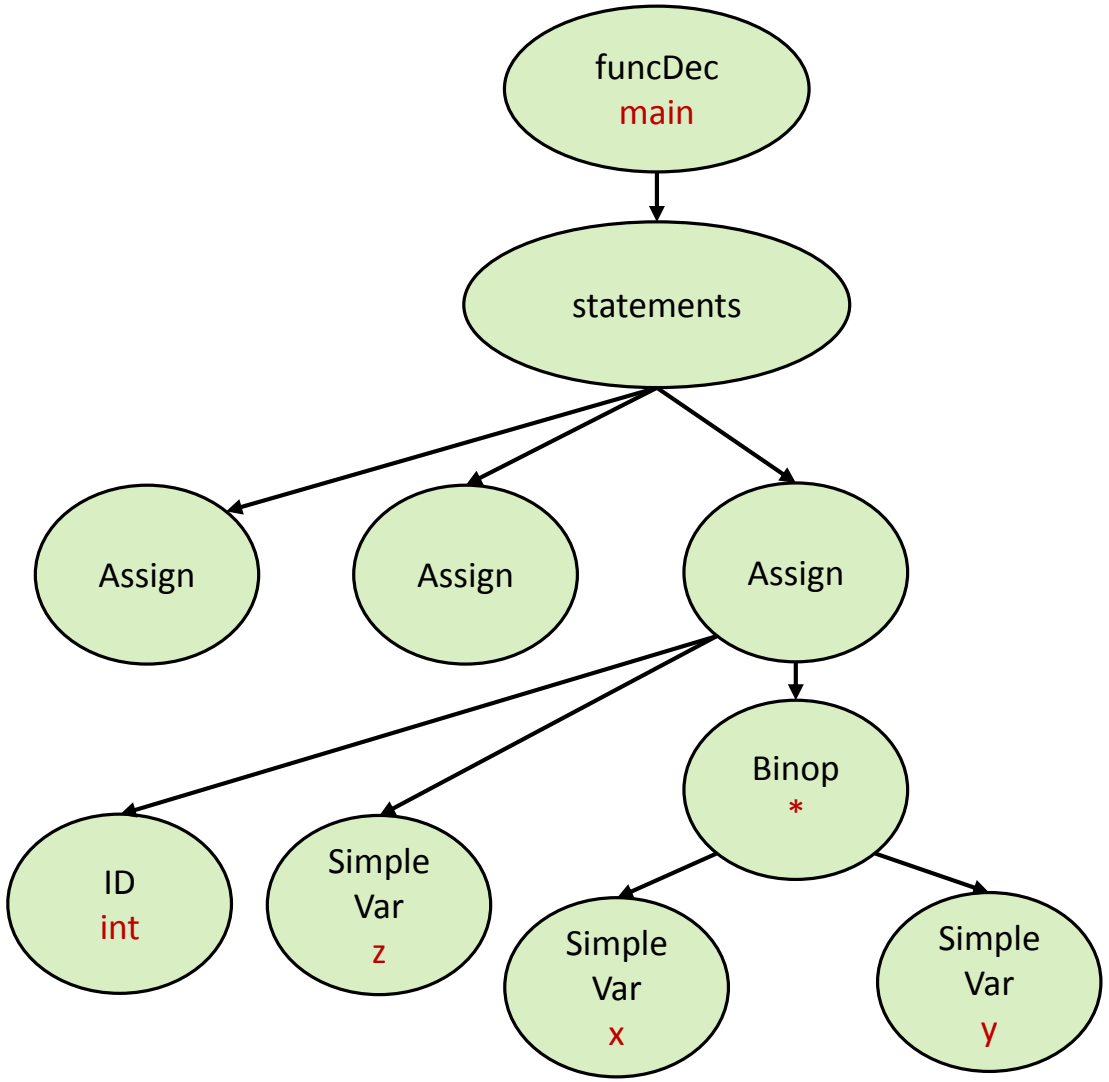
```
void main() {
   int x = 1;
   string y = "A";
   int z = x < y;
}
```

Invalid



Binary Operations

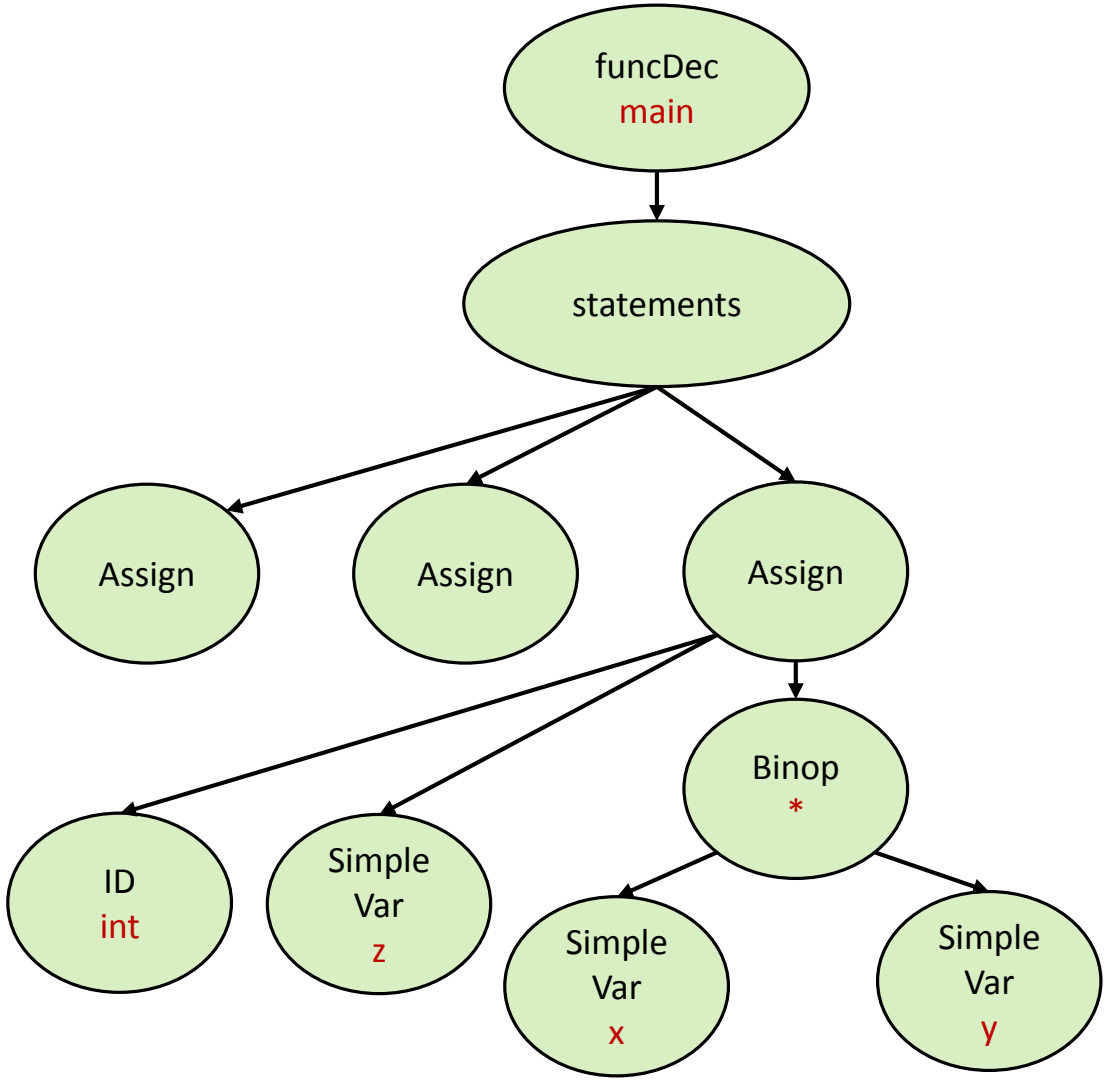
```
void main() {
   string x = "A";
   string y = "B";
   string z = x * y;
}
```



Binary Operations

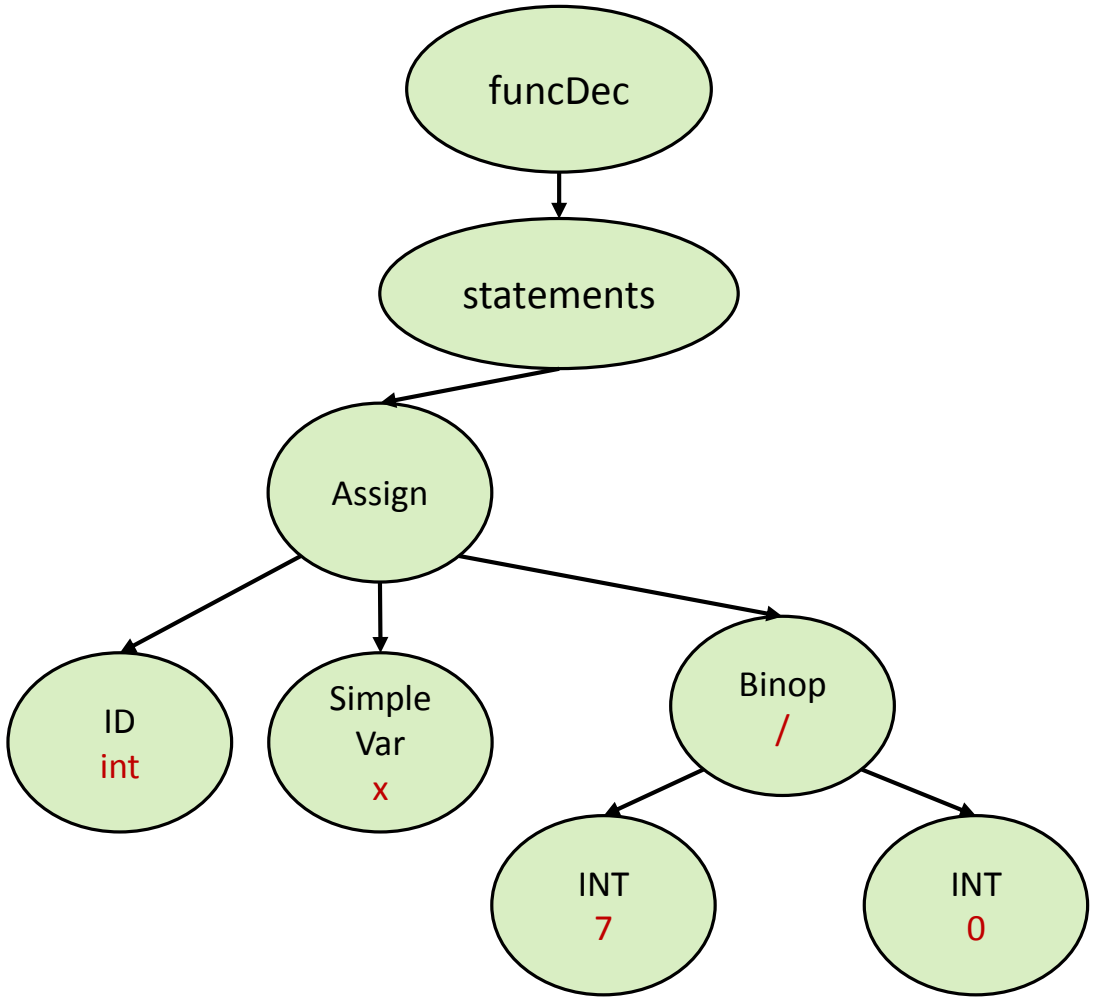
```
void main() {
   string x = "A";
   string y = "B";
   string z = x * y;
}
```

Invalid



Binary Operations

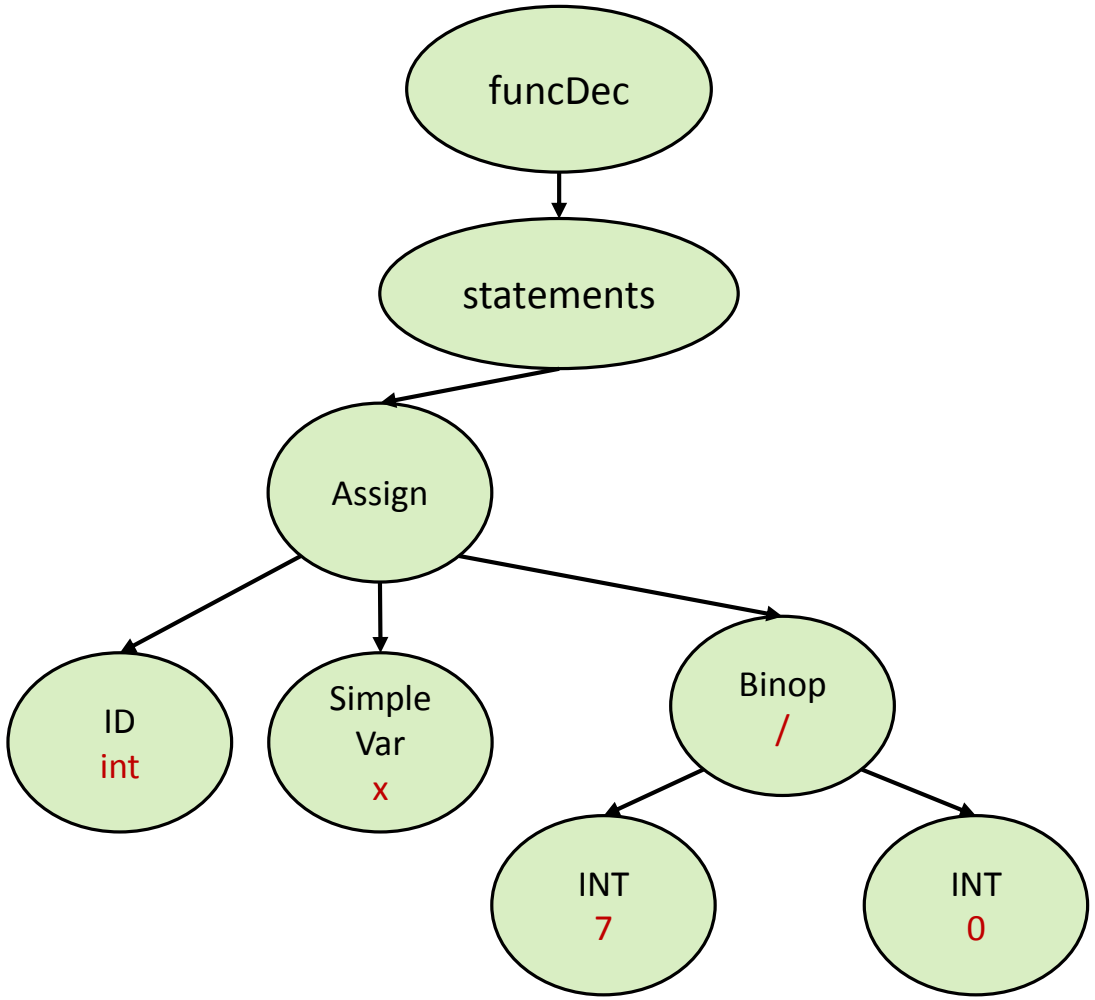
```
void main() {
   int x = 7 / 0;
}
```



Binary Operations

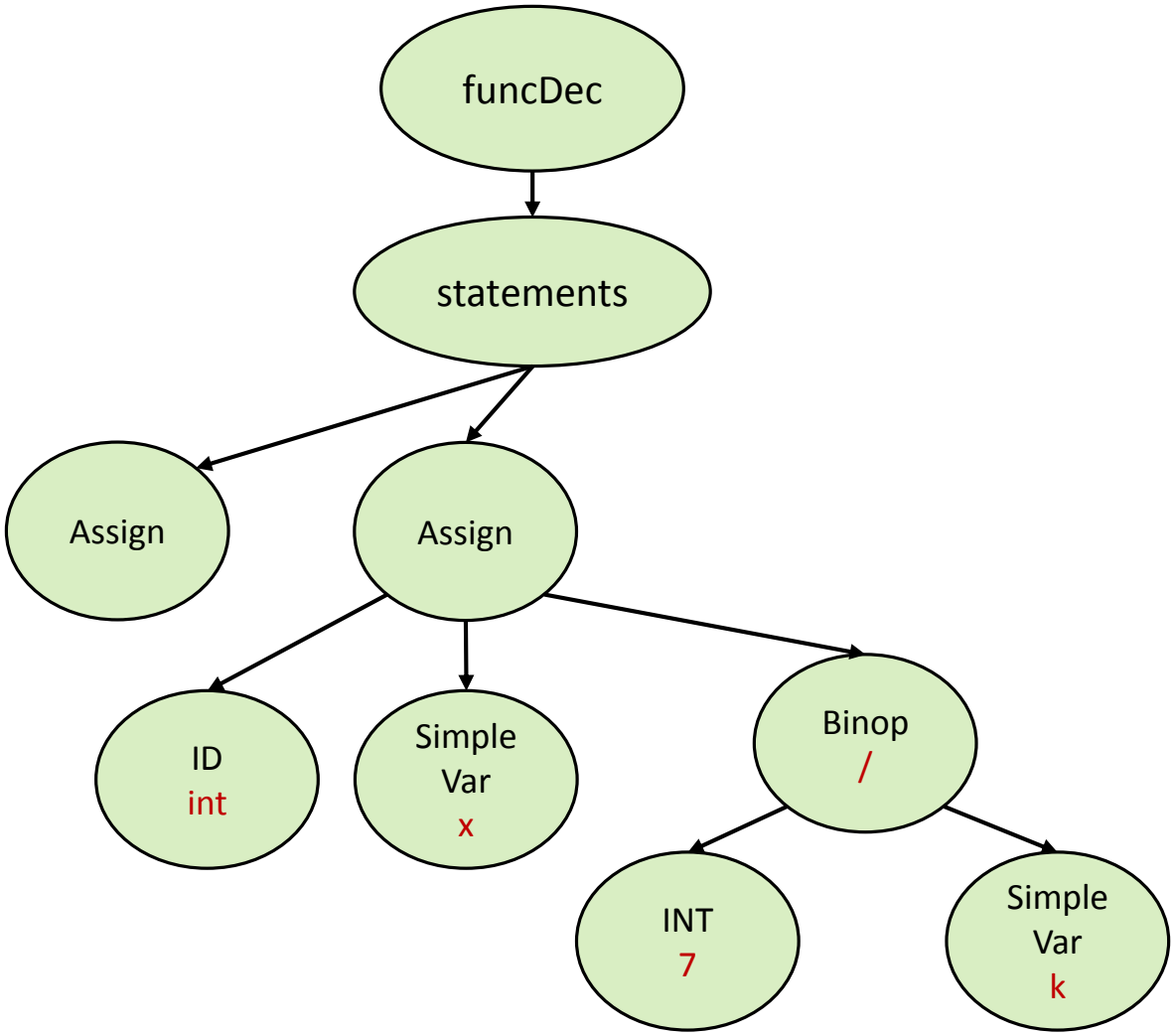
```
void main() {
   int x = 7 / 0;
}
```

Invalid



Binary Operations

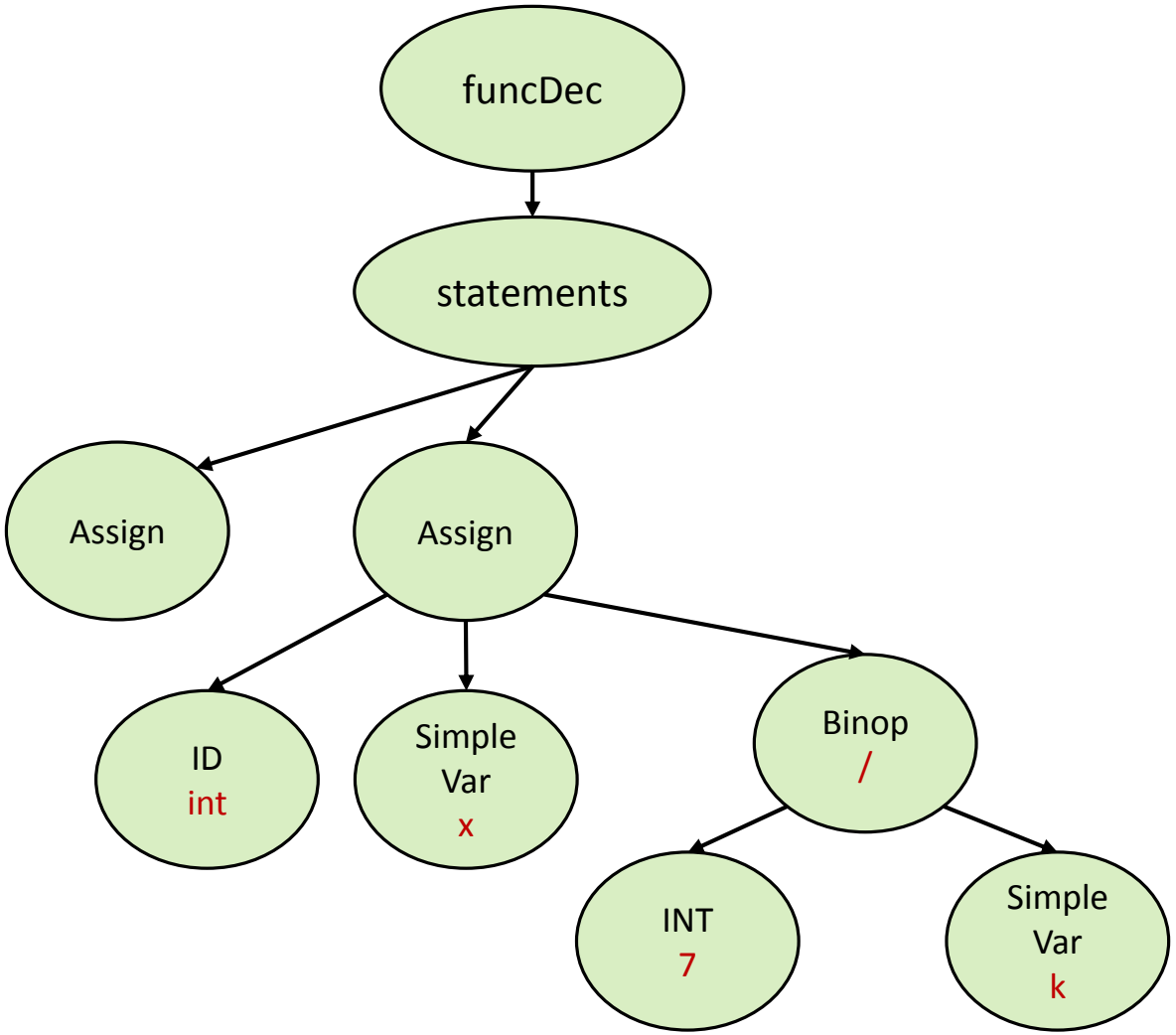
```
void main() {
   int k = 0;
   int x = 7 / k;
}
```



Binary Operations

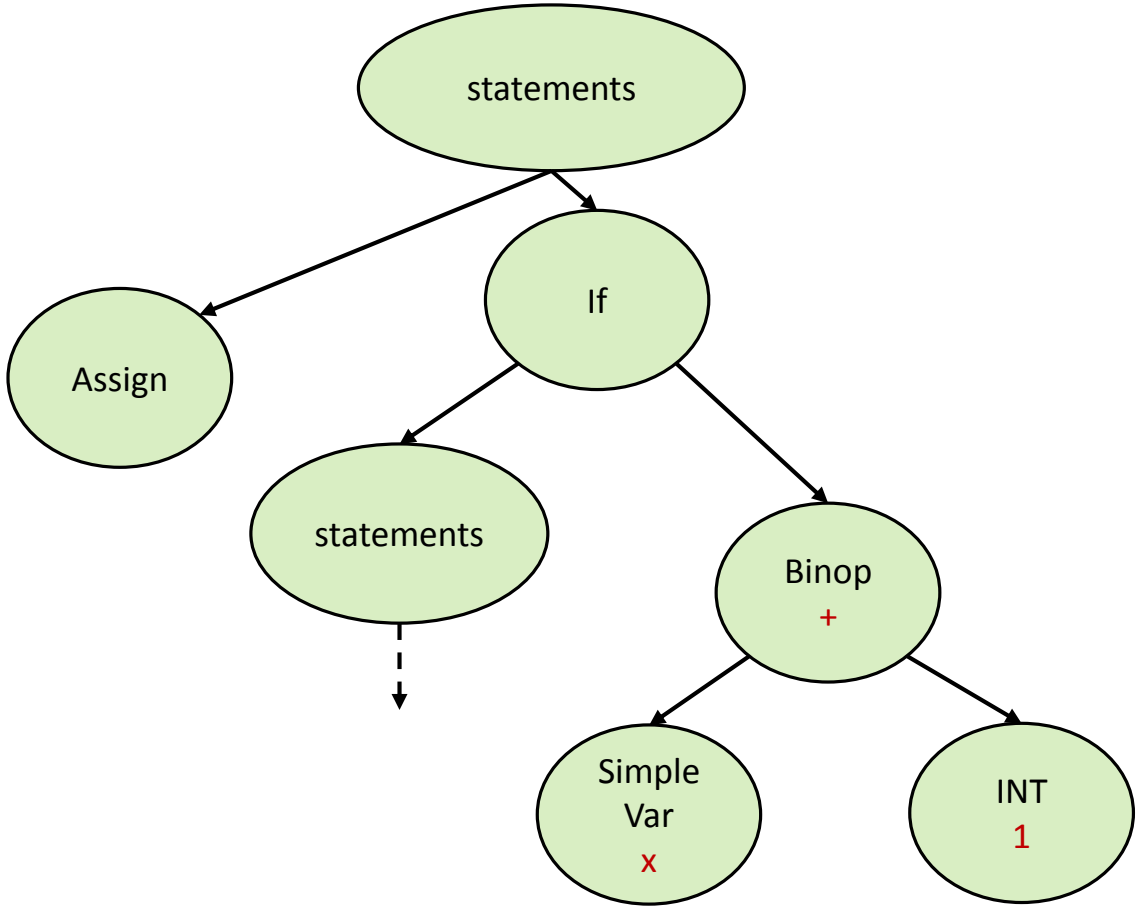
```
void main() {
   int k = 0;
   int x = 7 / k;
}
```

Depends



If, While, …

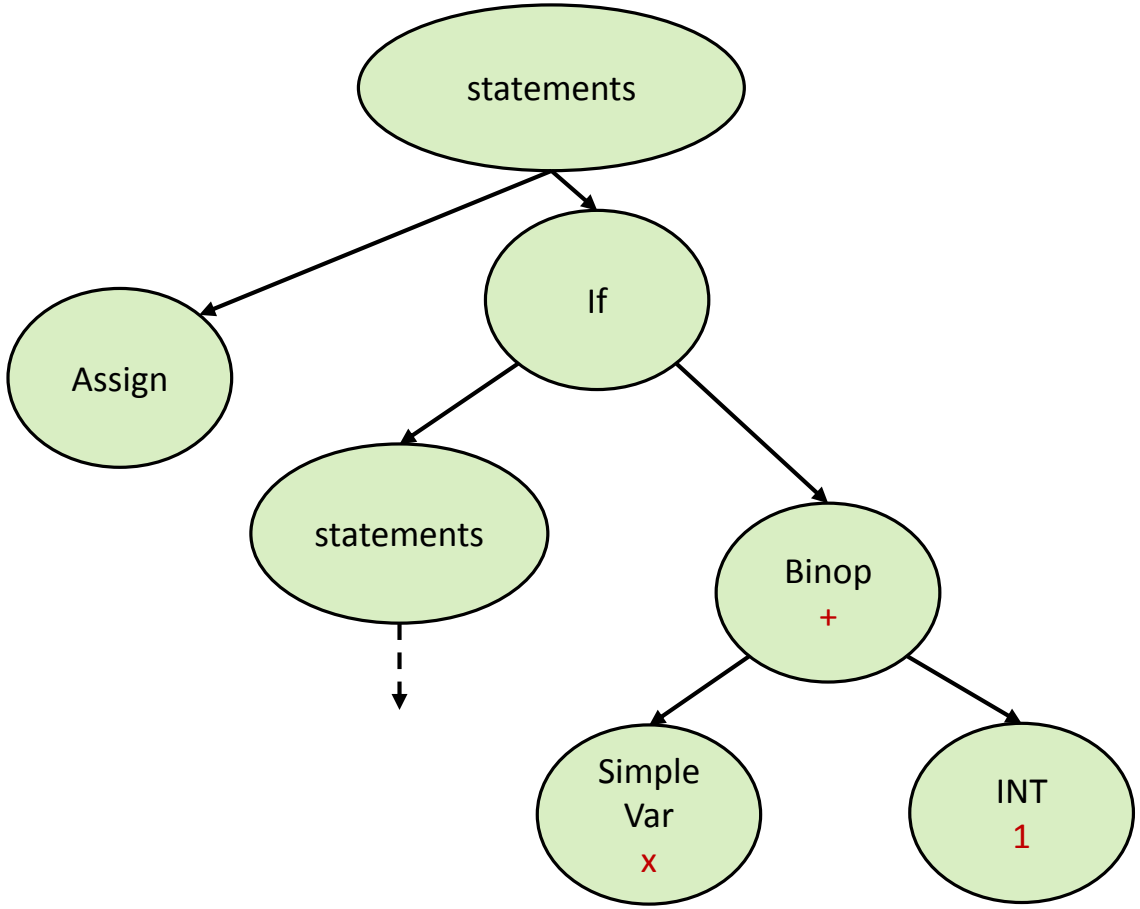
```
void main() {
   int x = 1;
   if (x + 1) {
      int z = 2;
   }
}
```



If, While, …

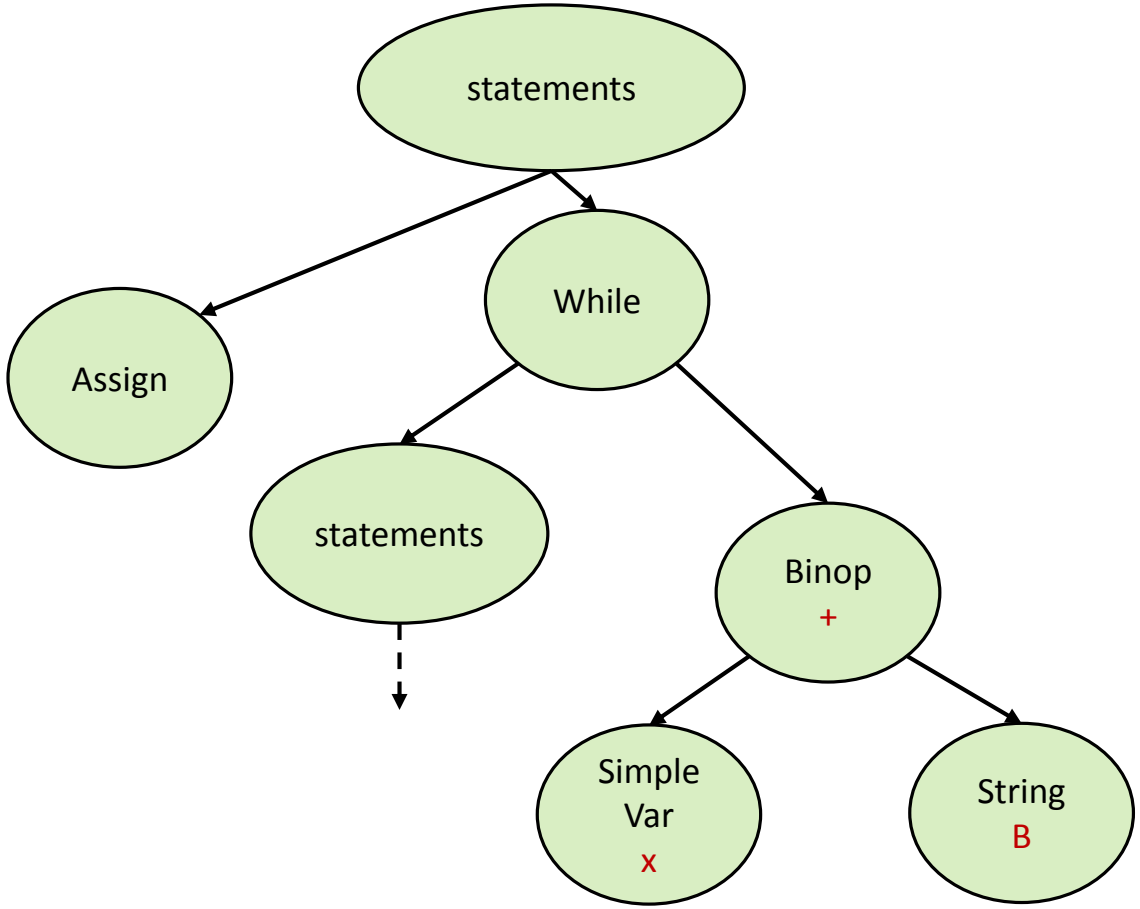
```
void main() {
  int x = 1;
  if (x + 1) {
    int z = 2;
  }
}
```

Valid



If, While, …

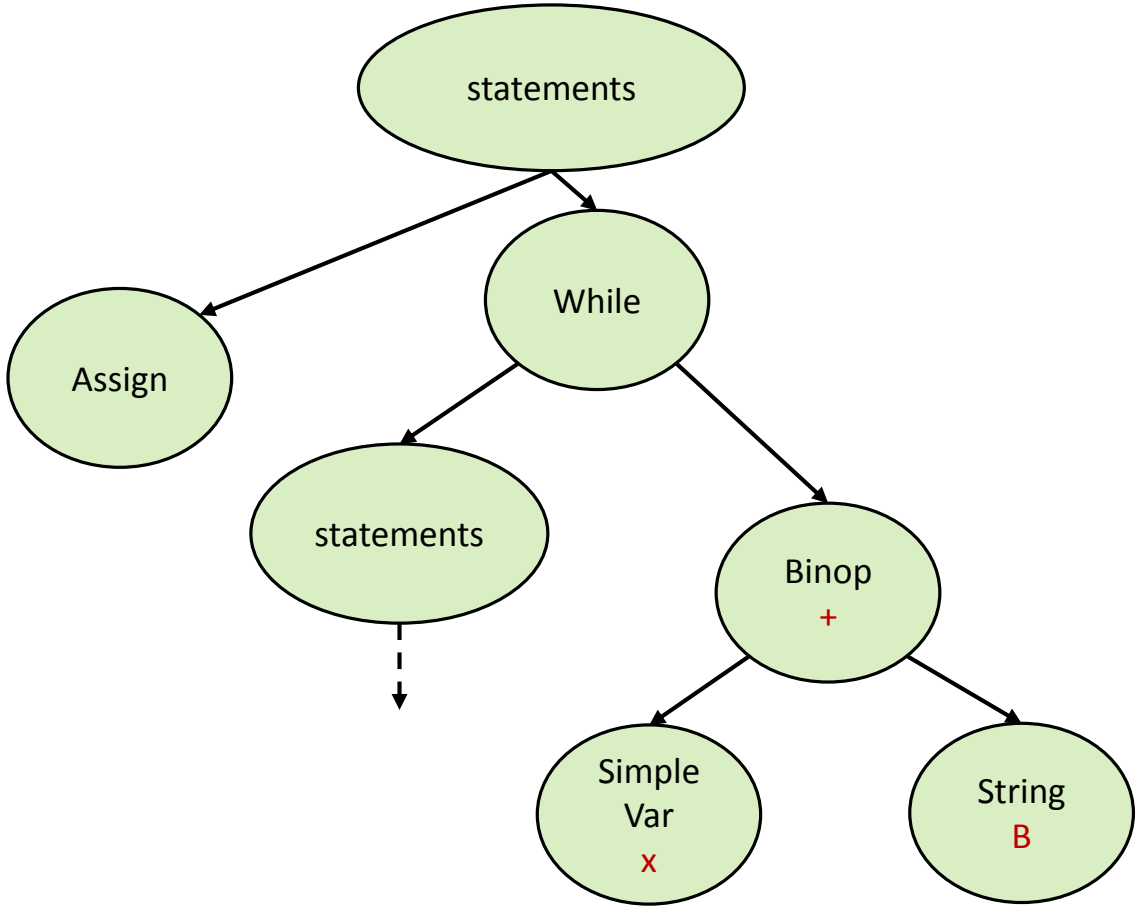
```
void main() {
   string x = "A";
   while (x + "B") {
      int z = 2;
   }
}
```



If, While, …

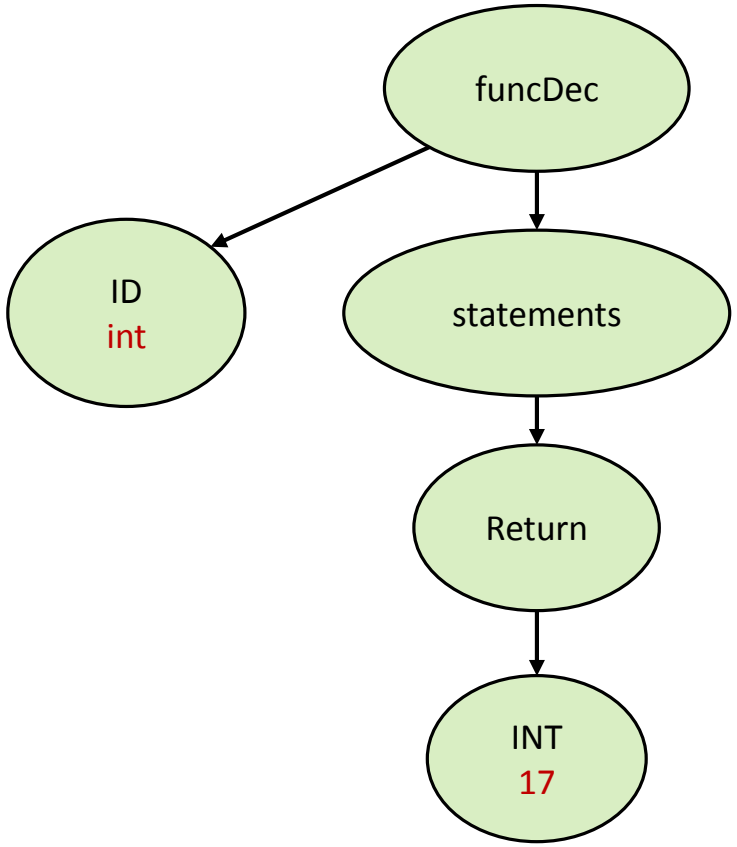
```
void main() {
   string x = "A";
   while (x + "B") {
      int z = 2;
   }
}
```

Invalid



Return Statement

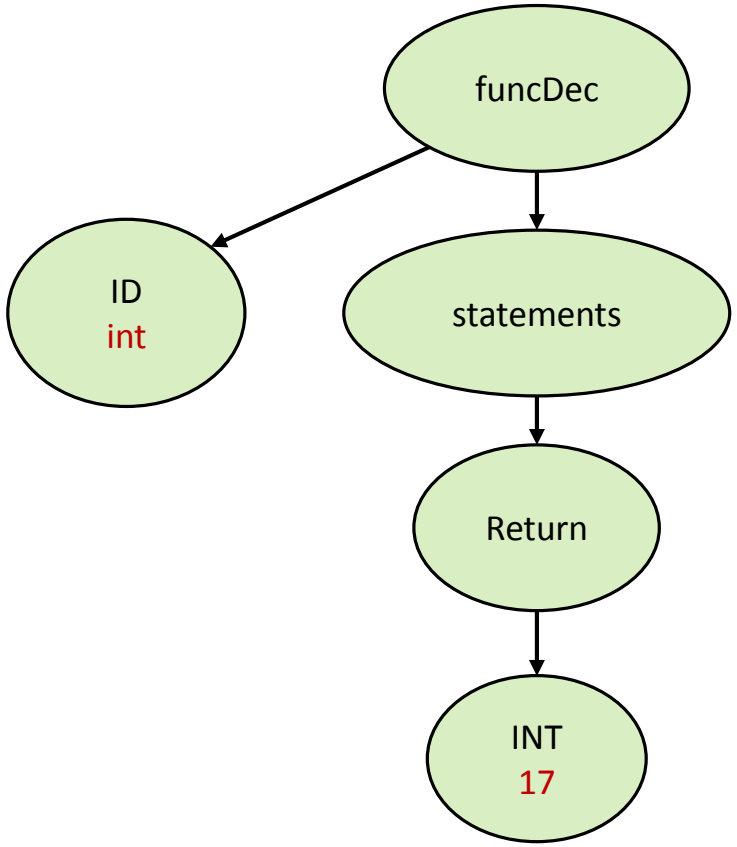
```
int main() {
   return 17;
}
```



Return Statement

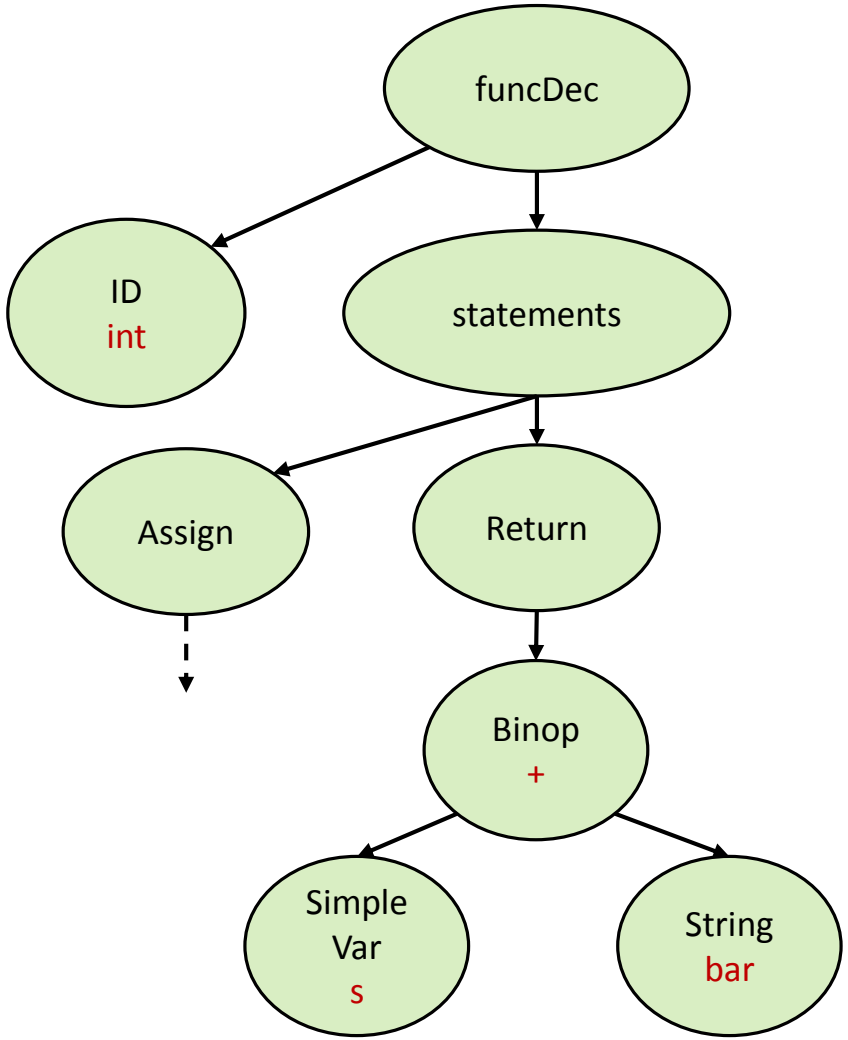
```
int main() {
   return 17;
}
```

Valid



Return Statement

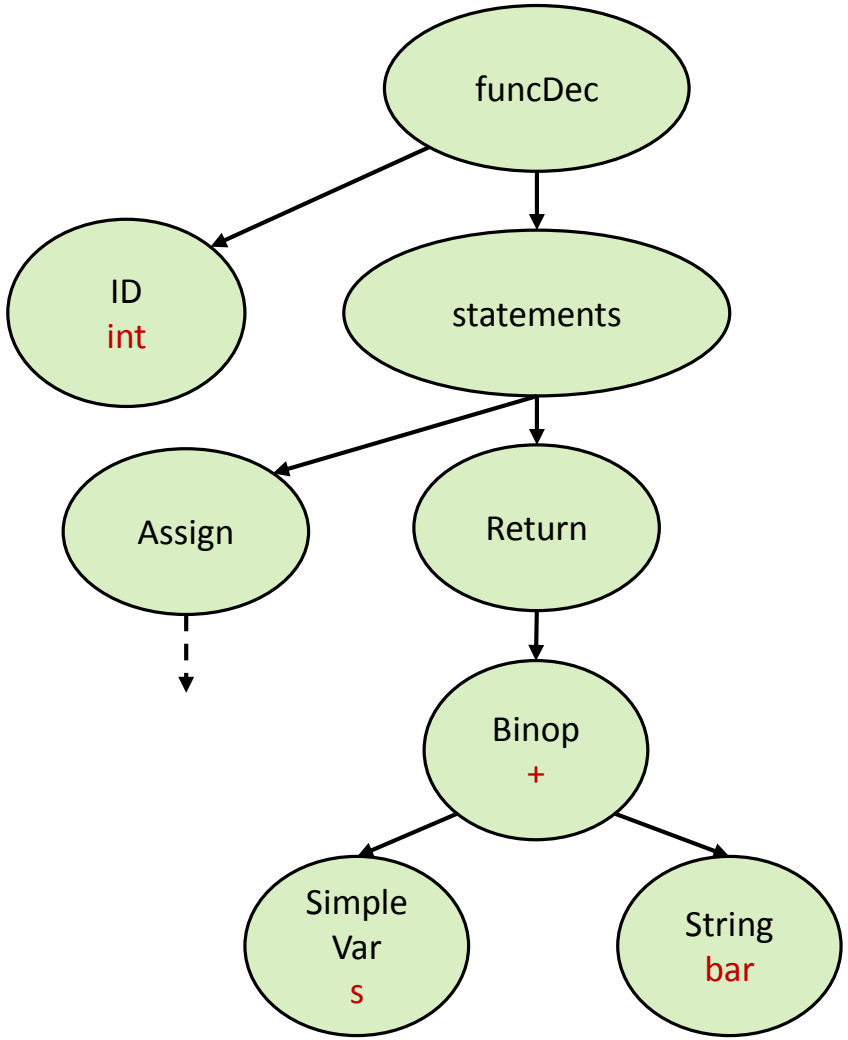
```
int main() {
   string s = "foo"
   return s + "bar";
}
```



Return Statement

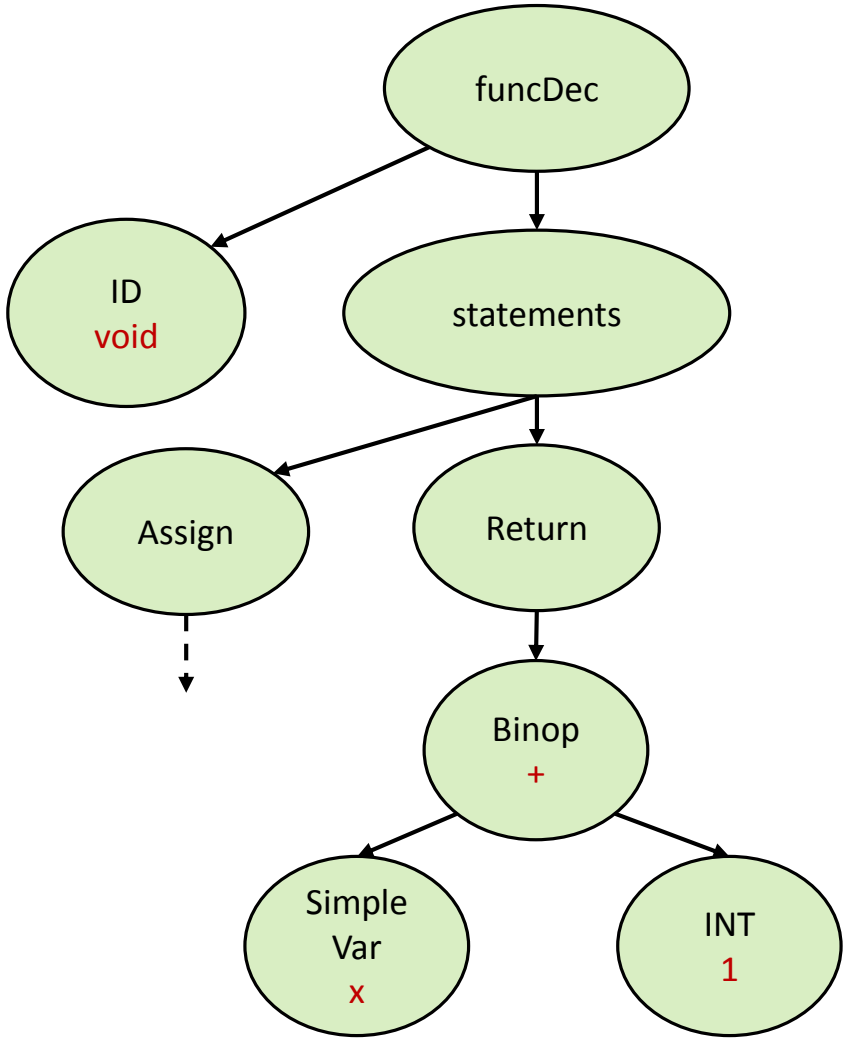
```
int main() {
   string s = "foo"
   return s + "bar";
}
```

Invalid



Return Statement

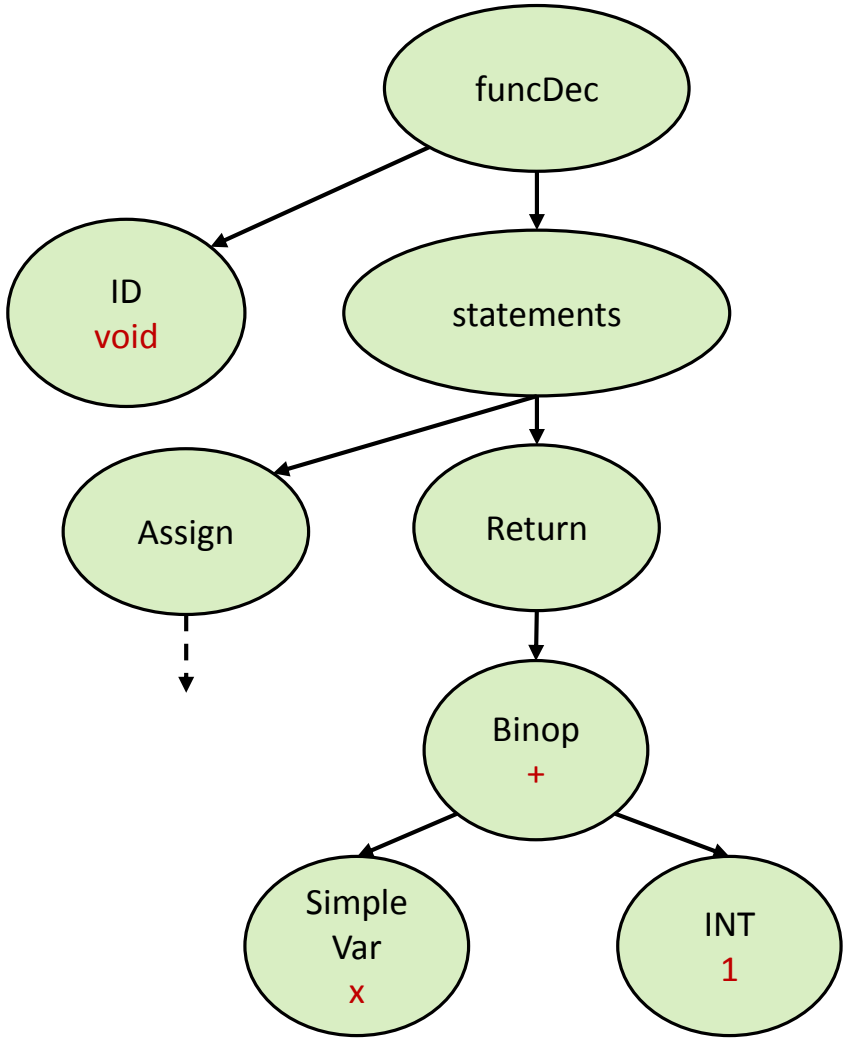
```
void main() {
   int x = 1;
   return x + 1;
}
```



Return Statement

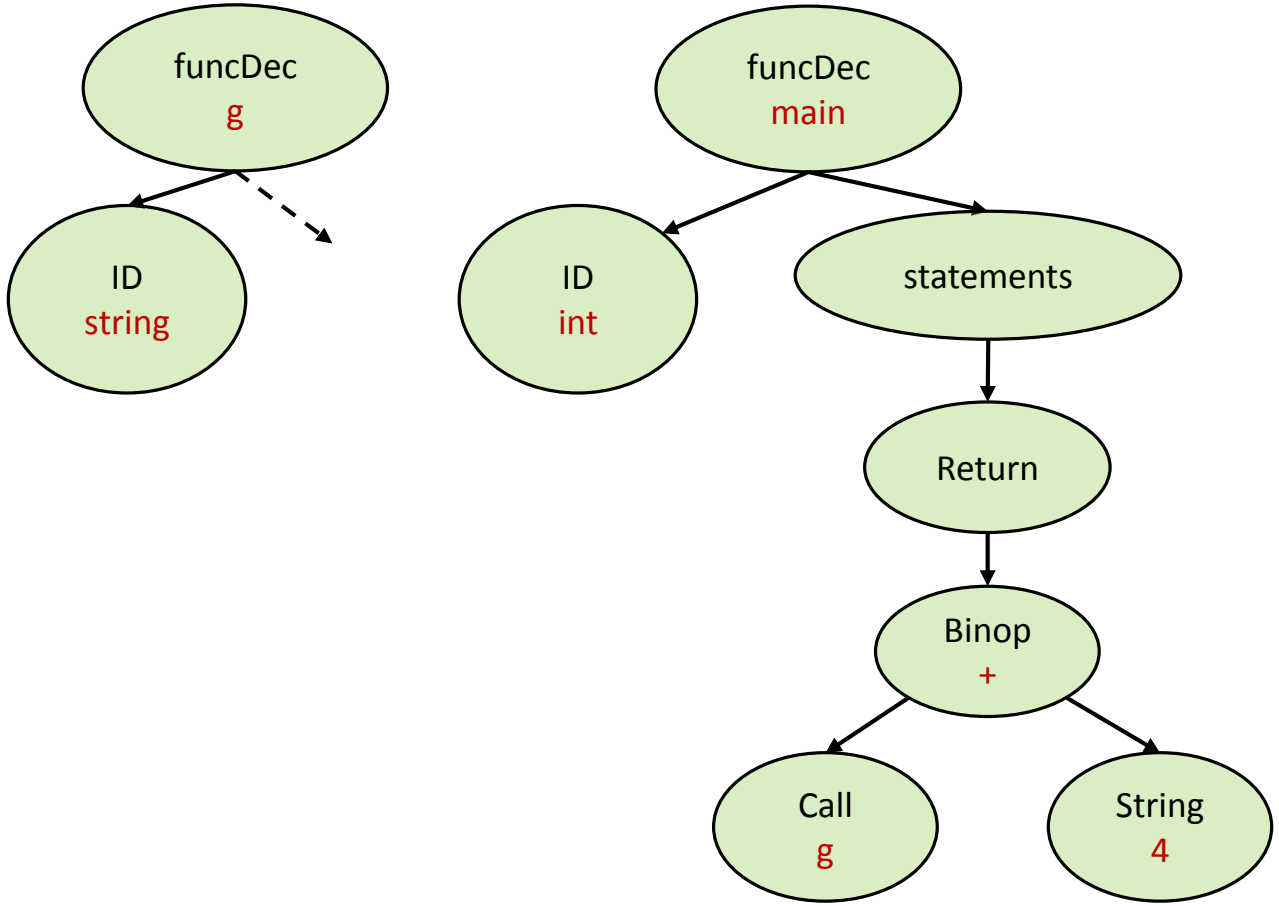
```
void main() {
   int x = 1;
   return x + 1;
}
```

Invalid



Return Statement

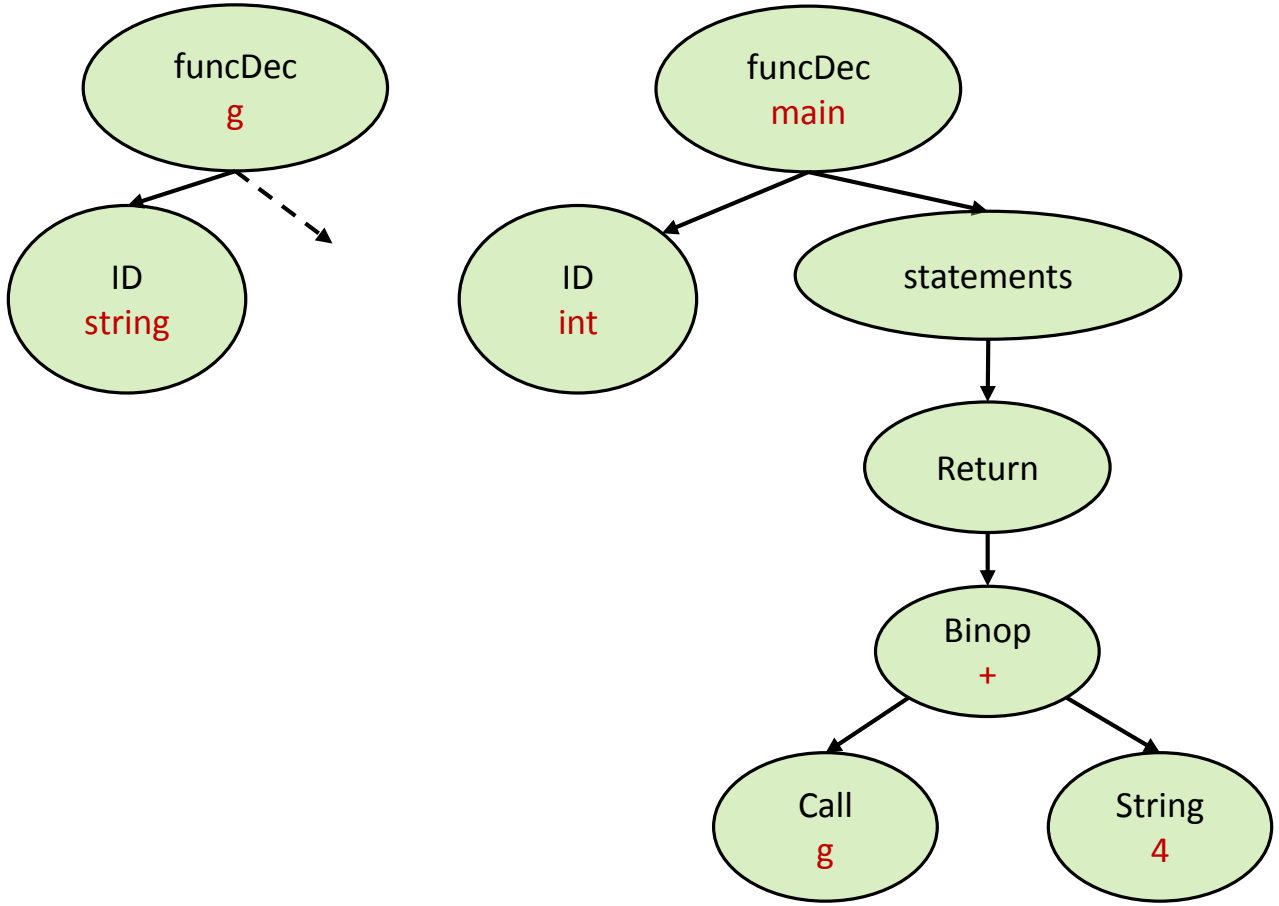
```
string g() {
  return "123";
}
int main() {
  return g() + "4";
}
```



Return Statement

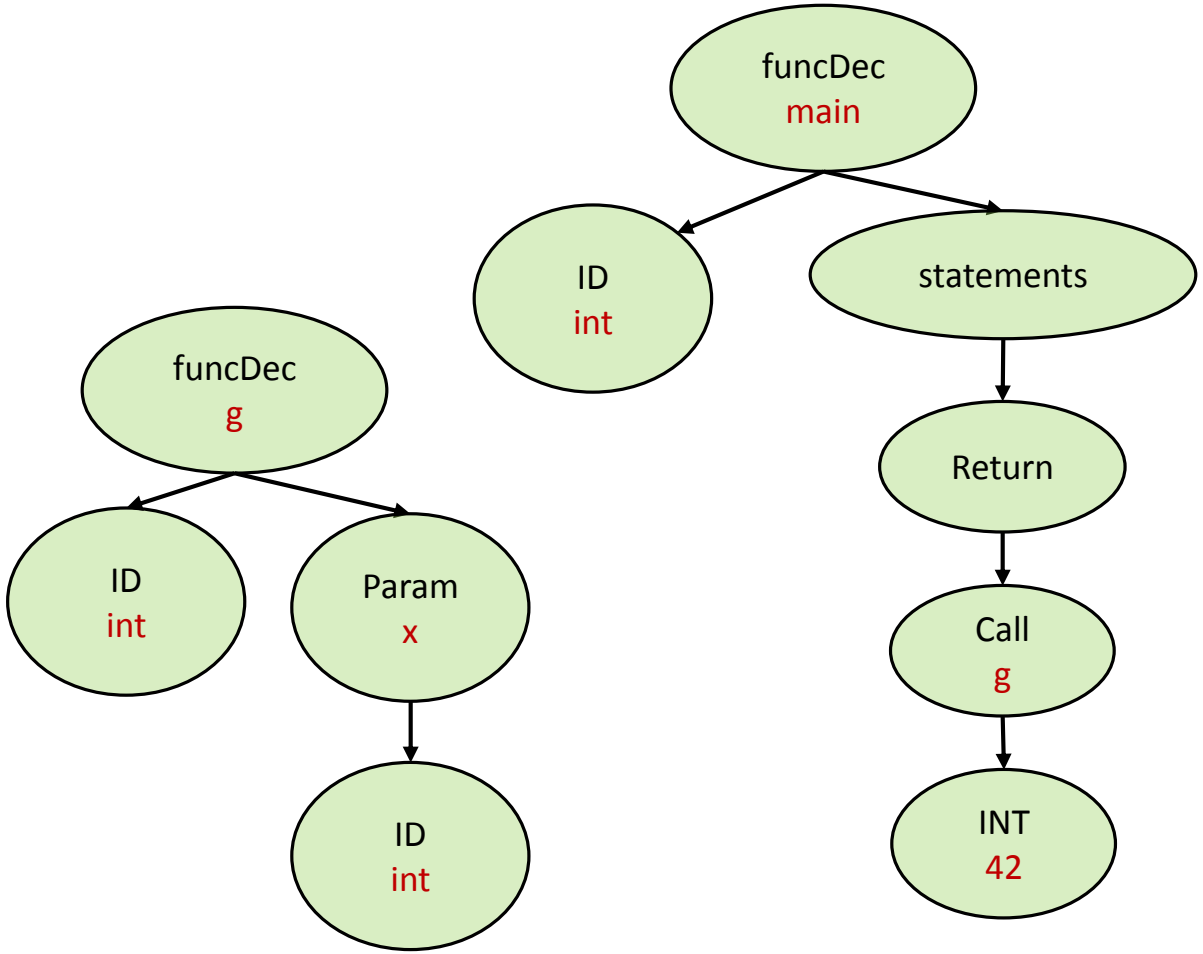
```
string g() {
  return "123";
}
int main() {
  return g() + "4";
}
```

Invalid



Function Calls

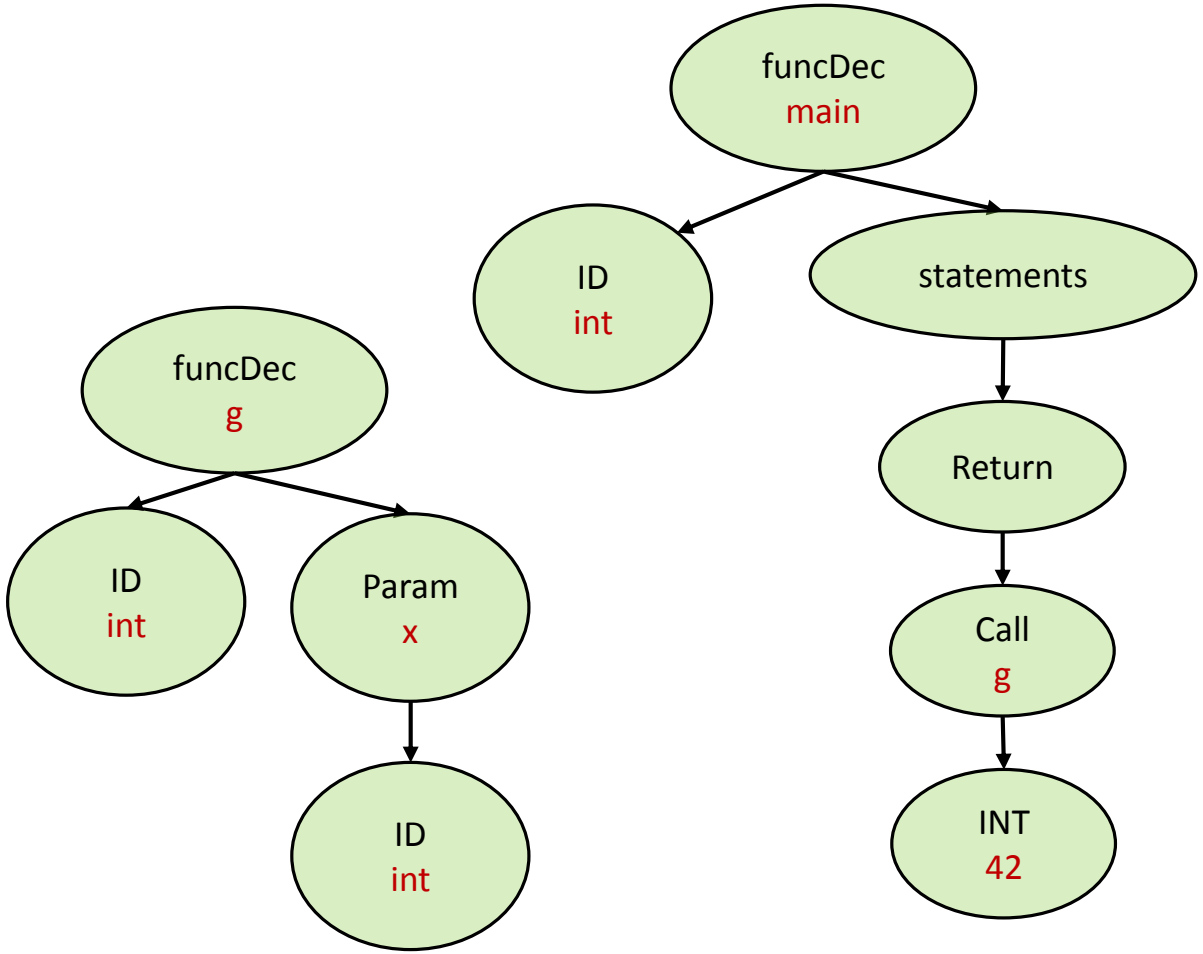
```
int g(int x) {
  return x + 1;
}
int main() {
  return g(42);
}
```



Function Calls

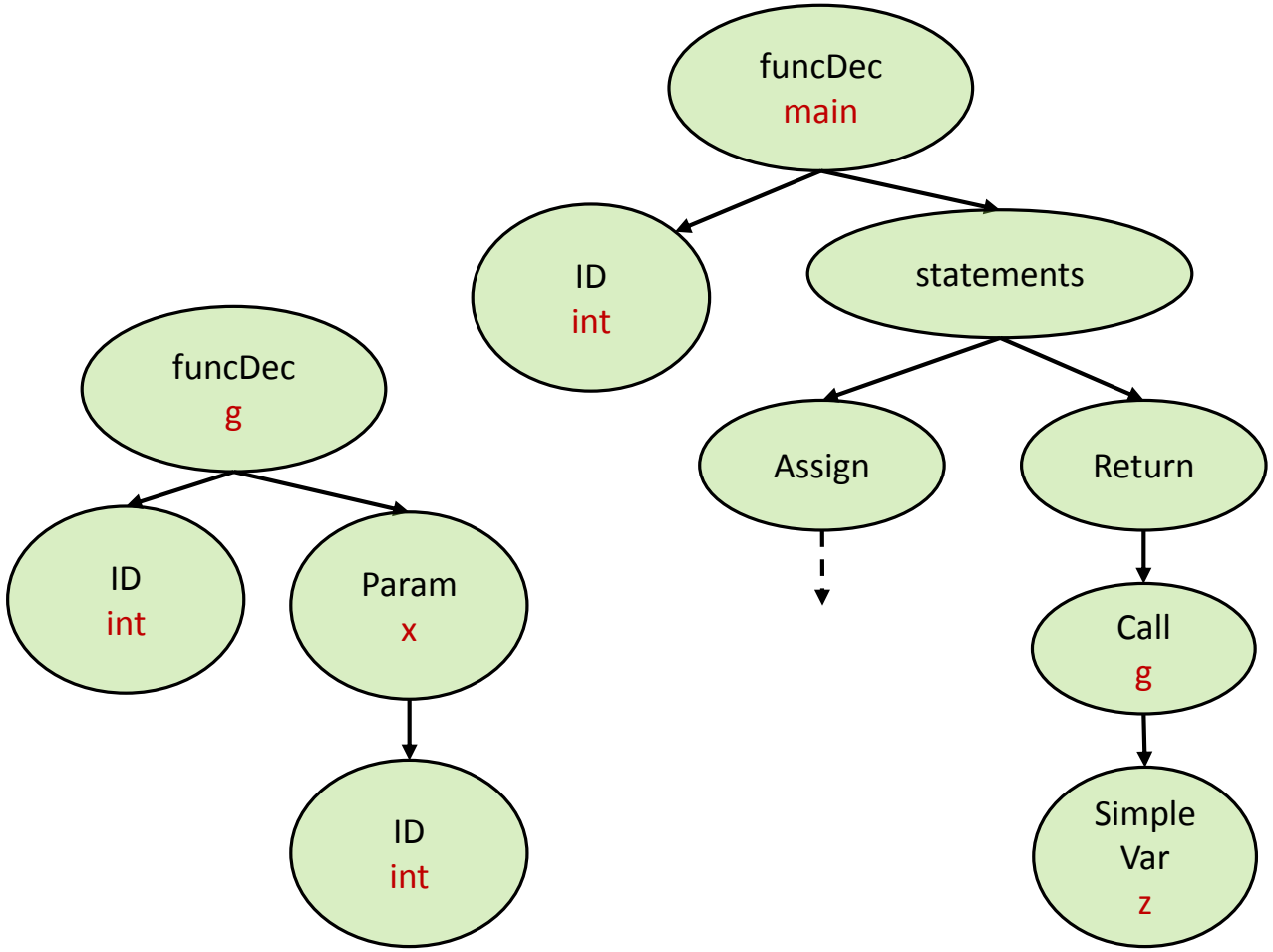
```
int g(int x) {
  return x + 1;
}
int main() {
  return g(42);
}
```

Valid



Function Calls

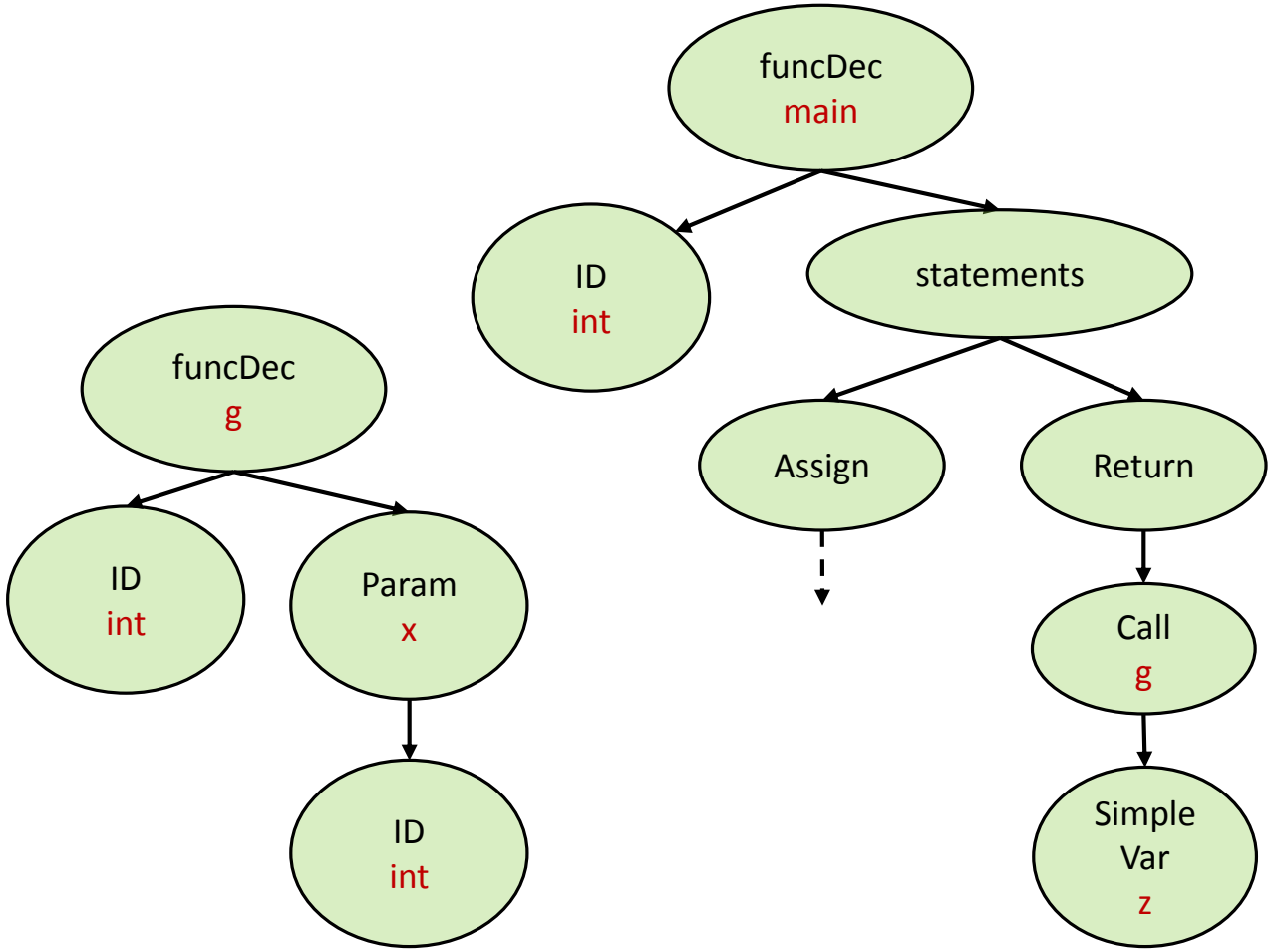
```
int g(int x) {
  return x + 1;
}
int main() {
  string z = "...";
  return g(z);
}
```



Function Calls

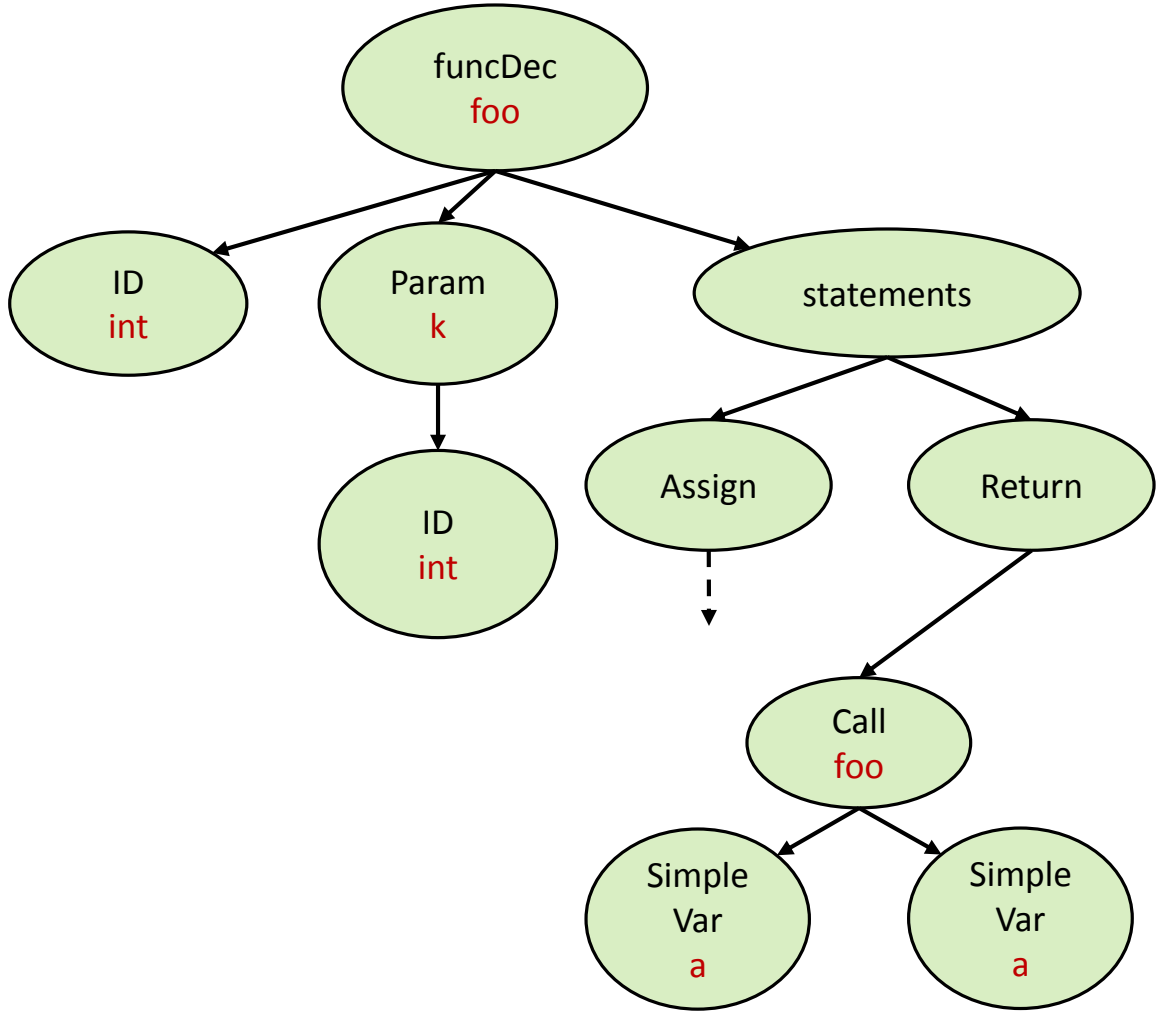
```
int g(int x) {
   return x + 1;
}
int main() {
   string z = "..."
   return g(z);
}
```

Invalid



Function Calls

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



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```
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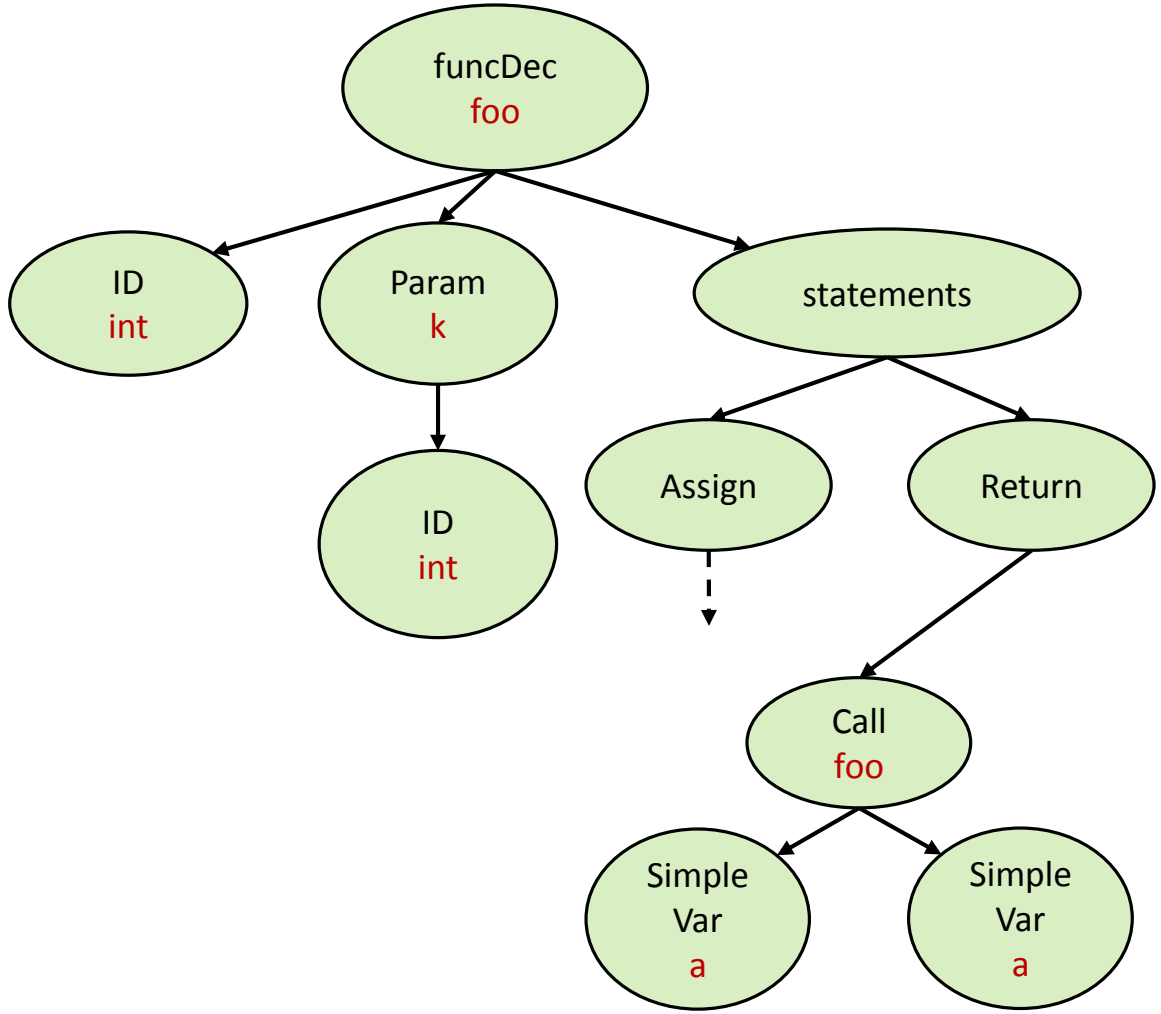
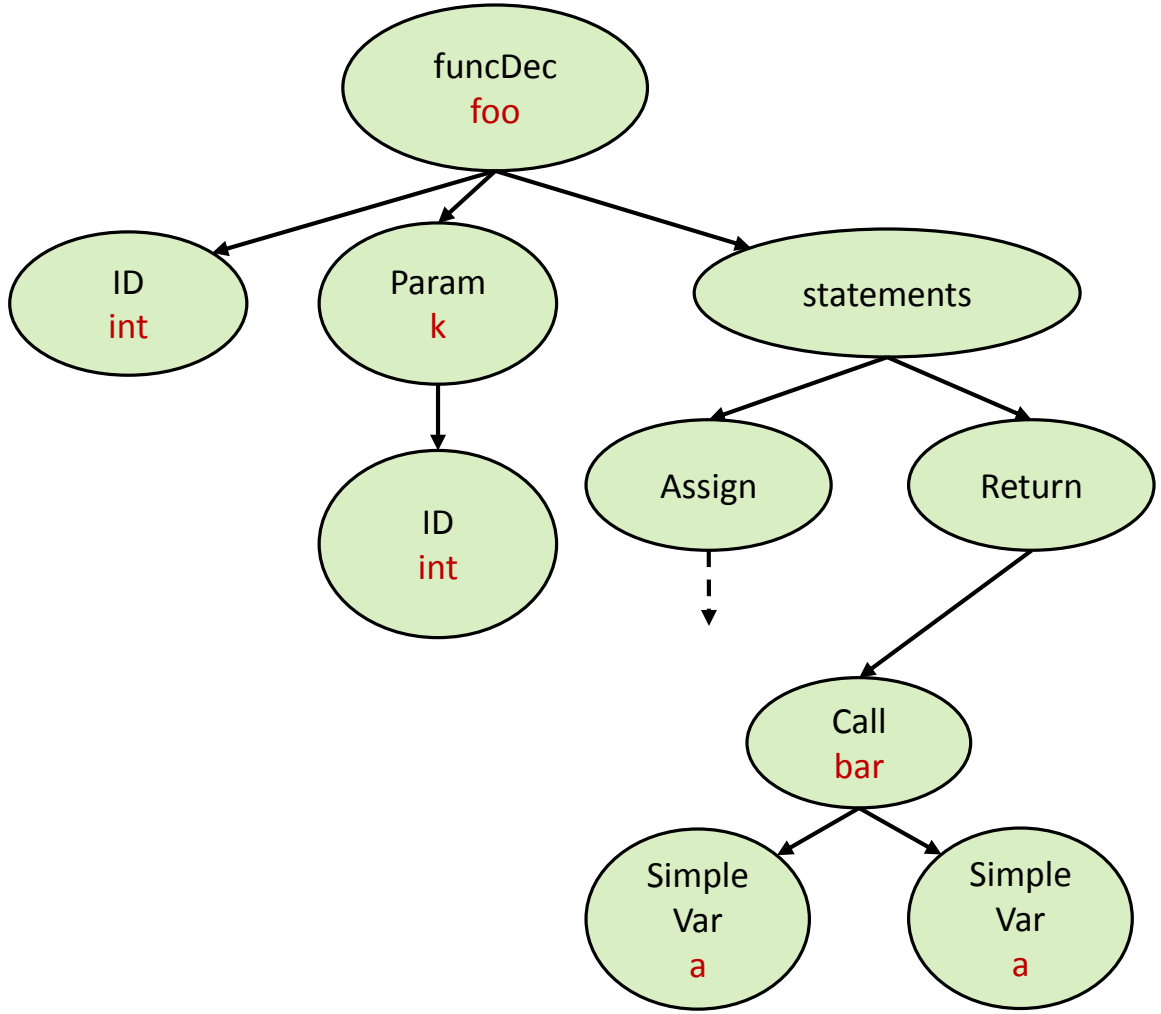
}
```

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;
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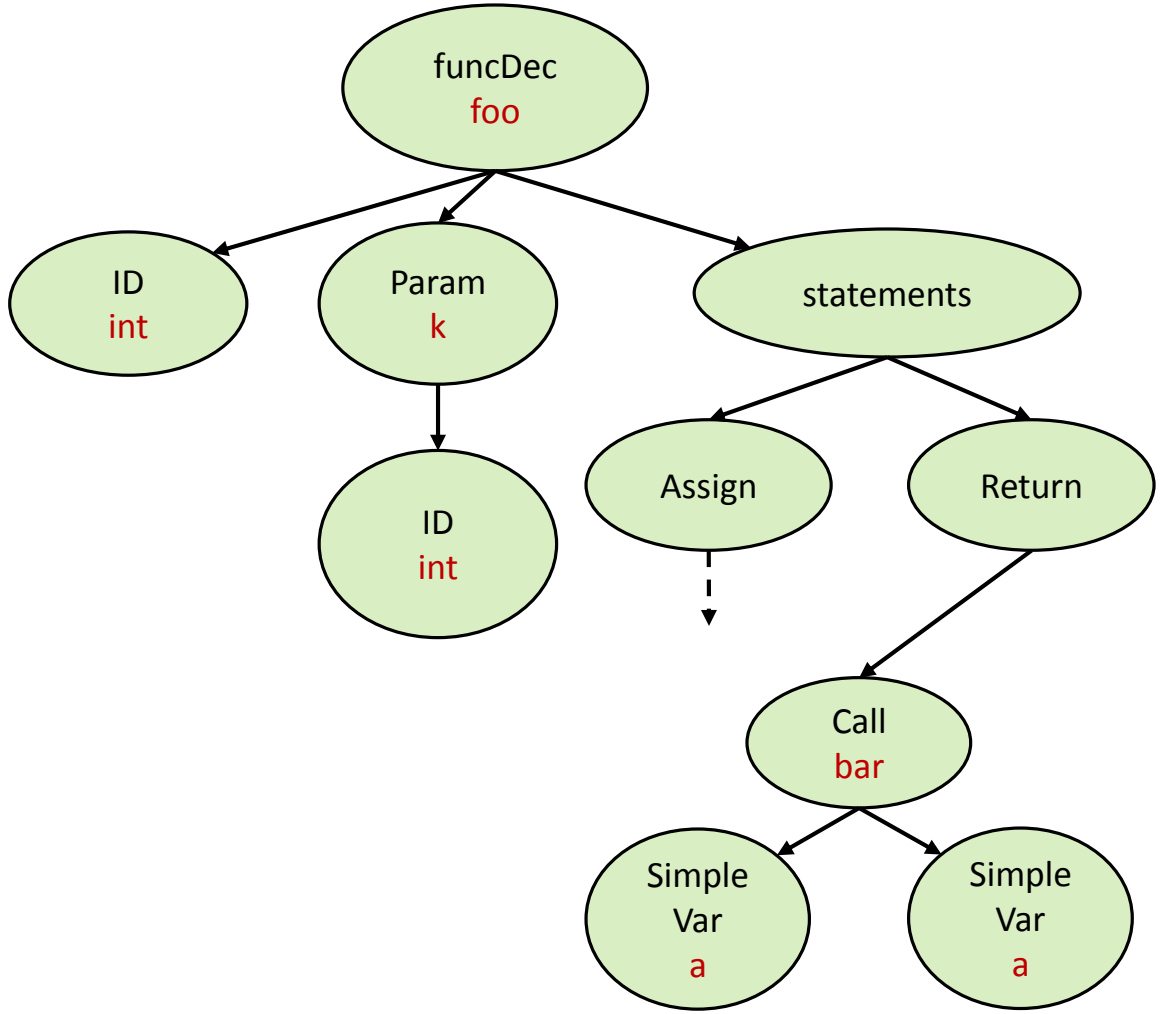
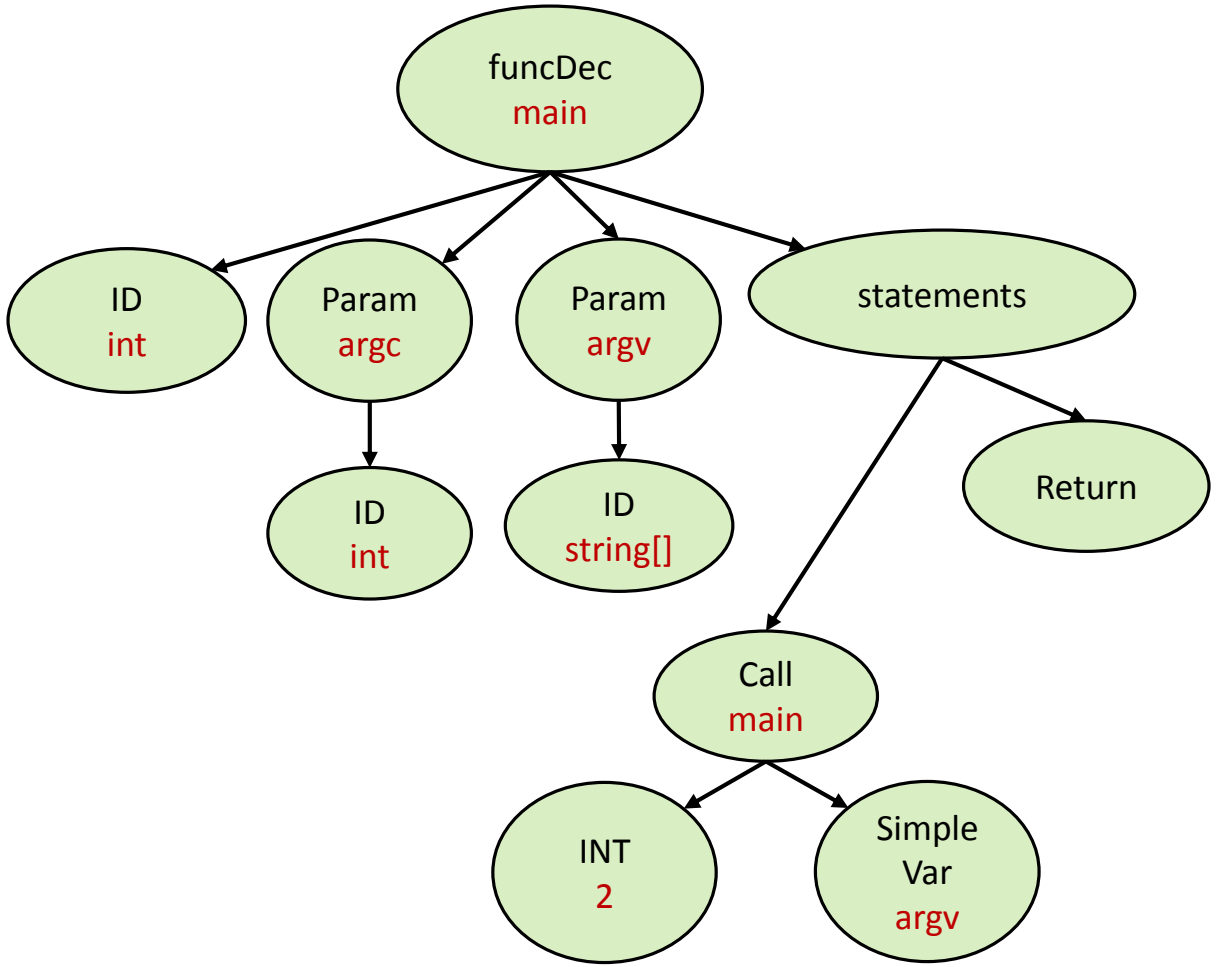
}
```

Invalid



Function Calls

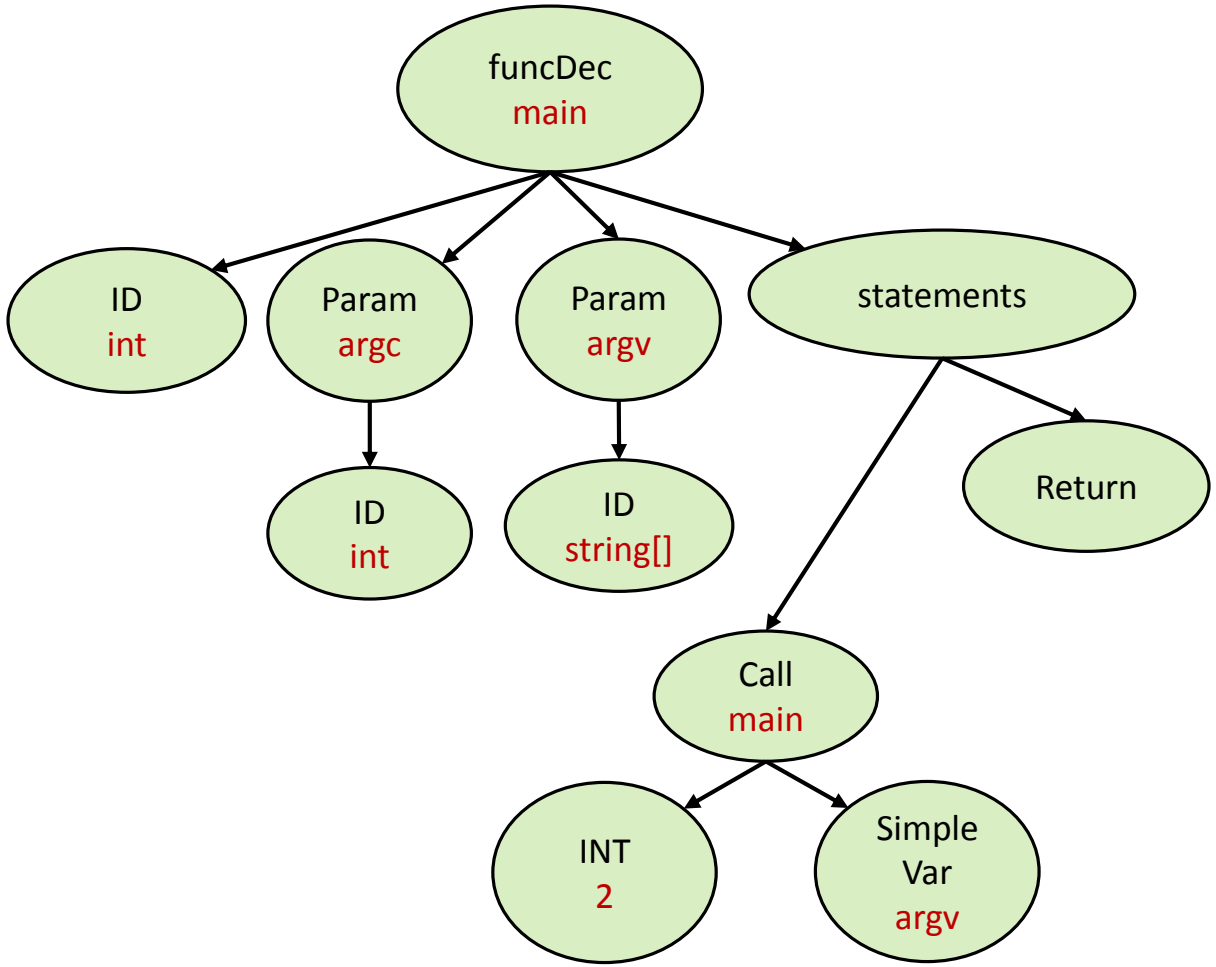
```
int main(int argc,
         string argv[]){
  main(2, argv);
  return 0;
}
```



Function Calls

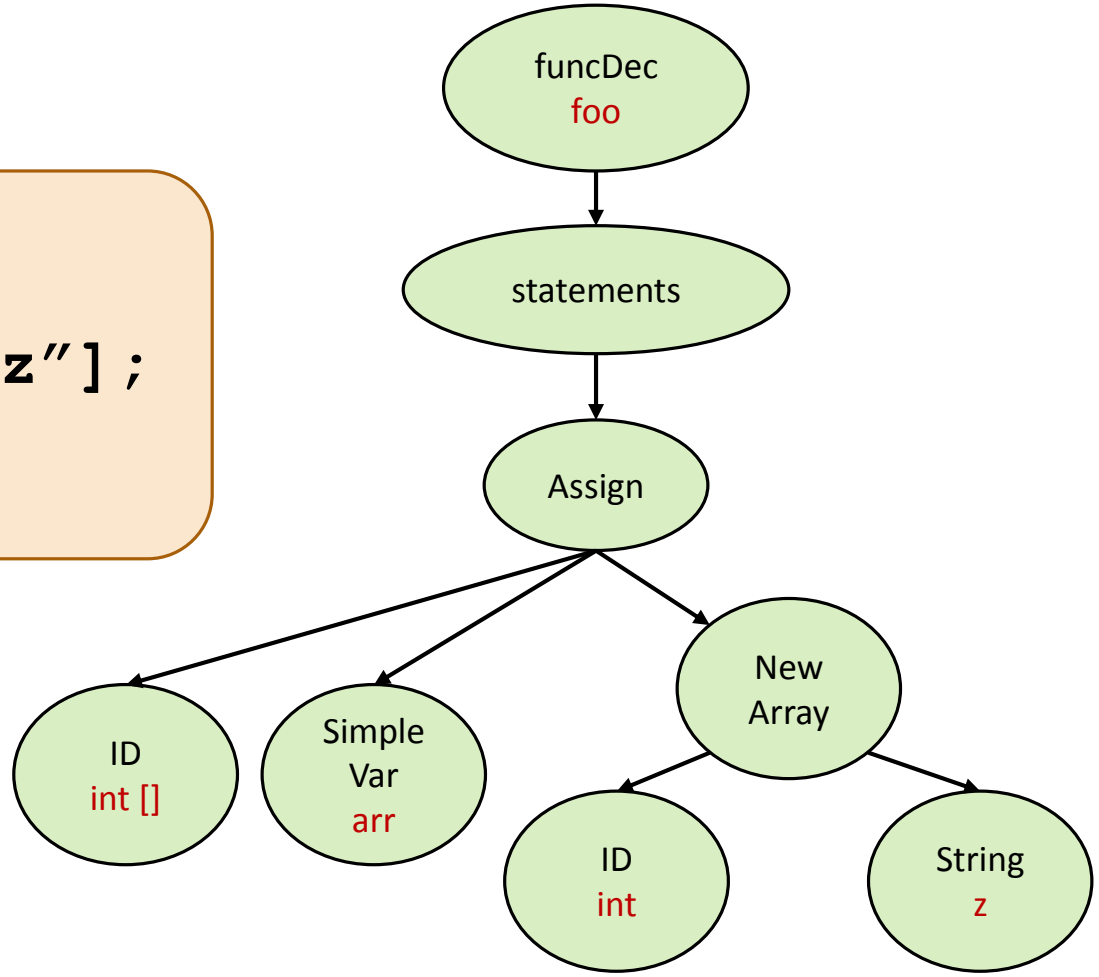
```
int main(int argc,
         string argv[]){
  main(2, argv);
  return 0;
}
```

Valid



Arrays

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



Arrays

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}
```
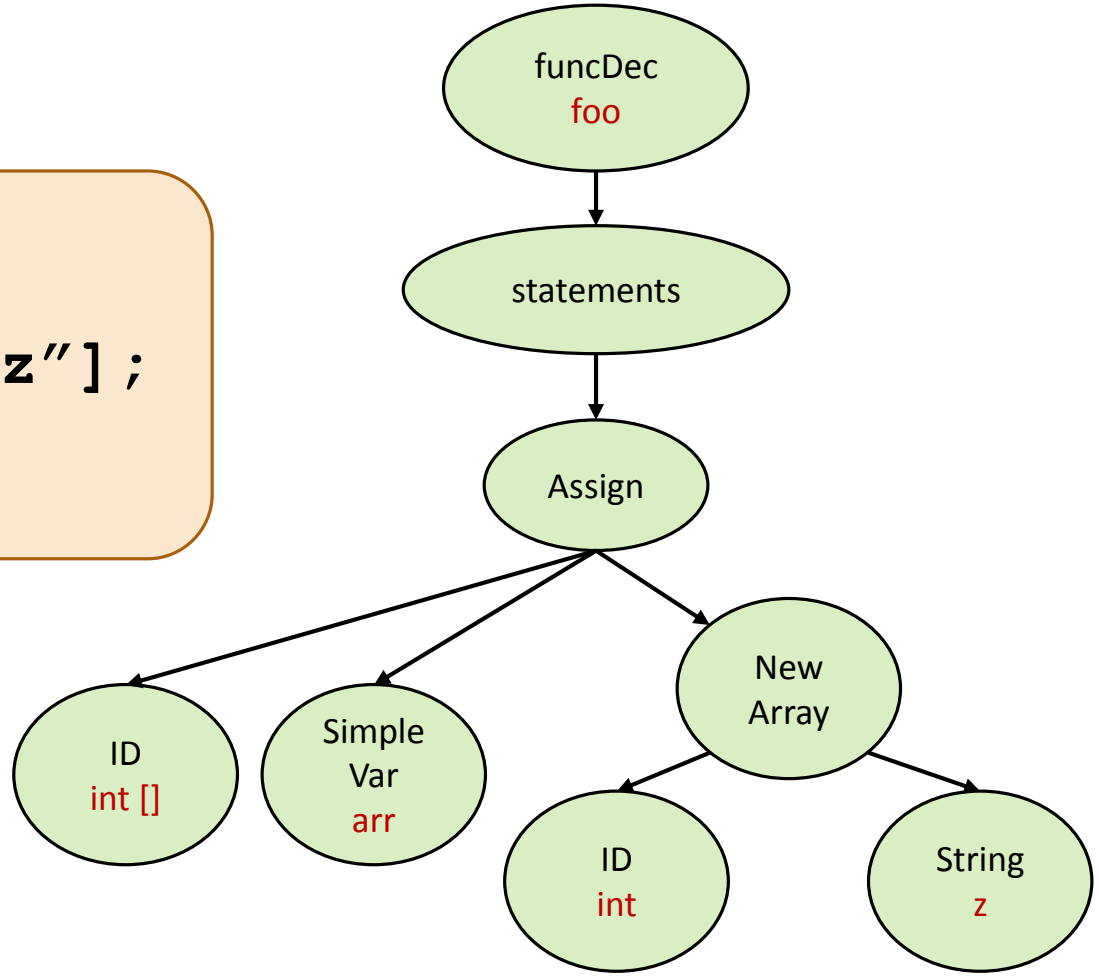
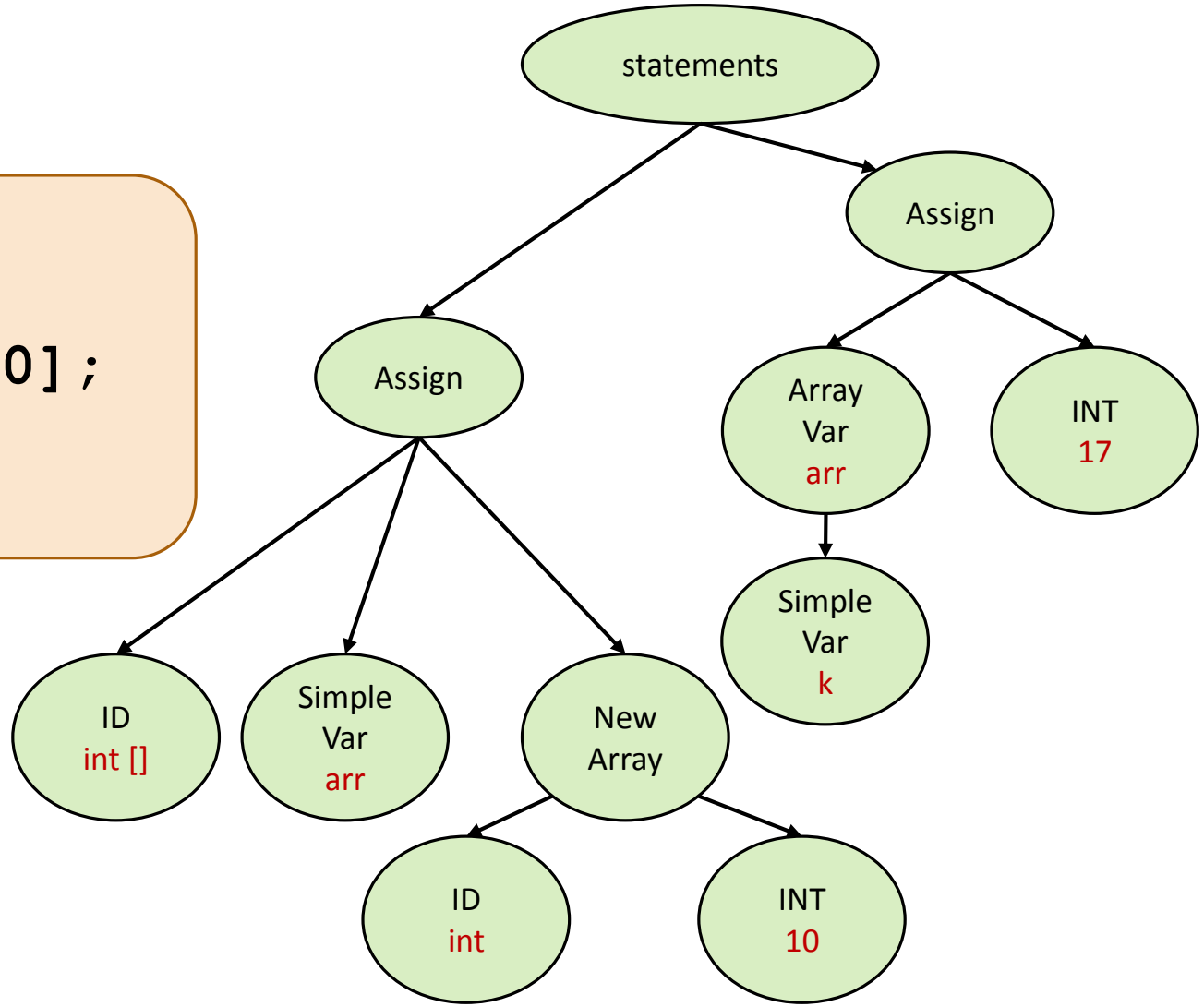

Invalid



Arrays

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



Arrays

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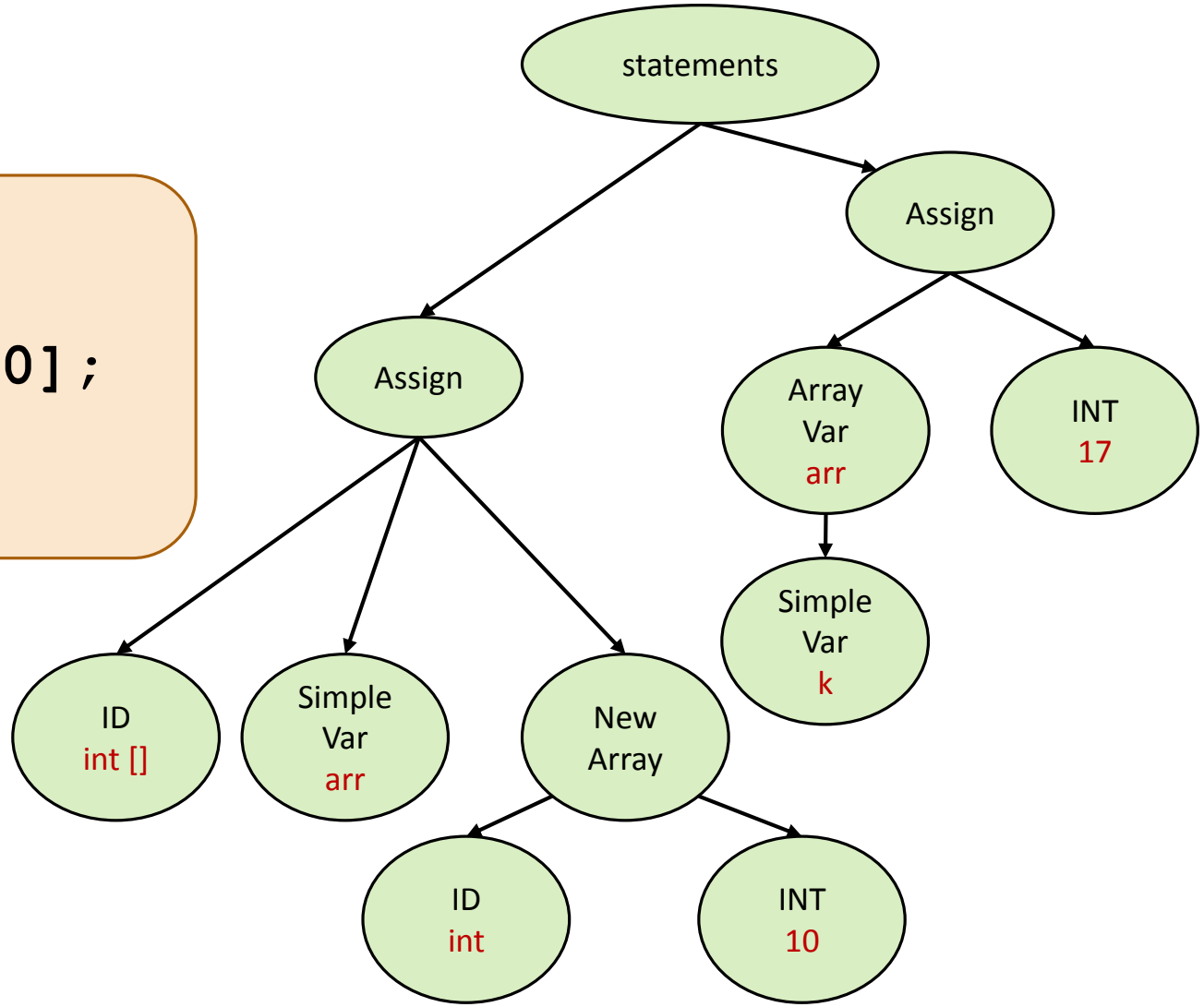
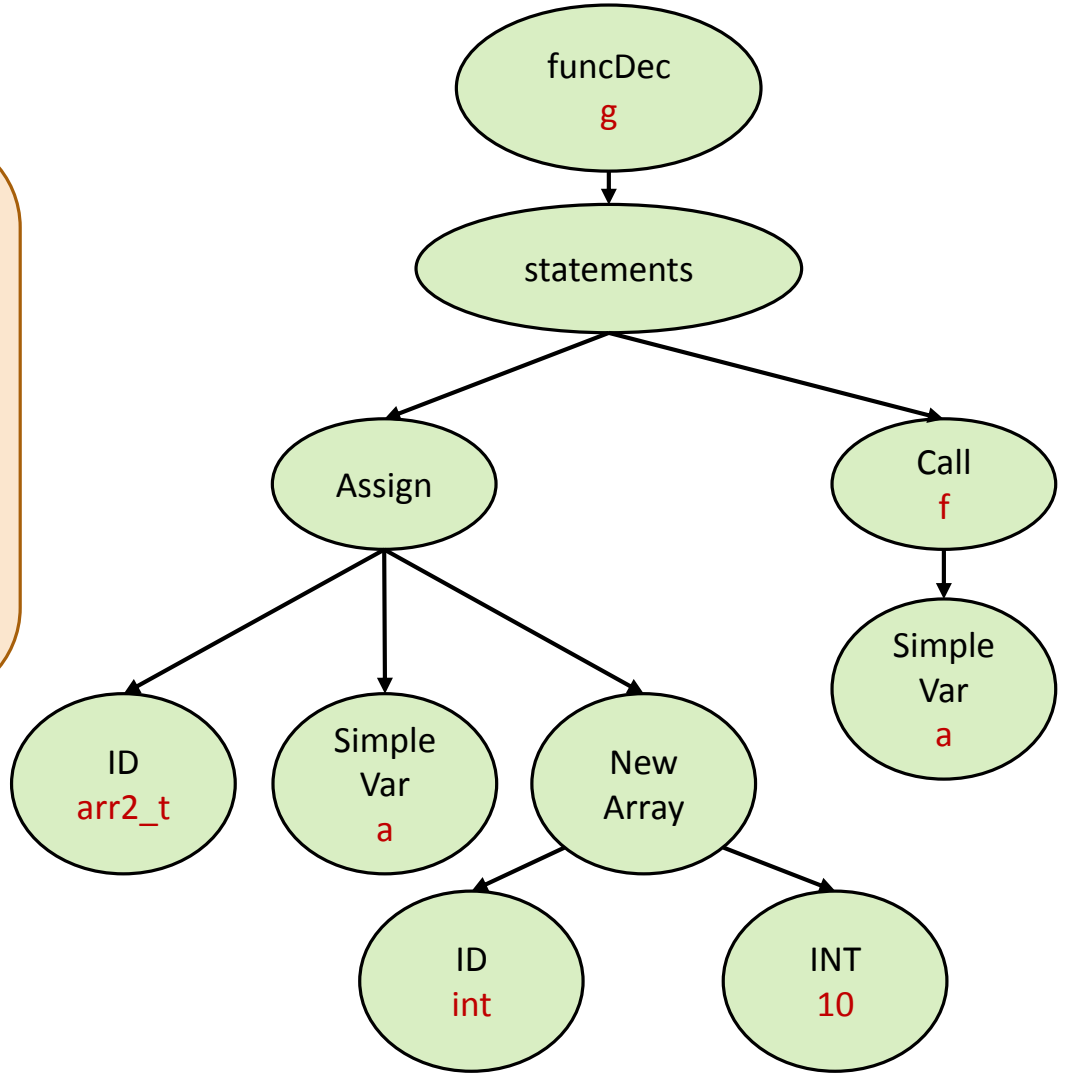
   arr[k] = 17;
}
```

Valid



Arrays

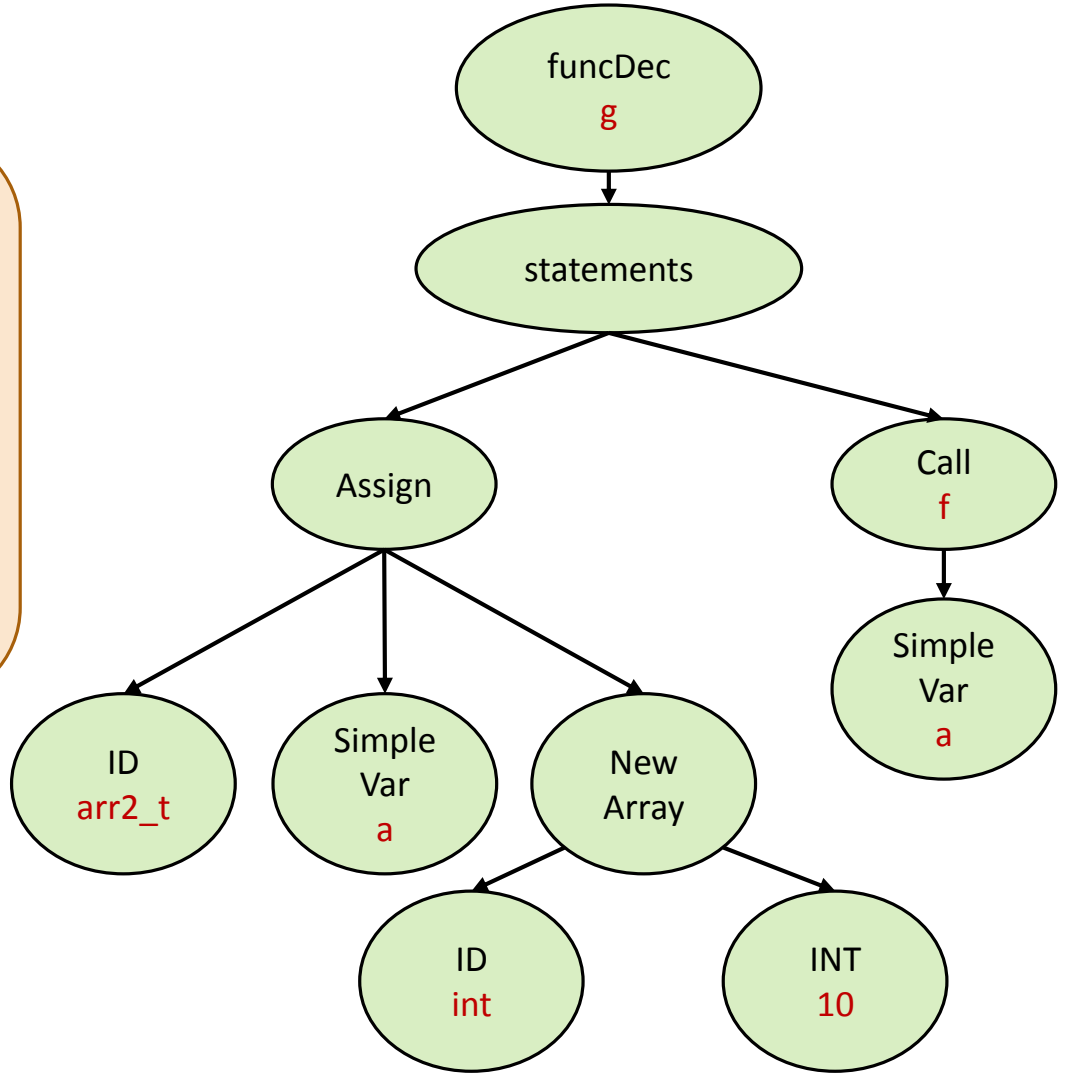
```
typedef int arr1_t[];
typedef int arr2_t[];
void f(arr1_t a) { }
void g() {
  arr2_t a = new int[10];
  f(a);
}
```



Arrays

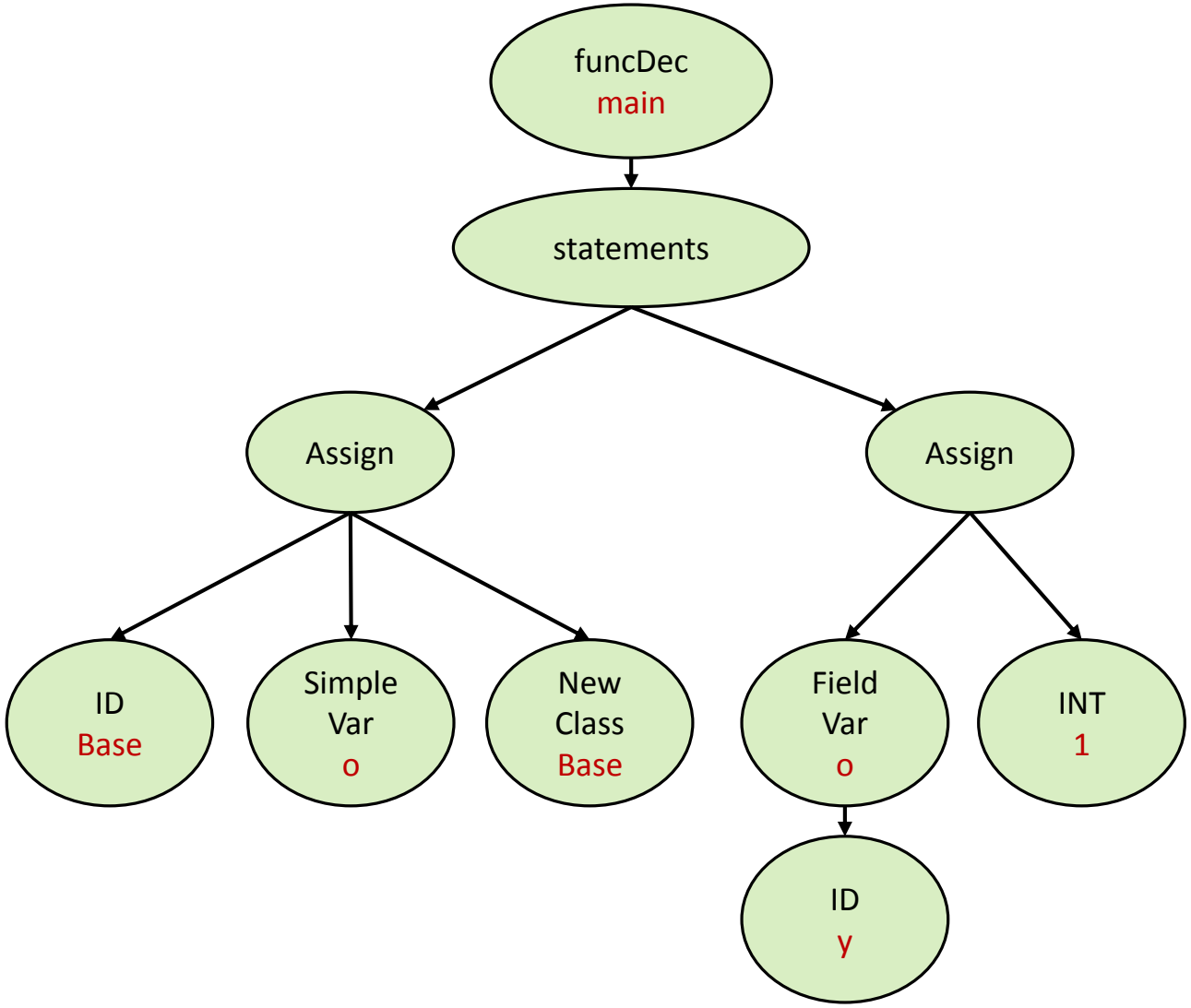
```
typedef int arr1_t[];
typedef int arr2_t[];
void f(arr1_t a) { }
void g() {
  arr2_t a = new int[10];
  f(a);
}
```

Invalid



Classes

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



Classes

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}
```
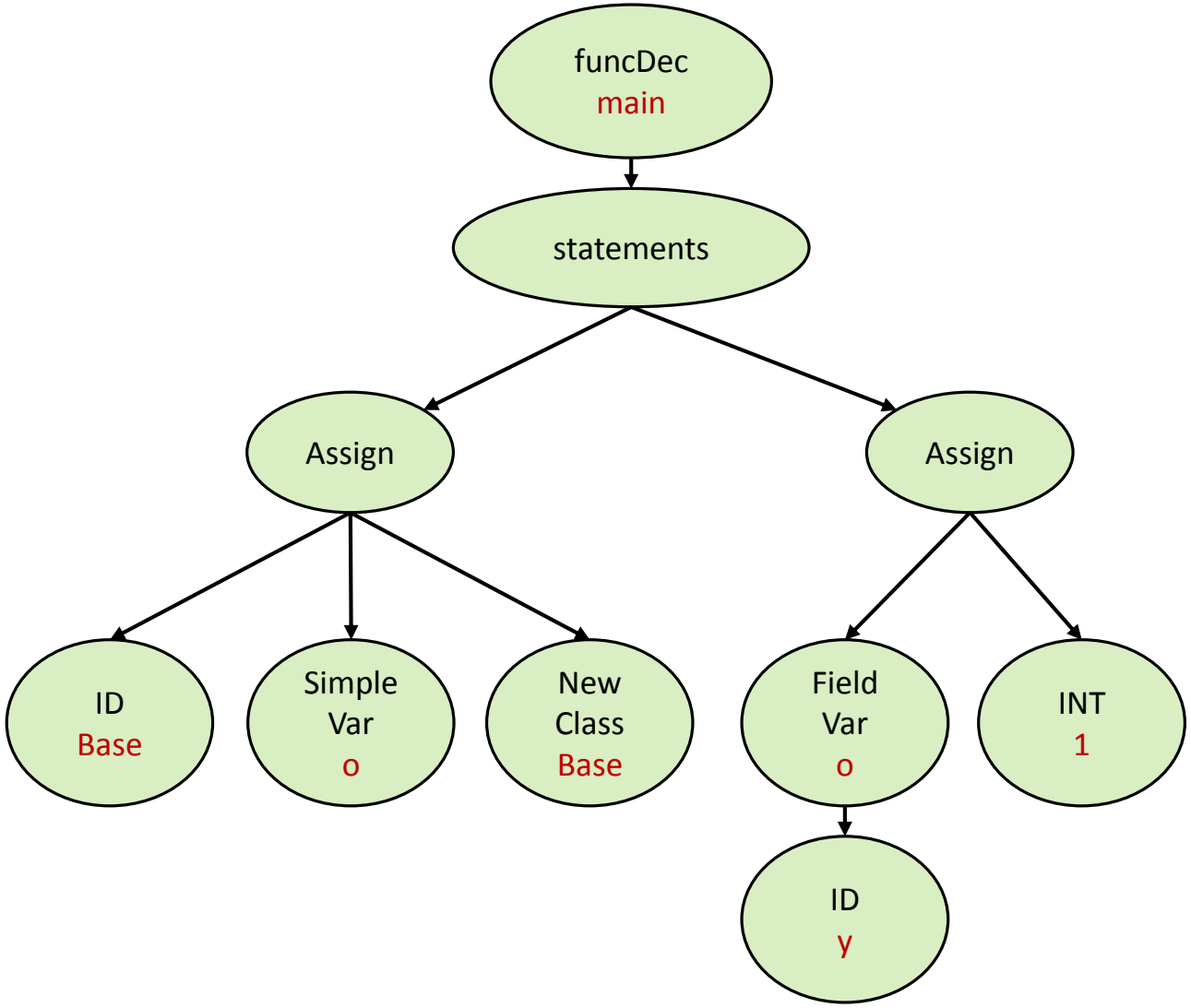
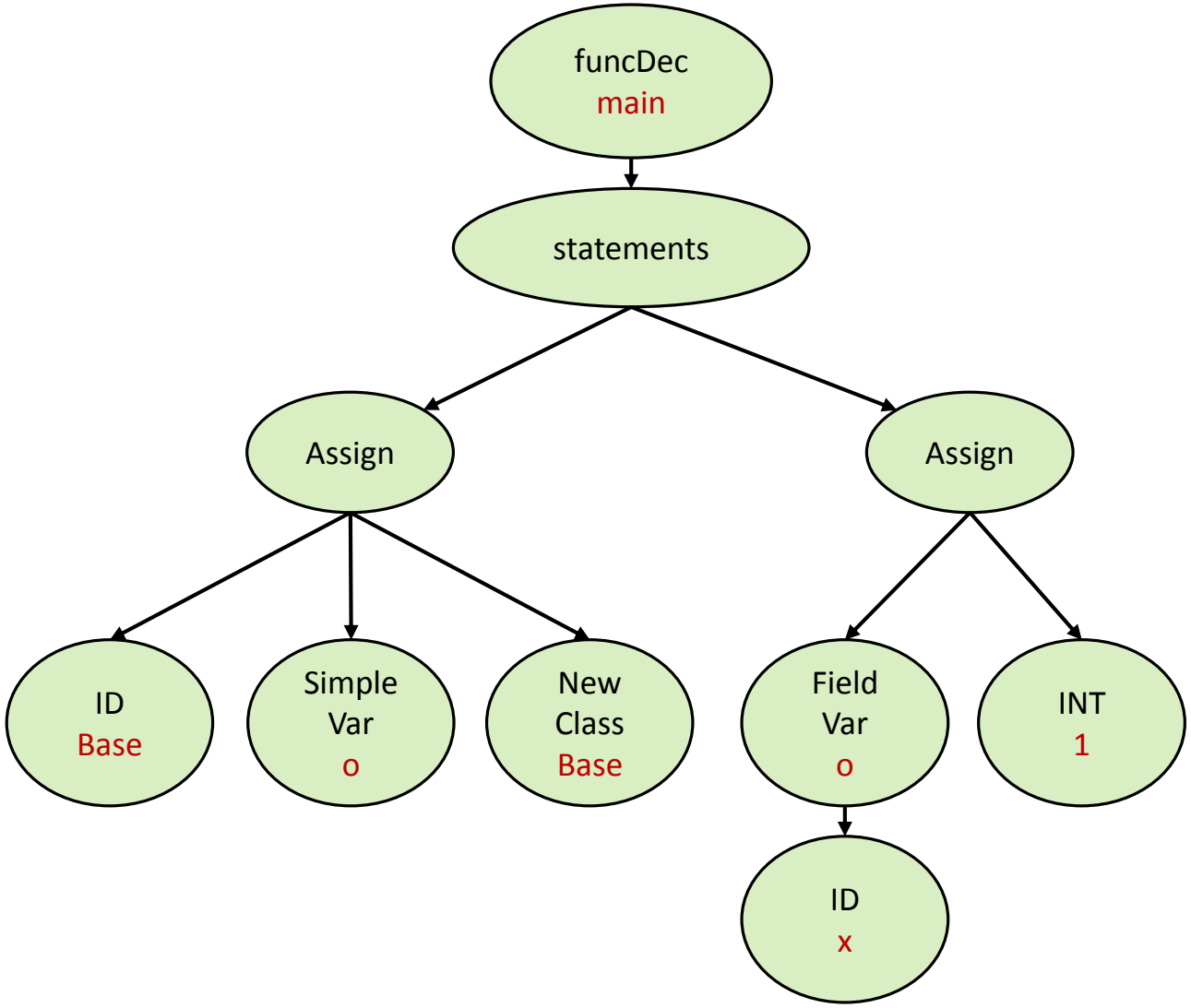

Invalid



Classes

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



Classes

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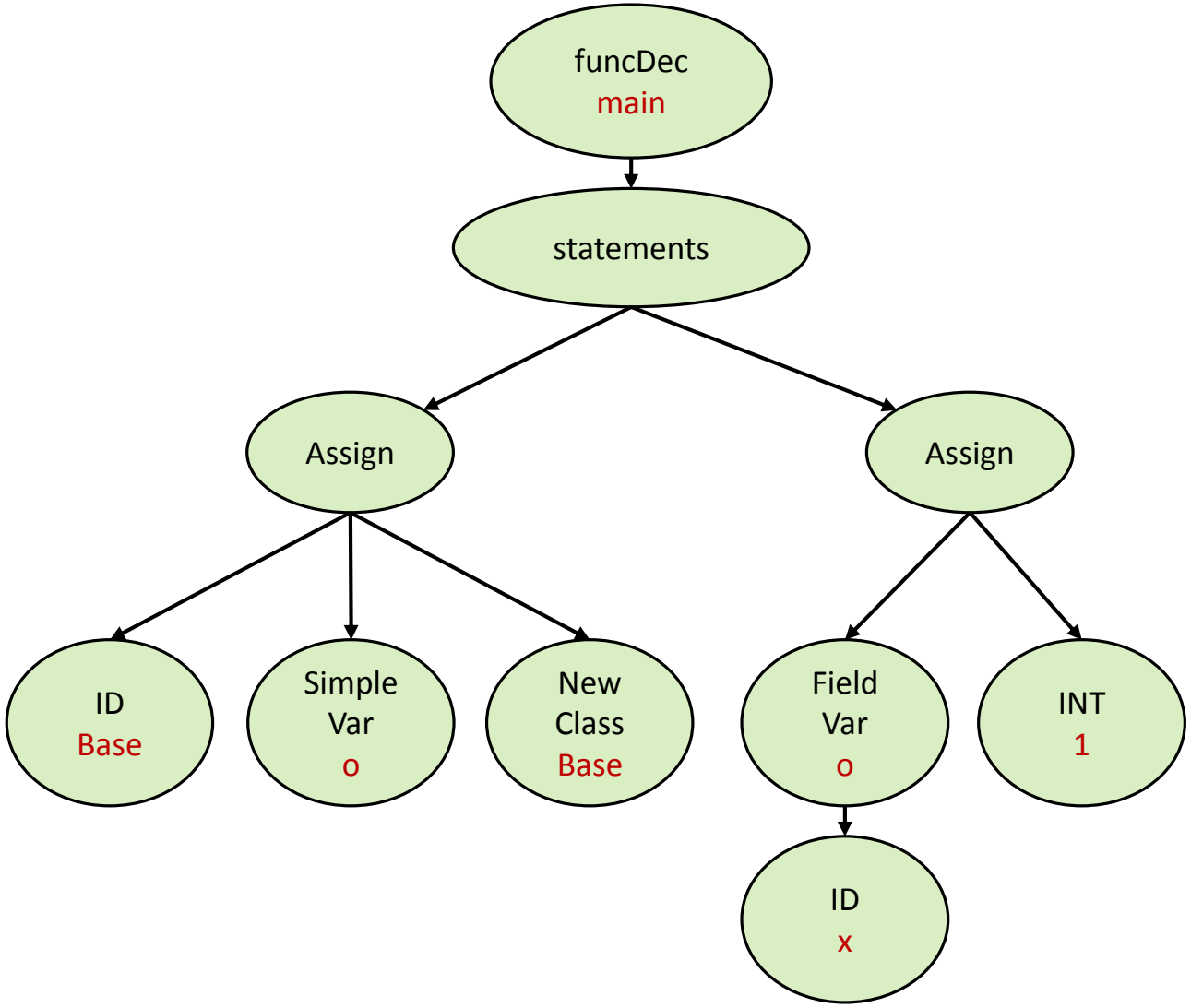
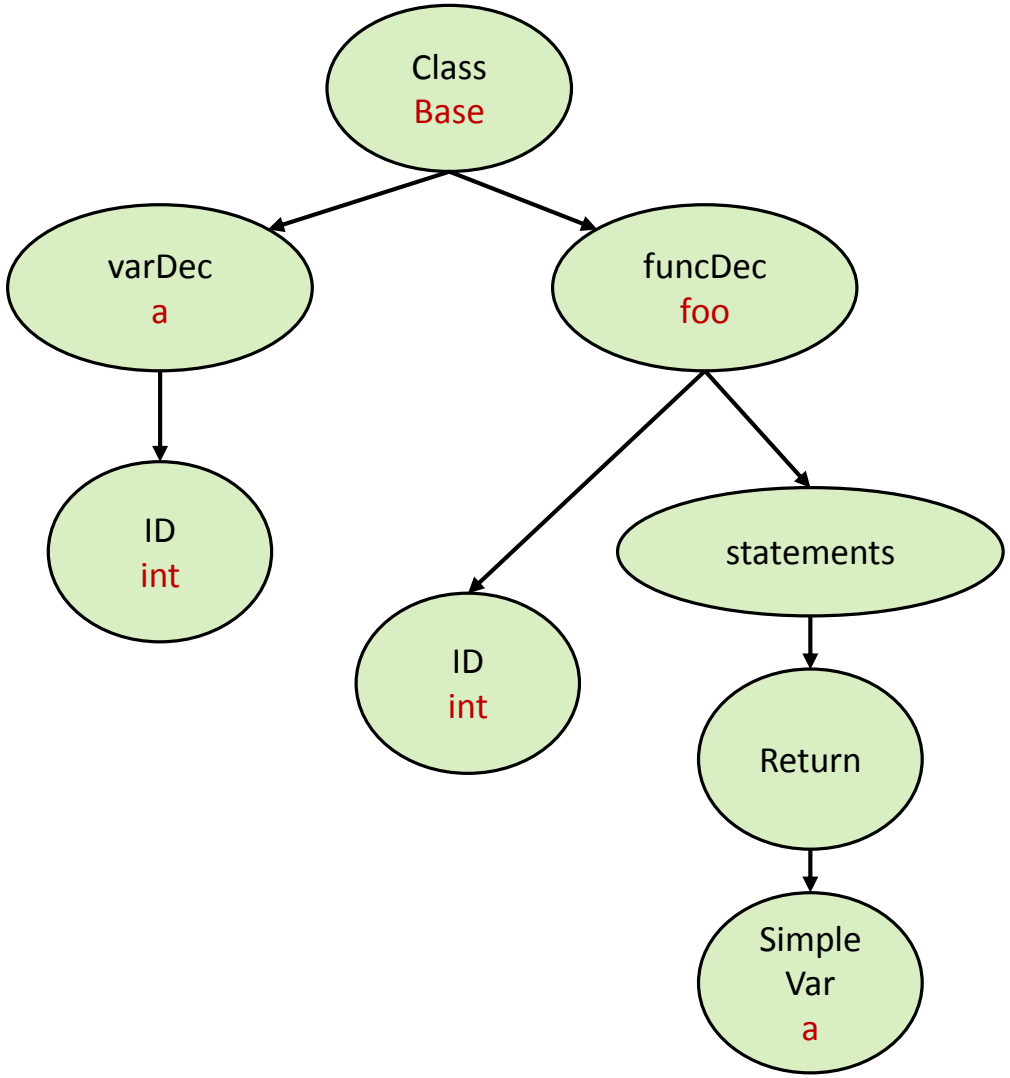
  int x;
}
void main() {
  Base o = new Base;
  o.x = 1;
}
```

Valid



Classes

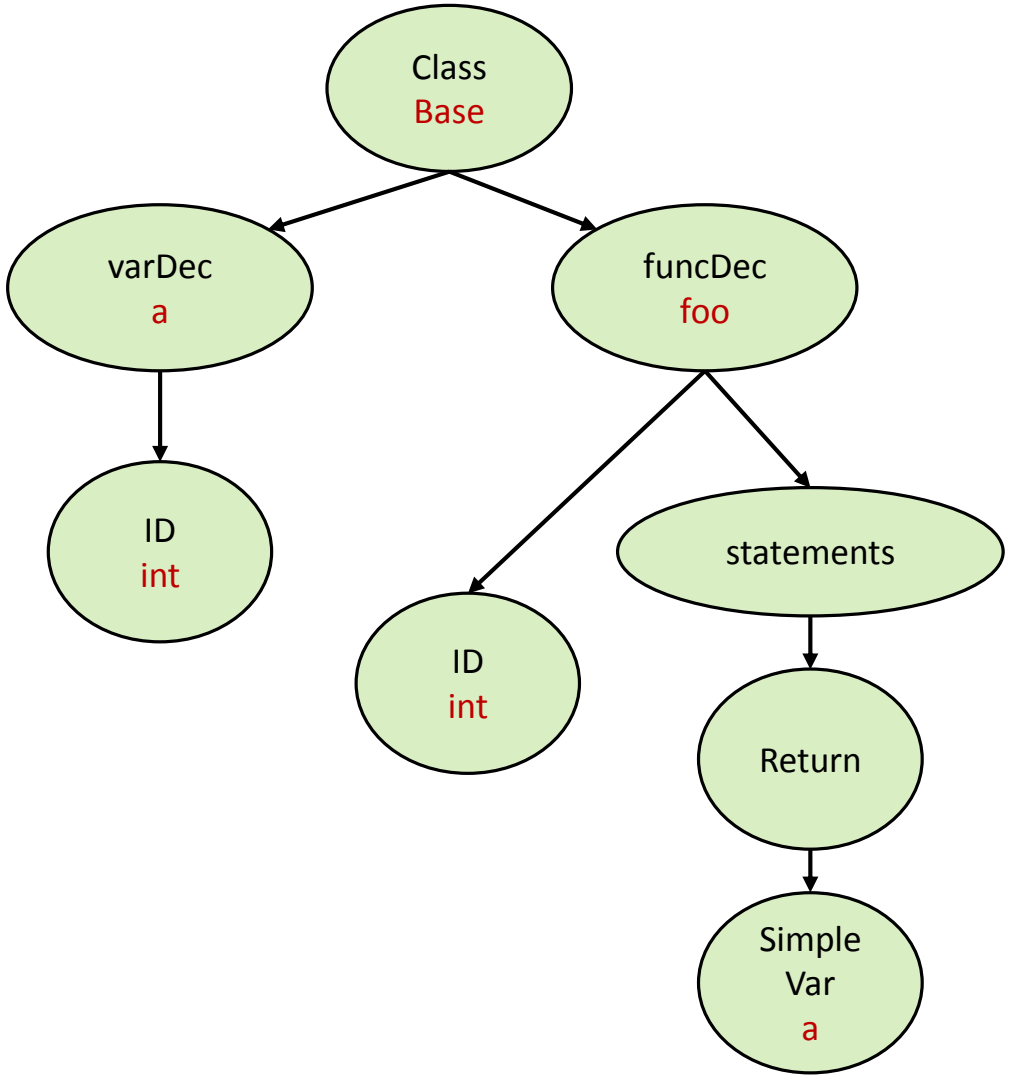
```
class Base {
   int a;
   int foo() {
      return a;
   }
}
```



Classes

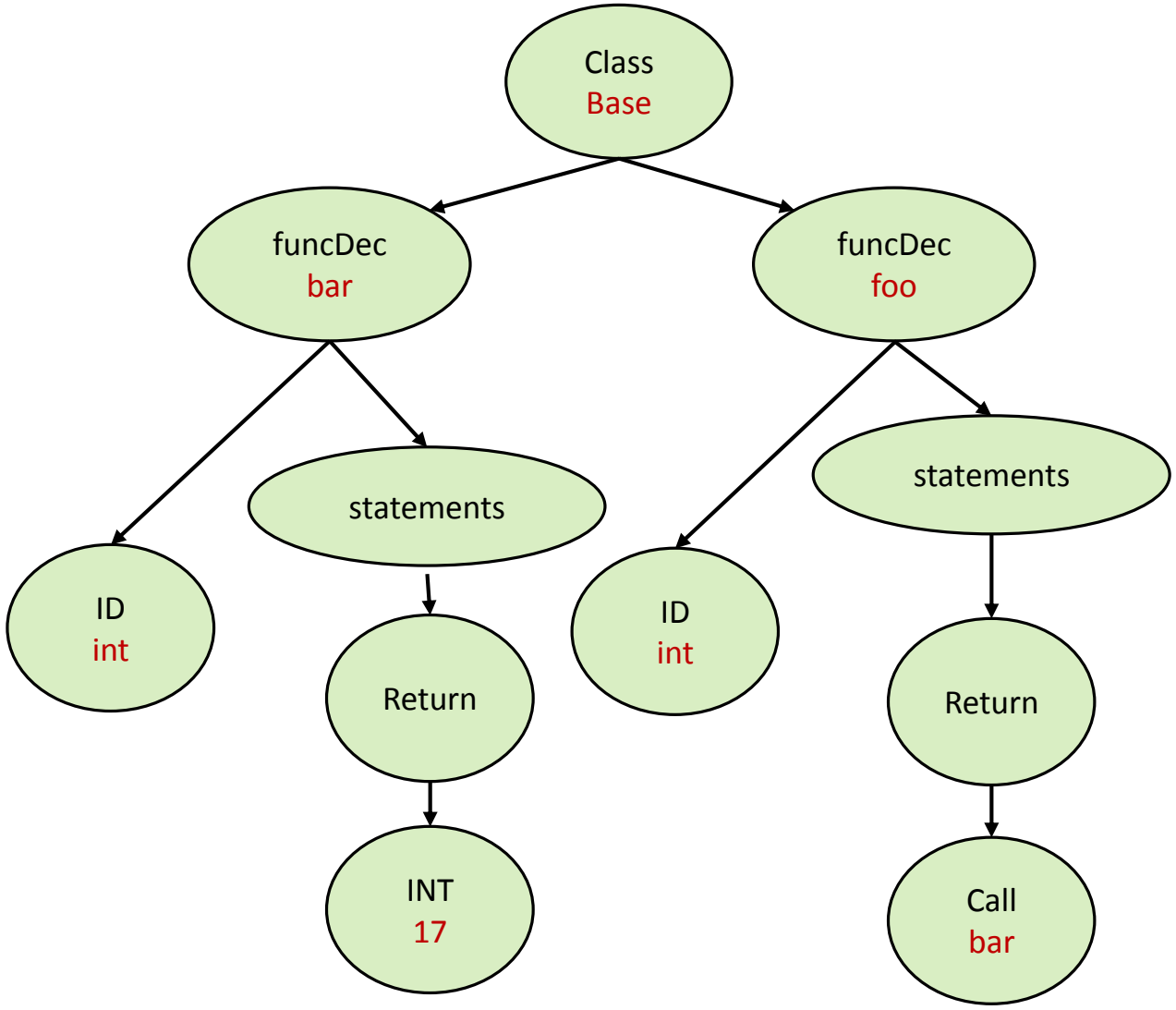
```
class Base {
   int a;
   int foo() {
      return a;
   }
}
```

Valid



Classes

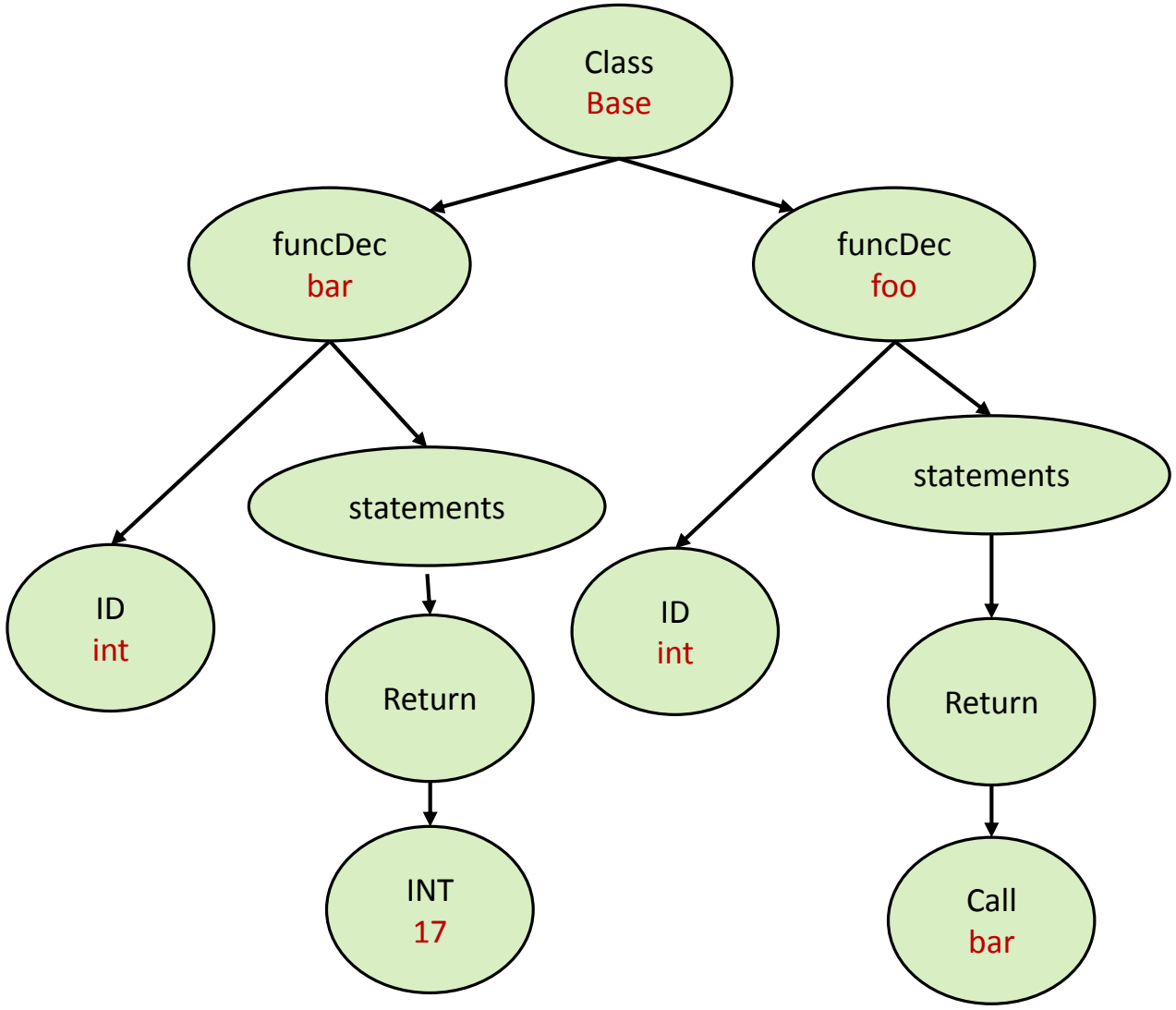
```
class Base {
  int bar() {
    return 17;
  }
  int foo() {
    return bar();
  }
}
```



Classes

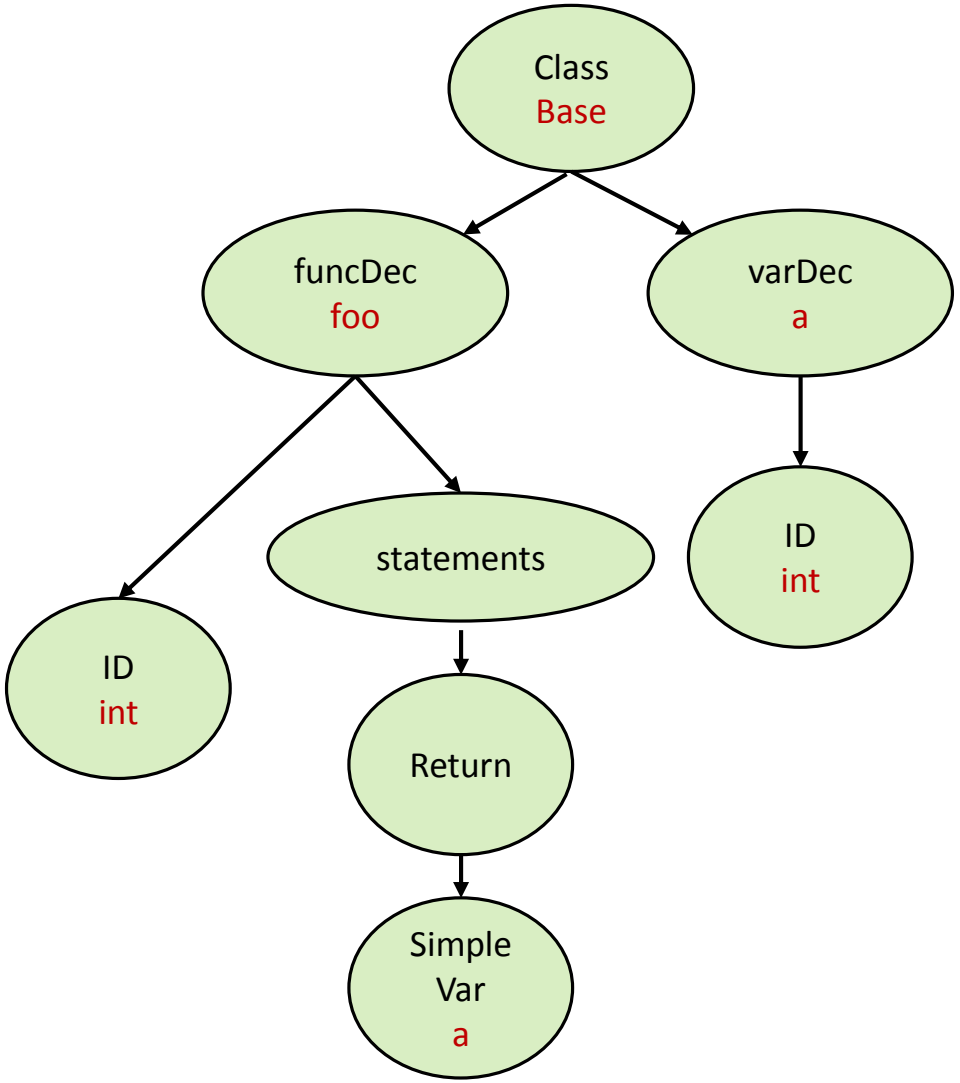
```
class Base {
   int bar() {
      return 17;
   }
   int foo() {
      return bar();
   }
}
```

Valid



Classes

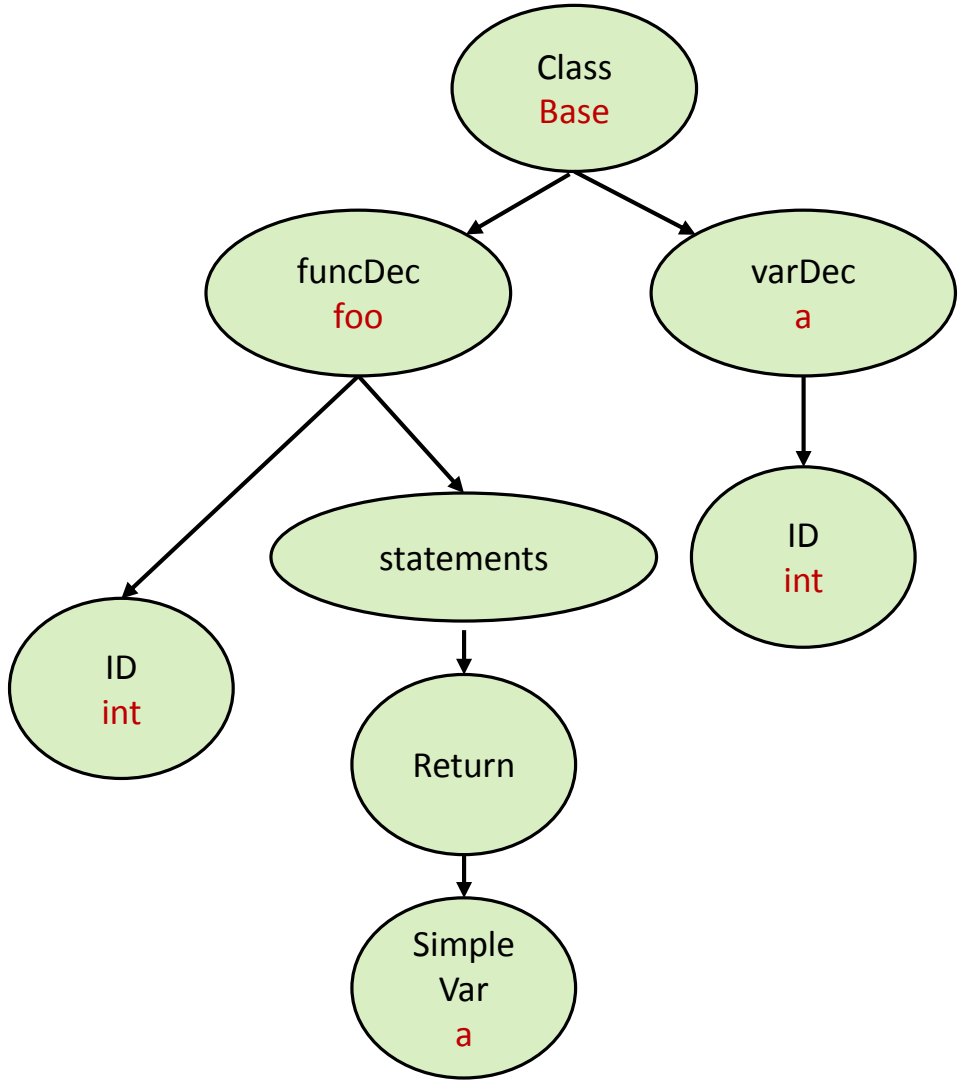
```
class Base {
  int foo() {
    return a;
  }
  int a;
}
```



Classes

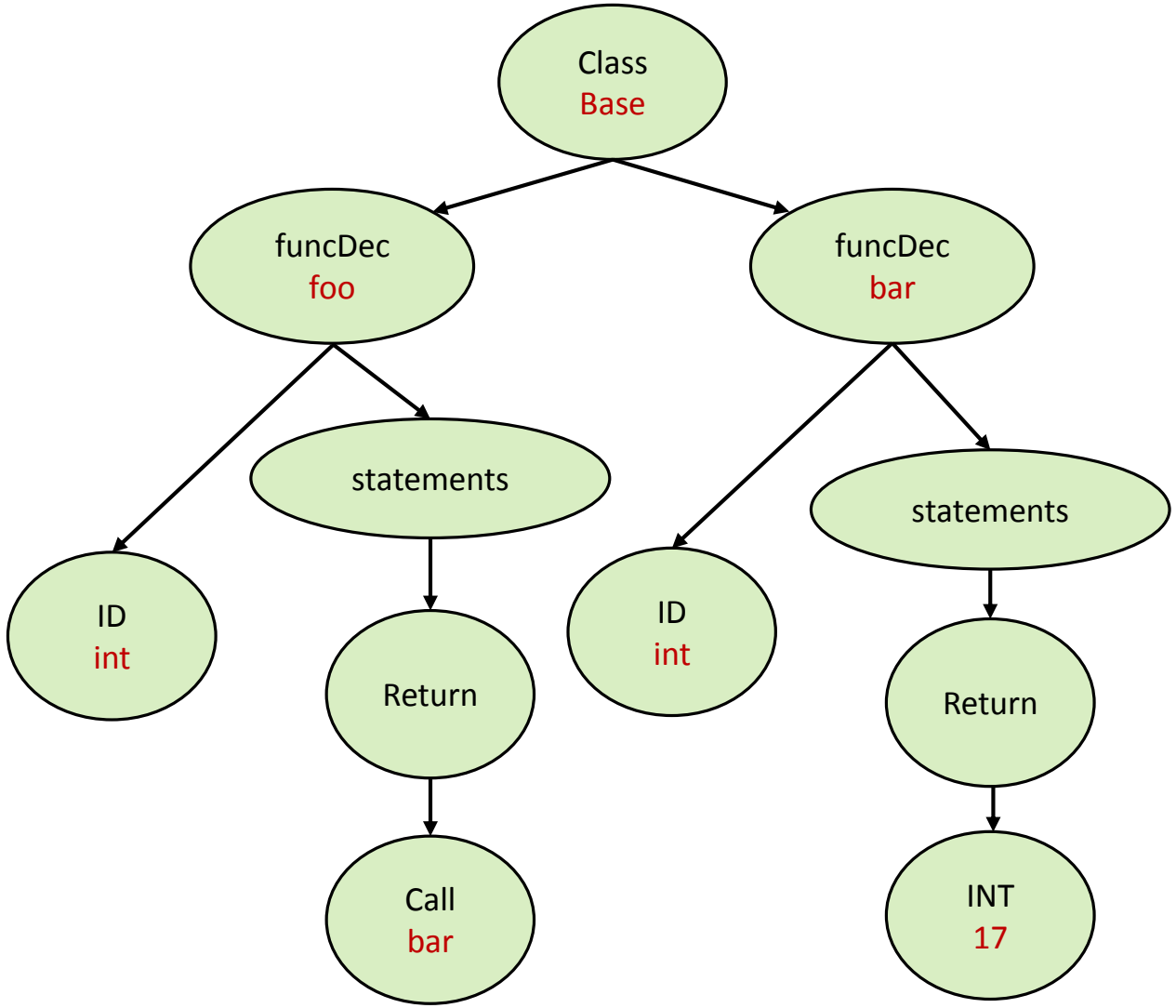
```
class Base {
   int foo() {
      return a;
   }
   int a;
}
```

Invalid



Classes

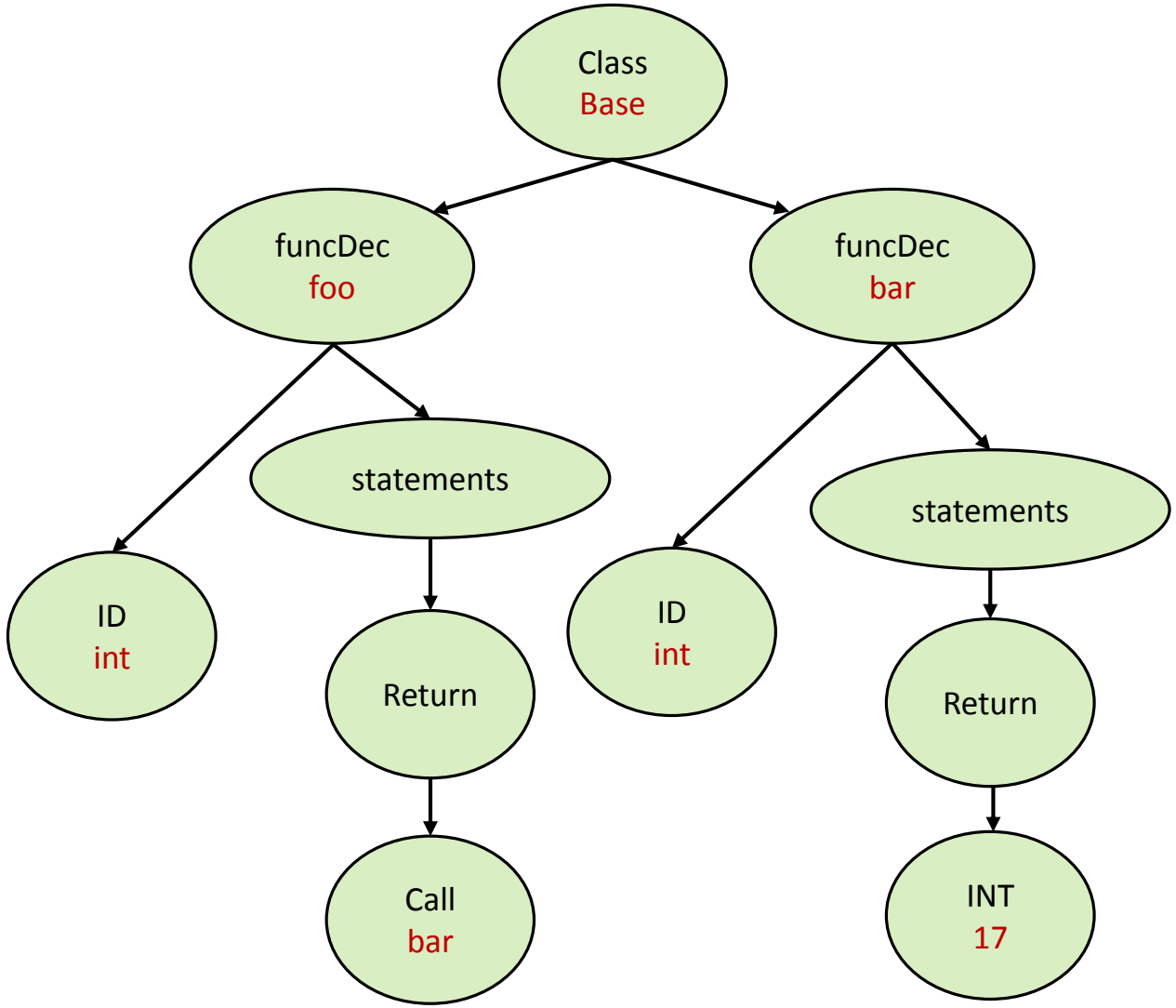
```
class Base {
  int foo() {
    return bar();
  }
  int bar() {
    return 17;
  }
}
```



Classes

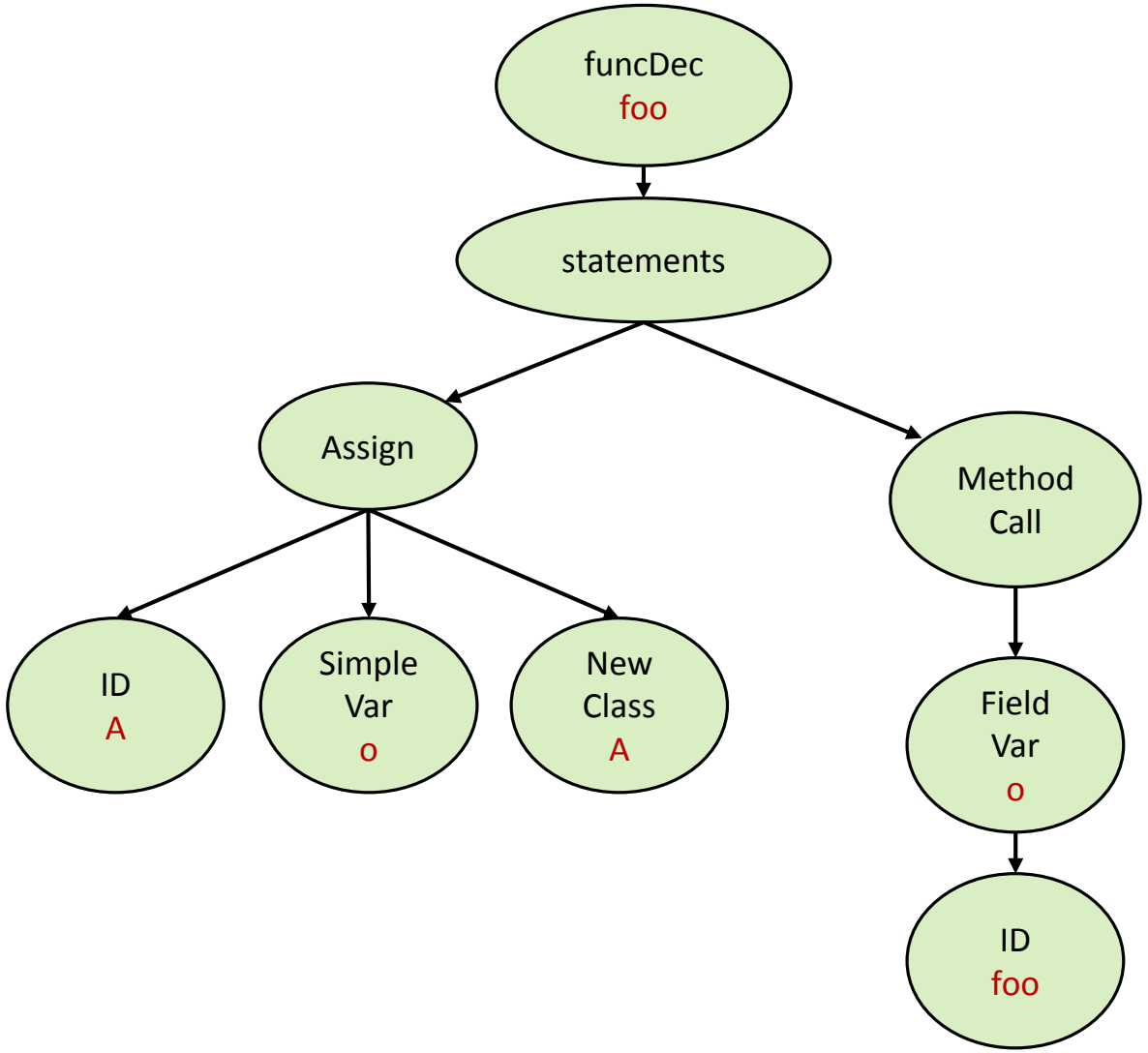
```
class Base {
   int foo() {
      return bar();
   }
   int bar() {
      return 17;
   }
}
```

Invalid



Classes

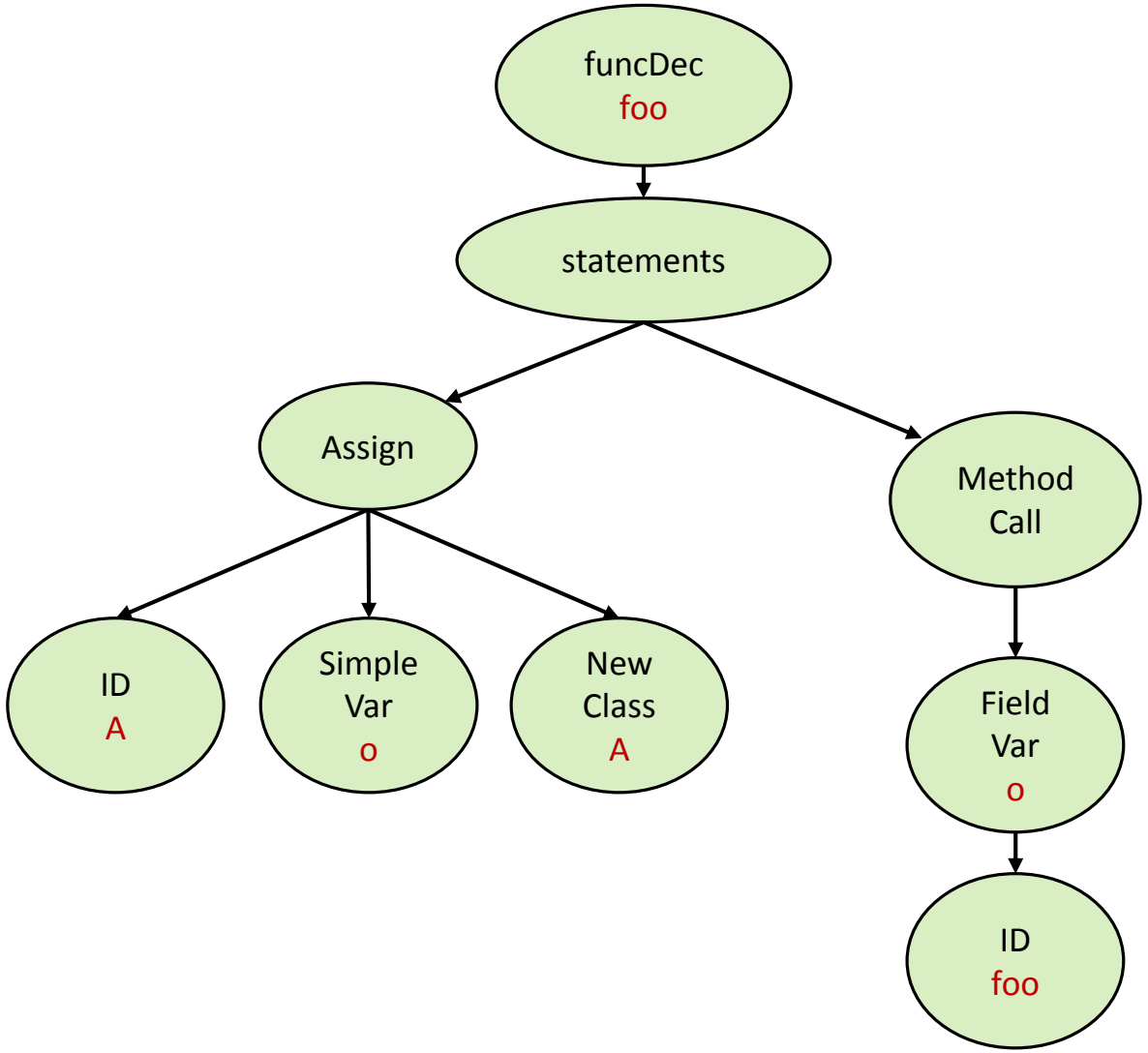
```
class A {
  void foo() {
    A o = new A;
    o.foo();
  }
}
```



Classes

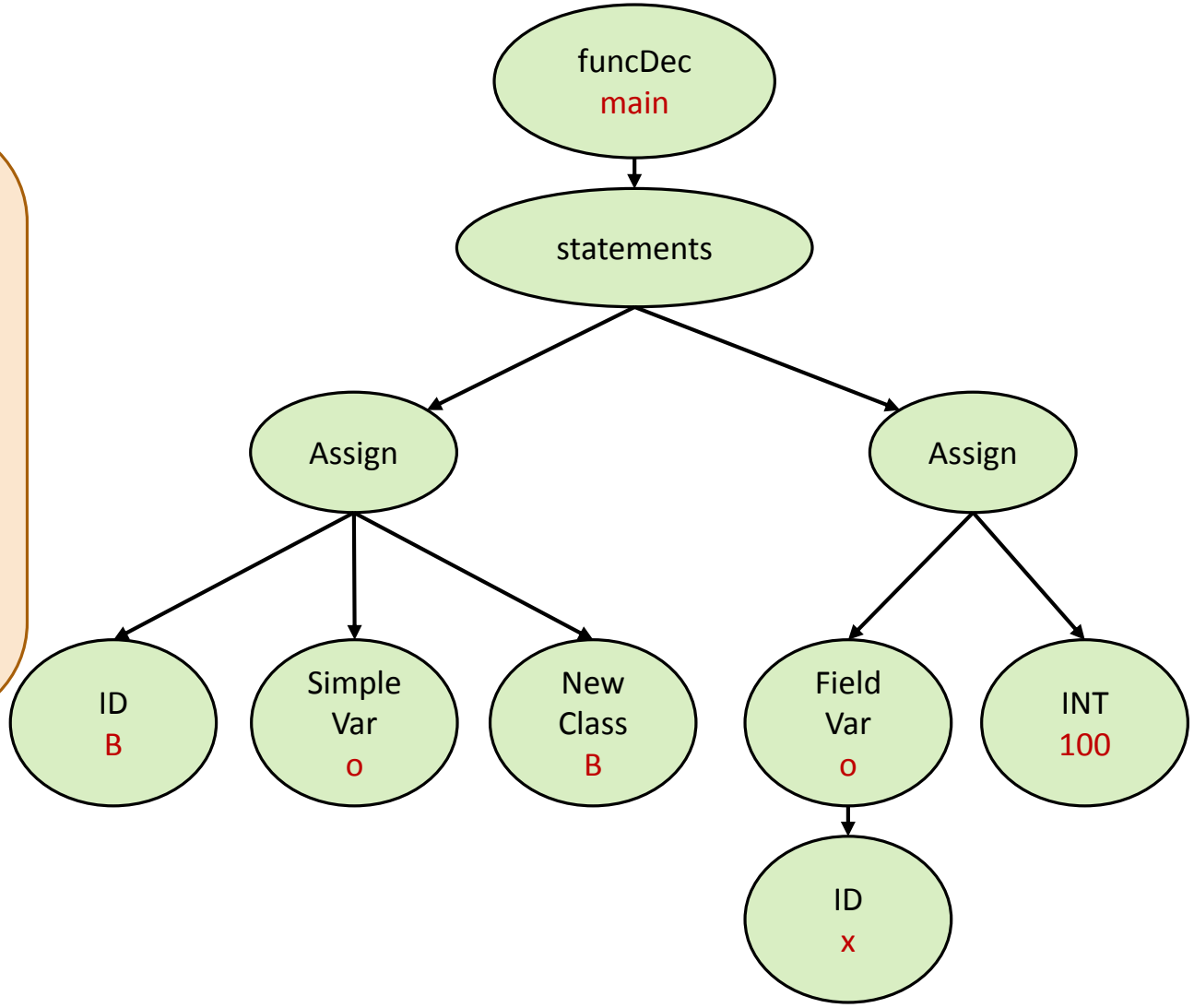
```
class A {
  void foo() {
    A o = new A;
    o.foo();
  }
}
```

Valid



Inheritance

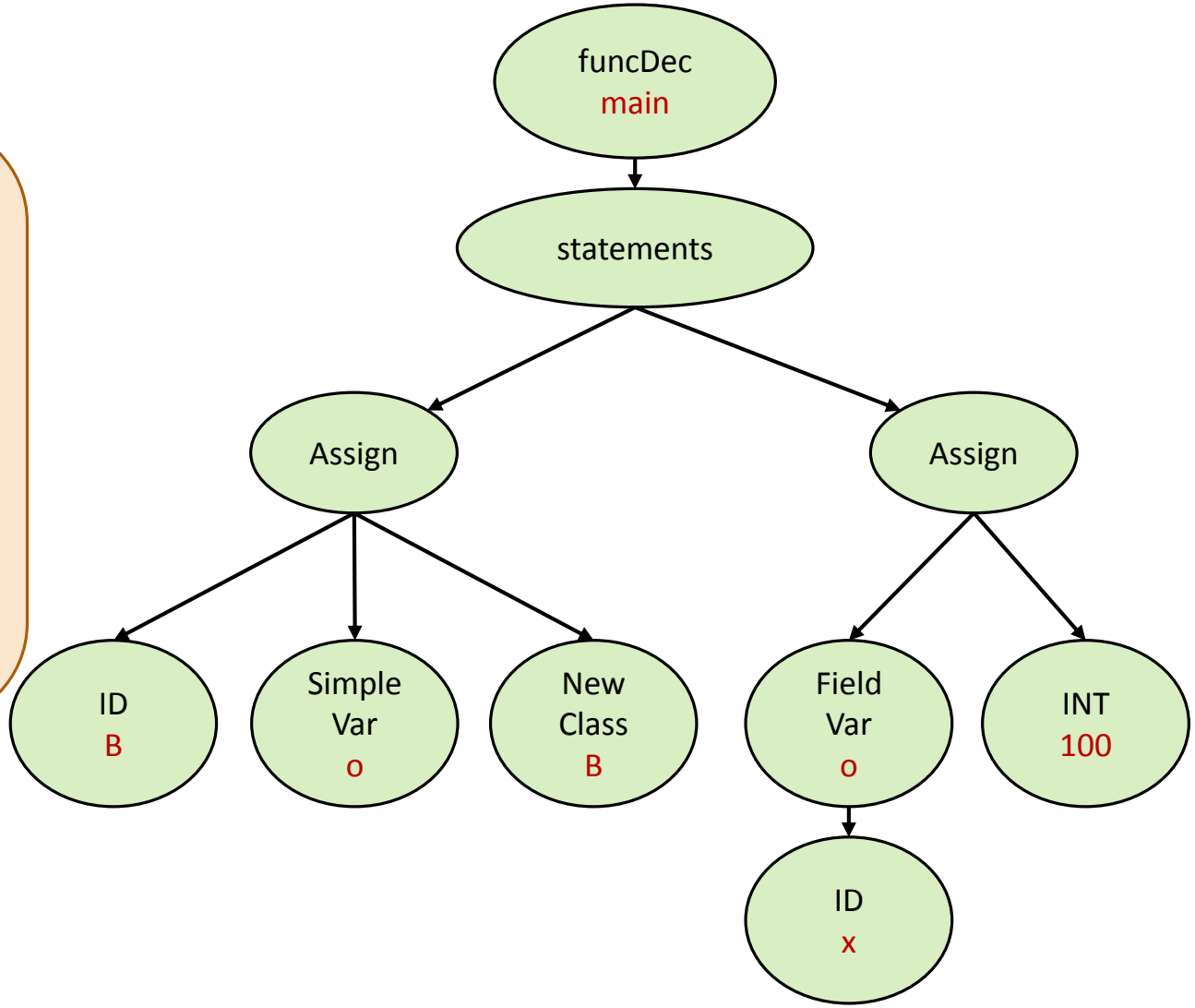
```
class A {
   int x;
}
class B extends A { }
void main() {
   B o = new B;
   o.x = 100;
}
```



Inheritance

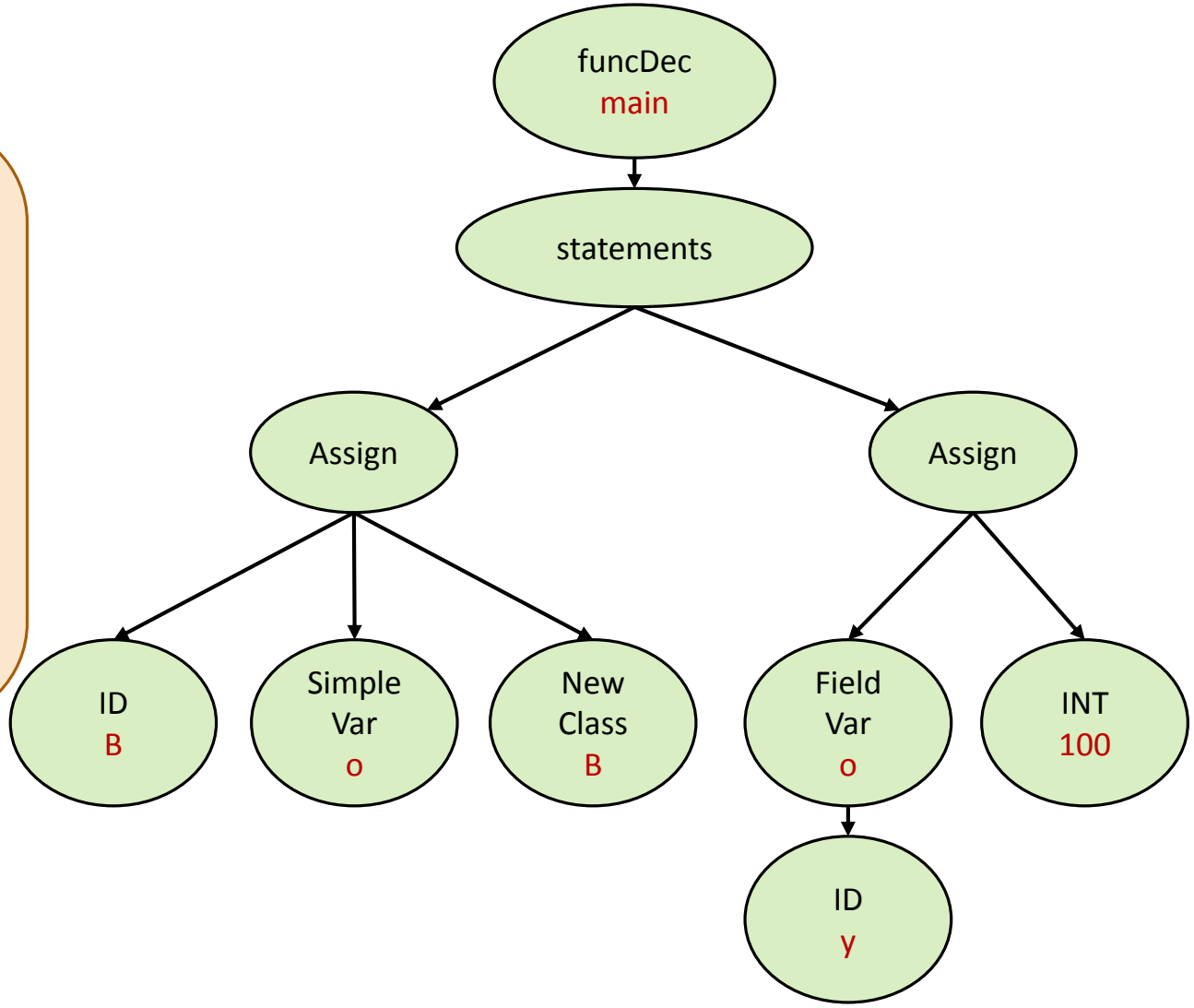
```
class A {
   int x;
}
class B extends A { }
void main() {
   B o = new B;
   o.x = 100;
}
```

Valid



Inheritance

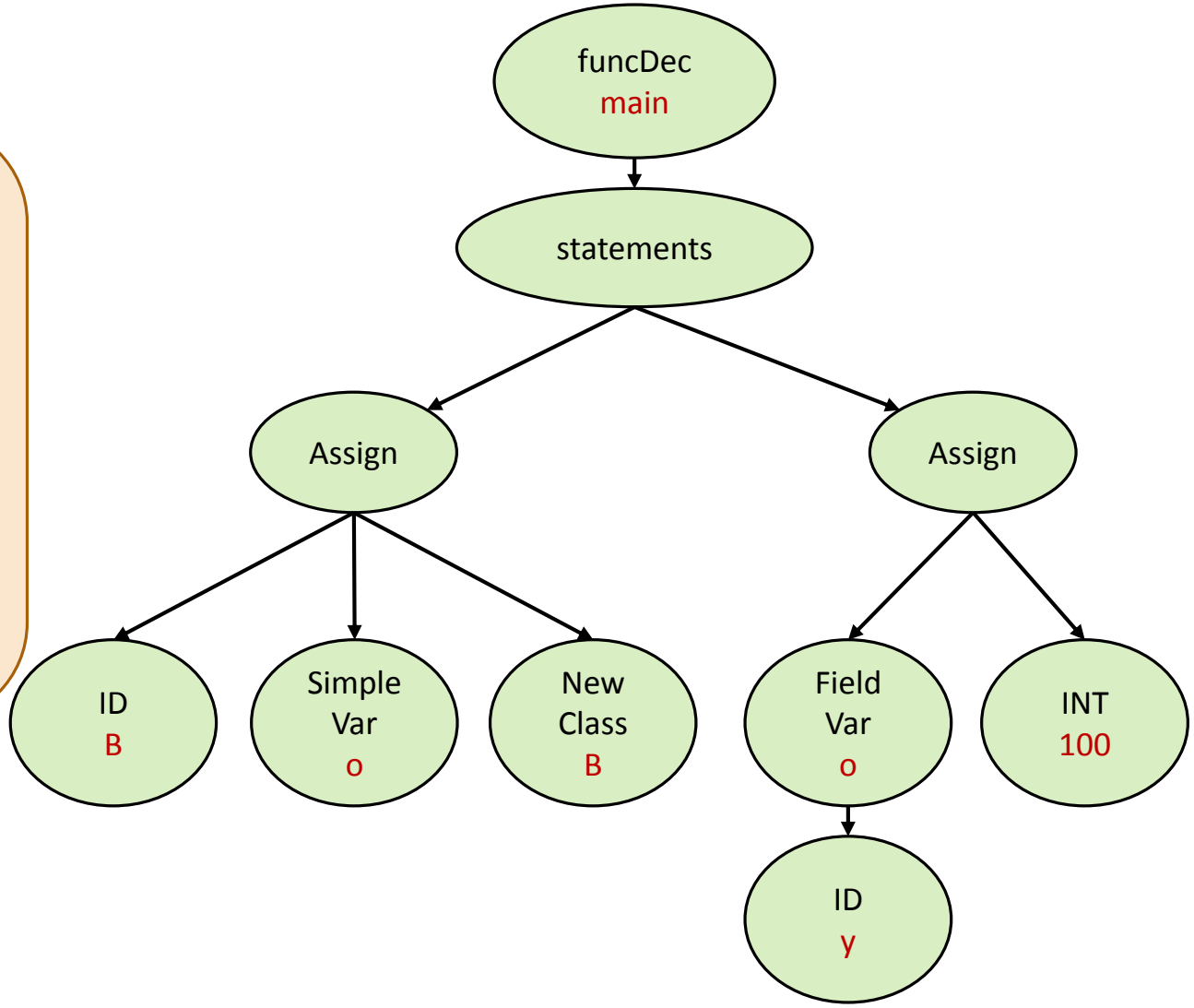
```
class A {
   int x;
}
class B extends A { }
void main() {
   B o = new B;
   o.y = 100;
}
```



Inheritance

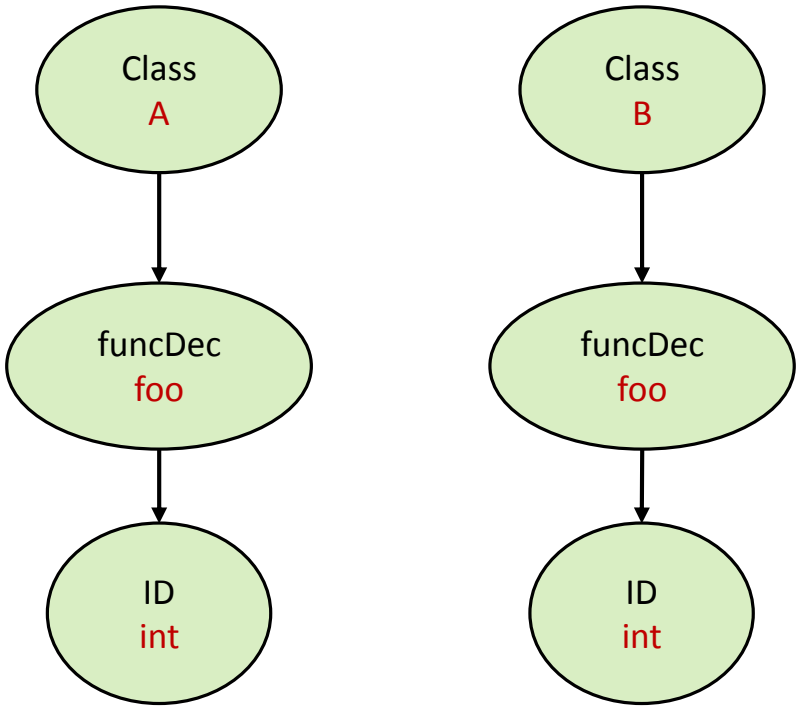
```
class A {
   int x;
}
class B extends A { }
void main() {
   B o = new B;
   o.y = 100;
}
```

Invalid



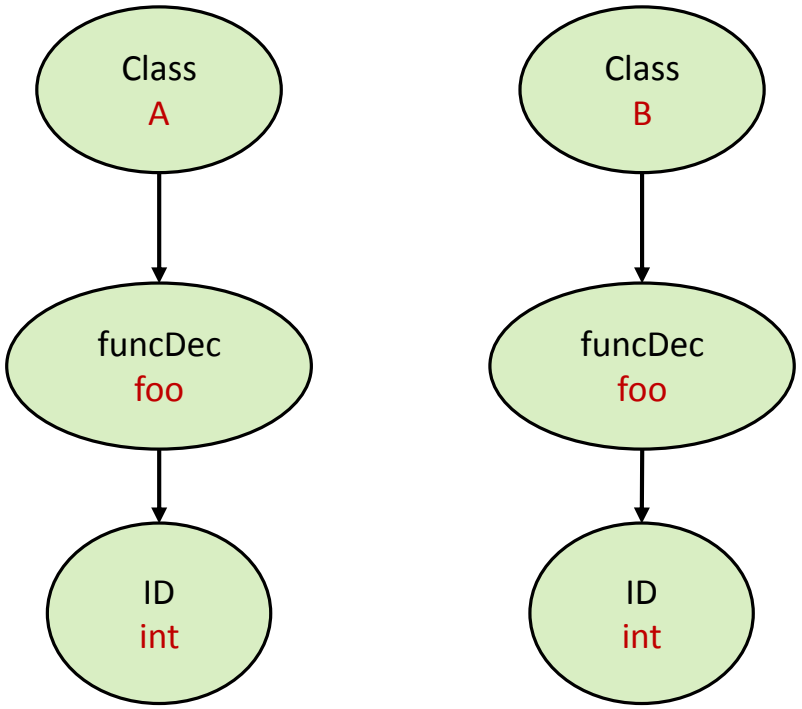
Inheritance

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



Inheritance

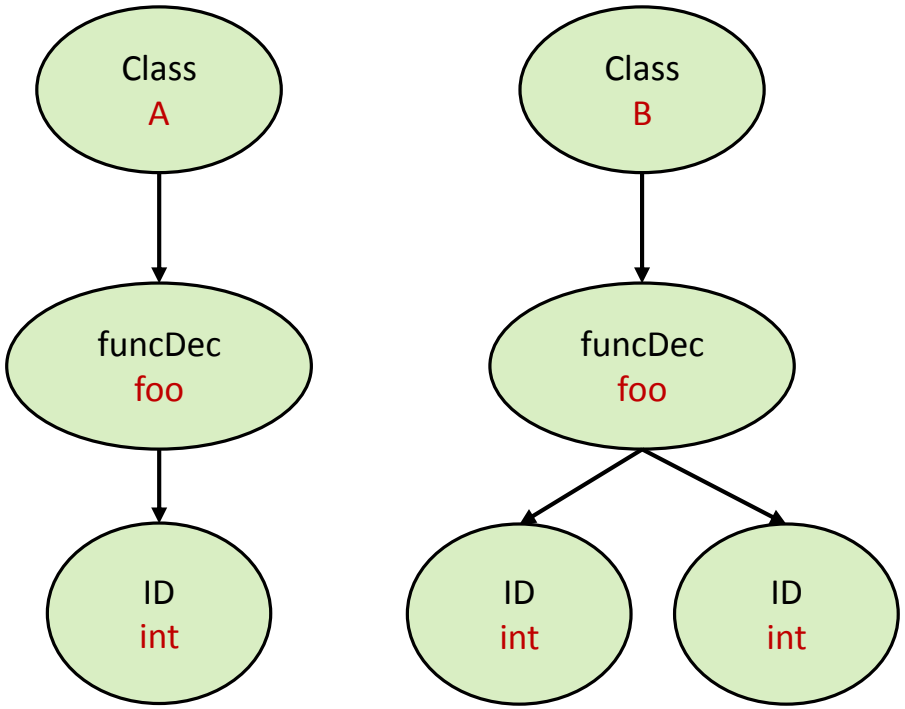
```
class A {
   int foo() {
      return 17;
   }
}
class B extends A {
   int foo() {
      return 18;
   }
}
```



Valid

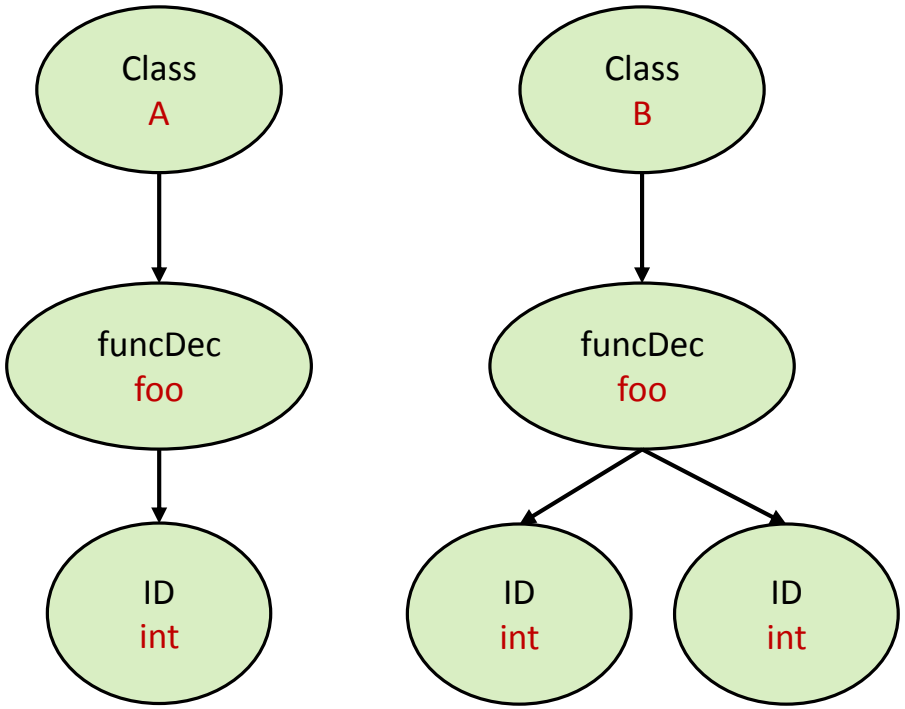
Inheritance

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



Inheritance

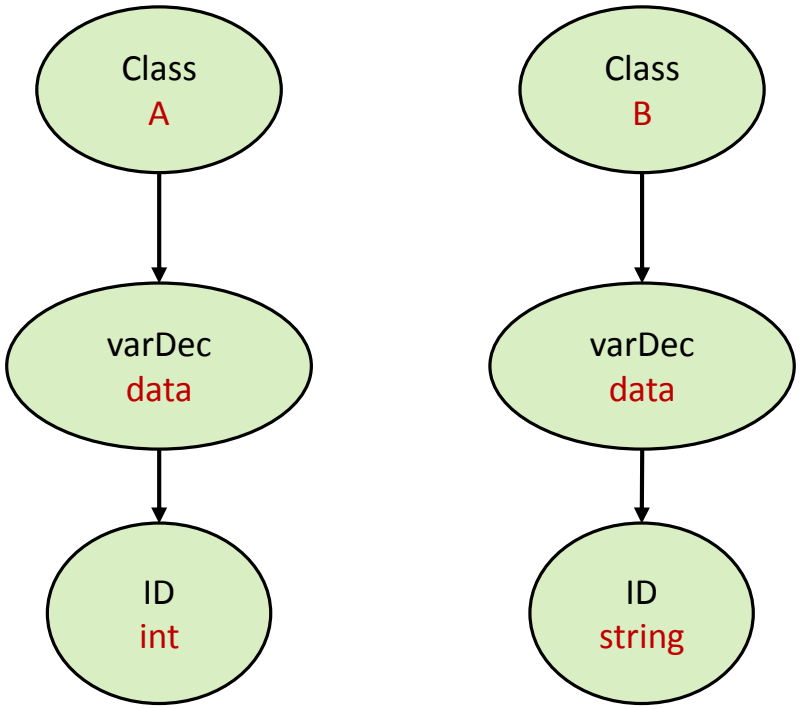
```
class A {
   int foo() {
      return 17;
   }
}
class B extends A {
   int foo(int x) {
      return x + 1;
   }
}
```



Invalid

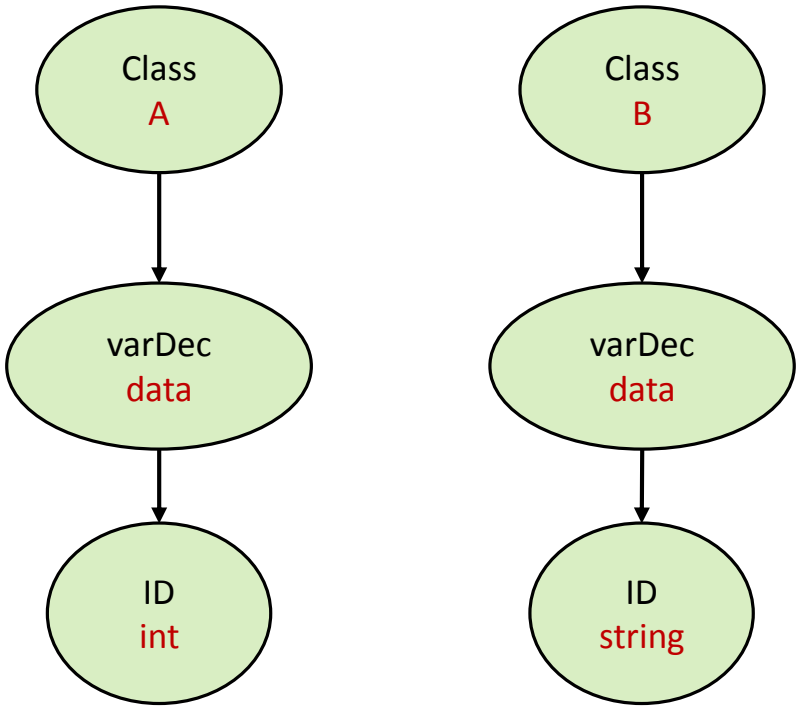
Inheritance

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



Inheritance

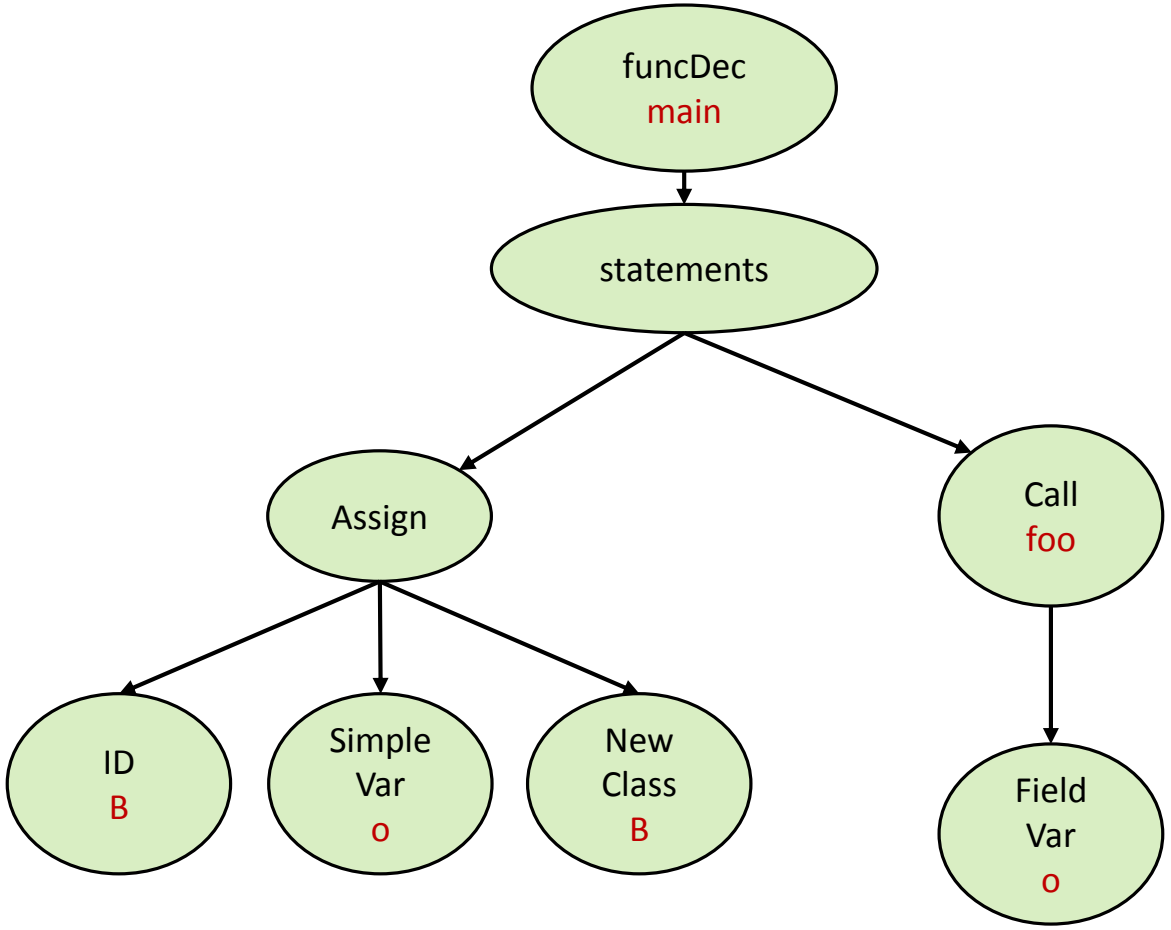
```
class A {
   int data;
}
class B extends A {
   string data;
}
```



Invalid

Inheritance

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



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  foo(o);
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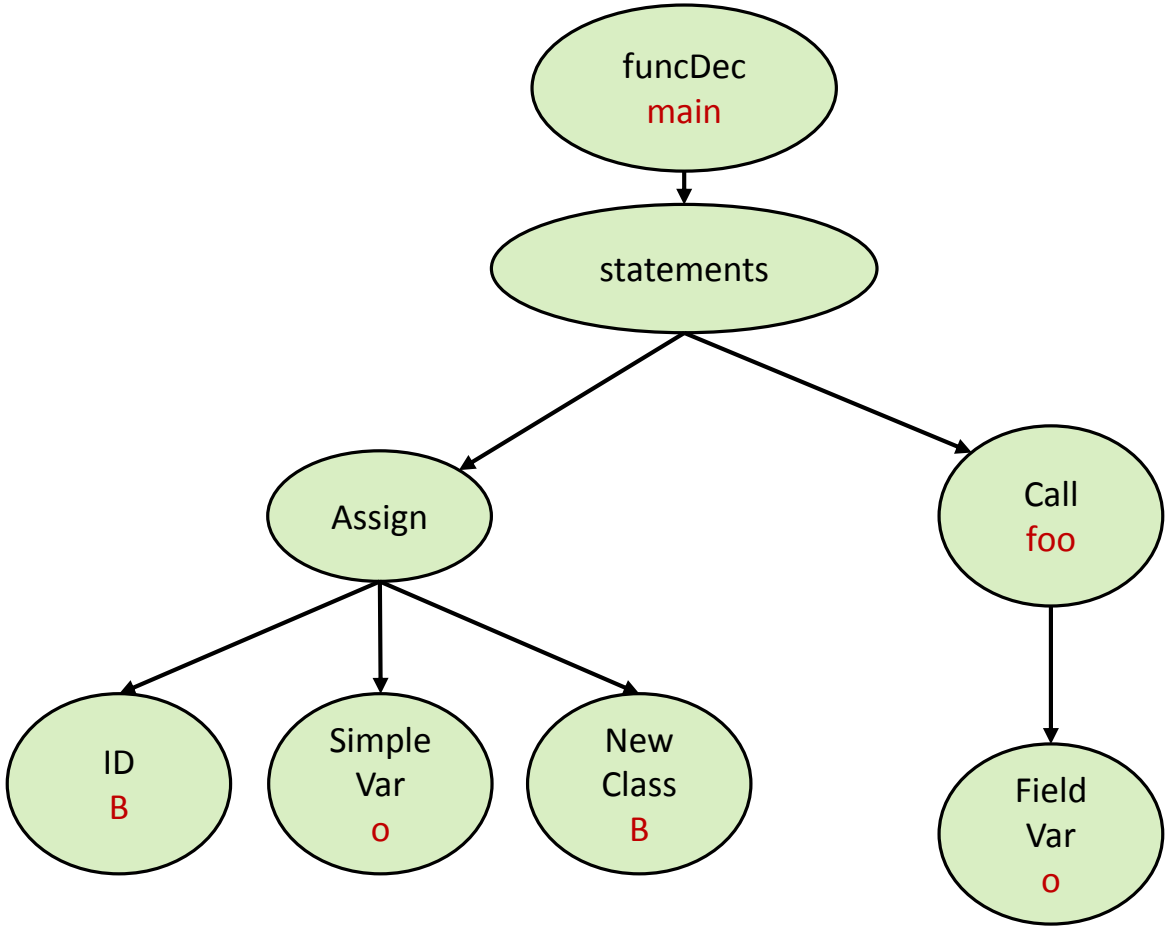
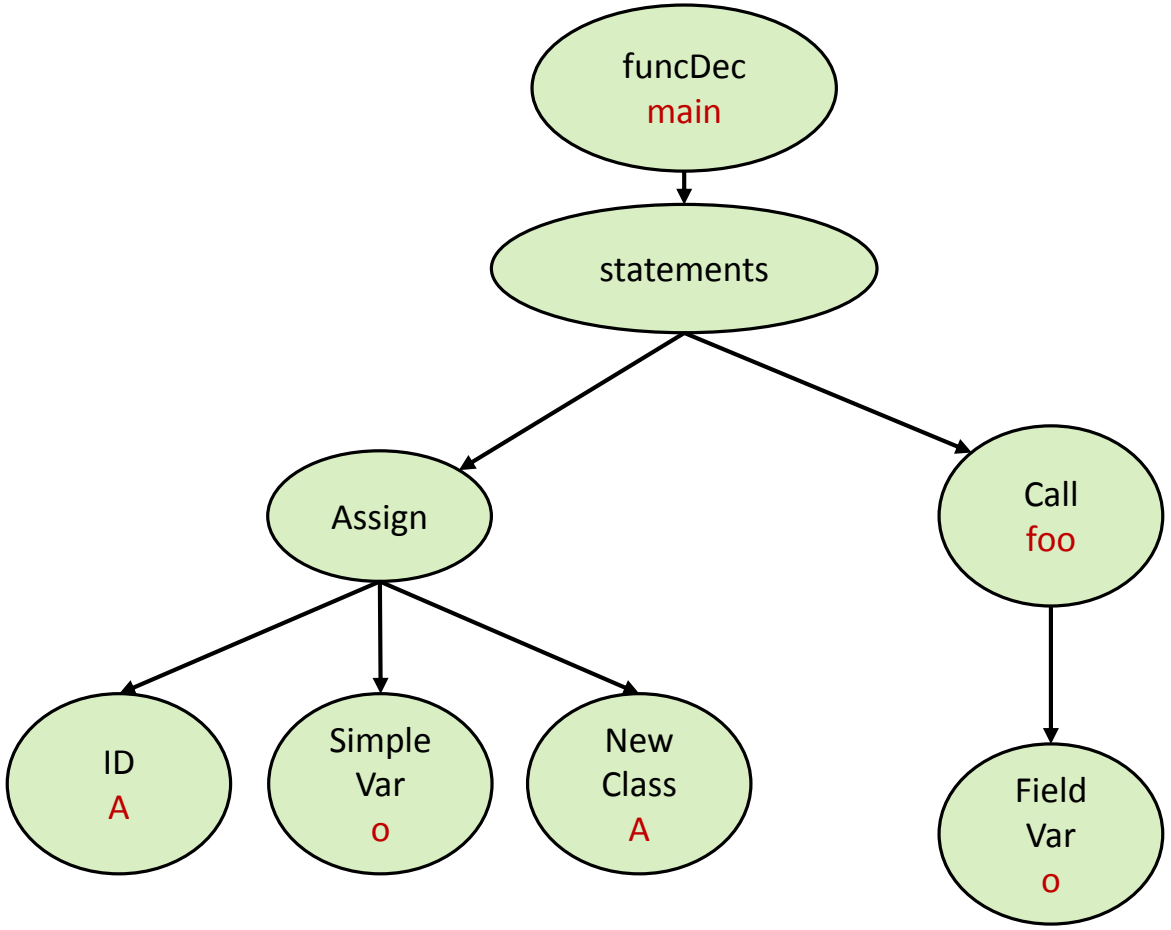
Valid



Inheritance

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



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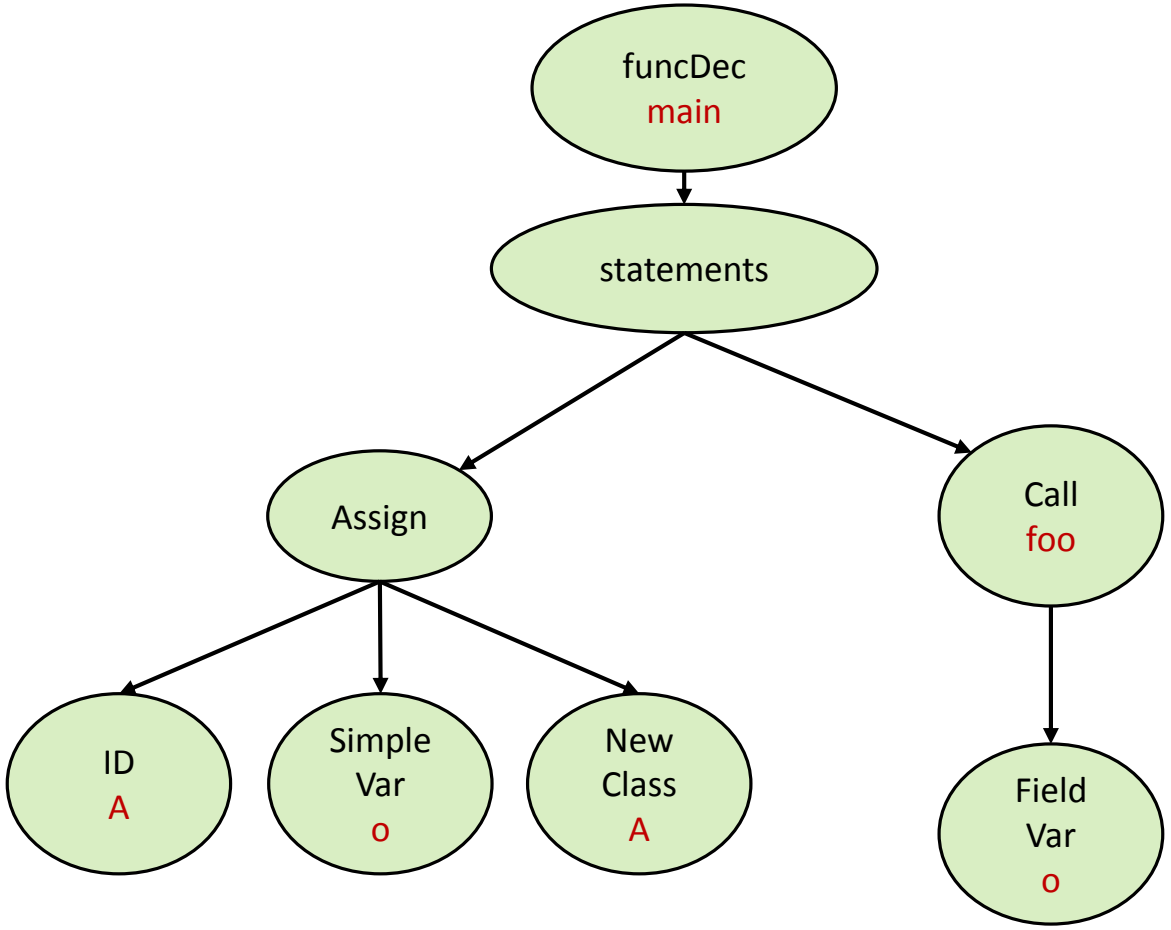
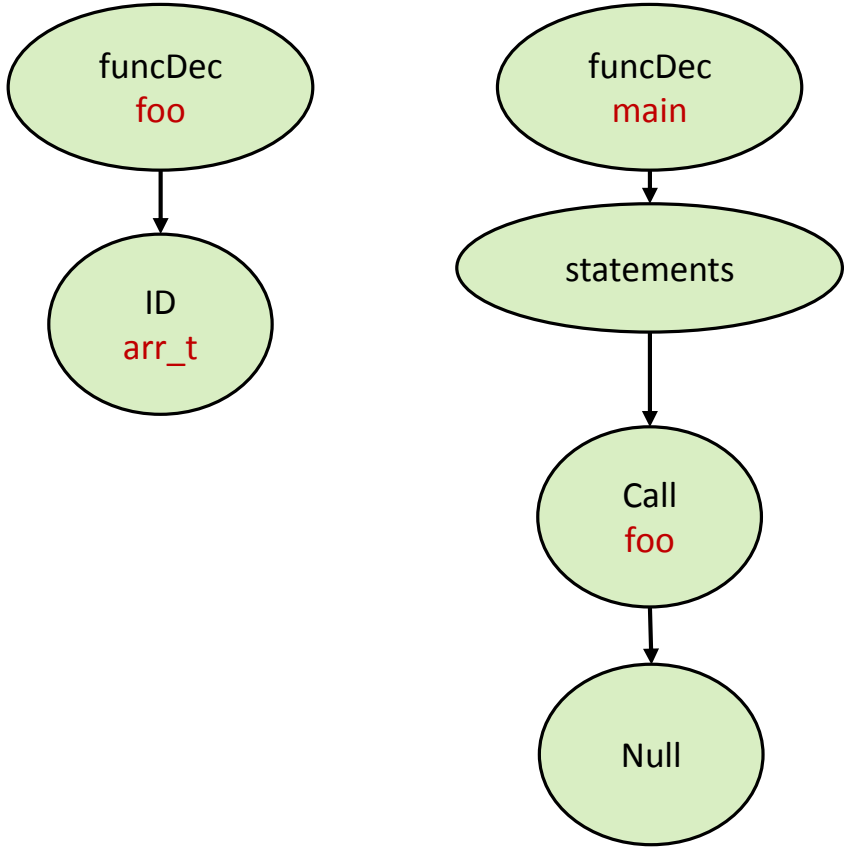

Invalid



Null

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



Null

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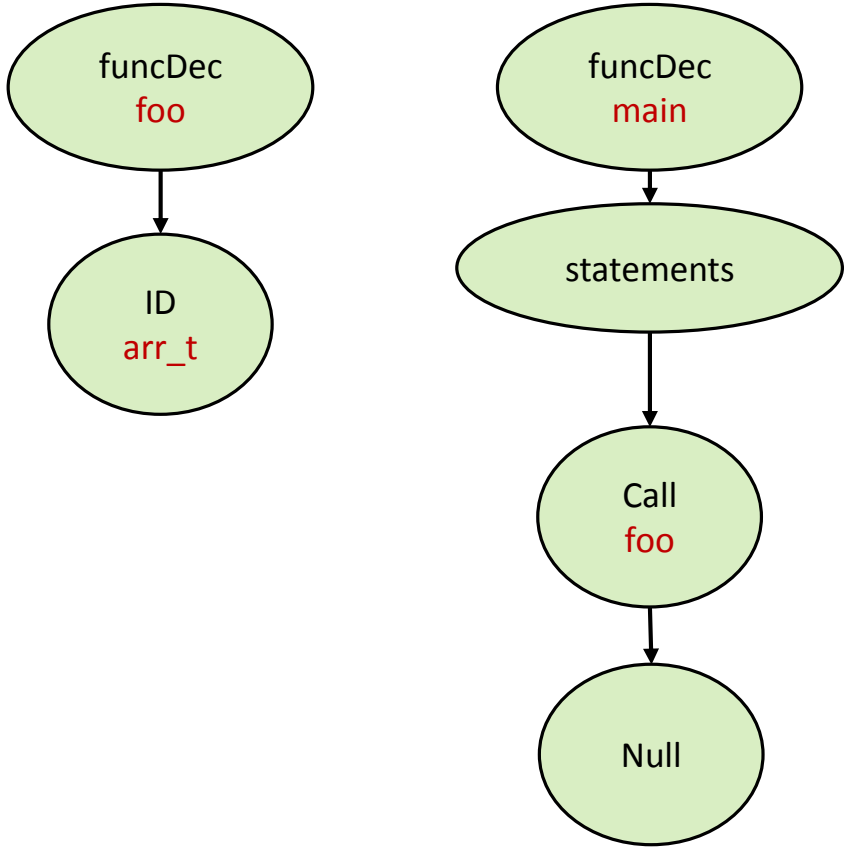
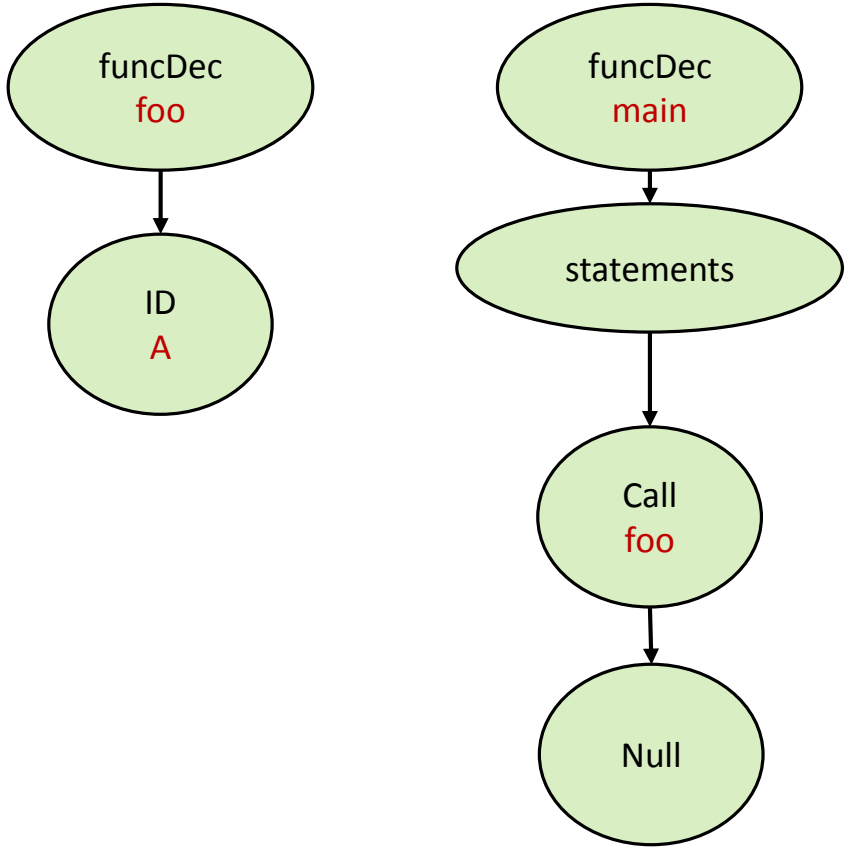


Null

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



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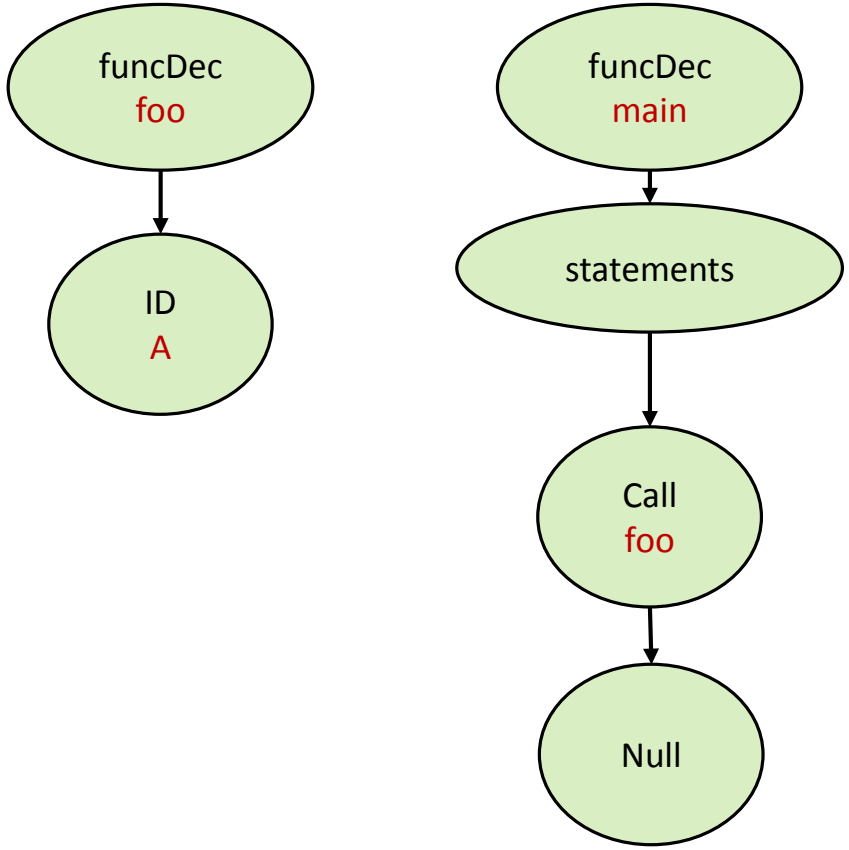
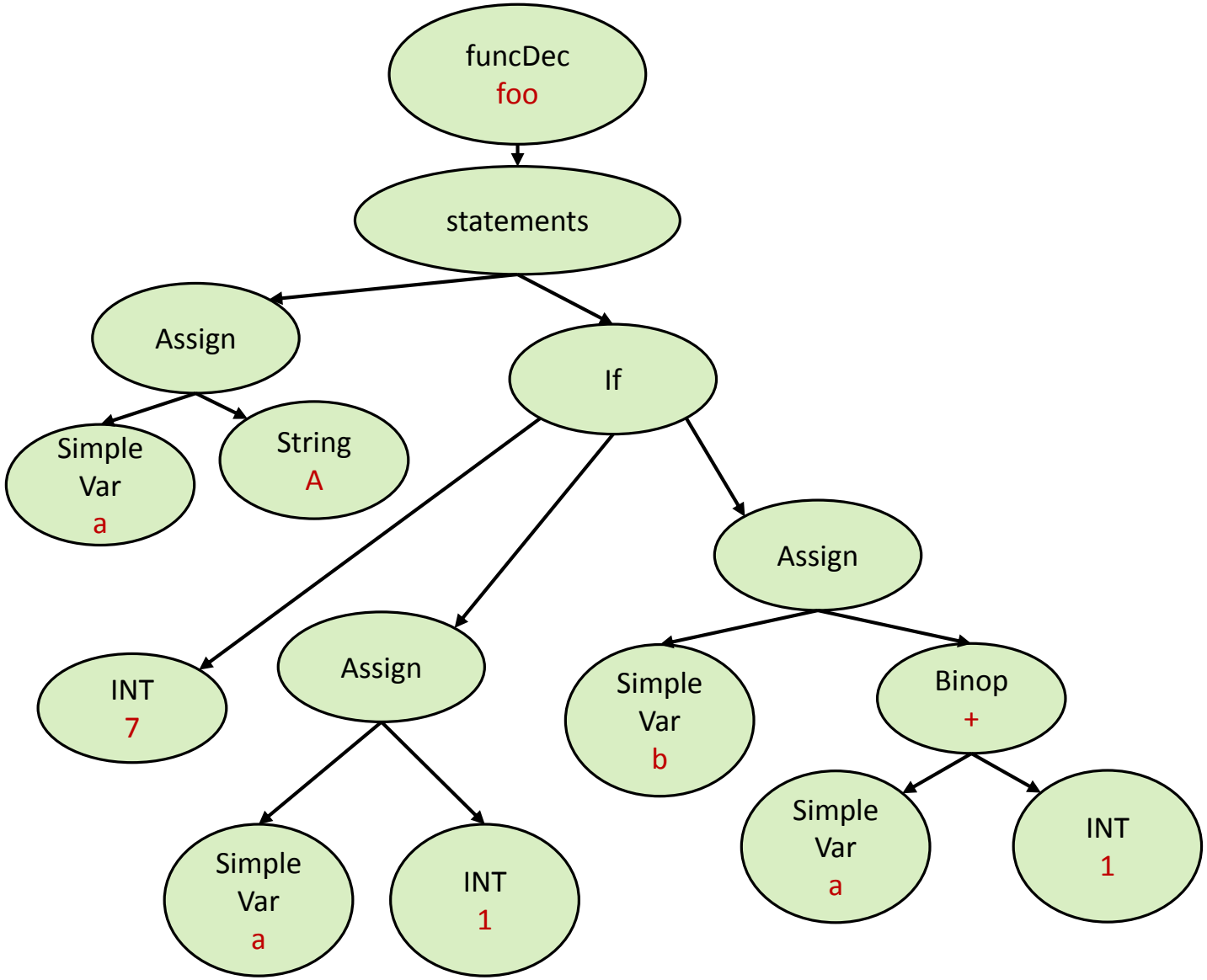


Valid

Scopes

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



Scopes

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   string a = "A";
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      int a = 1;
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   }
}
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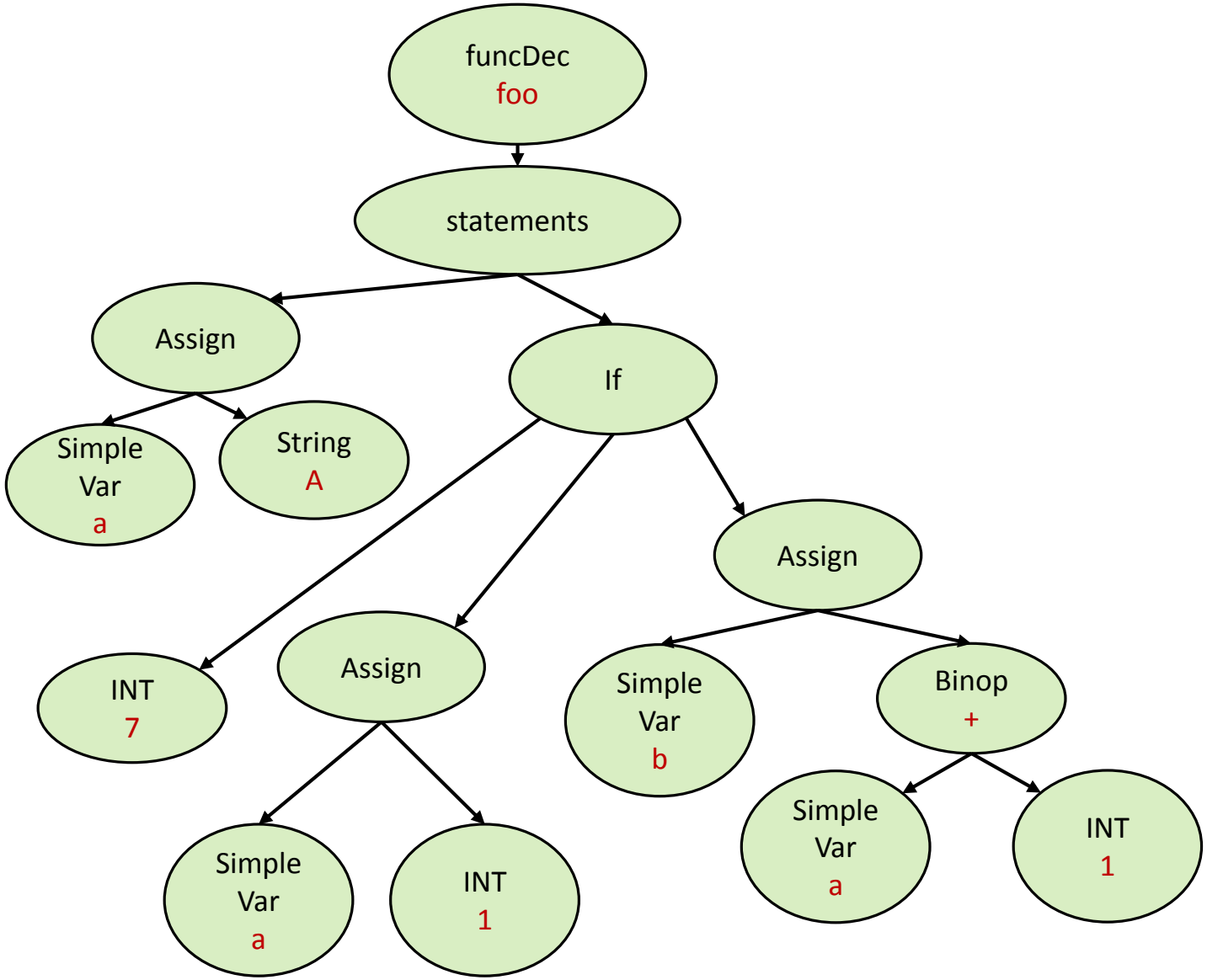
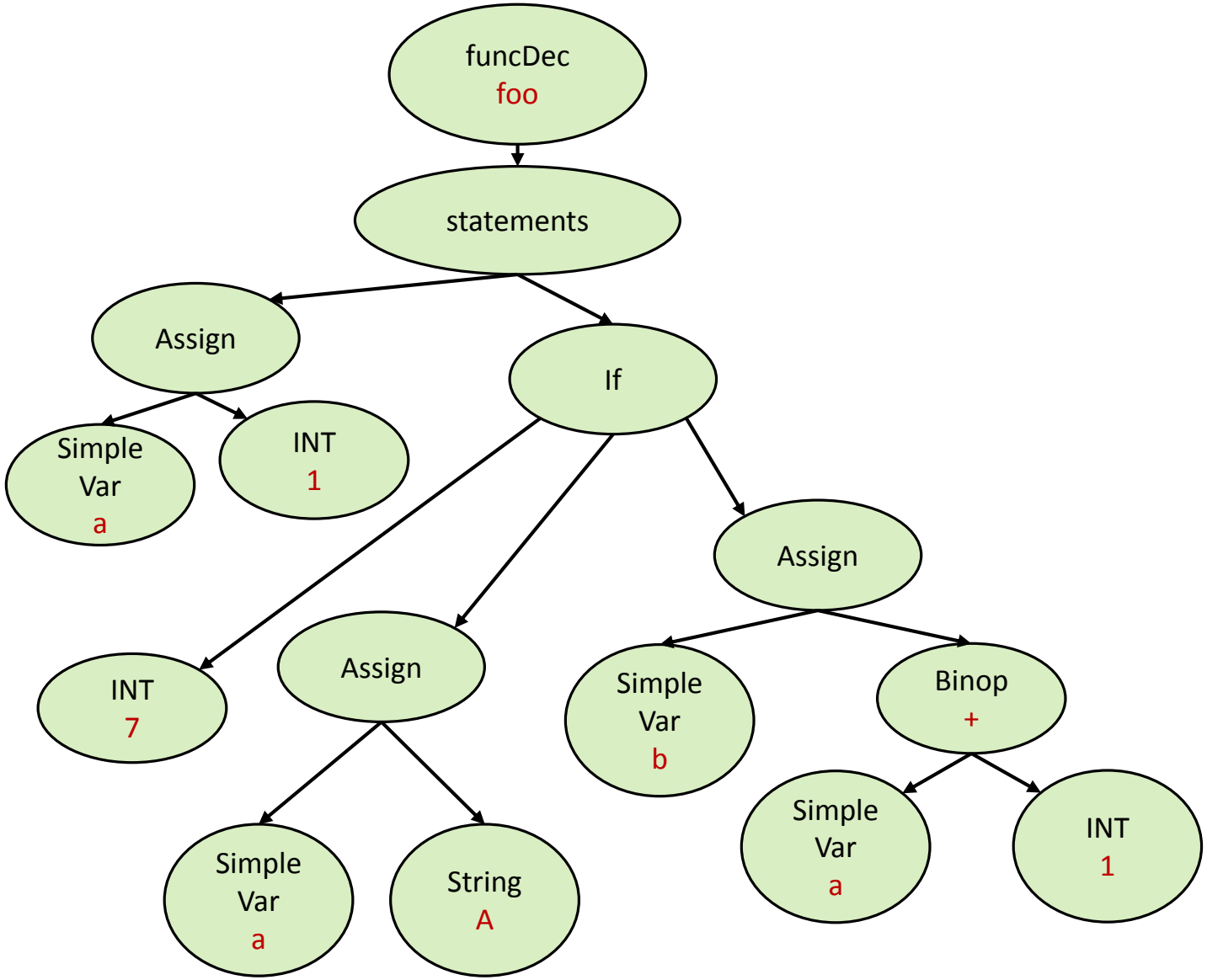
Valid



Scopes

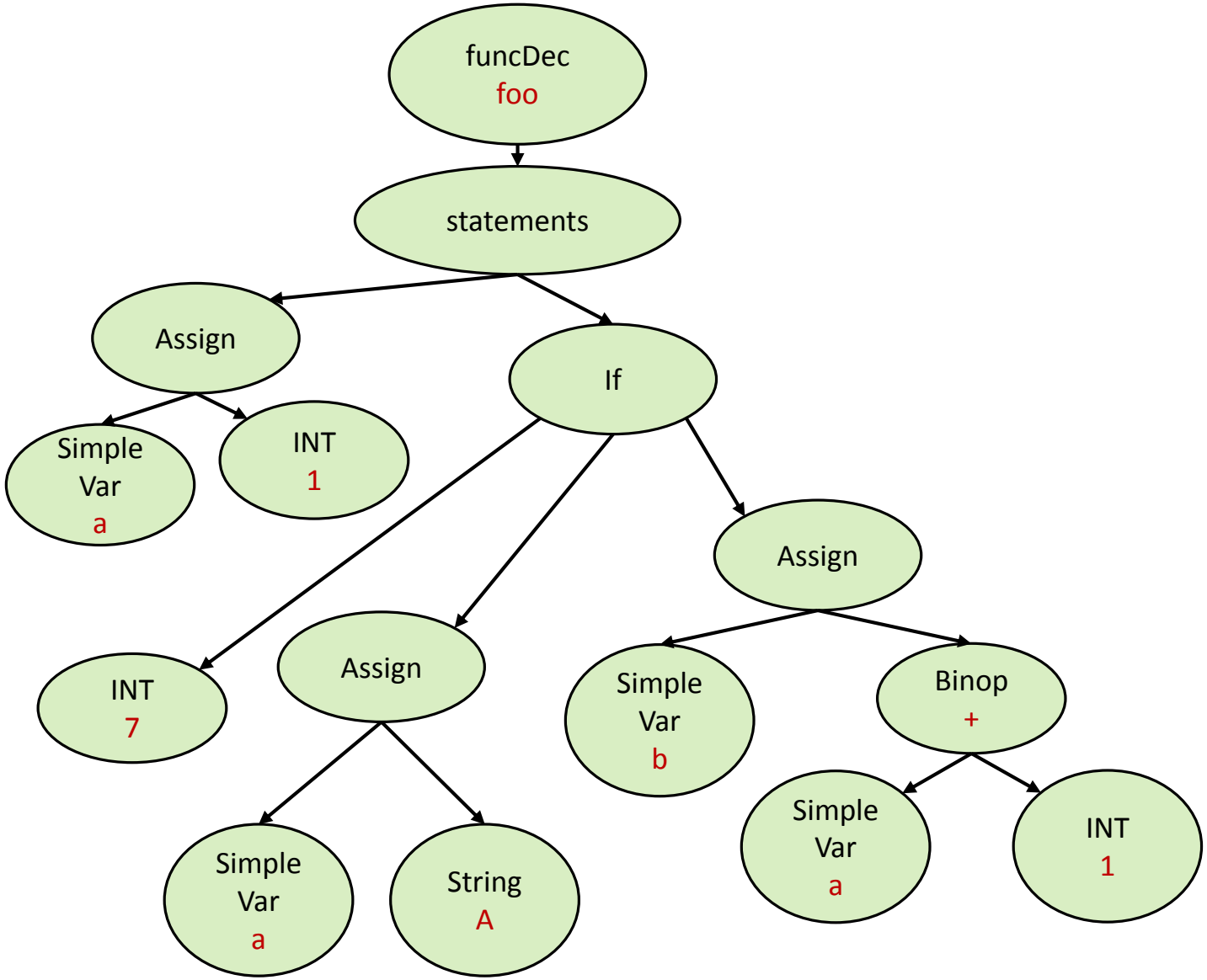
```
void foo(void) {
  int a = 1;
  if (7) {
    string a = "A";
    int b = a + 1;
  }
}
```



Scopes

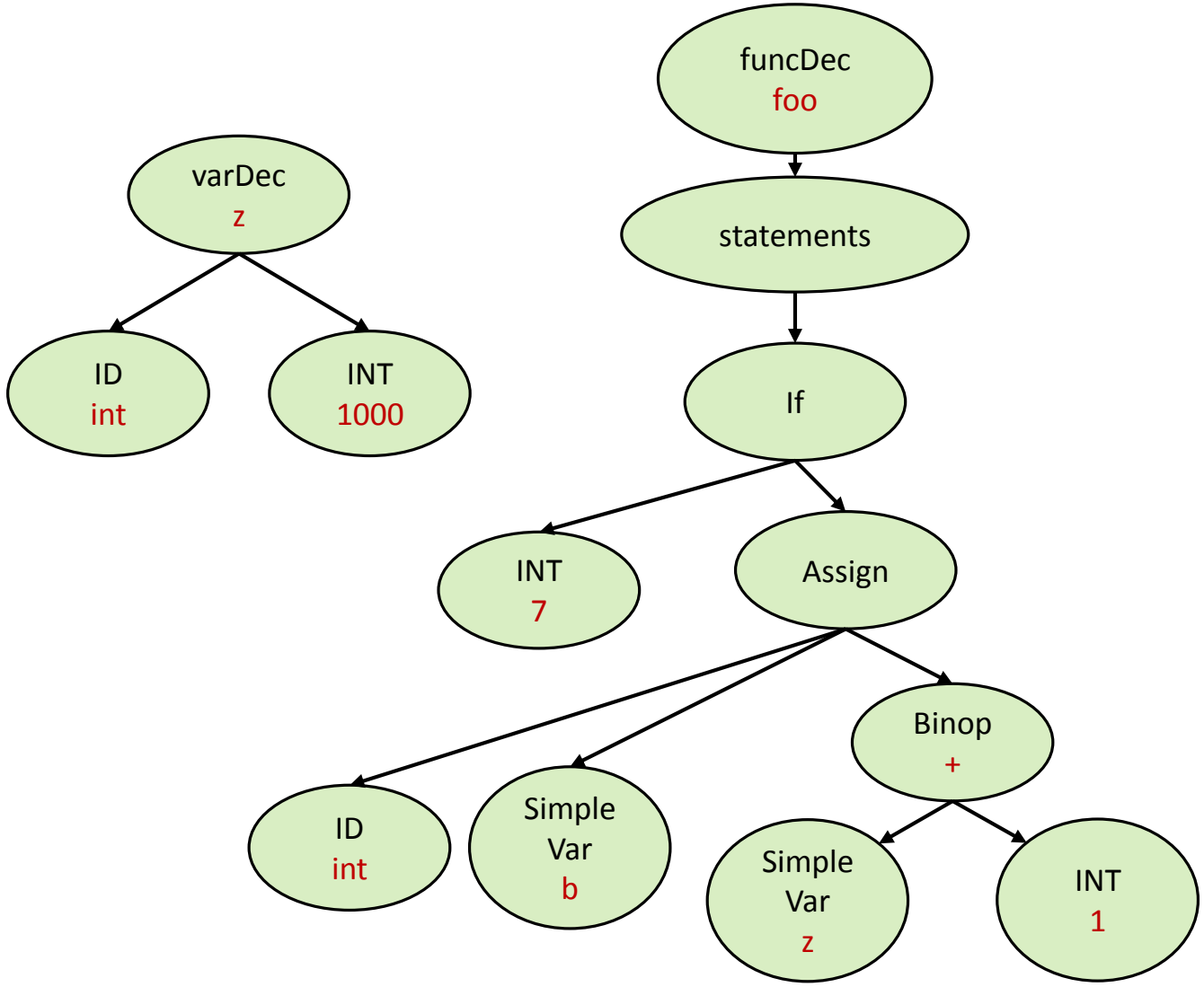
```
void foo(void) {
  int a = 1;
  if (7) {
    string a = "A";
    int b = a + 1;
  }
}
```

Invalid



Scopes

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



Scopes

```
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      int b = z + 1;
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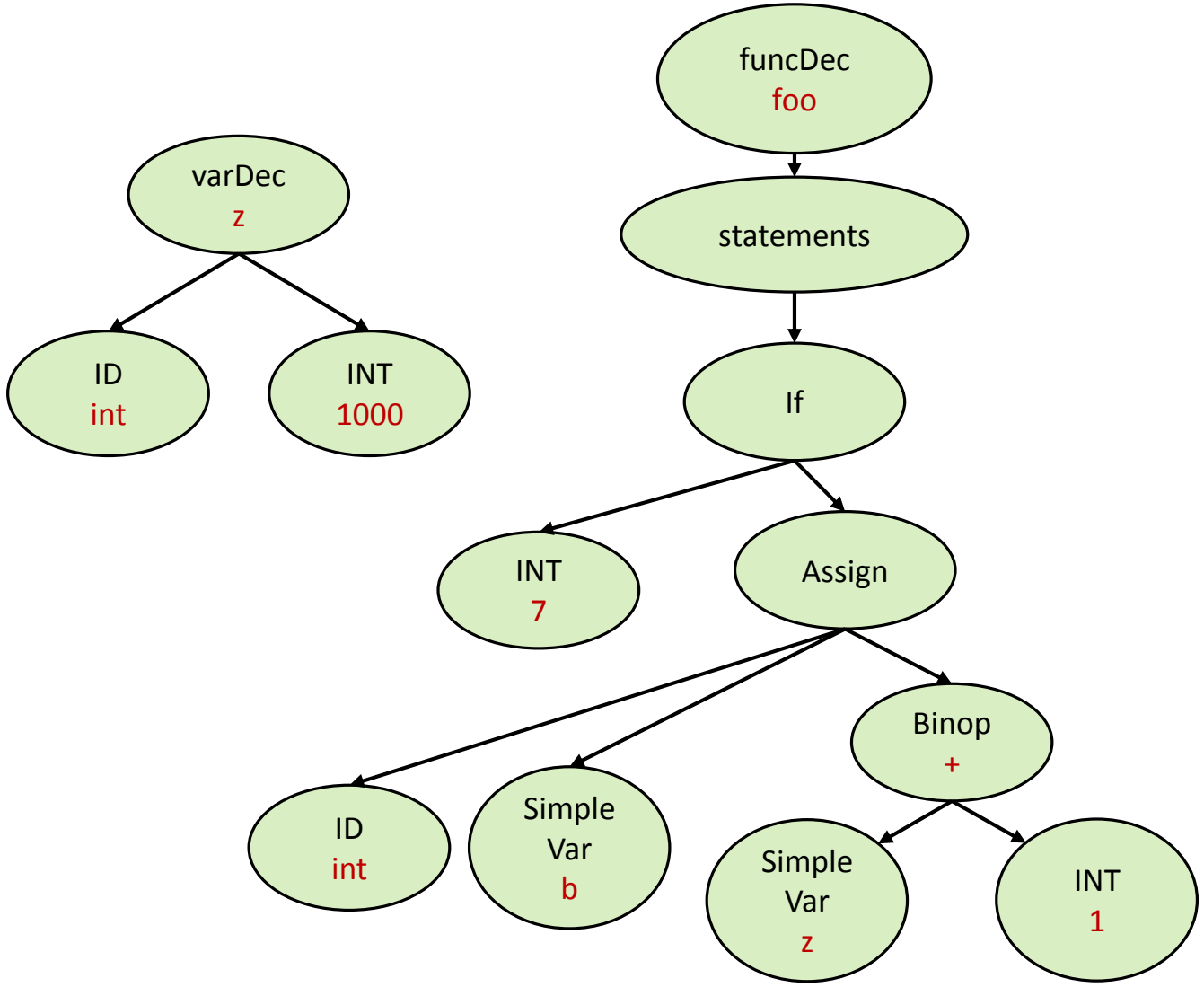
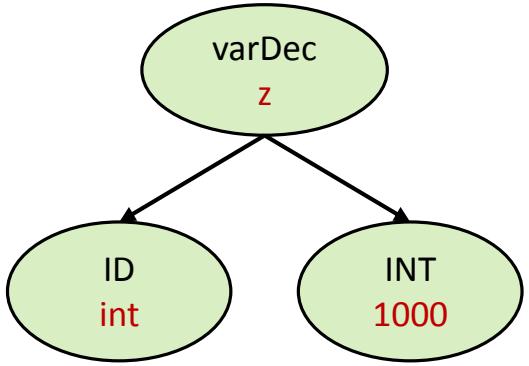
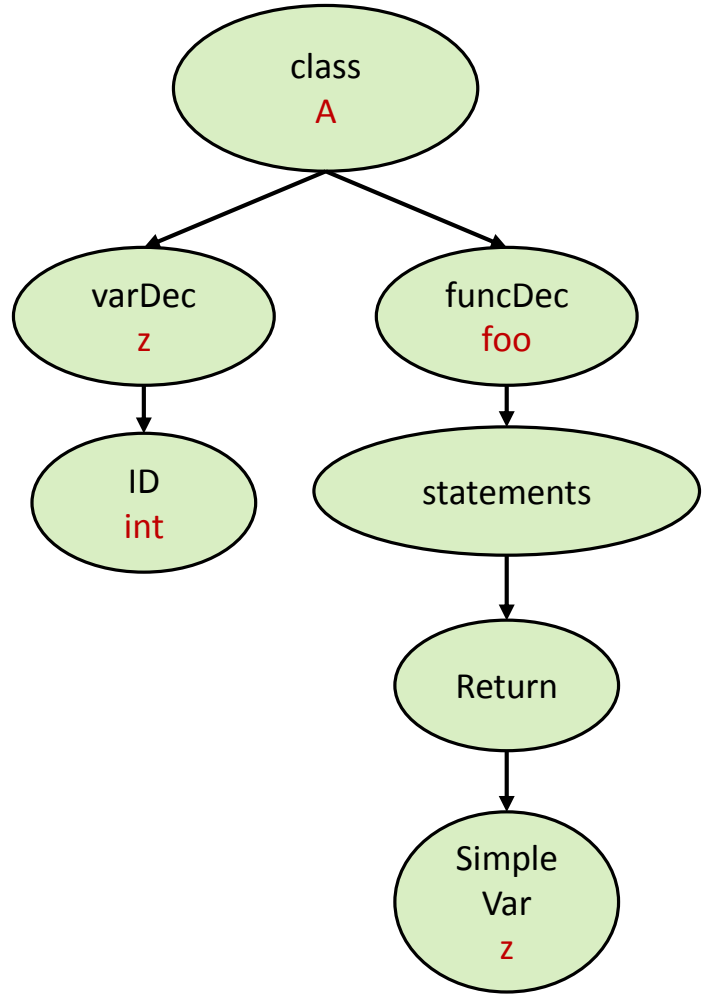
Valid



Scopes

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





Scopes

```
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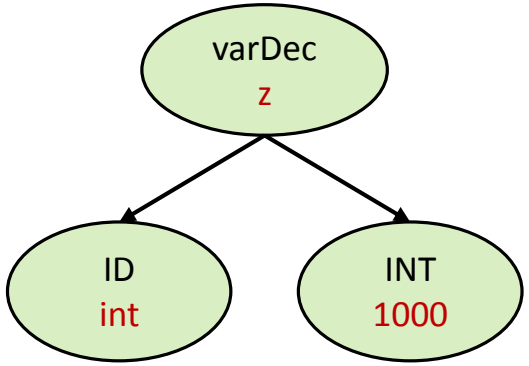
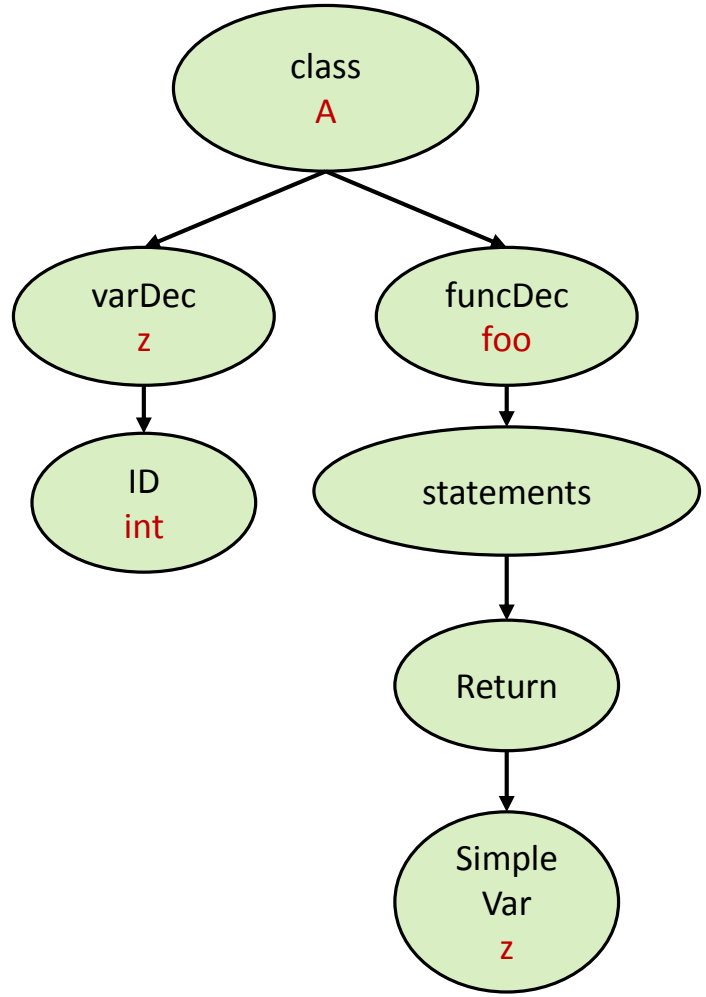
   int z;
   int foo() {
      return z;
   }
}
```

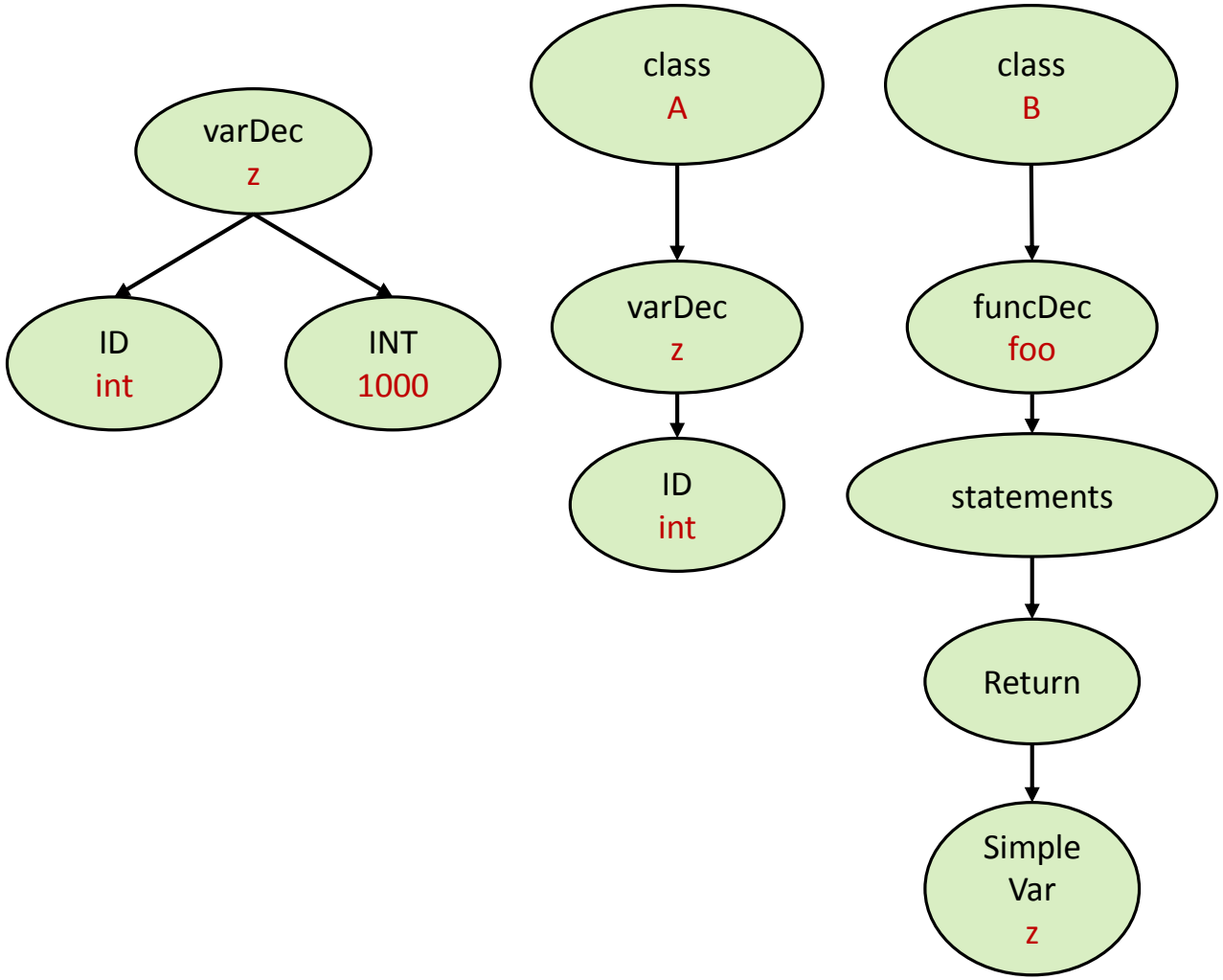
Valid





Scopes

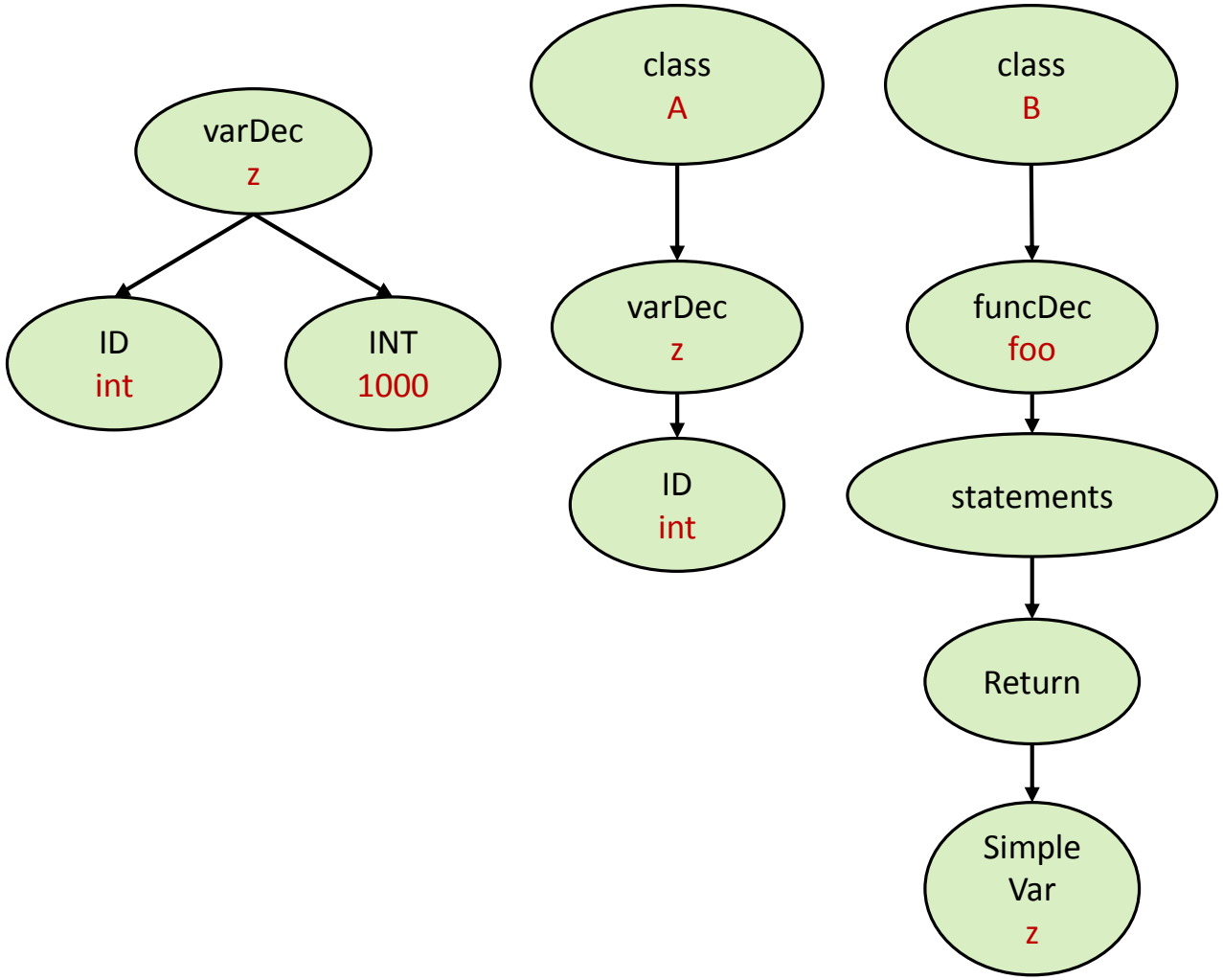
```
int z = 1000;
class A {
  int z;
}
class B extends A {
  int foo() {
    return z;
  }
}
```



Scopes

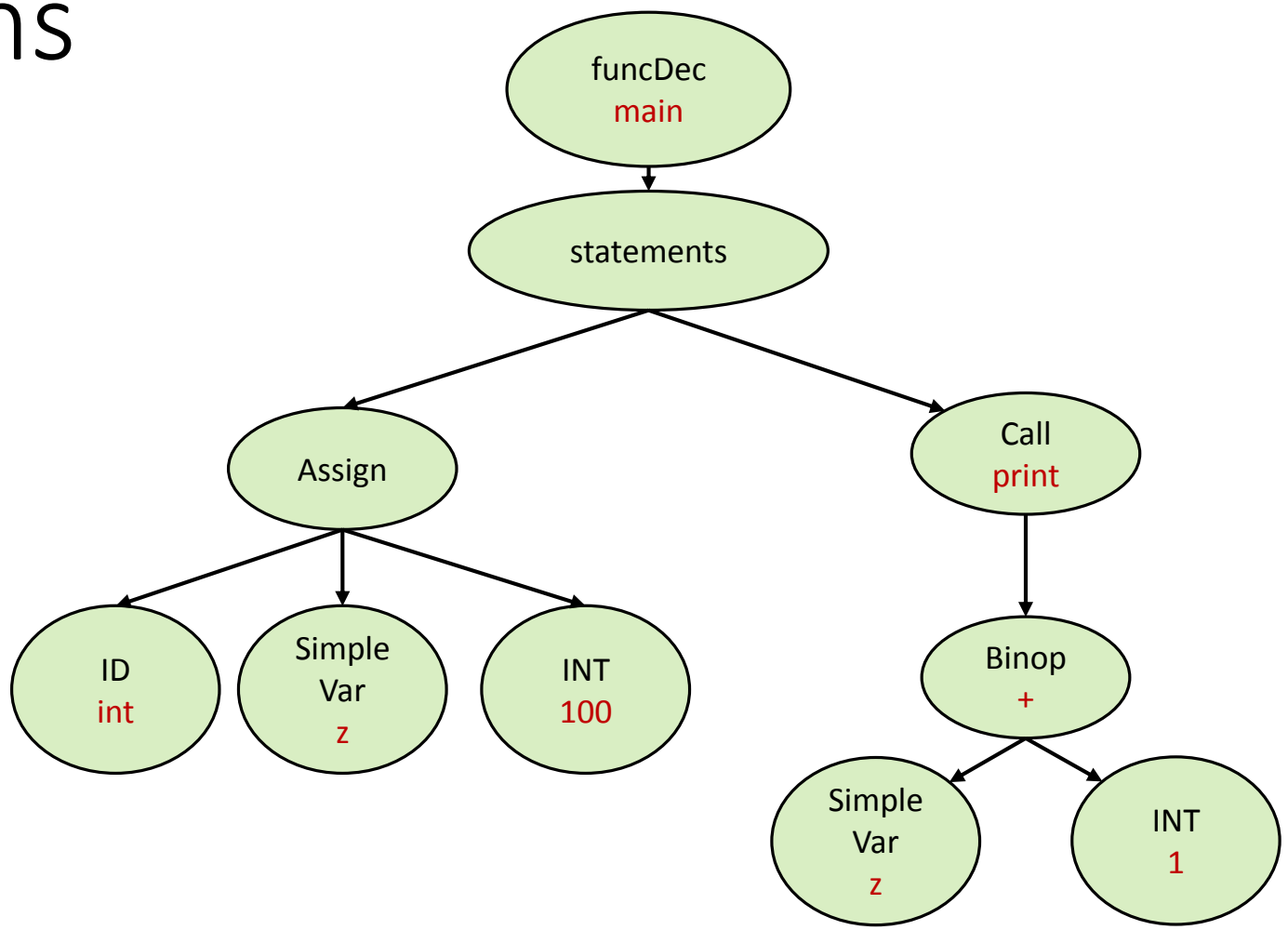
```
int z = 1000;
class A {
  int z;
}
class B extends A {
  int foo() {
    return z;
  }
}
```

Valid



Library Functions

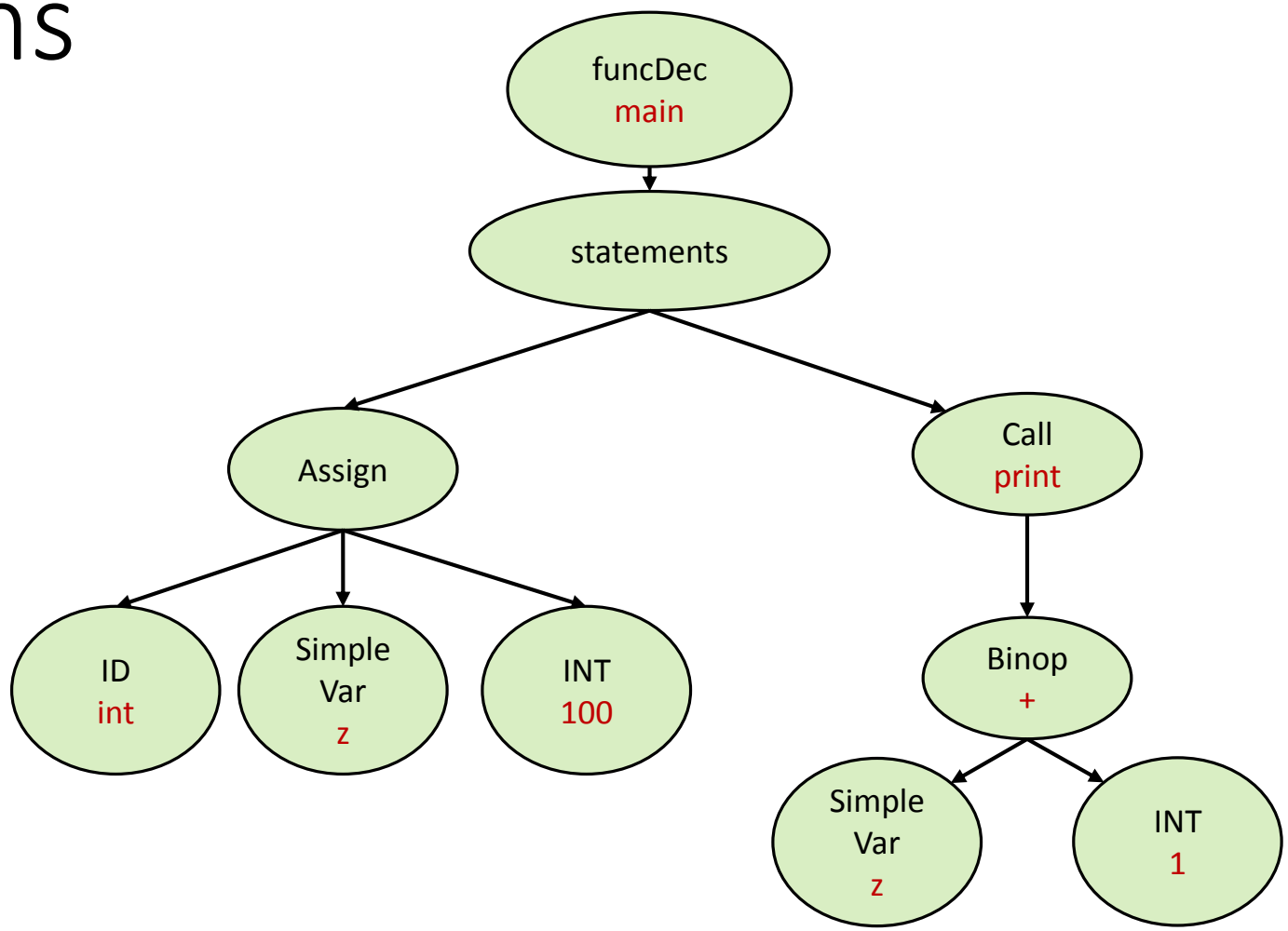
```
void main() {
  int z = 100;
  print(z + 1);
}
```



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;
  }
}
```

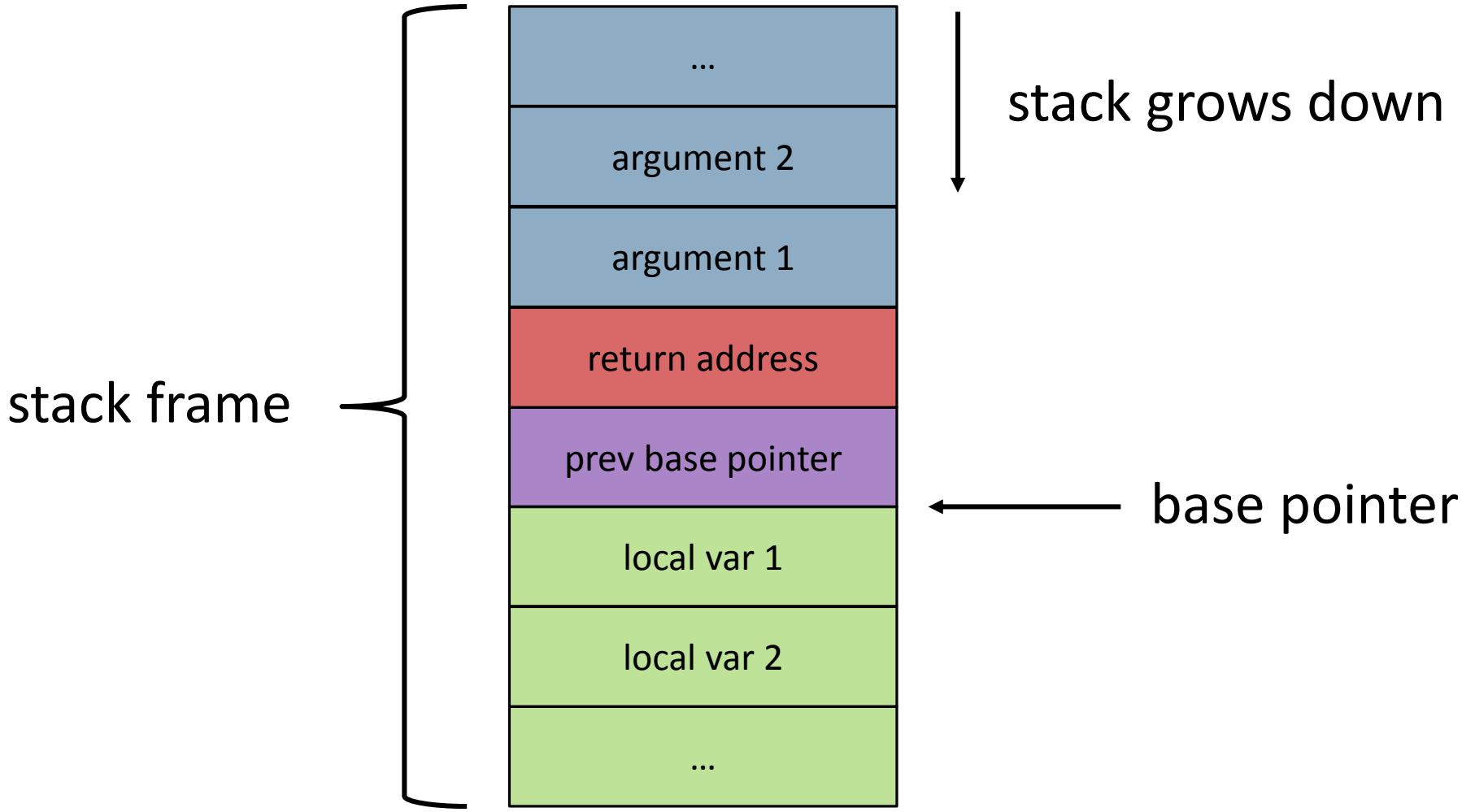
AST Annotations

AST Annotations

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

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

Stack


...
argument 2
argument 1
return address
prev base pointer
local var 1
local var 2
...
stack grows down
stack frame
base pointer

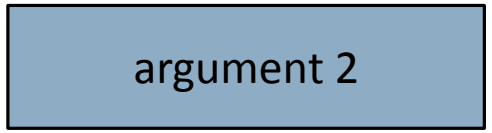
Stack

```
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

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

```
g:
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sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```
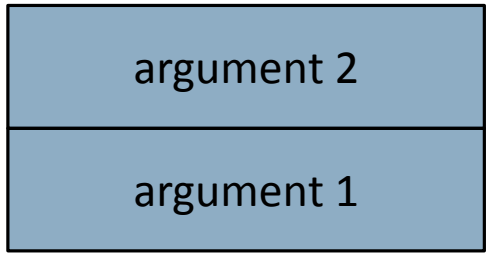

Stack

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f:
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lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

```
g:
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subu $sp, $sp, 4
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li $t0, 10
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sw $t0, 0($sp)
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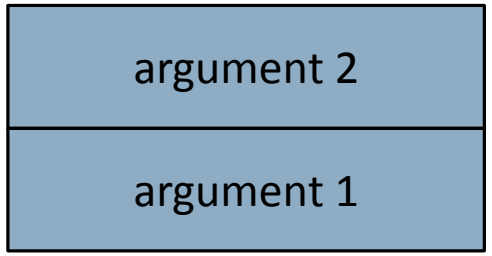
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack

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addu $sp, $sp, 8
jr $ra
```

```
g:
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addu $sp, $sp, 8
move $t0, $v0
...
```
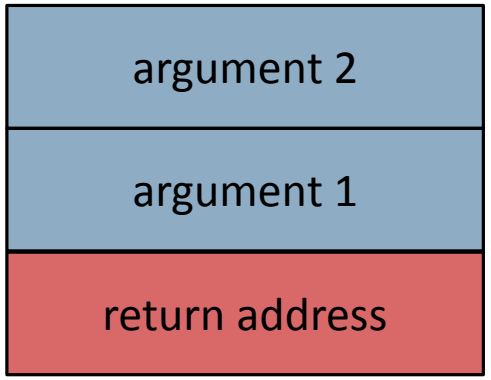

Stack

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```
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...
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sw $t0, 0($sp)
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addu $sp, $sp, 8
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...
```
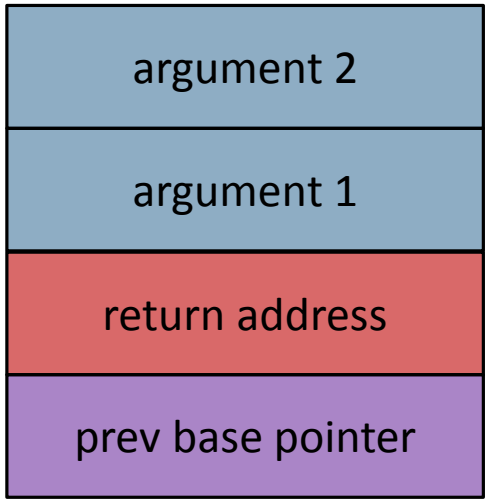

Stack

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lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

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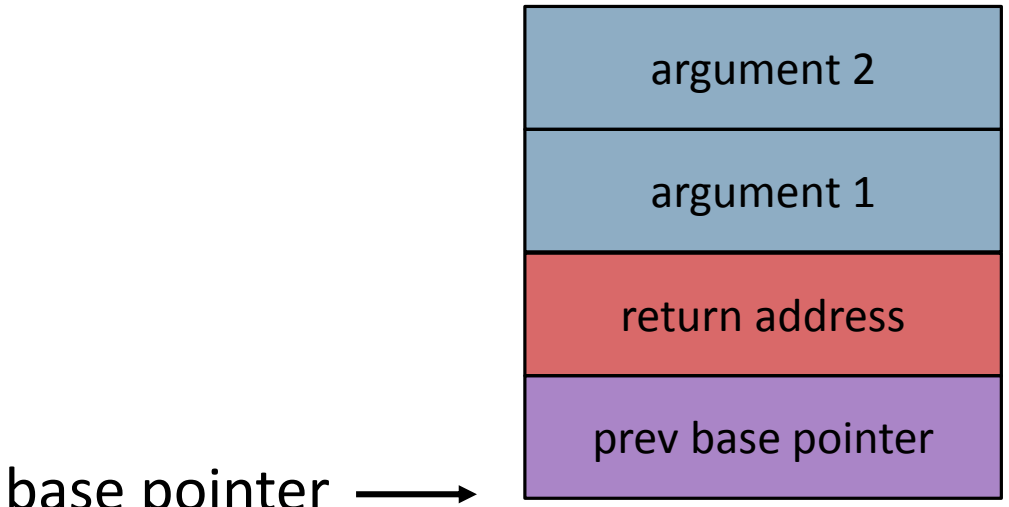
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack

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move $t0, $v0
...
```
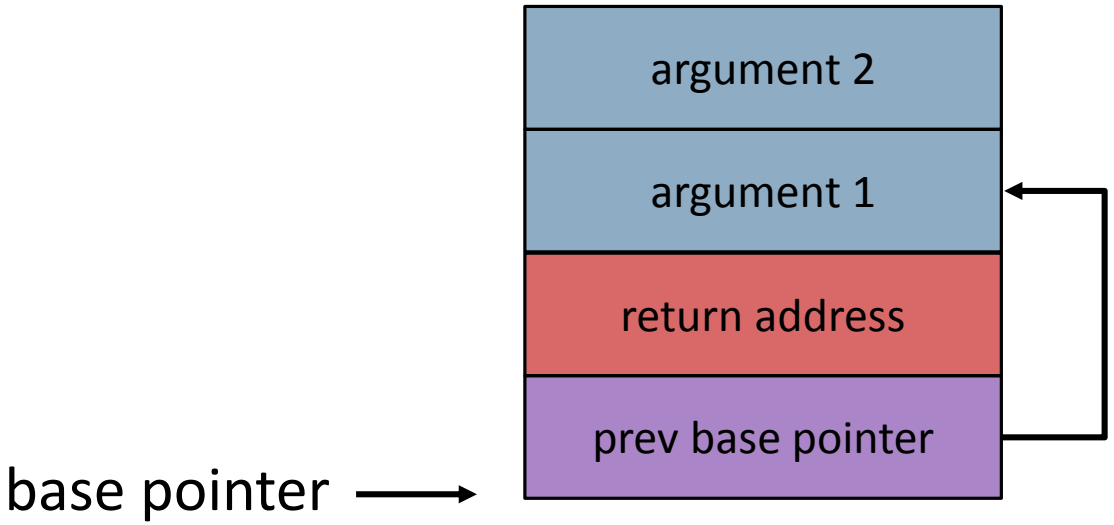

Stack

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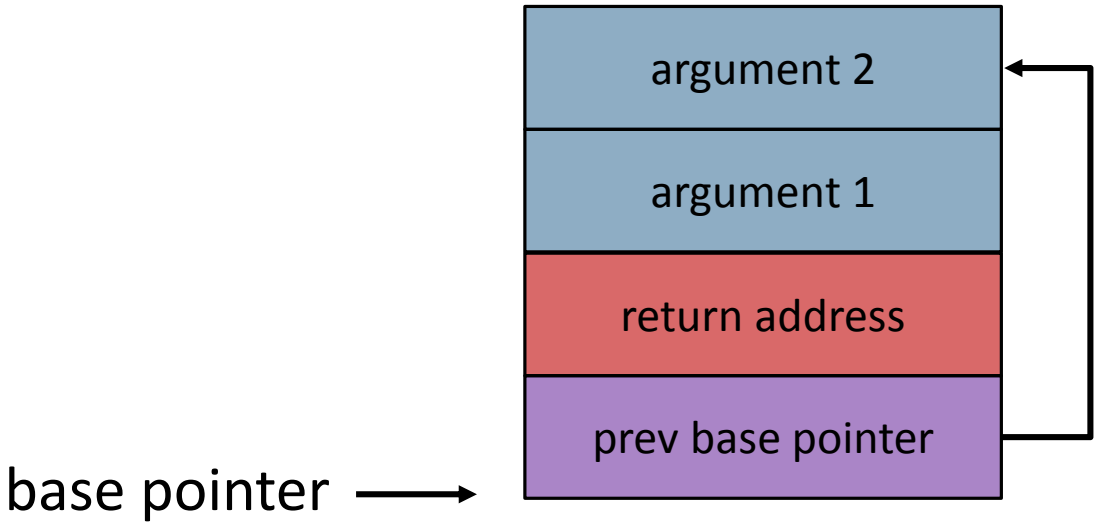
Stack

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move $t0, $v0
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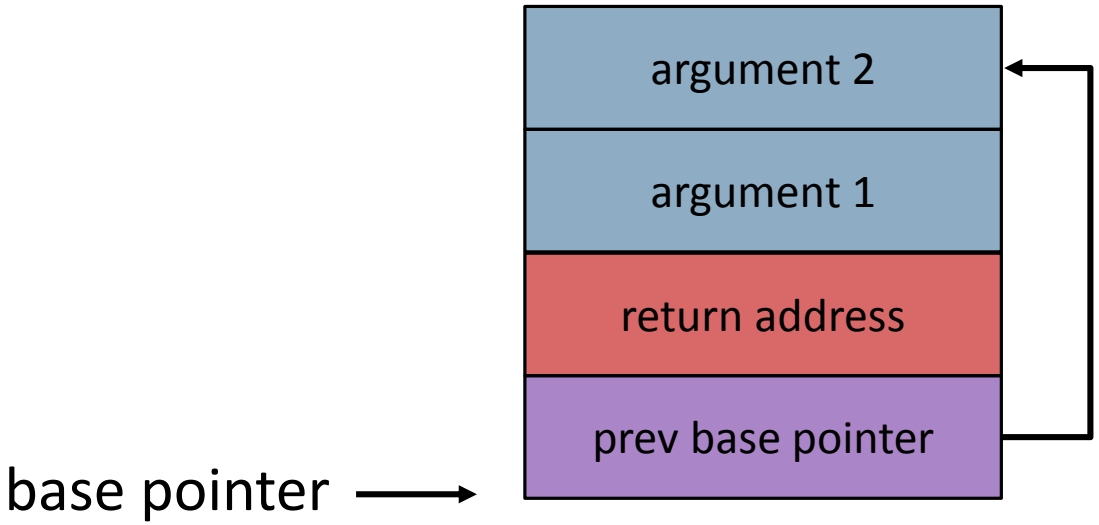
```

Stack

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move $t0, $v0
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```
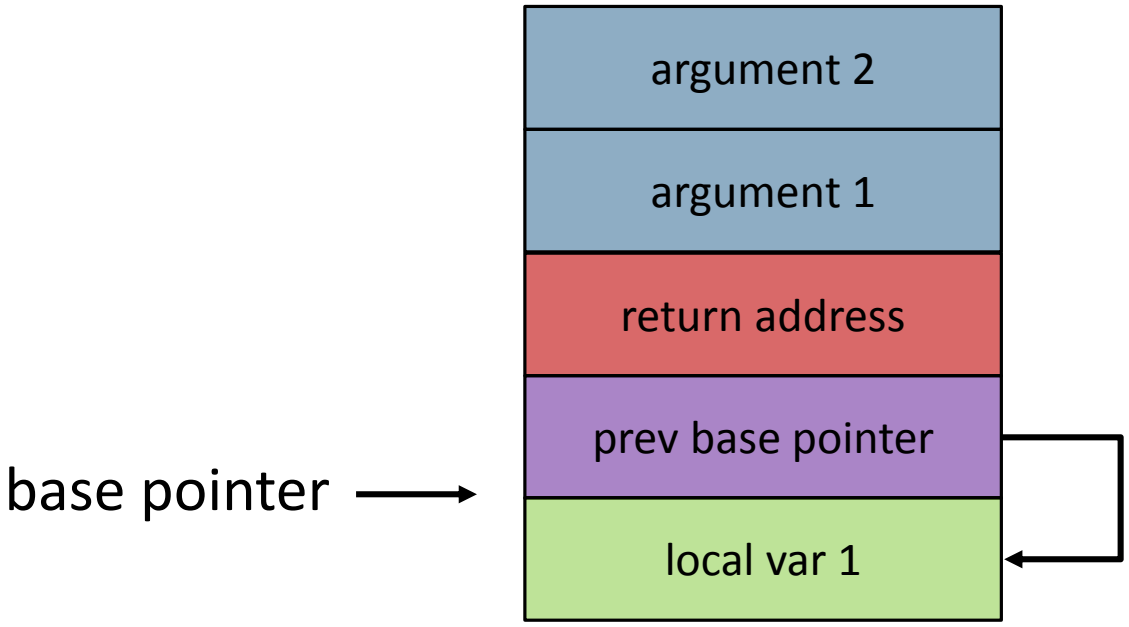

Stack

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lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

```
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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

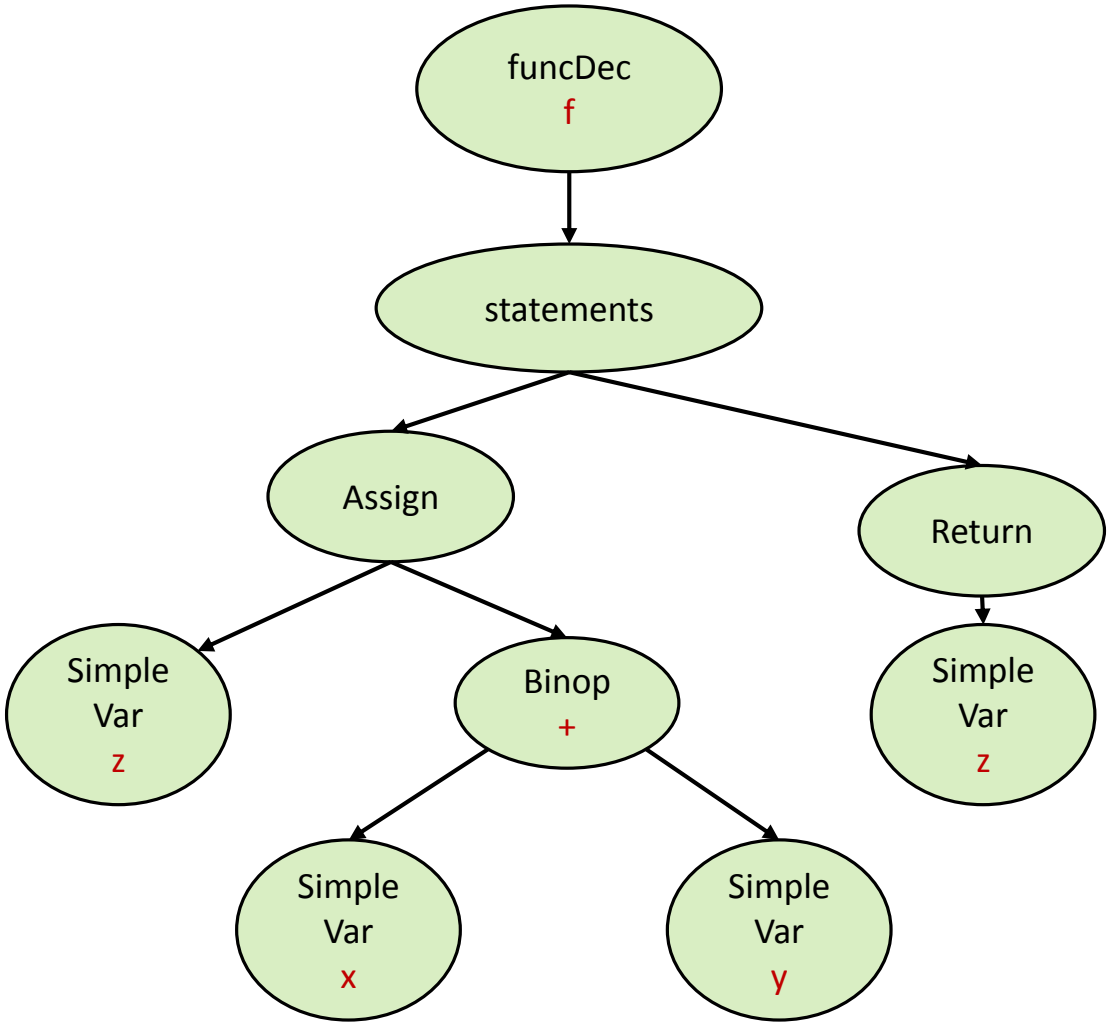
Machine code **does not** contain names of:

- 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

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int f(int x, int y){
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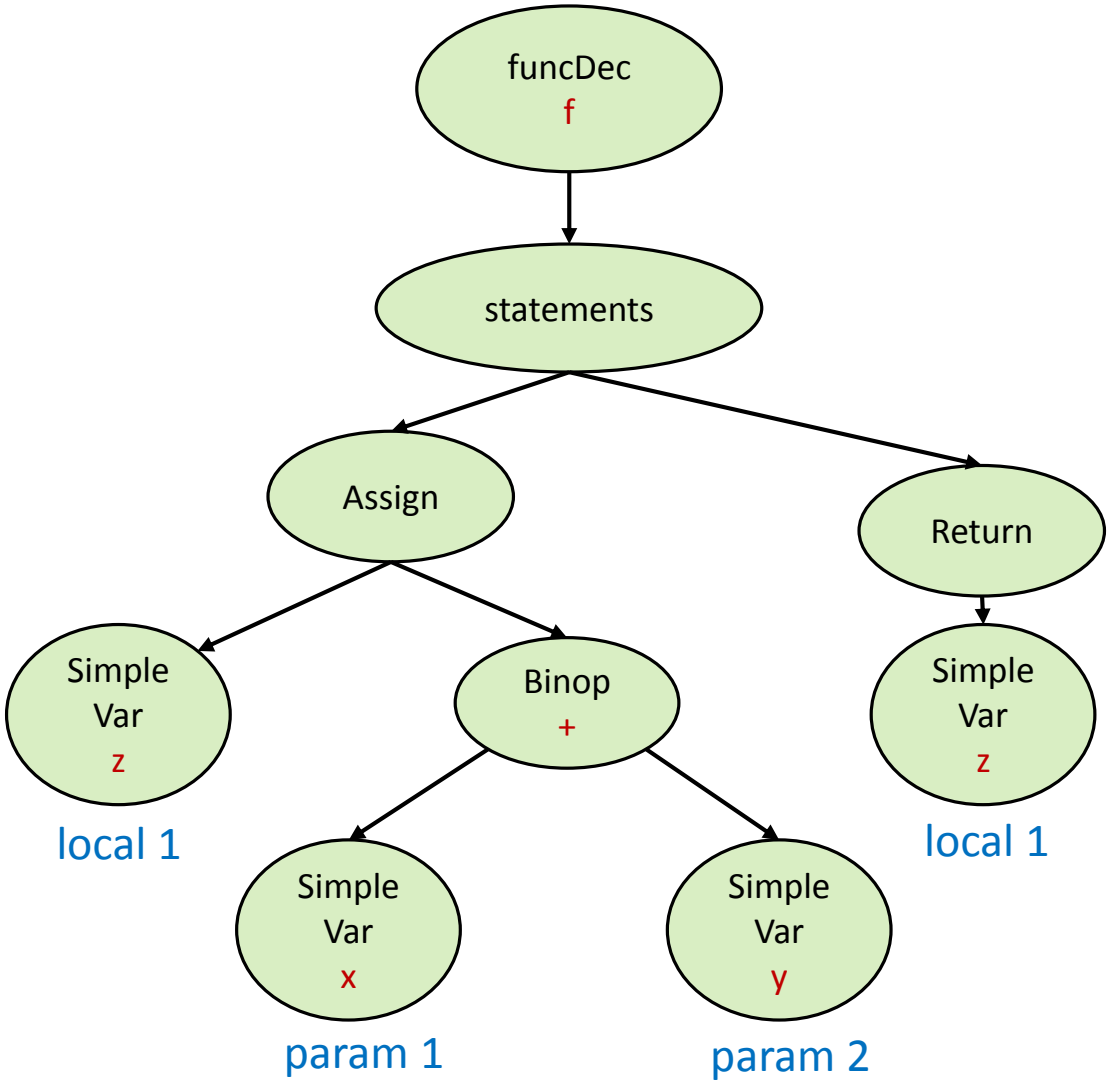

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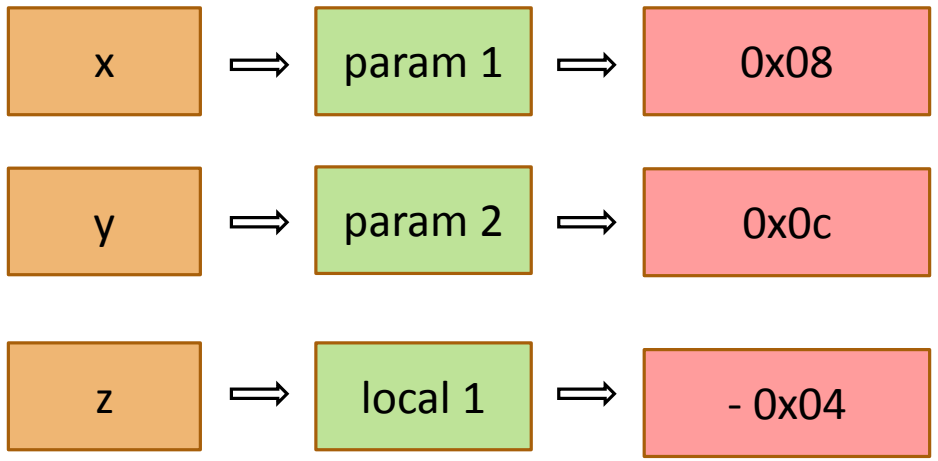
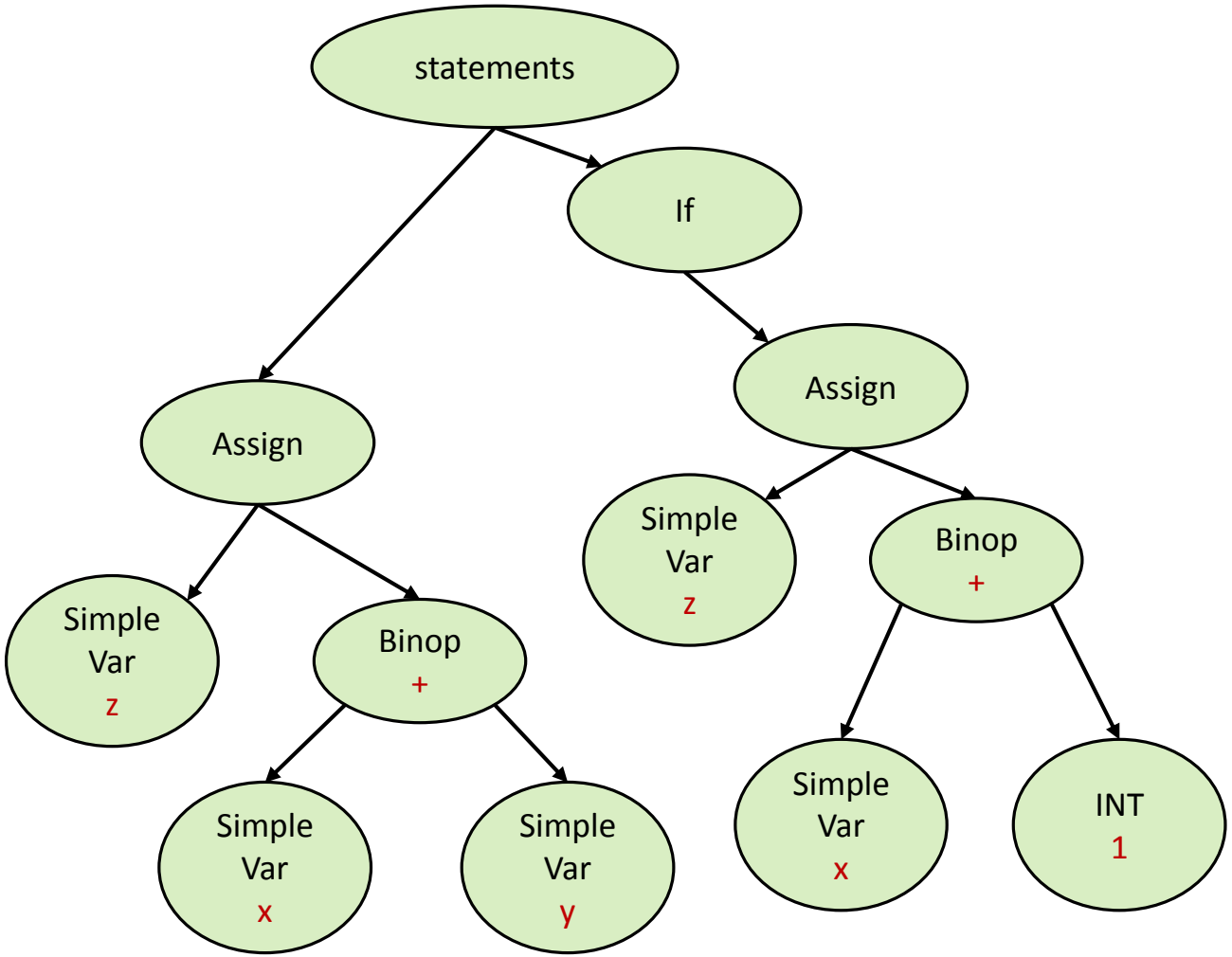


Variable Offsets

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



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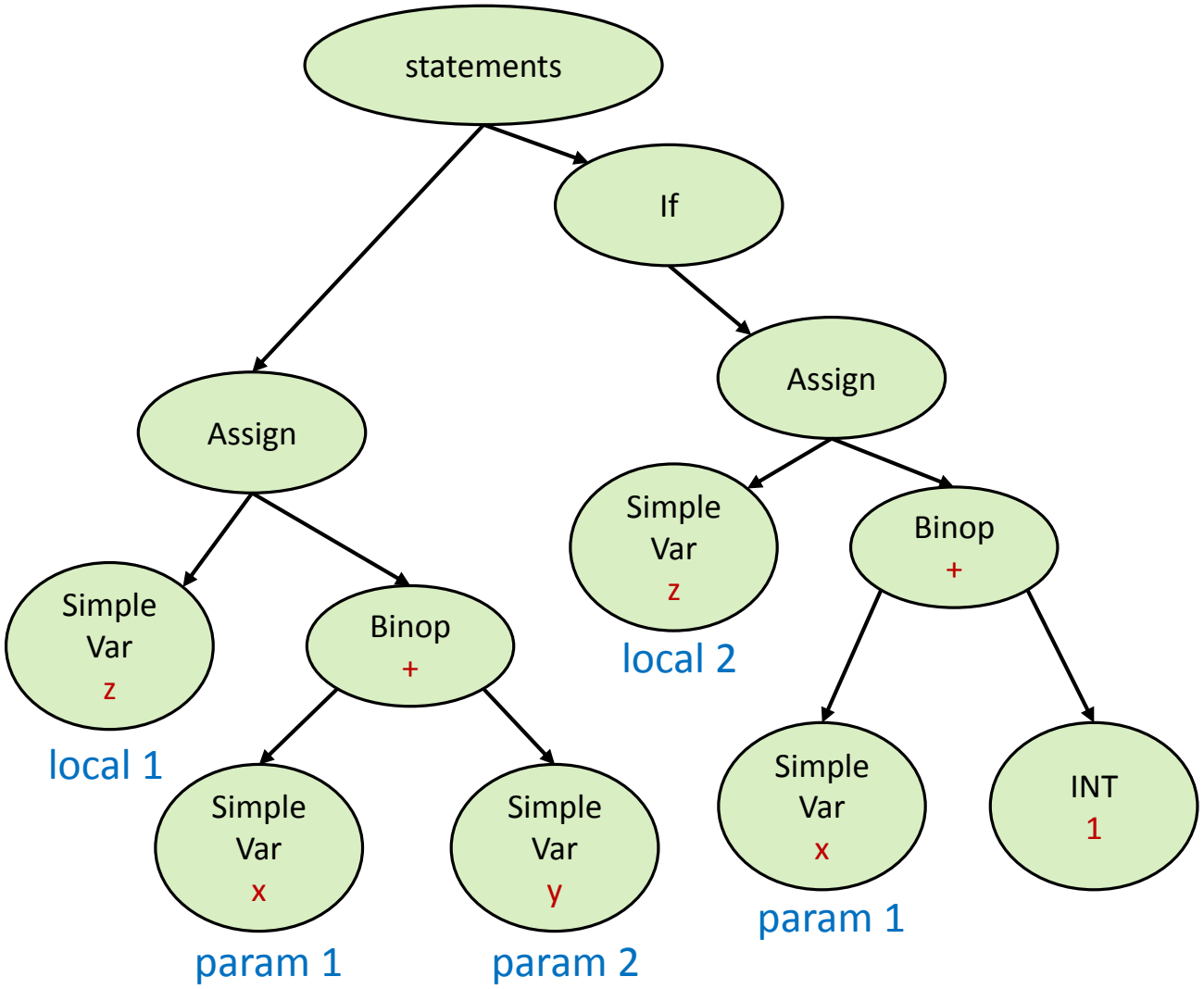

Field Offsets

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?

```
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void f(Point p) {
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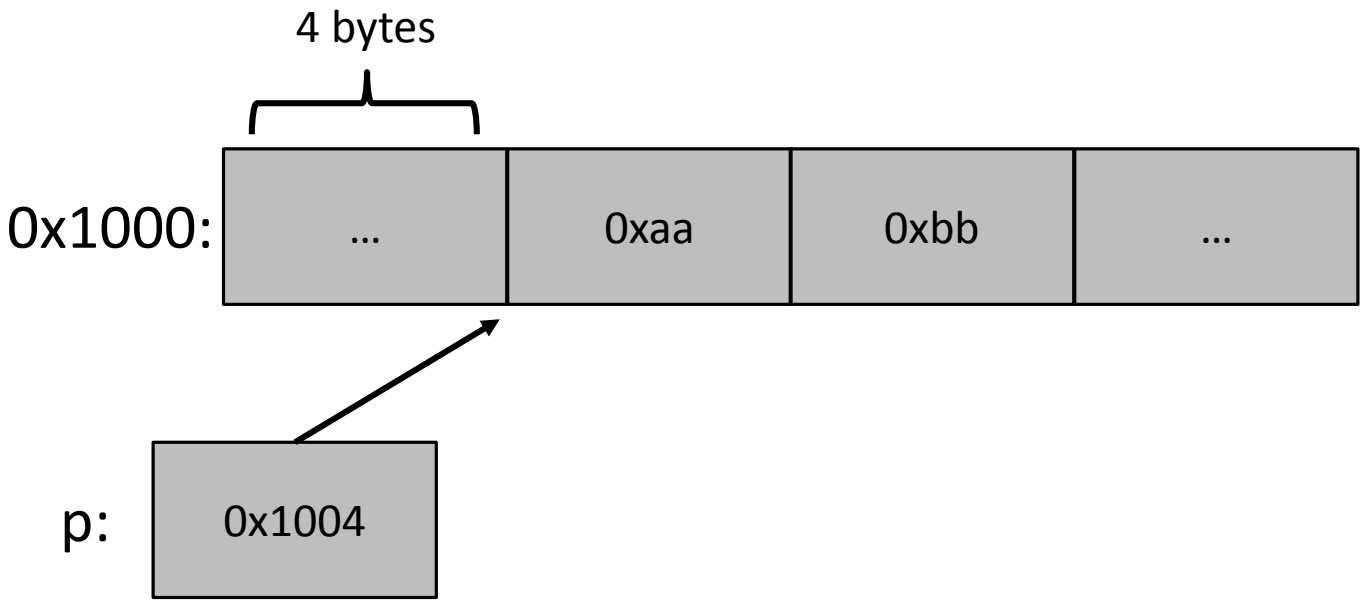

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  int y;
}
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  p.x = 0xaa;
  p.y = 0xbb;
}
```

```
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?

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Field Offsets

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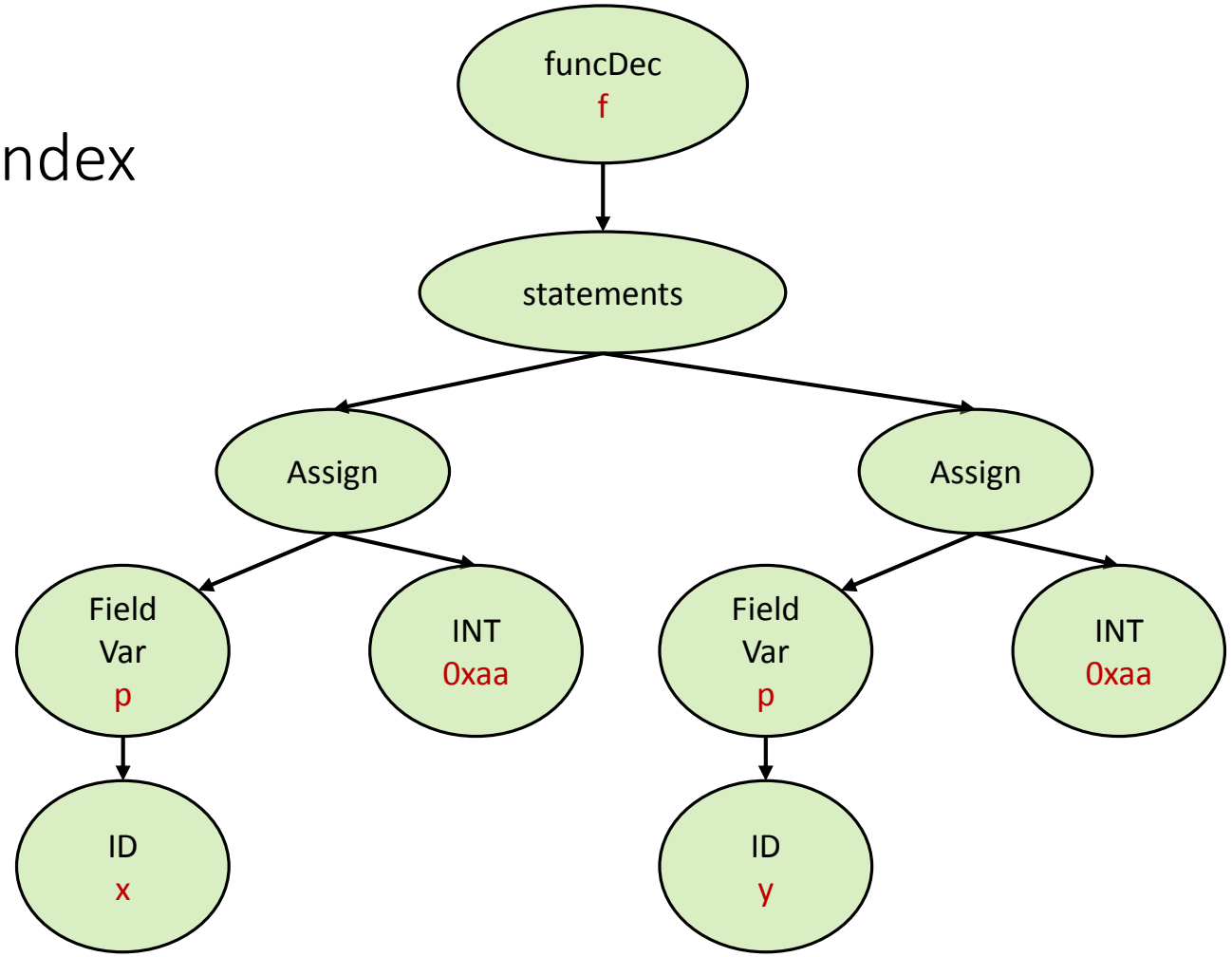

Field Offsets

Each class field should have an index

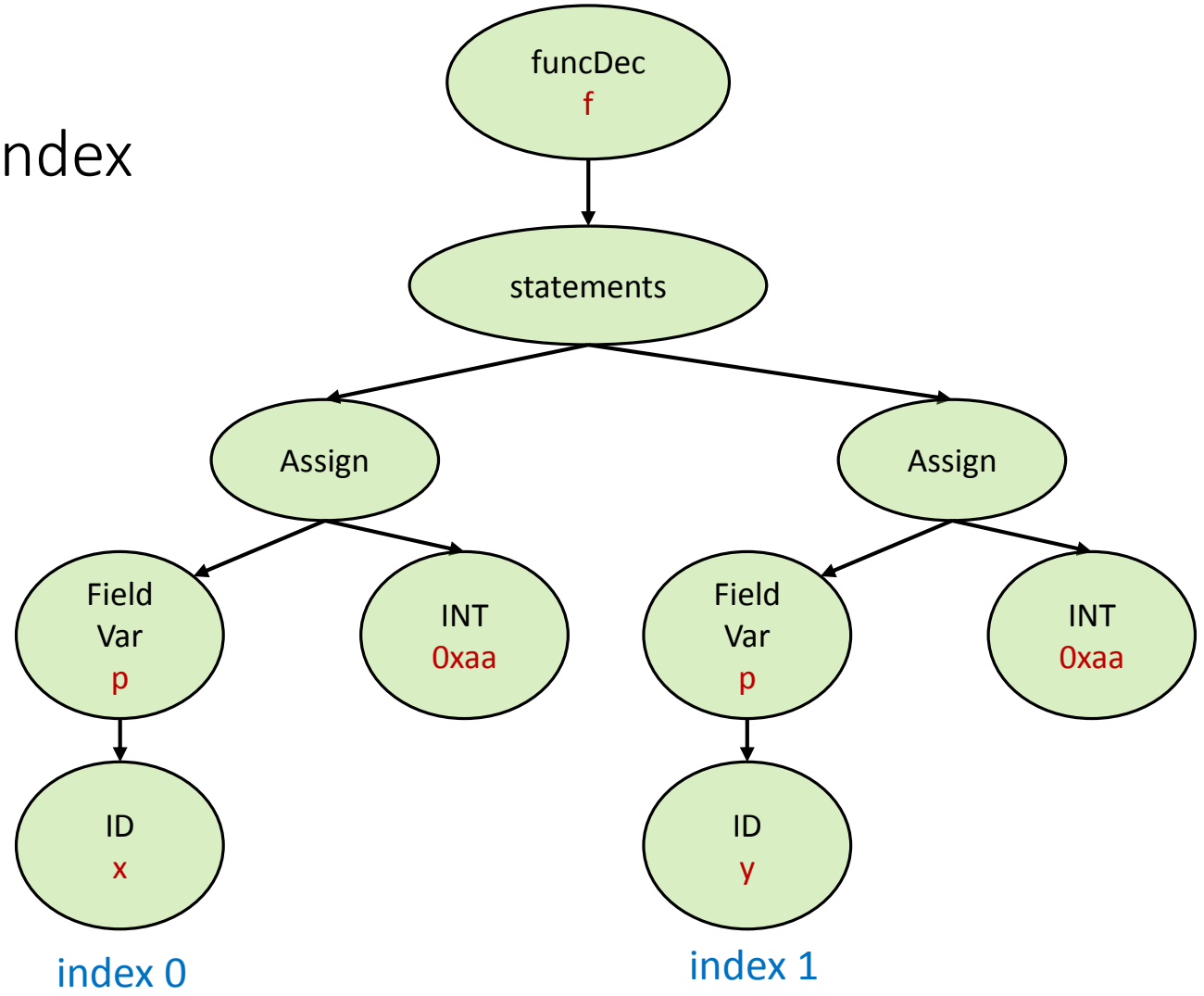
```
class Point {
  int x;
  int y;
}
void f(Point p) {
  p.x = 0xaa;
  p.y = 0xbb;
}
```



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>
```