Compiler Construction: Practical Introduction

Lecture 7
Semantic Analysis

Eugene Zouev

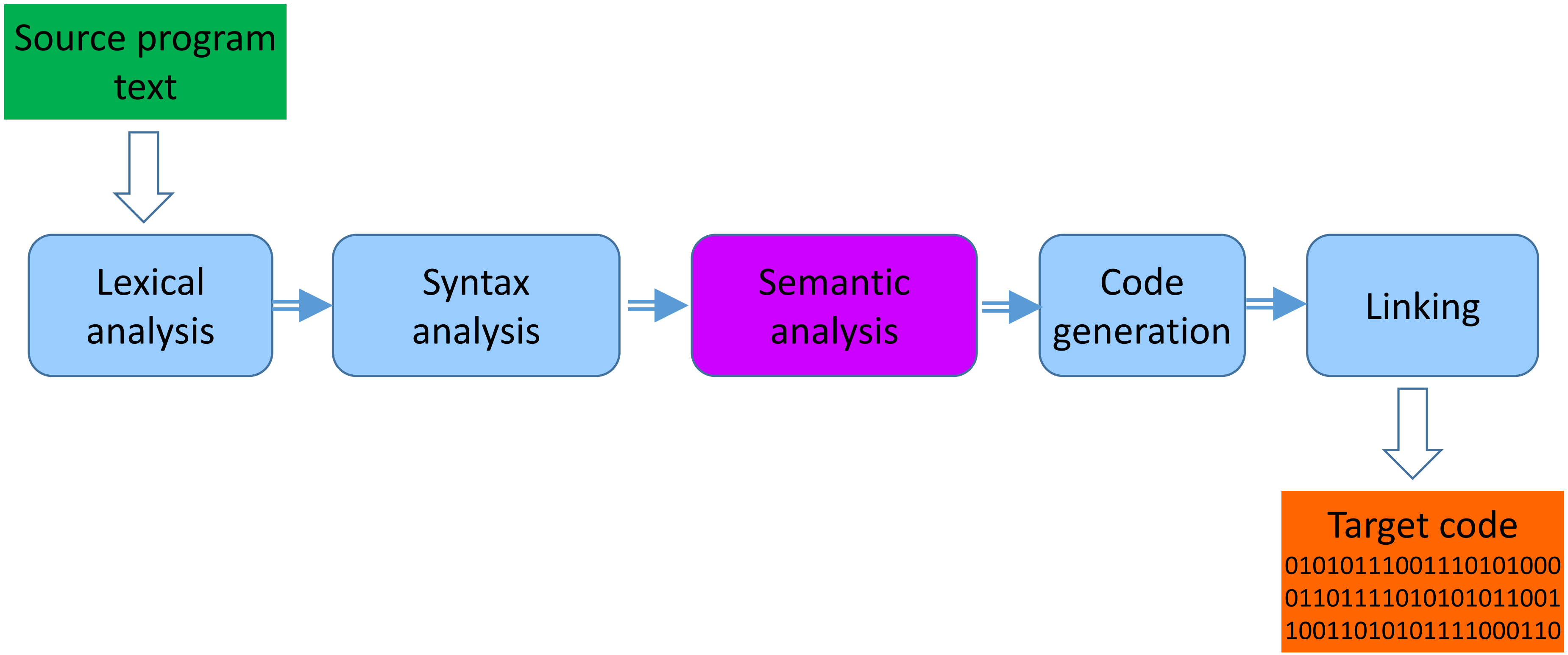
Spring Semester 2023
Innopolis University

Main Topics

- Why and for semantic analysis is?
- Examples: standard conversions, initialization semantics, user-defined conversions, calculating constant expressions
- Source code optimizations: the general idea
- Examples: eliminating repeated calculations, replacing slow instructions, excluding redundant calculations, constant propagation etc.

Compilation: An Ideal Picture

A program written by a human
(or by another program)



Source program text

Lexical analysis

Syntax analysis

Semantic analysis

Code generation

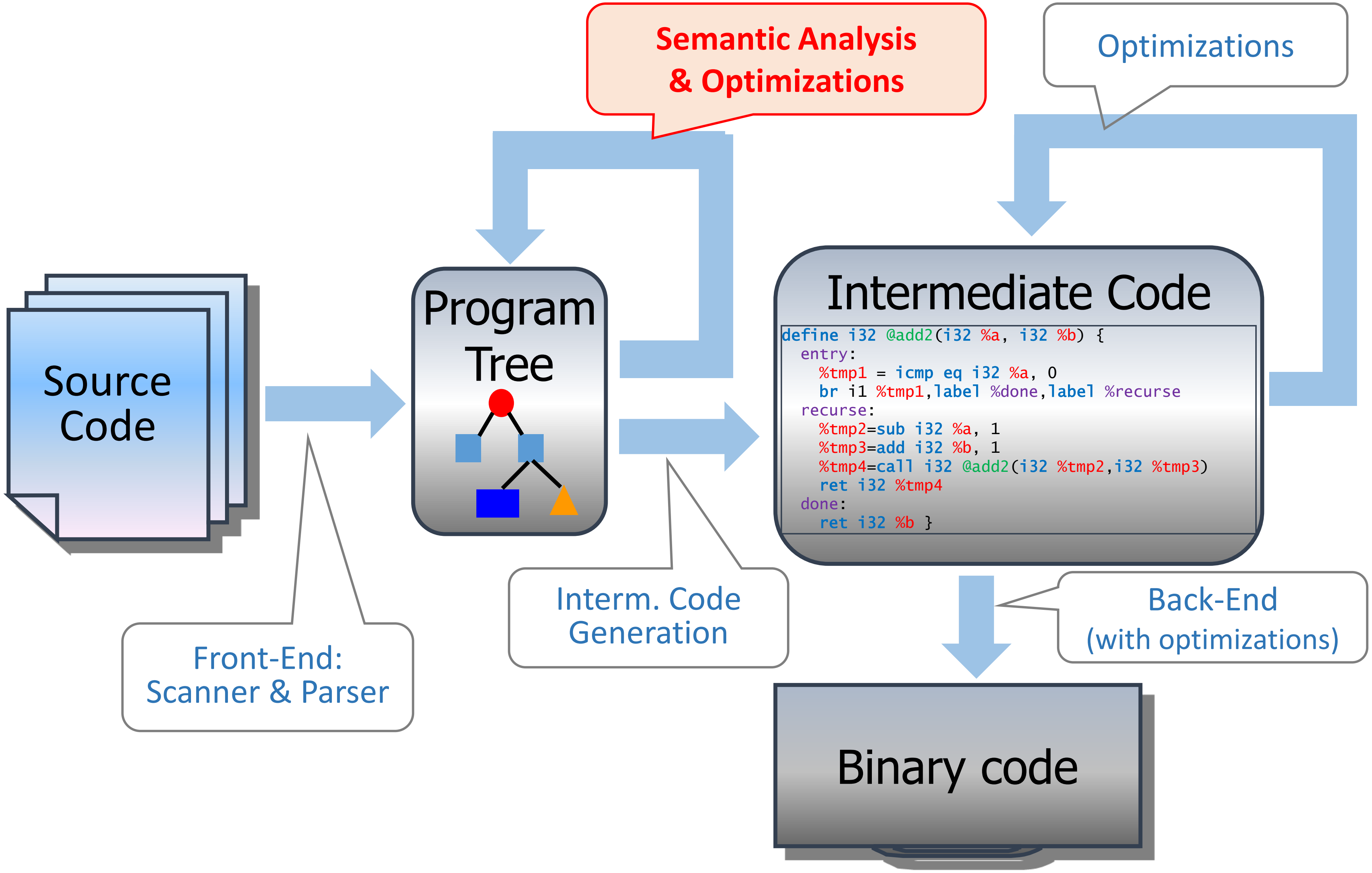
Linking

Target code
01010111001110101000
01101111010101011001
10011010101111000110

A program binary image
suitable for immediate
execution by a machine

Coming back to the today's topic

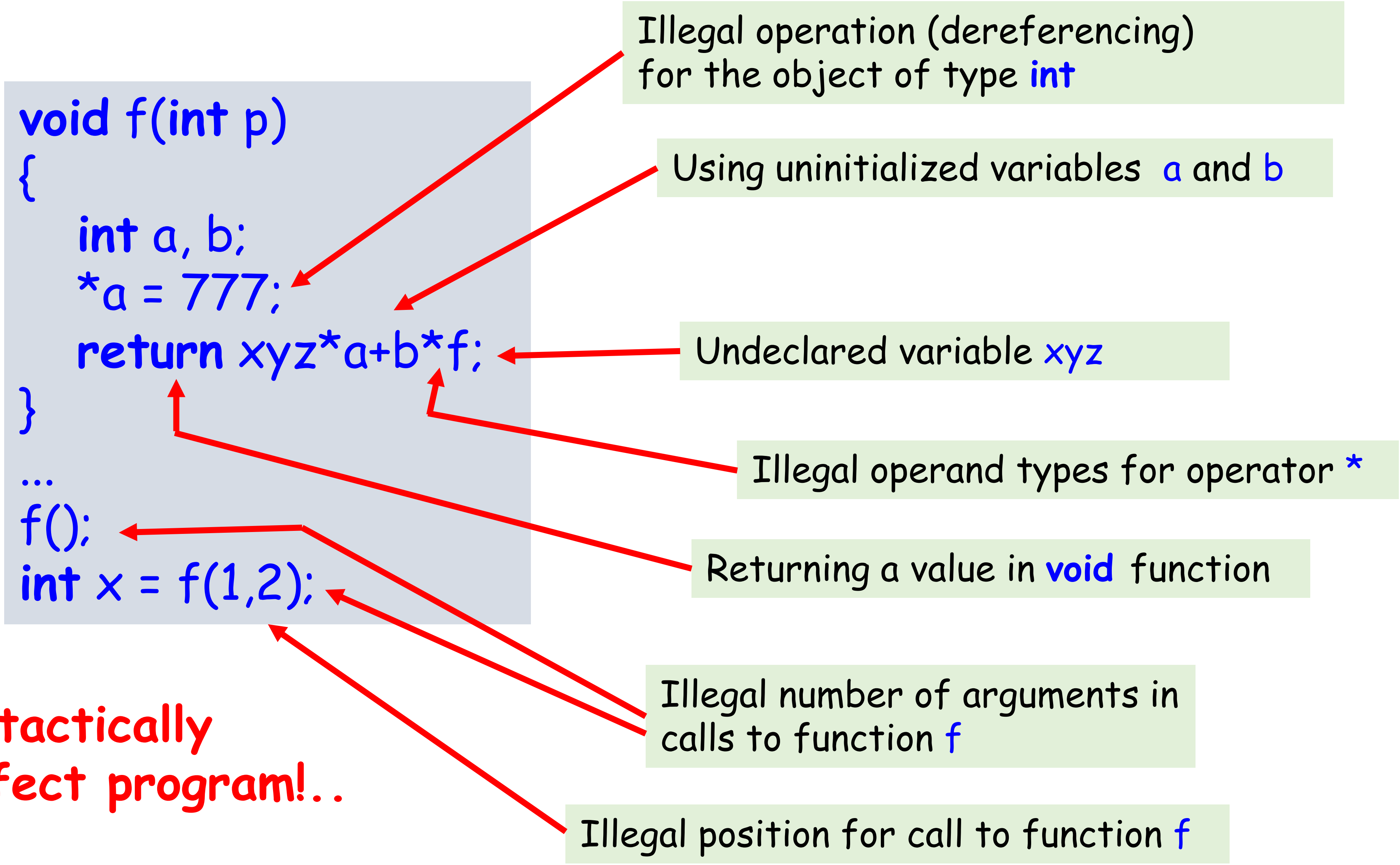
Where We Are Today



Semantic Analysis & Optimizations
Optimizations
Source Code
Program Tree
Intermediate Code
Front-End: Scanner & Parser
Interm. Code Generation
Back-End (with optimizations)
Binary code

```
define i32 @add2(i32 %a, i32 %b) {
  entry:
    %tmp1 = icmp eq i32 %a, 0
    br i1 %tmp1,label %done,label %recurse
  recurse:
    %tmp2=sub i32 %a, 1
    %tmp3=add i32 %b, 1
    %tmp4=call i32 @add2(i32 %tmp2,i32 %tmp3)
    ret i32 %tmp4
  done:
    ret i32 %b }
```

What Is Semantic Analysis For?



```
void f(int p)
{
    int a, b;
    *a = 777;
    return xyz*a+b*f;
}
...
f();
int x = f(1,2);
```

Illegal operation (dereferencing) for the object of type **int**

Using uninitialized variables a and b

Undeclared variable xyz

Illegal operand types for operator *

Returning a value in **void** function

Illegal number of arguments in calls to function f

Illegal position for call to function f

Syntactically perfect program!..

What Is Semantic Analysis For?

Some remarks

1. Errors like "undeclared identifier" are typically detected on syntax analysis stage – while building symbol tables and/or program tree.
2. Errors like "uninitialized variable" usually are not detected by all compilers because it requires deeper control flow and data flow analysis.
3. Analysis of the code snippet ...xyz*a... typically results in a message like "illegal operand types for * operator". Formally that's true but in fact the reason is that xyz is not declared – this is an example of and ***induced error***.

Наведенные ошибки

Semantic Analysis

- Typically semantic analysis runs on the program tree built on previous compilation stages (while syntax analysis).
- Semantic analysis is typically implemented as a series of tree traverses with some actions related to the source language semantics.
- The more complex semantics is the more passes (traverses) are needed.
    - For relatively simple languages semantic analysis can be done **together** with syntax analysis while building the program tree.
    - Usually, the last tree walk implements target code generation – either an intermediate representation (like C--) or assembler code.
    - Often, before code generation, some **additional stages** after semantic analysis are necessary like building CFG & SSA representations…

Semantic Analysis

- One or several semantic actions are performed on each tree walk.
- What's the result of each tree walk?
  - Either a modified program tree with **the same node types**; perhaps complex nodes get replaced for simpler ones.

    Example is the C# compiler: after each tree walk the tree consists of the same node types.

  - Or a modified program tree **with different node types** that are more primitive but are "closer" to the target architecture.

    Example is the Scala compiler: node types representing source program constructs get replaced for more primitive nodes ("ICode"), and the JVM (or MSIL) code is generated from ICode finally.

Semantic Analysis

The result of each tree walk is typically twofold:

- The tree changes its structure: some nodes/subtrees are added or removed, some nodes/subtrees get replaced for other nodes/subtrees…
- Tree nodes are annotated (“decorated” ☺) by attributes reflecting various semantic features; the attributes are deduced during the analysis process.

=> The Abstract Syntax Tree (AST) is converted to the **Annotated** Syntax Tree (AAST).

(An alternative solution is **attribute grammars**.)

Semantic Analysis: Actions

Four categories of actions while semantic analysis:

- Semantic checks

  Operand types consistency in expressions
  Checking correctness for function calls (including destructors)

- Semantic conversions

  Replacing conversions for function calls

  Replacing infix operators for operator function calls

  Inserting necessary type conversions

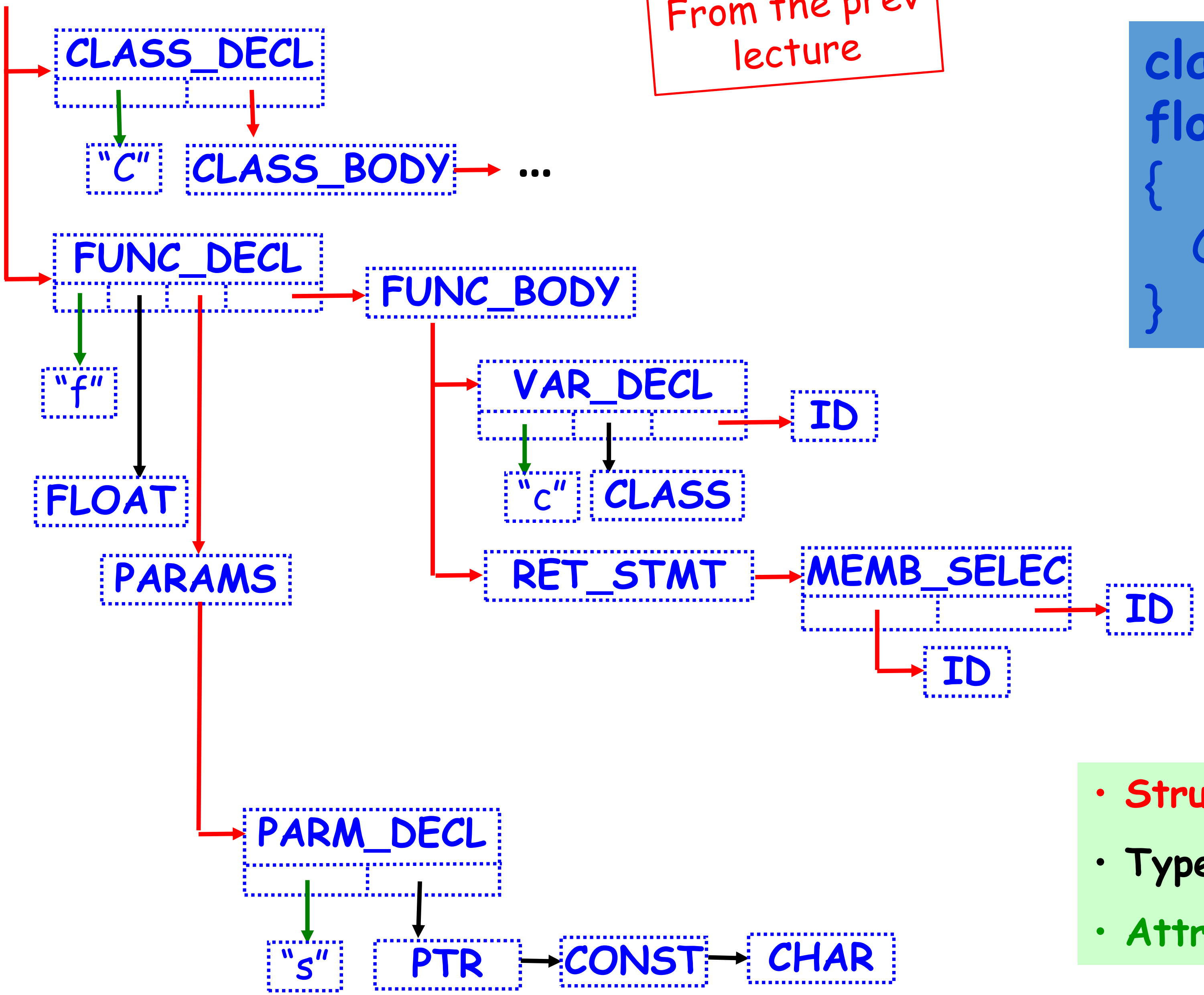
  Template instantiating

- Identification of hidden semantics

  Implicit destructor calls
  Temporary objects

- Optimizations (!)

AAST example (a fragment)



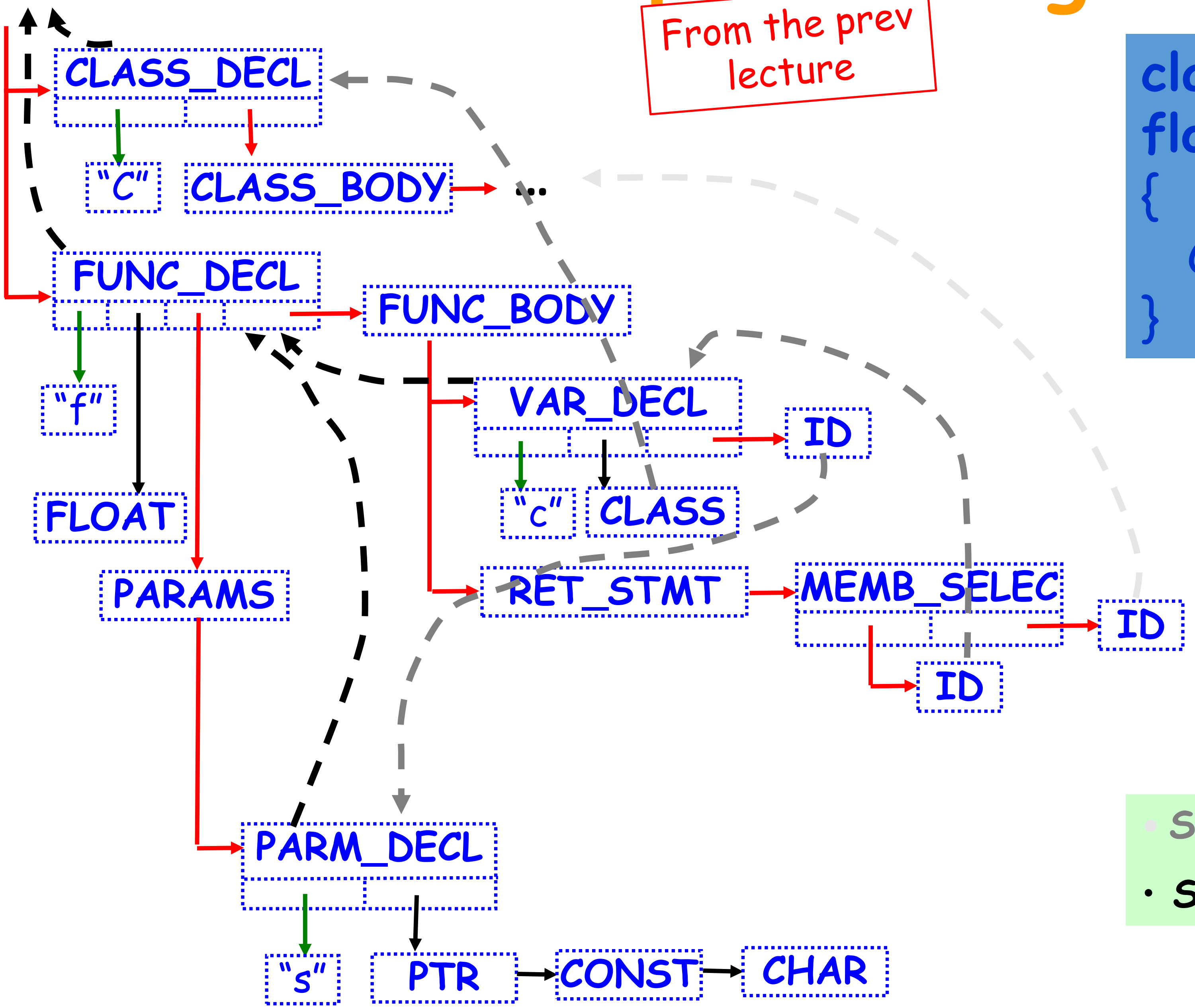
From the prev lecture

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

- Structural links
- Type information
- Attributes

Ext1

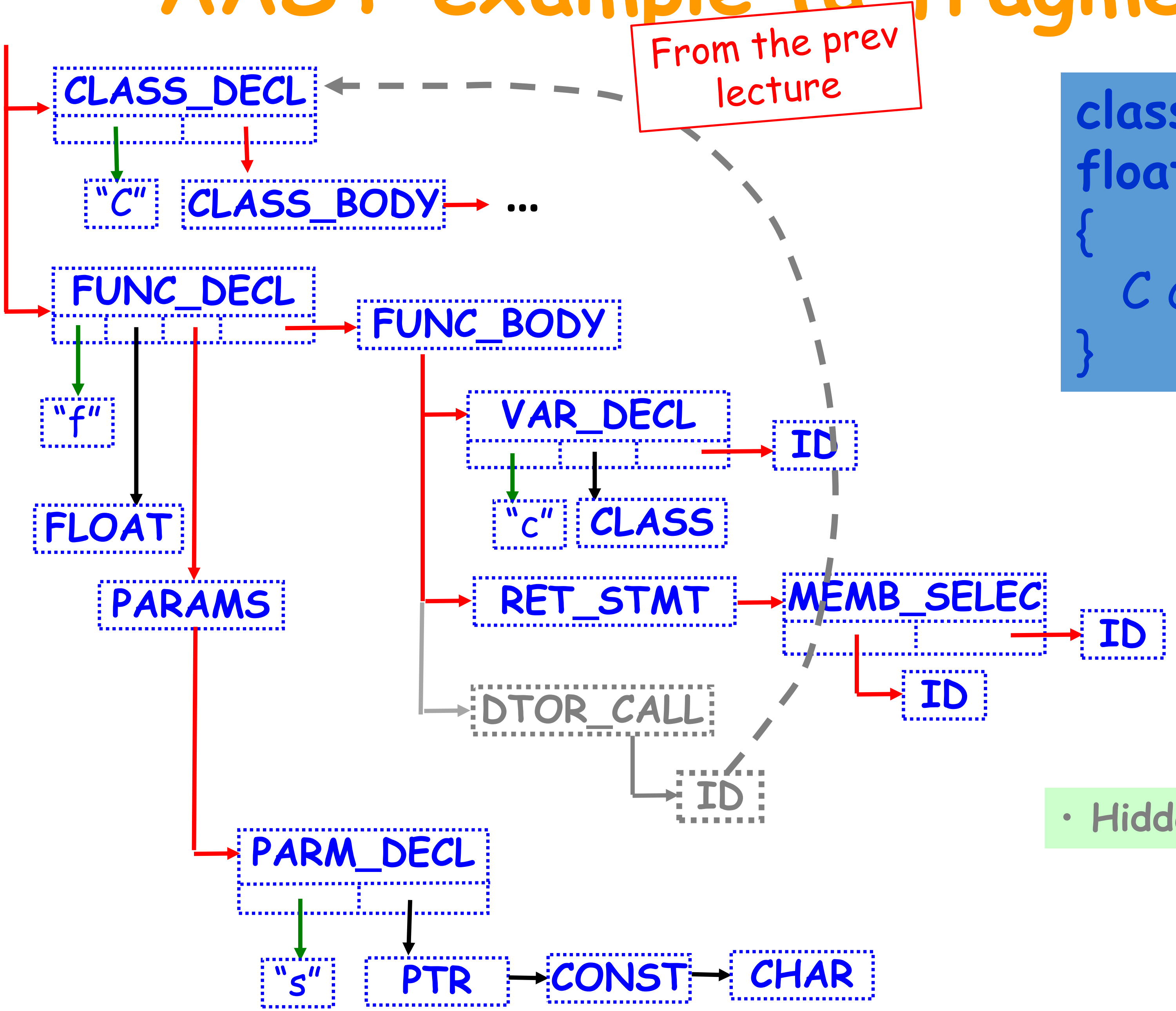
AAST example (a fragment)



```
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;
}
```

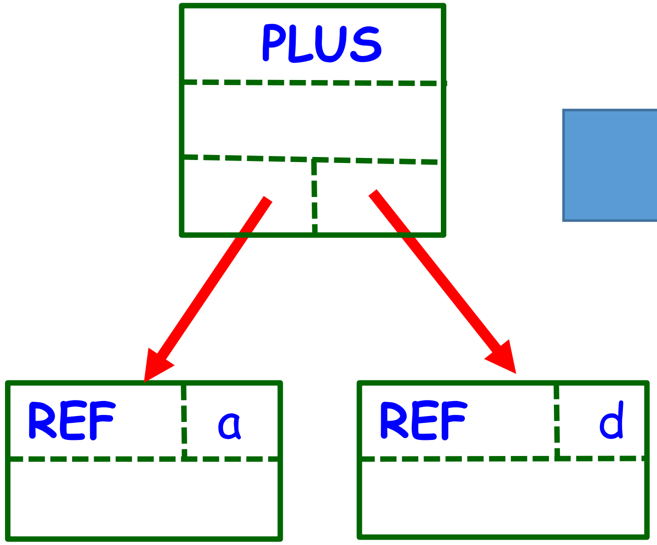
- Hidden semantics

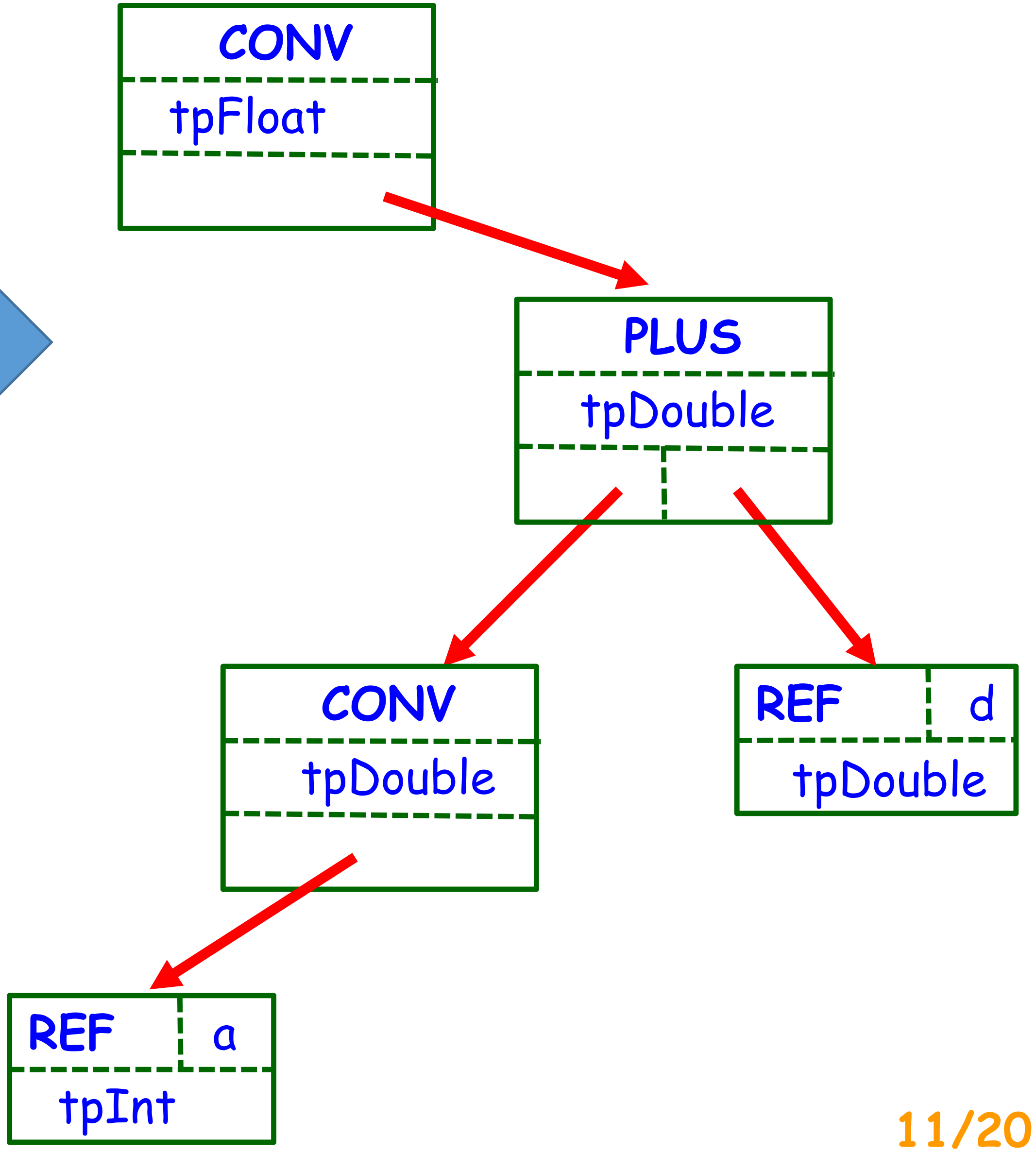
Ext3

Semantic Analysis: Example 1

Standard conversions

```
int a = 3;
double d = 7.55;
float x = a + d;
```





```
...
float x = (float)((double)a + d);
```

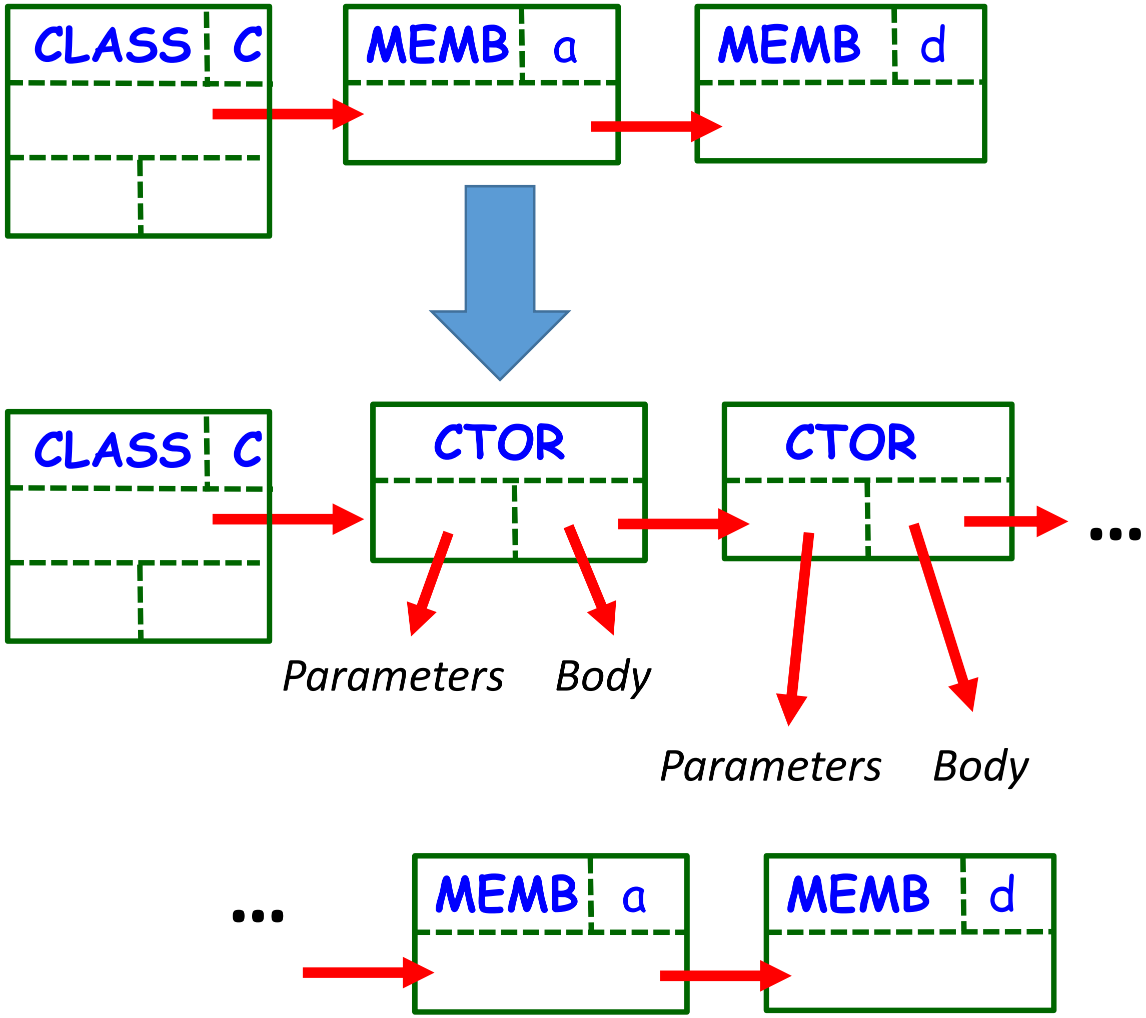
Semantic Analysis: Example 2

Class declaration

```
class C {
   public:
      int a, b;
};
```

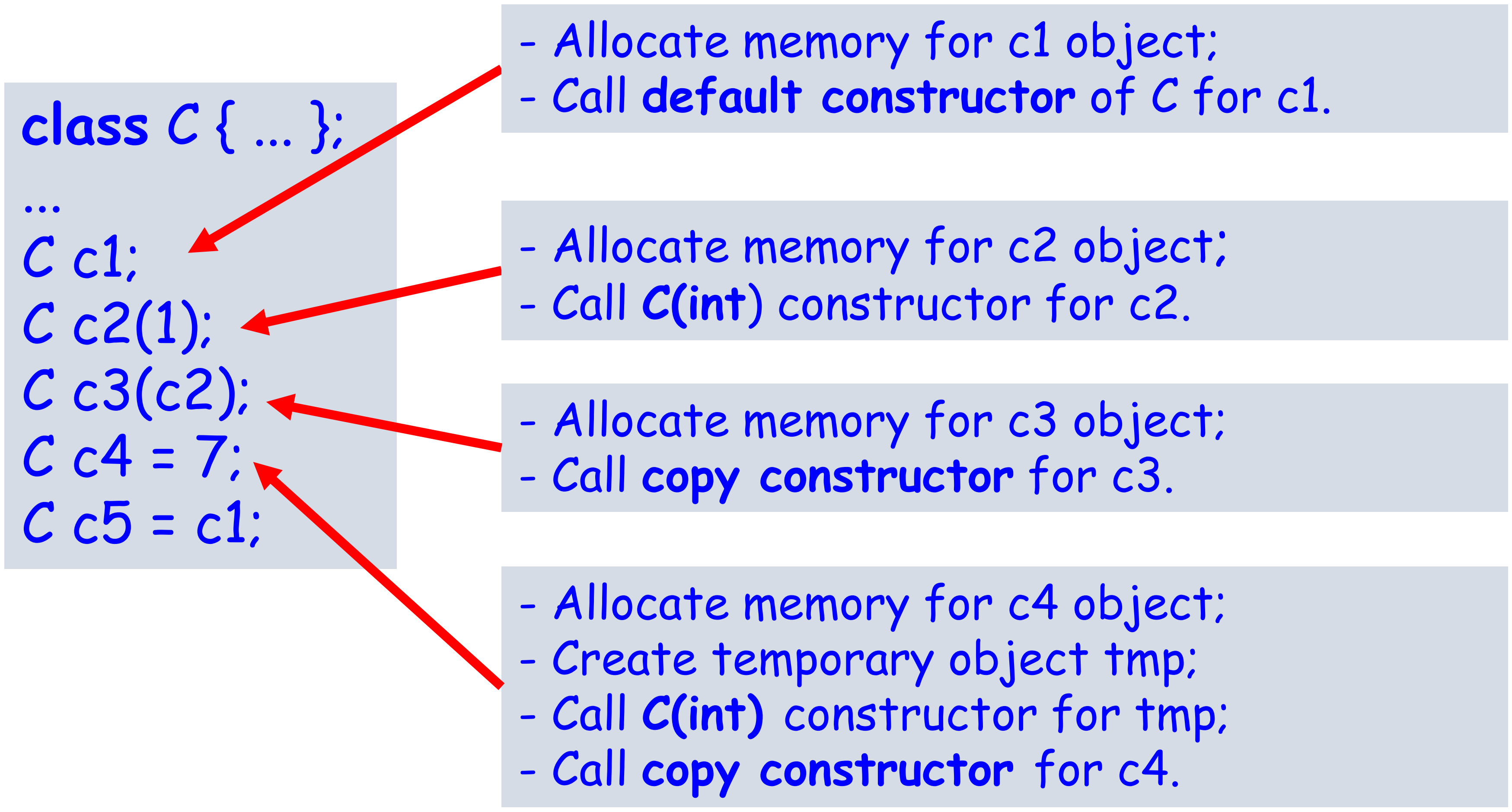
```
class C {
   public:
      C() { a = 0; b = 0; }
      C(const C& c) { a = c.a; b = c.b; }
      …
   int a, b;
};
```

Automatically generated:
- Default constructor
- Copy constructor
- Move constructor
- Copy assignment operator
- …



Semantic Analysis: Example 3

Initialization semantics



```
class C { ... };
...
C c1;
C c2(1);
C c3(c2);
C c4 = 7;
C c5 = c1;
```

- Allocate memory for c1 object;
- Call **default constructor** of C for c1.

- Allocate memory for c2 object;
- Call **C(int)** constructor for c2.

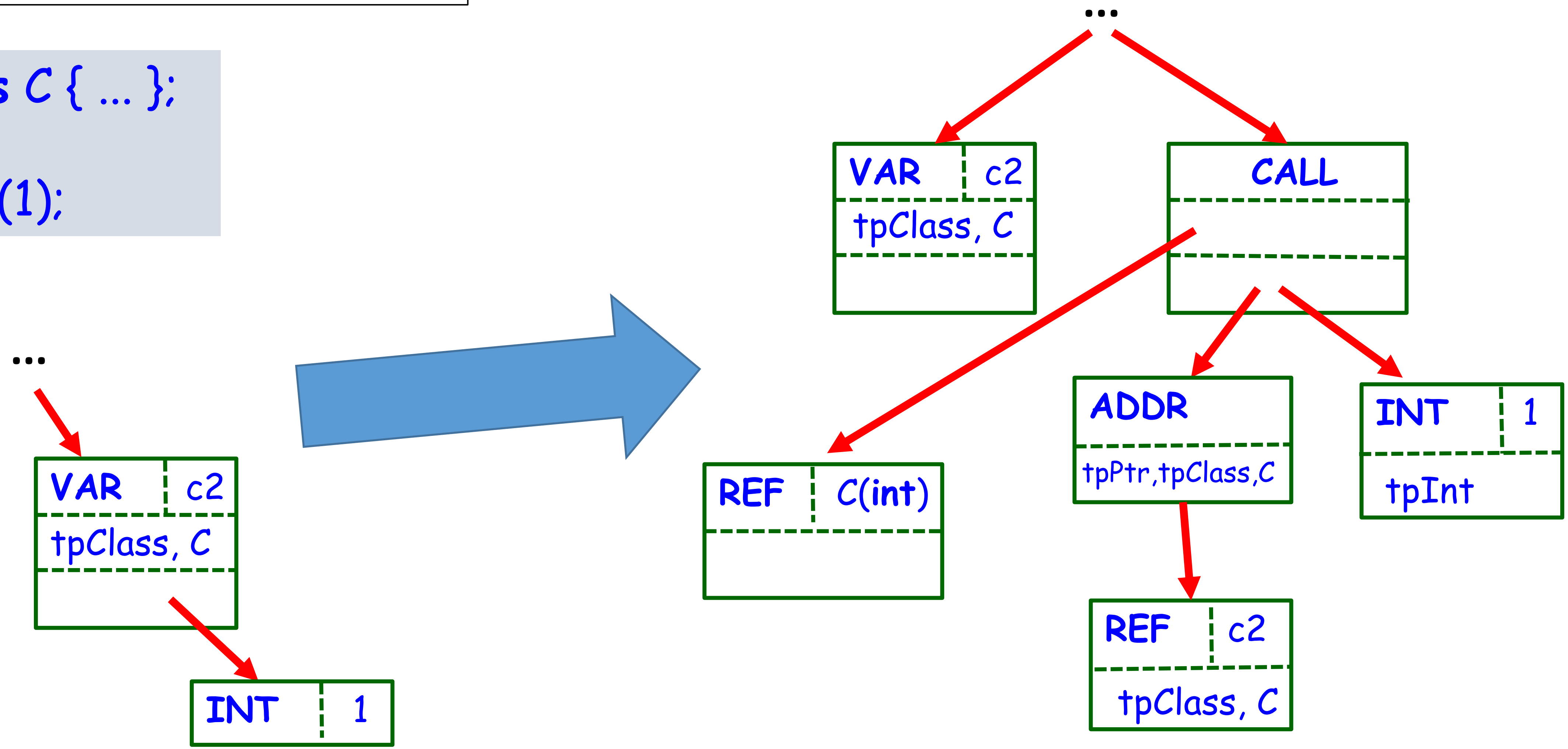
- Allocate memory for c3 object;
- Call **copy constructor** for c3.

- Allocate memory for c4 object;
- Create temporary object tmp;
- Call **C(int)** constructor for tmp;
- Call **copy constructor** for c4.

Semantic Analysis: Example 3

Initialization semantics

```
class C { … };
…
C c2(1);
```



Semantic Analysis: Example 4

User-defined conversions

```
class C {
private:
    bool m;
public:
    operator bool() { return m; }
};
...
C c;
...
if ( c ) ...  ←  if ( (bool)c ) ...  ←  if ( c.operator bool() ) ...
```

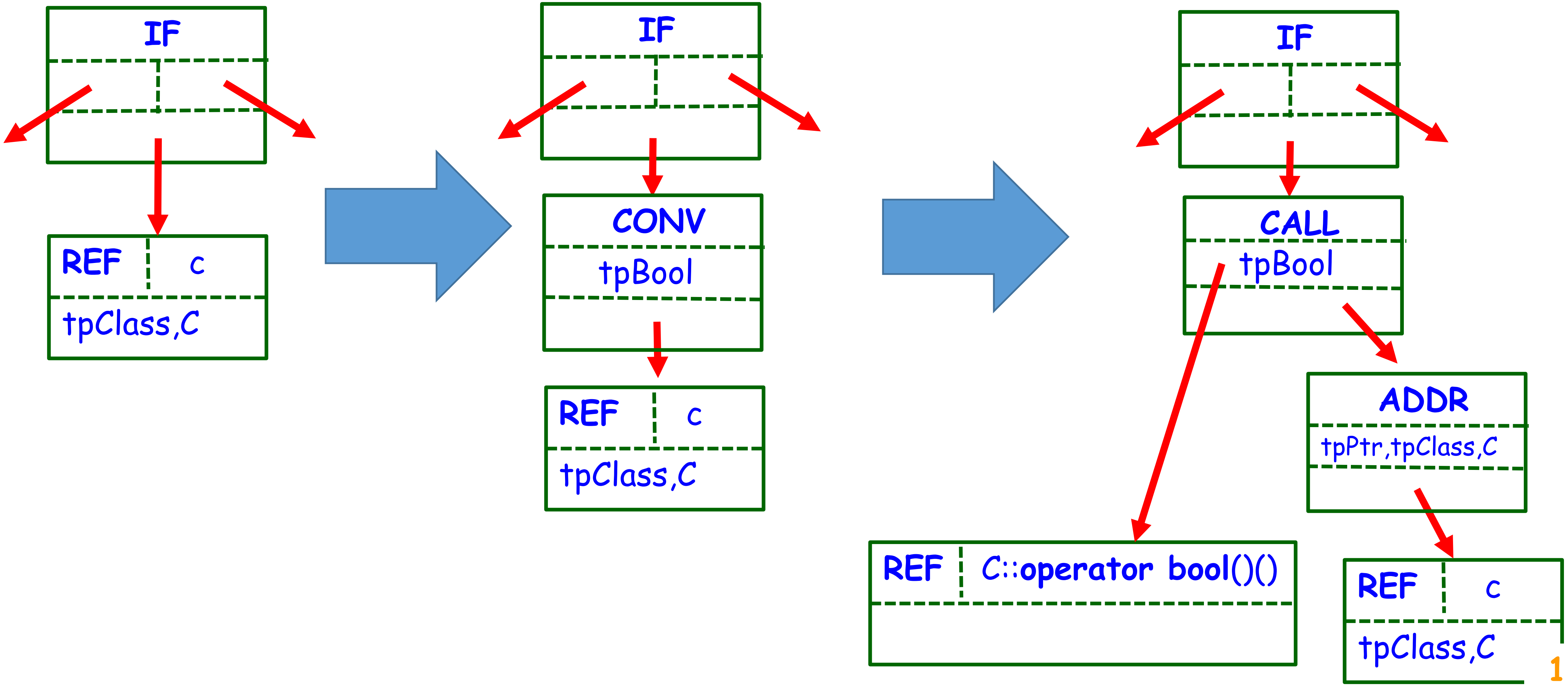
Semantic Analysis: Example 4

```
if ( c ) …
```

```
if ( (bool)c ) …
```

```
if ( c.operator bool() ) …
```

```
if ( C::operator bool(&c) ) …
```



IF

REF | c

tpClass,C

IF

CONV

tpBool

REF | c

tpClass,C

IF

CALL

tpBool

REF | C::operator bool()()

ADDR

tpPtr,tpClass,C

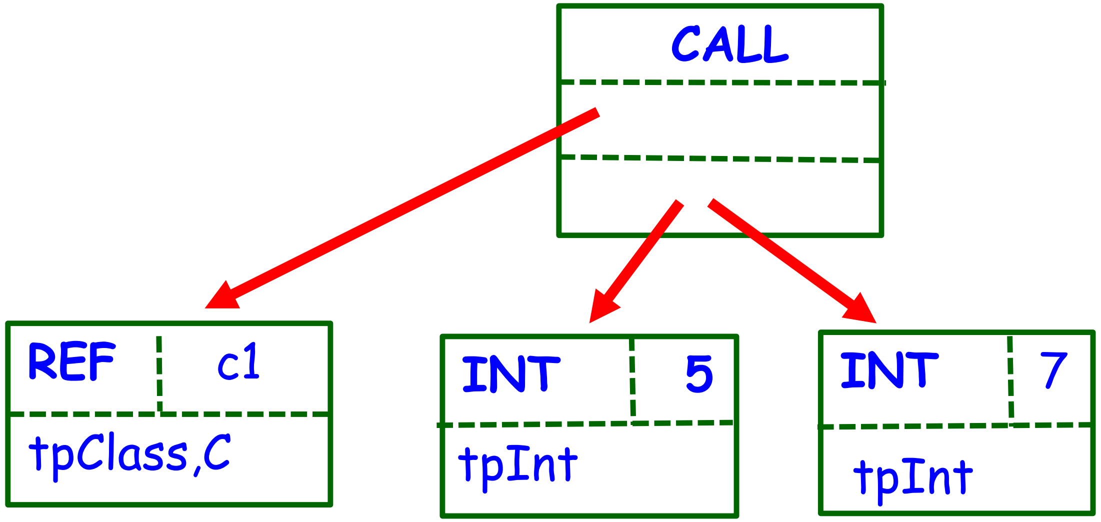
REF | c

tpClass,C

Semantic Analysis: Example 5

Functional objects (“functors”)

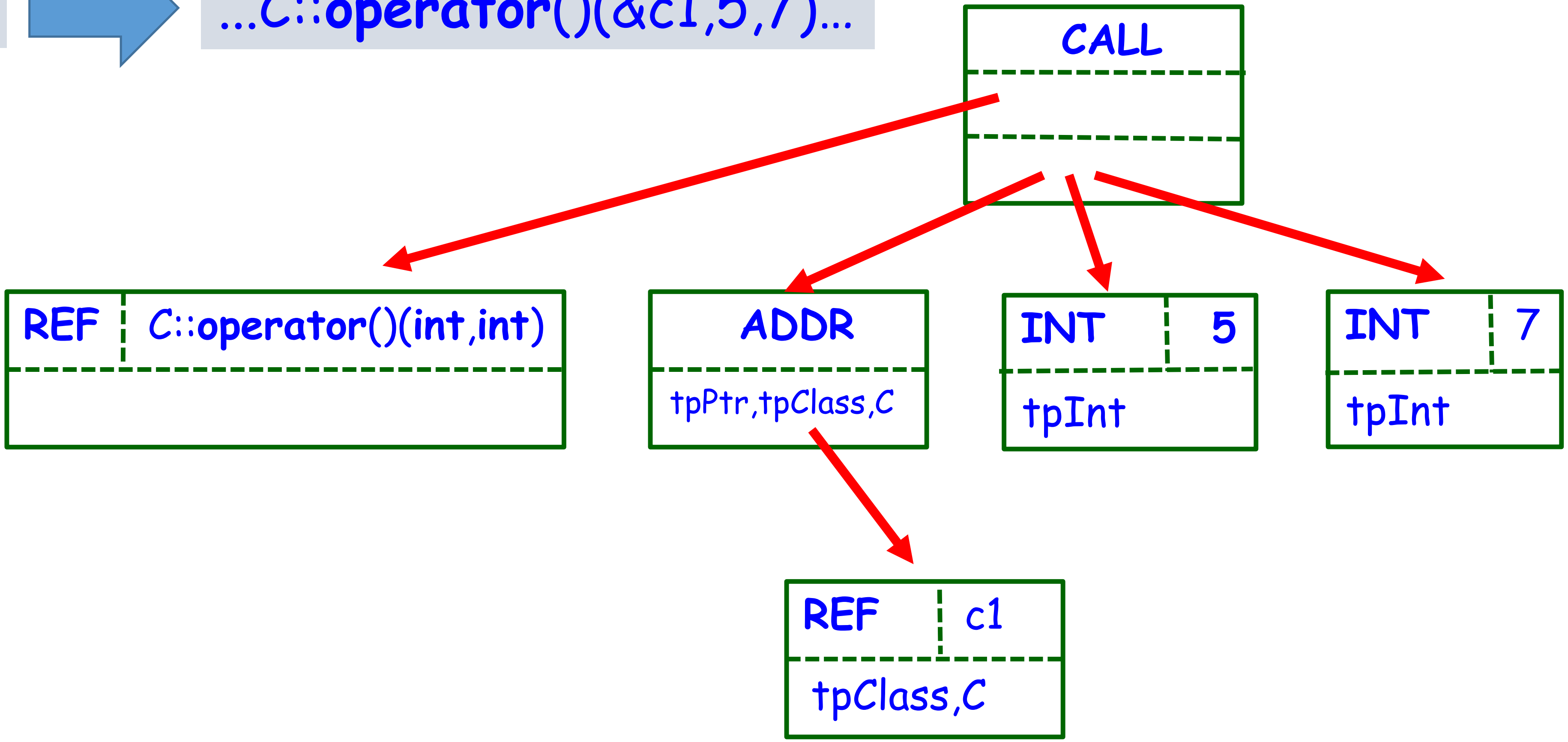
```
class C {
public:
    int operator()(int a,int b)
    { return a+b; }
};
...
C c1;
...
int res = c1(5,7);
```



Semantic Analysis: Example 5

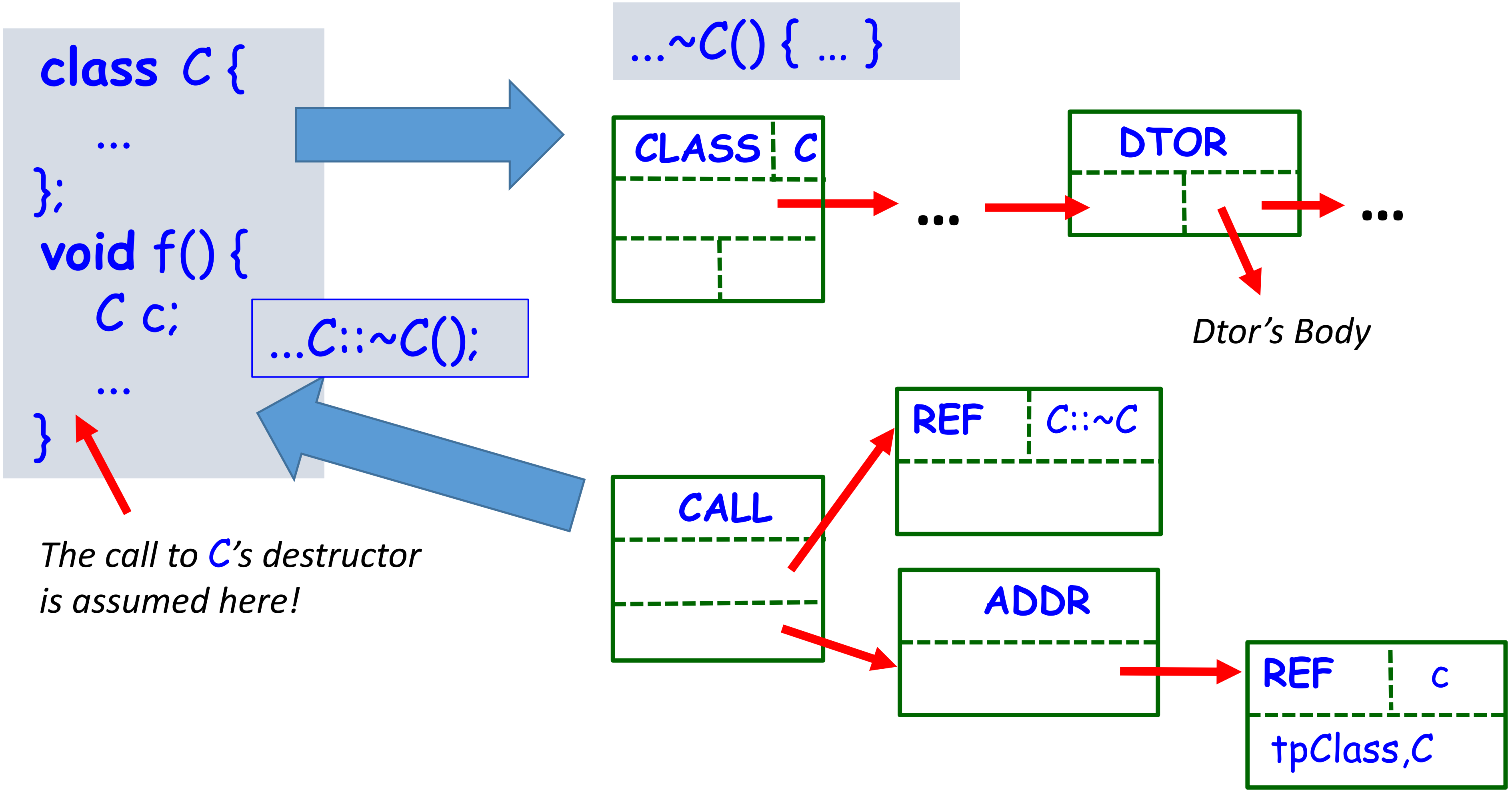
Functional objects (“functors”)

...c1(5,7)... → ...C::**operator**()(&c1,5,7)...



Semantic Analysis: Example 6

Hidden semantics: destructor call



```
class C {
    ...
};
void f() {
    C c;
    ...
}
```

```
...~C() { ... }
```

```
...C::~C();
```

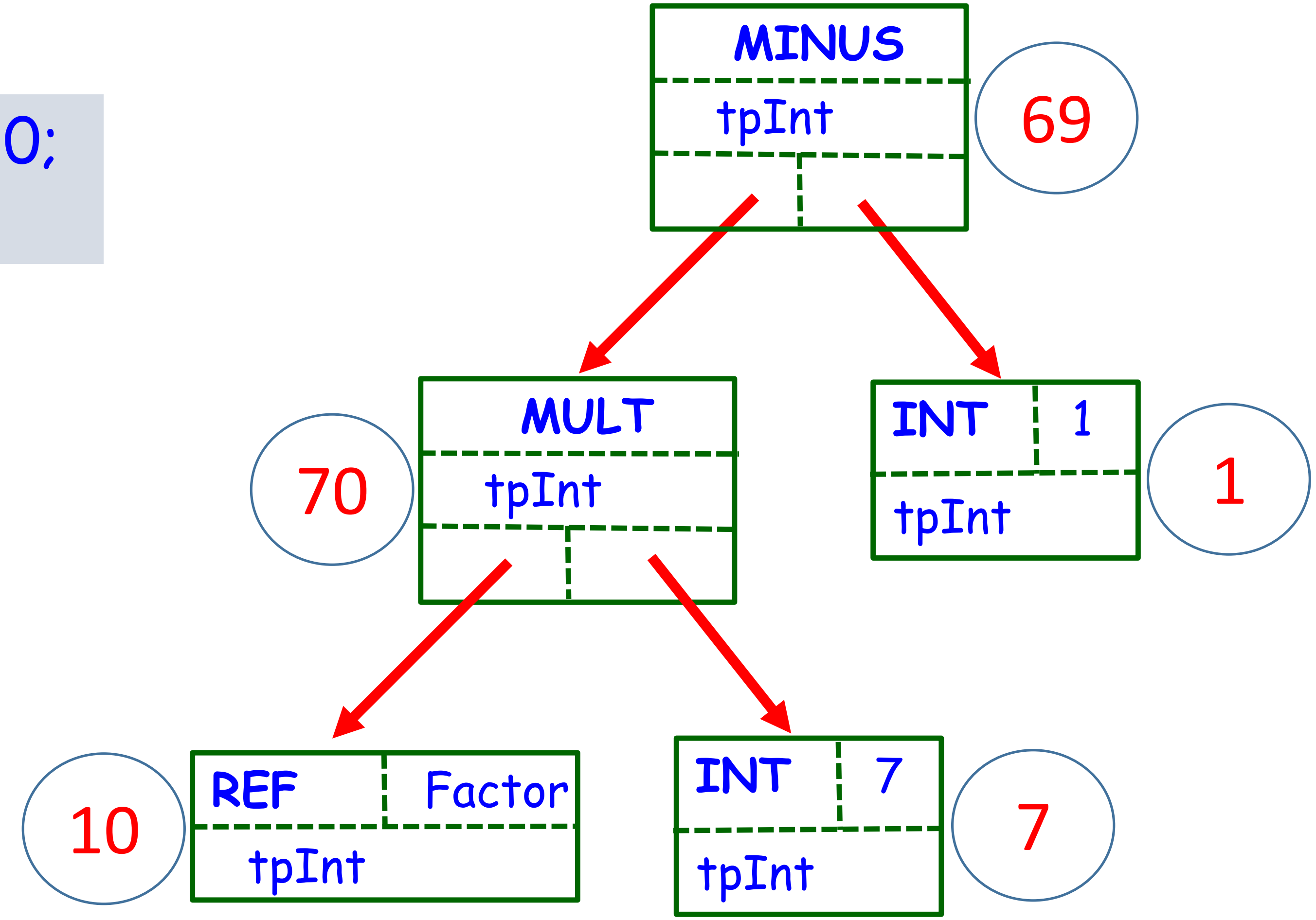
Dtor's Body

The call to C's destructor is assumed here!

Semantic Analysis: Example 7

Calculating constant expressions

```
const int Factor = 10;
int A[Factor*7-1];
```


MINUS
tpInt
69
MULT
tpInt
70
INT
1
tpInt
1
10
REF
Factor
tpInt
INT
7
tpInt
7