# Clang Tutorial

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# Content

- Motivation of learning code analysis technique
- Overview of Clang
- AST structure of Clang
  - Decl class
  - Stmt class
- Traversing Clang AST

# Motivation for Learning Code Analysis Technique

- Biologists know how to **analyze** laboratory mice. In addition, they know how to **modify** the mice by applying new medicine or artificial organ
- Mechanical engineers know how to analyze and modify mechanical products using CAD **tools**.
- Software engineers also have to know how to analyze and modify software code which is far more complex than any engineering product. Thus, software analysis/modification requires **automated analysis tools.**
  - Using source level analysis framework (e.g., Clang, C Intermediate Language (CIL), EDG parser)
  - Using low-level intermediate representation (IR) analysis framework (e.g., LLVM IR)

# Overview

- There are frequent chances to analyze/modify program code mechanically/automatically
  - Ex1. Refactoring code for various purposes
  - Ex2. Generate test driver automatically
  - Ex3. Insert probes to monitor target program behavior
- Clang is a library to convert a C program into an abstract syntax tree (AST) and manipulate the AST
  - Clang, the LLVM C/C++ front-end supports the full-features of C/C++ and compatible with GCC
  - Ex) finding branches, renaming variables, pointer alias analysis, etc
- Clang is particularly useful to simply modify C/C++ code
  - Ex1. Add `printf("Branch Id:%d\n",bid)` at each branch
  - Ex2. Add `assert(pt != null)` right before referencing `pt`

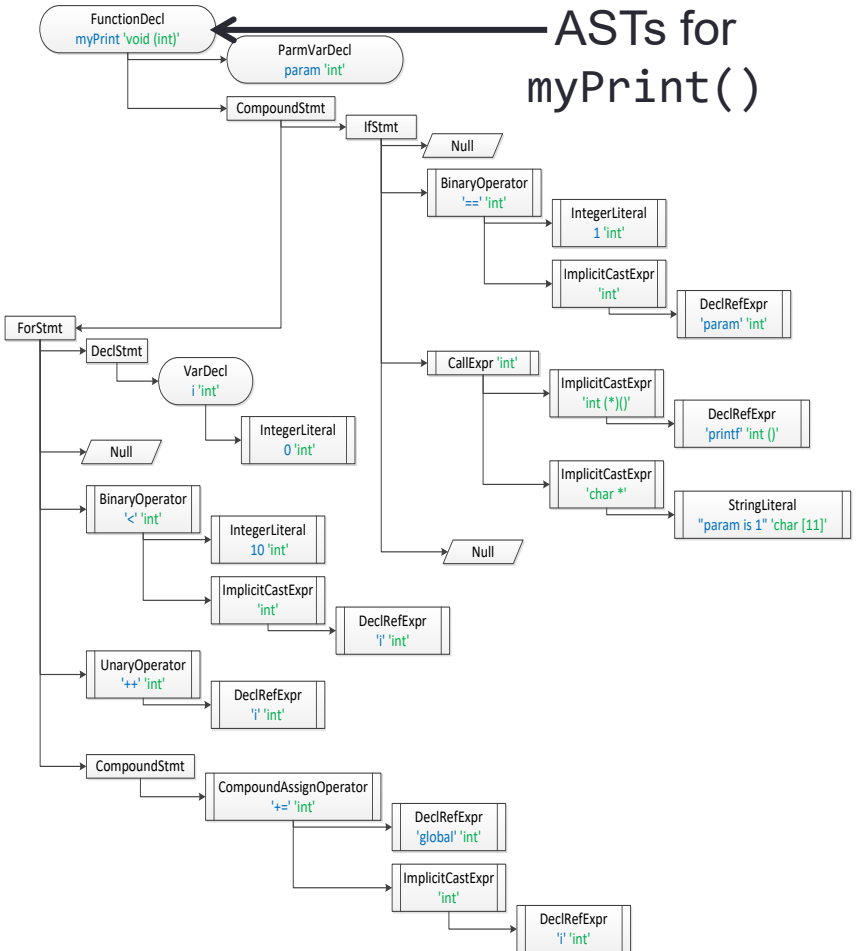
# Example C code

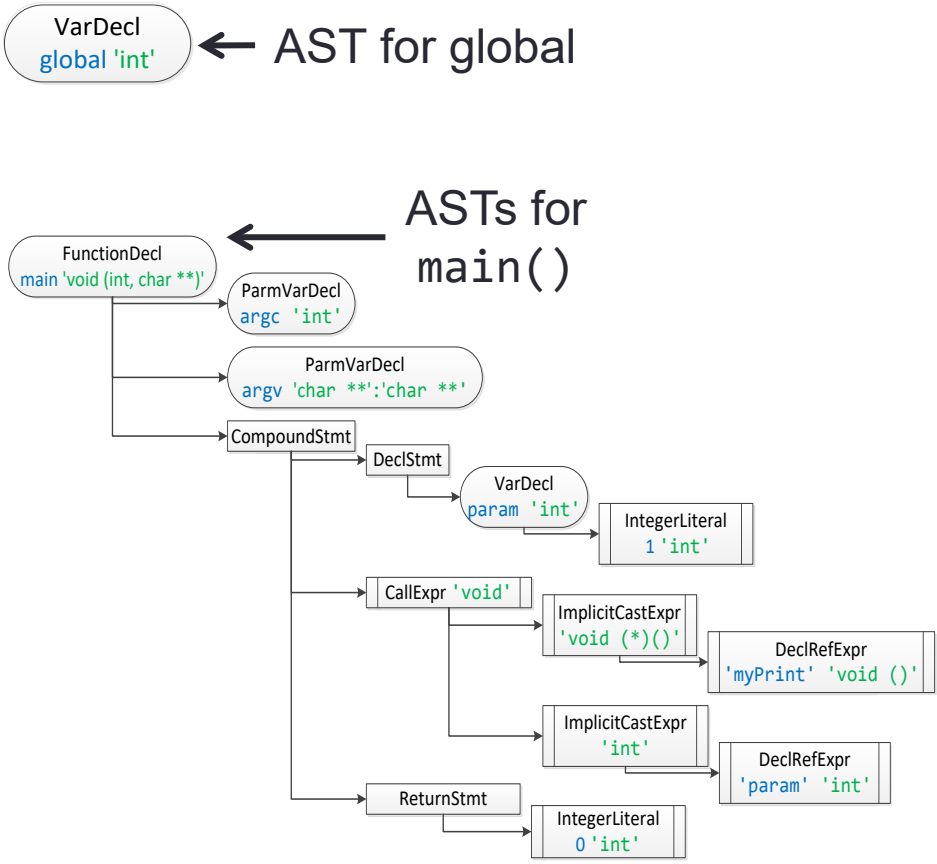
- 2 functions are declared: `myPrint` and `main`
  - `main` function calls `myPrint` and returns 0
  - `myPrint` function calls `printf`
    - `myPrint` contains if and for statements
- 1 global variable is declared: global

```
//clang_example.c
#include <stdio.h>

int global;

void myPrint(int param) {
  if (param == 1)
    printf("param is 1");
  for (int i = 0 ; i < 10 ; i++ ) {
    global += i;
  }
}

int main(int argc, char *argv[]) {
  int param = 1;
  myPrint(param);
  return 0;
}
```

# Example AST

- Clang generates 3 ASTs for `myPrint()`, `main()`, and global
  - A function declaration has a function body and parameters



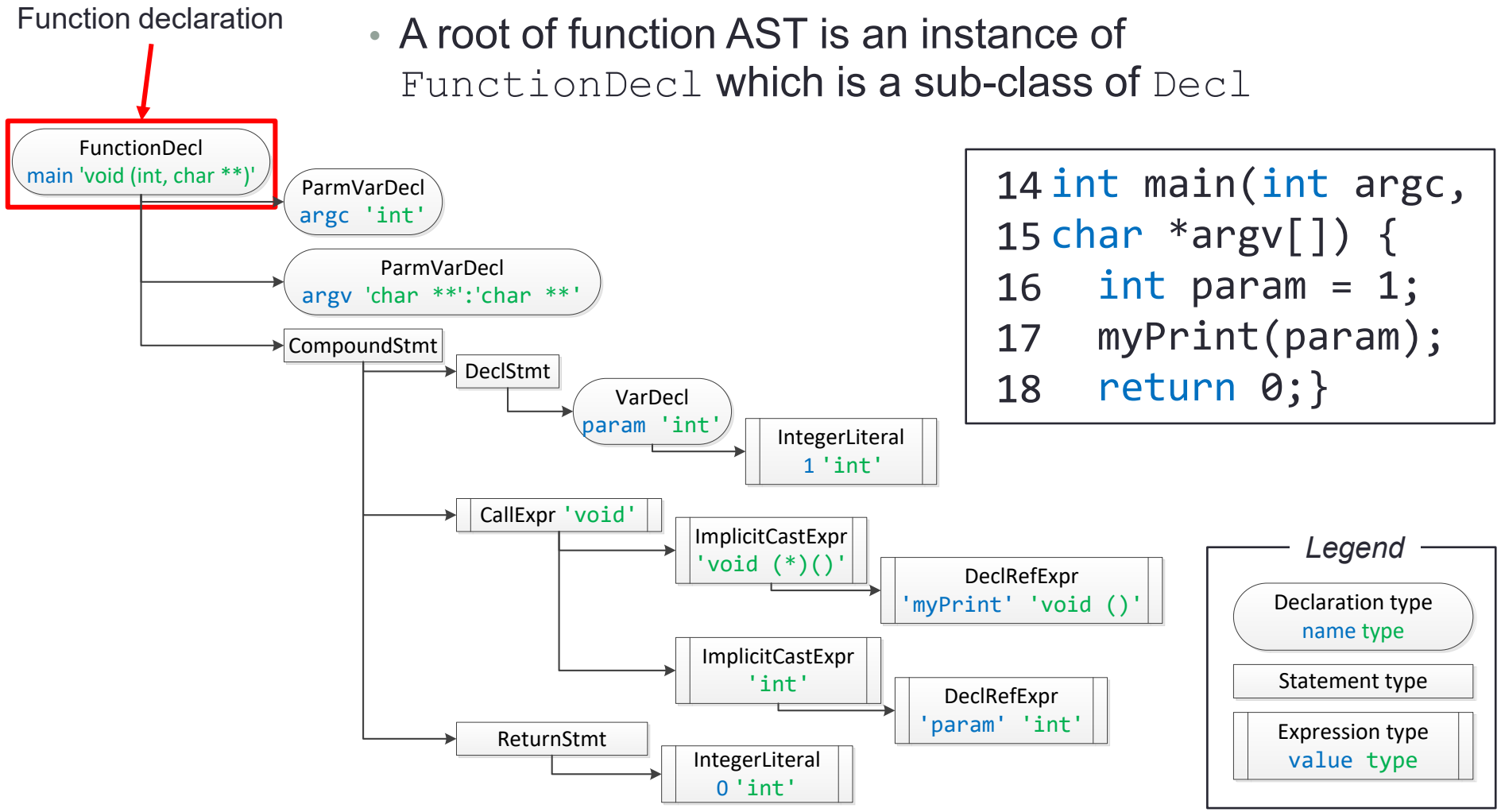



# Structure of AST

- Each node in AST is an instance of either `Decl` or `Stmt` class
  - `Decl` represents declarations and there are sub-classes of `Decl` for different declaration types
    - Ex) `FunctionDecl` class for function declaration and `ParmVarDecl` class for function parameter declaration
  - `Stmt` represents statements and there are sub-classes of `Stmt` for different statement types
    - Ex) `IfStmt` for `if` and `ReturnStmt` class for function return
  - Comments (i.e. `/* */`, `//` ) are not built into an AST

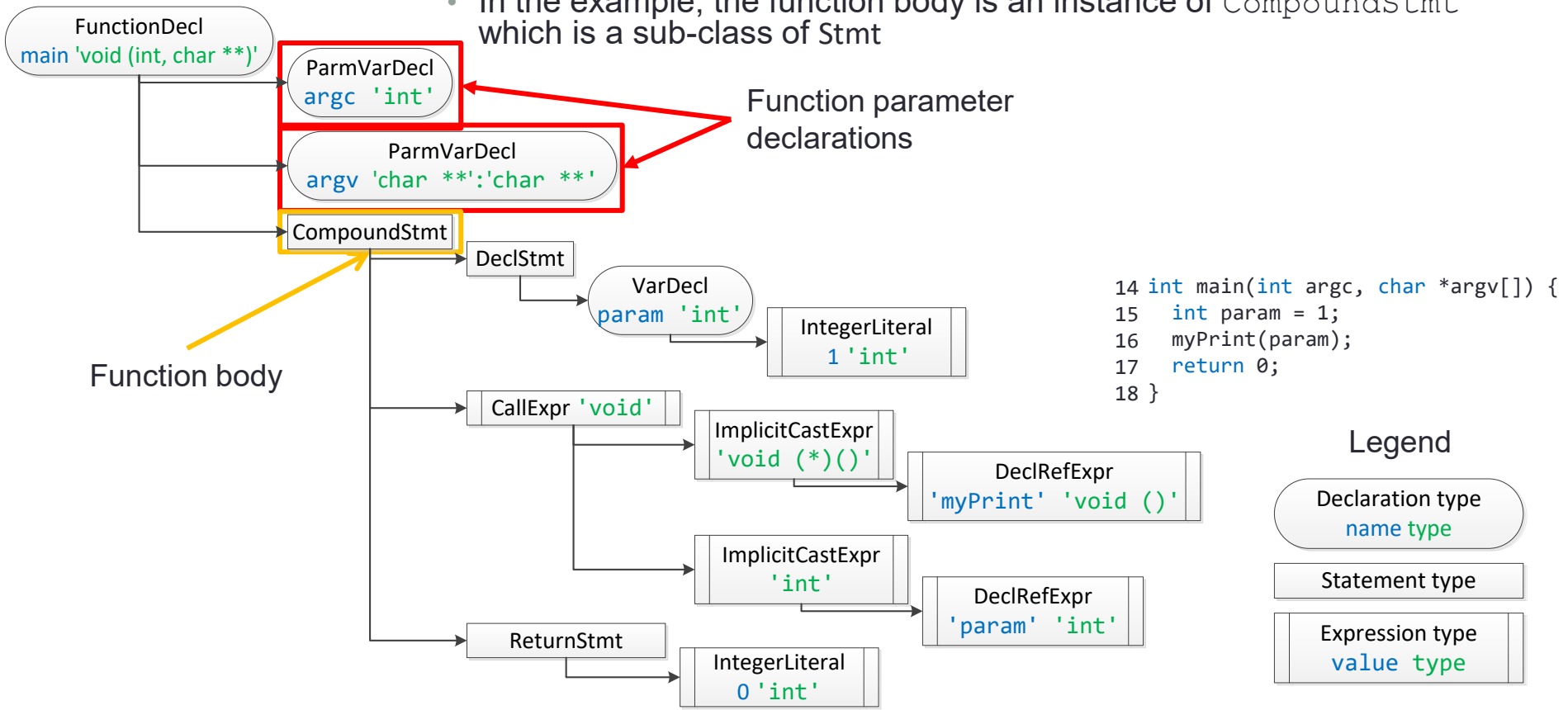
# Decl (1/4)

- A root of the function AST is a `Decl` node
  - A root of function AST is an instance of `FunctionDecl` which is a sub-class of `Decl`



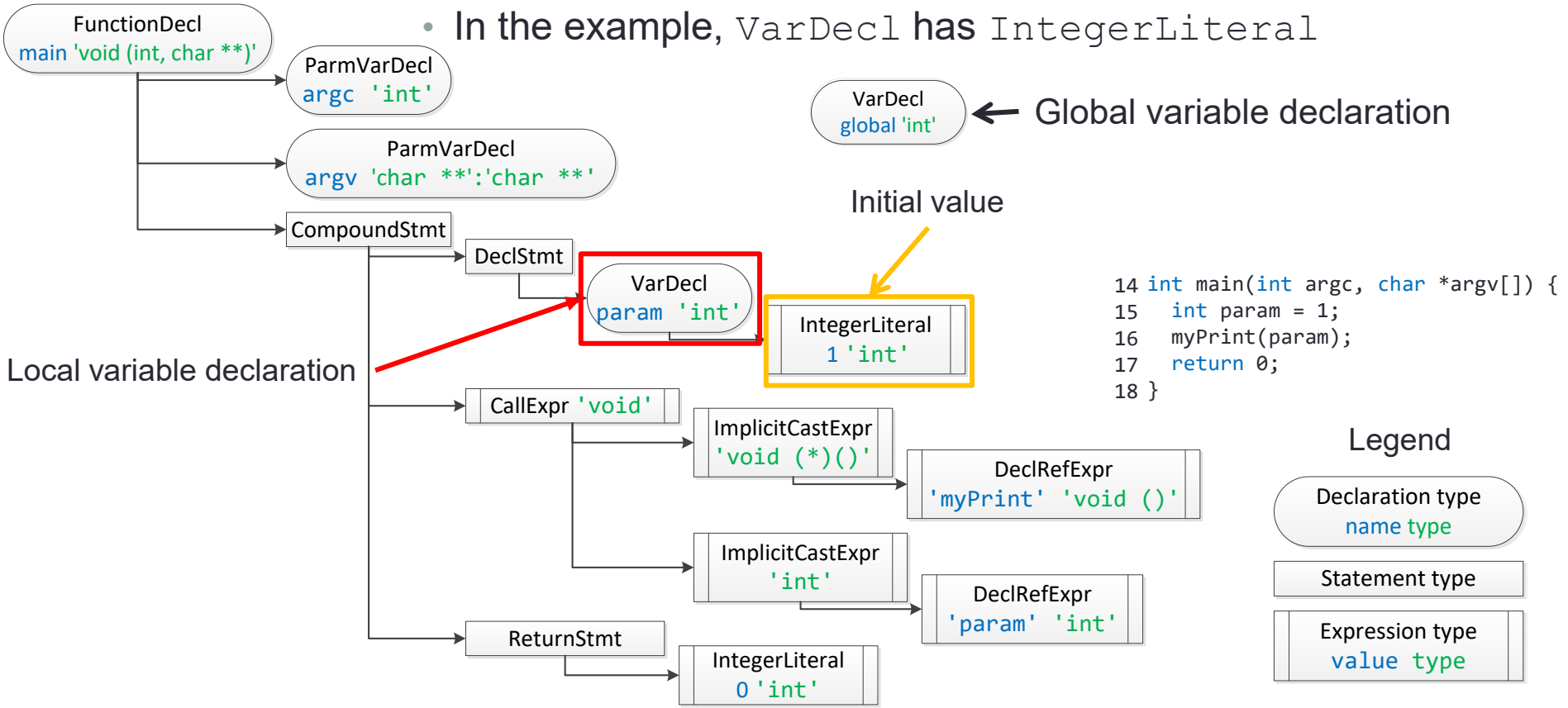
# Decl (2/4)

- `FunctionDecl` can have an instance of `ParmVarDecl` for a function parameter and a function body
  - `ParmVarDecl` is a child class of `Decl`
  - Function body is an instance of `Stmt`
    - In the example, the function body is an instance of `CompoundStmt` which is a sub-class of Stmt



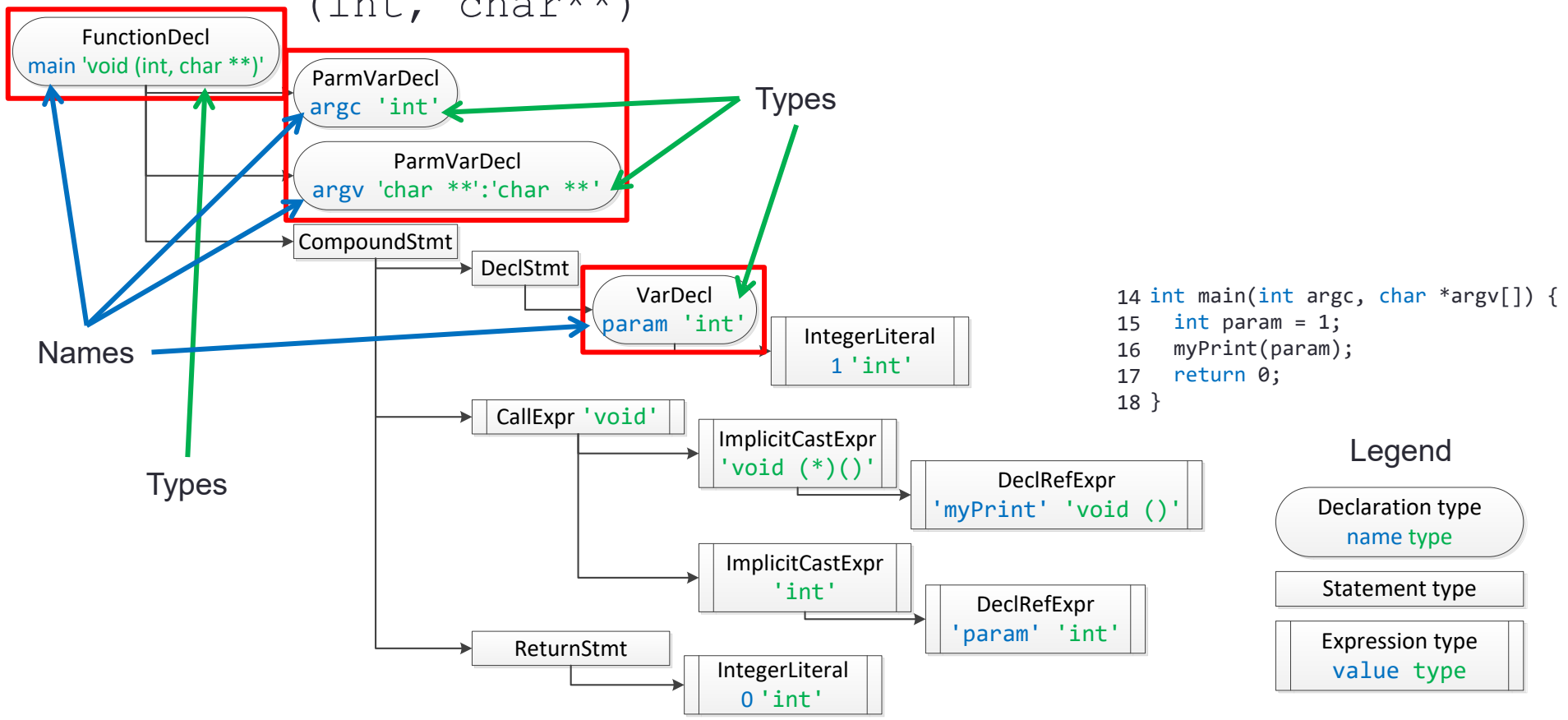
# Decl (3/4)

- `VarDecl` is for a local and global variable declaration
  - `VarDecl` has a child if a variable has a initial value
    - In the example, `VarDecl` has `IntegerLiteral`



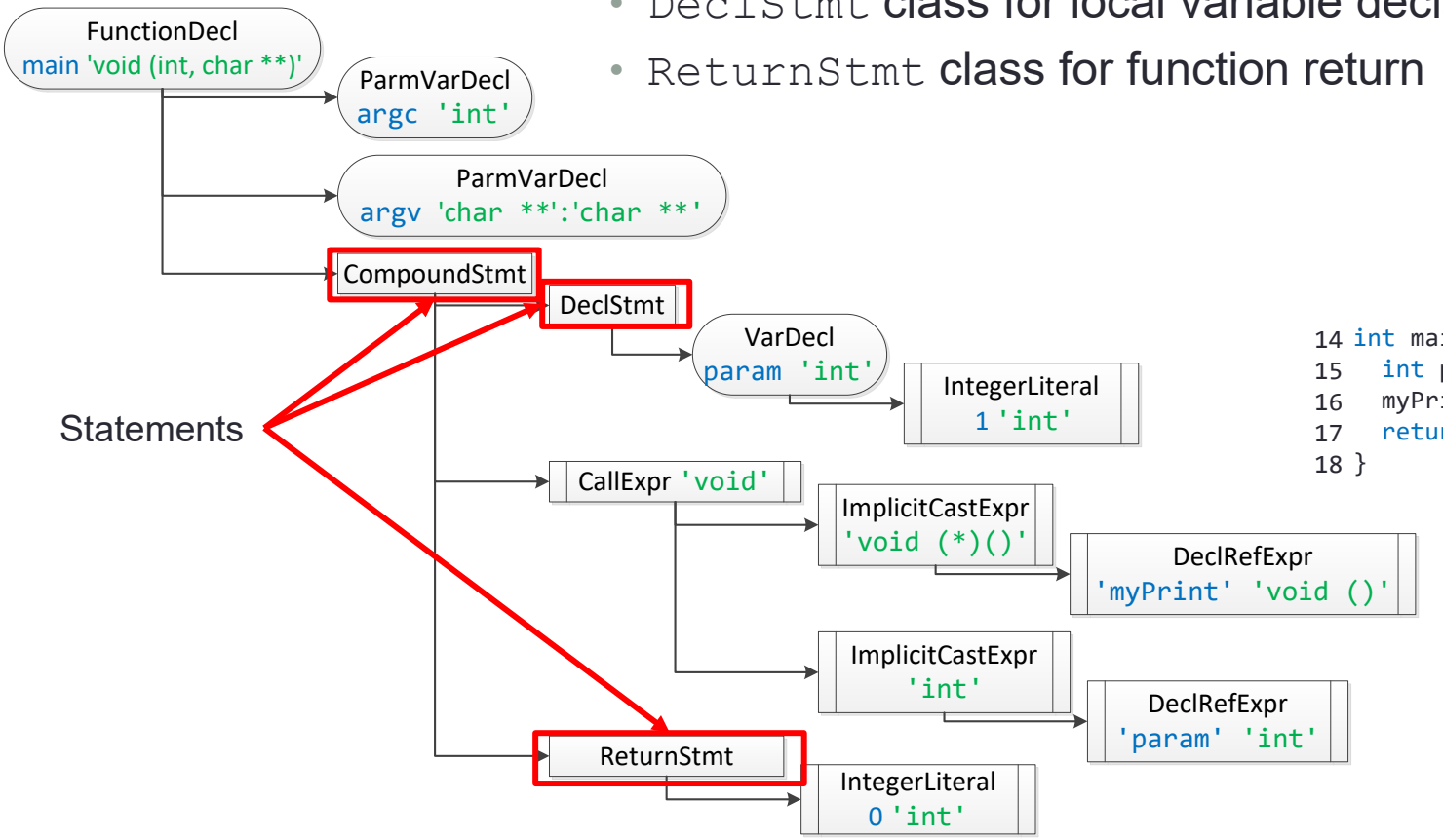
# Decl (4/4)

- `FunctionDecl`, `ParmVarDecl` and `VarDecl` have a name and a type of declaration
  - Ex) `FunctionDecl` has a name '`main`' and a type '`void (int, char**)`'



# Stmt (1/9)

- `Stmt` represents a statement
  - Subclasses of `Stmt`
    - `CompoundStmt` class for code block
    - `DeclStmt` class for local variable declaration
    - `ReturnStmt` class for function return




```
14 int main(int argc, char *argv[]) {
15   int param = 1;
16   myPrint(param);
17   return 0;
18 }
```

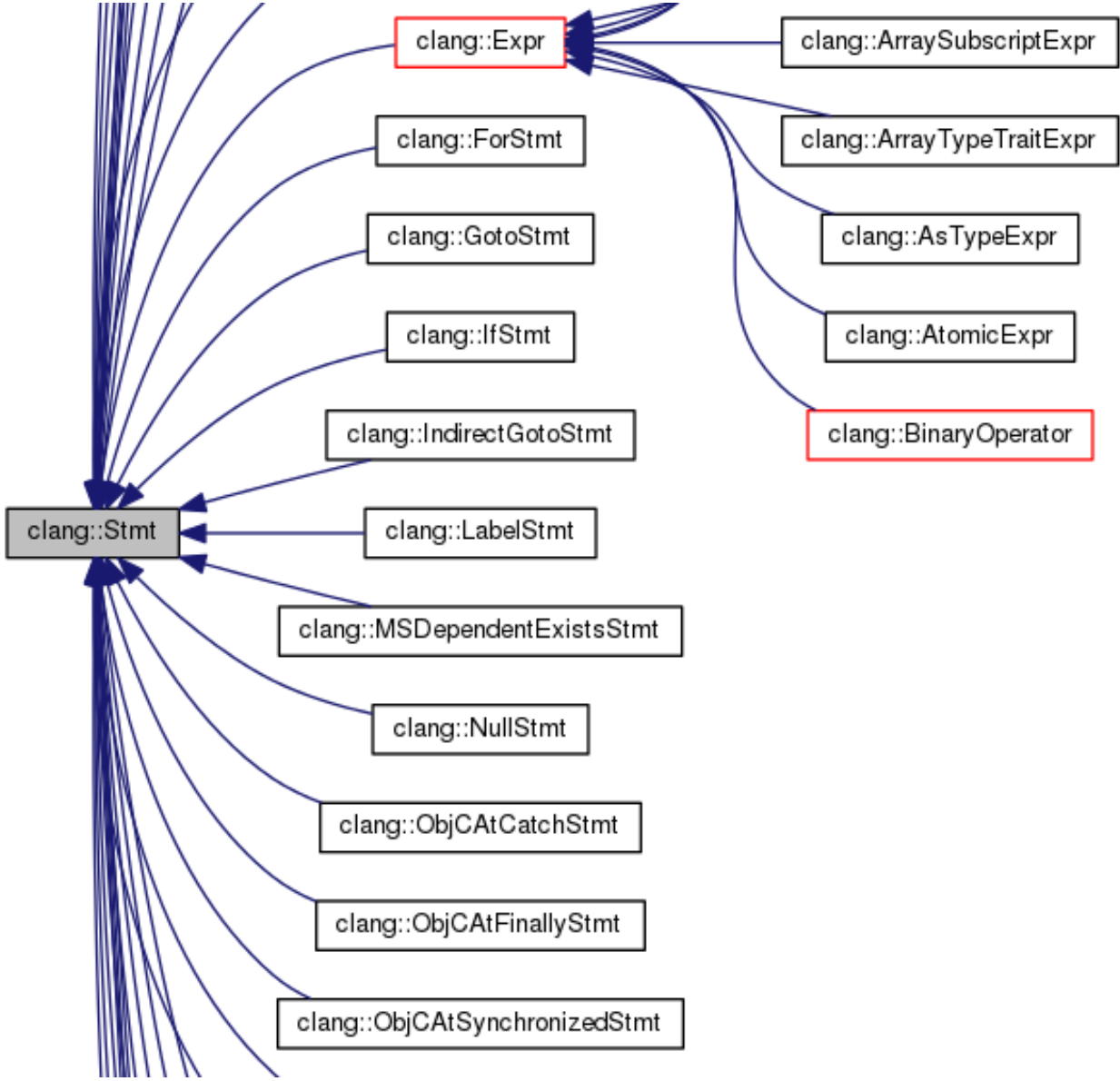
Legend

Declaration type
name type

Statement type

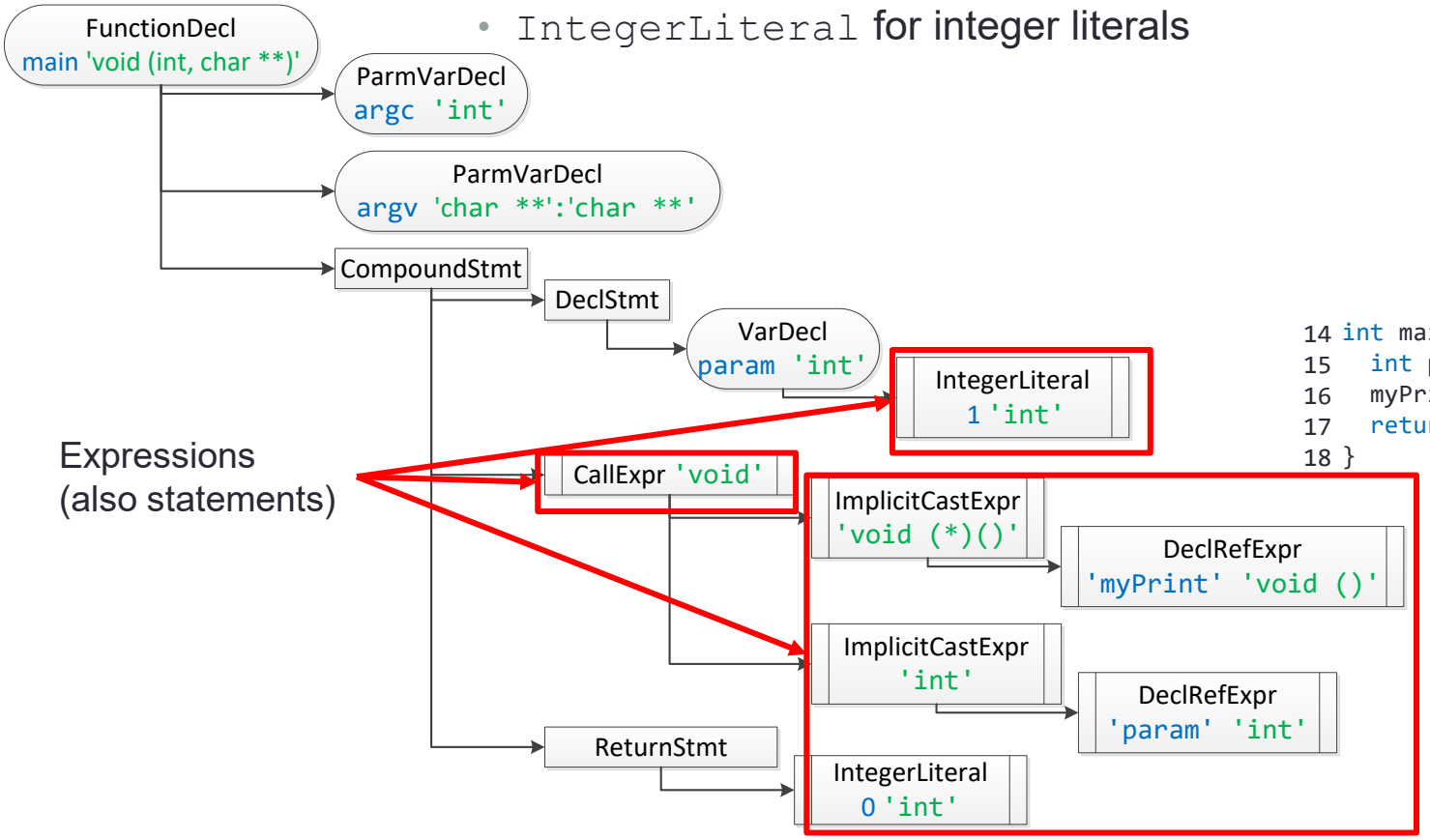
Expression type
value type

https://clang.llvm.org/doxygen/



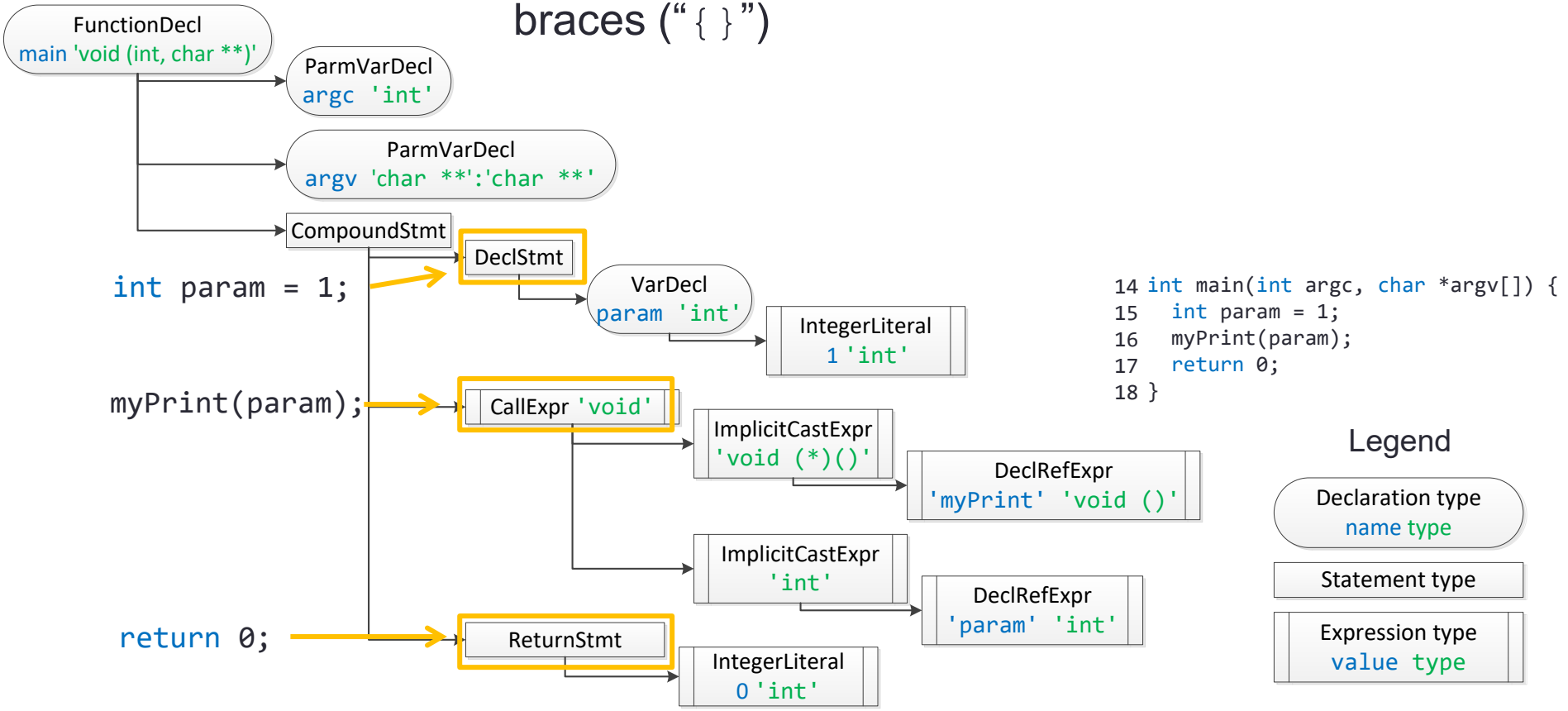
# Stmt (2/9)

- `Expr` represents an expression (a subclass of `Stmt`)
  - Subclasses of `Expr`
    - `CallExpr` for function call
    - `ImplicitCastExpr` for implicit type casts
    - `DeclRefExpr` for referencing declared variables and functions
    - `IntegerLiteral` for integer literals



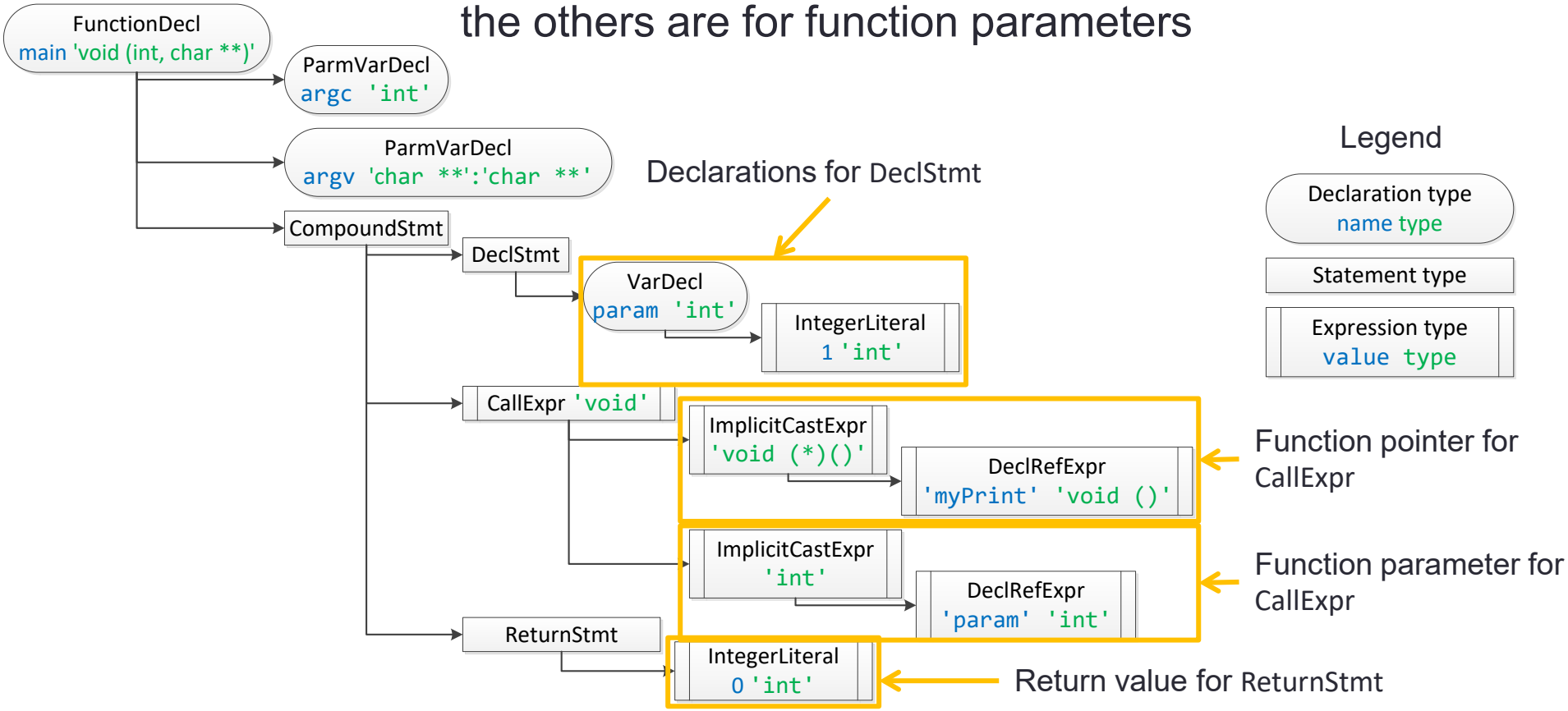
# Stmt (3/9)

- `Stmt` may have a child containing additional information
  - `CompoundStmt` has statements in a code block of braces (“`{}`”)



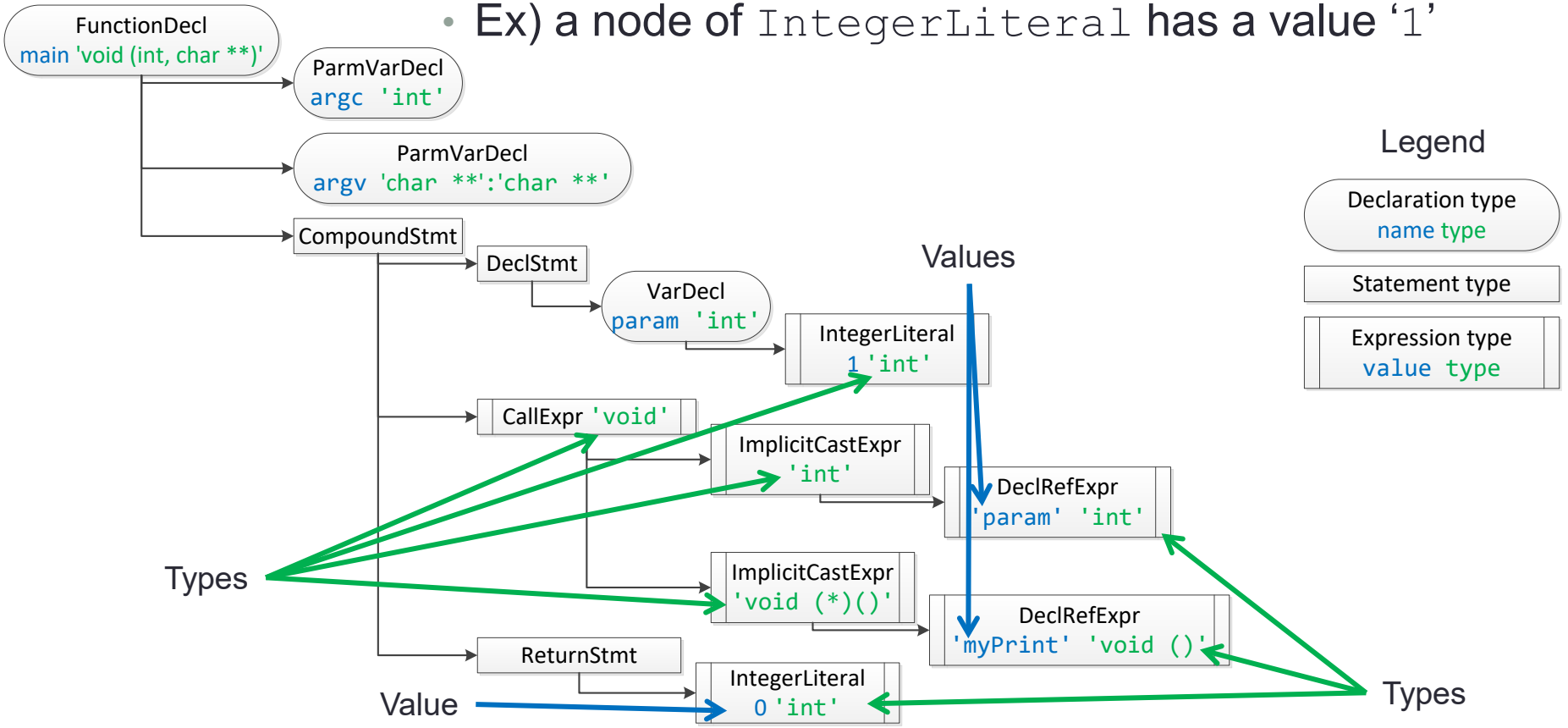
# Stmt (4/9)

- `Stmt` may have a child containing additional information (cont')
  - The first child of `CallExpr` is for a function pointer and the others are for function parameters

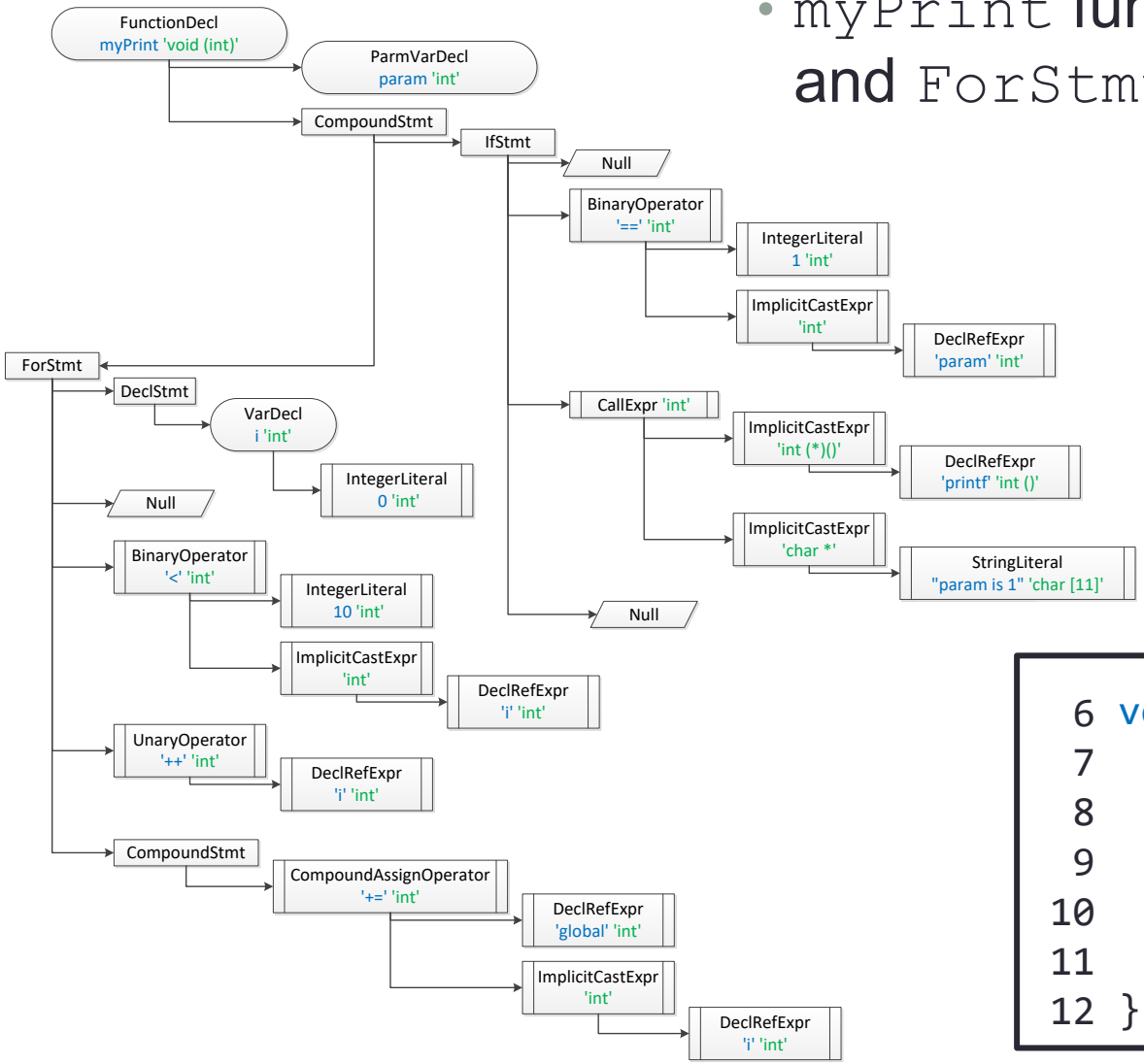


# Stmt (5/9)

- `Expr` has a type of an expression
  - Ex) a node of `CallExpr` has a type '`void`'
- Some sub-classes of `Expr` can have a value
  - Ex) a node of `IntegerLiteral` has a value '`1`'



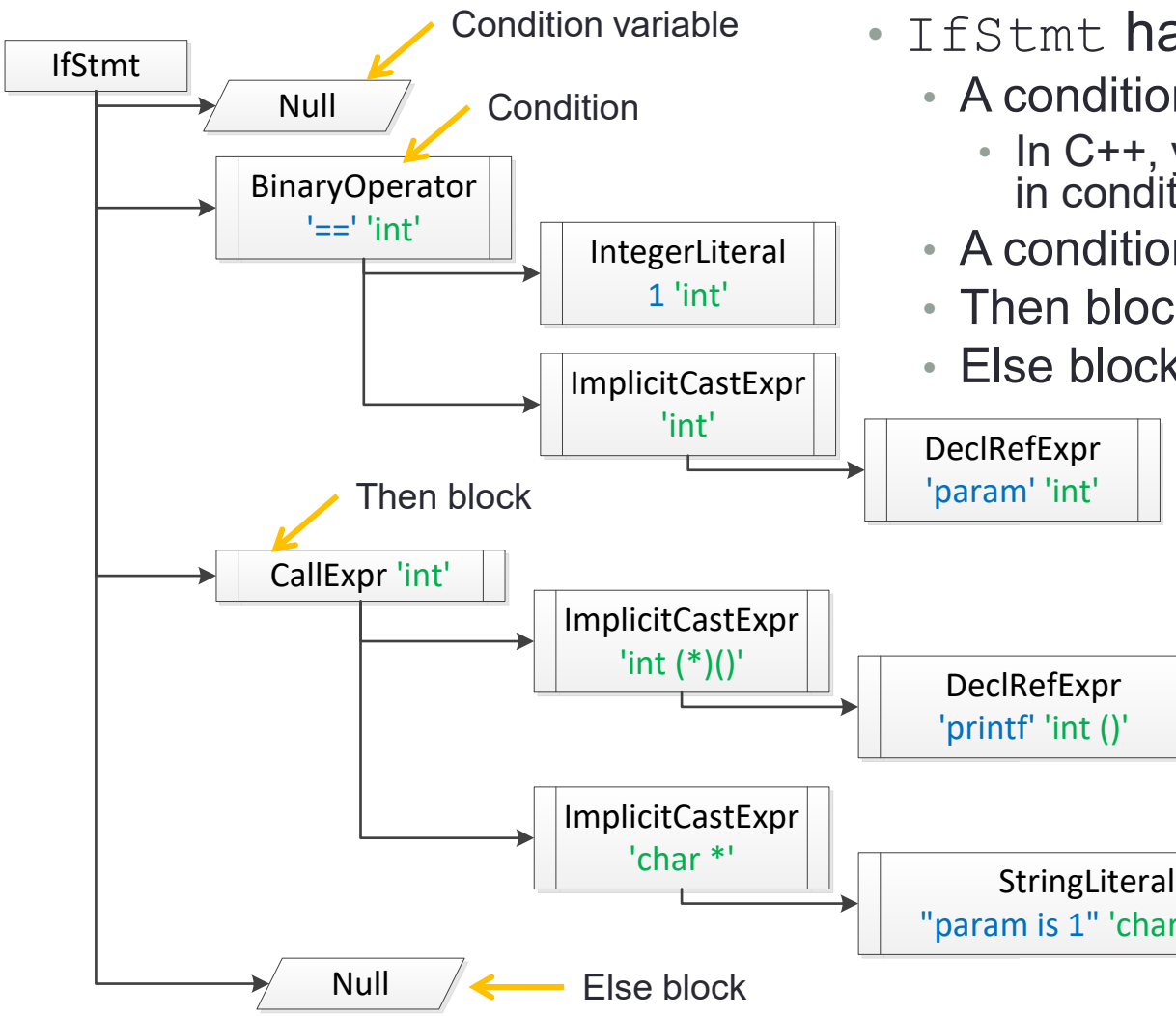
# Stmt (6/9)




- `myPrint` function contains `IfStmt` and `ForStmt` in its function body

```
 6 void myPrint(int param) {
 7   if (param == 1)
 8     printf("param is 1");
 9   for (int i=0;i<10;i++) {
10     global += i;
11   }
12 }
```

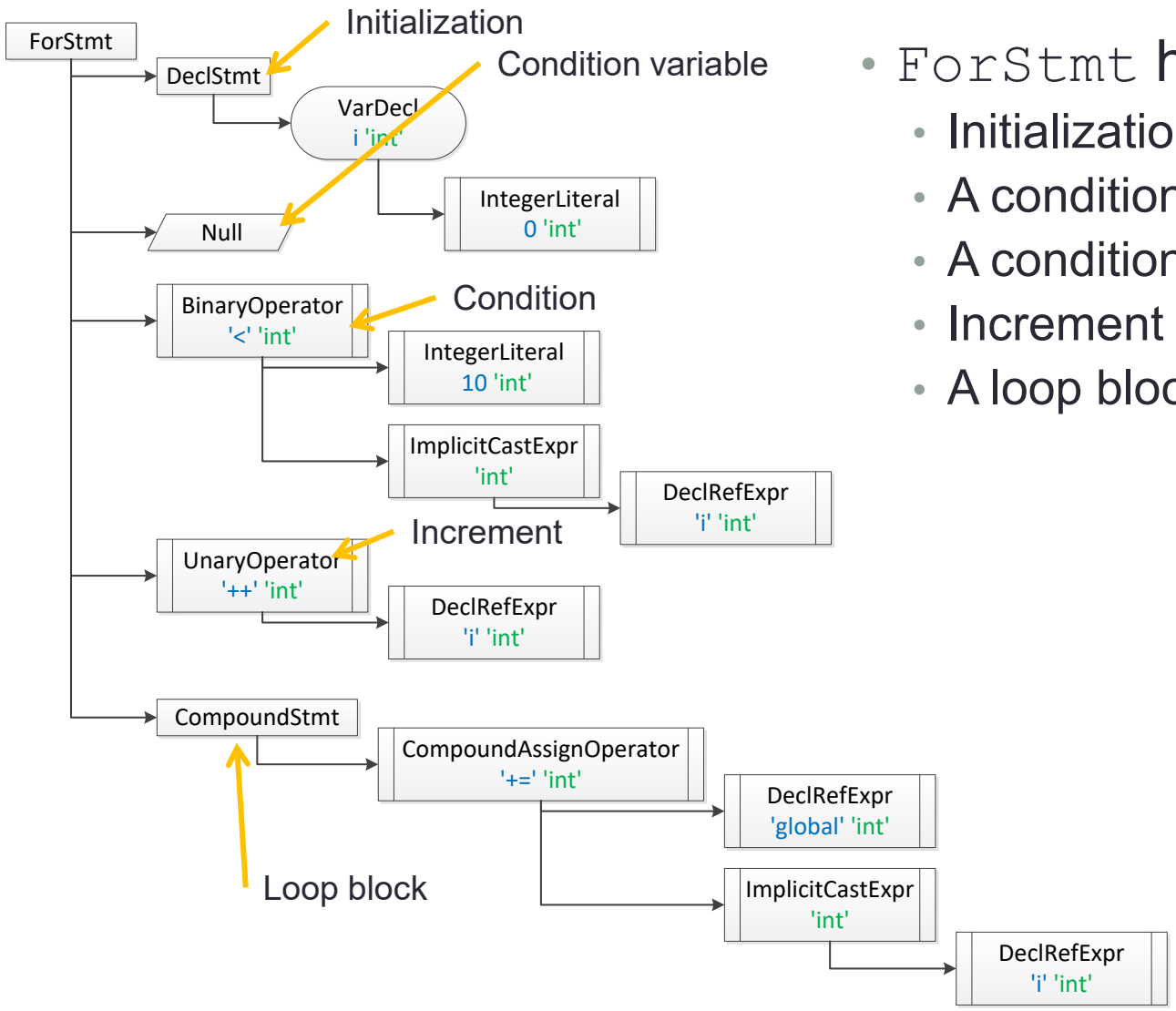
# Stmt (7/9)




- `IfStmt` has 4 children
  - A condition variable in `VarDecl`
    - In C++, you can declare a variable in condition (not in C)
  - A condition in `Expr`
  - Then block in `Stmt`
  - Else block in `Stmt`

```
 6 void myPrint(int param) {
 7   if (param == 1)
 8     printf("param is 1");
 9   for (int i = 0 ; i < 10 ; i++ ) {
10     global += i;
11   }
12 }
```

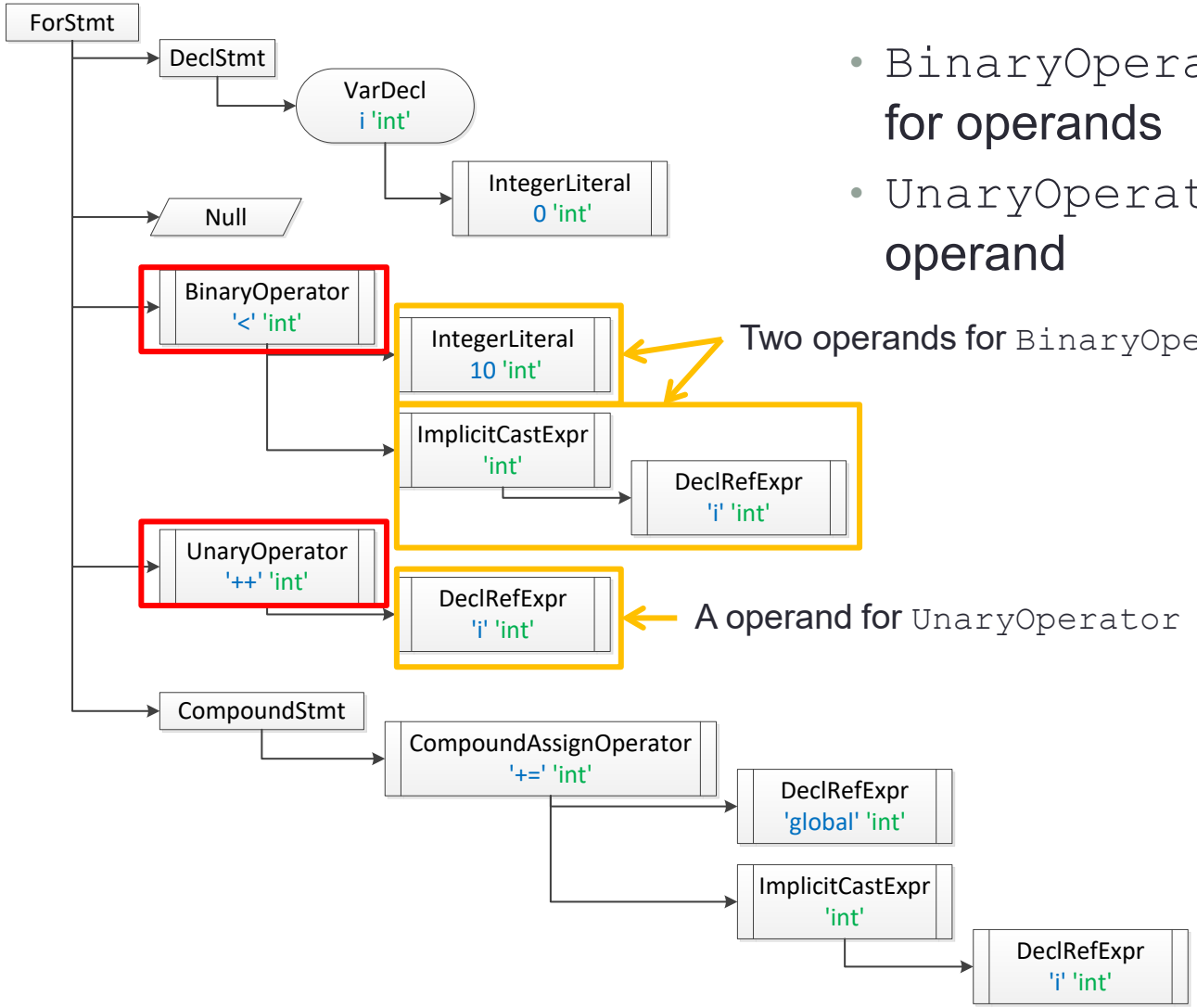
# Stmt (8/9)




- `ForStmt` has 5 children
  - Initialization in `Stmt`
  - A condition variable in `VarDecl`
  - A condition in `Expr`
  - Increment in `Expr`
  - A loop block in `Stmt`

```
 6  void myPrint(int param) {
 7    if (param == 1)
 8      printf("param is 1");
 9    for (int i = 0 ; i < 10 ; i++ ) {
10      global += i;
11    }
12  }
```

# Stmt (9/9)




- `BinaryOperator` has 2 children for operands
- `UnaryOperator` has a child for operand

Two operands for `BinaryOperator`

A operand for `UnaryOperator`

```
 6  void myPrint(int param) {
 7    if (param == 1)
 8      printf("param is 1");
 9    for (int i = 0 ; i < 10 ; i++ ) {
10      global += i;
11    }
12  }
```

# Traversing Clang AST (1/3)

- Clang provides a visitor design pattern for user to access AST
- ParseAST() starts building and traversal of an AST:

  void clang::ParseAST (Preprocessor &pp, **ASTConsumer *C**, ASTContext &Ctx, …)

  - The callback function HandleTopLevelDecl() in ASTConsumer is called for each top-level declaration
    - HandleTopLevelDecl() receives a list of function and global variable declarations as a parameter
- A user has to customize ASTConsumer to build his/her own program analyzer

```
 1 class MyASTConsumer : public ASTConsumer
 2 {
 3   public:
 4   MyASTConsumer(Rewriter &R) {}
 5
 6   virtual bool HandleTopLevelDecl(DeclGroupRef DR) {
 7     for(DeclGroupRef::iterator b=DR.begin(), e=DR.end(); b!=e;++b){
 8       … // variable b has each decleration in DR
 9     }
10     return true;
11   }
12 };
```

# Traversing Clang AST (2/3)

- HandleTopLevelDecl() calls TraverseDecl() which recursively travel a target AST from the top-level declaration by calling VisitStmt (), VisitFunctionDecl(), etc.

```
1  class MyASTVisitor : public RecursiveASTVisitor<MyASTVisitor> {
2    bool VisitStmt(Stmt *s) {
3      printf("\t%s \n", s->getStmtClassName() );
4      return true;
5    }
6    bool VisitFunctionDecl(FunctionDecl *f) {
7      if (f->hasBody()) {
8        Stmt *FuncBody = f->getBody();
9        printf("%s\n", f->getName());
10     }
11     return true;
12   }
13 };
14 class MyASTConsumer : public ASTConsumer {
15   virtual bool HandleTopLevelDecl(DeclGroupRef DR) {
16     for (DeclGroupRef::iterator b = DR.begin(), e = DR.end(); b != e; ++b) {
17       MyASTVisitor Visitor;
18       Visitor.TraverseDecl(*b);
19     }
20     return true;
21   }
22   …
23 };
```

`VisitStmt` is called when `Stmt` is encountered

`VisitFunctionDecl` is called when FunctionDecl is encountered

# Traversing Clang AST (3/3)

- VisitStmt() in `RecursiveASTVisitor` is called for every `Stmt` object in the AST `RecursiveASTVisitor` visits each `Stmt` in a depth-first search order
  - If the return value of `VisitStmt` is false, recursive traversal halts
  - Example: `main` function of the previous example