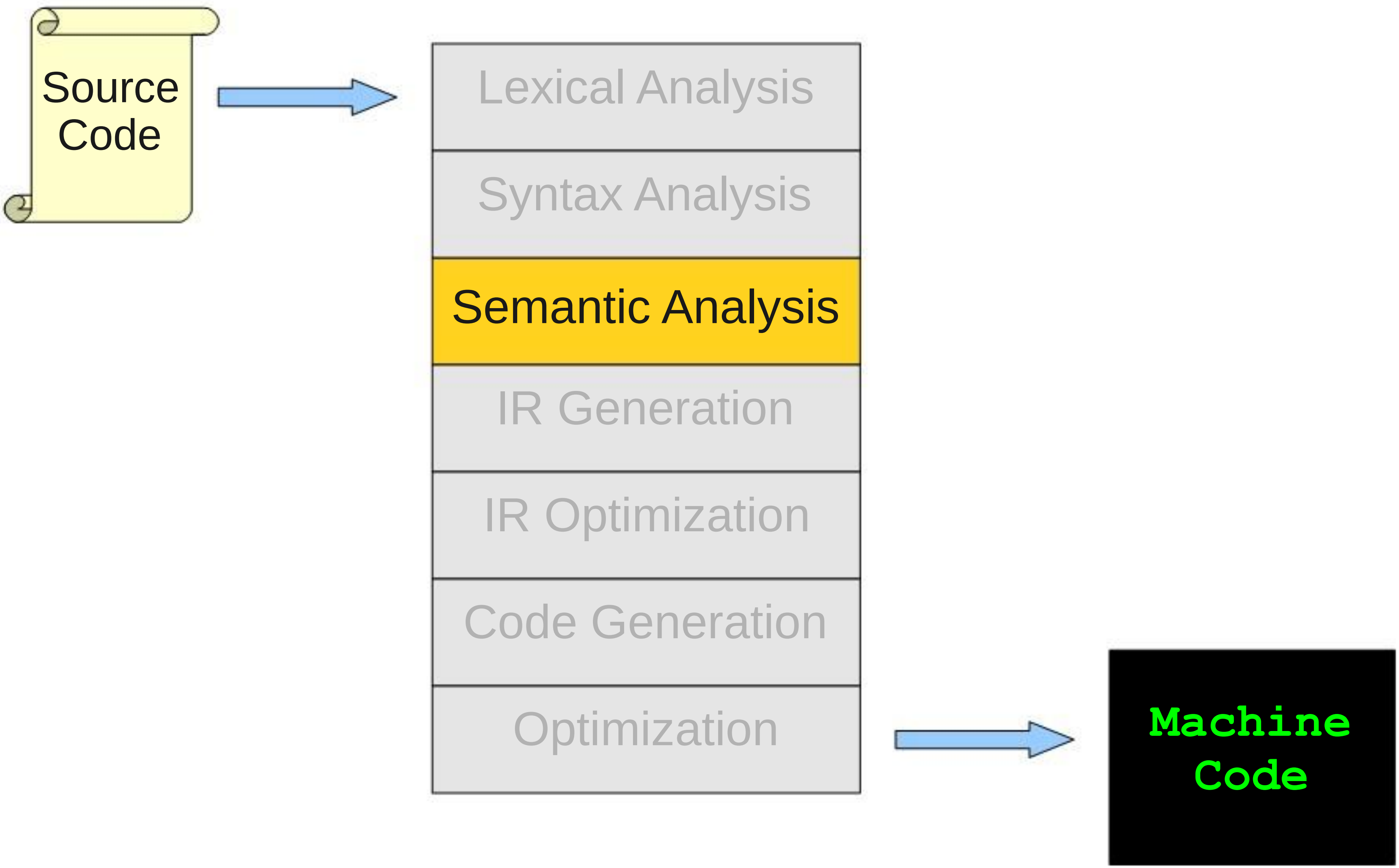
Type Checking

Where We Are


Source Code
Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization
Machine Code

Type-Checking

- **Type errors** arise when operations are performed on values that do not support that operation.

- **Static type checking.**
  - Analyze the program during compile-time to prove the type of values. E.g. C, C++, Java
  - Explicitly declare type at compile time. Never let bad things happen at runtime.

Ex: int x;
x=1;
{ float x; x =2.0 }; // most-closely nested rule
x= 0;

Type-Checking

- **Dynamic type checking.**
  - Check operations at runtime before performing them.
  - More flexible than static type checking, but usually less efficient.

  E.g. LISP, Python, Perl

Ex:

```
Class A { … }
Class B inherits Class A { … }
Class Main {  Class A   x ; // type of x is A
          if(Condition==True)
                x = new A;   // dynamic type of x is A
          else
                x = new B;   // dynamic type of x is B
}
```

Type Systems

- **Strong type system** is a system that require the programmer to do an explicit type conversion (casting).
  - Java, C++, C#, Python, etc.
  - There is no way you can add a number to a string without doing an explicit conversion.

- **Weak type system** is a system that do automatic type conversion.
  - Visual BASIC, JavaScript, Perl, PHP
  - You can do things like adding numbers to strings and the language will do an implicit coercion for you.

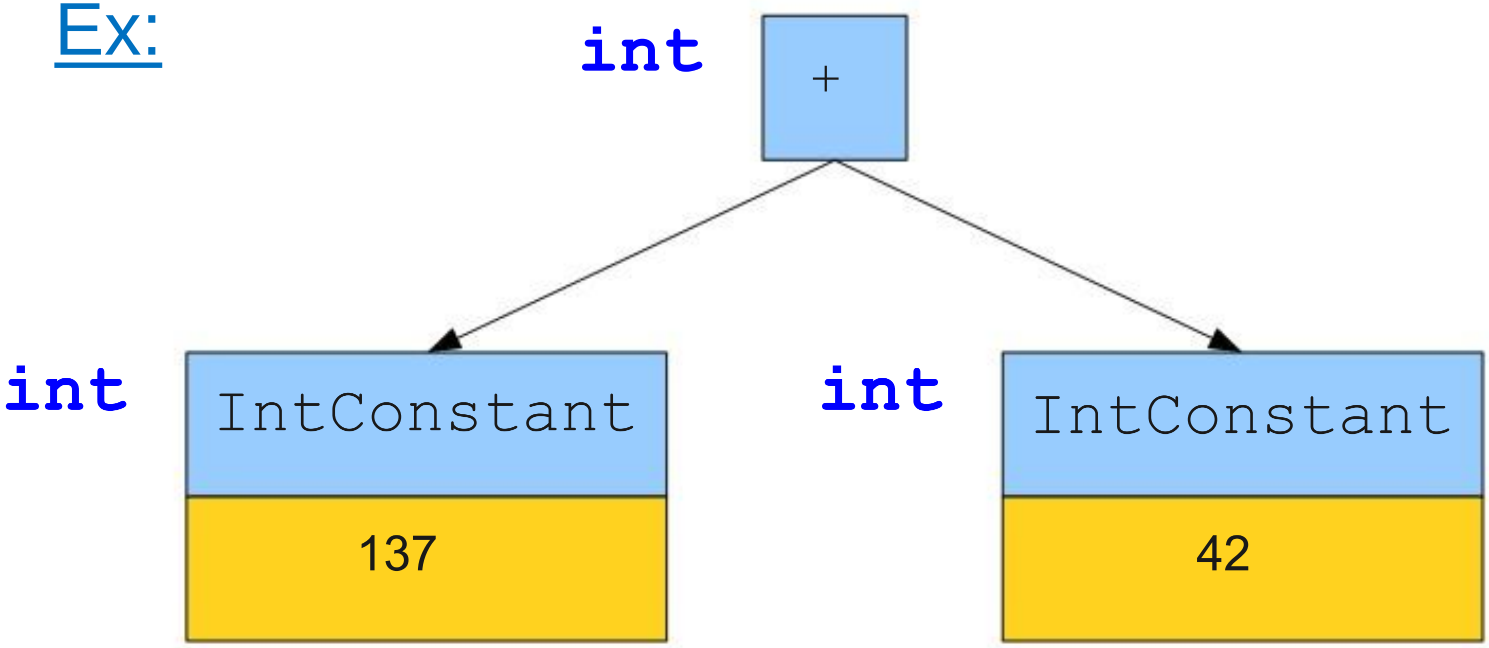
Type Wars

- Endless debate about what the “right” system is.
- **Dynamic type** systems make it easier to prototype; **static type** systems have fewer bugs.
- **Strongly-typed** languages are more efficient, **weakly-typed** systems are less effort on programming.

Inferring Expression Types

- How do we determine the type of an expression?
- Think of process as **logical inference**.

Ex:



Sample Inference Rules

- "If **x** is an identifier that refers to an object of type **t**, then **x** has type **t**."
- "If **e** is an integer constant, then **e** has type **`int`**."
- "If the operands e_1 and e_2 of $\mathbf{e_1 + e_2}$ are known to have types **`int`** and **`int`**, then $\mathbf{e_1 + e_2}$ has type **`int`**."

Type Checking as Proofs

- We begin with a set of **axioms**, then apply our **inference rules** to determine the types of expressions.

- We will encode our axioms and inference rules using this syntax:

$$\frac{\text{Preconditions}}{\text{Postconditions}}$$

- This is read “if **preconditions** are true, we can infer **postconditions**.”

Formal Notation for Type Systems

- We write

$$\vdash \mathbf{e} : \mathbf{T}$$

  if the expression **e** has type **T**.

- The symbol $\vdash$ means "we can infer..."

Our Starting Axioms

$$\frac{}{\vdash \texttt{true} : \texttt{bool}} \qquad \frac{}{\vdash \texttt{false} : \texttt{bool}}$$

Without any hypotheses, it is provable that both **true** and **false** constants have type Boolean.

Some Simple Inference Rules

$$\frac{i \text{ is an integer constant}}{\vdash i : \texttt{int}}$$

$$\frac{s \text{ is a string constant}}{\vdash s : \texttt{string}}$$

$$\frac{d \text{ is a double constant}}{\vdash d : \texttt{double}}$$

$$\frac{e : bool}{\vdash \mathrm{!e} : \texttt{bool}}$$

Negation of e

More Complex Inference Rules

If we can show that e_1 and e_2 have type int…

$$\frac{\vdash e_1 : \mathtt{int} \quad \vdash e_2 : \mathtt{int}}{\vdash e_1 + e_2 : \mathtt{int}}$$

$$\frac{\vdash e_1 : \mathtt{double} \quad \vdash e_2 : \mathtt{double}}{\vdash e_1 + e_2 : \mathtt{double}}$$

... then we can show that $e_1 + e_2$ has type int as well

Even More Complex Inference Rules

$$\frac{\vdash e_1 : T \quad \vdash e_2 : T \quad T \text{ is a primitive type}}{\vdash e_1 \texttt{ == } e_2 : \texttt{bool}}$$

$$\frac{\vdash e_1 : T \quad \vdash e_2 : T \quad T \text{ is a primitive type}}{\vdash e_1 \texttt{ != } e_2 : \texttt{bool}}$$

Why Specify Types this Way?

- Gives a **rigorous definition of types** independent of any particular implementation.

- Gives **maximum flexibility in implementation**.

- Allows formal verification of program properties. This is what's **used in the literature**.

Strengthening our Inference Rules

- Since the same object may have different types in different scopes, we need to strengthen our inference rules to remember **under what circumstances the inference rules are valid**.

- We write $$S \vdash \mathbf{e} : \mathbf{T}$$

  if **in scope S**, the expression **e** has type **T**.

- Types are now proven relative to the scope they are in.

Old Rules Revisited

$$\frac{}{S \vdash \mathtt{true} : \mathtt{bool}}$$

$$\frac{}{S \vdash \mathtt{false} : \mathtt{bool}}$$

$$\frac{i \text{ is an integer constant}}{S \vdash i : \mathtt{int}}$$

$$\frac{s \text{ is a string constant}}{S \vdash s : \mathtt{string}}$$

$$\frac{d \text{ is a double constant}}{S \vdash d : \mathtt{double}}$$

$$\frac{S \vdash e_1 : \mathtt{double} \quad S \vdash e_2 : \mathtt{double}}{S \vdash e_1 + e_2 : \mathtt{double}}$$

$$\frac{S \vdash e_1 : \mathtt{int} \quad S \vdash e_2 : \mathtt{int}}{S \vdash e_1 + e_2 : \mathtt{int}}$$

Rule for Identifier

$$\frac{x \text{ is an identifier.} \quad \boldsymbol{x} \textbf{ is a variable in scope S} \text{ with type T.}}{\mathbf{S} \vdash x : \mathrm{T}}$$

Rules for Functions

f is an identifier.

f is a function in scope S.

f has type $(T_1, \ldots, T_n) \rightarrow U$

$S \vdash e_i : T_i$ for $1 \leq i \leq n$

$$\frac{}{S \vdash f(e_1, \ldots, e_n) : U}$$

Rules for Arrays

$$\frac{S \vdash e_1 : T\texttt{[]} \qquad S \vdash e_2 : \texttt{int}}{S \vdash e_1[e_2] : T}$$

Array of type

Index of array must have type int

Type of an element in an array

Rule for Assignment

$$\frac{\begin{array}{c} S \vdash e_1 : T \\ S \vdash e_2 : T \end{array}}{S \vdash e_1 = e_2 : T}$$

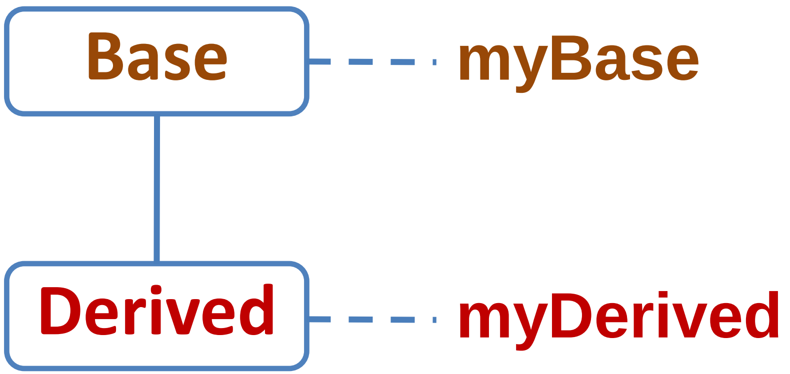
Rule for Assignment

$$\frac{S \vdash e_1 : T \qquad S \vdash e_2 : T}{S \vdash e_1 = e_2 : T}$$

Problem

If **`Derived`** extends **`Base`**, will this rule work for this code?

```
Base    myBase;
Derived myDerived;
myBase = myDerived;
```



- Some information in myDerived will be thrown away after the assignment statement.
- We need partial orders to solve this problem.

Properties of Inheritance Structures

- Any class is convertible to itself. **(Reflexivity)**
- If A is convertible to B and B is convertible to C, then A is convertible to C. **(Transitivity)**
- If A is convertible to B and B is convertible to A, then A and B are the same type. **(Antisymmetry)**
- The above properties define the **partial orders** over types.

- Base class has more objects, but fewer data and function members

- When we say the class is bigger, it means the class has more data and function members, i.e., Derived class is bigger than Base class.

Types and Partial Orders

- We say that A ≤ B if A is convertible to B.
- We have that
  - A ≤ A
  - A ≤ B and B ≤ C implies A ≤ C
  - A ≤ B and B ≤ A implies A = B

Types and Partial Orders

- Bigger type must be explicitly convertible to Small type. However, there might be a lost in conversion.

  Ex: double x = 1234.7; int a;

  a = (int)x; // Cast double into int.

  In OOP, childclass (bigger) ≤ parentclass (smaller), not vice versa.

- There are pairs of types (/classes) that can not be convertible (neither implicit nor explicit). E.g. In C#, string is not convertible with Integer.

Updated Rule for Assignment

$$\frac{\begin{array}{l} S \vdash e_1 : T_1 \\ S \vdash e_2 : T_2 \\ T_2 \leq T_1 \end{array}}{S \vdash e_1 = e_2 : T_1}$$

Updated Rule for Comparisons

$$\frac{S \vdash e_1 : T \quad S \vdash e_2 : T \quad T \text{ is a primitive type}}{S \vdash e_1 \;\texttt{==}\; e_2 : \texttt{bool}}$$

$$\Rightarrow$$

$$\frac{S \vdash e_1 : T_1 \quad S \vdash e_2 : T_2 \quad T_1 \text{ and } T_2 \text{ are of class type.} \quad T_1 \leq T_2 \text{ or } T_2 \leq T_1}{S \vdash e_1 \;\texttt{==}\; e_2 : \texttt{bool}}$$

This makes the comparison between int and string impossible.

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

Something is wrong here !

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{x \text{ is an identifier.} \quad x \text{ is a variable in scope S with type T.}}{S \vdash x : T}$$

Facts
$S \vdash$ **x : int**
$S \vdash$ **y : int**
$S \vdash$ **z : int**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
      /* … */
}
```

$$\frac{S \vdash e_1 : T_1 \quad S \vdash e_2 : T_2 \quad T_1 \leq T_2 \text{ or } T_2 \leq T_1}{S \vdash e_1 \mathbin{\texttt{==}} e_2 : \texttt{bool}}$$

Facts
$S \vdash$ **`x`** : **`int`**
$S \vdash$ **`y`** : **`int`**
$S \vdash$ **`z`** : **`int`**
$S \vdash$ **`x == y`** : **`bool`**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{i \text{ is an integer constant}}{S \vdash i : \texttt{int}}$$

Facts
$S \vdash$ **x : int**
$S \vdash$ **y : int**
$S \vdash$ **z : int**
$S \vdash$ **x == y : bool**
$S \vdash$ **5 : int**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{S \vdash e_1 : \texttt{int} \qquad S \vdash e_2 : \texttt{int}}{S \vdash e_1 + e_2 : \texttt{int}}$$

Facts
$S \vdash$ **x** : **int**
$S \vdash$ **y** : **int**
$S \vdash$ **z** : **int**
$S \vdash$ **x == y** : **bool**
$S \vdash$ **5** : **int**
$S \vdash$ **x + y** : **int**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{S \vdash e_1 : \texttt{int} \qquad S \vdash e_2 : \texttt{int}}{S \vdash e_1 < e_2 : \texttt{bool}}$$

Facts
$S \vdash$ **x** : **int**
$S \vdash$ **y** : **int**
$S \vdash$ **z** : **int**
$S \vdash$ **x == y** : **bool**
$S \vdash$ **5** : **int**
$S \vdash$ **x + y** : **int**
$S \vdash$ **x + y < z** : **bool**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{S \vdash e_1 : T_1 \quad S \vdash e_2 : T_2 \quad T_1 \leq T_2 \text{ or } T_2 \leq T_1}{S \vdash e_1 == e_2 : \mathbf{bool}}$$

Facts
$S \vdash$ **x : int**
$S \vdash$ **y : int**
$S \vdash$ **z : int**
$S \vdash$ **x == y : bool**
$S \vdash$ **5 : int**
$S \vdash$ **x + y : int**
$S \vdash$ **x + y < z : bool**
$S \vdash$ **x == z : bool**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{S \vdash e_1 : \texttt{int} \qquad S \vdash e_2 : \texttt{int}}{S \vdash e_1 > e_2 : \texttt{bool}}$$

Facts
S ⊢ **x : int**
S ⊢ **y : int**
S ⊢ **z : int**
S ⊢ **x == y : bool**
S ⊢ **5 : int**
S ⊢ **x + y : int**
S ⊢ **x + y < z : bool**
S ⊢ **x == z : bool**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{S \vdash e_1 : \texttt{int} \quad S \vdash e_2 : \texttt{int}}{S \vdash e_1 > e_2 : \texttt{bool}}$$

```
> Error: Cannot compare int and bool
```

Facts
$S \vdash$ **x : int**
$S \vdash$ **y : int**
$S \vdash$ **z : int**
$S \vdash$ **x == y : bool**
$S \vdash$ **5 : int**
$S \vdash$ **x + y : int**
$S \vdash$ **x + y < z : bool**
$S \vdash$ **x == z : bool**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
     /* … */
}
```

$$\frac{S \vdash e_1 : \texttt{bool} \qquad S \vdash e_2 : \texttt{bool}}{S \vdash e_1 \;\texttt{\&\&}\; e_2 : \texttt{bool}}$$

```
> Error: Cannot compare int and bool
  Error: Cannot compare ??? and bool
```

Facts
$S \vdash$ **x** : **int**
$S \vdash$ **y** : **int**
$S \vdash$ **z** : **int**
$S \vdash$ **x == y** : **bool**
$S \vdash$ **5** : **int**
$S \vdash$ **x + y** : **int**
$S \vdash$ **x + y < z** : **bool**
$S \vdash$ **x == z** : **bool**

Example: Type Inference

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
    /* … */
}
```

$$\frac{S \vdash e_1 : \texttt{bool} \qquad S \vdash e_2 : \texttt{bool}}{S \vdash e_1 \;||\; e_2 : \texttt{bool}}$$

```
> Error: Cannot compare int and bool
  Error: Cannot compare ??? and bool
  Error: Cannot compare ??? and bool
```

Facts
$S \vdash \texttt{x} : \texttt{int}$
$S \vdash \texttt{y} : \texttt{int}$
$S \vdash \texttt{z} : \texttt{int}$
$S \vdash \texttt{x == y} : \texttt{bool}$
$S \vdash \texttt{5} : \texttt{int}$
$S \vdash \texttt{x + y} : \texttt{int}$
$S \vdash \texttt{x + y < z} : \texttt{bool}$
$S \vdash \texttt{x == z} : \texttt{bool}$

Cascading Errors

- A **type error** occurs when we cannot prove the type of an expression.
- Type errors can easily **cascade**:
  - Can't prove a type for e1, so can't prove a type for e1+e2, so can't prove a type for (e1+e2)+e3, etc.
  - Cascade of type error is annoying. Type error recovery method could be applied.

Cascading Errors

Solution (Type-Error Recovery)

- Define a new type called "NoType" which is a subtype of Boolean type. NoType ≤ Boolean type.
- When we see NoType, we don't produce an error message.

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
```

Boolean Int

$$\frac{S \vdash e_1 : \mathbf{int} \qquad S \vdash e_2 : \mathbf{int}}{S \vdash e_1 > e_2 : \mathbf{bool}}$$

```
> Error: Cannot compare int
         with bool
```

After report an error, we conclude (x==y) > 5 having **NoType**.

Cascading Errors

Solution

- Define a new type called "NoType" which is a subtype of Boolean type. NoType ≤ Boolean type.
- When we see NoType, we don't produce an error message.

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
```

NoType Bool

Cascading Errors

Solution

- Define a new type called "NoType" which is a subtype of Boolean type. NoType ≤ Boolean type.
- When we see NoType, we don't produce an error message.

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
```

$$\frac{S \vdash e_1 : \mathbf{bool} \quad S \vdash e_2 : \mathbf{bool}}{S \vdash e_1 \ \&\& \ e_2 : \mathbf{bool}}$$

Update rule

$$\frac{S \vdash e_1 : \mathbf{T1} \quad S \vdash e_2 : \mathbf{T2} \quad \mathbf{T1}, \mathbf{T2} \leq \mathbf{bool}}{S \vdash e_1 \ \&\& \ e_2 : \mathbf{bool}}$$

Cascading Errors

Solution

- Define a new type called “NoType” which is a subtype of Boolean type. NoType ≤ Boolean type.
- When we see NoType, we don’t produce an error message.

```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
```

Bool **Bool**

Cascading Errors

Solution

- Define a new type called “NoType” which is a subtype of Boolean type. NoType ≤ Boolean type.
- When we see NoType, we don’t produce an error message.

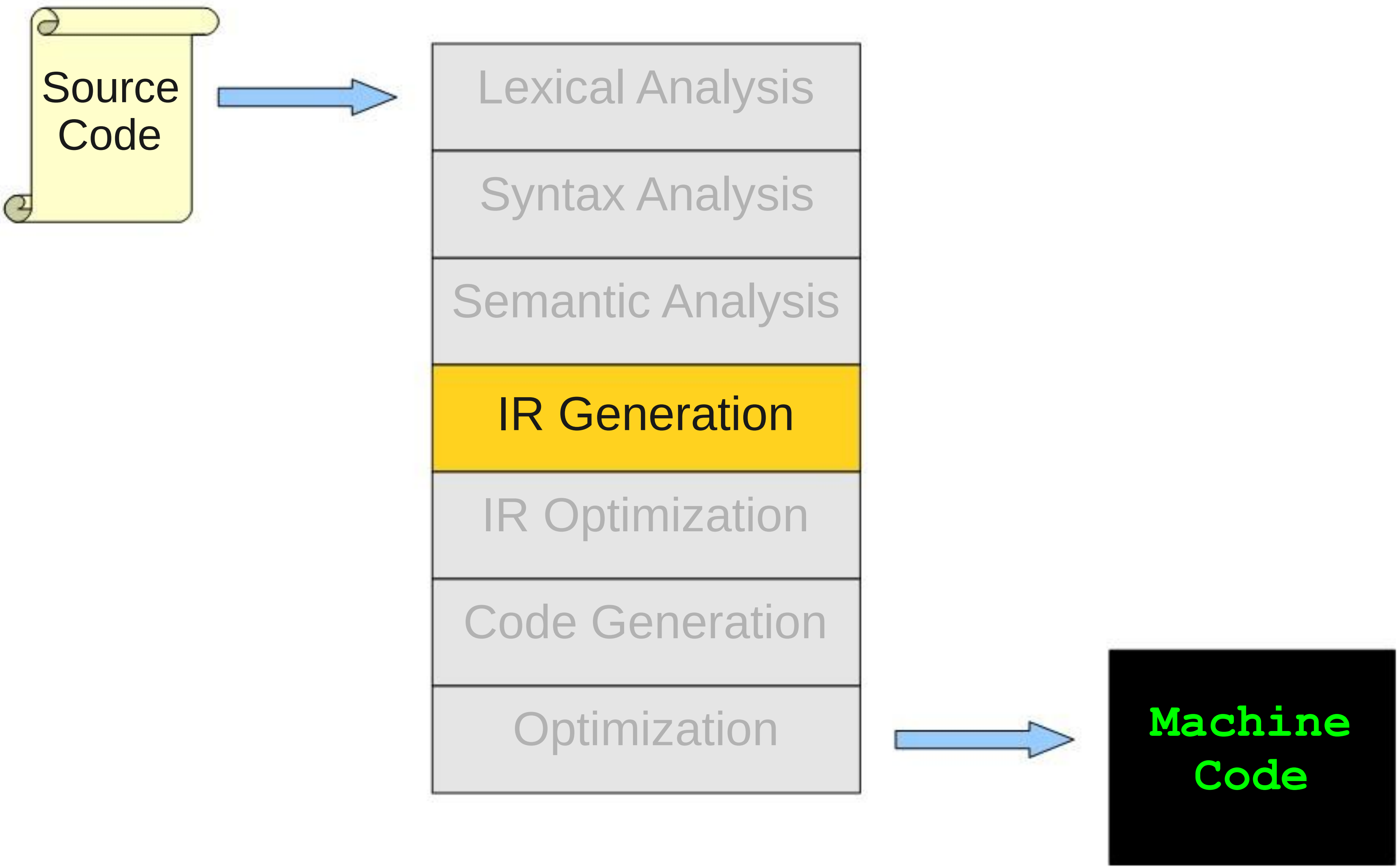
```
int x, y, z;
if (((x == y) > 5 && x + y < z) || x == z) {
```

Bool

No more error message.

IR Generation

Where We Are



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What is IR Generation?

- **Intermediate Representation Generation**.
- The final phase of the compiler front-end.
- Goal: Translate the program into the format (assembly-like) expected by the compiler back-end.

Why do IR Generation?

- Working with an intermediate language makes optimizations easier and clearer.

Outline

- **Runtime Environments**
- **Three-Address Code**
- **TAC generation**

Runtime Environment

- A **runtime environment** is a set of data structures maintained at runtime (E.g. the stack, the heap, static data, etc.).

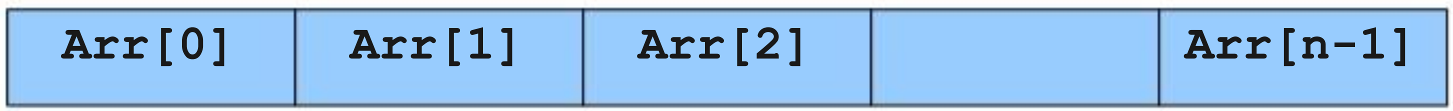
  - What do objects look like in memory?
  - What do functions look like in memory?
  - Where in memory should they be placed?
  - How are function calls implemented?

Encoding Primitive Types

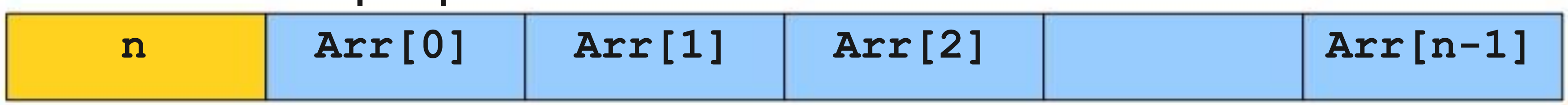
- Primitive **integral** types (**`byte`**, **`char`**, **`short`**, **`int`**, **`long`**, **`unsigned`**, **`uint16_t`**, etc.) typically map directly to the underlying machine type.
- Primitive **real-valued** types (**`float`**, **`double`**, **`long double`**) typically map directly to underlying machine type.
- **Pointers** typically implemented as integers holding memory addresses.

Encoding Arrays

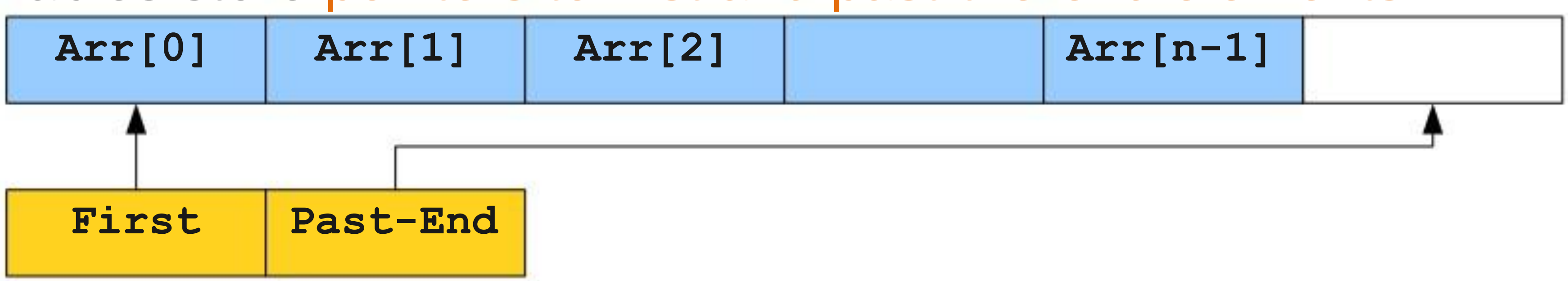
- **C-style** arrays: Elements laid out consecutively in memory.



- **Java-style** arrays: Elements laid out consecutively in memory with size information prepended.



- **D-style** arrays: Elements laid out consecutively in memory; array variables store pointers to first and past-the-end elements.



D is a language with C-like syntax and static typing.(http://dlang.org/index.html)

Encoding Multidimensional Arrays

- Often represented as an array of arrays.

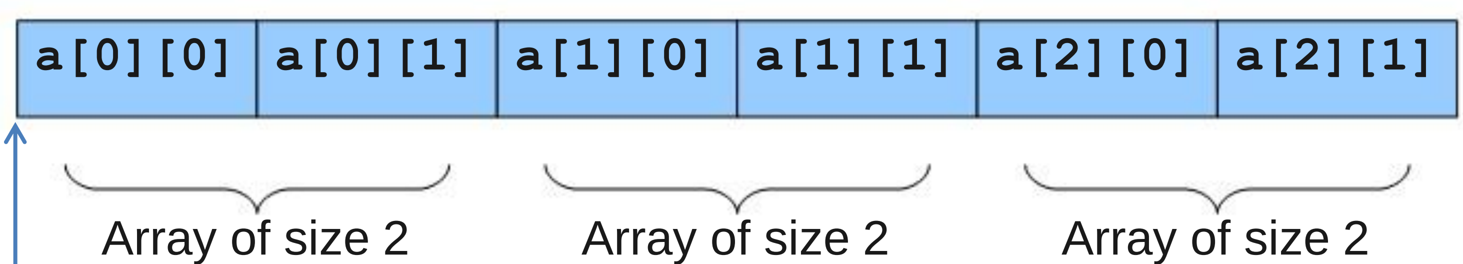
- **C-style** arrays:

`int a[3][2];`

4 Bytes

How do you know an address for an element a[i][j] ?

= base address + (i - 0)*4*2 + (j - 0)*4



Row size

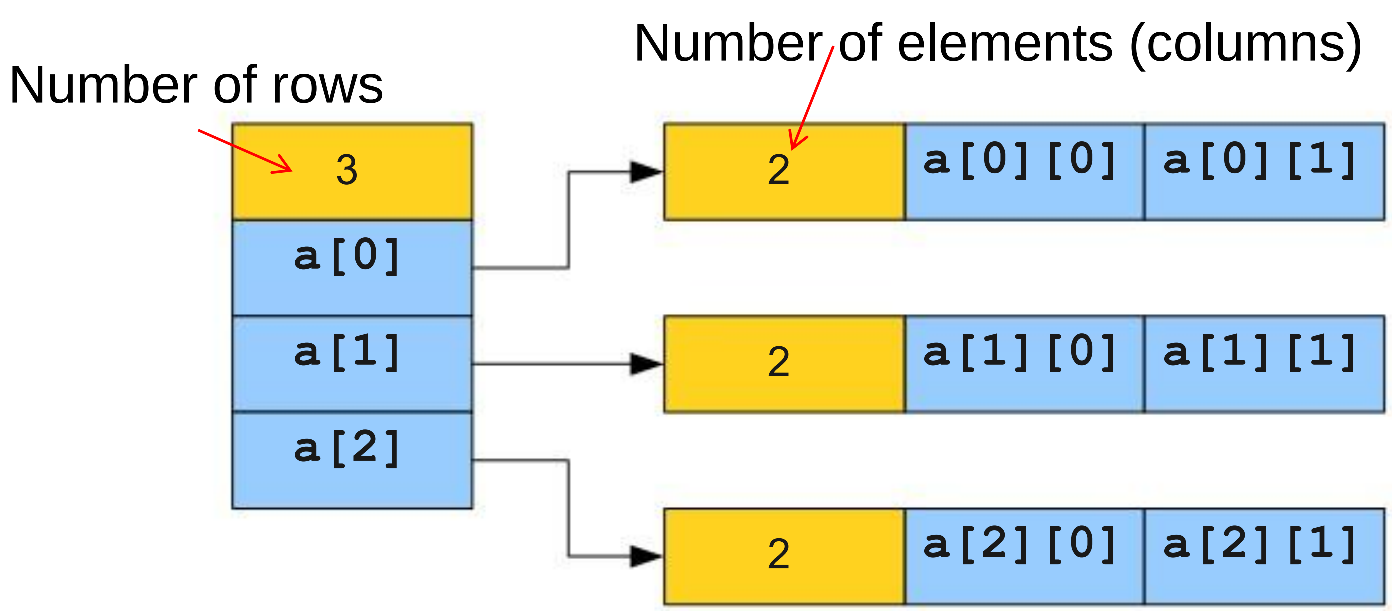
Element size

Base address

Encoding Multidimensional Arrays

- **Java-style** arrays:

```
int[][] a = new int [3][2];
```

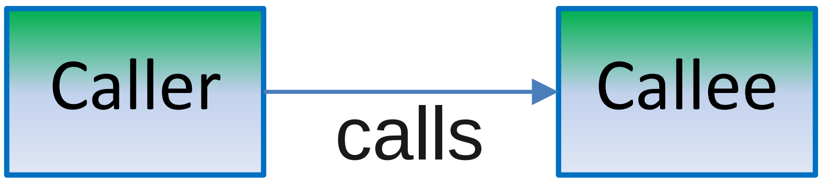


Implementing Function Calls

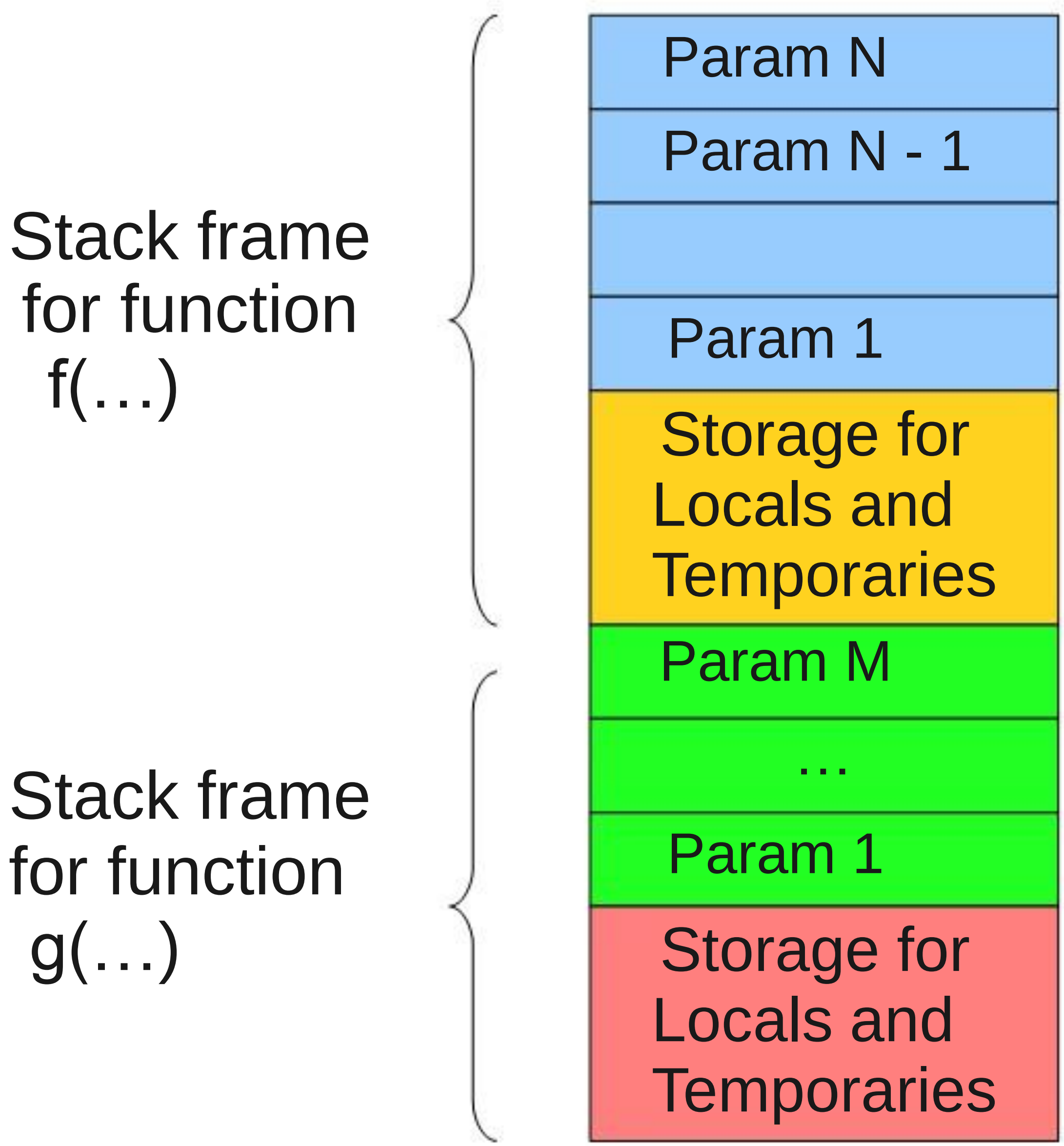
- Function calls are often implemented using a **stack of activation records** (or **stack frames**).
- **Calling** a function **pushes** a new activation record onto the stack.
- **Returning** from a function **pops** the current activation record from the stack.

Implementing Function Calls

- Each **activation record** needs to hold
  - All of its parameters.
  - All of its local variables.
  - All temporary variables.
- Caller responsible for pushing and popping space for callee's arguments.
- Callee responsible for pushing and popping space for its own temporaries.



A Logical Stack Frame
(Logical Activation Record)

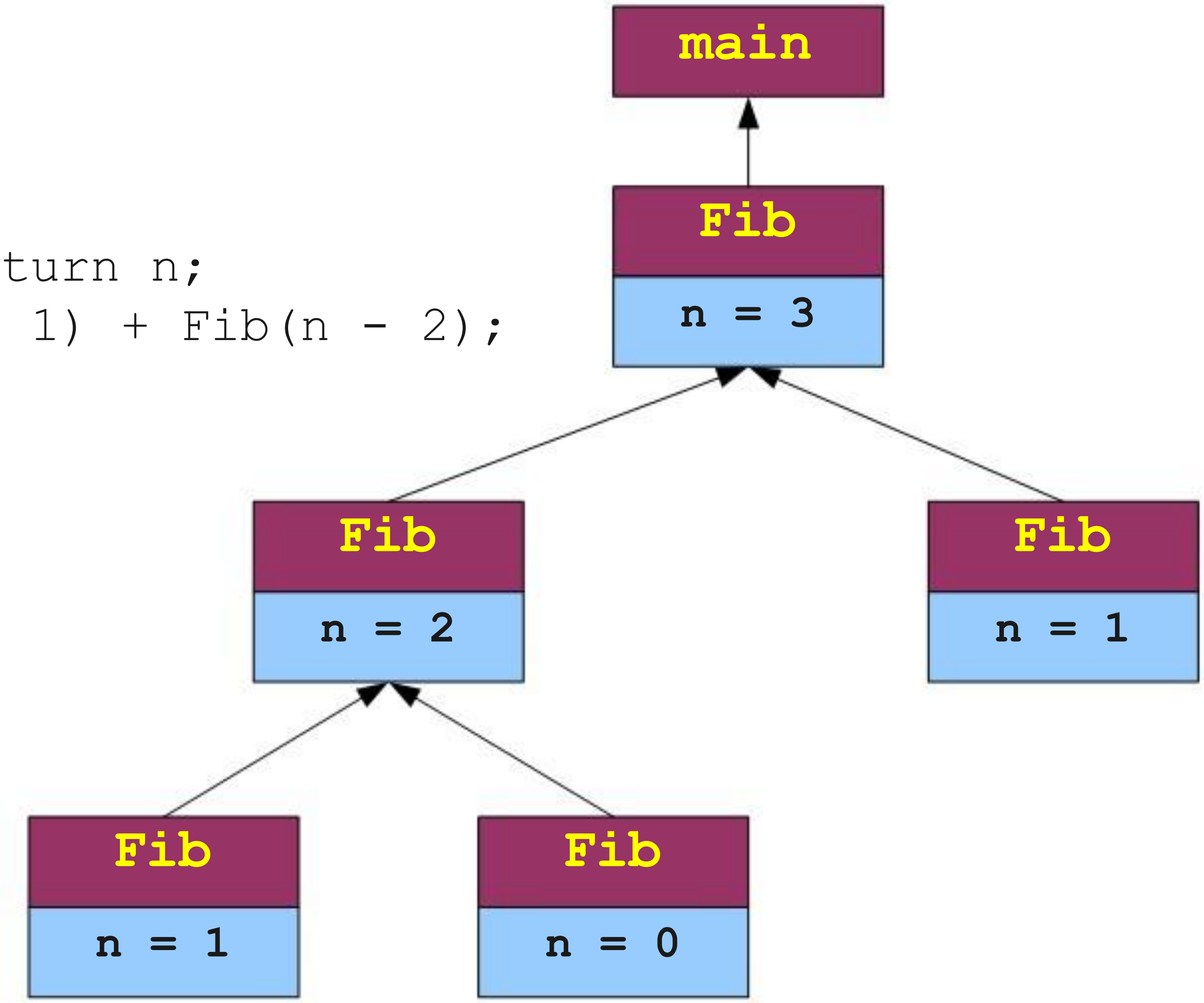


Activation Trees

- An **activation tree** is a tree structure representing all of the function calls made by a program on execution.
- Each **node** in the tree is an **activation record**.
- Each activation record stores a **control link** to the activation record of the function that invoked it.

Activation Trees

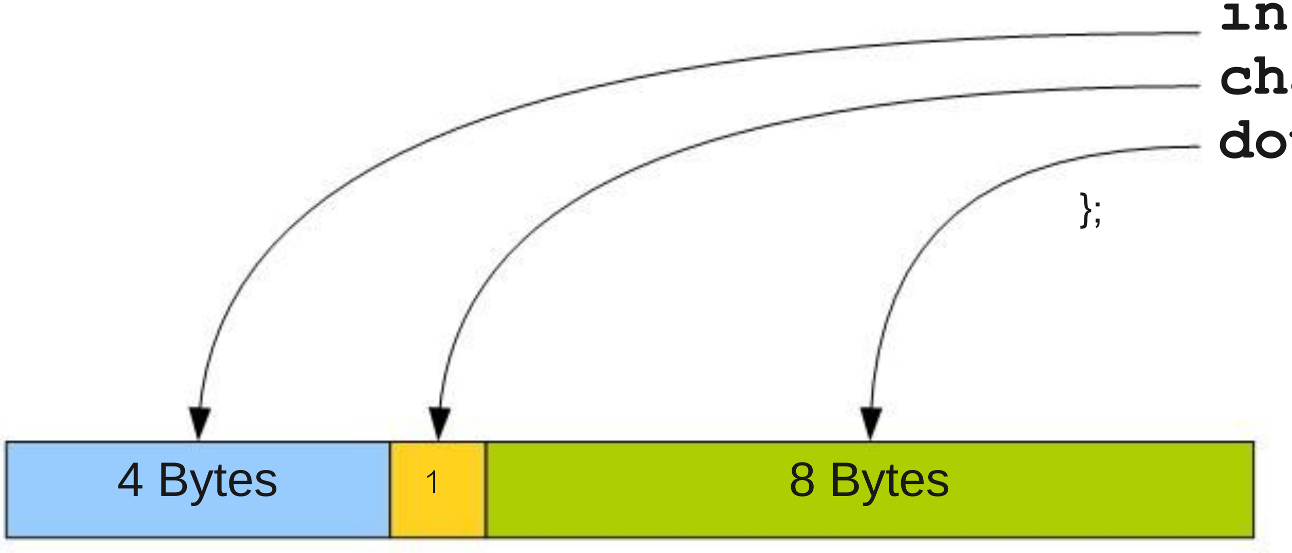
```
int main() {
    Fib(3);
}

int Fib(int n) {
    if (n <= 1) return n;
    return Fib(n - 1) + Fib(n - 2);
}
```



Encoding C-Style `structs`

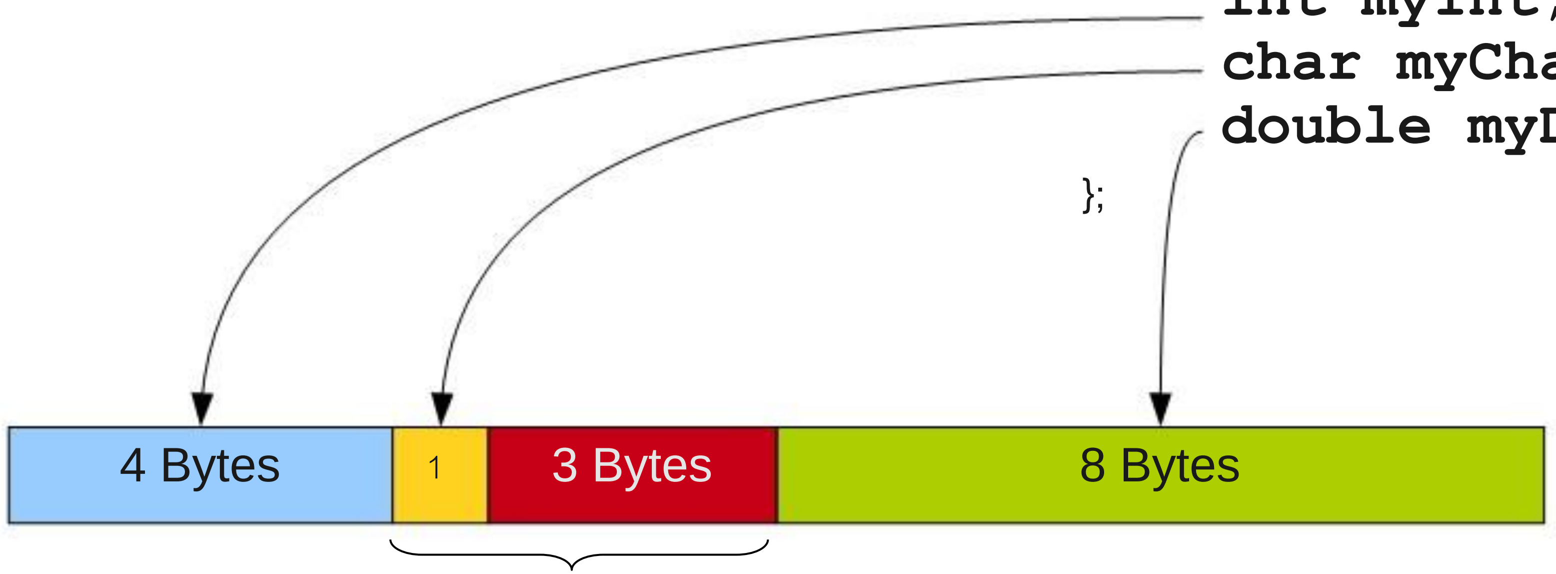
- A `struct` is a type containing a collection of named values.
- Most common approach: lay each field out in the order it's declared.

```
struct MyStruct {
    int myInt;
    char myChar;
    double myDouble;
};
```



Encoding C-Style **`structs`**

```
struct MyStruct {
    int myInt;
    char myChar;
    double myDouble;
};
```



Physical memory layout : Assume that memory is allocated **4-byte/block**

OOP Inheritance

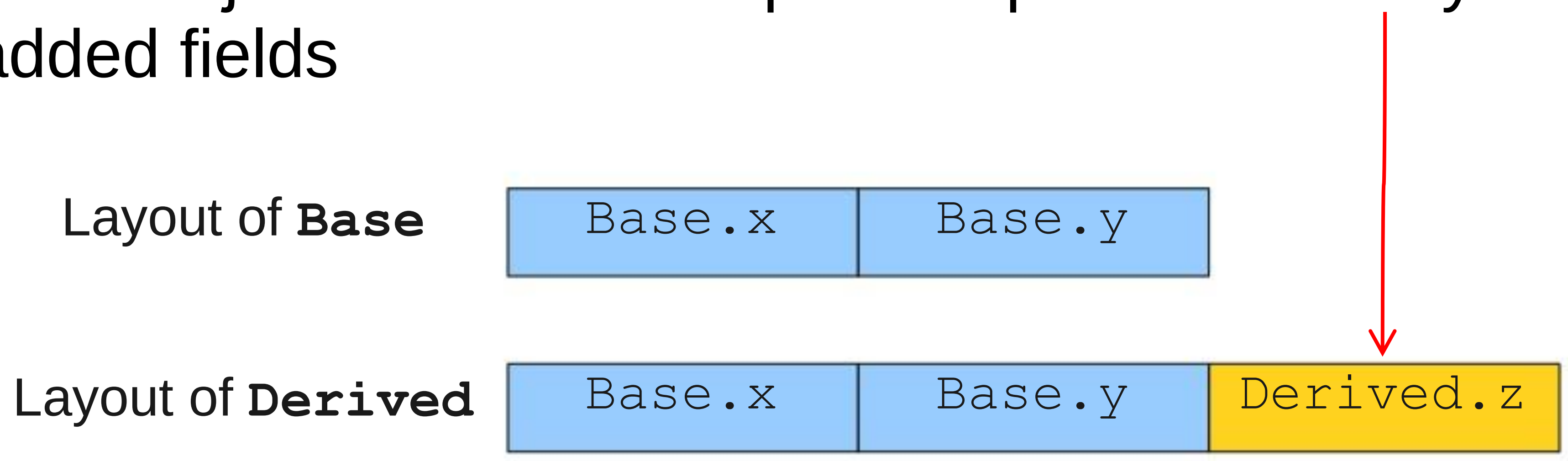
- Consider the following code:

```
class Base {
    int x;
    int y;
}
class Derived extends Base {
    int z;
}
```

- What will `Derived` look like in memory?

An Observation

- Child object has the same memory layout as parent objects.
- Child object needs more space to place the newly added fields



Implementing Dynamic Dispatch

- **Dynamic dispatch** means determining which function to call at runtime based on the dynamic type of the object.

Example:

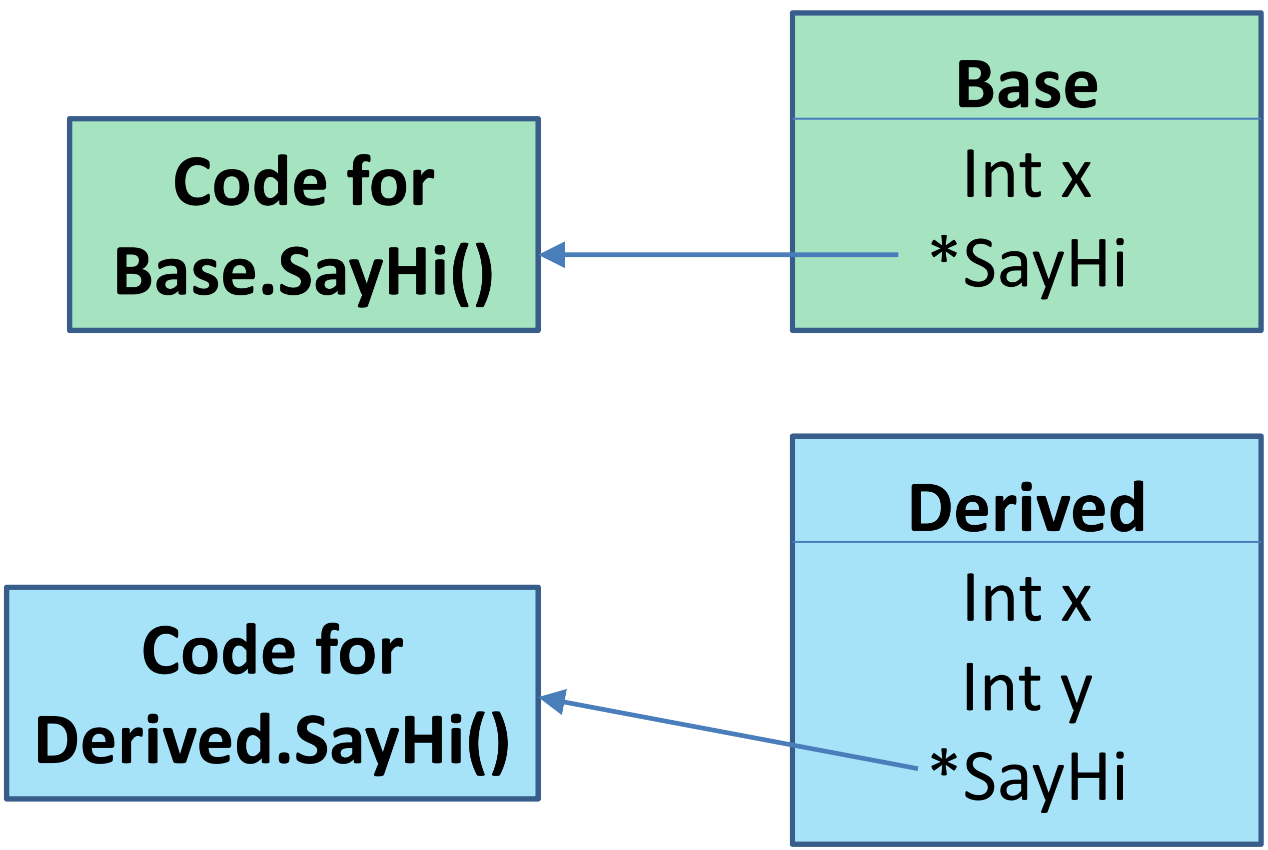
```
class Base {
    int x;
    void sayHi() {
        Print("Base");
    }
}
```

```
class Derived extends Base {
    int y;
    void sayHi() {
        Print("Derived");
    }
}
```

Virtual function tables can solve the problem.

Virtual Function Tables

- A **virtual function table** (or **vtable**) is an array of pointers to the code of the member function for a particular class.



This is a Pretty Good Idea

- Advantages:
  - Time to determine function to call is O(1).

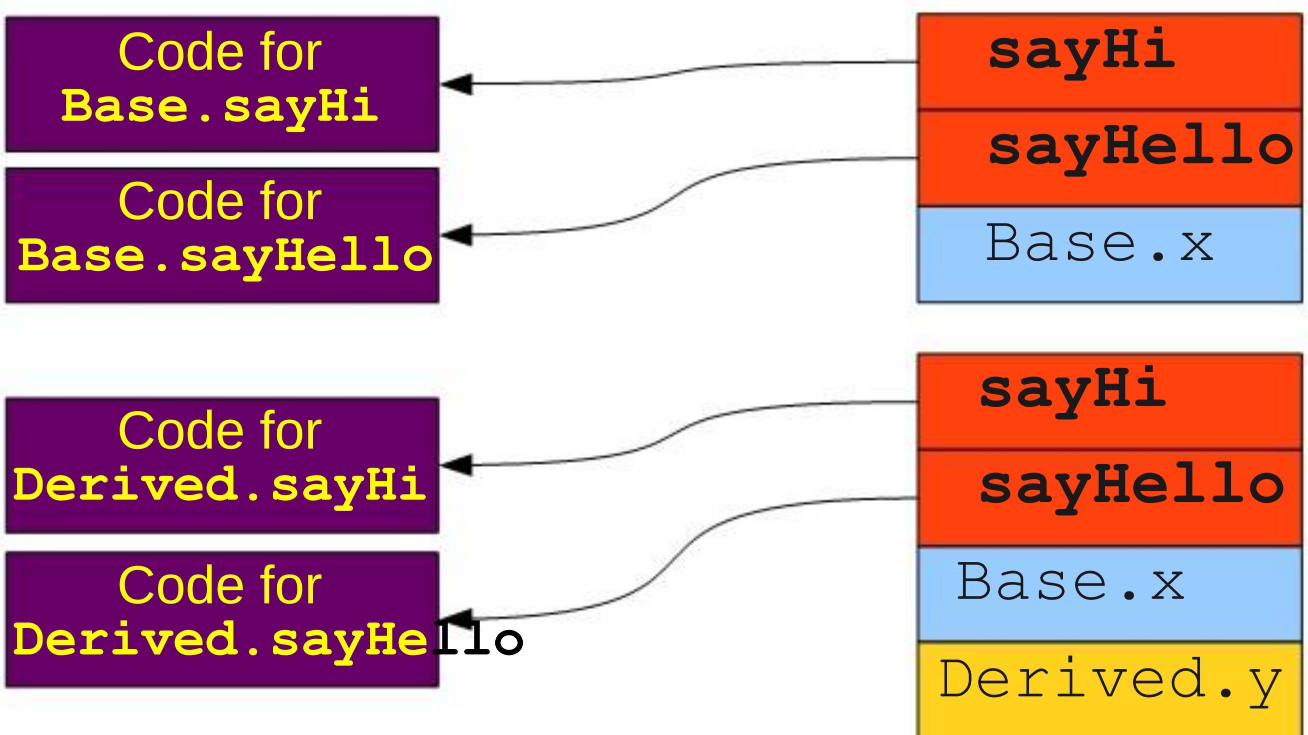
- What are the disadvantages?
  - Each object has its own virtual function table.
  - Wasteful space.

A Common Optimization

```
class Base {
     int x;
     void sayHi() {
          Print("Base1");
     }
     void sayHello() {
          Print(“Base2”);
     }
}
```

```
class Derived extends Base {
     int y;
     void sayHi() {
          Print("Derived1");
     }
     Derived sayHello() {
           Print("Derived2");
     }
}
```

Before optimization

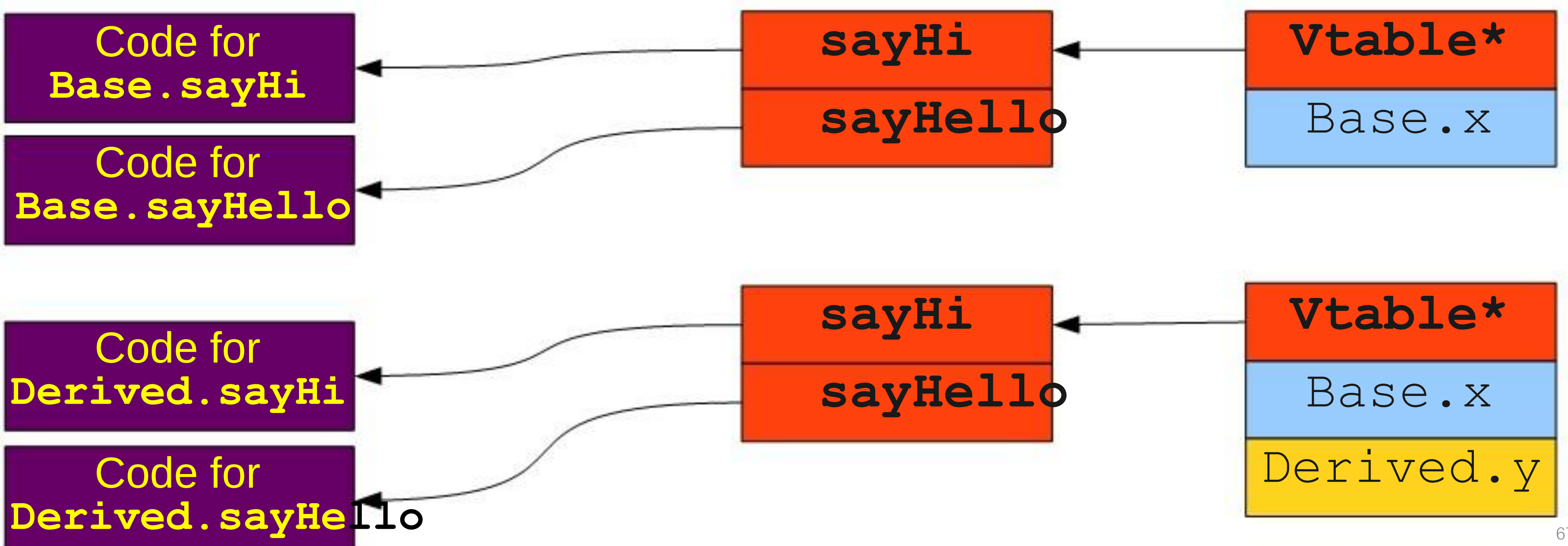


A Common Optimization

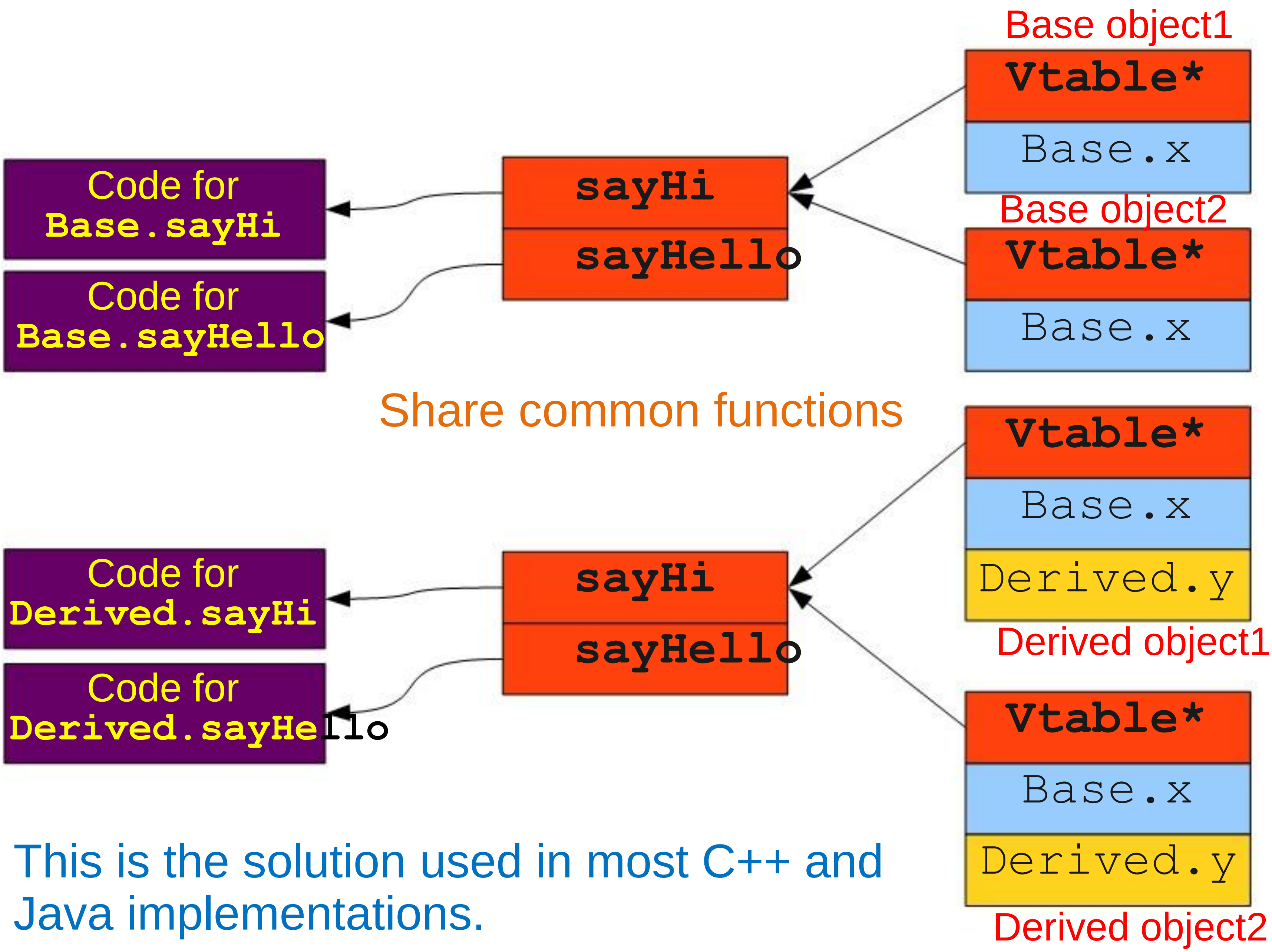
```
class Base {
    int x;
    void sayHi() {
        Print("Base1");
    }
    void sayHello() {
        Print("Base2");
    }
}
```

```
class Derived extends Base {
    int y;
    void sayHi() {
        Print("Derived1");
    }
    Derived sayHello() {
        Print("Derived2");
    }
}
```

After optimization



Objects in Memory



This is the solution used in most C++ and Java implementations.

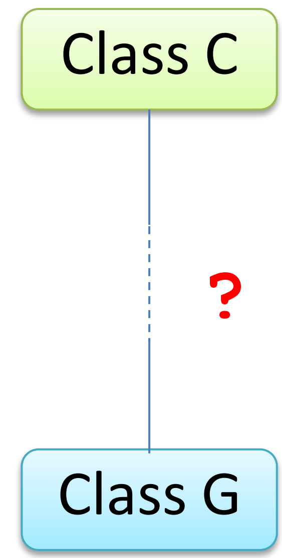
Implementing Dynamic Type Checks

Dynamic Type Checks

- Some languages require dynamic type checking.

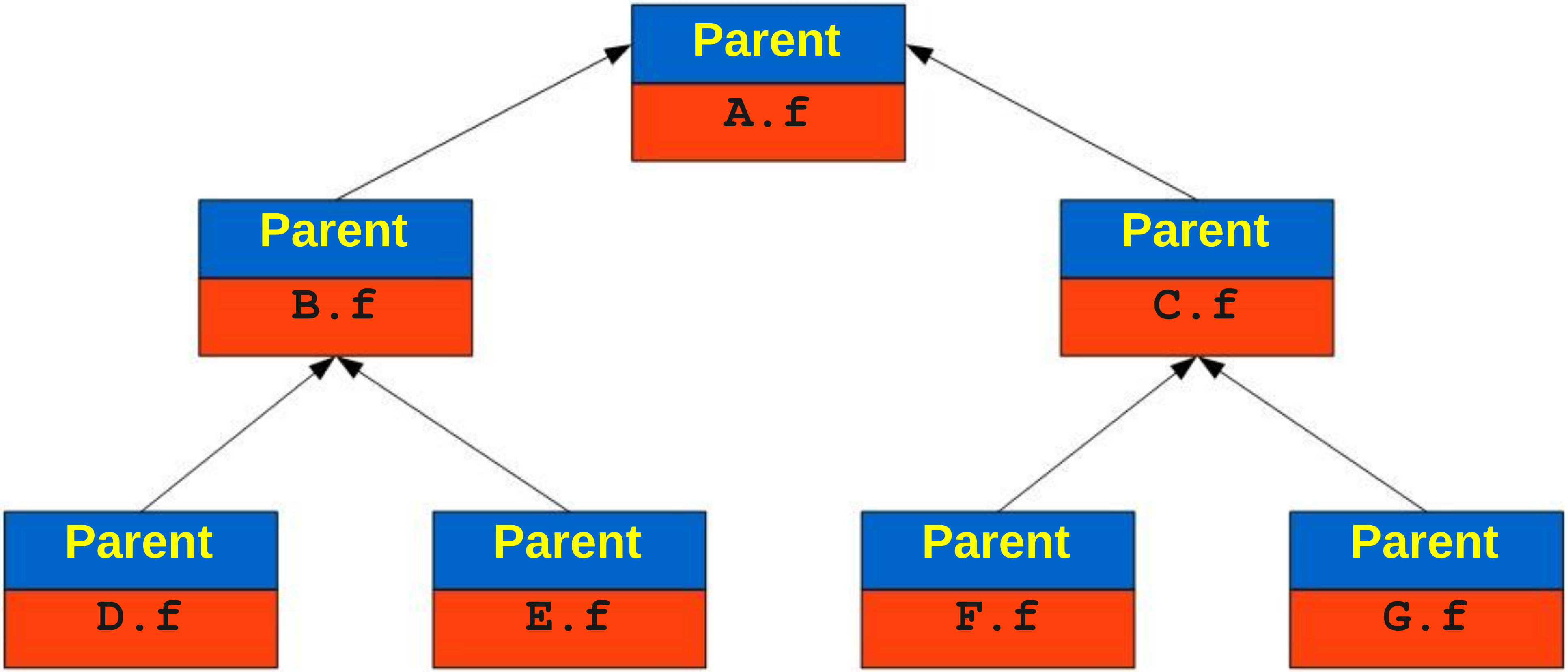
Ex:

```
If(…)
    G myObject = New instance of B
Else
    G myObject = New instance of C

if (myObject instanceof C) {
     /* … */
}
```



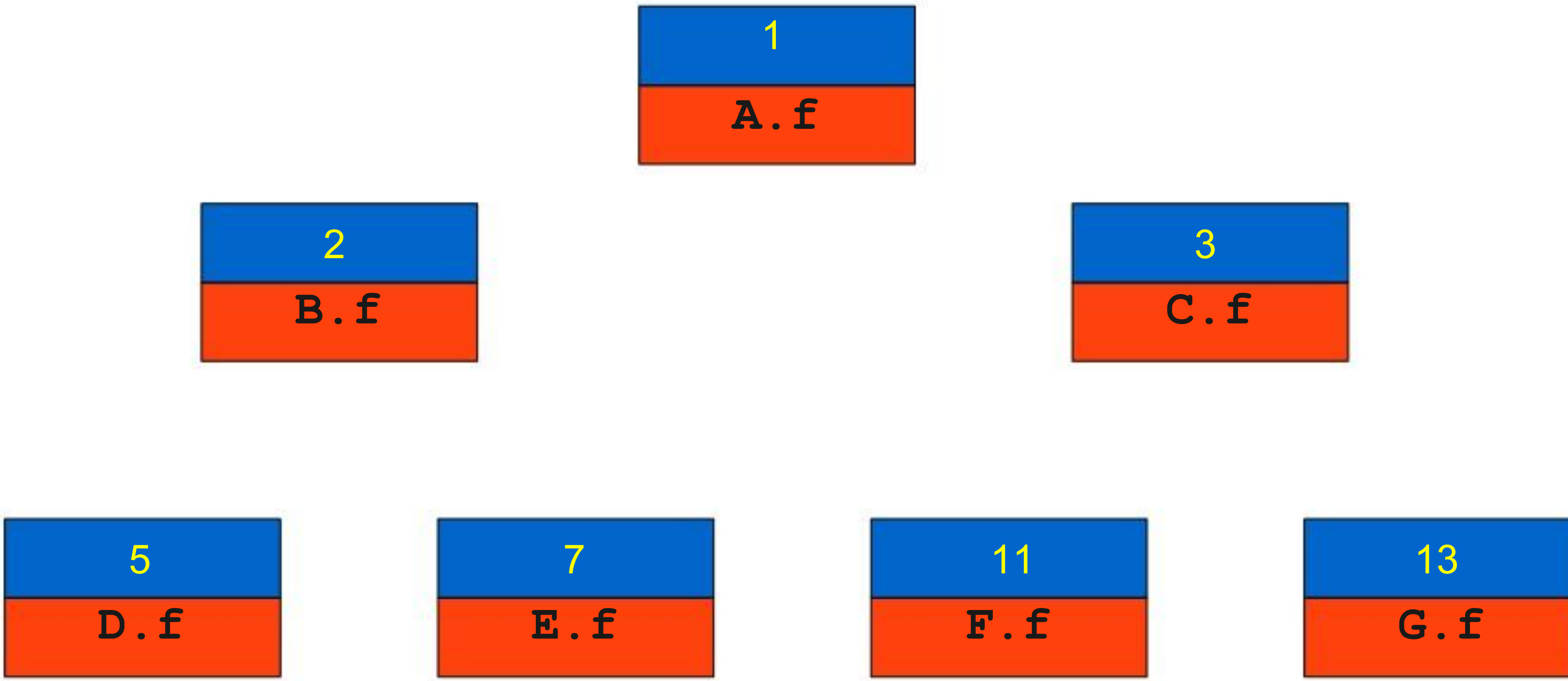
- May want to determine whether the dynamic type is **convertible** to some other type.
- How can we implement this?

Example



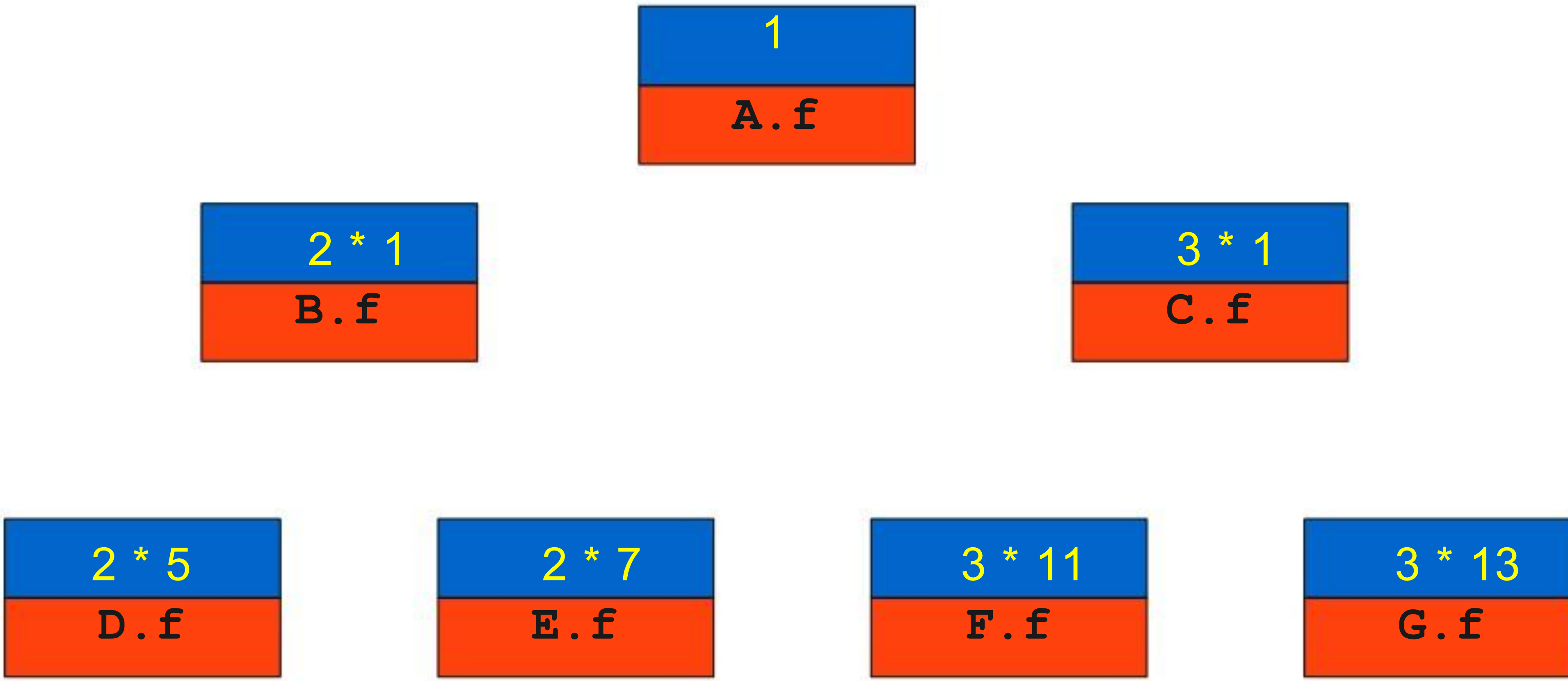
It takes O(log n) time to find out whether X is convertible to Y.
Is there any better idea ?

A Marvelous Idea



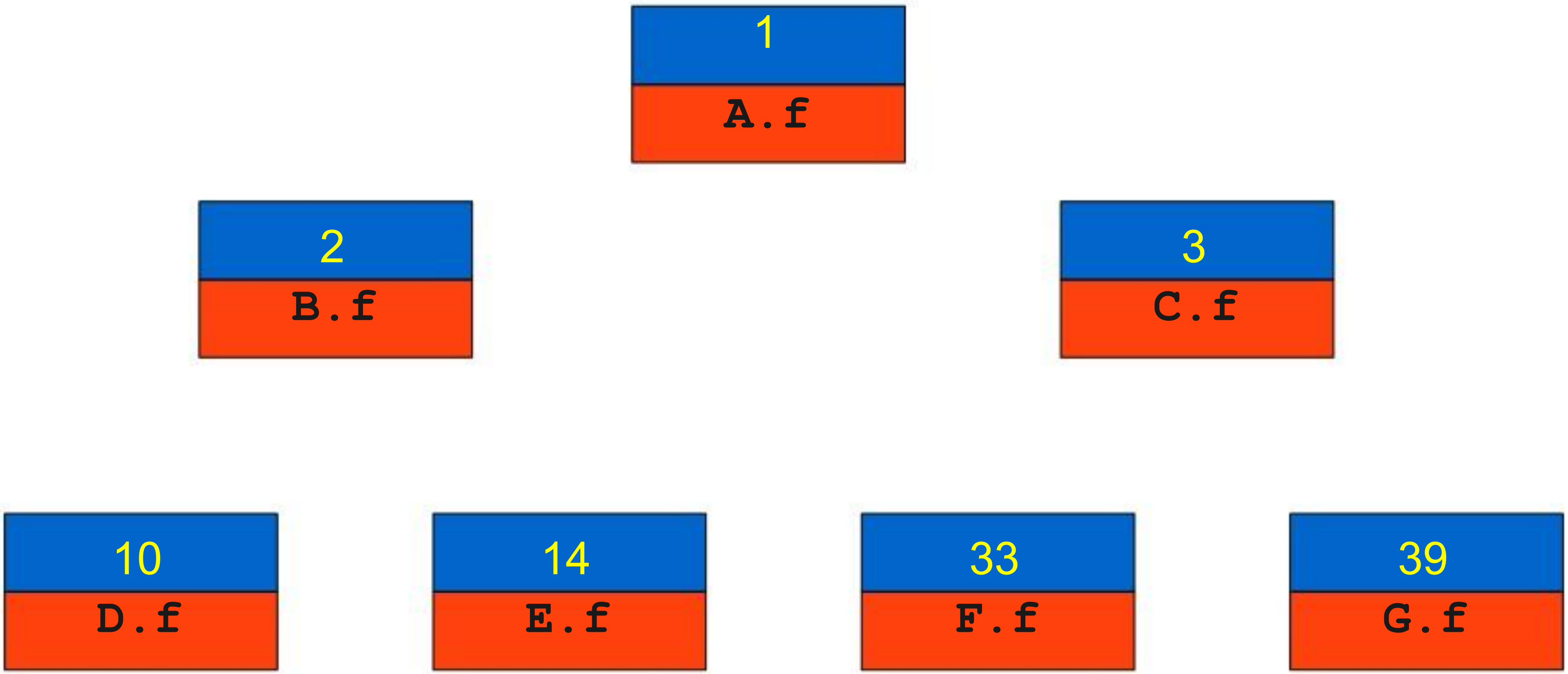
These are prime numbers.

A Marvelous Idea

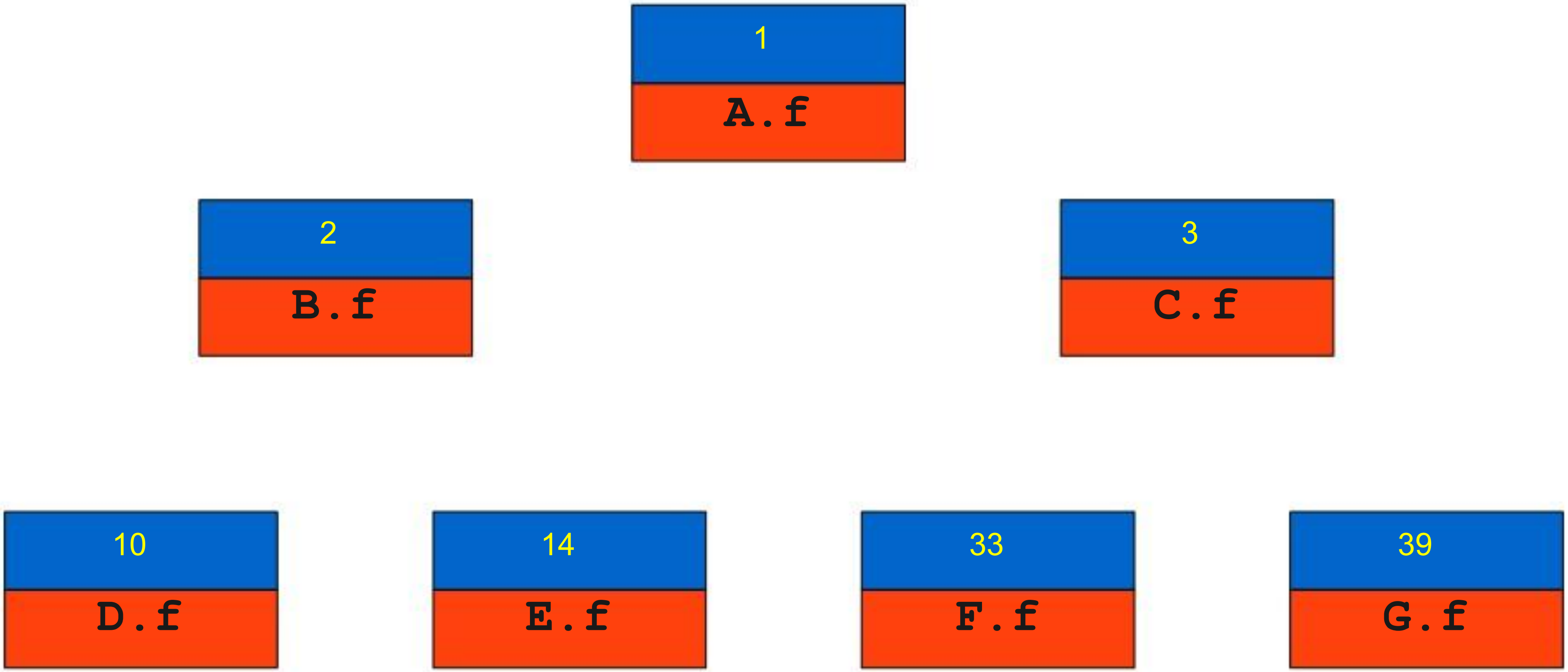


Multiply prime numbers of the class and it’s parent.

A Marvelous Idea

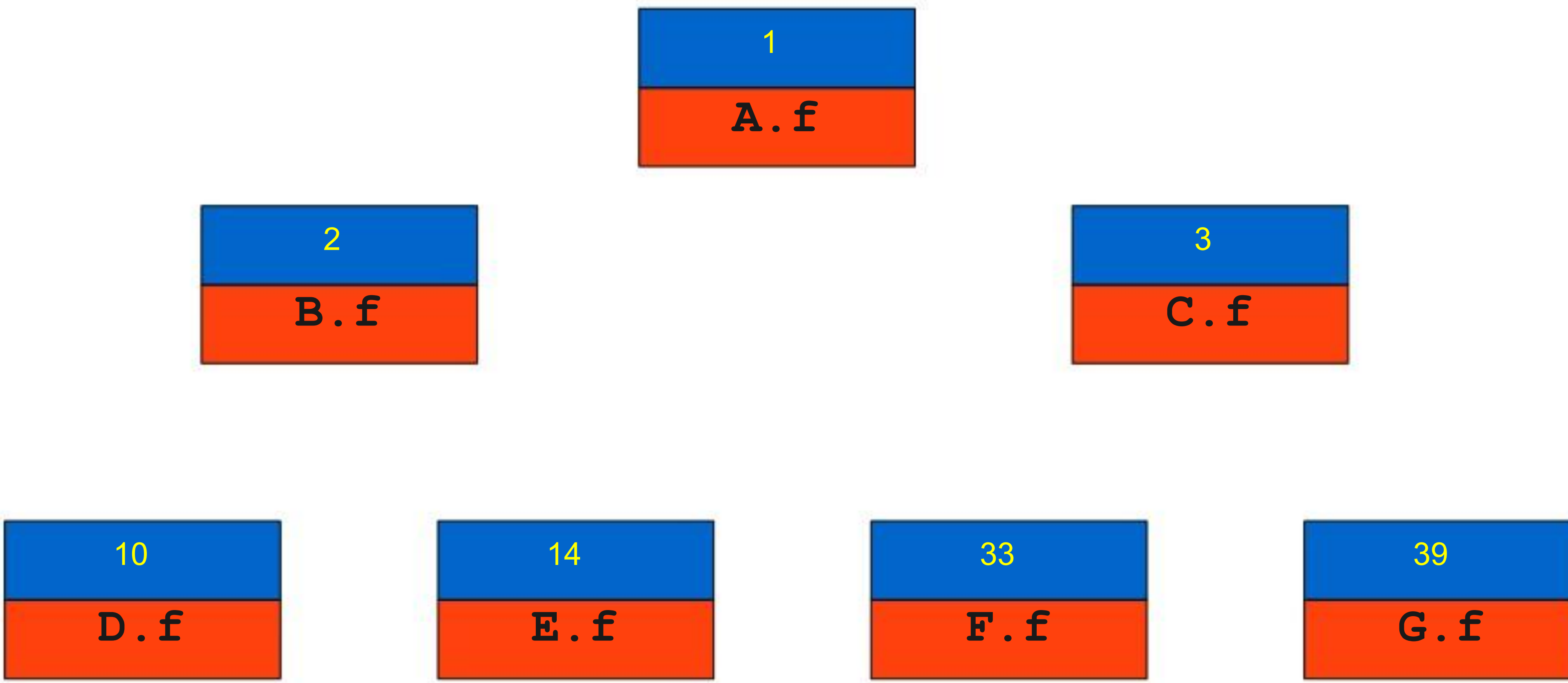


A Marvelous Idea



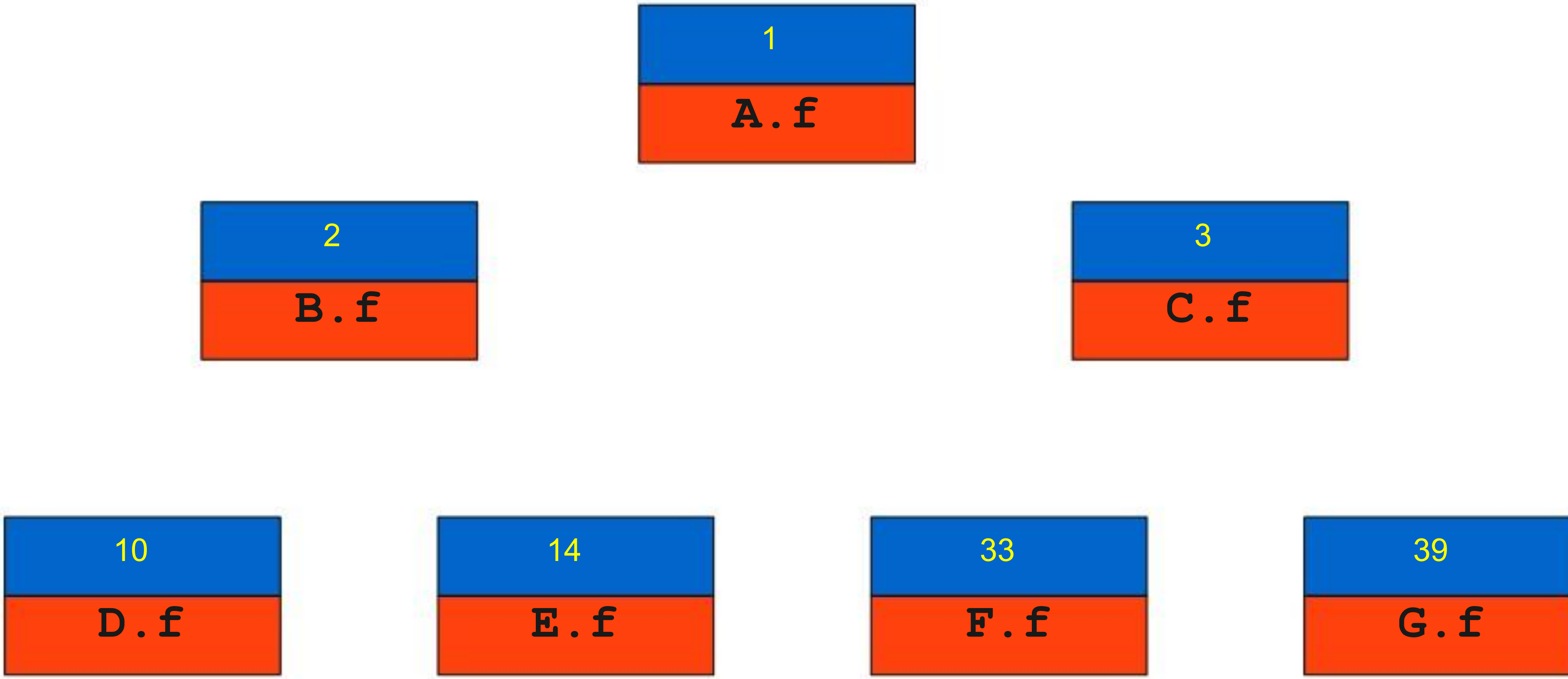

```
G myObject = /* … */
if (myObject instanceof C) {
    /* … */
}
```

A Marvelous Idea




```
G myObject = /* … */
if (myObject->vtable.key % 3 == 0) {
    /* … */
}
```

A Marvelous Idea




```
G myObject = /* … */
if (39 % 3 == 0) {// myObject is an instance of class C
    /* … */
}
```