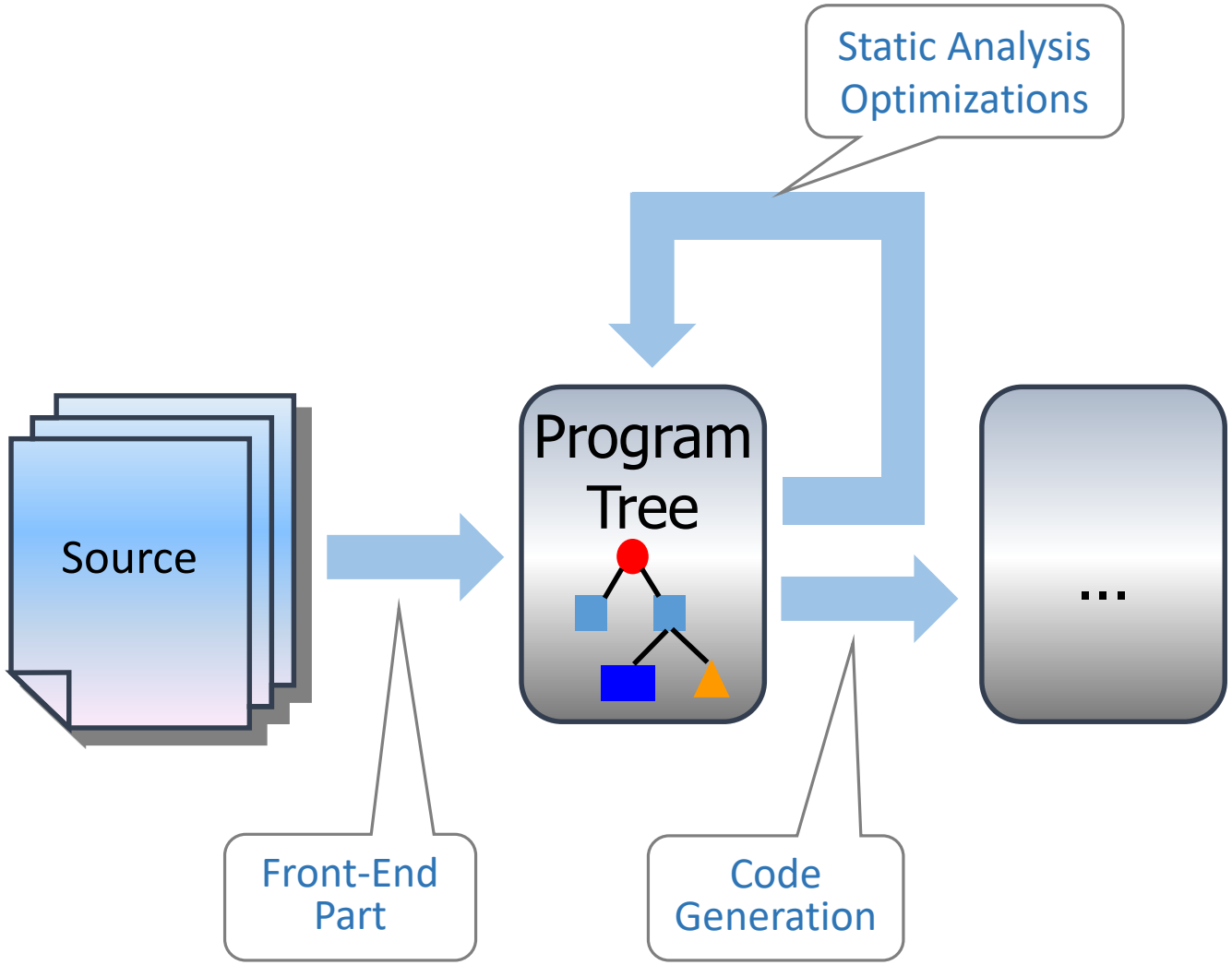
# Compiler Construction: Practical Introduction

## Lecture 4
## Compilation Structures

**Eugene Zouev**

Spring Semester 2023
Innopolis University

# Compilation structures



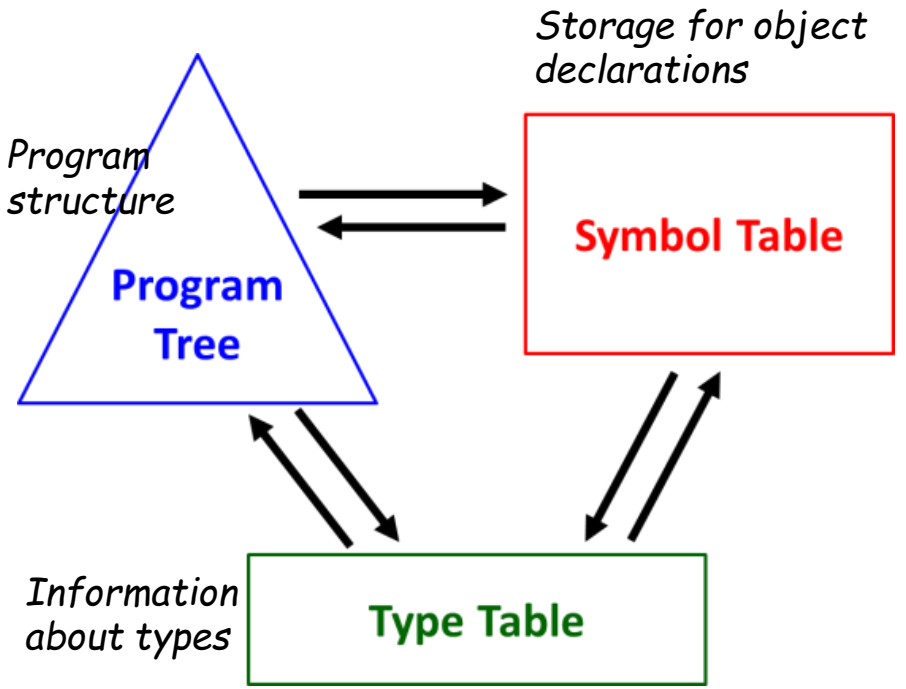
# Compilation structures

**What for:**

Represent all information from the source program (lexical, syntactical, semantic) **in a way convenient for further analysis** and processing.

**Three entity categories of any language:**

- Objects/declarations
- Executable parts: expressions, statements
- Types



# Symbol table (1)

```
procedure Swap ( a, b : in out Integer )
is
   Temp : Integer := a;
begin
   a := b;
   b := Temp;
end Swap;
```

- Old compiler example
- Old language (Ada)
- Old implementation platform
- *…But still good as an example* ☺

**What should we need to know about declarations?**

- **Entity name**
- **Entity category**
- **Entity type (if any)**
- **Initializer (if any)**
- **Span info**
- **Extra info**

# Symbol table (2)

What should we need to know about declarations?

- Entity name
- Entity category
- Entity type (if any)
- Initializer (if any)
- Span info
- Extra info

- Just a string
- A reference to a string table

- Variable
- Constant
- Type
- Function
- …

- int, float, char, …
- class, struct, enum, …
- pointer, reference, …
- auto-deduced type
- …

Initializer is an expression and therefore is represented as a tree

- parameter
- in, out, in+out
- used/non-used
- …

- Line number
- Position number
- File name

# Symbol table (3)

```
void f ( int a, float b )
{
    int x = a*b;
    enum color { red, yellow, green };
    typedef int* pint;
    extern int h(int);
    h(x+1);
    int y;
    pint v;
}
```

**Comments**:

- There are **nine** entities declared in the function body.
- The entities are:
  - Variables `x`, `v`, `y`
  - Types `color`, `pint`
  - Constants `red`, `yellow`, `green`
  - Function `h`
- Variable `x` is initialized by an expression, variables `y` and `v` are left uninitialized.
- Variable `x` and function `h` are used within the body, others are not.
- Declarations are intermixed with statements (see `h(x+1)` call).

# Symbol table (4)

```
void f ( int a, float b )
{
    int x = a*b;
    enum color { red, yellow, green };
    typedef int* pint;
    extern int h(int);
    h(x+1);
    int y;
    pint v;
}
```

| Category | Name | Initializer | Type | Extra | … |
|---|---|---|---|---|---|
| **Variable** | x | Tree for **a*b** | int | | |
| **Enum type** | color | --- | --- | | |
| **Constant** | red | 0 | color | | |
| **Constant** | yellow | 1 | color | | |
| **Constant** | green | 2 | color | | |
| **Type synonym** | pint | --- | int* | | |
| **Function** | h | --- | int | **Function specification** | |
| … | … | … | … | | |

# Symbol table (5)

## An idea for implementation

```
abstract class Declaration {
    Span span;
    string name;
    // Other properties representing
    // features common to all
    // categories of declarations
    ...
}
```

```
class  Variable: Declaration {
    // Properties representing
    // features that are specific
    // for variables
    Type type;
    Tree initializer;
    ...
}
```

```
class  Constant: Declaration {
    // Properties representing
    // features that are specific
    // for constants
    Type type;
    Tree initializer;
    ...
}
```

# Symbol table (6)

## An idea for implementation

```
abstract class Declaration        // Any declaration
    abstract class Object         // Constants and variables
        class Variable
        class Constant
    abstract class TypeDecl       // All type declarations
        class Enum
        class Struct
        class Array
    class FunctionDecl            // Function declarations
    ...
```

# Symbol table (6)

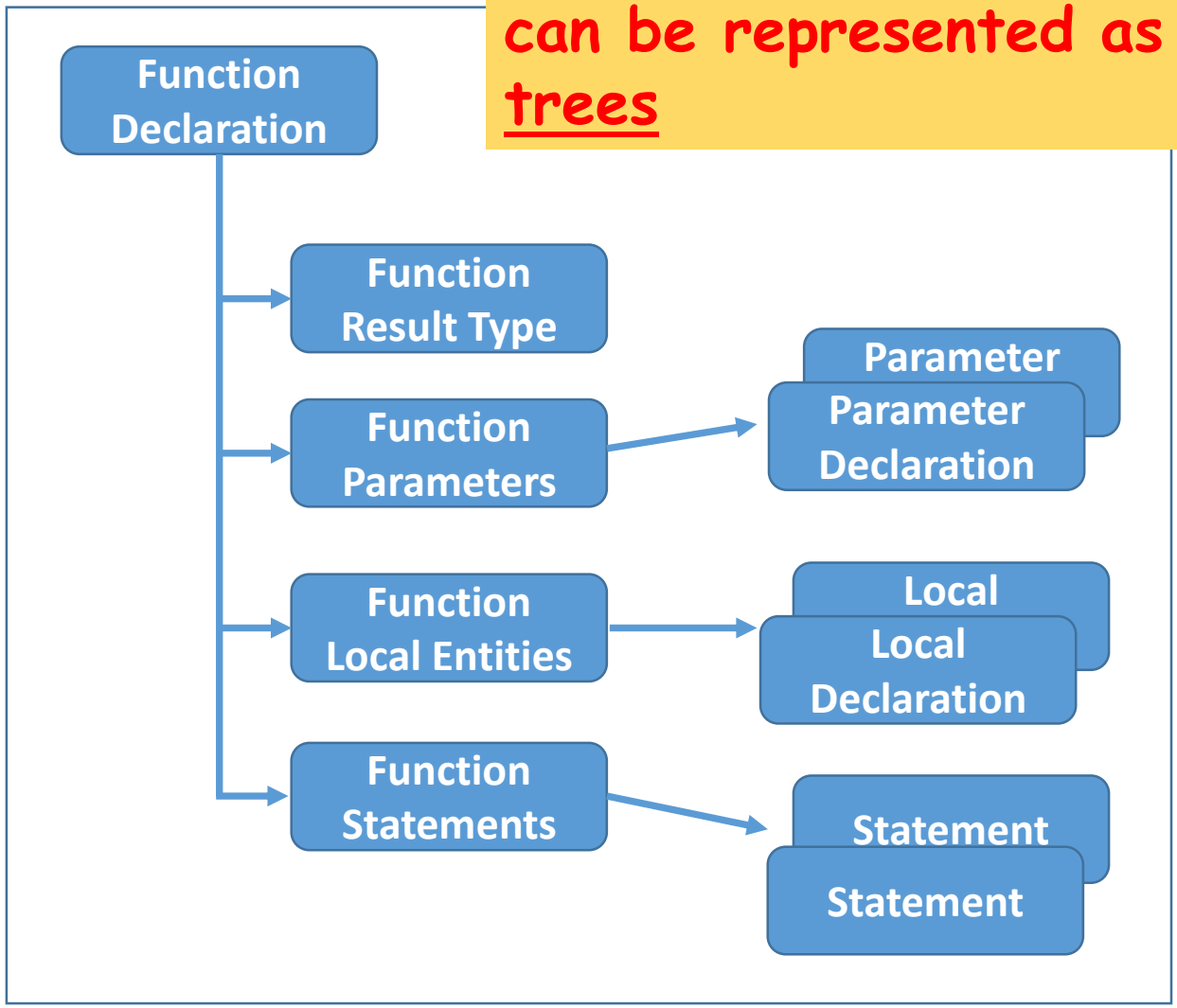
## An idea for implementation

```
void f ( int a, float b )
{
    return a*b;
}
```

FunctionDecl instance

```
Span span;
string name;
Object[] parameters;
Type resutlType;
Declaration[] localDeclarations;
Statement[] statements;
...
```

**In general, declarations can be represented as trees**



# Nested blocks & symbol tables

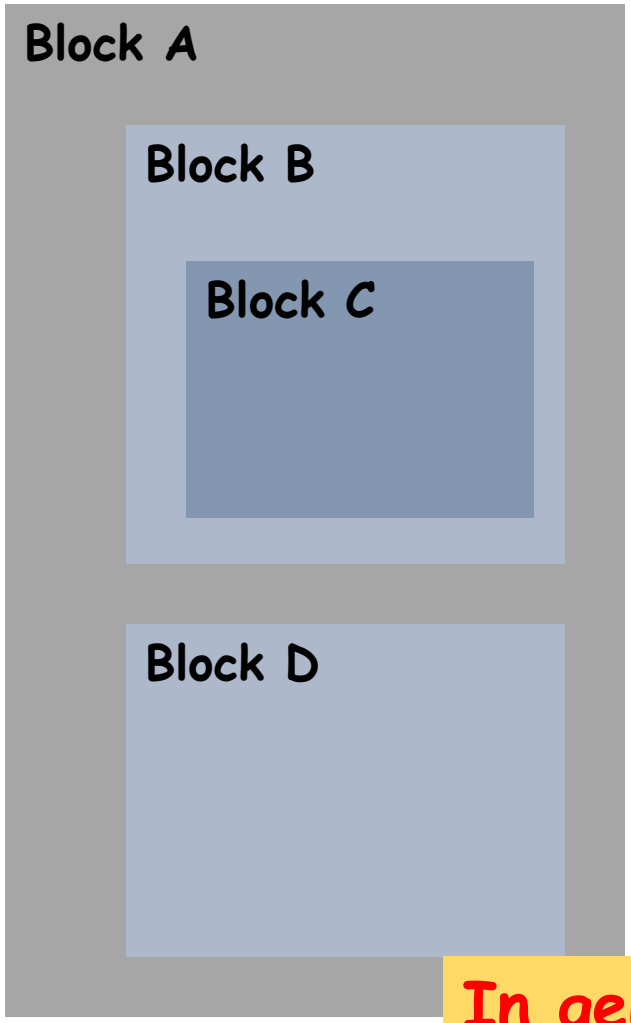
A

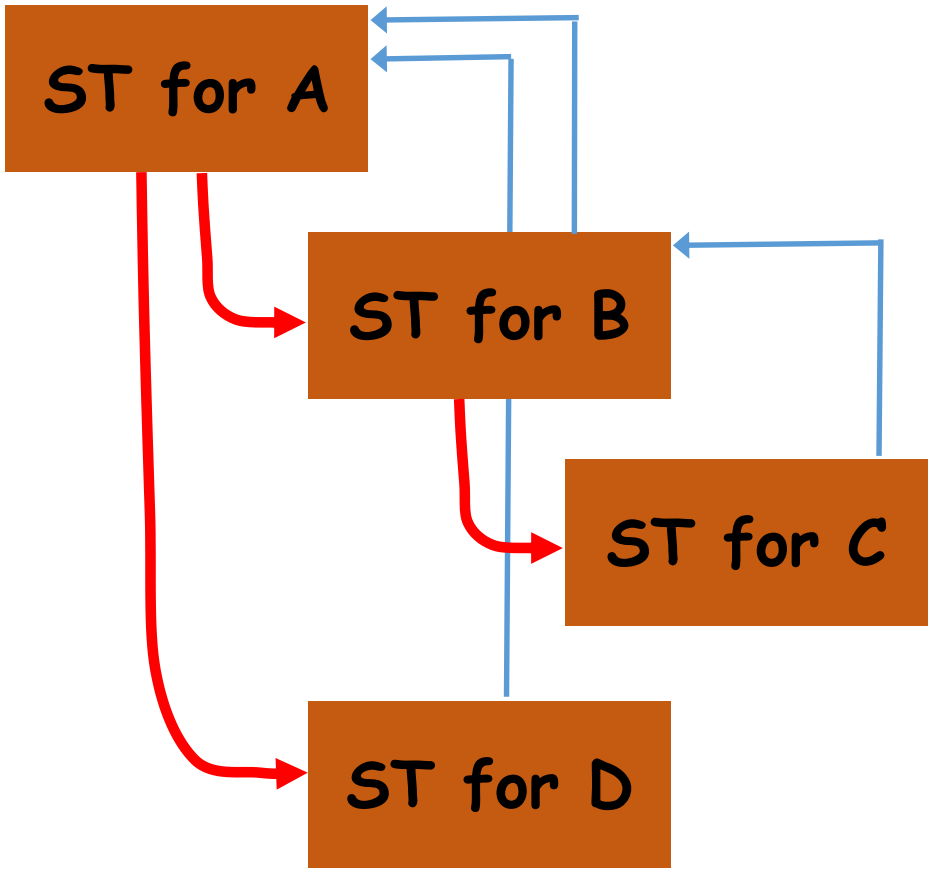
```
double f(int x, int y)
{
    float a = 1.0, b = 2.0;
    if ( x > y )
    {
        float tmp = a+b;
        for (int i=0; i<10; i++)
            tmp += i;
        return tmp/y;
    }
    else
    {
        double m = a%b;
        return x*m;
    }
}
```

B

C

D



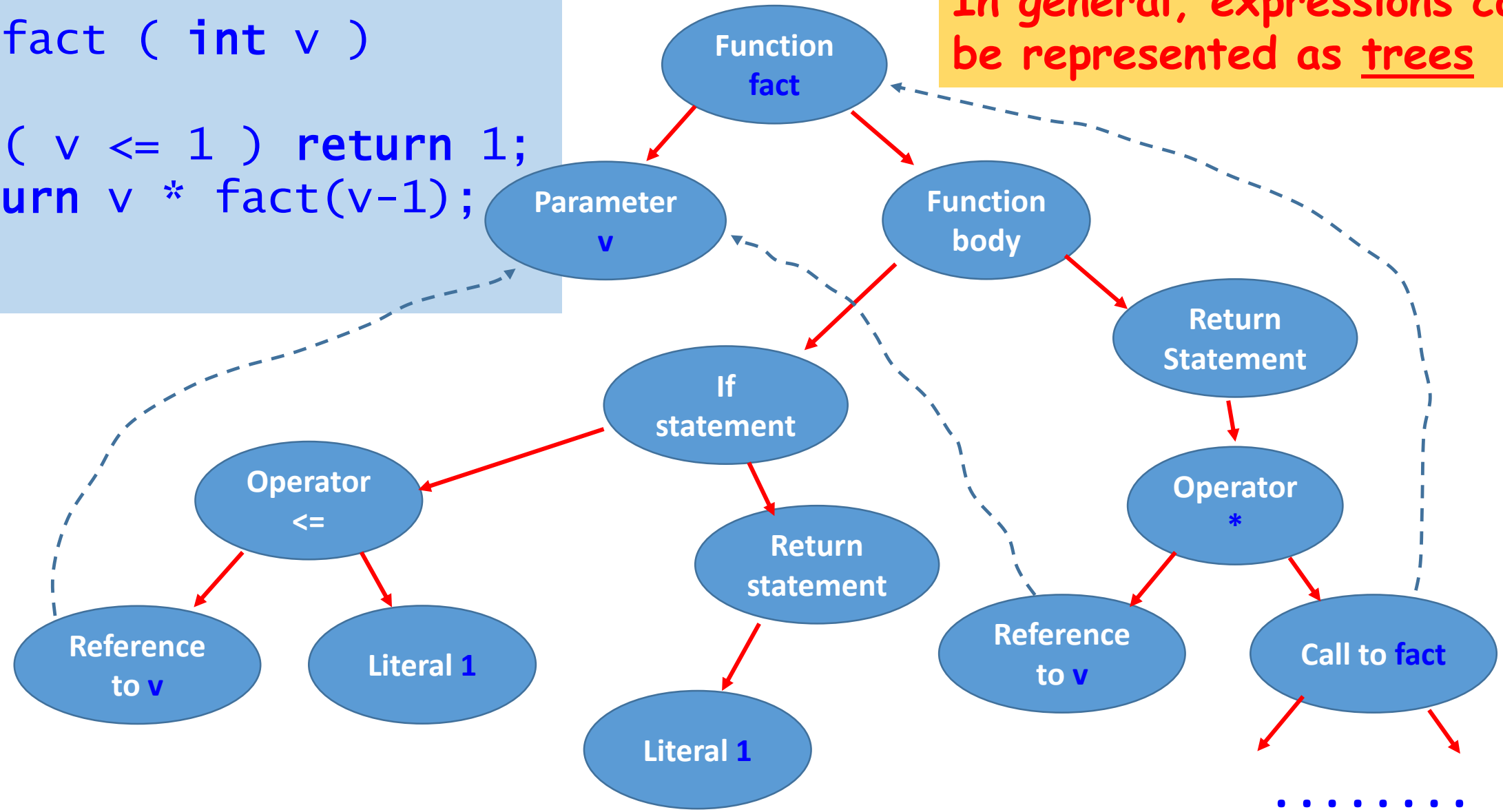




In general, scopes can be represented as trees

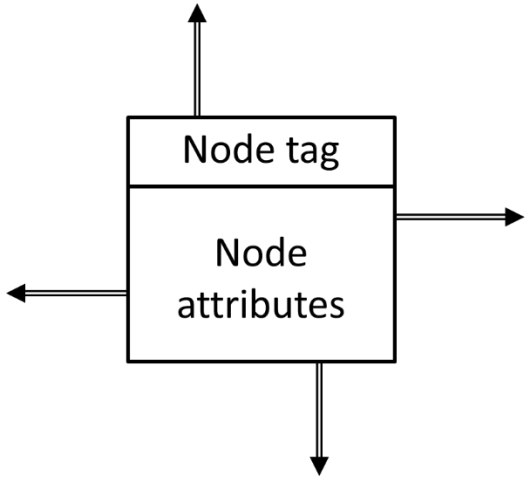
# Expressions & expression-like constructs

```
long fact ( int v )
{
  if ( v <= 1 ) return 1;
  return v * fact(v-1);
}
```

In general, expressions can be represented as trees



# Program tree: Interstron C++ implementation (1)

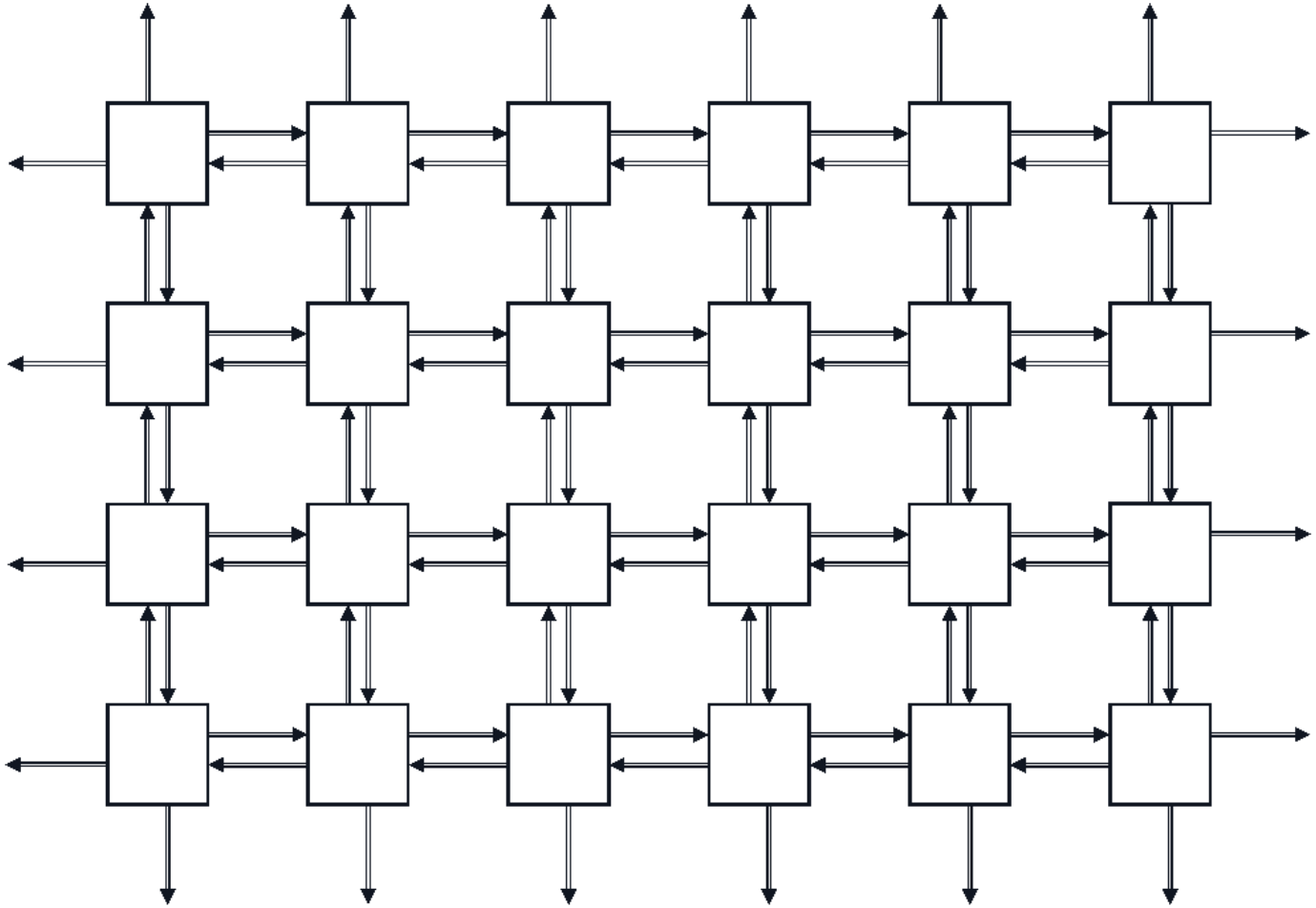



```
struct Node {
    int Tag;
    Node* left;
    Node* right;
    Node* up;
    Node* down;
    void* semantics;
};
```

**The tree node is a small structure:**

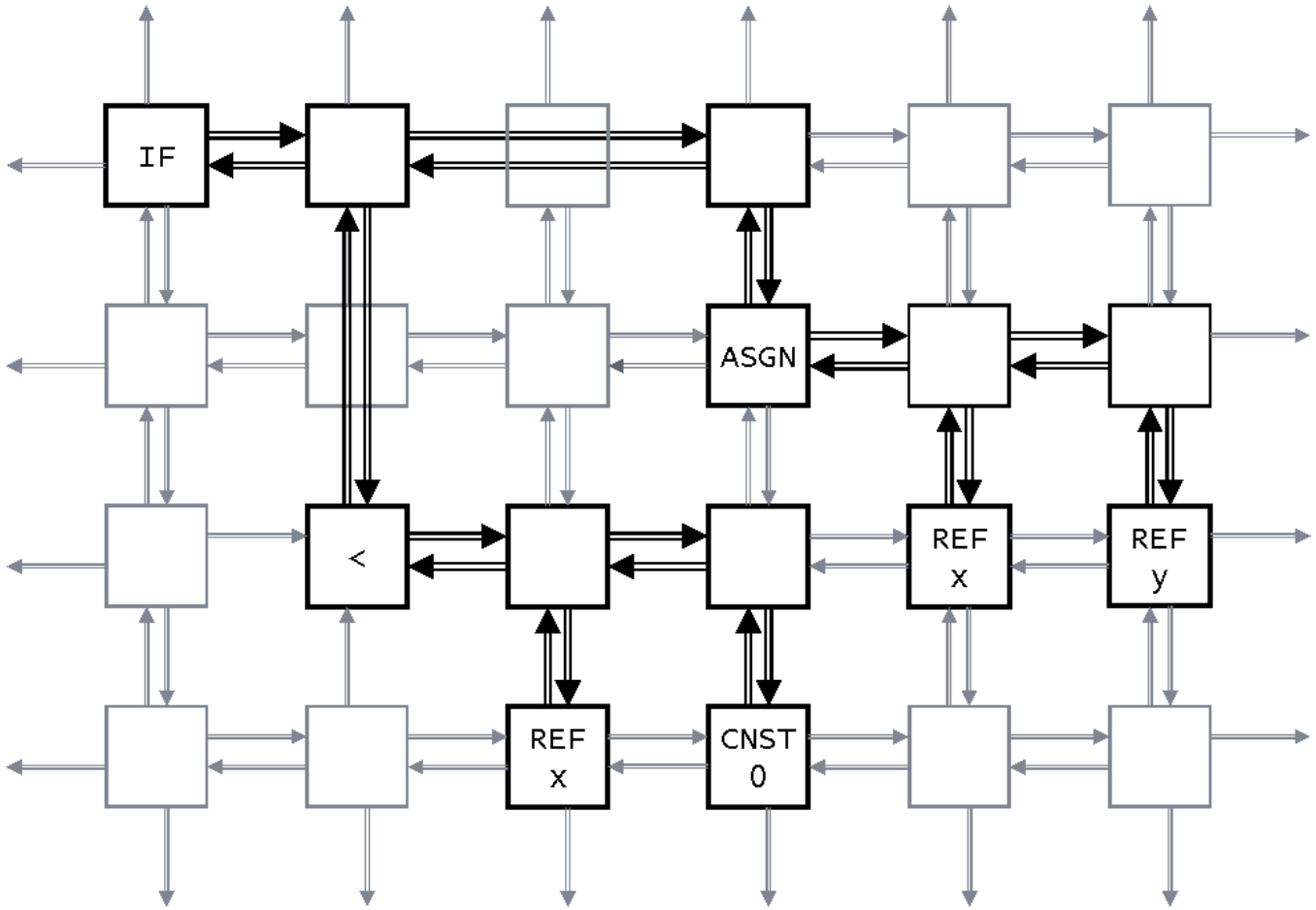
- The unique node tag.
- Each tag represents a particular language construct.
- There are four pointers to make links between nodes: «up», «down», «left», «right».
- Each node has a set of attributes; attributes depend on node's tag.
- There are "empty" nodes (without semantics) for organizing complex configurations.

# Program tree:
# Interstron C++ implementation (2)



# Program tree: Interstron C++ implementation (3)

```
if (x < 0) x = y;
```



# Program tree: Interstron C++ implementation (4)

**Advantages**

- High regularity, simple and obvious structure. It's quite easy to create a structure for any kind of language construct.
- Easy-to-use: all processing functions are written using the same pattern.

**Disadvantages:**

- Low level: no semantics – just structure.
- Low code reuse: for structurally similar sub-trees we have to write separate processing functions.
- A lot of empty nodes that connect significant nodes.

# AST implementation: CCI approach

**CCI – Common Compiler Infrastructure**

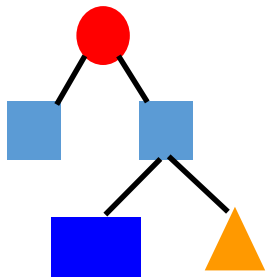
- Developed in Microsoft
- The author: Herman Venter (*now in Facebook* ☺)
- Used in experimental Microsoft projects: e.g., Cw, Spec#, Xen languages are implemented using CCI.

**Main functions**:

- Provides an extendable tree for C#-like languages' representation.
- The tree gets built as a **hierarchy of classes**, corresponding to the main language notions.
- Provides a few base tree traversers (walkers).
- Automates MSIL code generation: the last tree walker
- Supports compiler integration into Visual Studio.

# AST implementation: CCI approach

Tree structure:
a «pure» tree



```
public class If : Statement
{
    Expression condition;
    Block      falseBlock;
    Block      trueBlock;
}
```

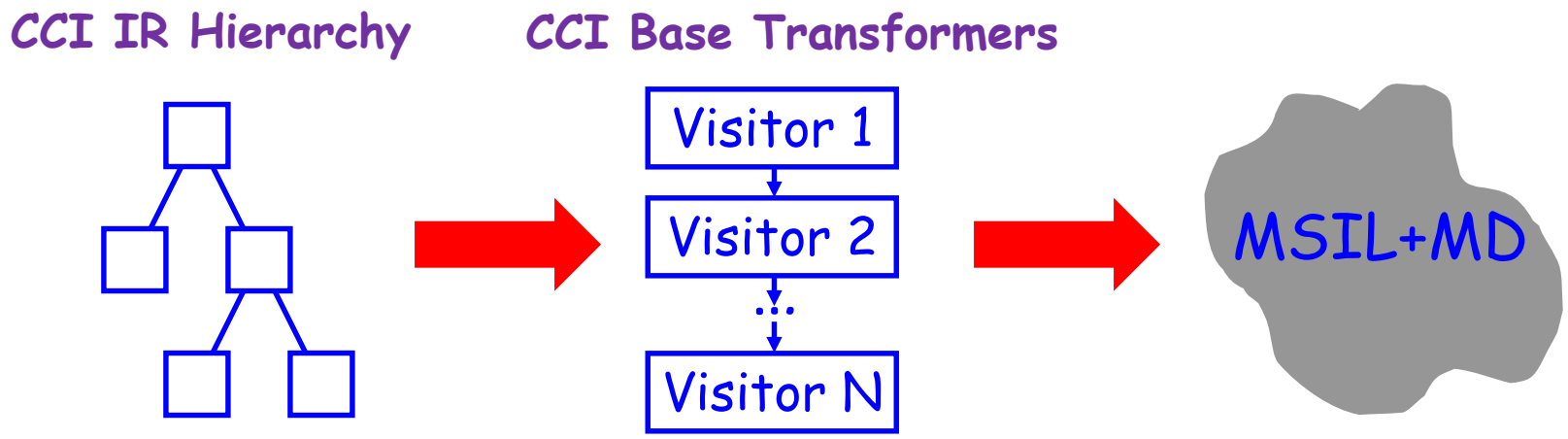
Pure subtree structure

Traversing algorithms
(Visitor pattern)

```
namespace System.Compiler {
  public class Looker {
     public Node Visit ( Node node )
     {
       switch ( node.NodeType ) {
         case NodeType.If:
           // working with If node
           return ProcessIf(node);
        case NodeType.While:
           // working with While node
           return ProcessWhile(node);
        ...
     }
  }
}
```

Pure functionality on the subtree

# AST implementation: CCI approach




**Advantages**:

- Flexibility: easily add and modify transformers, change their order without changing class hierarchy.

**Disadvantages**:

- Hard to refactor: if class hierarchy changes you have to modify all transformers correspondingly.

# Tables AND/OR trees? (1)

**Symbol Table**:

- Each ST is filled while processing declarations.
- Each ST have a linear structure.
- After completing processing declarations ST *does not change*.
- While further processing ST *does not change*.
- Typical actions on ST: adding new element; **look up**.

**Program Tree:**

- It gets constructed in accordance with the static construct nesting (tree form)
- It is constructed while parsing "executable" parts of the source program.
- After creation it is *actively modified*.
- Typical actions: recursive traversing, re-constructing.

# Tables AND/OR trees? (2)

***However:***

- In modern languages declarations & statements have the same status: they can be **mixed**.
- Tables reflect visibility scopes and therefore they are hierarchical – i.e., they compose *a tree*.
- Symbol table tree is *structurally identical* to the tree of "executable" program parts.
- Symbol tables & program tree are closely related. An example: initializers in declarations.

=> There are obvious reasons to create the single structure instead of two: **join tables and trees**.

# AST implementation: an integral approach (1)

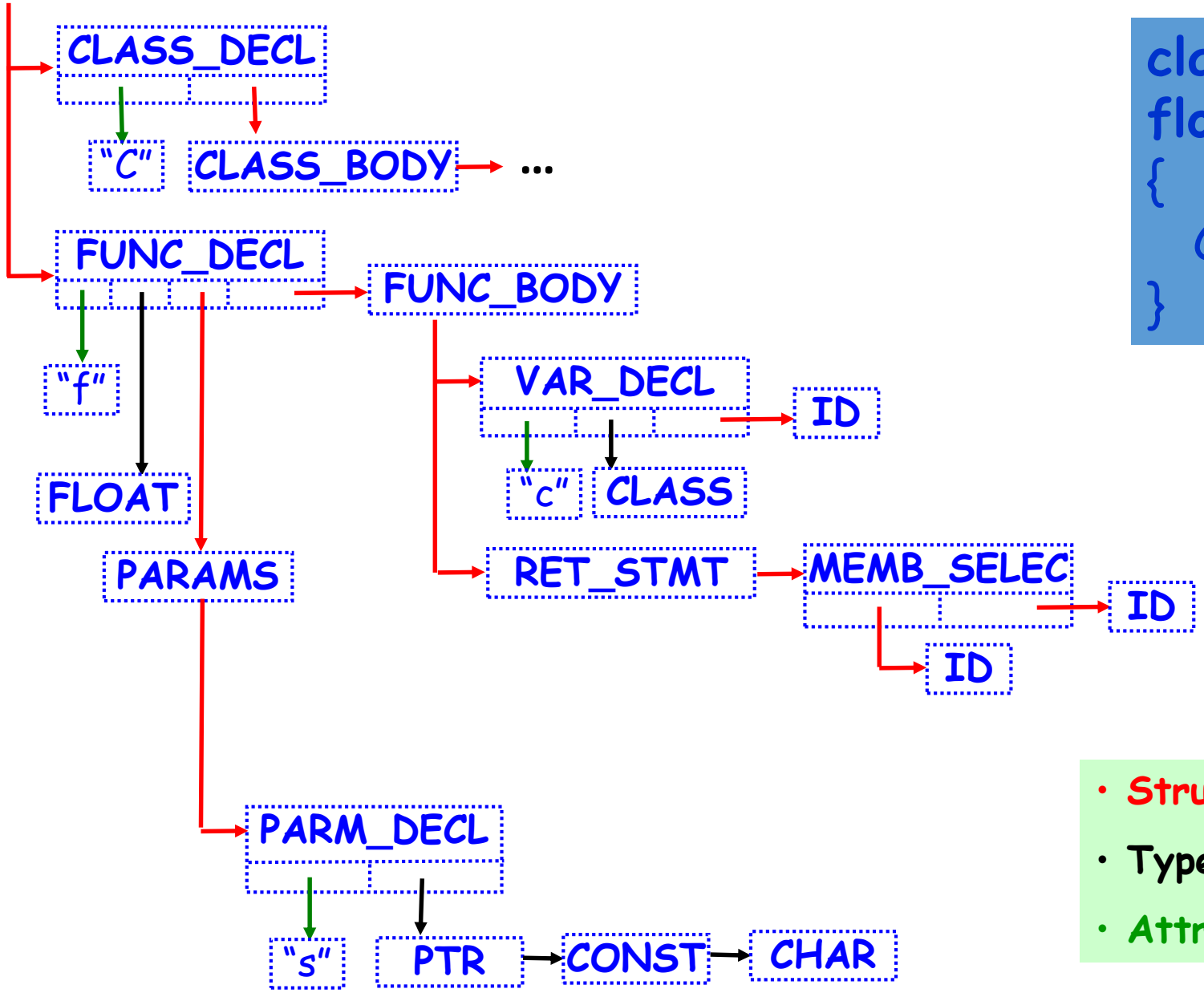
**Main project decision**:

- Each program tree node contains **both** structure (its parts) **and full set or operators** on the given node (and its sub-trees).

# AST implementation: an integral approach (2)

```
public class If : Statement
{
    // Sub-tree structure
    Expression condition;
    Block      falseBlock;
    Block      trueBlock;
    // Operations on sub-trees
    override bool validate()
    {
        if ( !condition.validate() ) return false;
        if ( falseBlock != null && !falseBlock.validate() ) return false;
        if ( !trueBlock.validate() ) return false;
        // Checking 'condition'
        // Other semantic checks...
        return true;
    }
    override void generate()
    {
        condition.generate();
        ...
        trueBlock.generate();
        ...
        if ( falseBlock != null ) falseBlock.generate();
        ...
    }
}
```

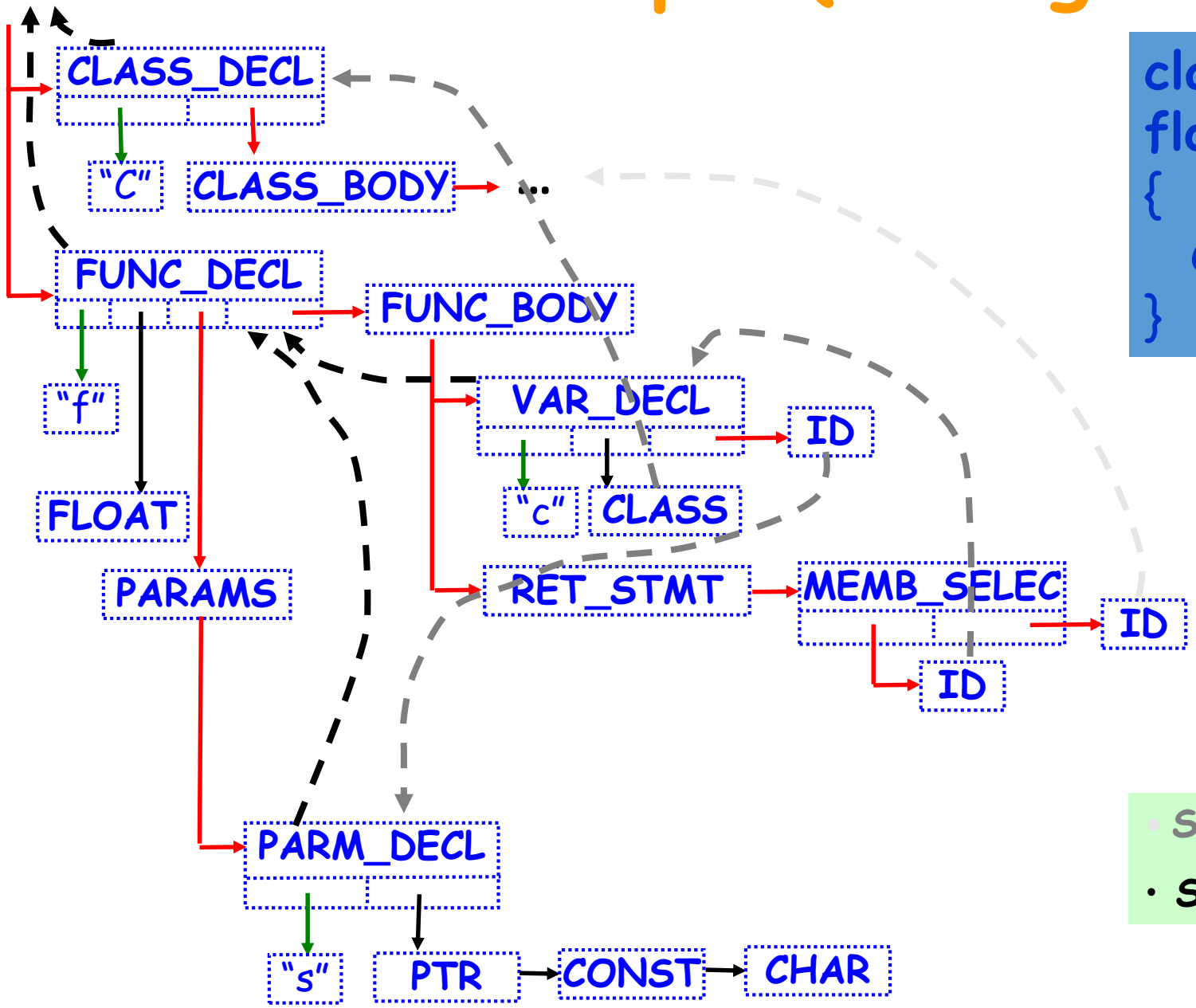
# AAST example (a fragment)




```
class C { ... };
float f(const char* s)
{
   C c(s); return c.m;
}
```

- Structural links
- Type information
- Attributes

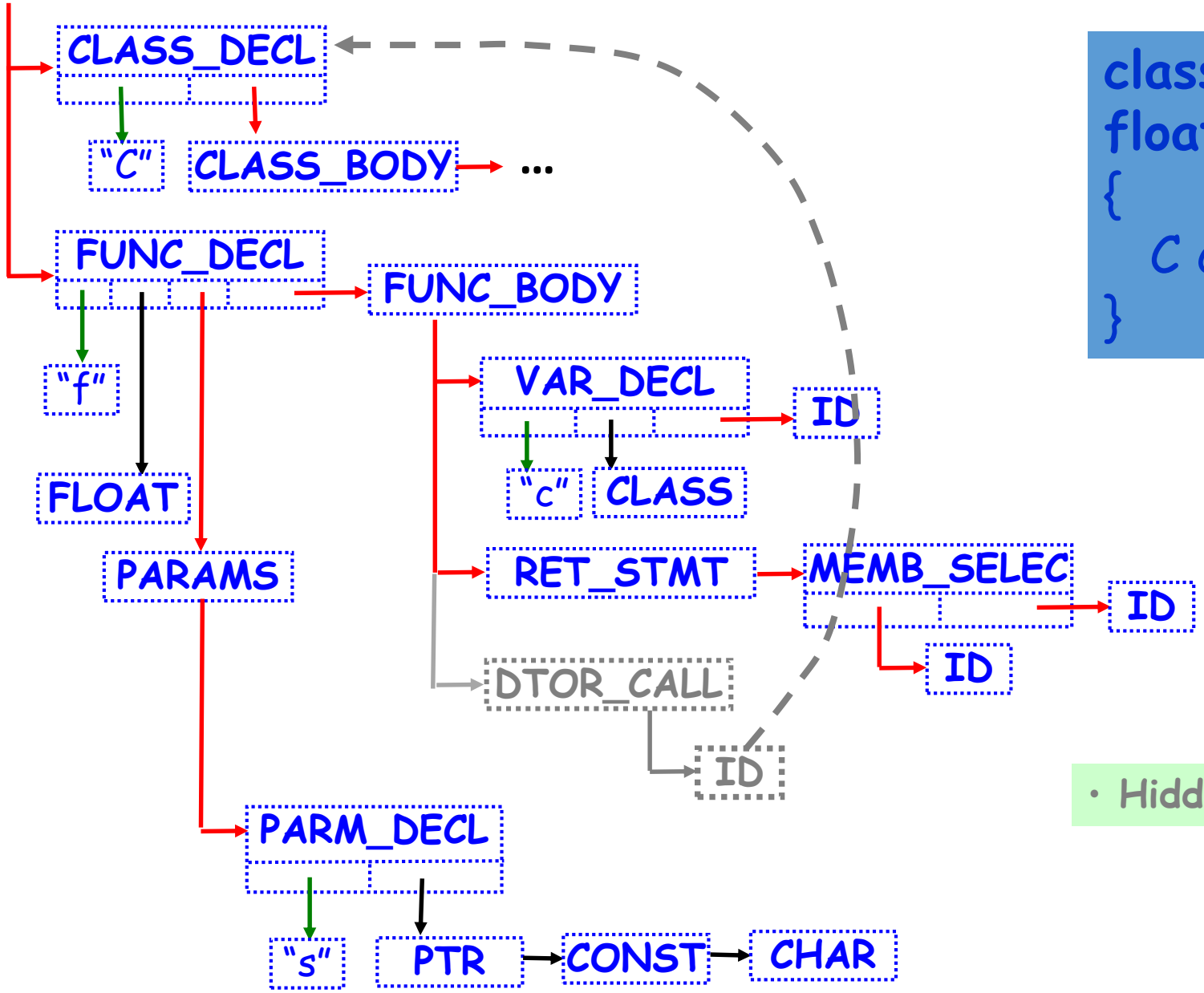
# AAST example (a fragment)




```
class C { ... };
float f(const char* s)
{
   C c(s); return c.m;
}
```

- Semantic links
- **Scopes**

# AAST example (a fragment)




```
class C { ... };
float f(const char* s)
{
   C c(s); return c.m;
}
```

- Hidden semantics

# Type representation (1)

C++ type system:

- Fundamental types: integer, float, character, ...
- Class and enumeration types
- Type modifiers: constants, pointers, references, pointers to class members
- Functional types, arrays
- Families of types (templates)

Many ways for defining new types, for example:

- Reference to pointer `int*& rp = p;`
- Pointer to function `double& (*f)(const C*);`
- Array of pointers to pointers to class members

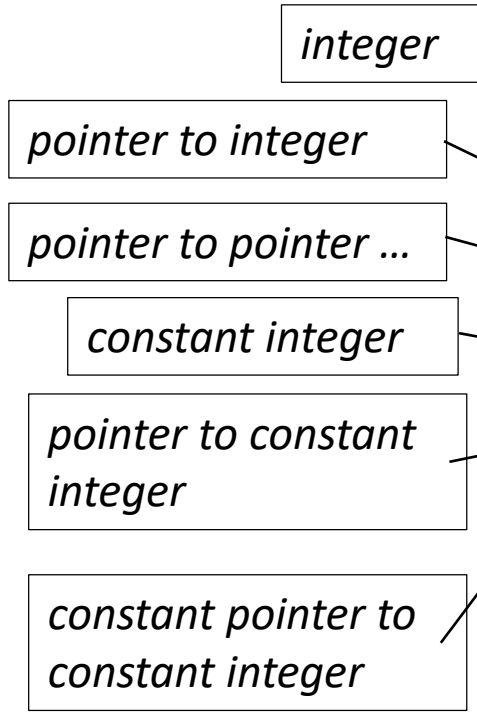
```
C<int,float>::*char A[10];
```

Many complex & non-obvious conversion rules

# Type representation (2)

**Solution for C++:**

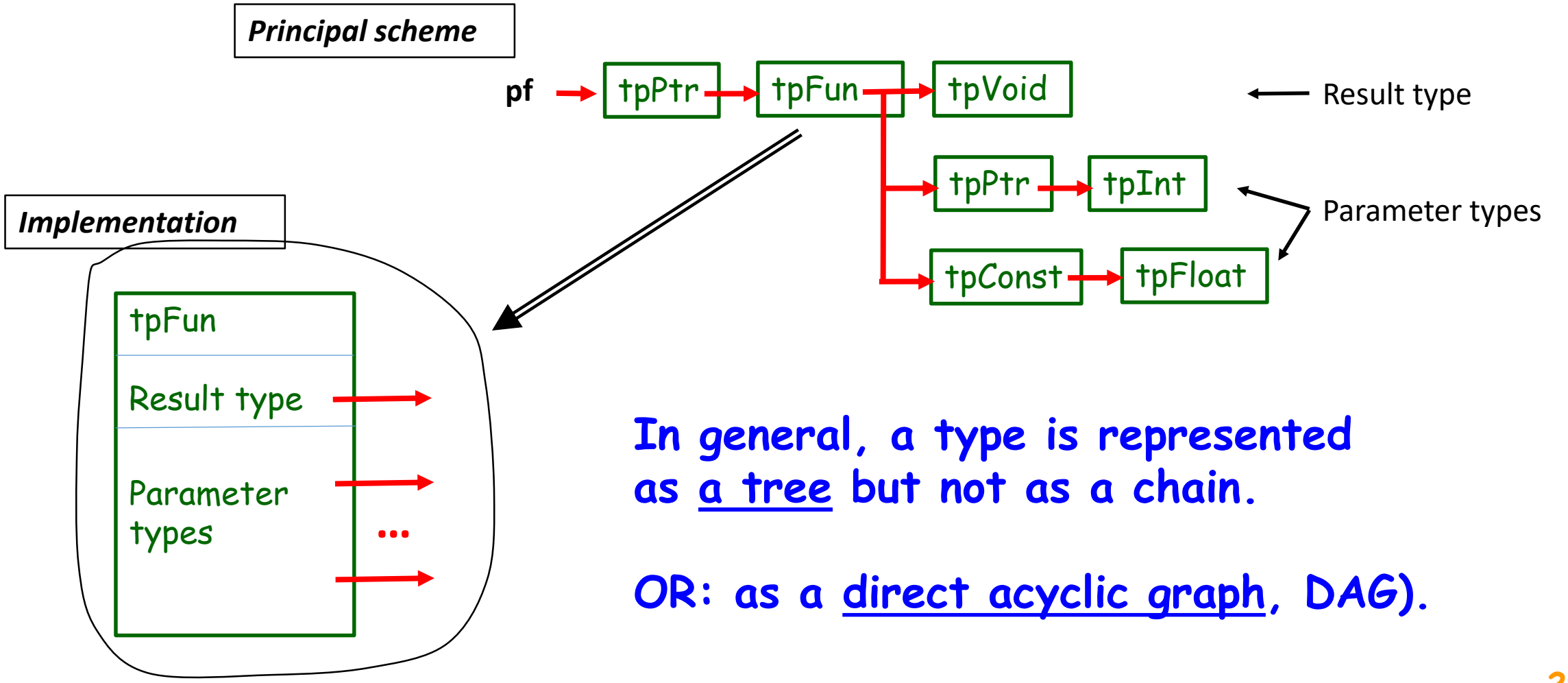
- Represent types as **type chains**




| | |
|---|---|
| **int** | tpInt |
| **int*** | tpPtr, tpInt |
| **long unsigned int**** | tpPtr, tpPtr, tpULI |
| **const int** | tpConst, tpInt |
| **const int*** | tpPtr, toConst, tpInt |
| **const int *const** | tpConst, tpPtr, tpConst, tpInt |
| **const** *C*[10] | tpArr, 10, tpPtr, tpConst, tpClass, *C* |
| **int**& (*f)(**float**)**const** | tpPtr, f |
| *C*::***int** | tpPtrMemb, *C*, tpInt |
| ... | |
| f | tpMembFun, tpRef, tpInt, 1, tpFloat |

# Type Representation: Example

```
typedef void (*pf)(int*, const float);
```



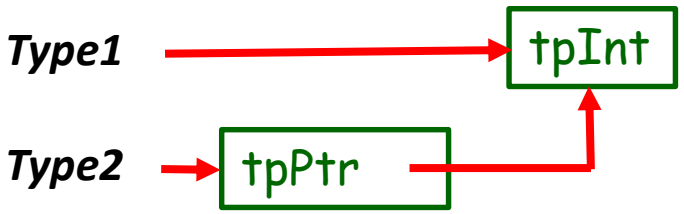

In general, a type is represented as a tree but not as a chain.

OR: as a direct acyclic graph, DAG).

# Operations on Types: Examples

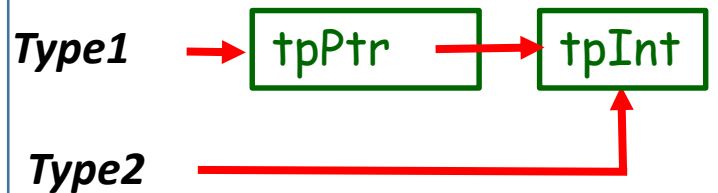
```
int* p = &x;
```

**Taking address:**
**int -> int***



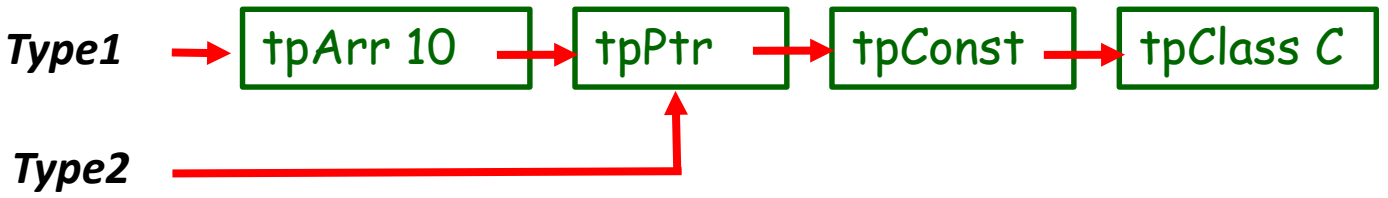

```
int v = *p;
```

**Dereferencing:**
**int* -> int**



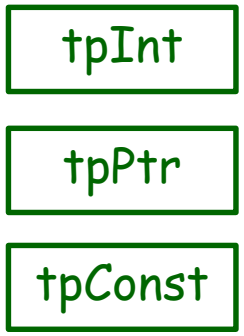

```
class C { ... };
const C* A[10];
...
const C* a = A[3];
```

**Access to a type of an array element:**
**tpArr,10,tpPtr,tpConst,tpClass,C ->**
**tpPtr,tpConst,tpClass,C**



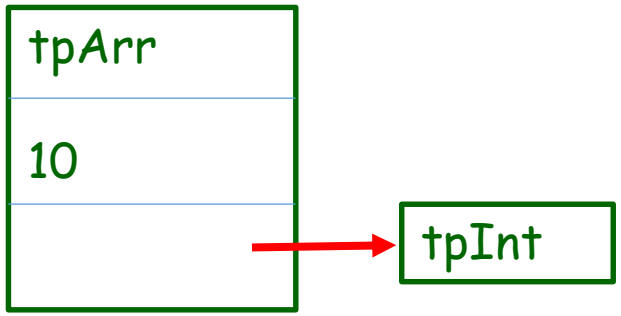
# Type Representation

## Fundamental types:




Just the single code

## Compound type: array
**int[10]**




## Compound type: class
**class *C***