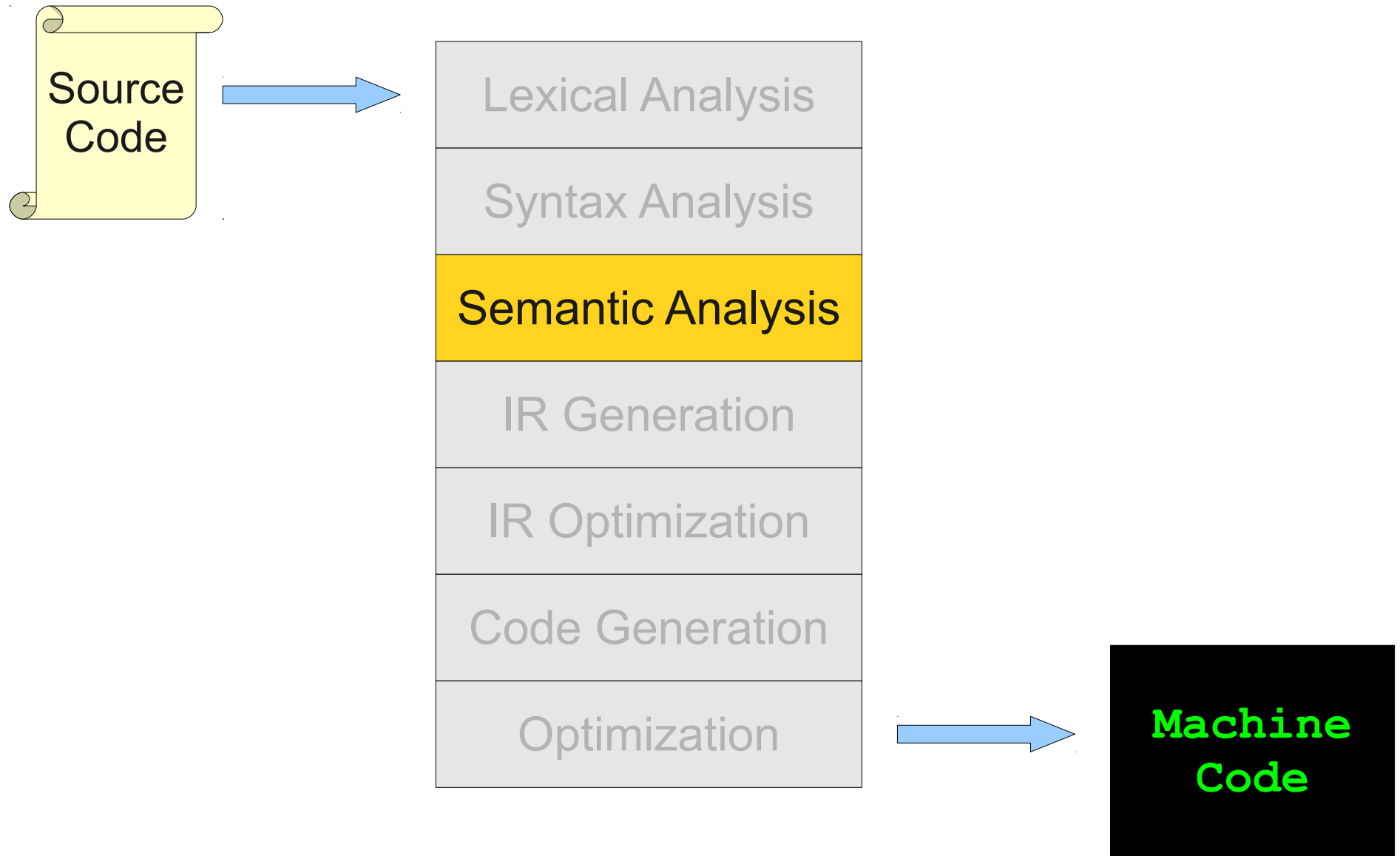


IR Generation

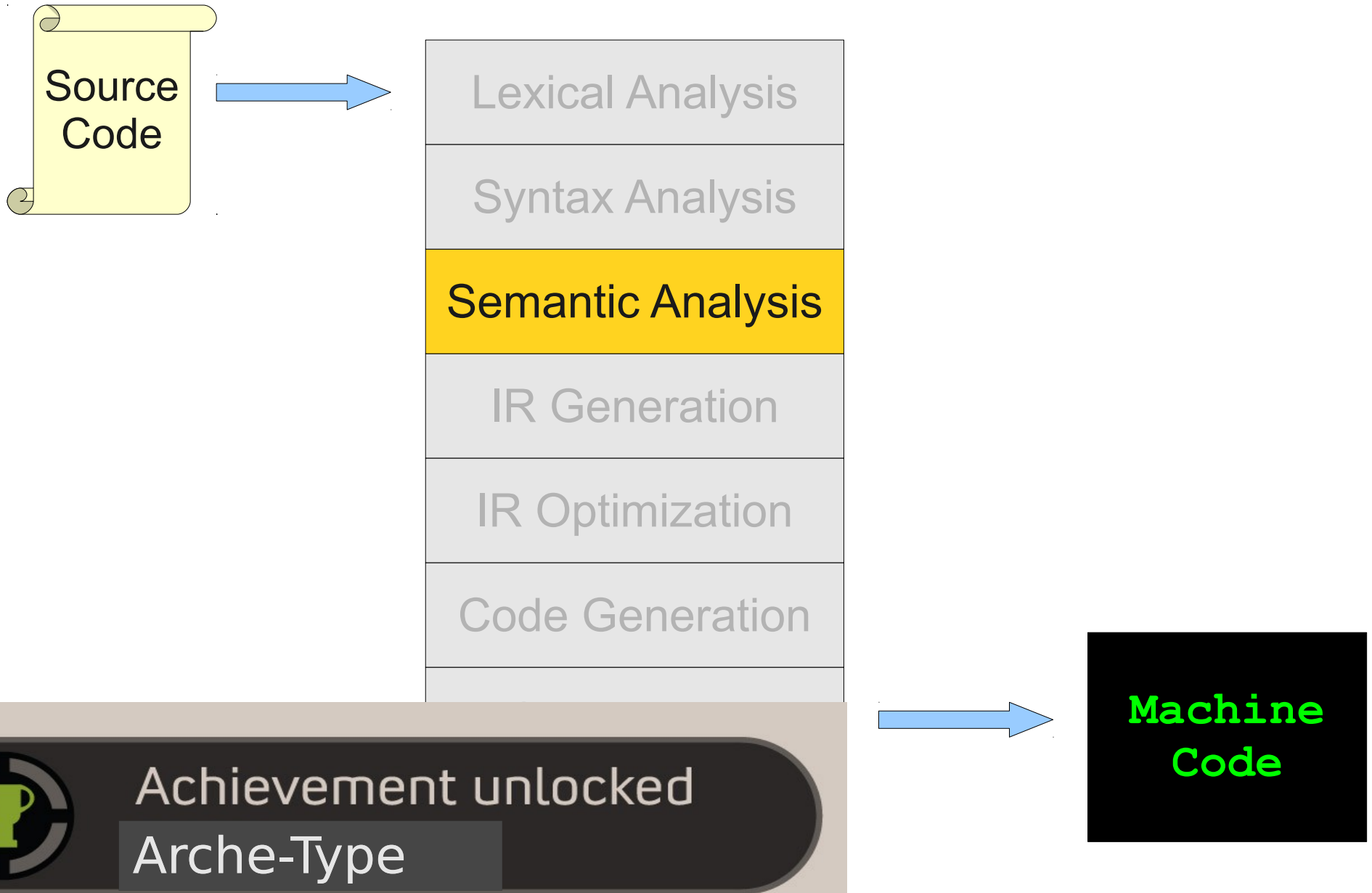
Announcements

- My office hours are today in Gates 160 from 1PM-3PM.
- Programming Project 3 checkpoint due **tomorrow night** at 11:59PM.
 - This is a **hard deadline** and no late submissions will be accepted, even with late days.
 - Remainder of the project due Wednesday at 11:59PM.
- Midterms graded; we'll hand them back at the end of class.

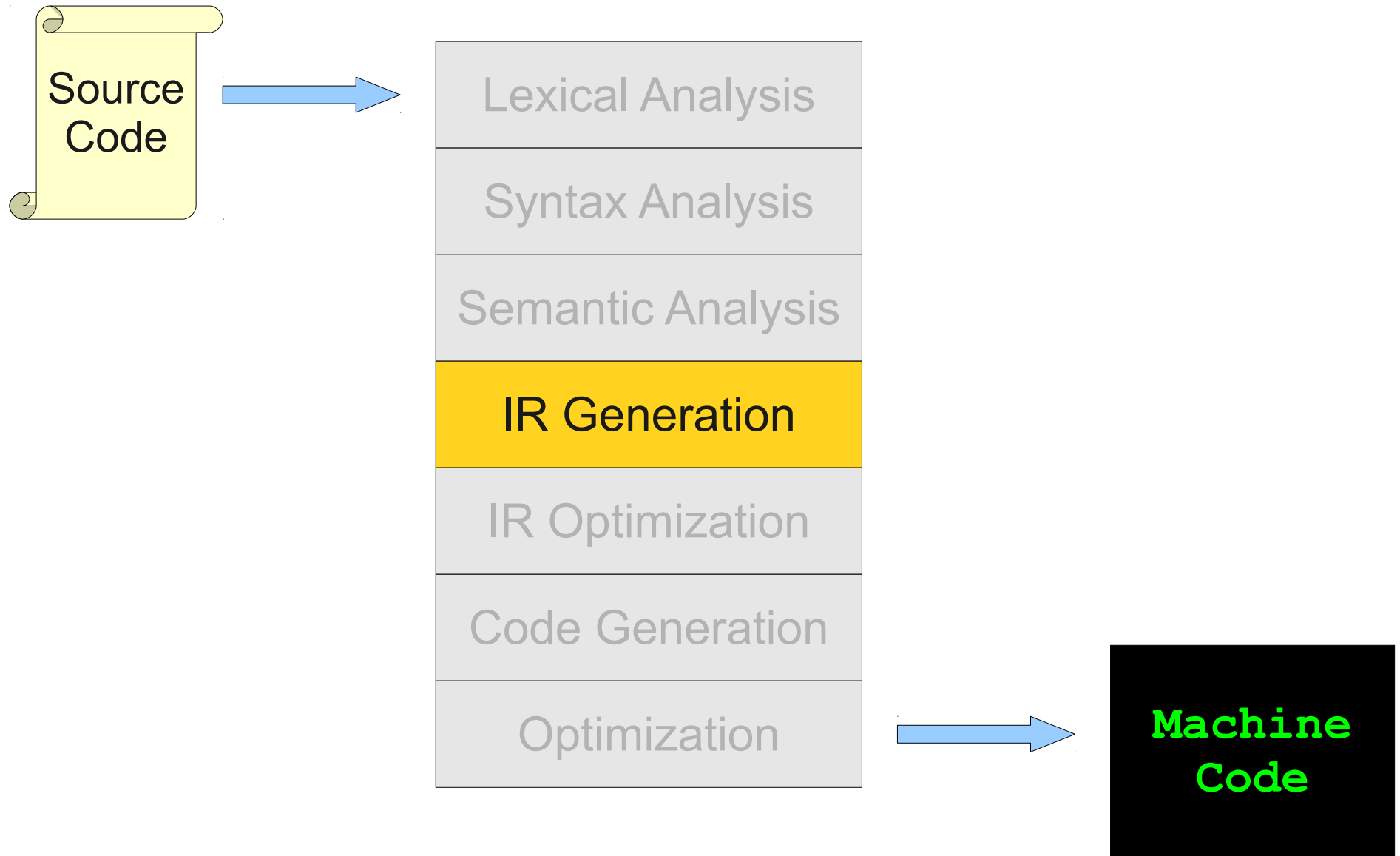
Where We Are



Where We Are



Where We Are



What is IR Generation?

- **Intermediate Representation Generation.**
- The final phase of the compiler front-end.
- Goal: Translate the program into the format expected by the compiler back-end.
- Generated code need not be optimized; that's handled by later passes.
- Generated code need not be in assembly; that can also be handled by later passes.

Why do IR Generation?

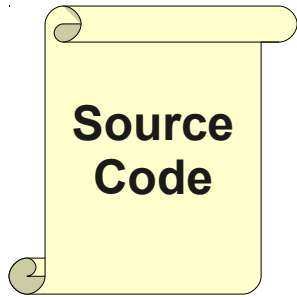
- **Simplify certain optimizations.**
 - Machine code has many constraints that inhibit optimization. (Such as?)
 - Working with an intermediate language makes optimizations easier and clearer.
- **Have many front-ends into a single back-end.**
 - `gcc` can handle C, C++, Java, Fortran, Ada, and many other languages.
 - Each front-end translates source to the GENERIC language.
- **Have many back-ends from a single front-end.**
 - Do most optimization on intermediate representation before emitting code targeted at a single machine.

Designing a Good IR

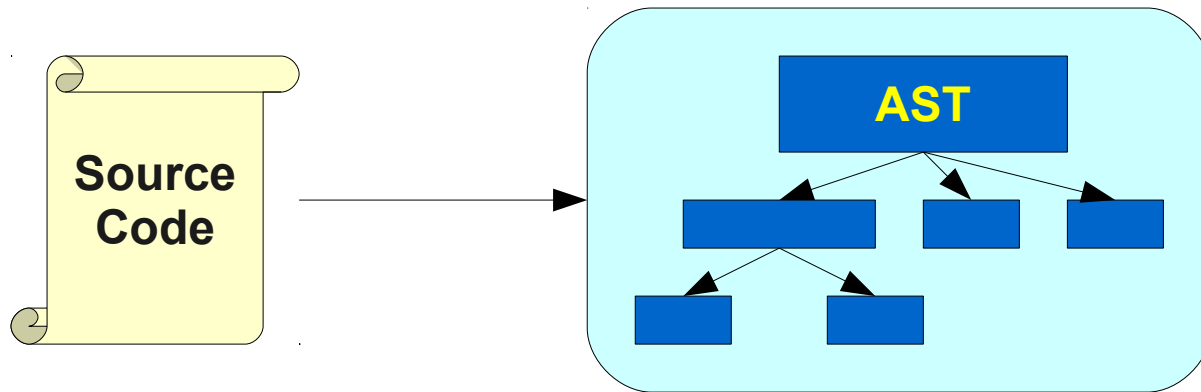
- IRs are like type systems – they're extremely hard to get right.
- Need to balance needs of high-level source language and low-level target language.
- Too high level: can't optimize certain implementation details.
- Too low level: can't use high-level knowledge to perform aggressive optimizations.
- Often have multiple IRs in a single compiler.

Architecture of gcc

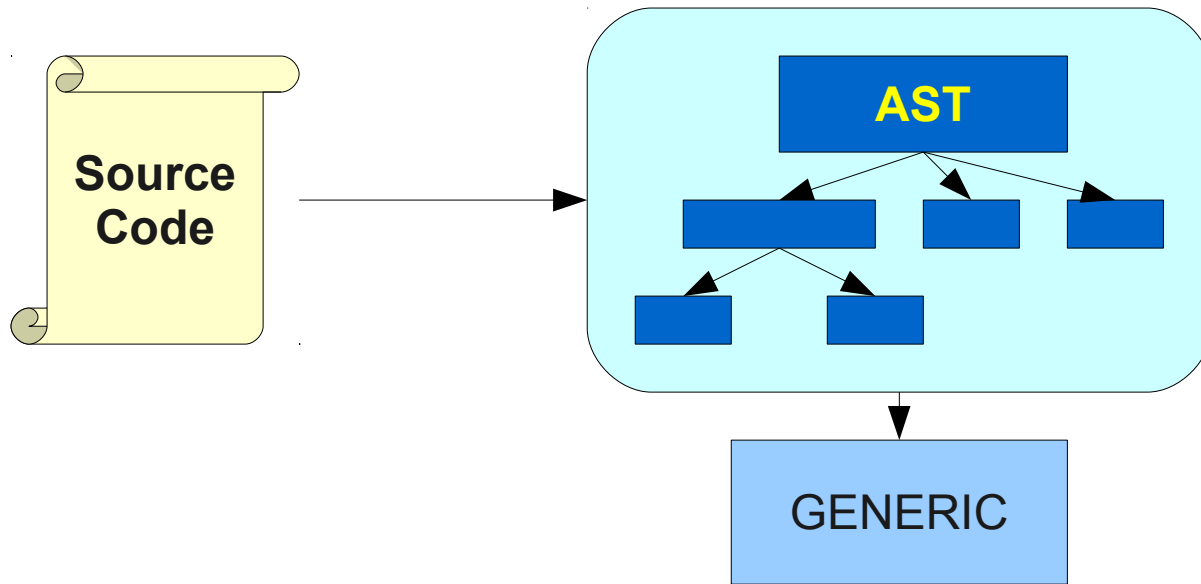
Architecture of gcc



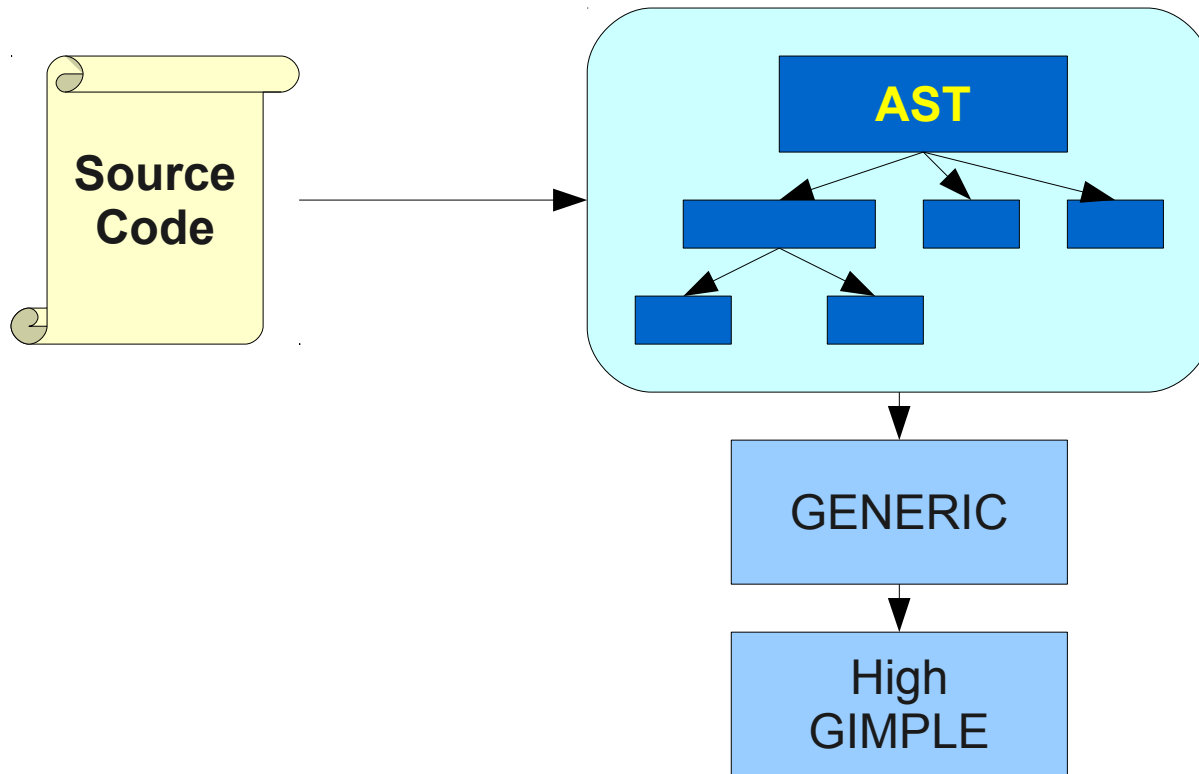
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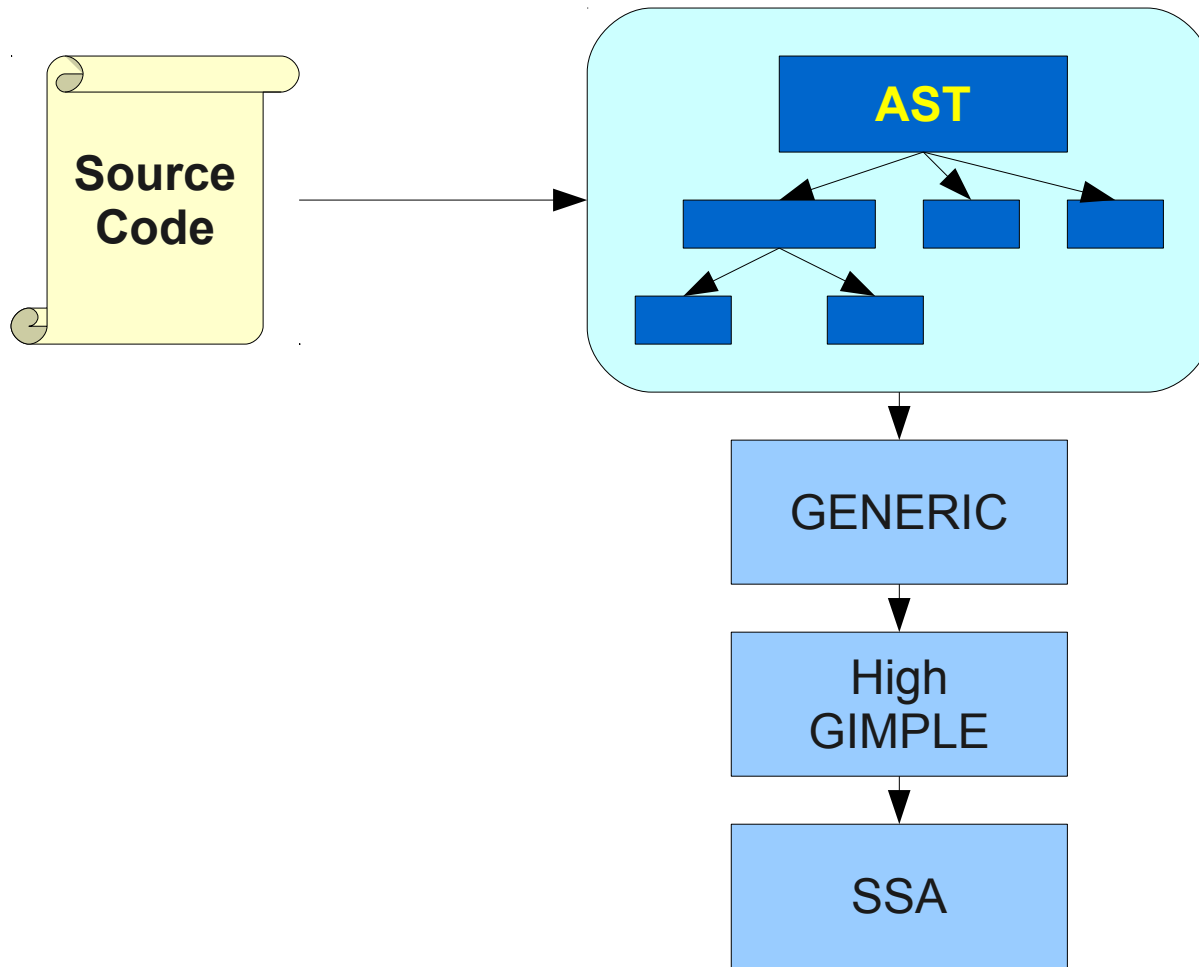
Architecture of gcc



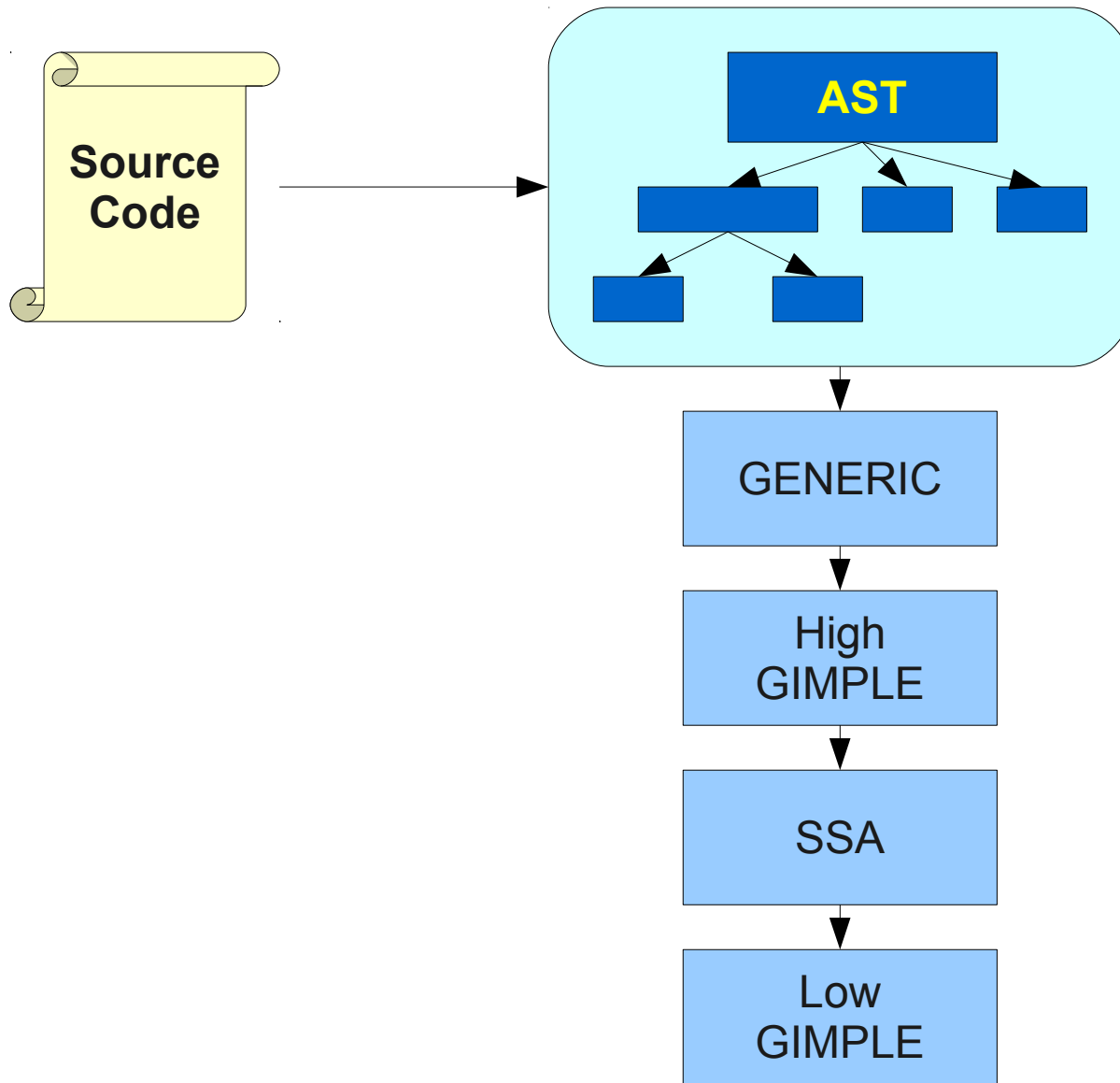
Architecture of gcc



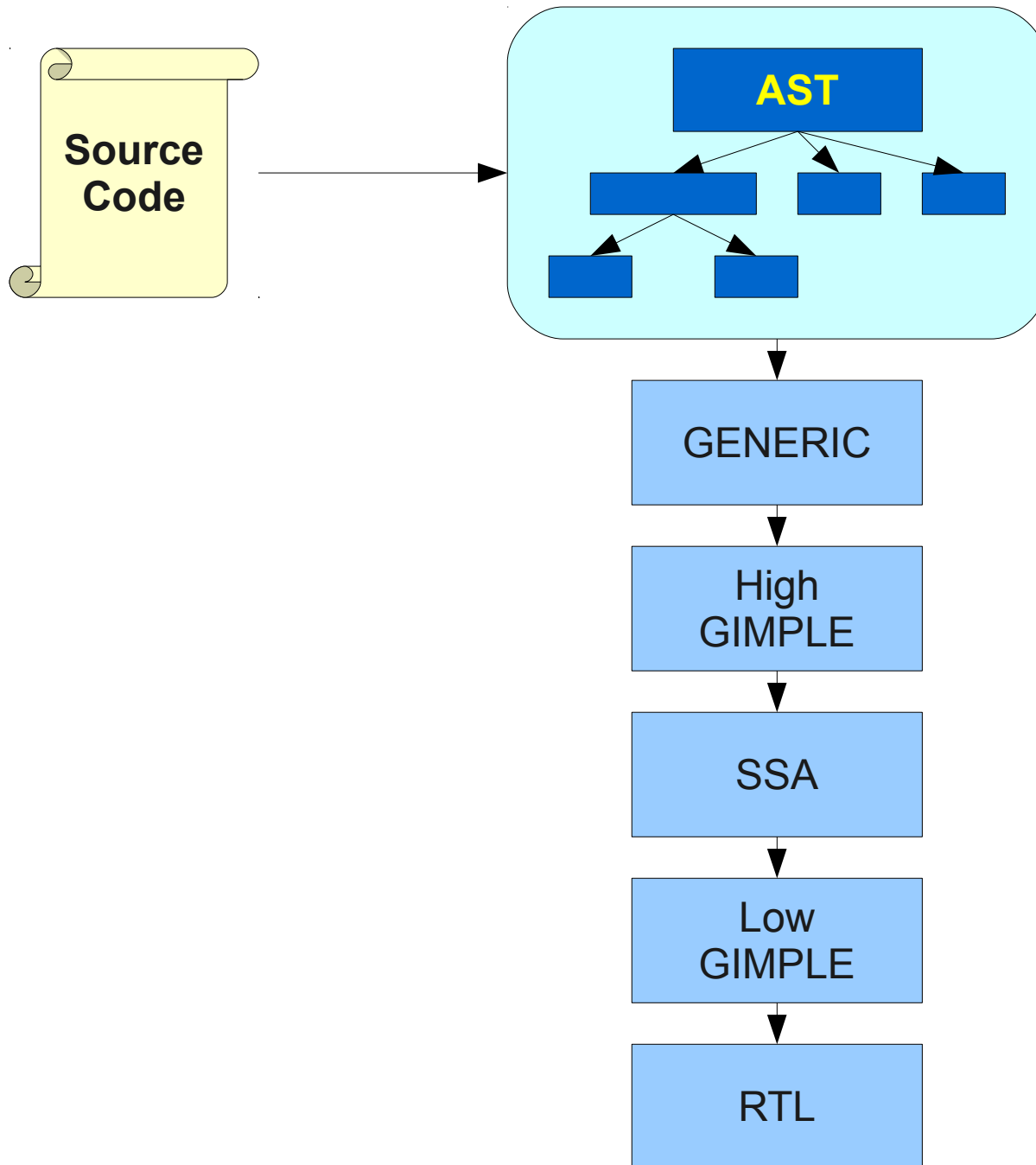
Architecture of gcc



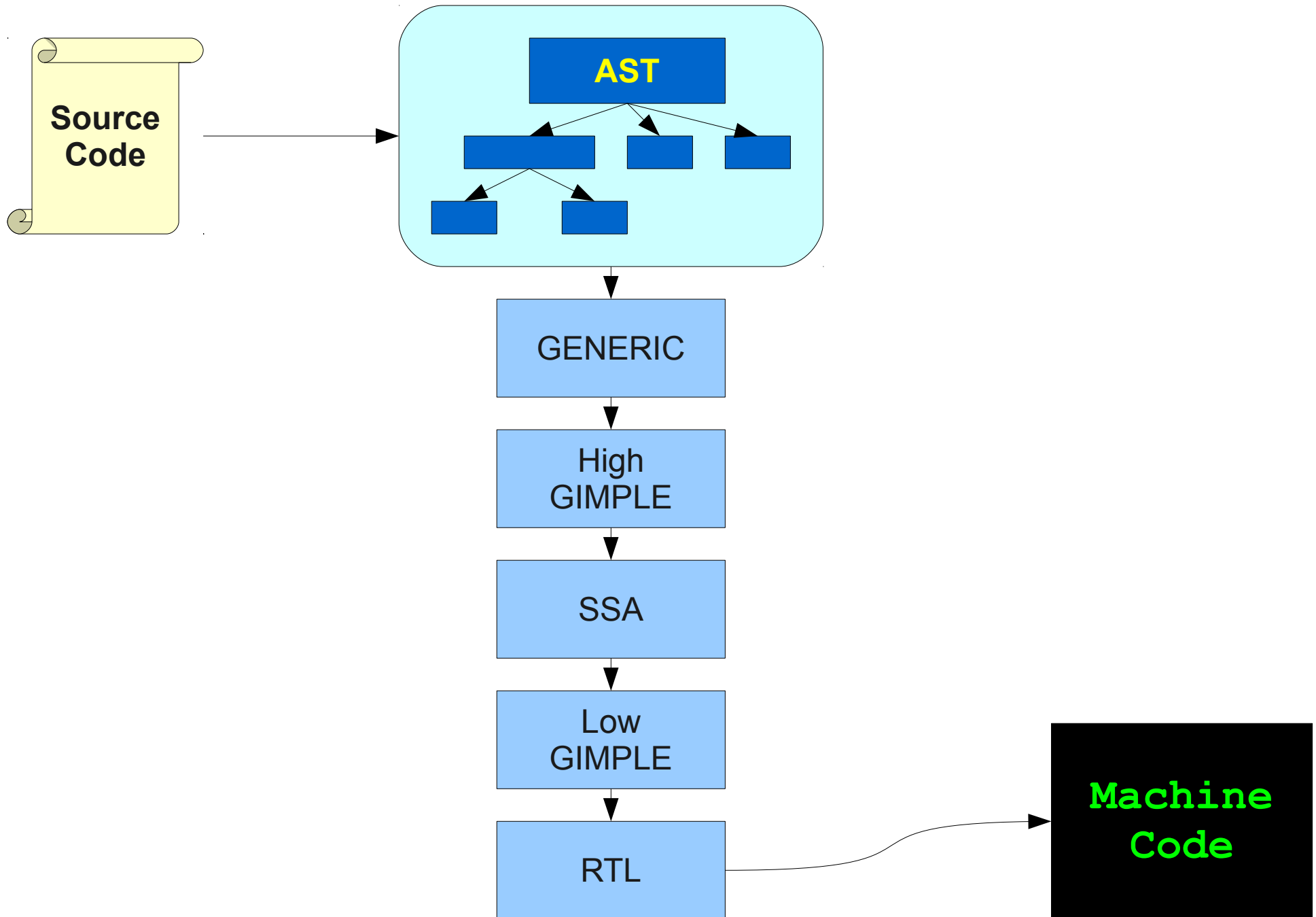
Architecture of gcc



Architecture of gcc



Architecture of gcc



Another Approach: High-Level IR

- Examples:
 - Java bytecode
 - CPython bytecode
 - LLVM IR
 - Microsoft CIL.
- Retains high-level program structure.
 - Try playing around with `javap` vs. a disassembler.
- Allows for compilation on target machines.
- Allows for JIT compilation or interpretation.

Outline

- **Runtime Environments (Today/Monday)**
 - How do we implement language features in machine code?
 - What data structures do we need?
- **Three-Address Code (Monday/Wednesday)**
 - What IR are we using in this course?
 - What features does it have?
- **TAC generation (Monday/Wednesday)**
 - How do we translate Decaf into TAC?

Runtime Environments

An Important Duality

- Programming languages contain high-level structures:
 - Functions
 - Objects
 - Exceptions
 - Dynamic typing
 - Lazy evaluation
 - (etc.)
- The physical computer only operates in terms of several primitive operations:
 - Arithmetic
 - Data movement
 - Control jumps

Runtime Environments

- We need to come up with a representation of these high-level structures using the low-level structures of the machine.
- A **runtime environment** is a set of data structures maintained at runtime to implement these high-level structures.
 - e.g. the stack, the heap, static area, virtual function tables, etc.
- Strongly depends on the features of both the source and target language. (e.g compiler vs. cross-compiler)
- Our IR design will depend on how we set up our runtime environment.

The Decaf Runtime Environment

- Need to consider
 - 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?
 - How is inheritance implemented?
- **There are no right answers to this question.**
 - Many different options and tradeoffs.
 - We will see several approaches.

Data Representations

- What do different types look like in memory?
- Machine typically supports only limited types:
 - Fixed-width integers: 8-bit, 16-bit- 32-bit, signed, unsigned, etc.
 - Floating point values: 32-bit, 64-bit, 80-bit IEEE 754.
- How do we encode our object types using these types?

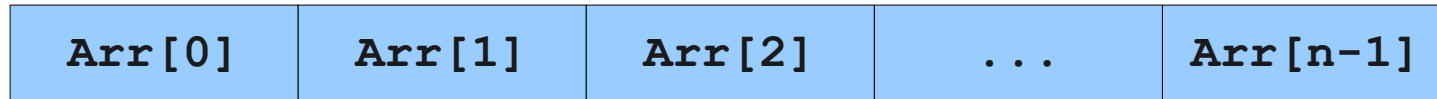
Encoding Primitive Types

- 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.
 - Size of integer depends on machine architecture; hence 32-bit compatibility mode on 64-bit machines.

Encoding Arrays

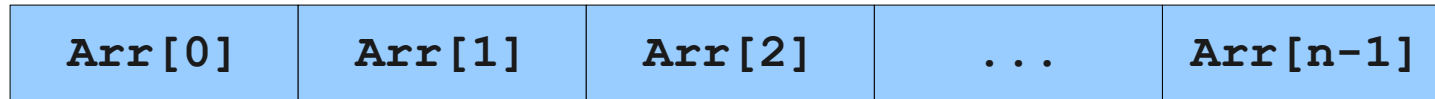
Encoding Arrays

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



Encoding Arrays

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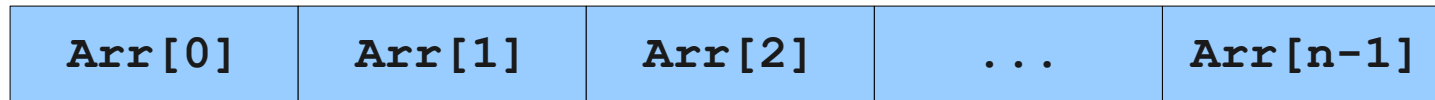


- Java-style arrays: Elements laid out consecutively in memory with size information prepended.

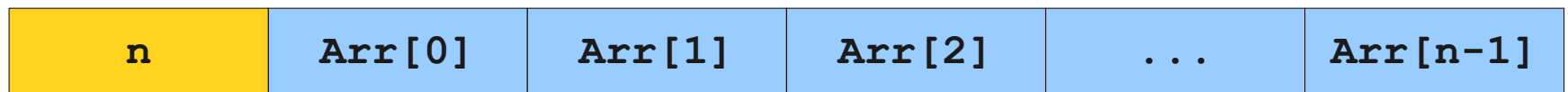


Encoding Arrays

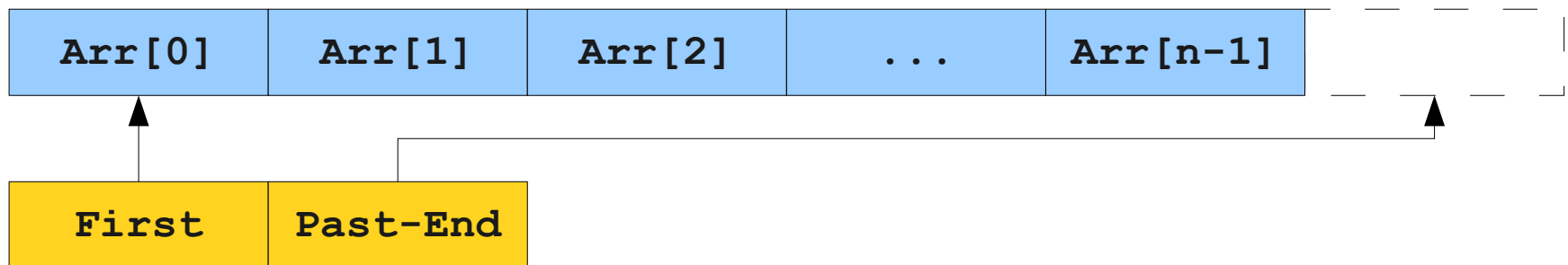
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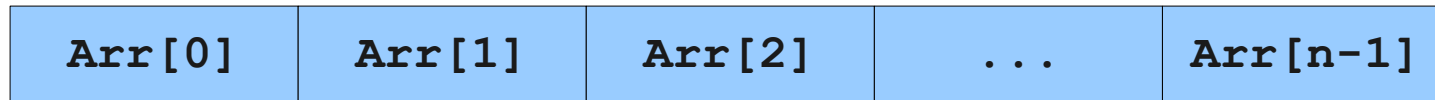


- D-style arrays: Elements laid out consecutively in memory; array variables store pointers to first and past-the-end elements.



Encoding Arrays

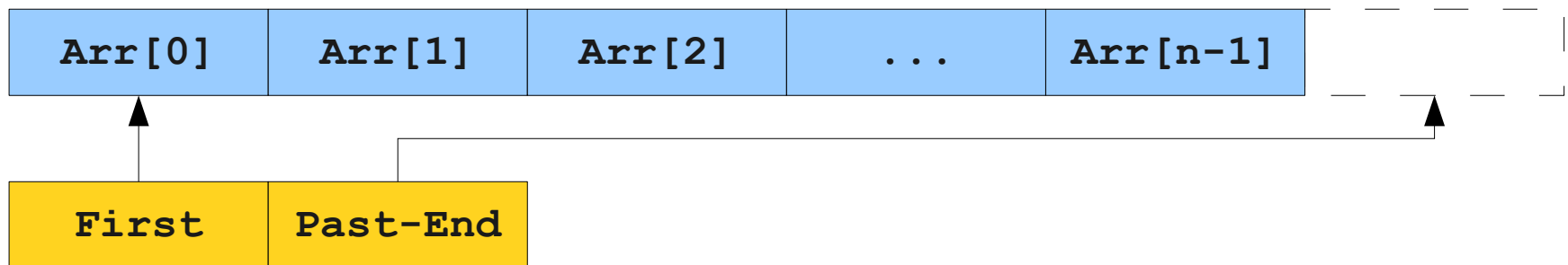
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- D-style arrays: Elements laid out consecutively in memory; array variables store pointers to first and past-the-end elements.



- (Which of these works well for Decaf?)

Encoding Multidimensional Arrays

- Often represented as an array of arrays.
- Shape depends on the array type used.
- C-style arrays:

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

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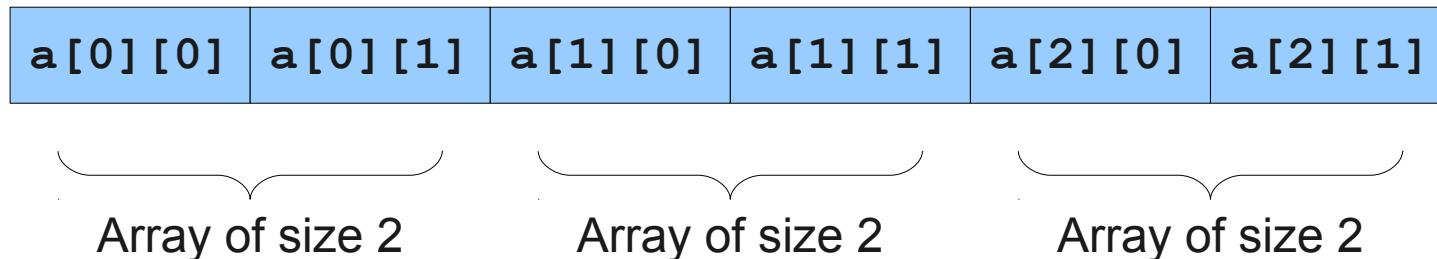
```
int a[3][2];
```

a[0][0]	a[0][1]	a[1][0]	a[1][1]	a[2][0]	a[2][1]
---------	---------	---------	---------	---------	---------

Encoding Multidimensional Arrays

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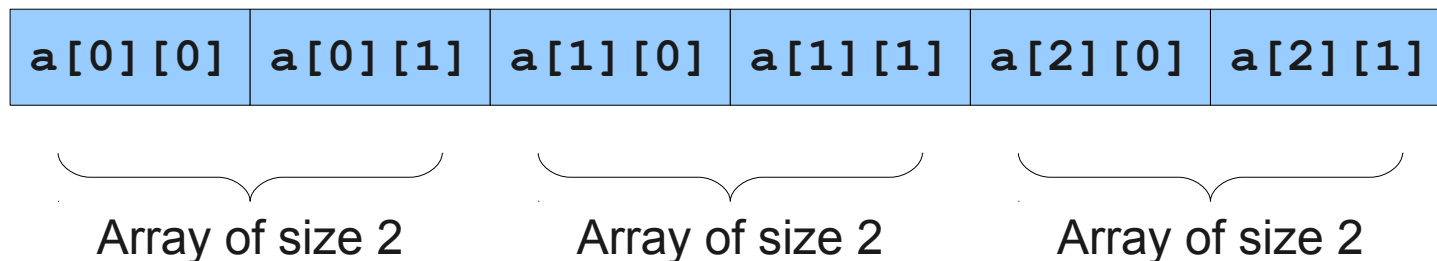


Encoding Multidimensional Arrays

- Often represented as an array of arrays.
- Shape depends on the array type used.
- C-style arrays:

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

How do you know
where to look for an
element in an array
like this?



Encoding Multidimensional Arrays

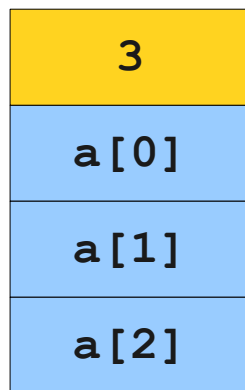
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int[][] a = new int [3] [2];
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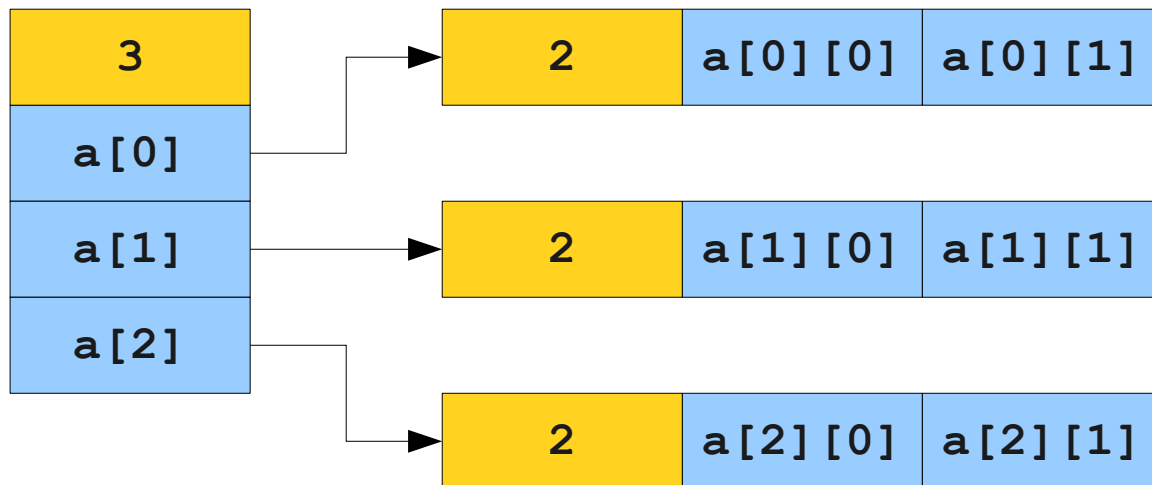
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Encoding Multidimensional Arrays

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Encoding Functions

- Many questions to answer:
 - What does the dynamic execution of functions look like?
 - Where is the executable code for functions located?
 - How are parameters passed in and out of functions?
 - Where are local variables stored?
- The answers strongly depend on what the language supports.

Review: The Stack

- 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.
- Questions:
 - **Why** does this work?
 - Does this **always** work?

Activation Trees

- An **activation tree** is a tree structure representing all of the function calls made by a program on a particular execution.
 - Depends on the **runtime behavior** of a program; can't always be determined at compile-time.
 - (The static equivalent is the **call graph**).
- 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

Activation Trees

```
int main() {  
    Fib(3);  
}  
  
int Fib(int n) {  
    if (n <= 1) return n;  
    return Fib(n - 1) + Fib(n - 2);  
}
```

Activation Trees

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int main() {  
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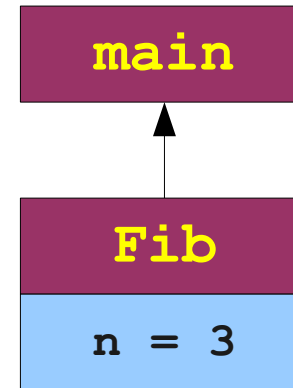


main

```
int Fib(int n) {  
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}
```

Activation Trees

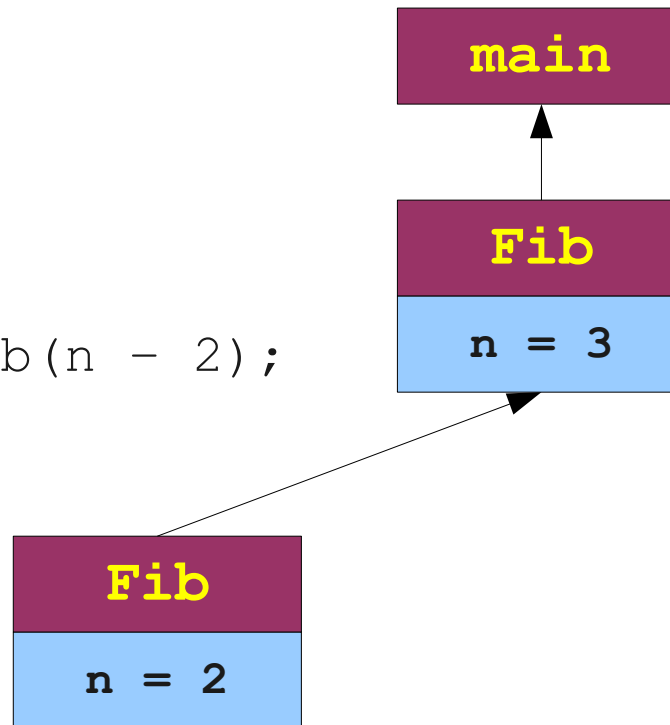
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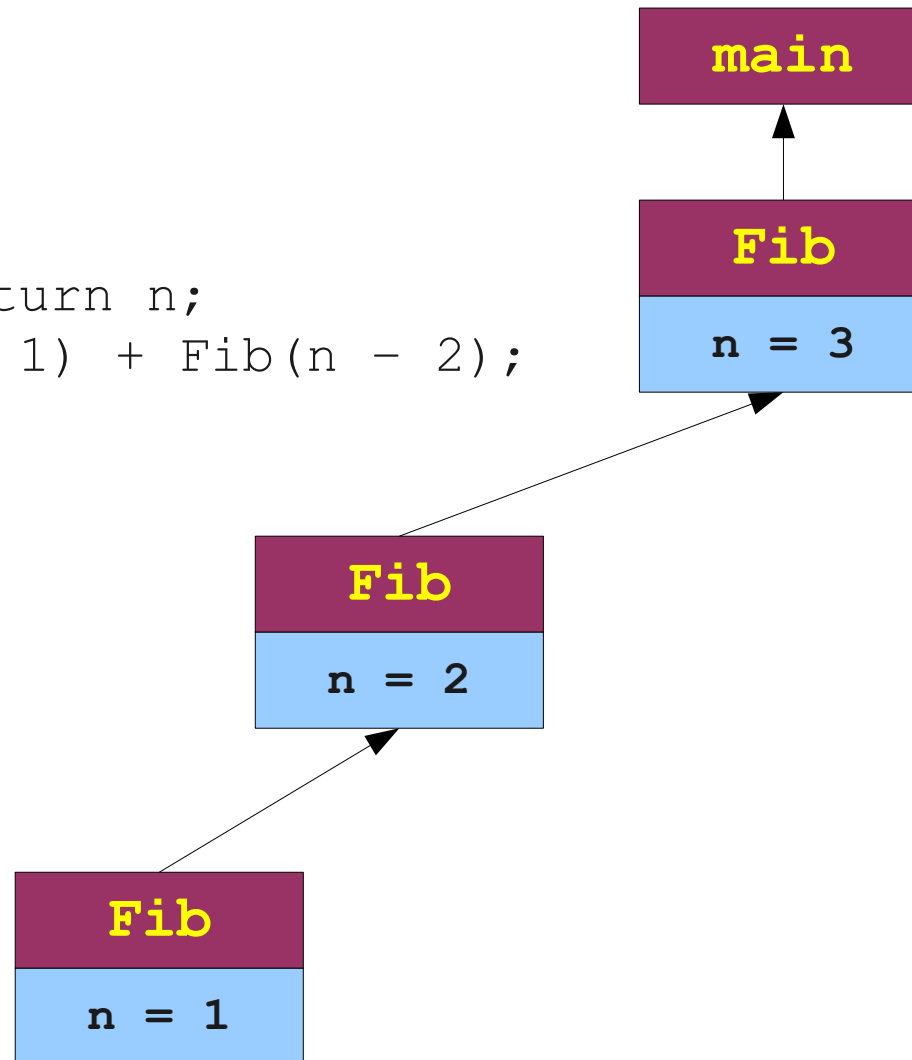
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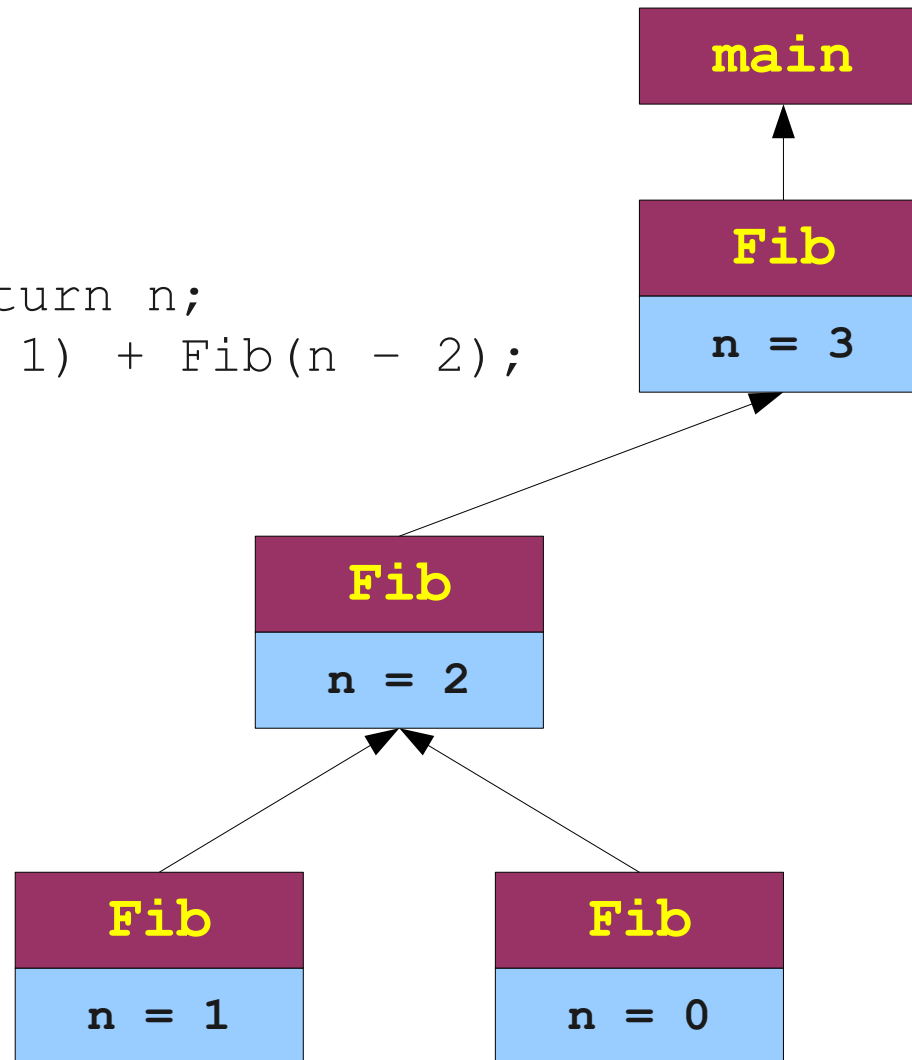
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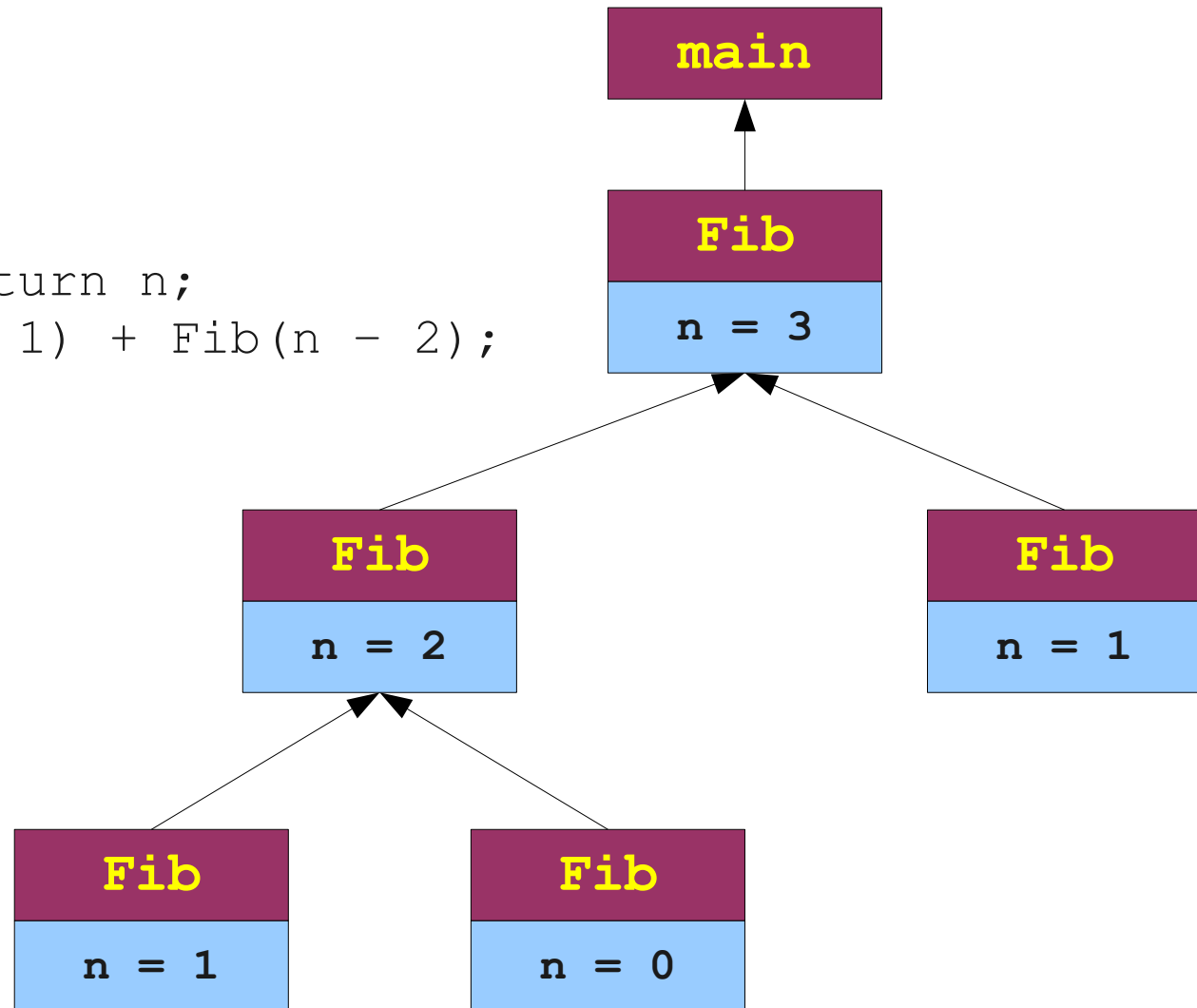
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}
```



An activation tree is a **spaghetti stack**.

The runtime stack is an **optimization**
of this spaghetti stack.

Why can we optimize the stack?

- Two main reasons:
- Once a function returns, its activation record cannot be referenced again.
 - We don't need to store old nodes in the activation tree.
- Every activation record has either finished executing or is an ancestor of the current activation record.
 - We don't need to keep multiple branches alive at any one time.
- **These are not true in general.**

Breaking Assumption 1

- **“Once a function returns, its activation record cannot be referenced again.”**
- Any ideas on how to break this?

Breaking Assumption 1

- **“Once a function returns, its activation record cannot be referenced again.”**
- Any ideas on how to break this?
- One option: Closures

```
function CreateCounter() {  
    var counter = 0;  
    return function() {  
        counter ++;  
        return counter;  
    }  
}
```

Closures

Closures

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function CreateCounter() {  
    var counter = 0;  
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function MyFunction() {  
    f = CreateCounter();  
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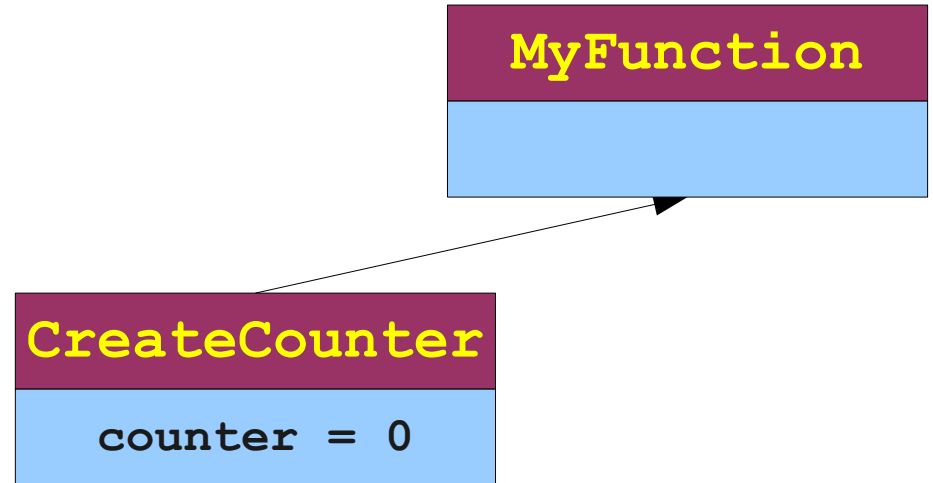
MyFunction



>

Closures

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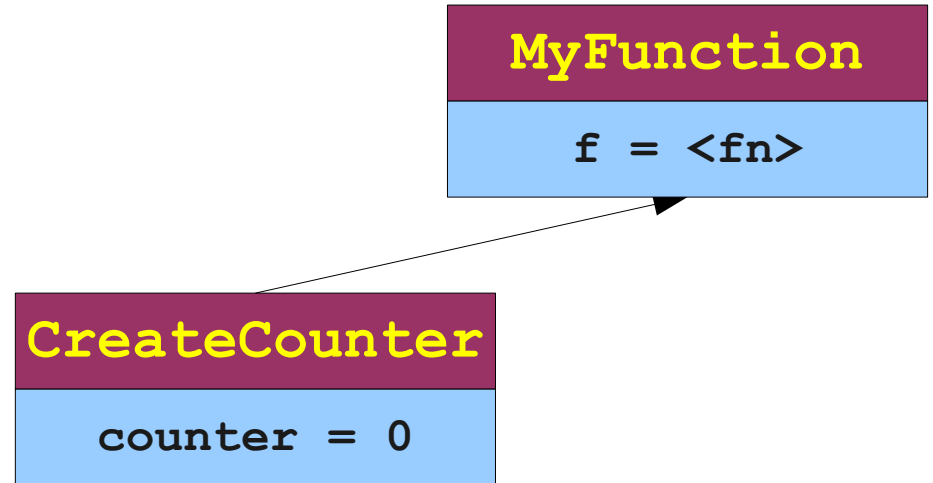


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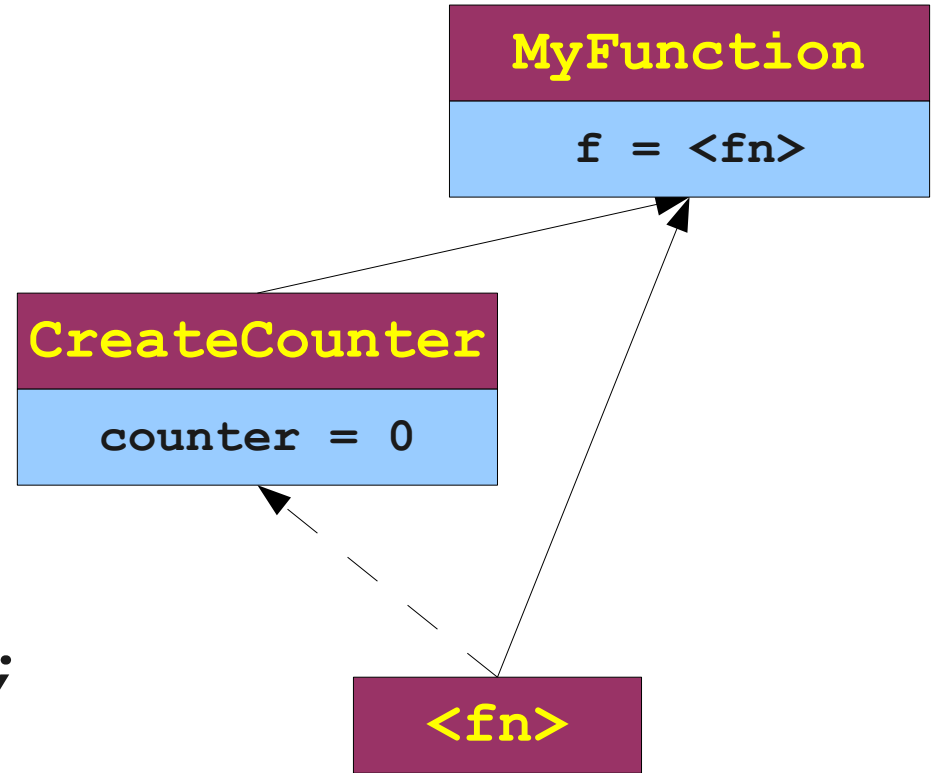
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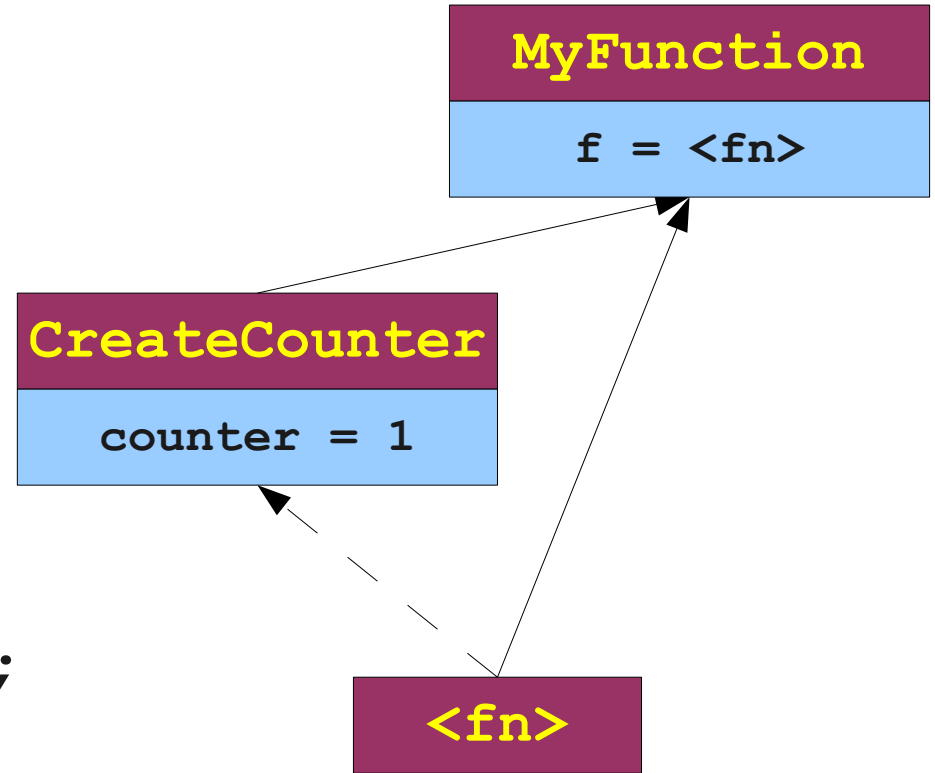


>

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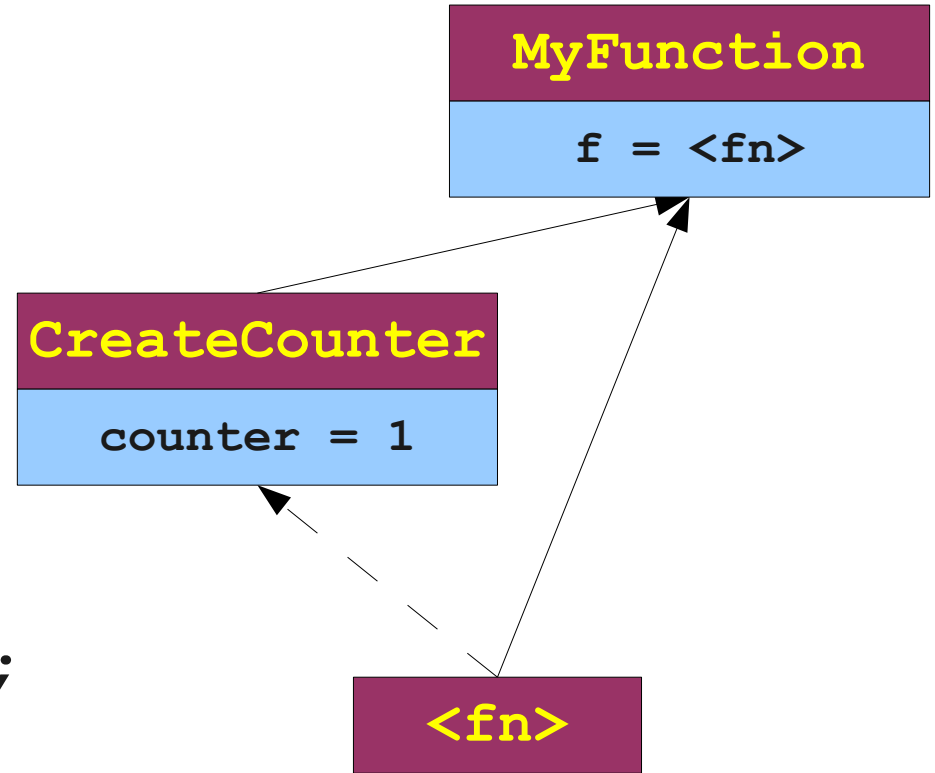


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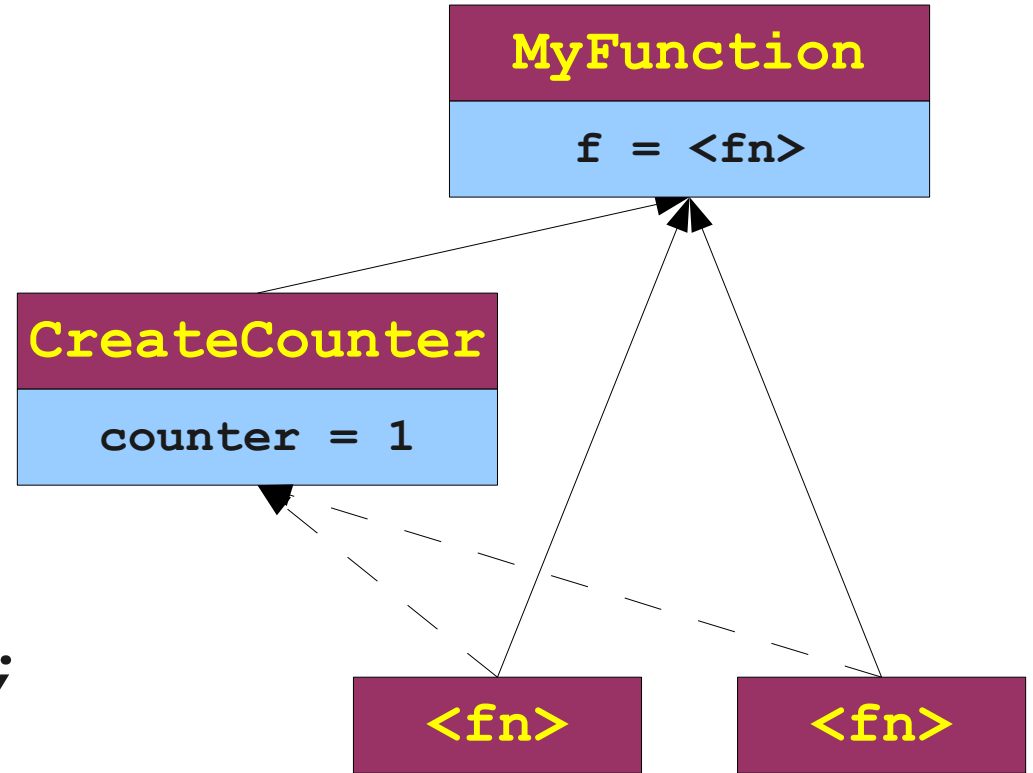


```
> 1
```

Closures

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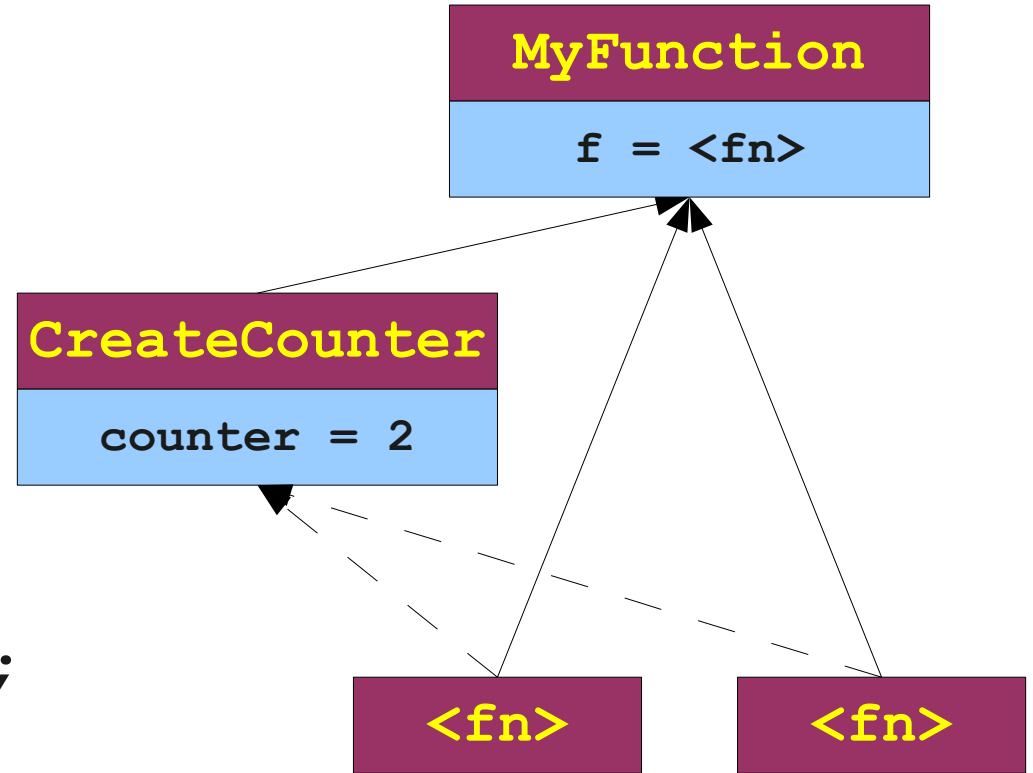


```
> 1
```

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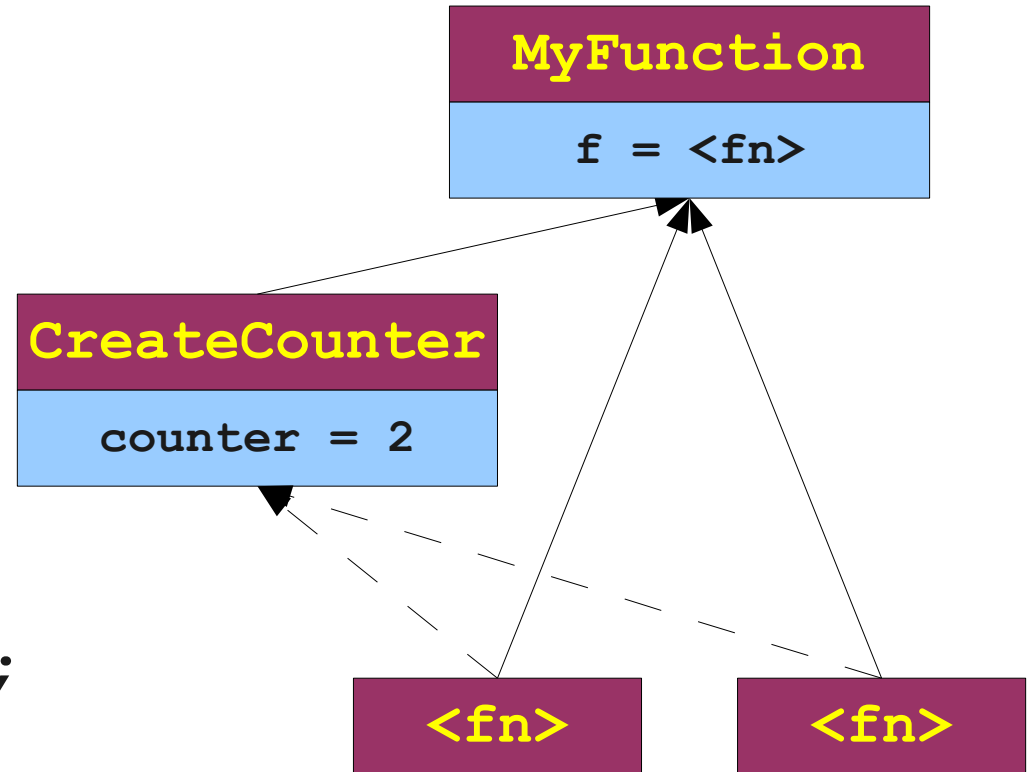


```
> 1
```


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```



```
> 1  
  2
```

Control and Activation Links

- The **control link** of a function is a pointer to the function that called it.
 - Used to determine where to resume execution after the function returns.
- The **access link** of a function is a pointer to the activation record in which the function was created.
 - Used by nested functions to determine the location of variables from the outer scope.

Closures and the Runtime Stack

- Languages supporting closures do not typically have a runtime stack.
- Activation records typically dynamically allocated and garbage collected.
- Interesting exception: `gcc C` allows for nested functions, but uses a runtime stack.
- Behavior is undefined if nested function accesses data from its enclosing function once that function returns.
 - (Why?)

Breaking Assumption 2

- **“Every activation record has either finished executing or is an ancestor of the current activation record.”**
- Any ideas on how to break this?

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- “**Every activation record has either finished executing or is an ancestor of the current activation record.**”
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- One idea: **Coroutines**

```
def downFrom(n):  
    while n > 0:  
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Breaking Assumption 2

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Coroutines

Coroutines

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def downFrom(n):  
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def myFunc():  
    for i in downFrom(3):  
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Coroutines

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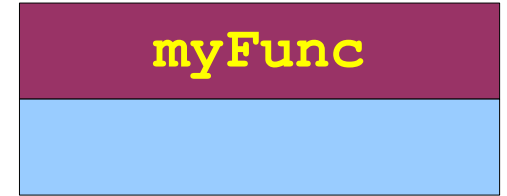


>

Coroutines

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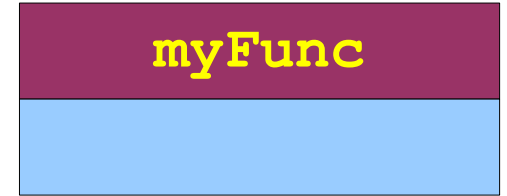


```
>
```

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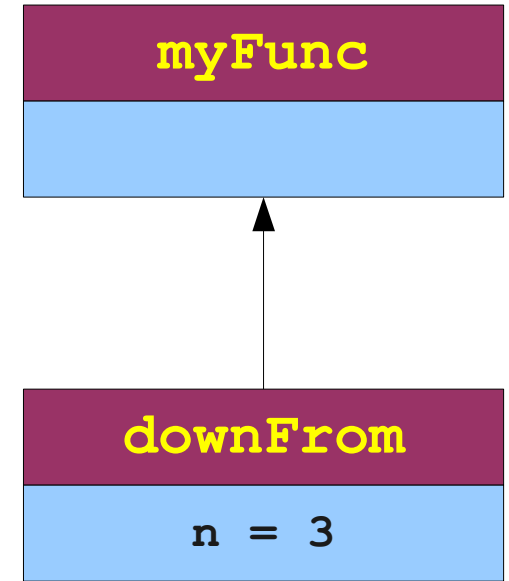


```
>
```

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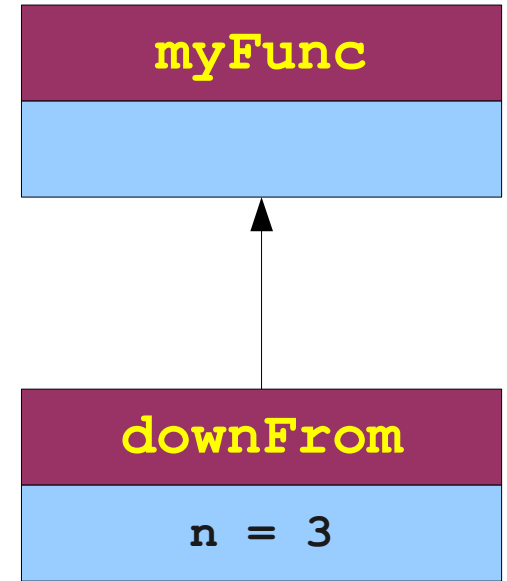


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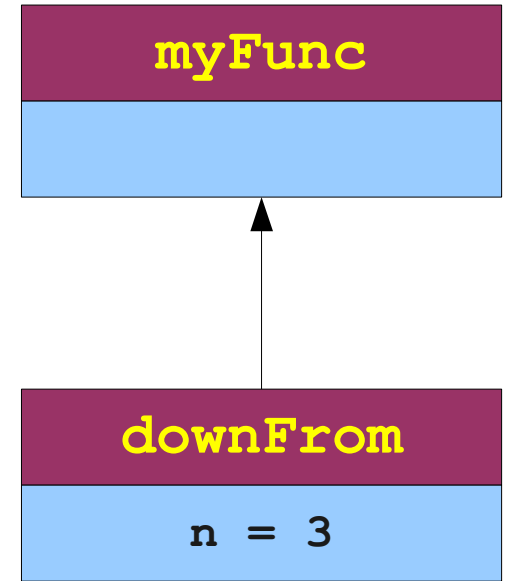


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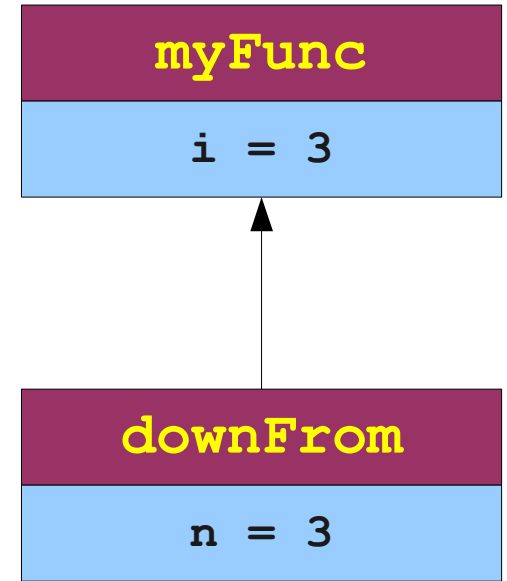


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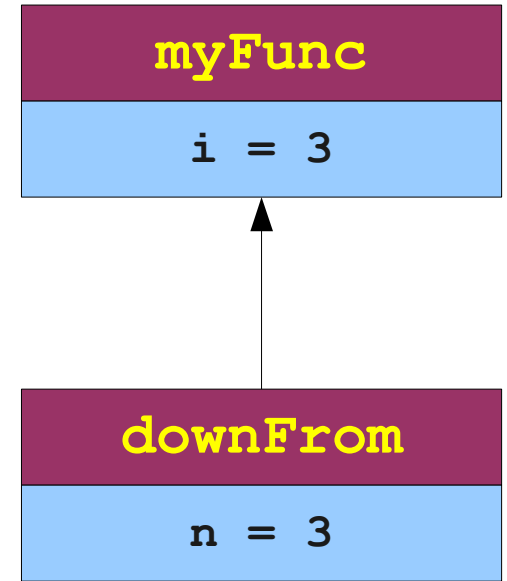


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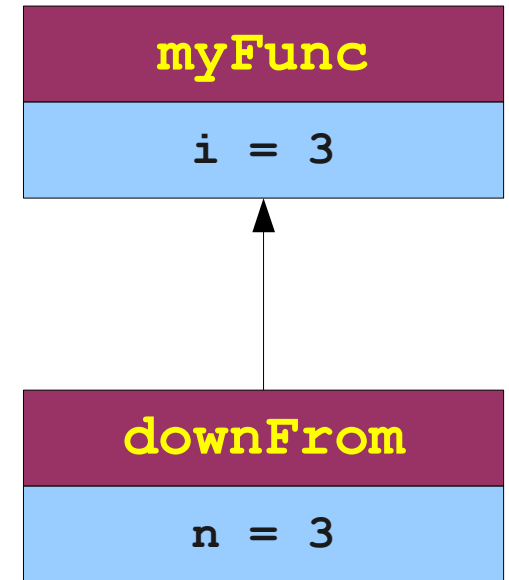
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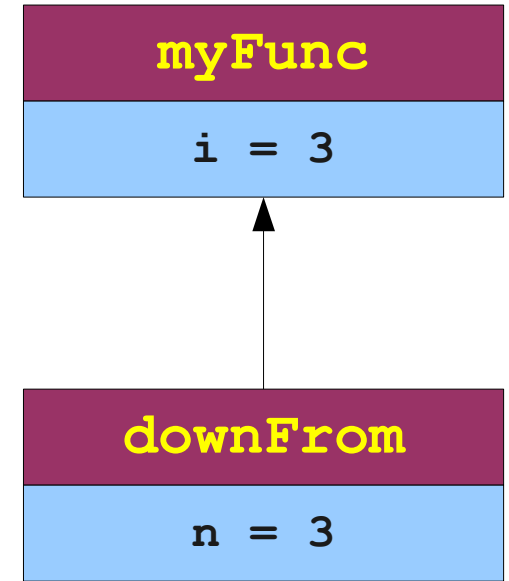
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> 3
```



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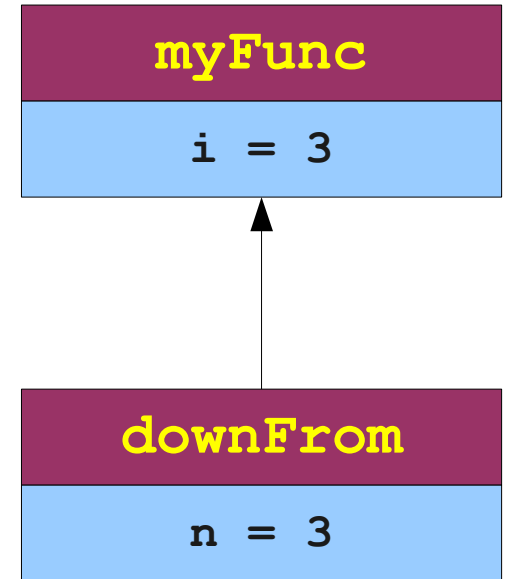
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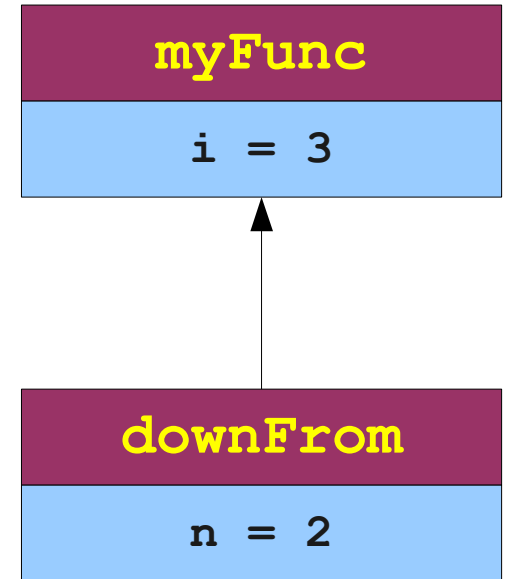


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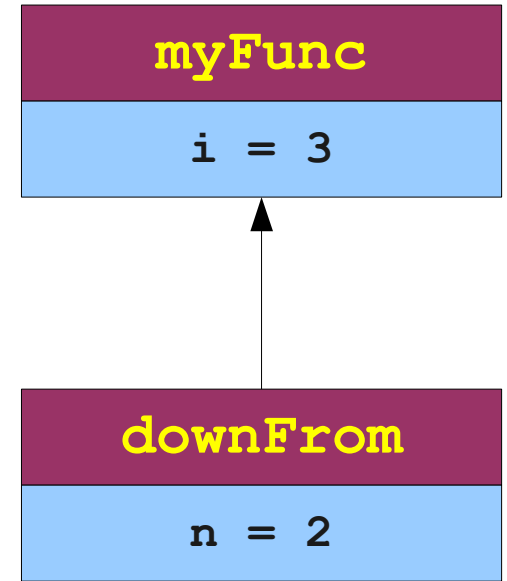


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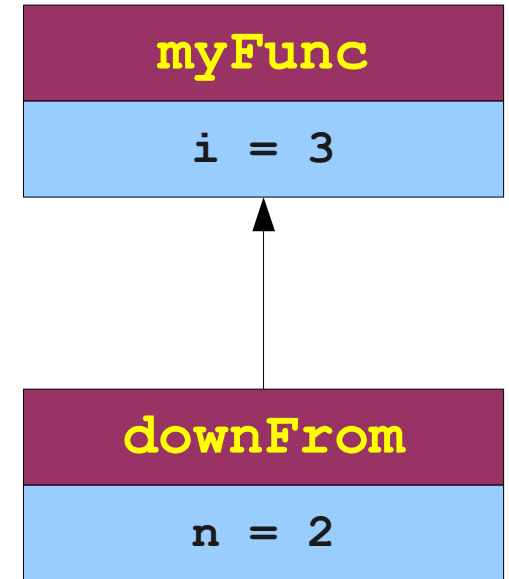


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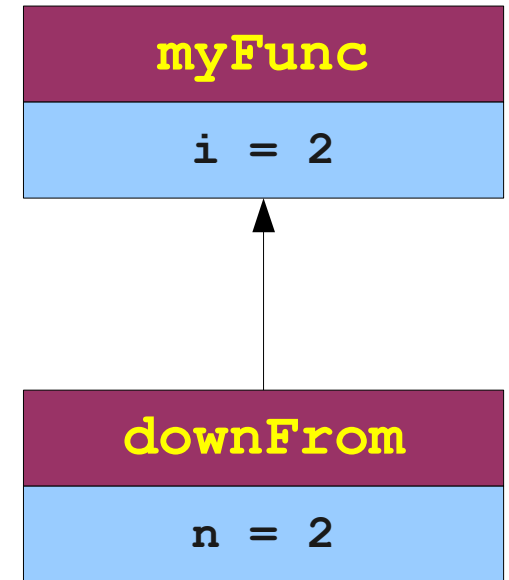


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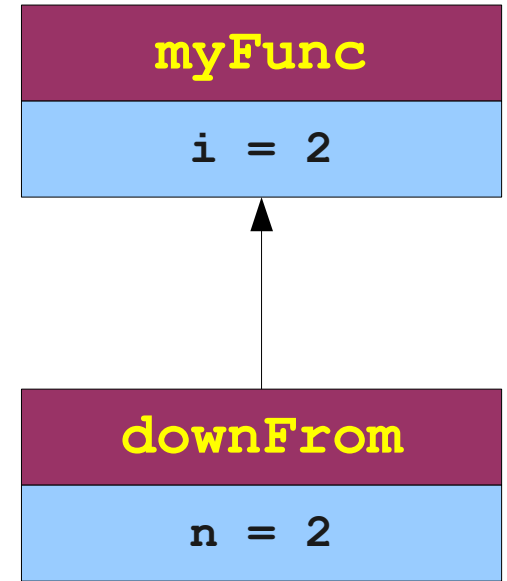


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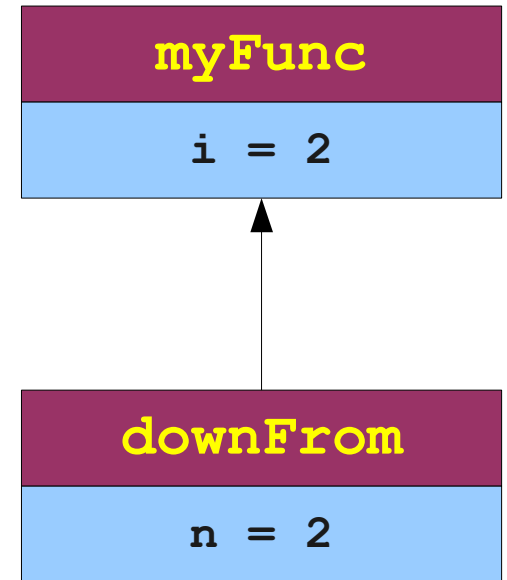


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```
> 3  
  2
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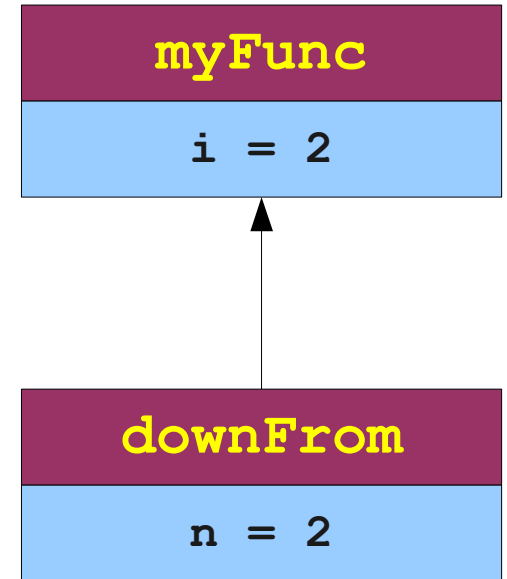


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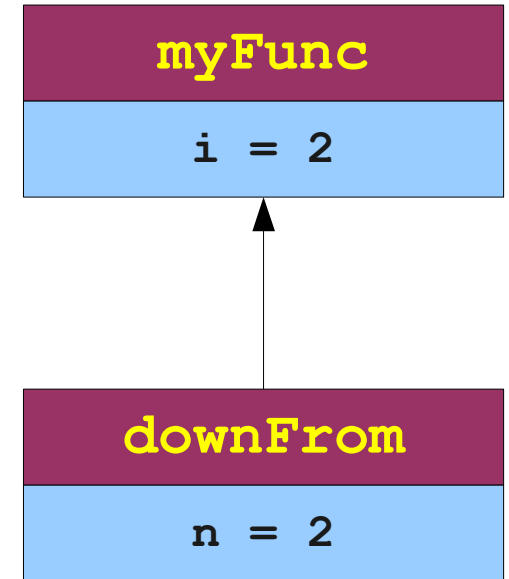


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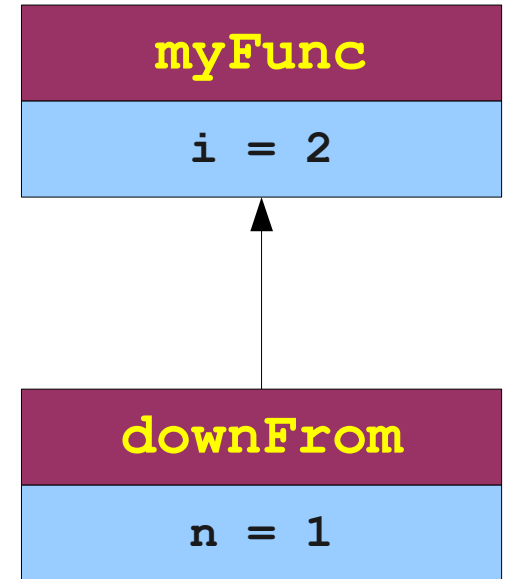


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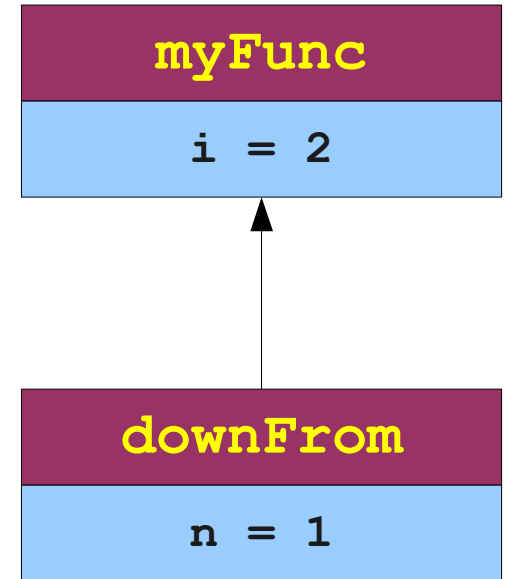


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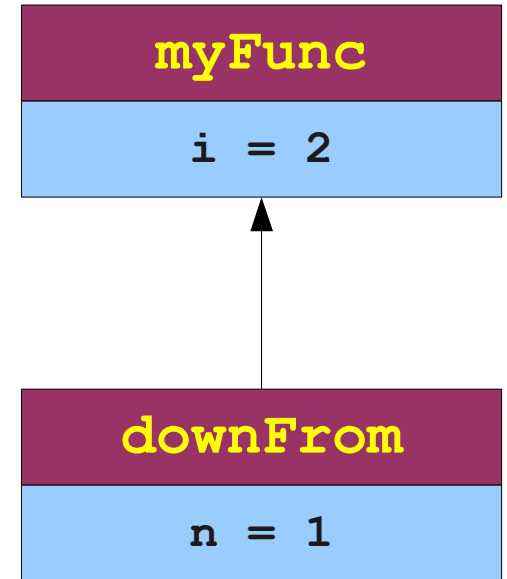


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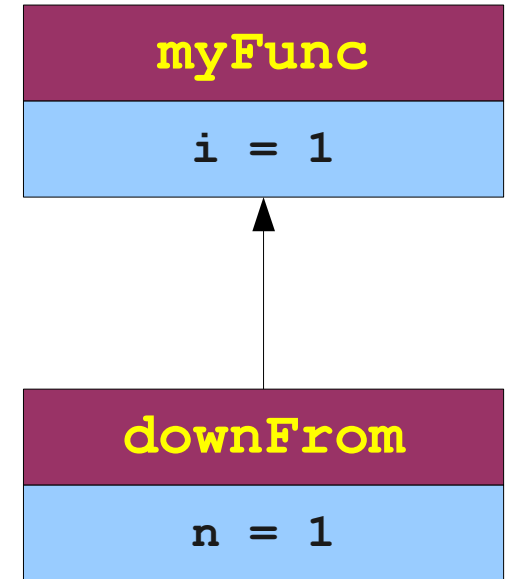


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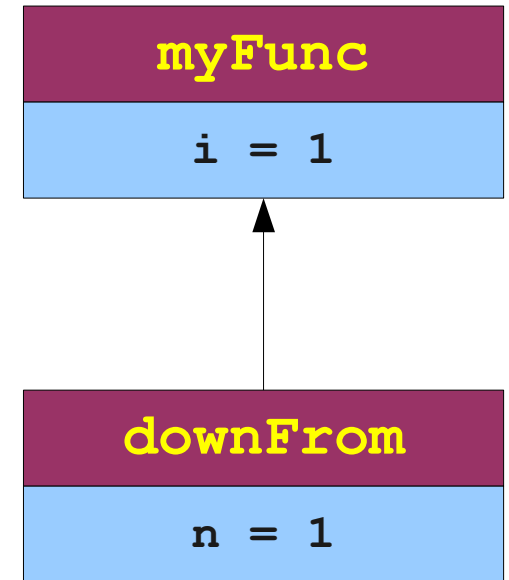


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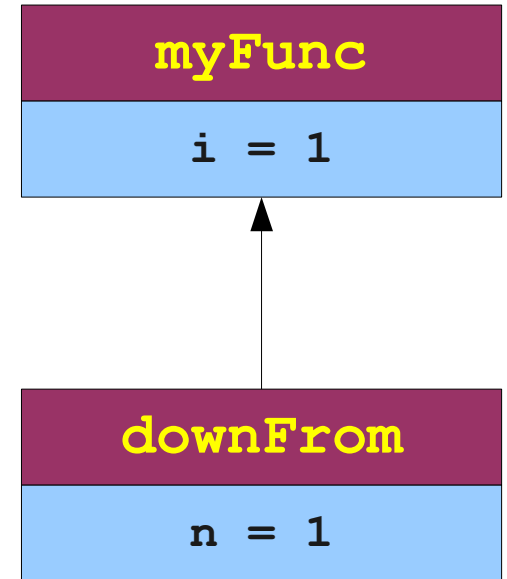


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  2  
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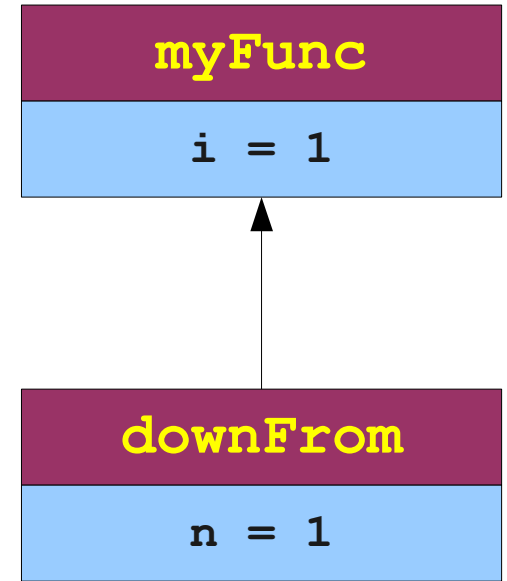


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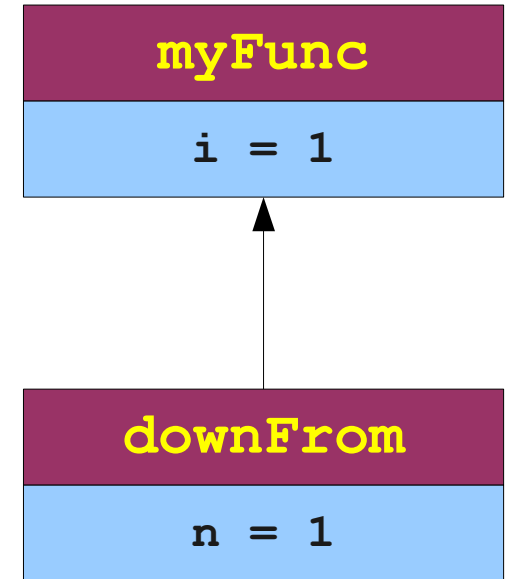


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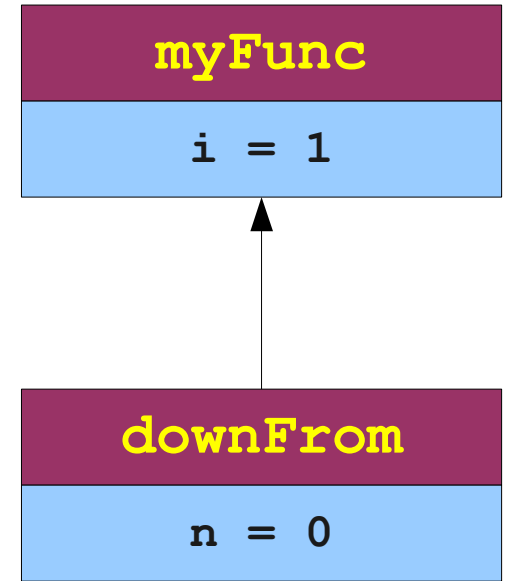


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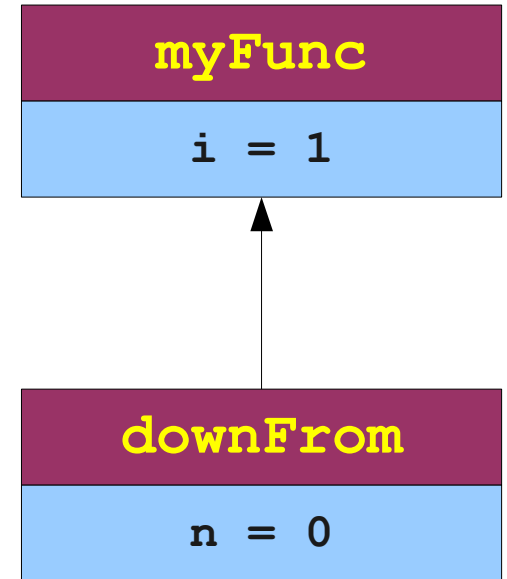


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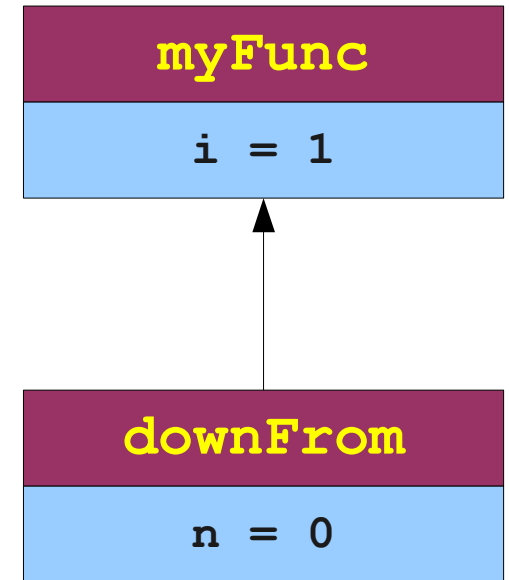


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```

```
> 3  
  2  
  1
```



Coroutines

- A **subroutine** is a function that, when invoked, runs to completion and returns control to the calling function.
 - Master/slave relationship between caller/callee.
- A **coroutine** is a function that, when invoked, does some amount of work, then returns control to the calling function. It can then be resumed later.
 - Peer/peer relationship between caller/callee.
- Subroutines are a special case of coroutines.

Coroutines and the Runtime Stack

- Coroutines often cannot be implemented with purely a runtime stack.
 - What if a function has multiple coroutines running alongside it?
- Few languages support coroutines, though some do (Python, for example).

So What?

- Even a concept as fundamental as “the stack” is actually quite complex.
- When designing a compiler or programming language, you must keep in mind how your language features influence the runtime environment.
- **Always be critical of the languages you use!**

Functions in Decaf

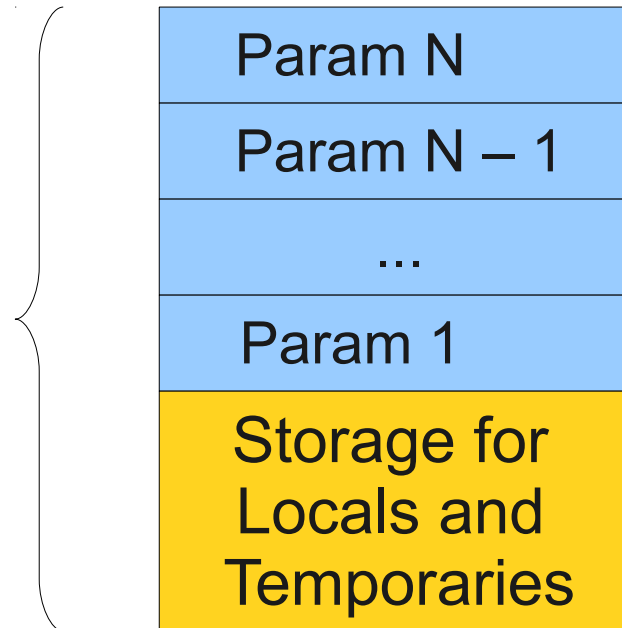
- We use an explicit runtime stack.
- Each activation record needs to hold
 - All of its parameters.
 - All of its local variables.
 - All temporary variables introduced by the IR generator (more on that later).
- Where do these variables go?
- Who allocates space for them?

Decaf Stack Frames

- The **logical** layout of a Decaf stack frame is created by the IR generator.
 - Ignores details about machine-specific calling conventions.
 - We'll discuss today.
- The **physical** layout of a Decaf stack frame is created by the code generator.
 - Based on the logical layout set up by the IR generator.
 - Includes frame pointers, caller-saved registers, and other fun details like this.
 - We'll discuss when talking about code generation.

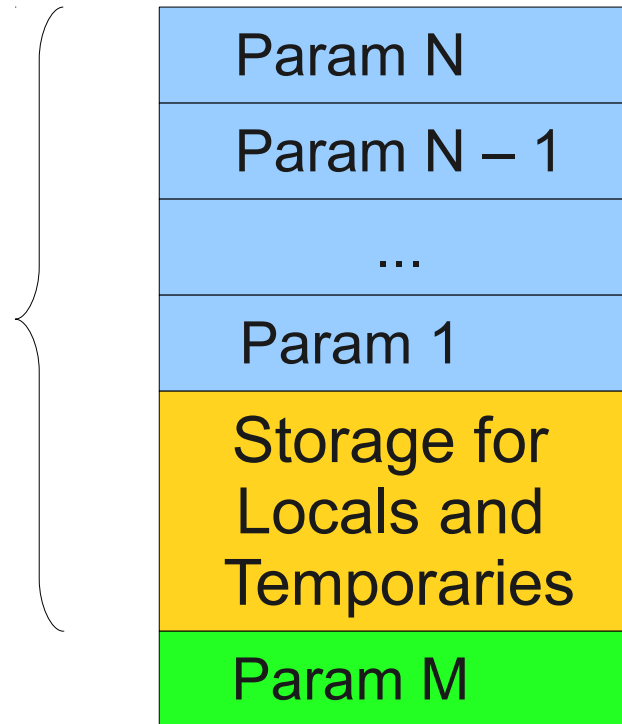
A Logical Decaf Stack Frame

Stack frame
for function
 $f(a, \dots, n)$



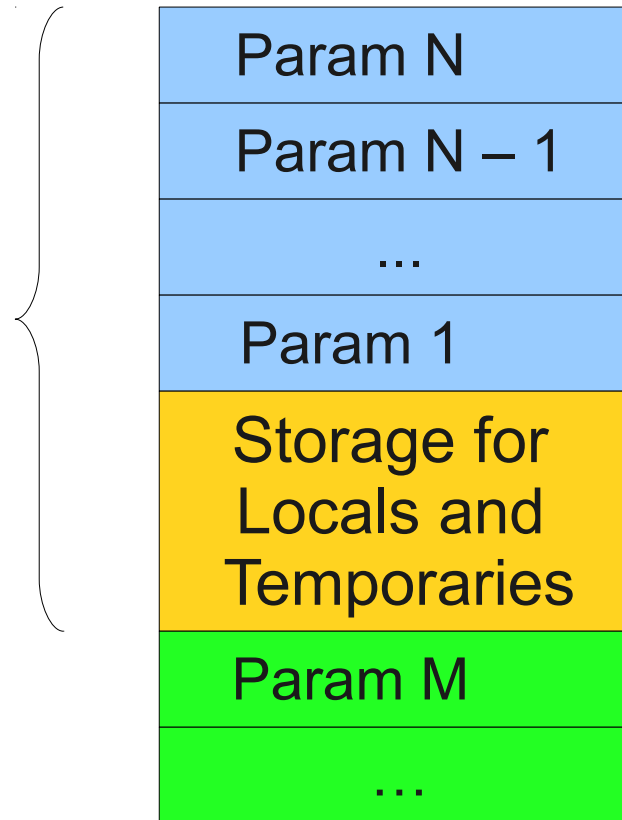
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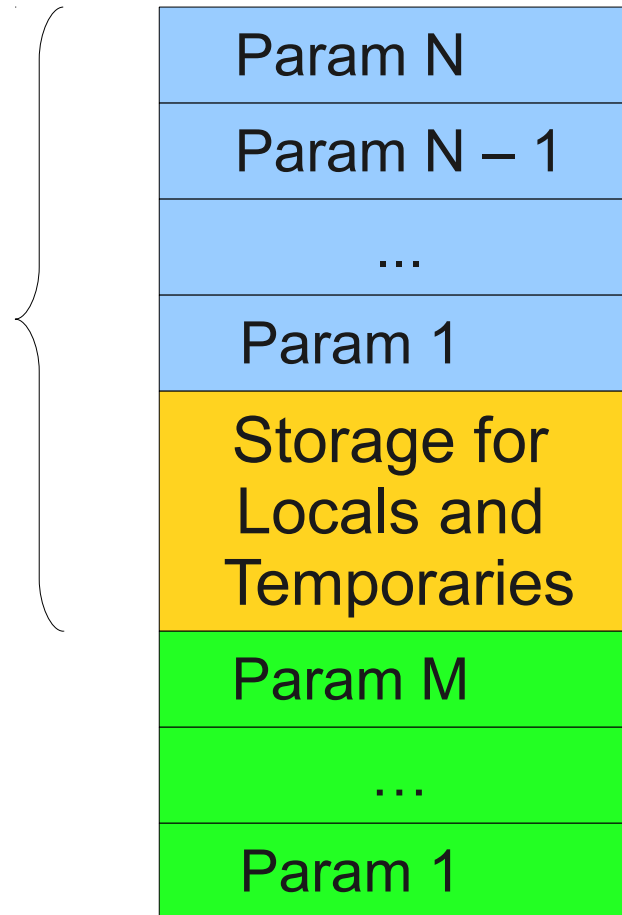
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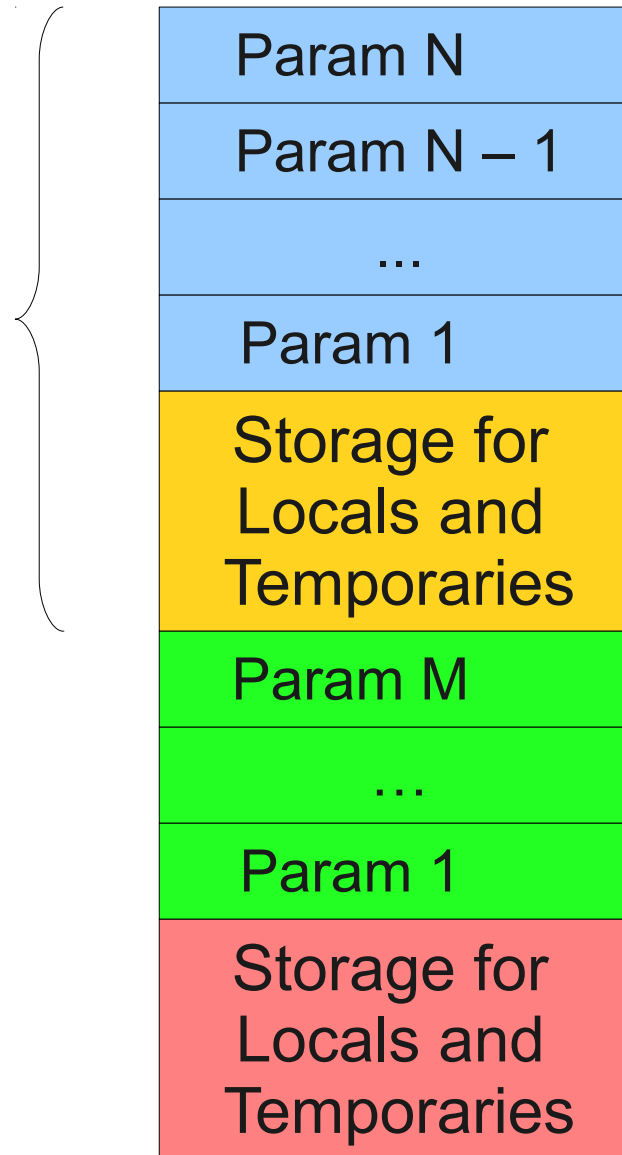
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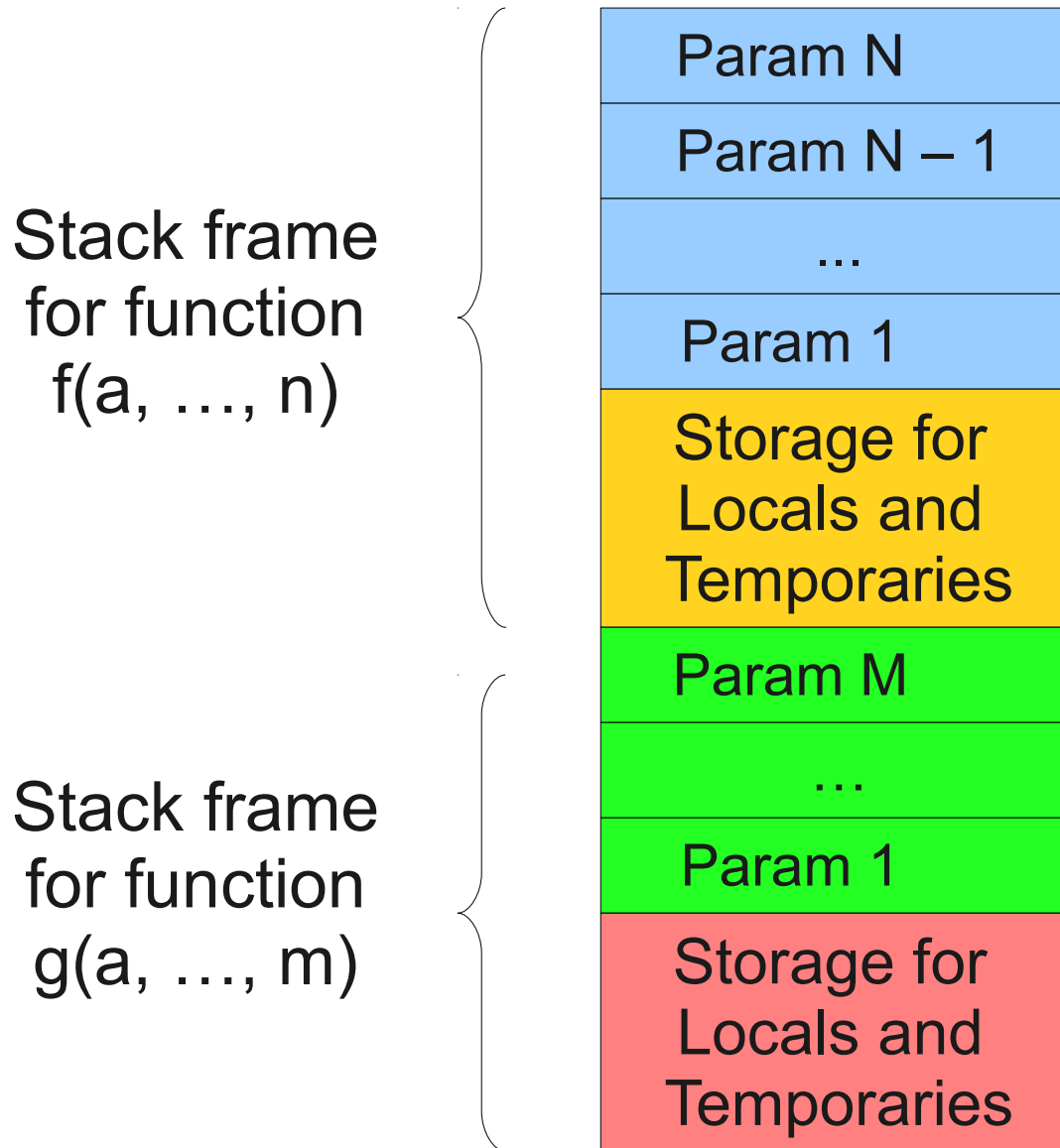


A Logical Decaf Stack Frame

Stack frame
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A Logical Decaf Stack Frame



Decaf IR Calling Convention

- Caller responsible for pushing and popping space for callee's arguments.
 - (Why?)
- Callee responsible for pushing and popping space for its own temporaries.
 - (Why?)

Parameter Passing Approaches

- Two common approaches.
- Call-by-value
 - Parameters are **copies** of the values specified as arguments.
- Call-by-reference:
 - Parameters are **pointers** to values specified as parameters.

Other Parameter Passing Ideas

- JavaScript: Functions can be called with any number of arguments.
 - Parameters are initialized to the corresponding argument, or **undefined** if not enough arguments were provided.
 - The entire parameters array can be retrieved through the **arguments** array.
- How might this be implemented?

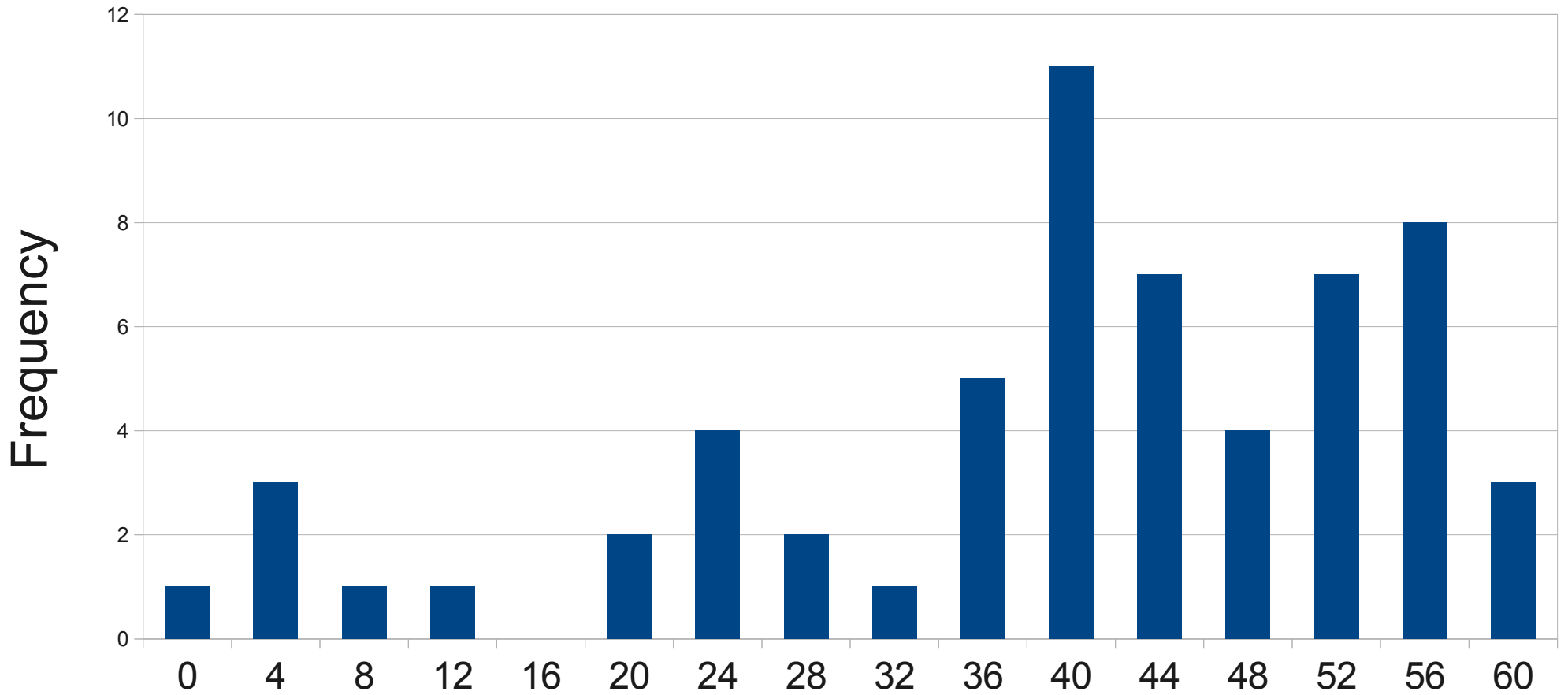
Other Parameter Passing Ideas

- Python: **Keyword Arguments**
 - Functions can be written to accept any number of key/value pairs as arguments.
 - Values stored in a special argument (traditionally named **kwargs**)
 - **kwargs** can be manipulated (more or less) as a standard variable.
- How might this be implemented?

Summary of Function Calls

- The runtime stack is an optimization of the activation tree spaghetti stack.
- Most languages use a runtime stack, though certain language features prohibit this optimization.
- Activation records **logically** store a **control link** to the calling function and an **access link** to the function in which it was created.
- Decaf has the caller manage space for parameters and the callee manage space for its locals and temporaries.
- Call-by-value and call-by-name can be implemented using copying and pointers.
- More advanced parameter passing schemes exist!

Midterm Scores



Mean: 38
Median: 40
Stdev: 15.3

Next Time

- Object layouts
 - The limits of standard vtables
 - Inline caching
 - Prototypical inheritance (ITA)
- Three-address code IR.
- Generating TAC.