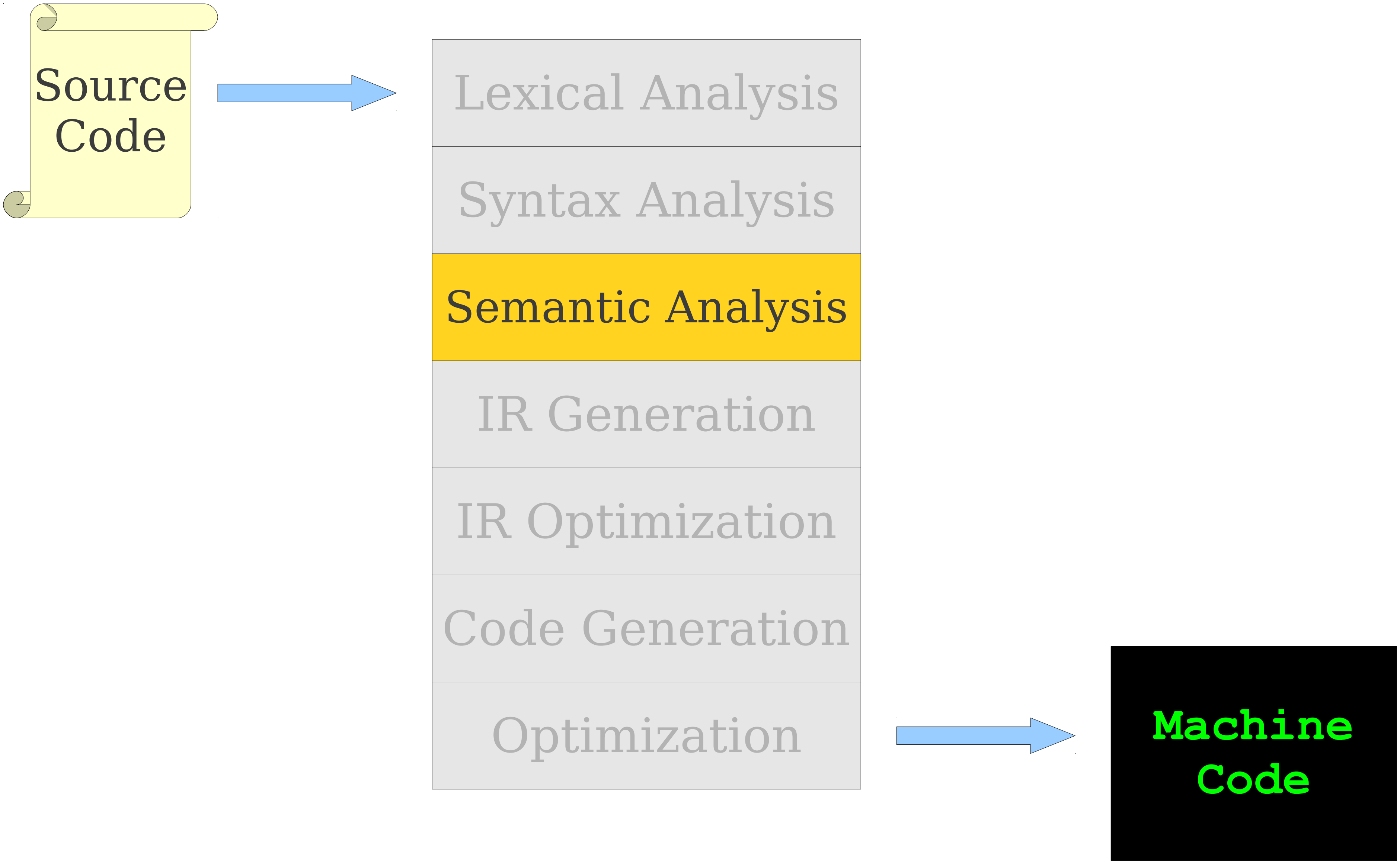
Runtime Environments

Announcements

- Programming Project 3 checkpoint due Monday at 11:59PM.
  - This is a **hard deadline** and no late submissions will be accepted, even with late days.
  - Remainder of the project due a week from Monday at 11:59PM.

Where We Are


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

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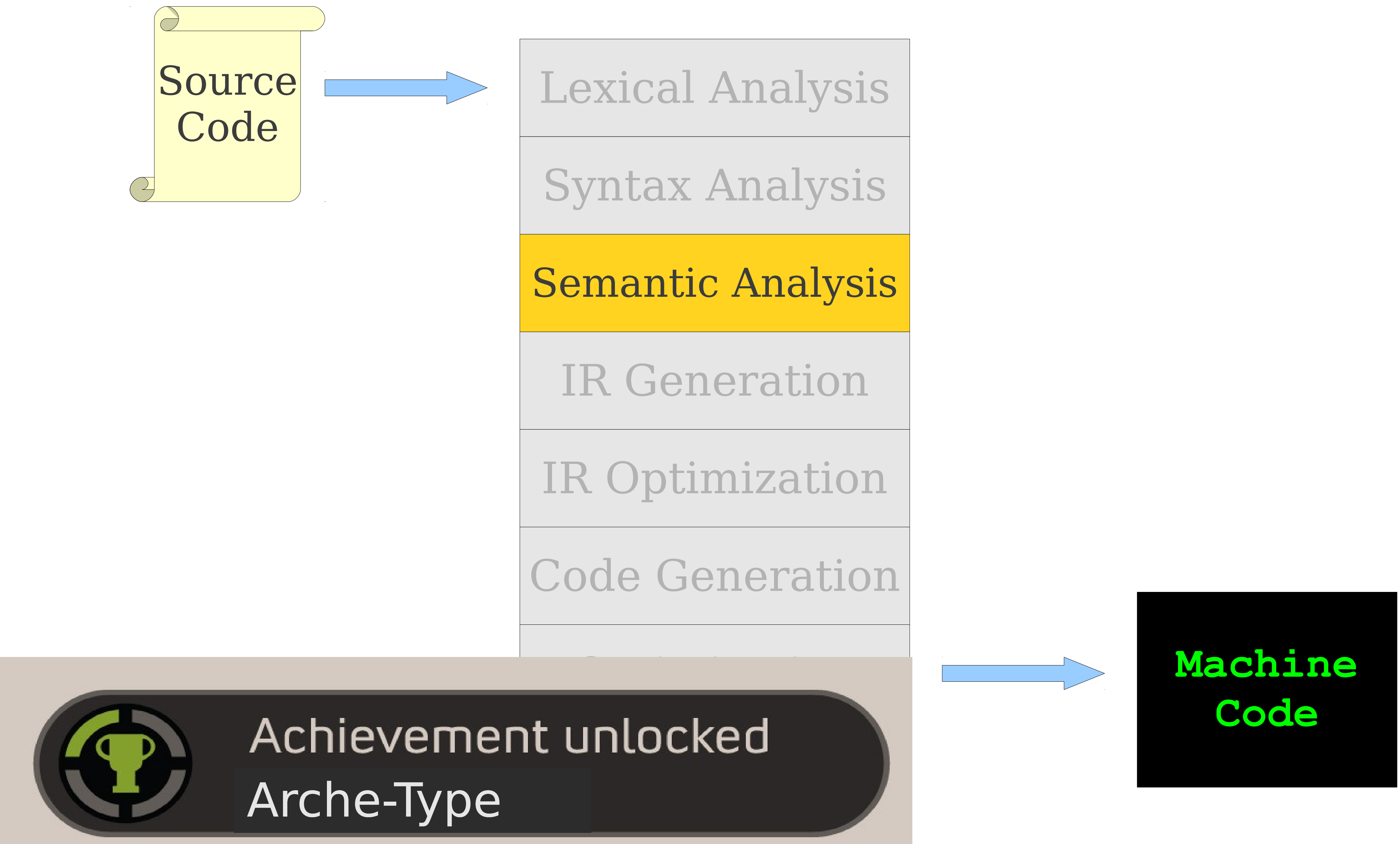
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Achievement unlocked
Arche-Type

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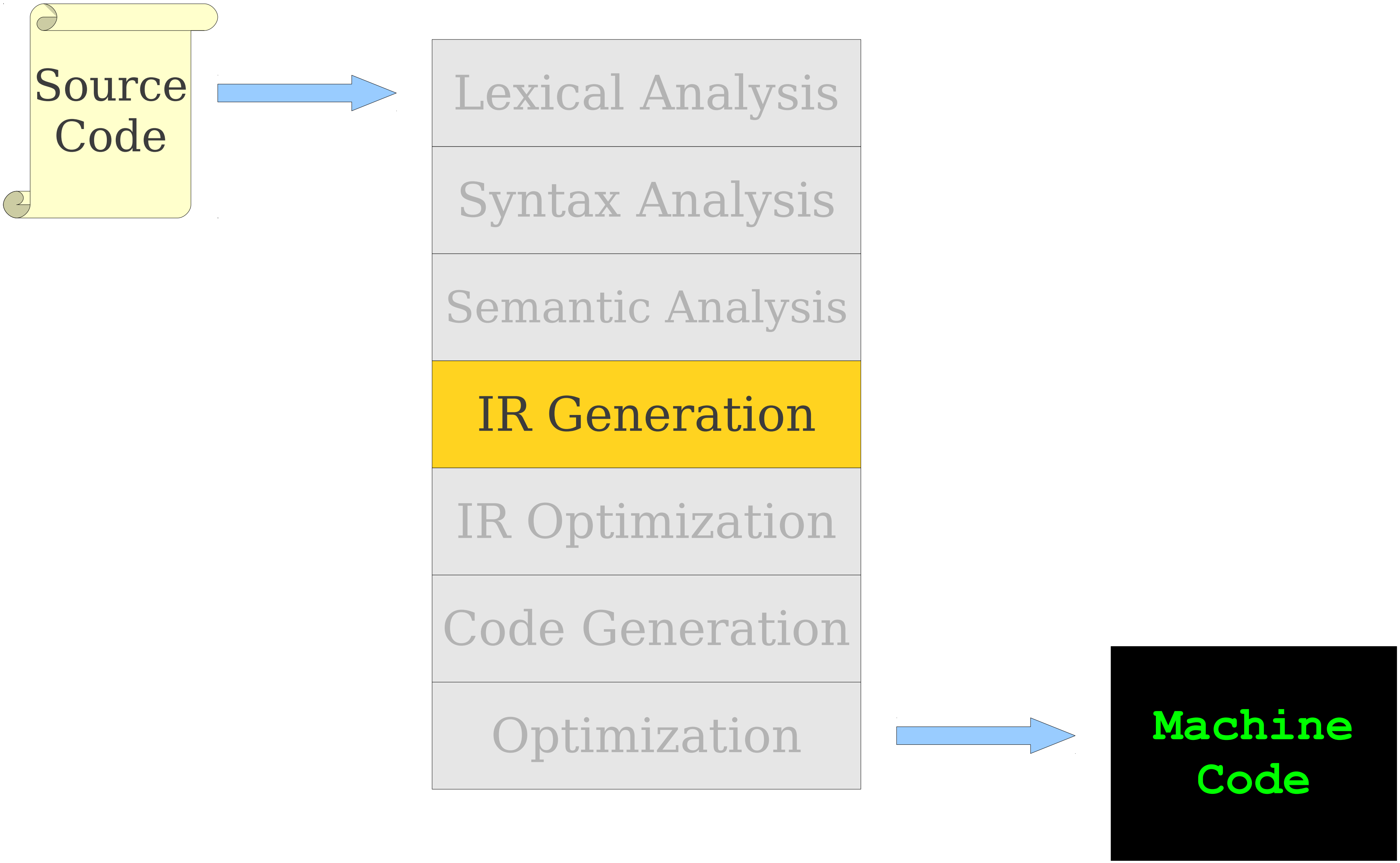

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What is IR Generation?

- **Intermediate Representation Generation**.
- The final phase of the compiler front-end.
- Goal: Translate the program into the format 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.

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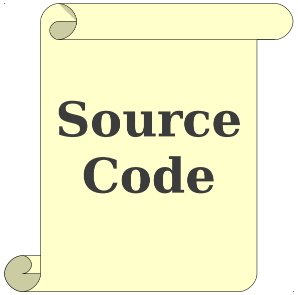

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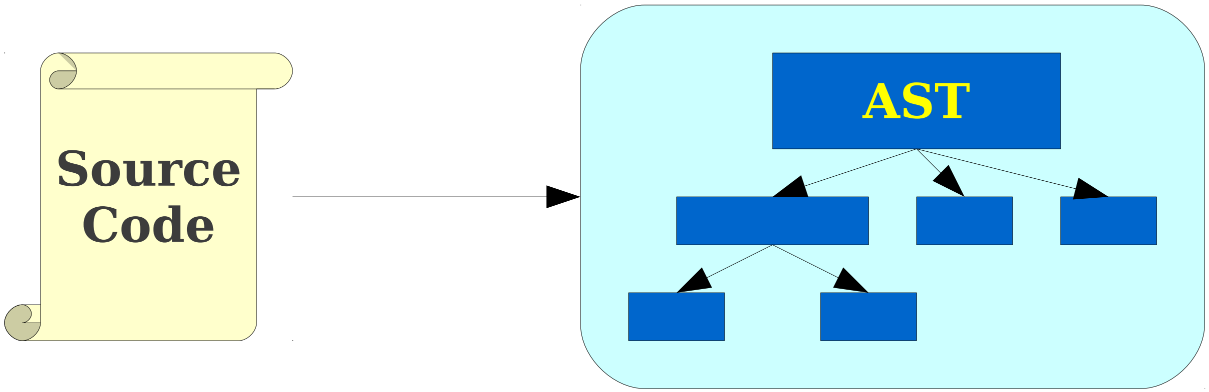

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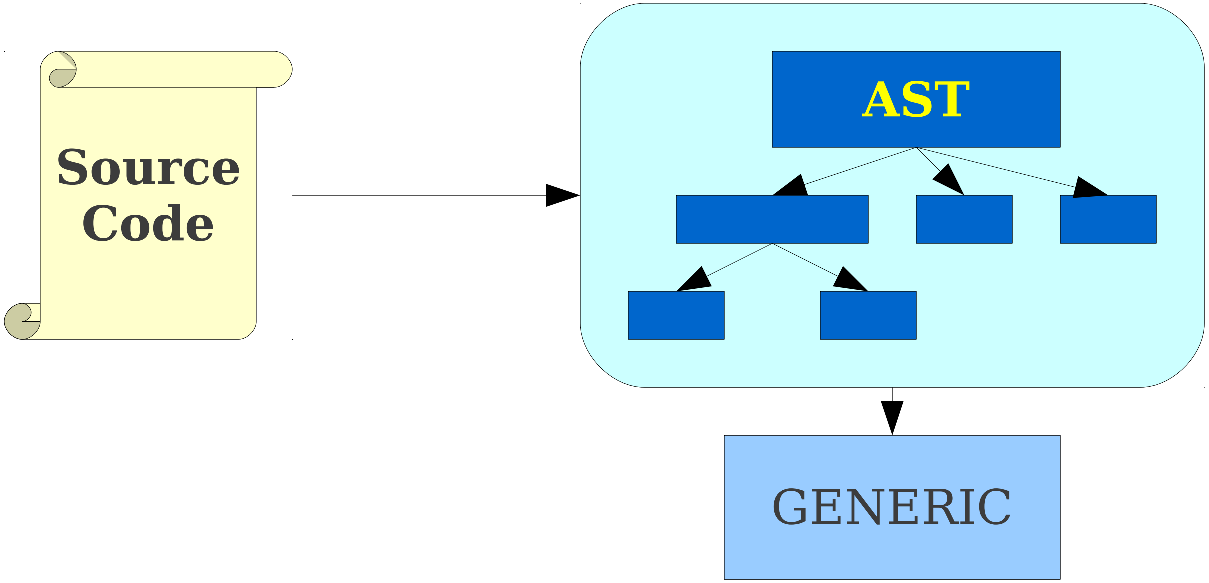

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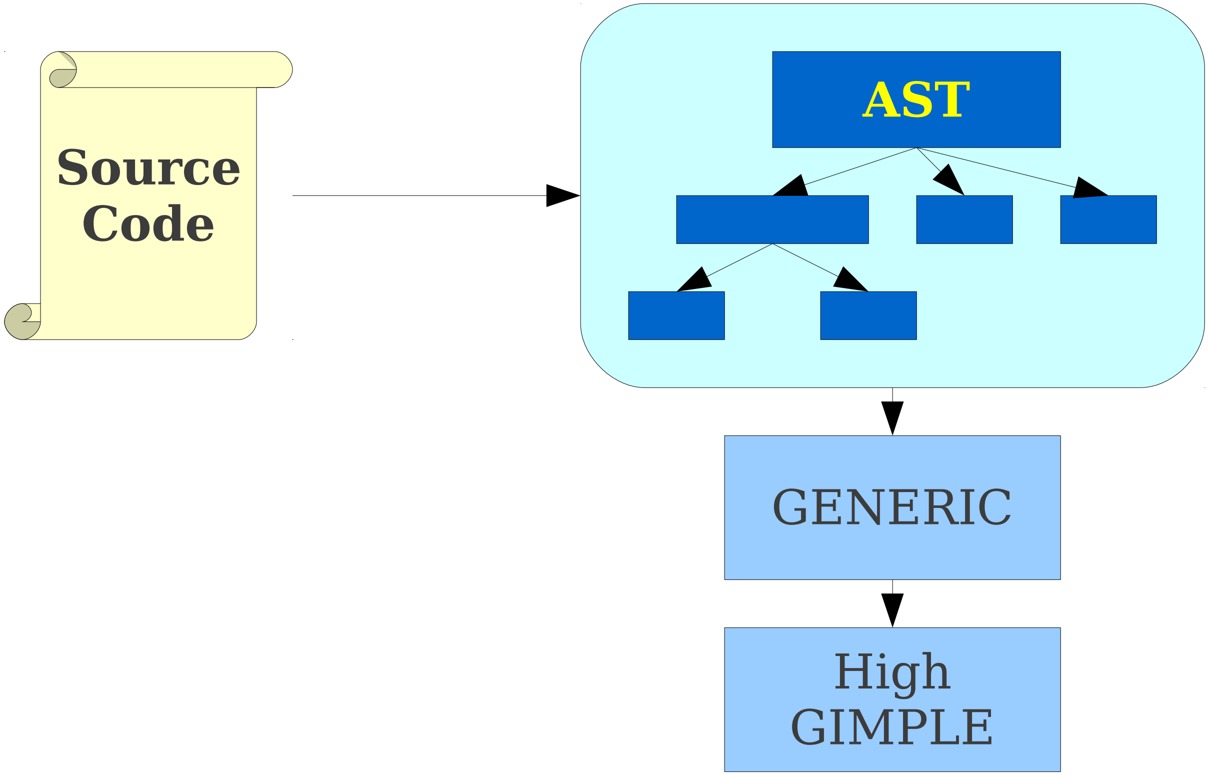

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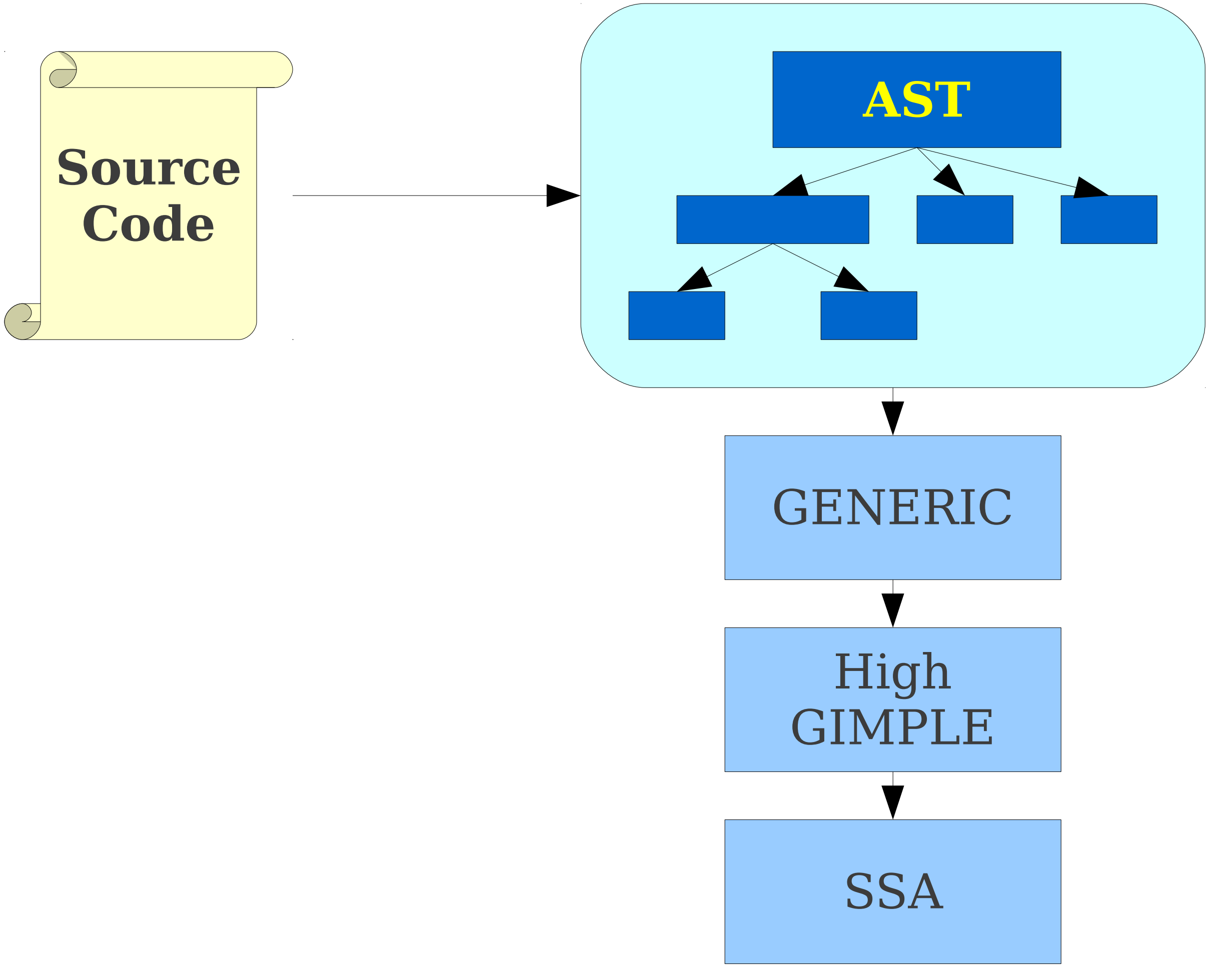

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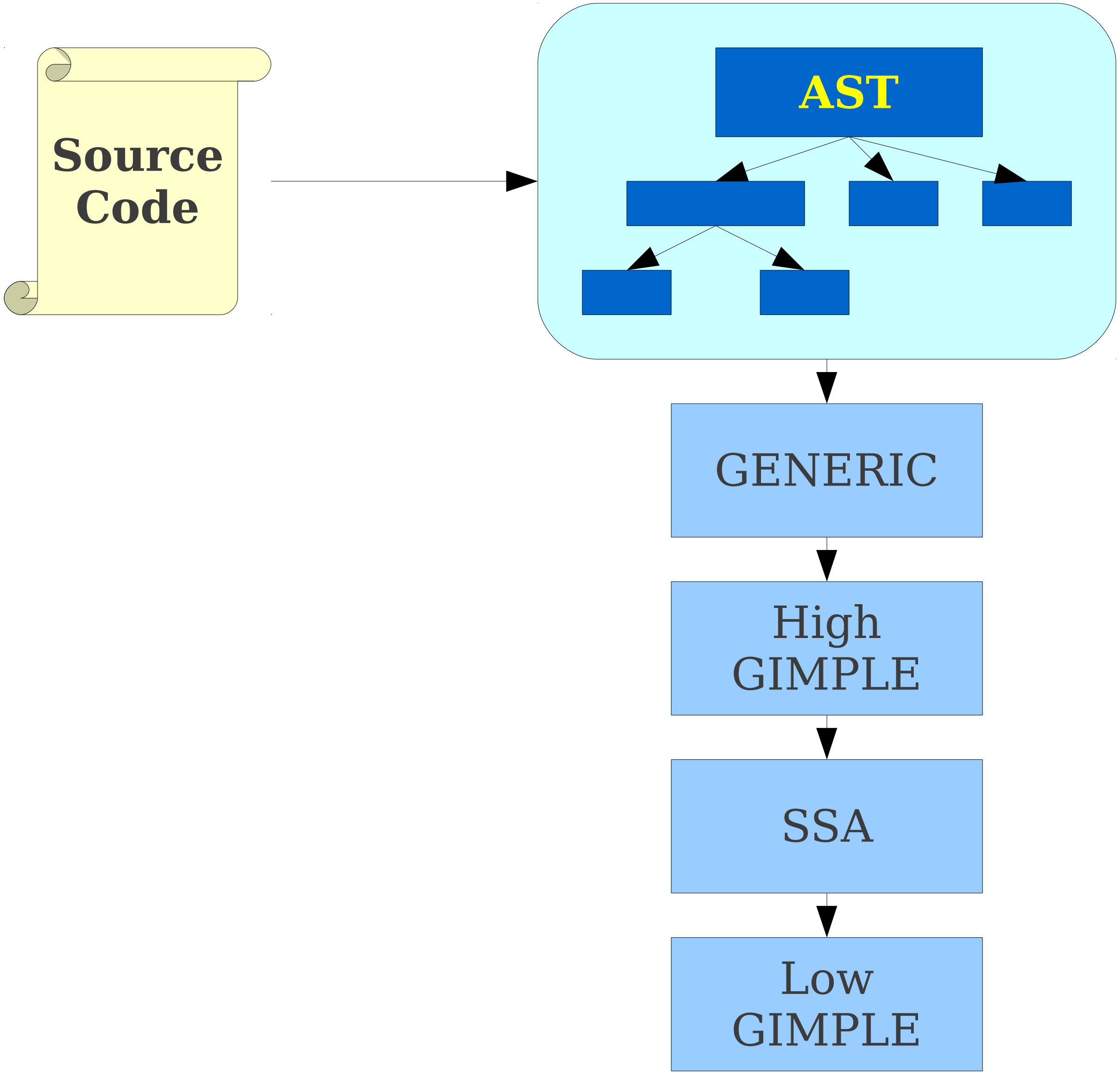

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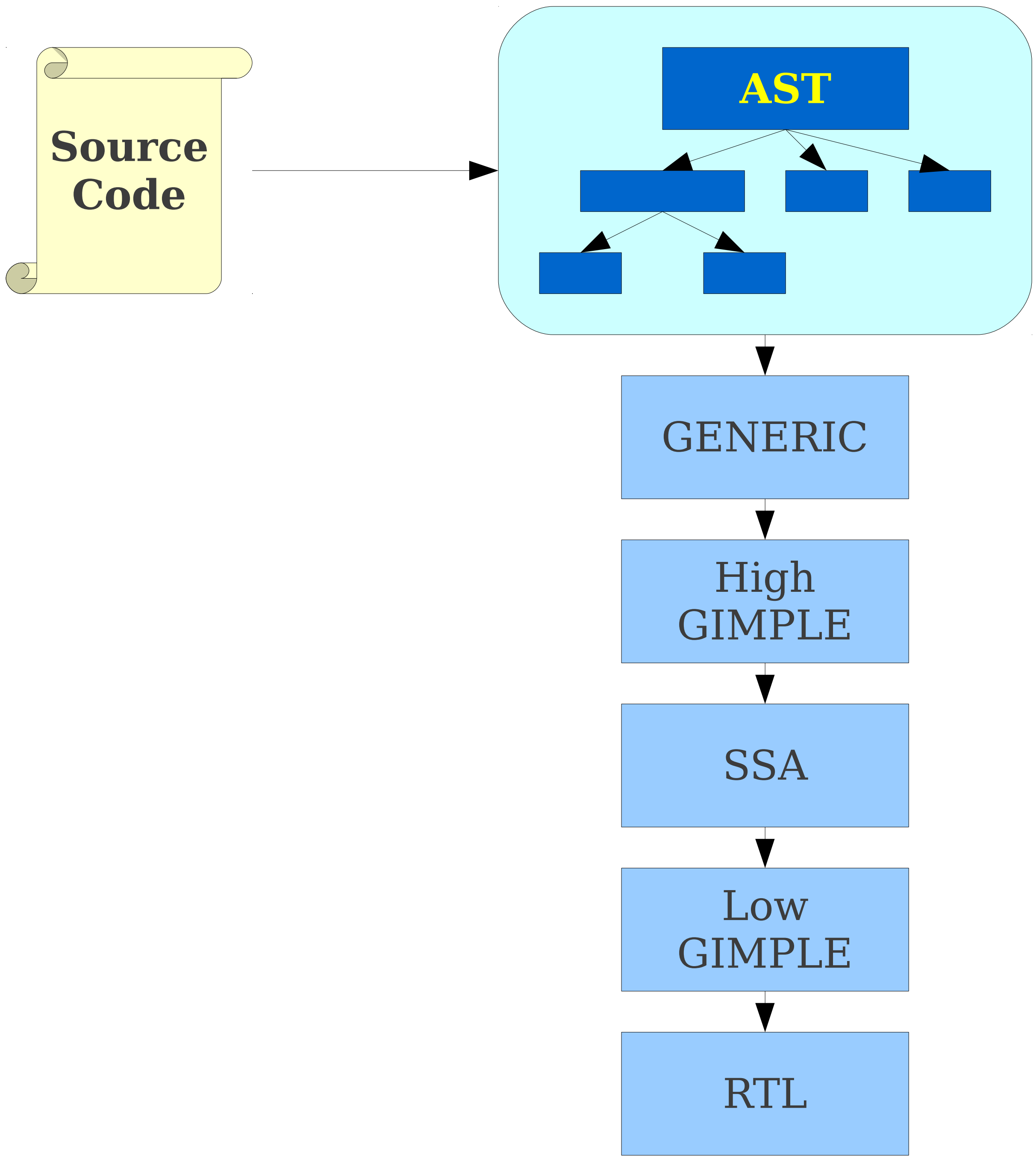

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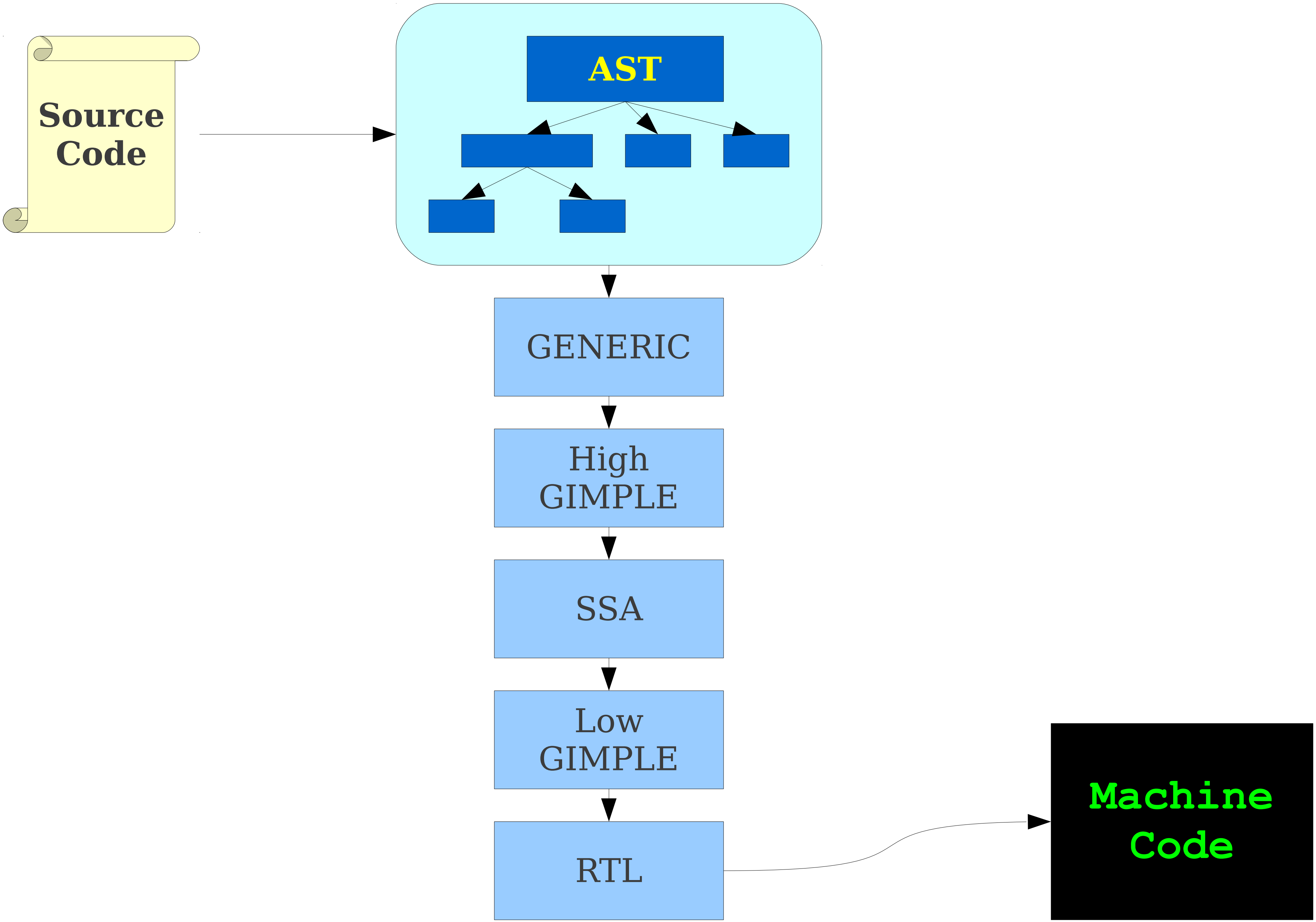

Another Approach: High-Level IR

- 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 IR** (Wednesday)
  - What IR are we using in this course?
  - What features does it have?

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 generator 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?
- **There are no right answers to these questions**.
  - 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

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

Arr[0]	**Arr[1]**	**Arr[2]**	**...**	**Arr[n-1]**

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

`n`	**`Arr[0]`**	**`Arr[1]`**	**`Arr[2]`**	**`...`**	**`Arr[n-1]`**

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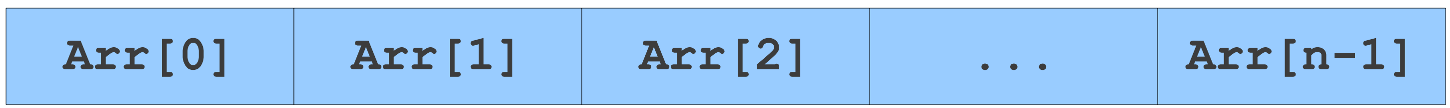

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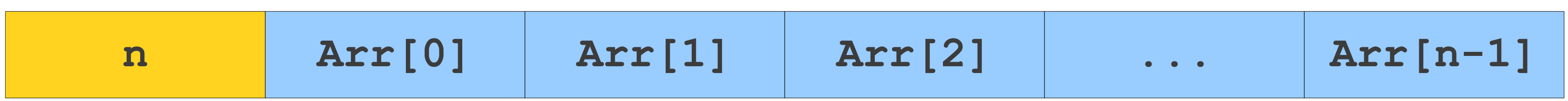

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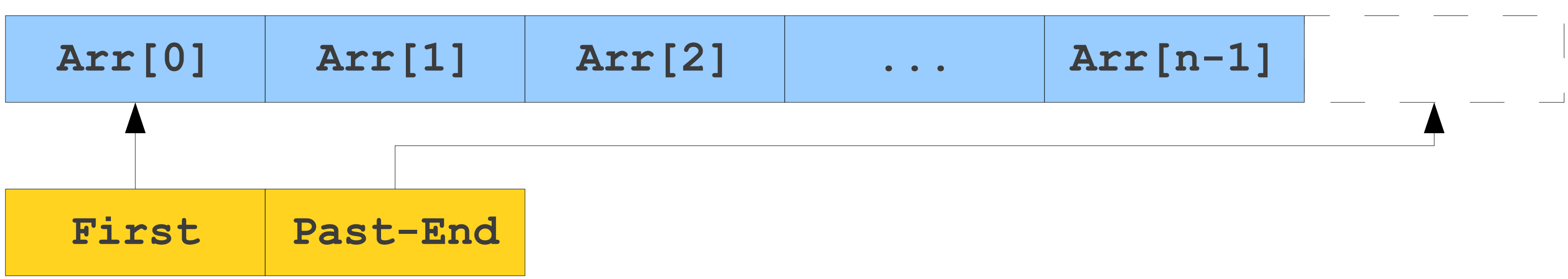

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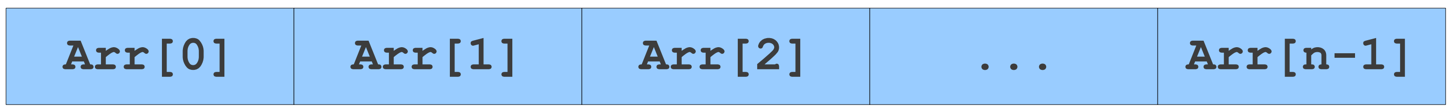

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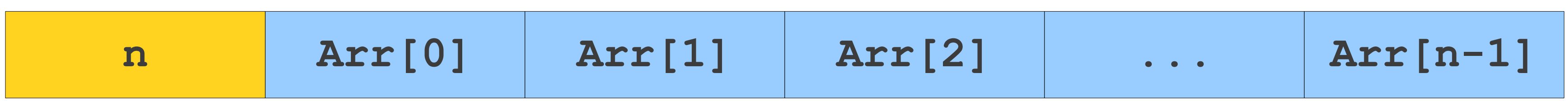

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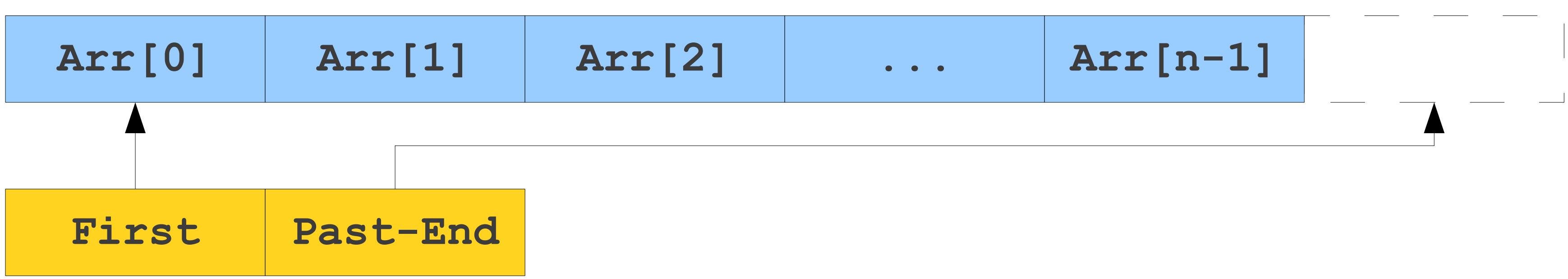

- (Which of these works well for Decaf?)

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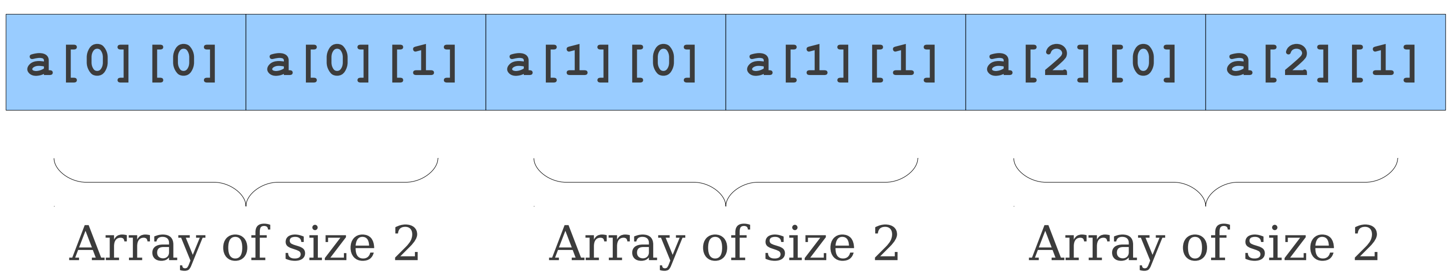

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How do you know where to look for an element in an array like this?

`a[0][0]`	`a[0][1]`	`a[1][0]`	`a[1][1]`	`a[2][0]`	`a[2][1]`
Array of size 2		Array of size 2		Array of size 2	

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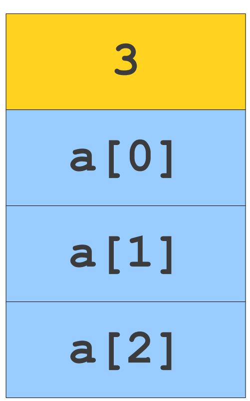

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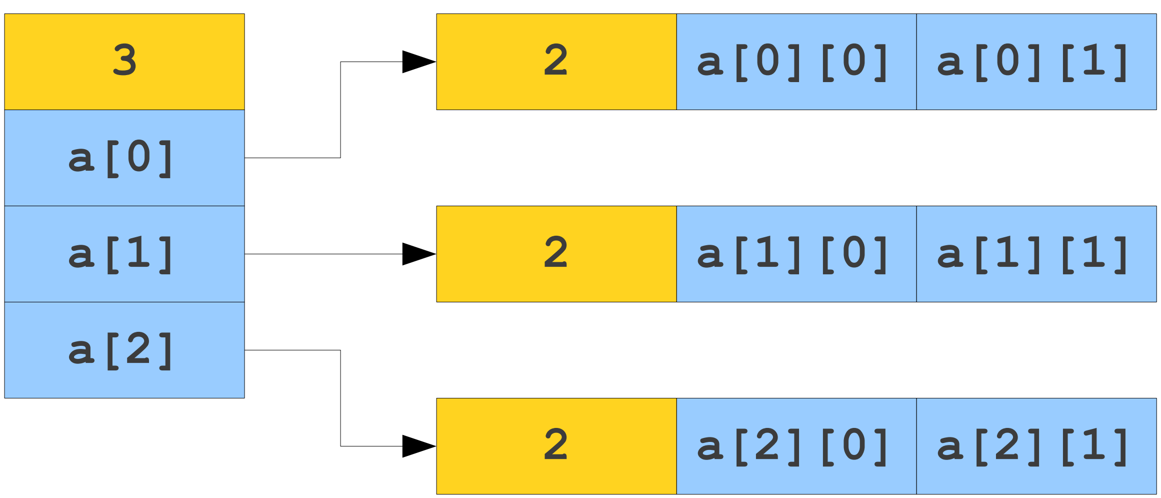

Encoding Functions

- 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.

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    Fib(3);
}

int Fib(int n) {
    if (n <= 1) return n;
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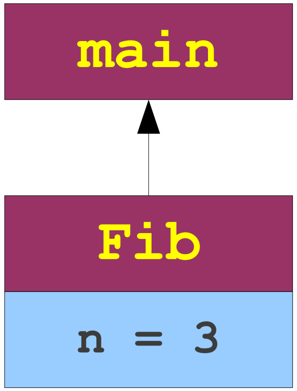

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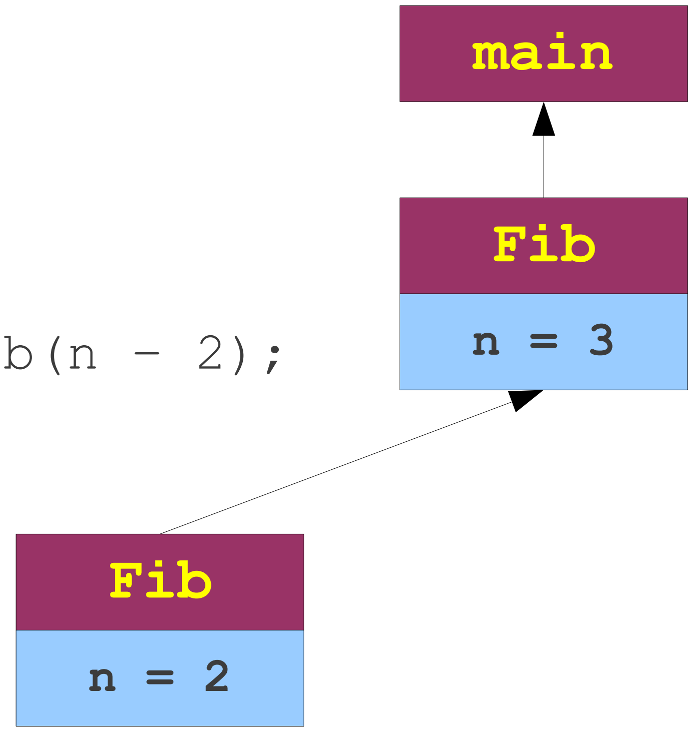

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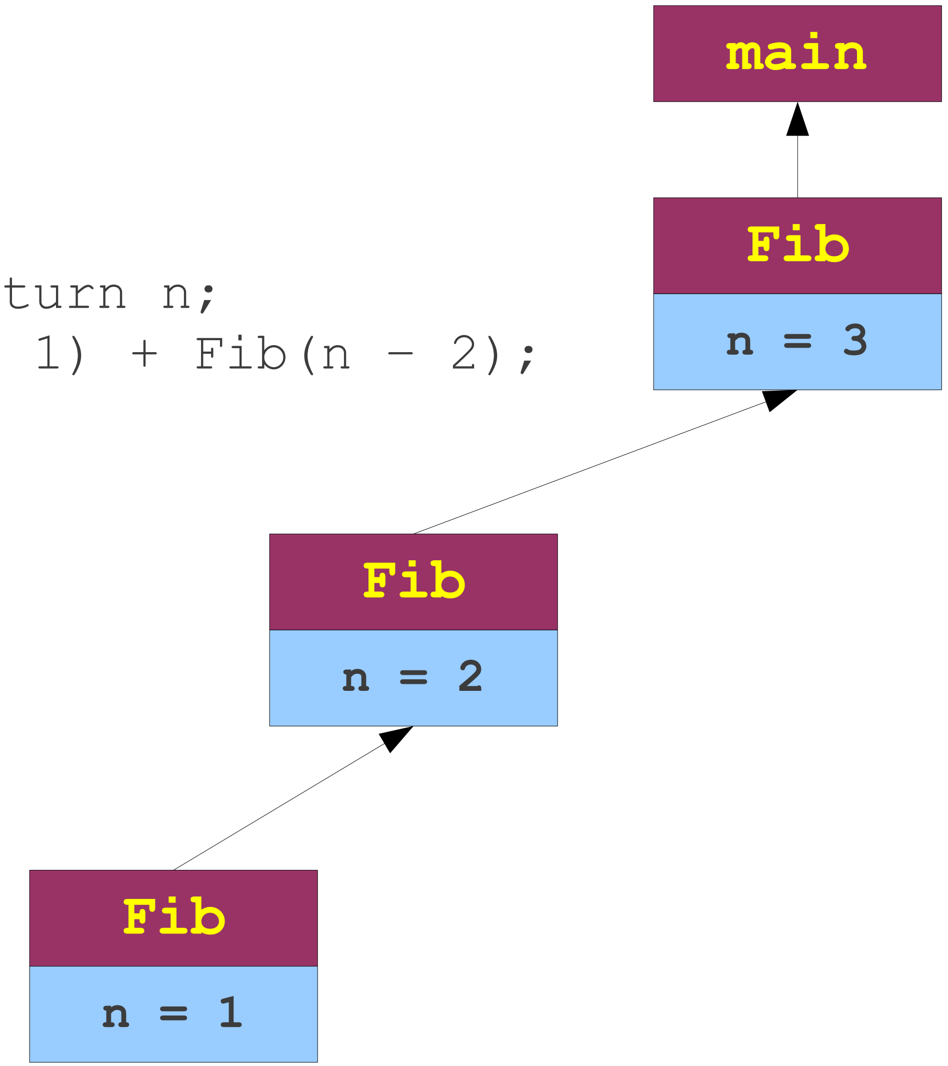

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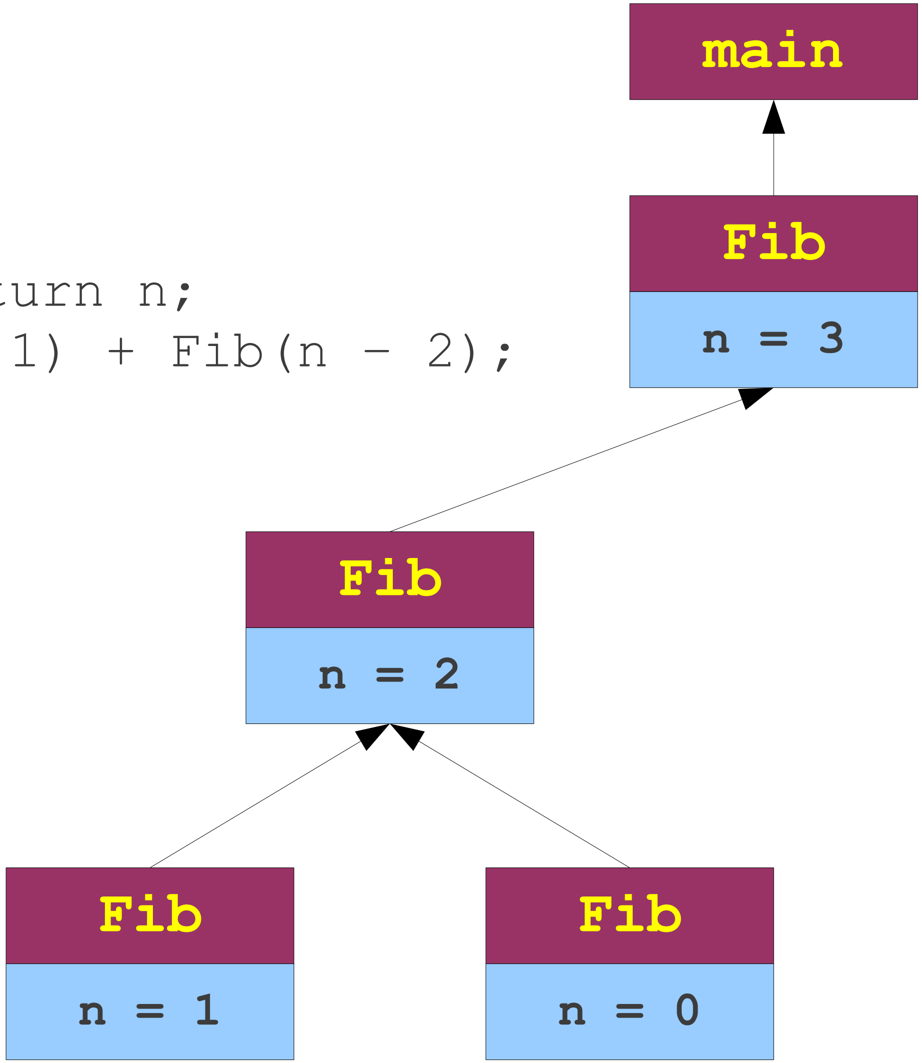

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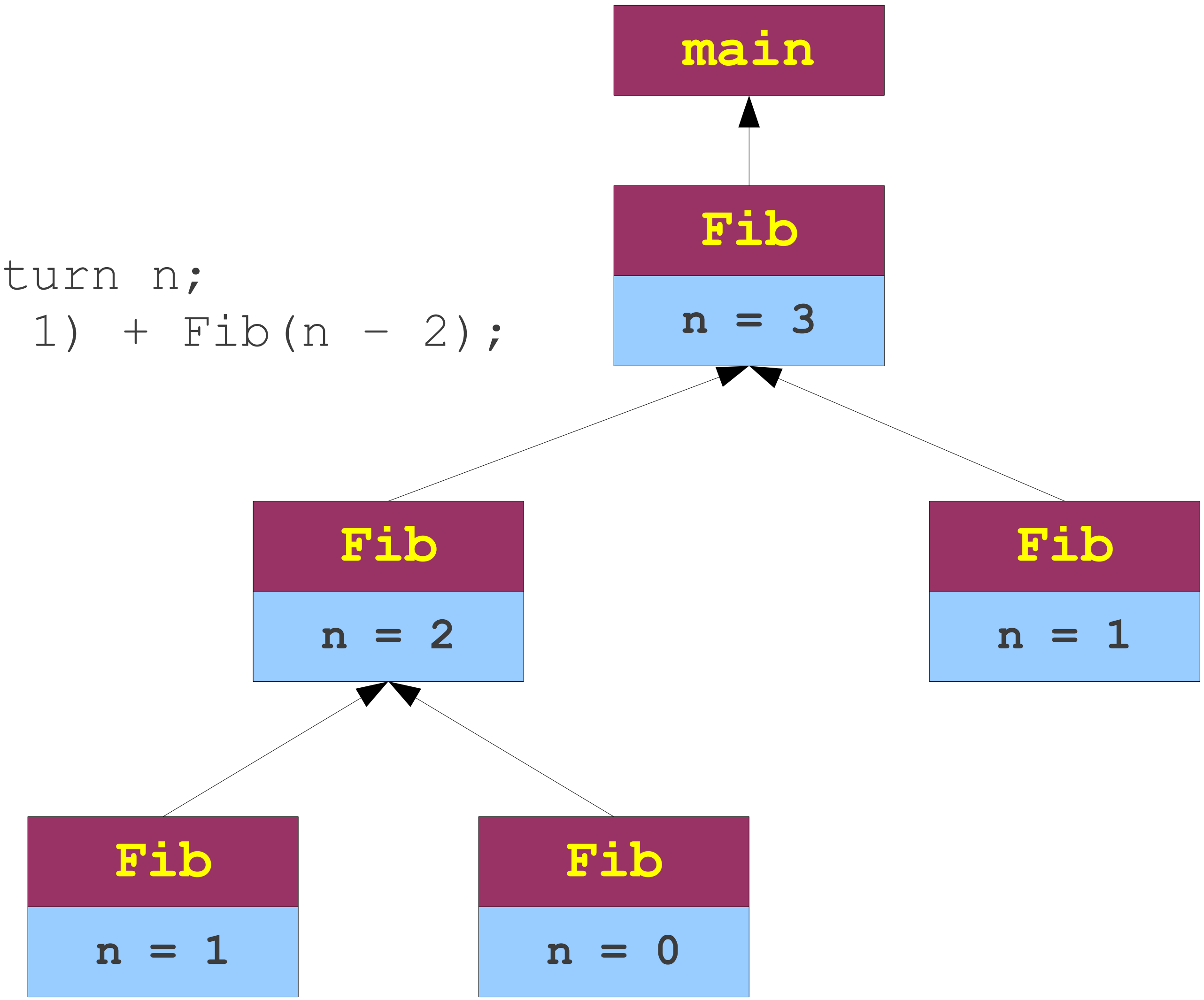

An activation tree is a **spaghetti stack**.

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

Why Can We Optimize the Stack?

- 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 always true!**

Breaking Assumption 1

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- Any ideas on how to break this?

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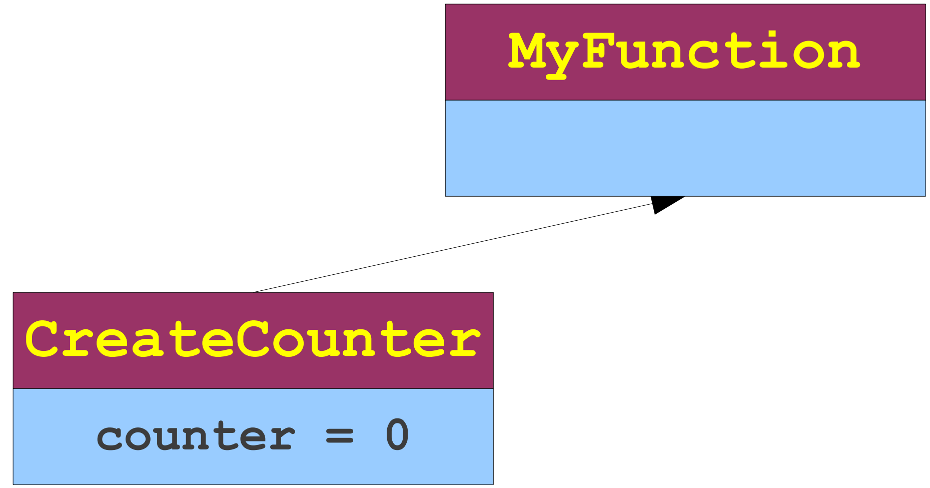


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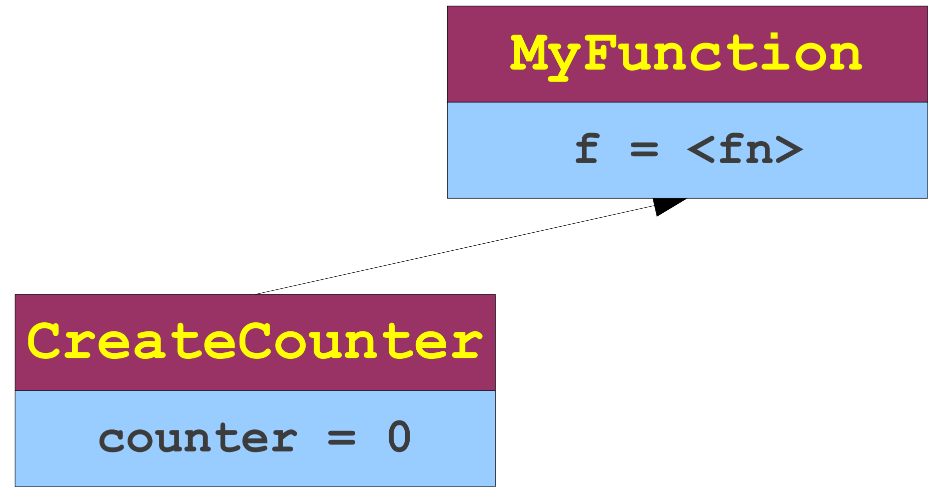


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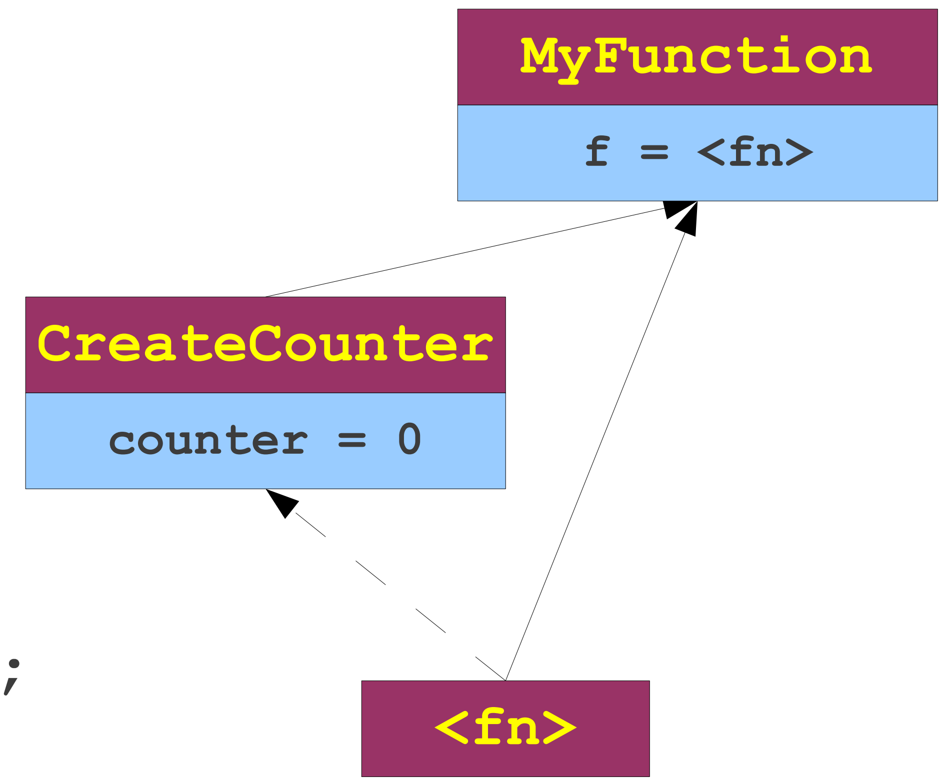


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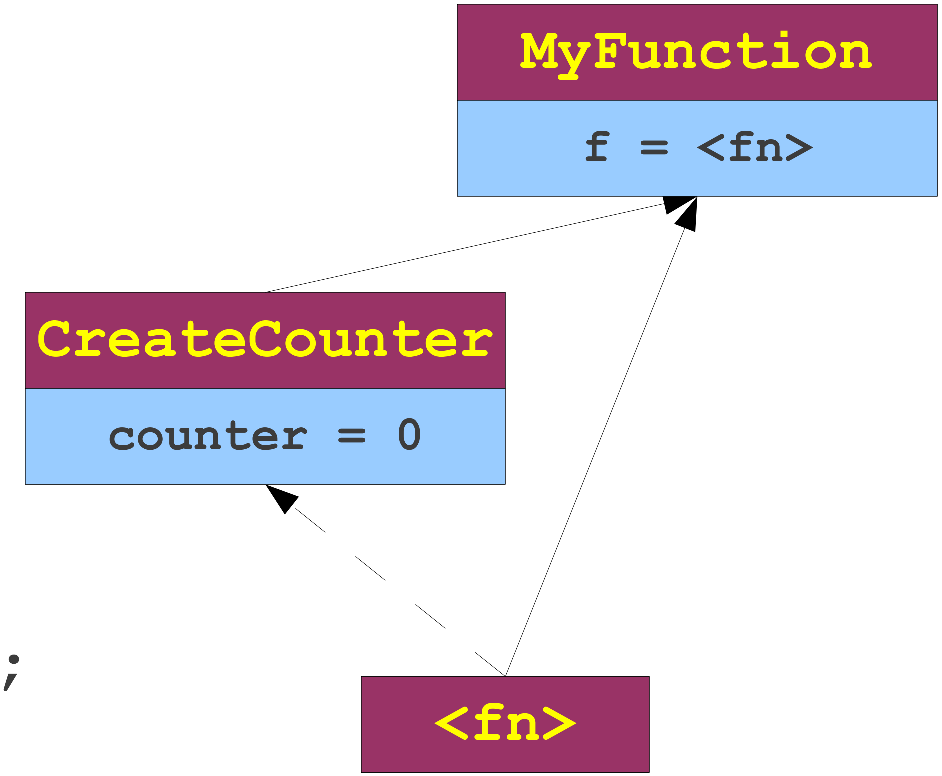


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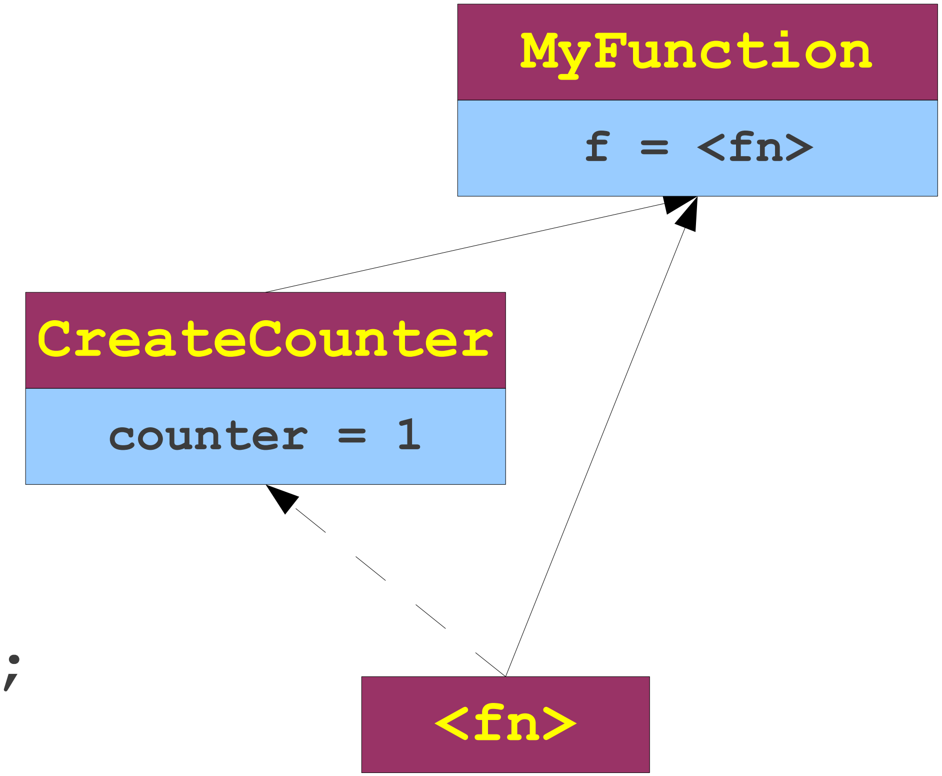


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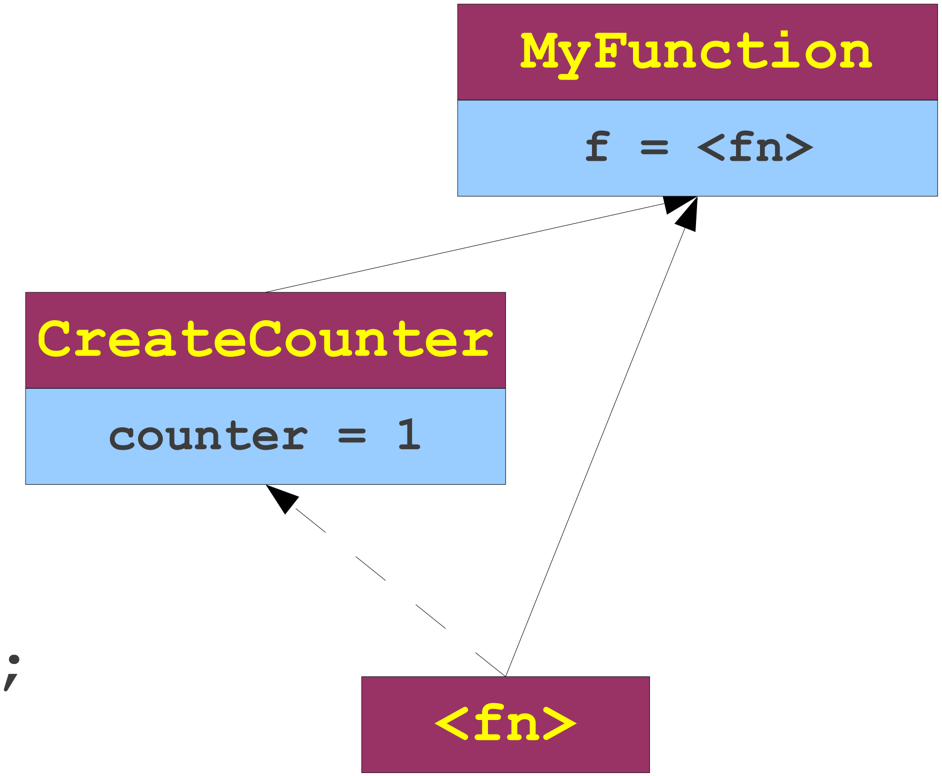


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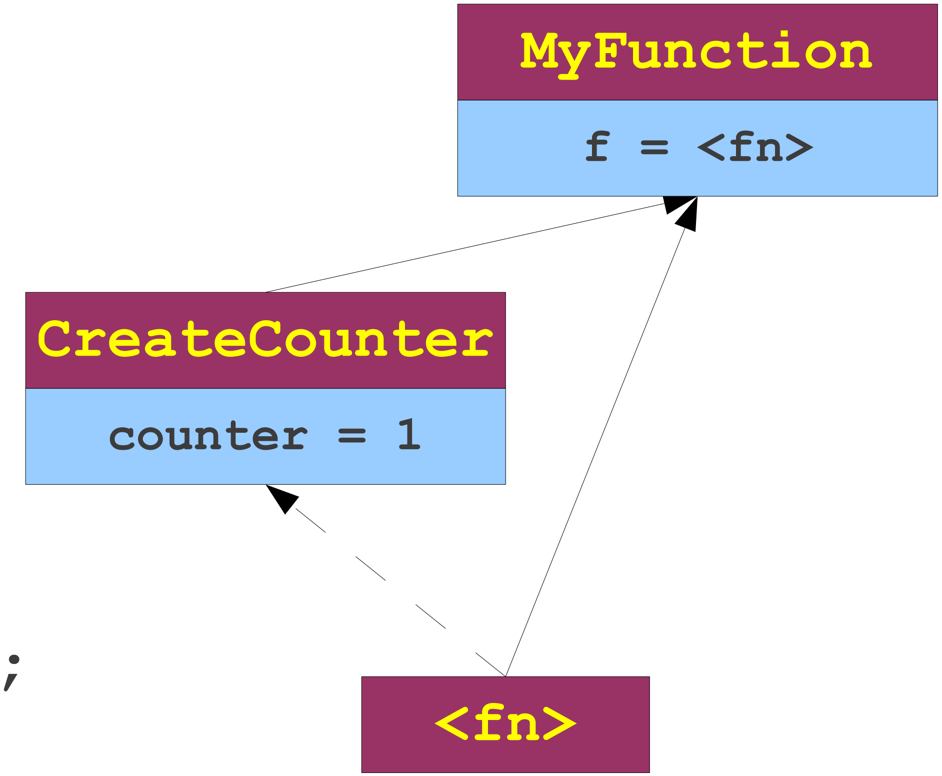


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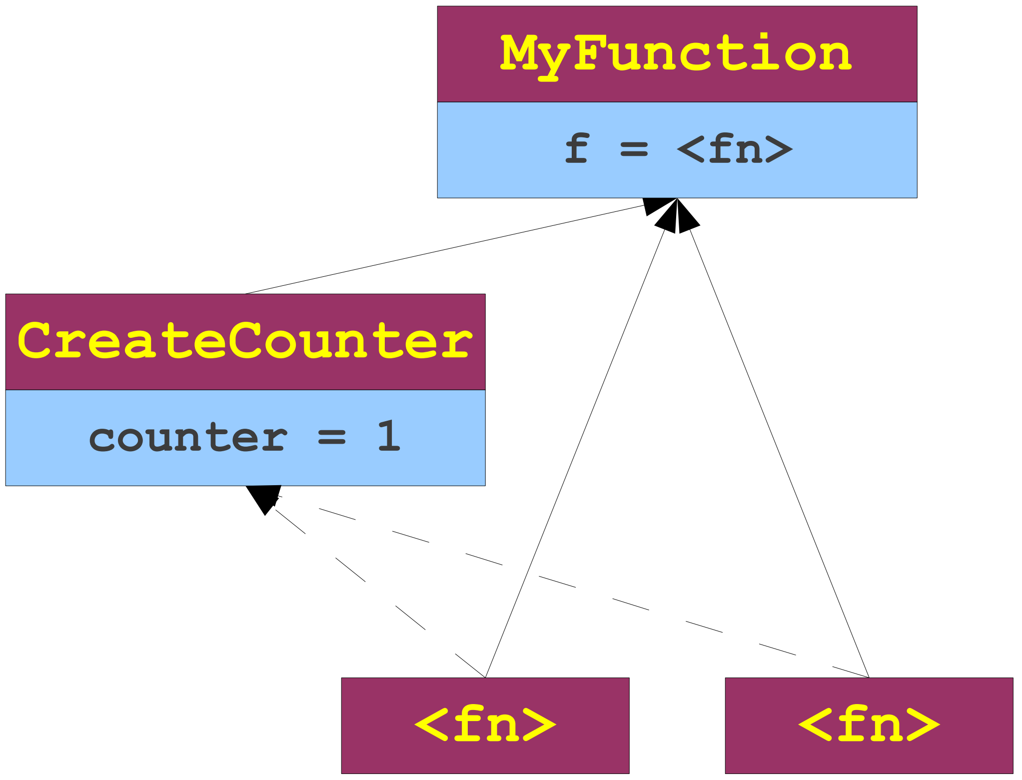


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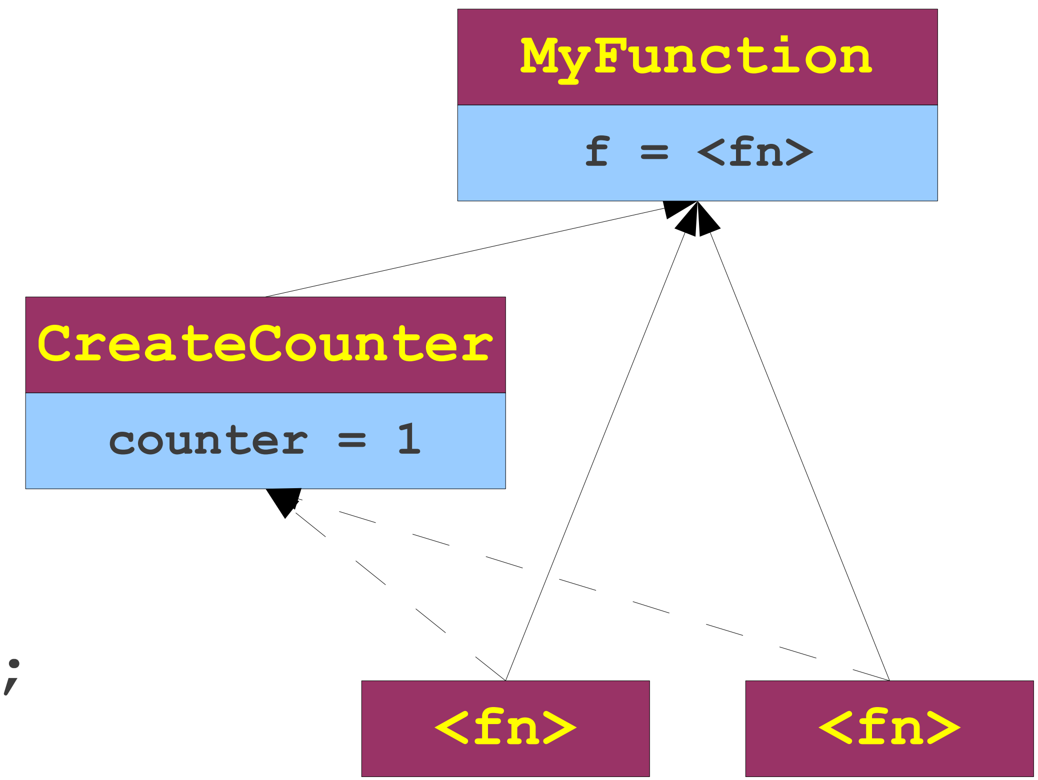


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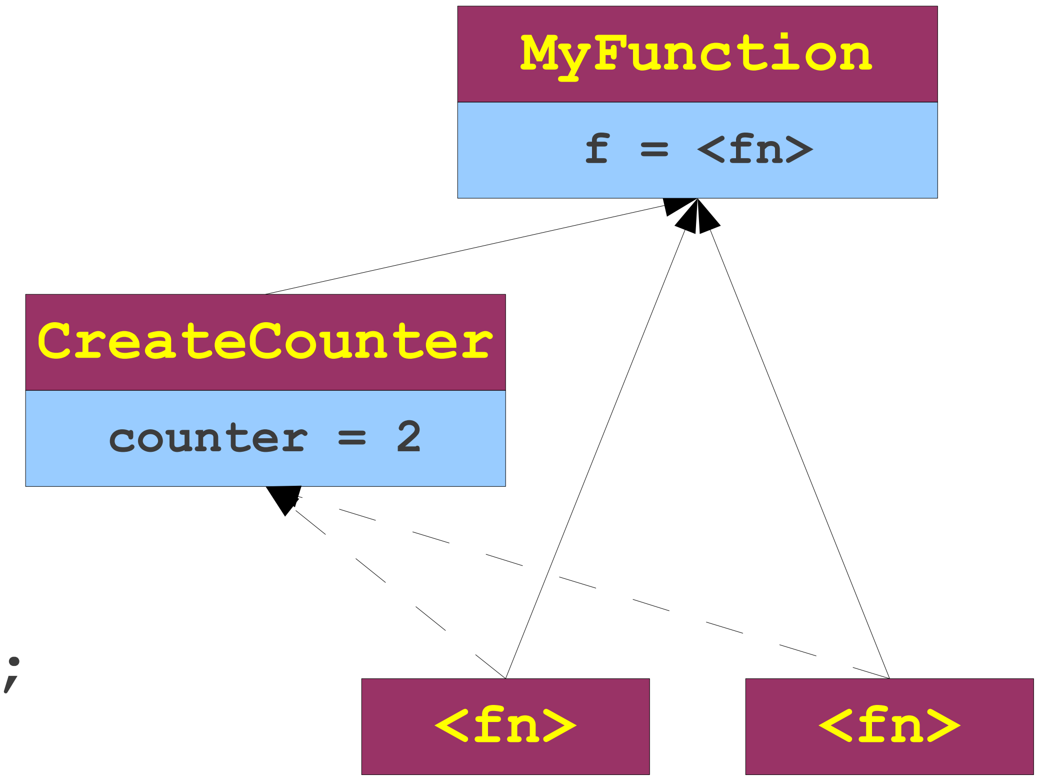

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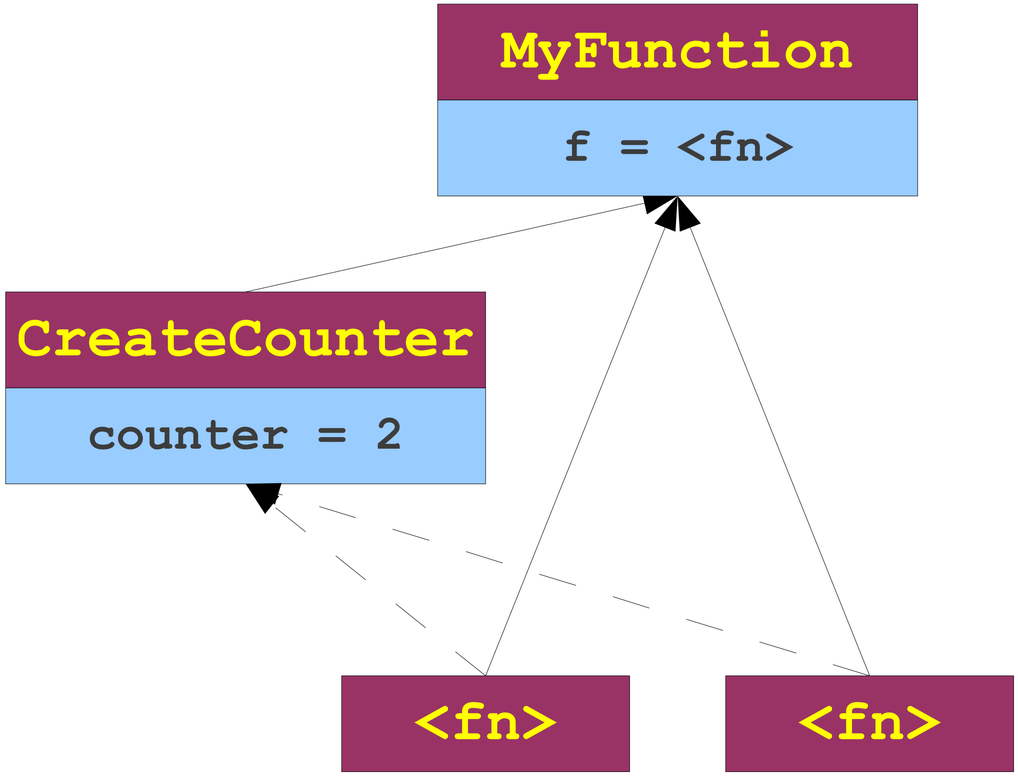
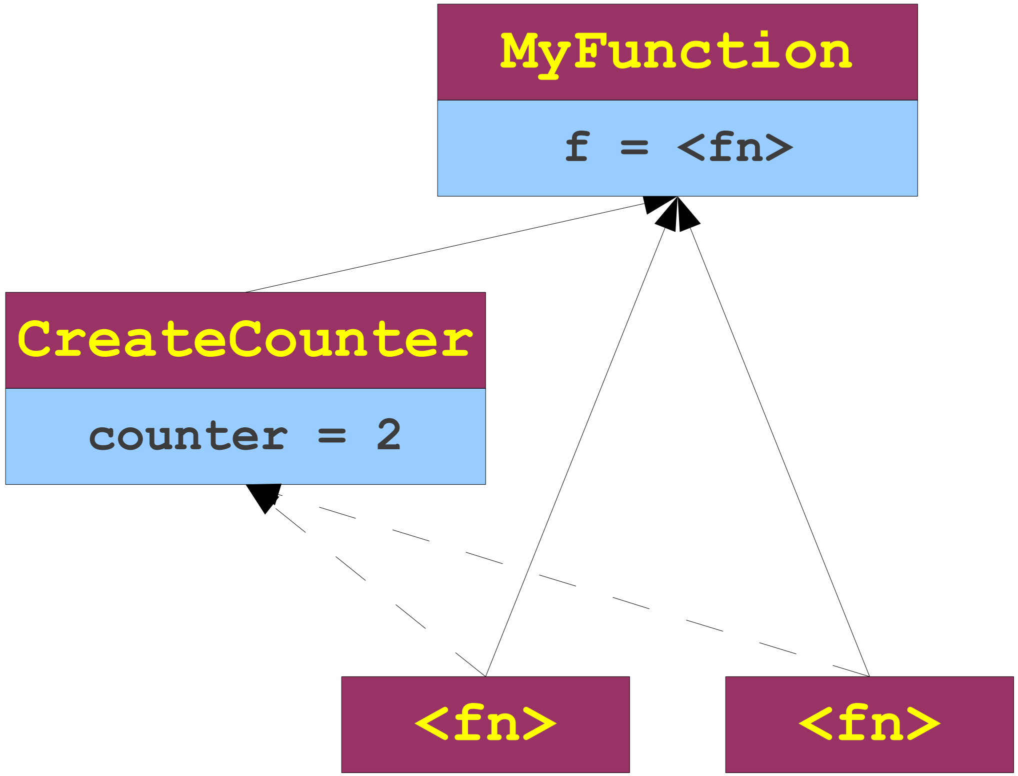



```
> 1
```

Closures

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

function MyFunction() {
    f = CreateCounter();
    print(f());
    print(f());
}
```




```
> 1
  2
```

Control and Access 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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Coroutines

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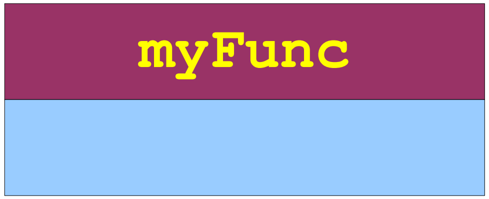


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```
>
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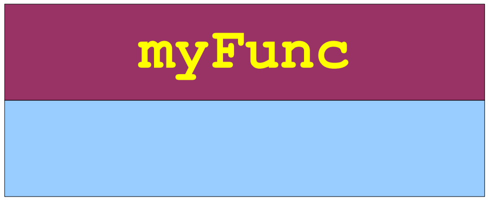


```
>
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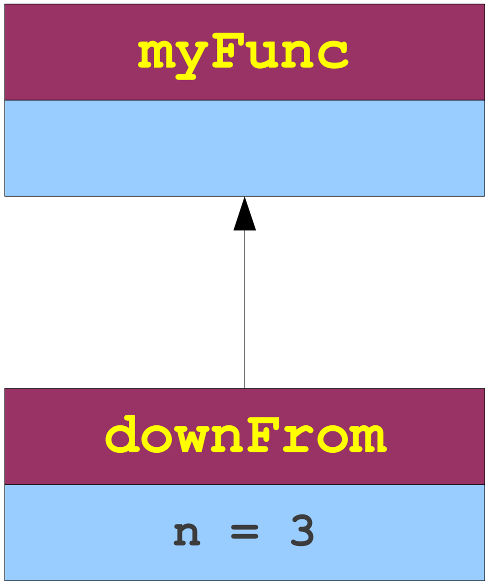


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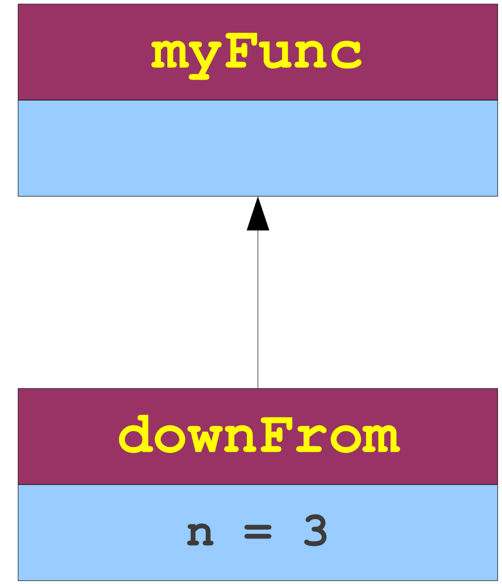


```
>
```

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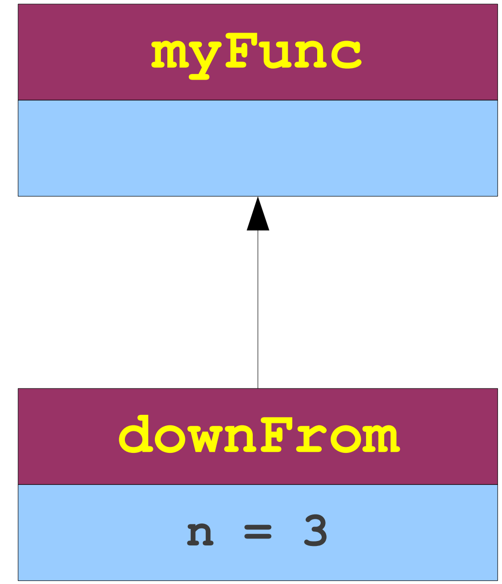


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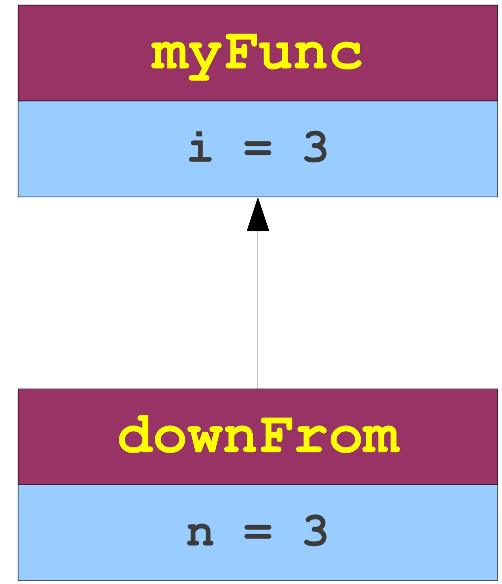


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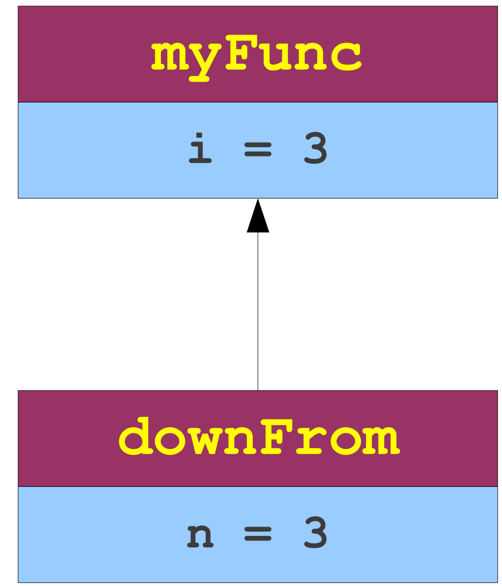


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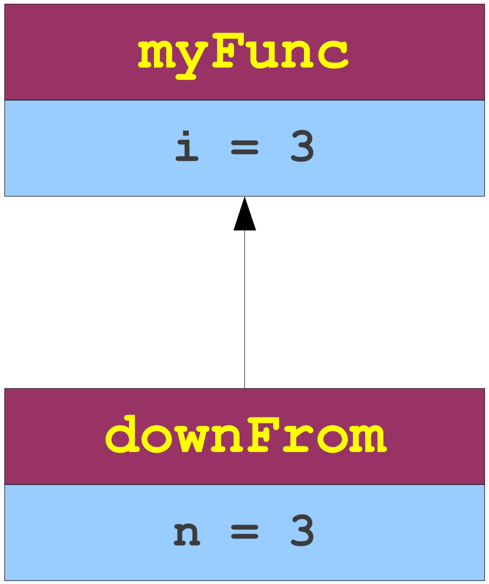


```
> 3
```

Coroutines

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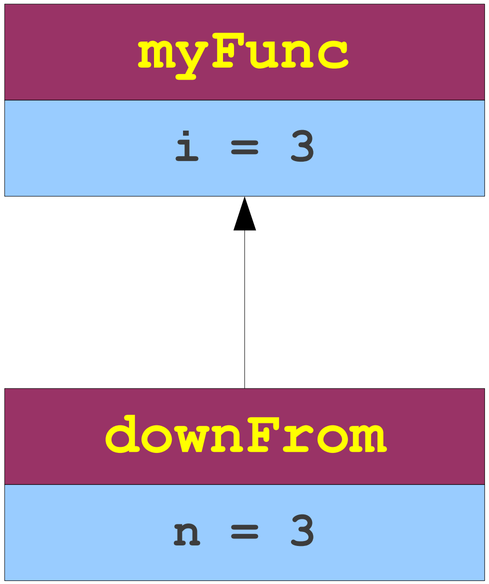
```

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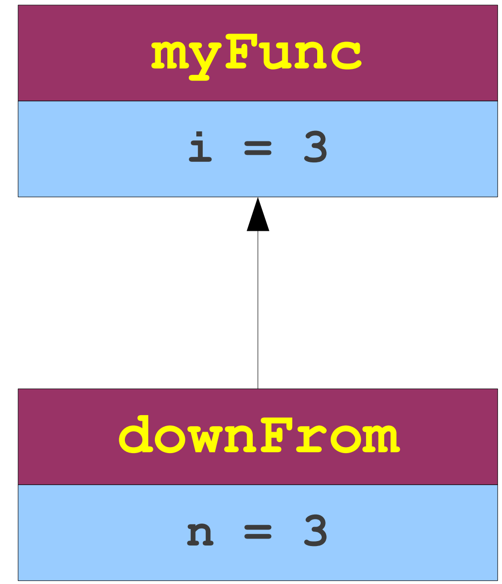


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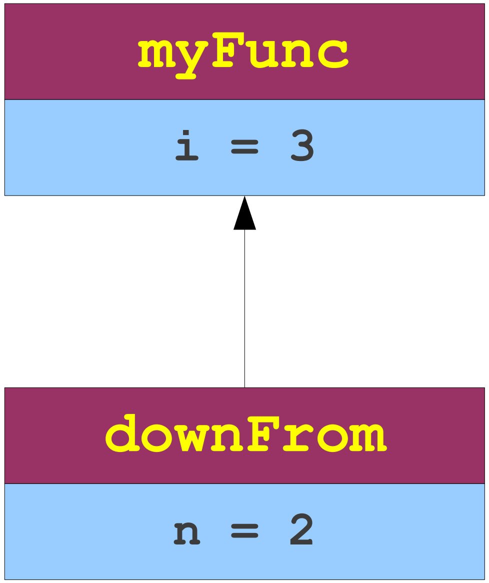

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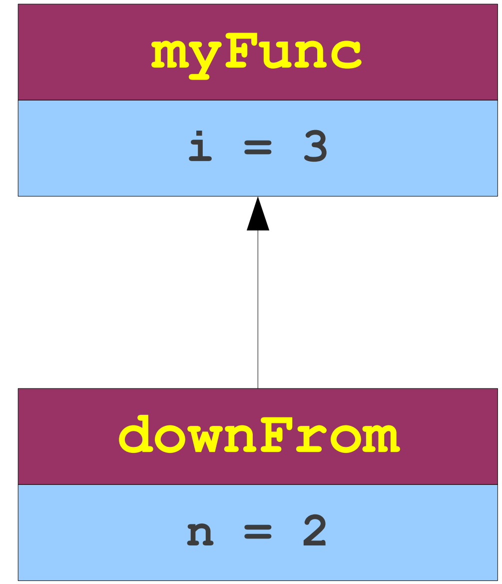


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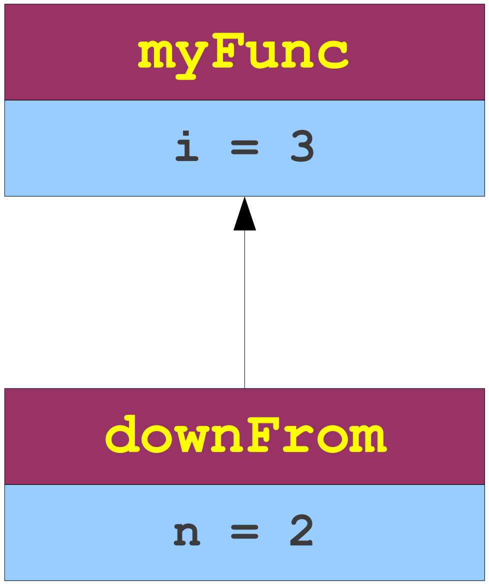


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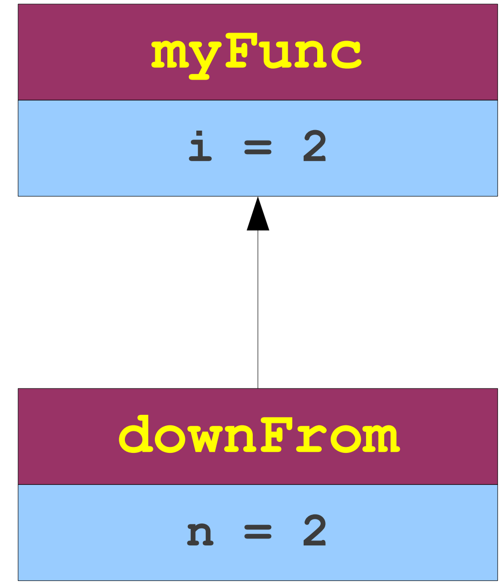


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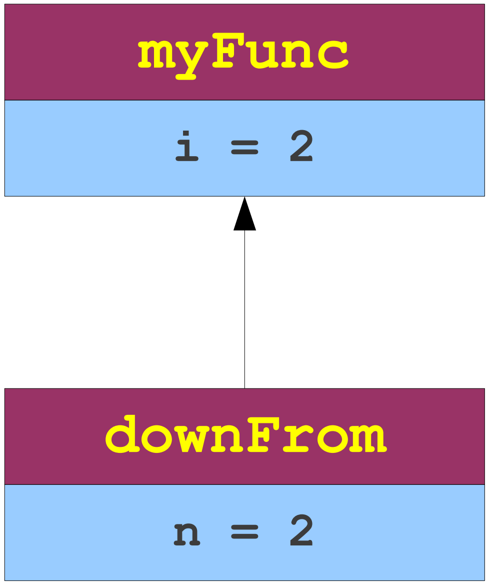


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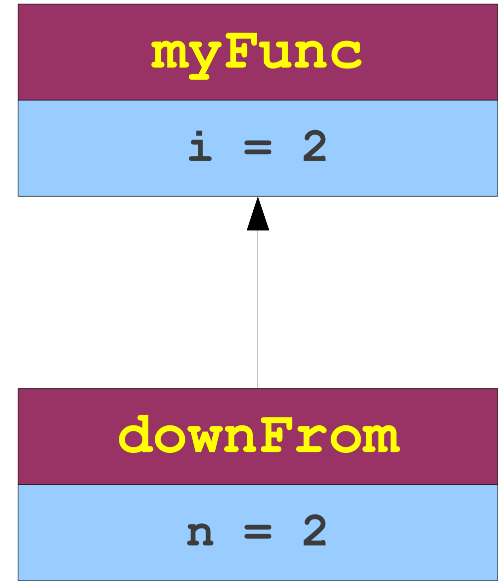


```
> 3
  2
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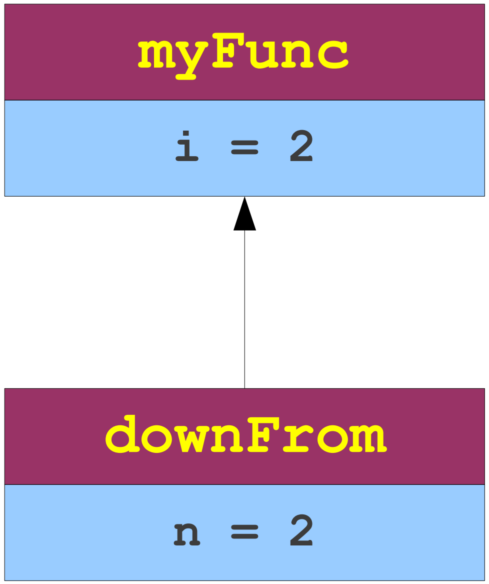


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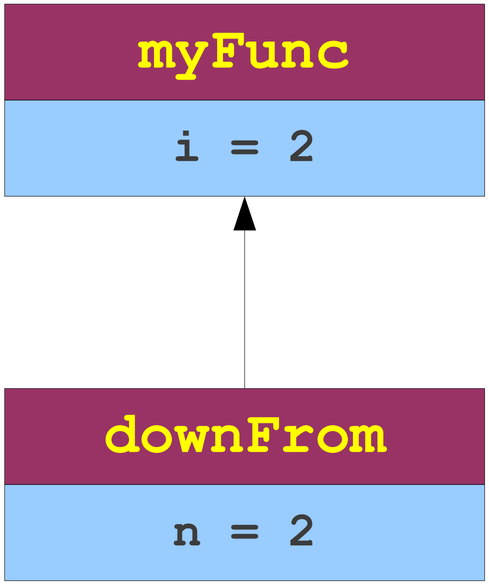


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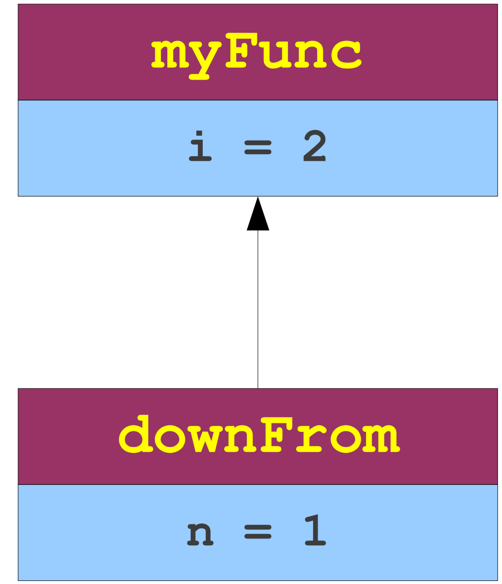


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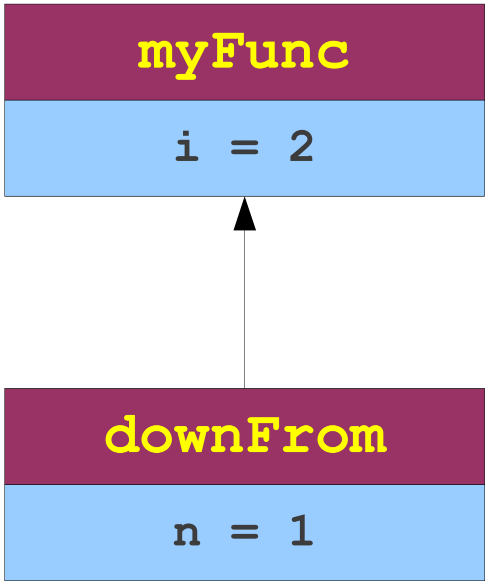


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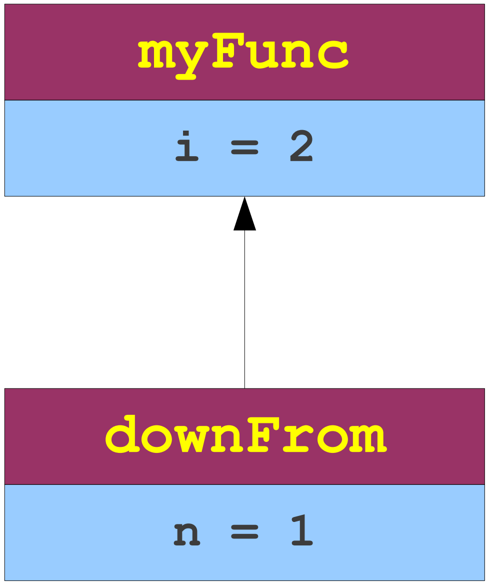


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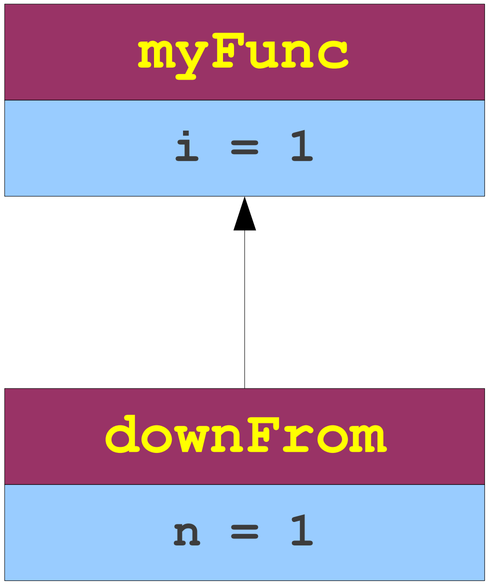


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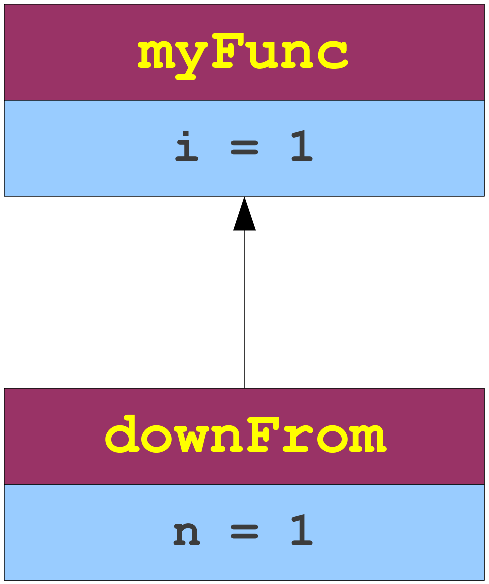


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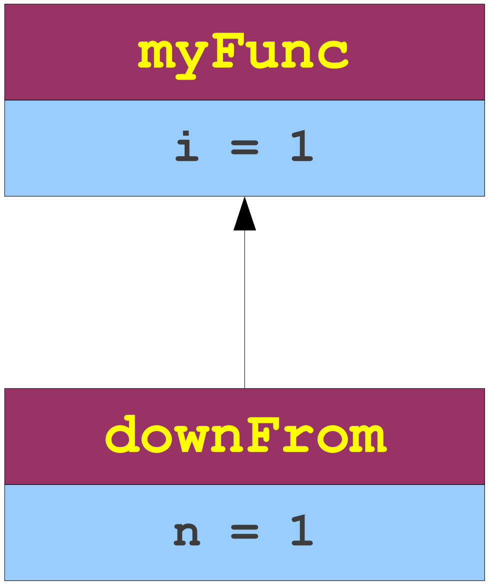


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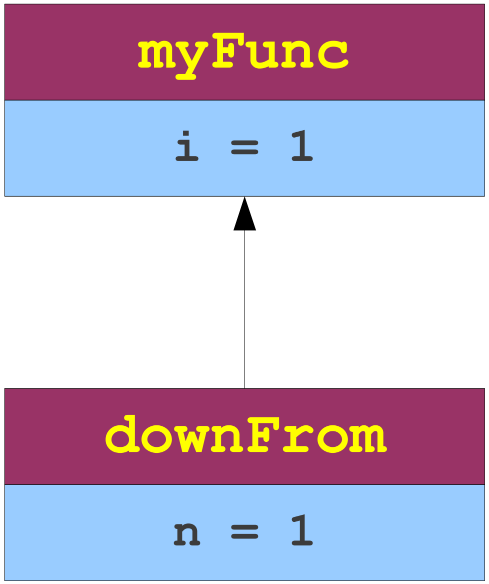


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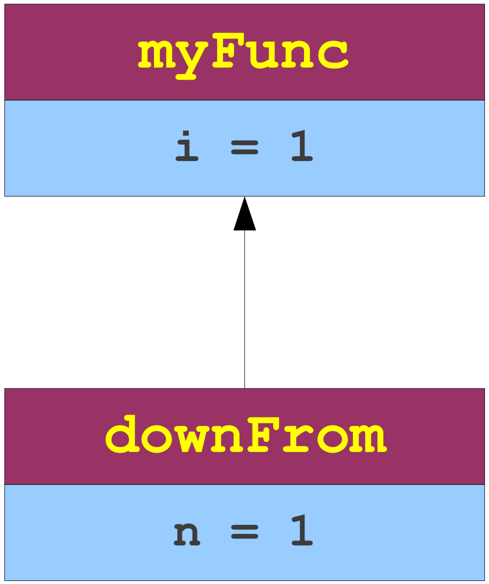


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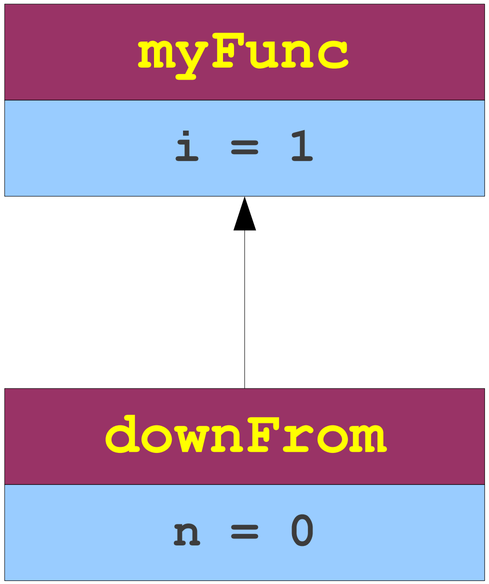


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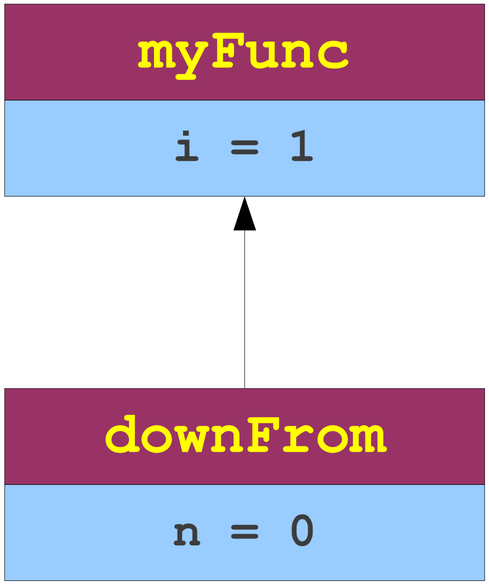


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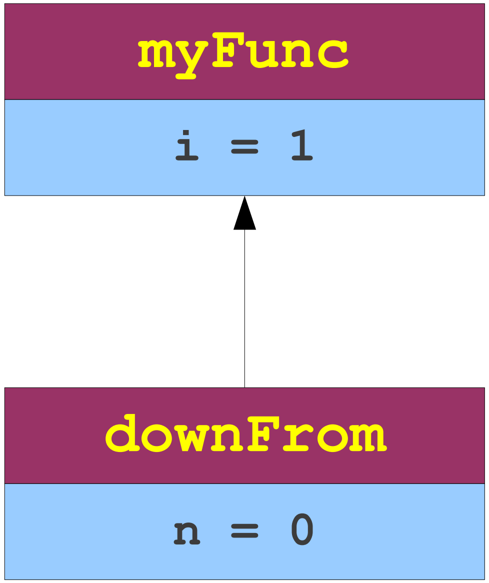



```
> 3
  2
  1
```

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!**

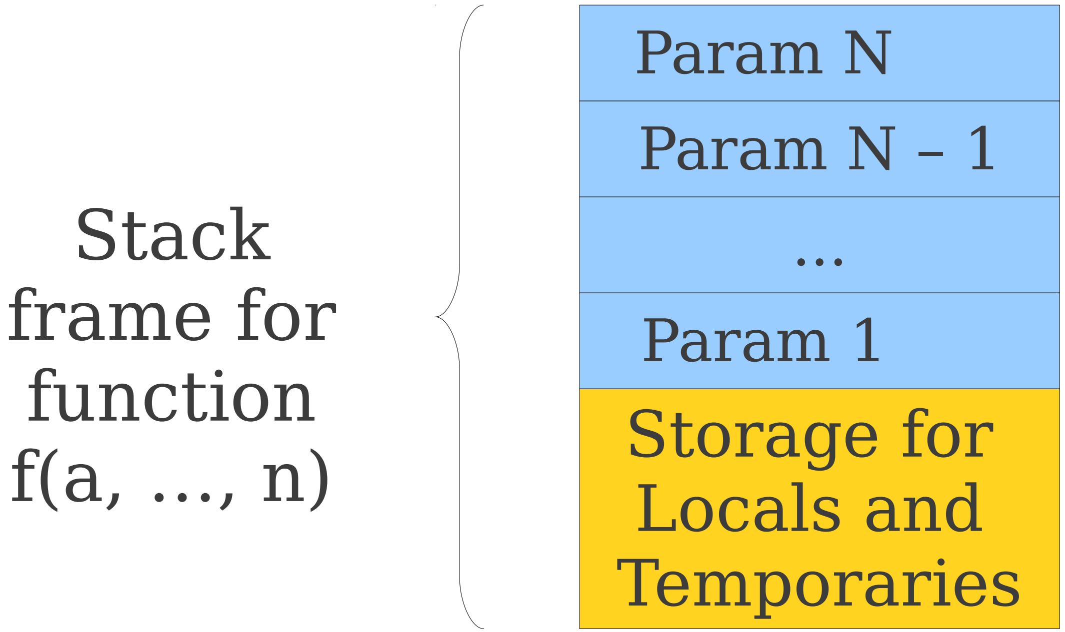
Functions in Decaf

- 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



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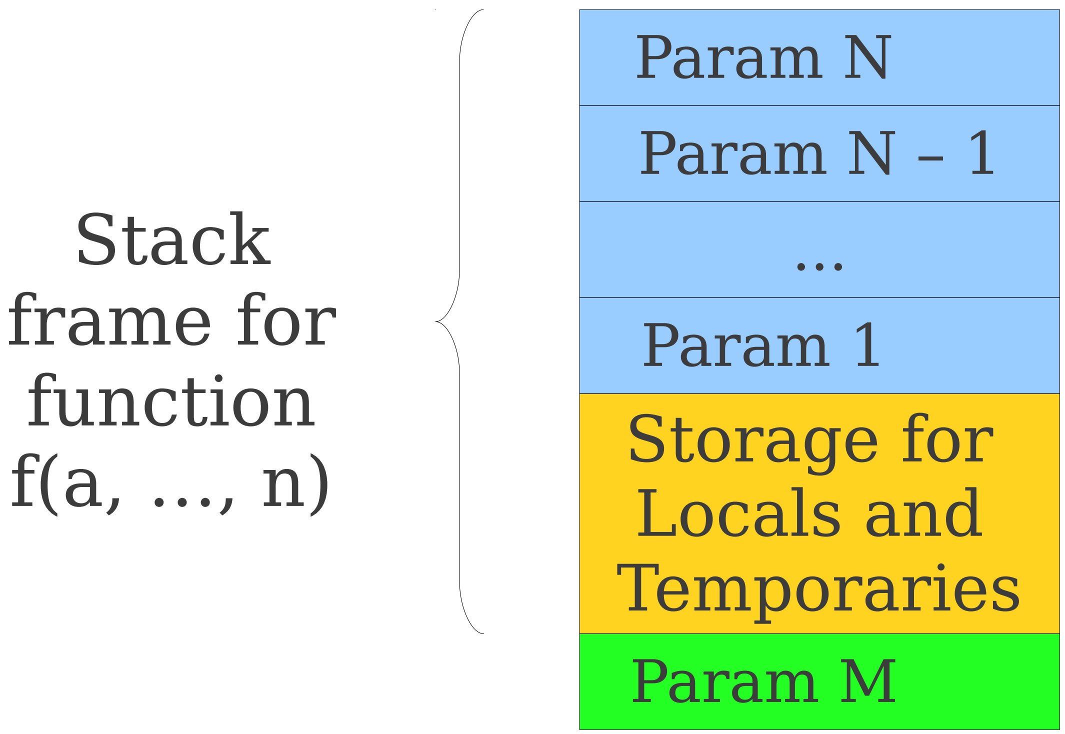
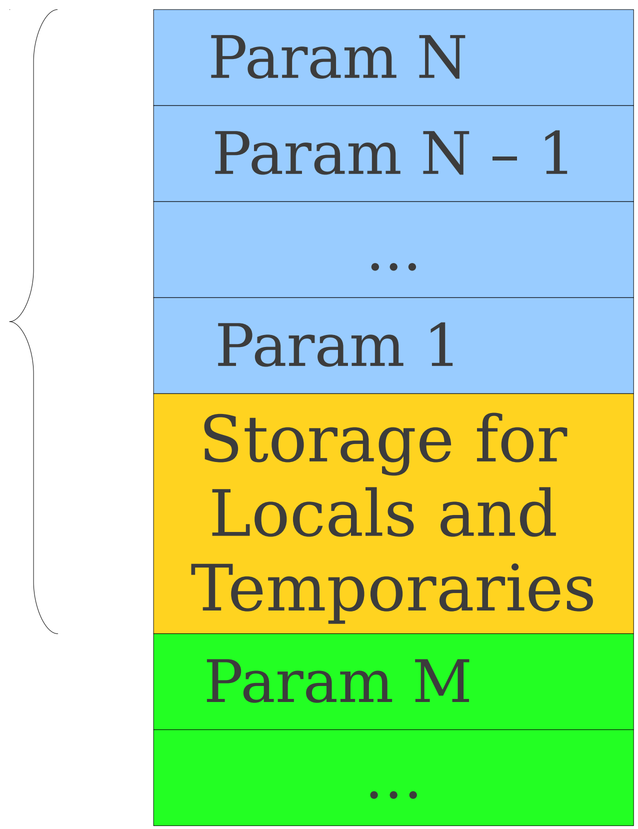


A Logical Decaf Stack Frame

Stack
frame for
function
f(a, …, n)



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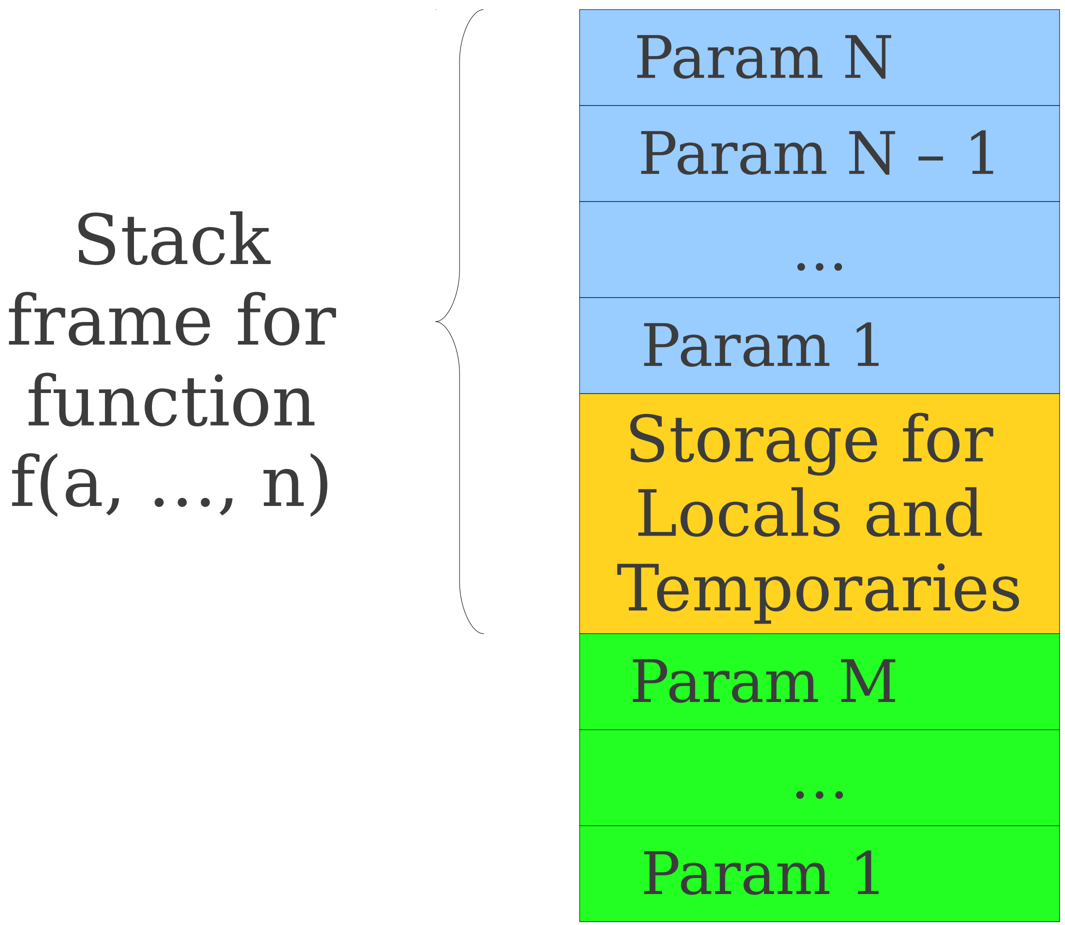

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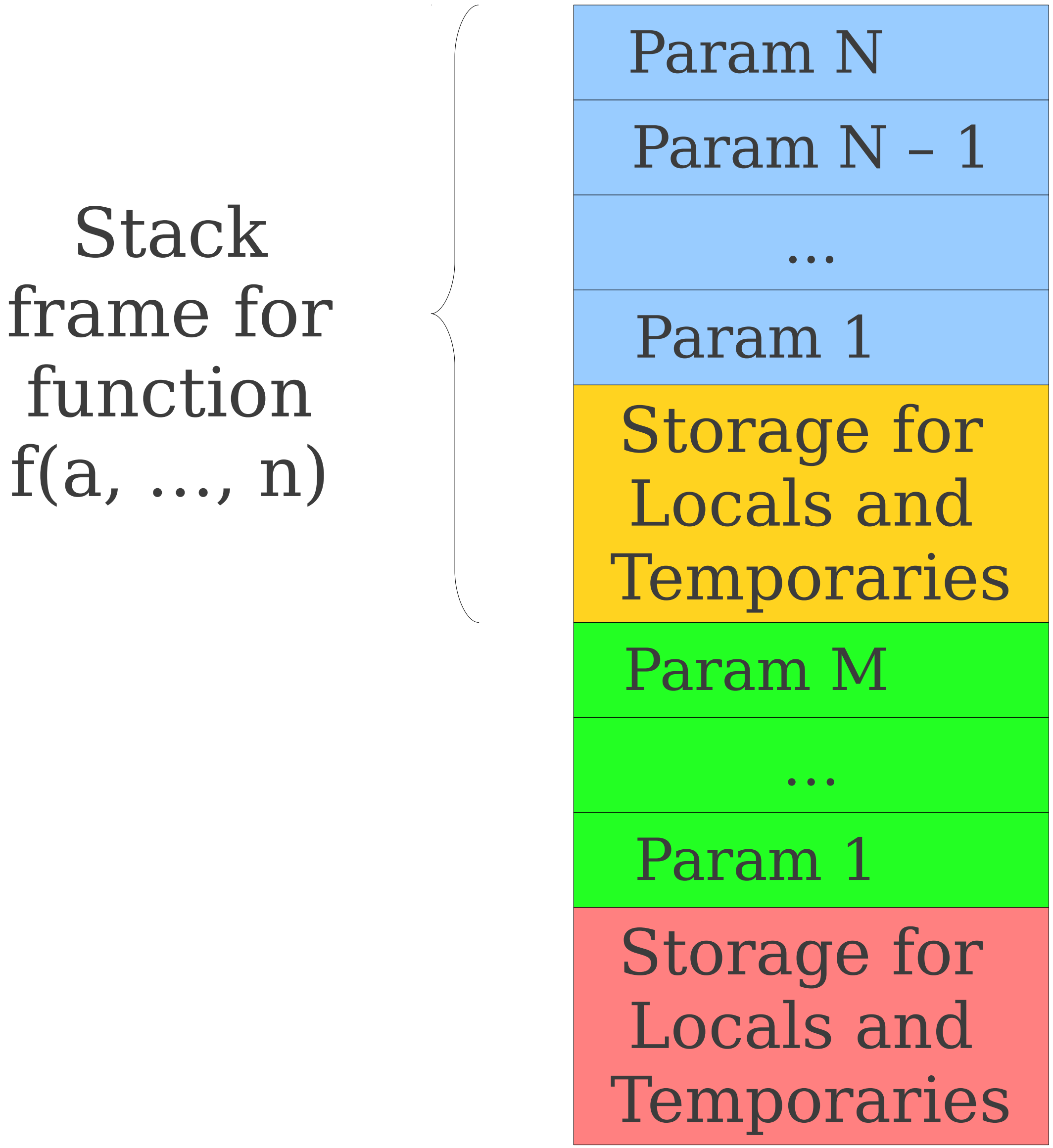

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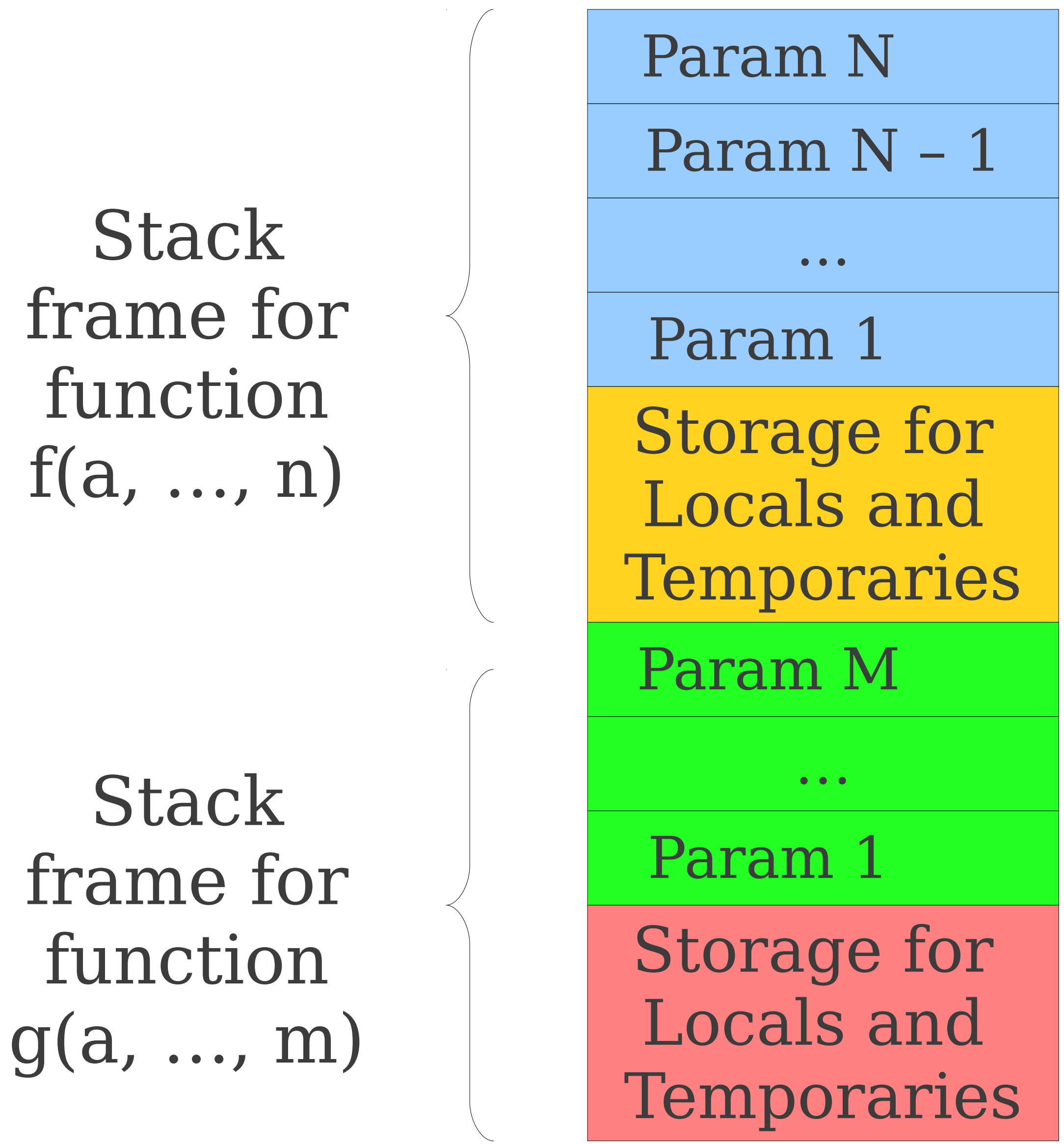

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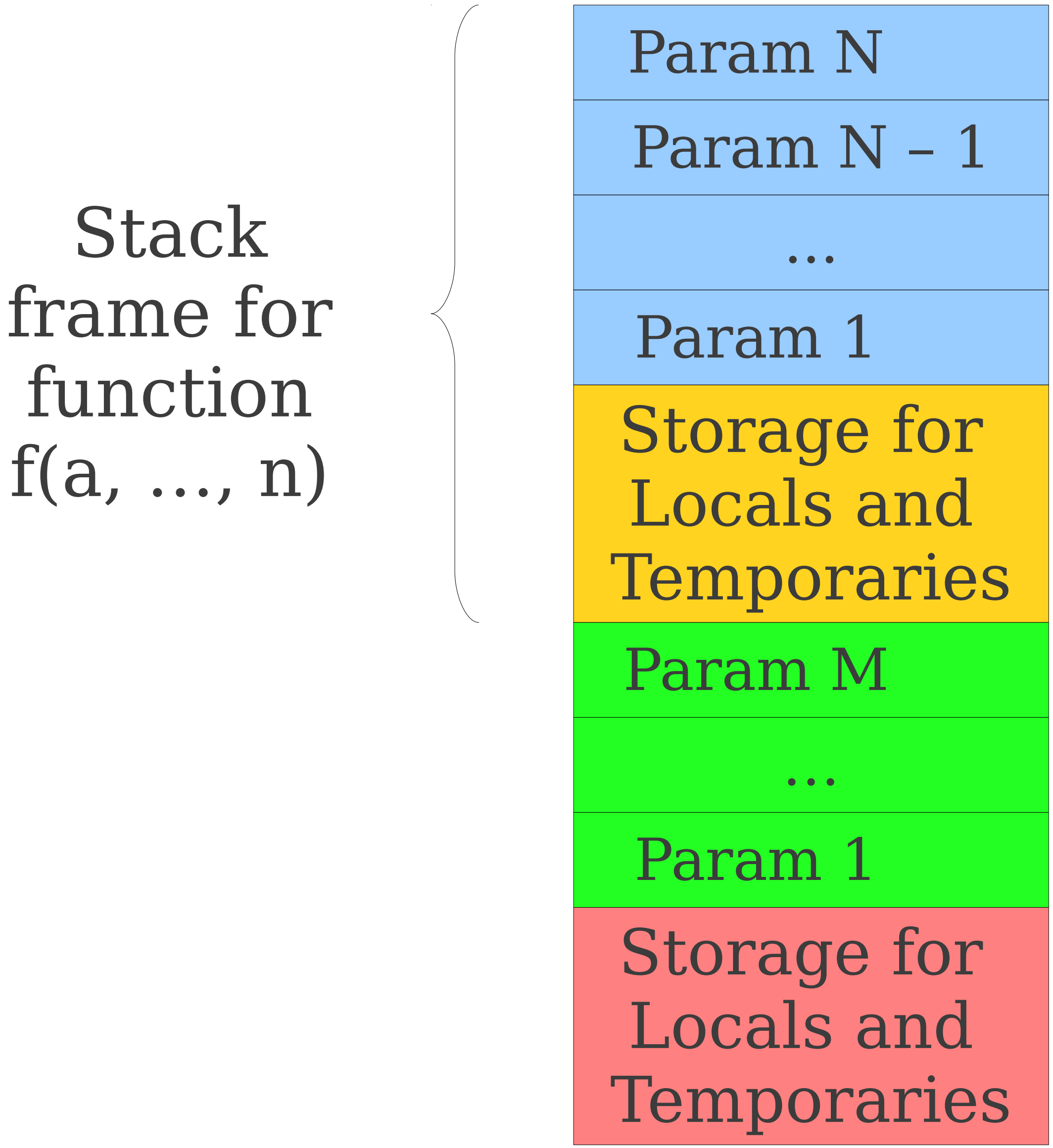

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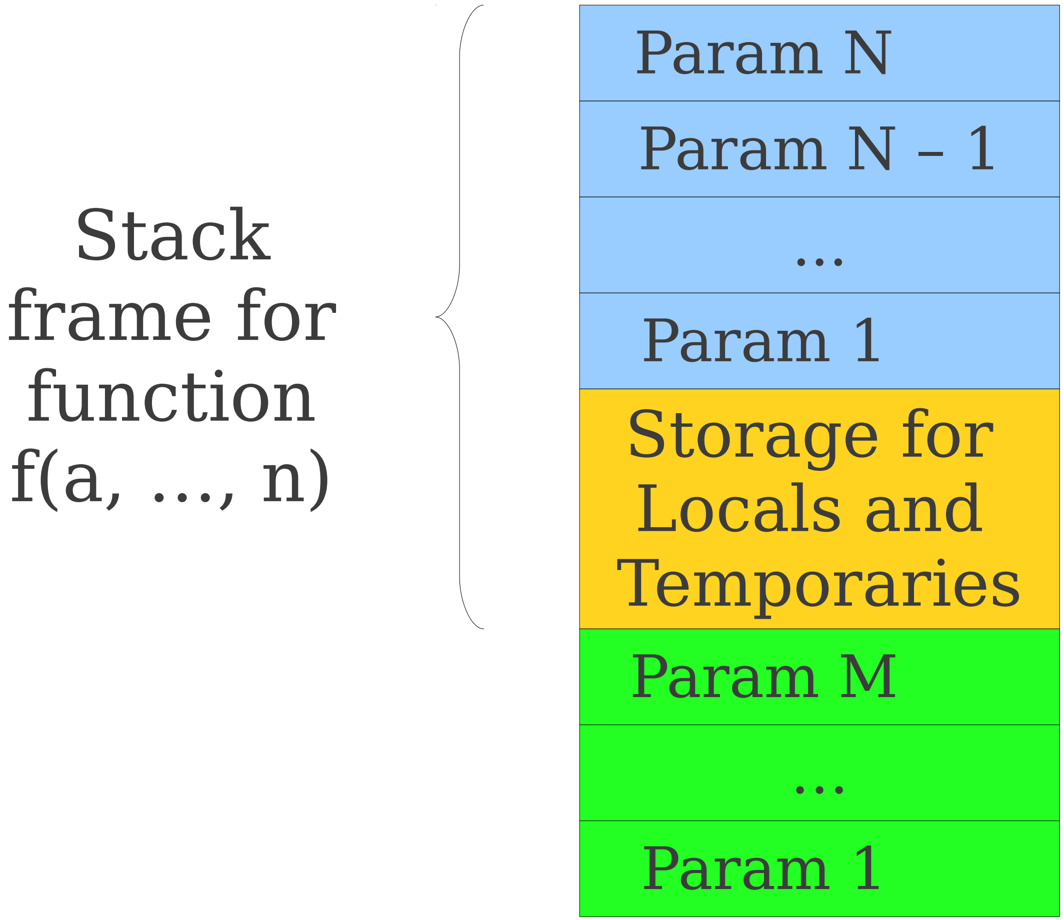

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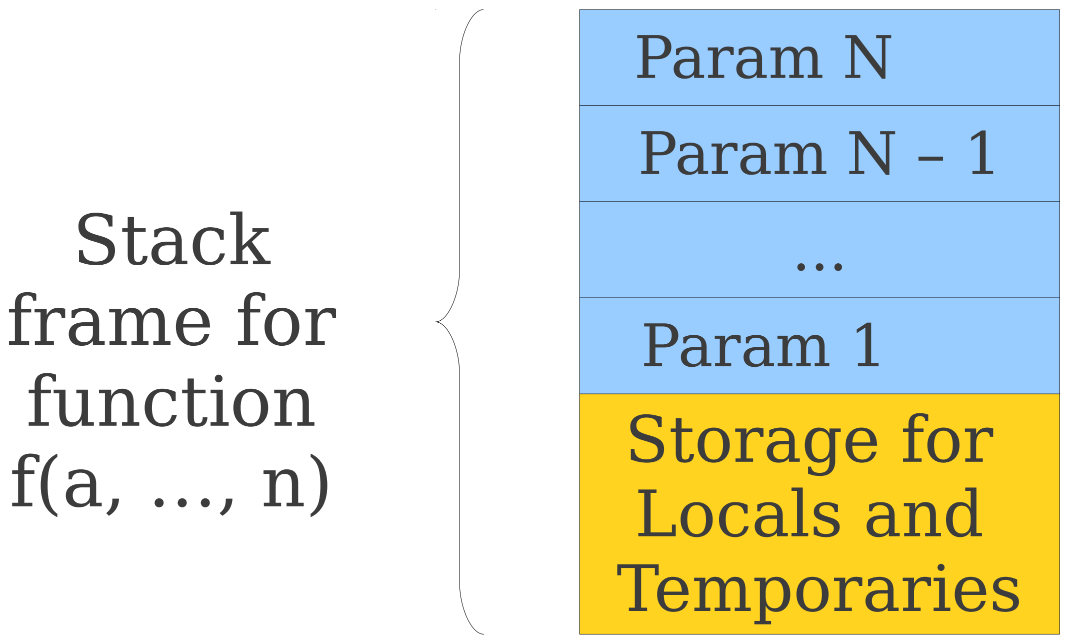

Decaf IR Calling Convention

- 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!

Next Time

- **Implementing Objects**
  - Standard object layouts.
  - Objects with inheritance.
  - Implementing dynamic dispatch.
  - Implementing interfaces.
  - … and doing so efficiently!