MIT 6.035

Unoptimized Code Generation

From the intermediate representation to the machine code

Outline

- Introduction
- Machine Language
- Overview of a modern processor
- Memory Layout
- Procedure Abstraction
- Procedure Linkage
- Guidelines in Creating a Code Generator

Anatomy of a compiler

Program (character stream)

Lexical Analyzer (Scanner)

Token Stream

Syntax Analyzer (Parser)

Parse Tree

Semantic Analyzer

Intermediate Representation

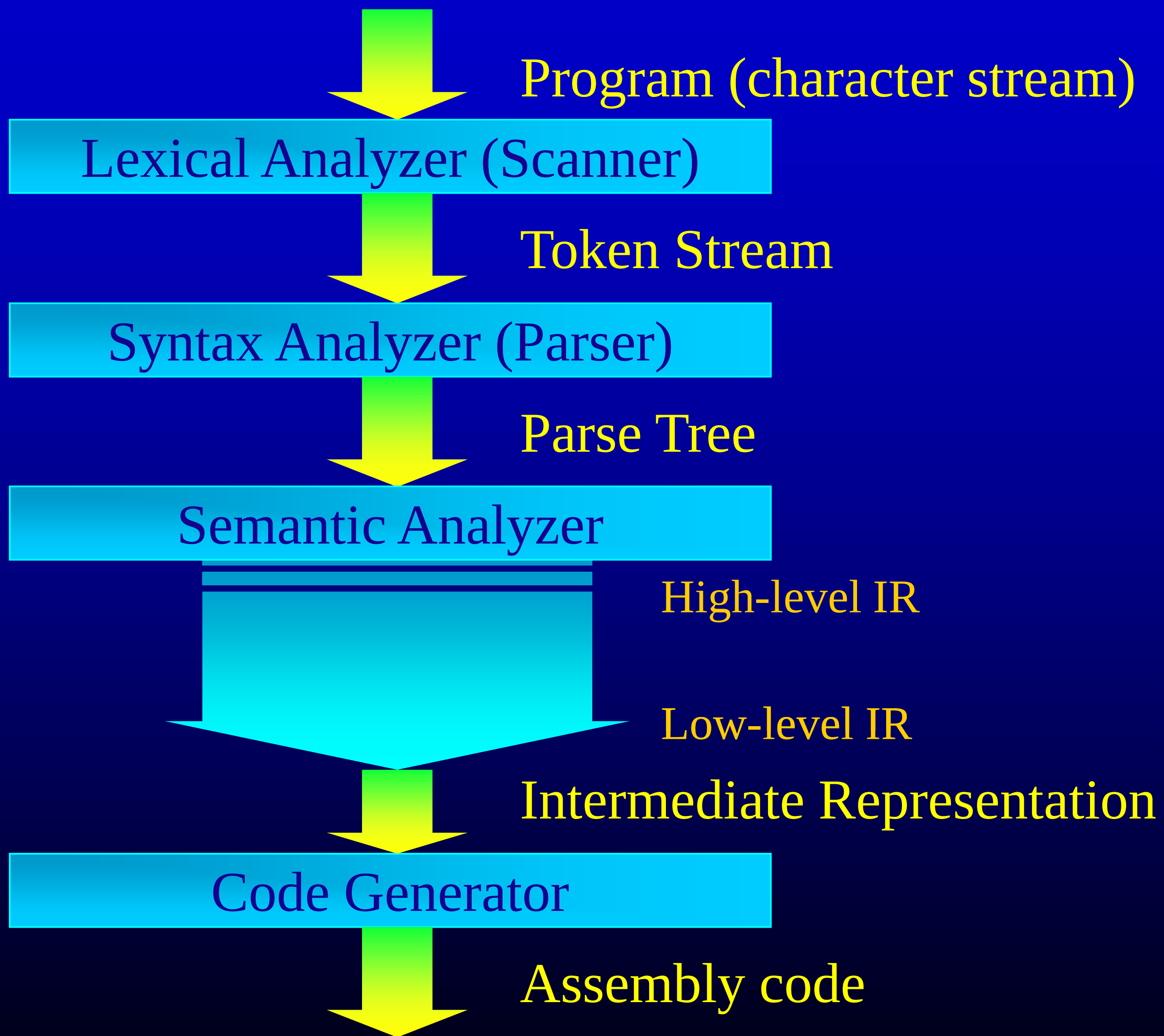
Intermediate Code Optimizer

Optimized Intermediate Representation

Code Generator

Assembly code

Anatomy of a compiler



Components of a High Level Language

CODE

- Procedures
- Control Flow
- Statements
- Data Access

DATA

- Global Static Variables
- Global Dynamic Data
- Local Variables
- Temporaries
- Parameter Passing
- Read-only Data

Machine Code Generator Should...

- Translate all the instructions in the intermediate representation to assembly language
- Allocate space for the variables, arrays etc.
- Adhere to calling conventions
- Create the necessary symbolic information

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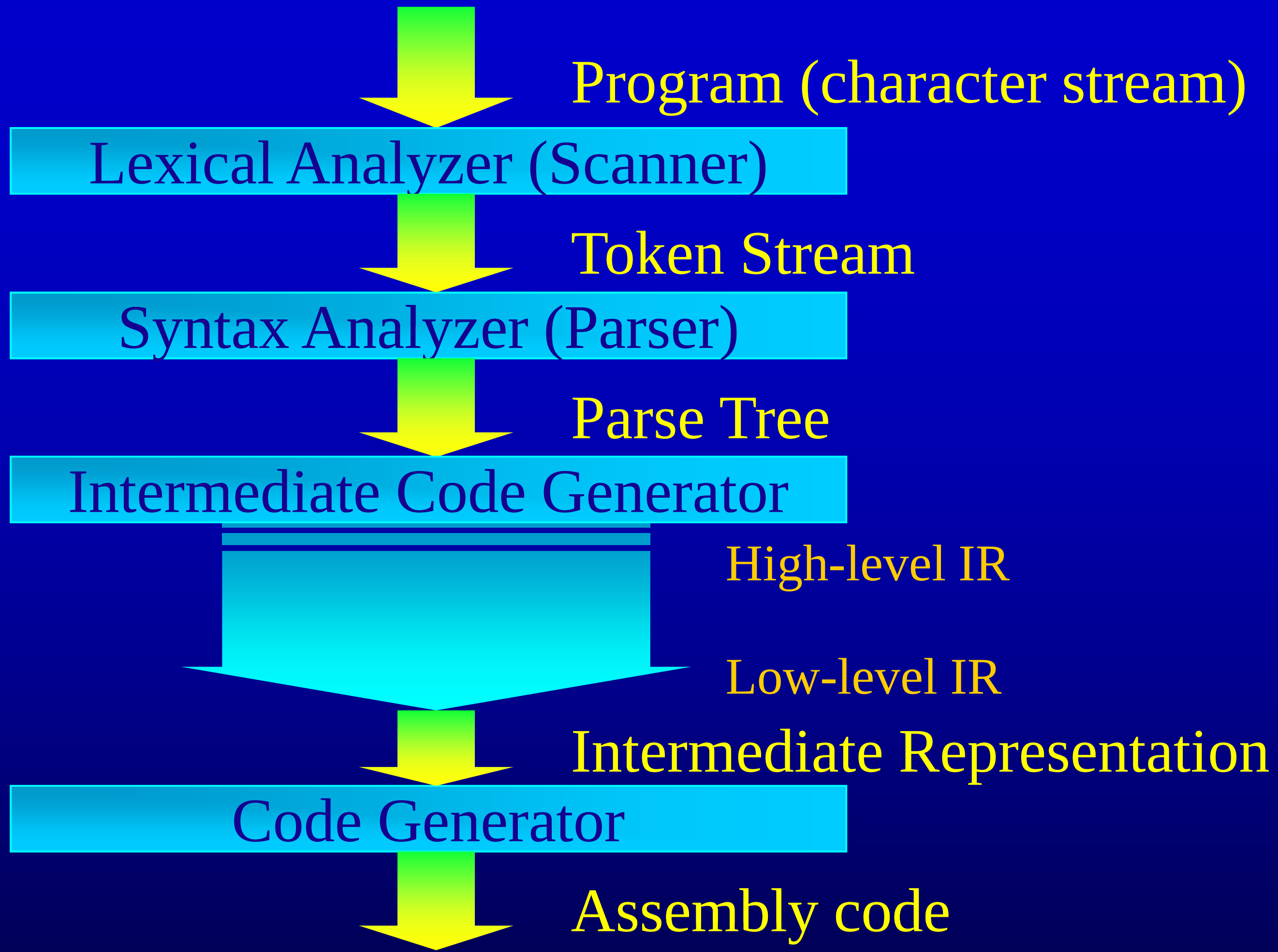
Machines understand...

LOCATION	DATA
0046	8B45FC
0049	4863F0
004c	8B45FC
004f	4863D0
0052	8B45FC
0055	4898
0057	8B048500
	000000
005e	8B149500
	000000
0065	01C2
0067	8B45FC
006a	4898
006c	89D7
006e	033C8500
	000000
0075	8B45FC
0078	4863C8
007b	8B45F8
007e	4898
0080	8B148500
	000000

Machines understand...

LOCATION	DATA	ASSEMBLY INSTRUCTION
0046	8B45FC	-4(%rbp), %eax
0049	4863F0	%eax,%rsi
004c	8B45FC	-4(%rbp), %eax
004f	4863D0	%eax,%rdx
0052	8B45FC	movl -4(%rbp), %eax
0055	4898	
0057	8B048500 000000	B(,%rax,4), %eax
005e	8B149500 000000	A(,%rdx,4), %edx
0065	01C2	%eax, %edx
0067	8B45FC	-4(%rbp), %eax
006a	4898	
006c	89D7	addl , %edi
006e	033C8500 000000	C(,%rax,4), %edi
0075	8B45FC	-4(%rbp), %eax
0078	4863C8	%eax,%rcx
007b	8B45F8	movl 8(%rbp), %eax
007e	4898	
0080	8B148500	B(,%rax,4), %edx

movl
movslq


Program (character stream)
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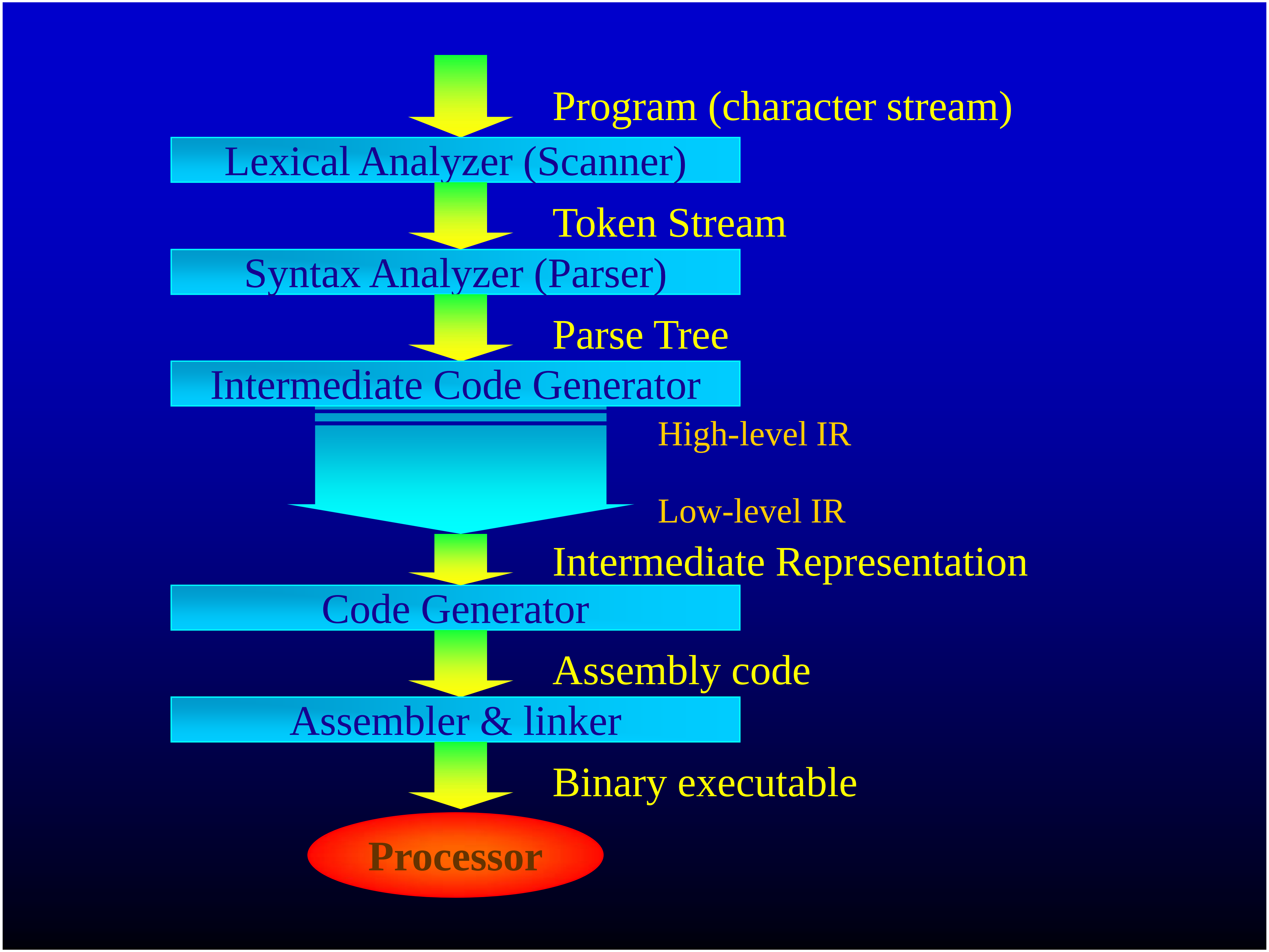
Parse Tree
Intermediate Code Generator
High-level IR
Low-level IR
Intermediate Representation
Code Generator
Assembly code


Program (character stream)
Lexical Analyzer (Scanner)
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Intermediate Code Generator
High-level IR
Low-level IR
Intermediate Representation
Code Generator
Assembly code
Assembler & linker
Binary executable
Processor

Assembly language

- Advantages
  - Simplifies code generation due to use of symbolic instructions and symbolic names

    Logical abstraction layer
  - Multiple Architectures can describe by a single assembly language

    $\Rightarrow$ can modify the implementation
    - macro assembly instructions
- Disadvantages
  - Additional process of assembling and linking
  - Assembler adds overhead

Assembly language

- Relocatable machine language (object modules)
  - all locations(addresses) represented by symbols
  - Mapped to memory addresses at link and load time
  - Flexibility of separate compilation
- Absolute machine language
  - addresses are hard-coded
  - simple and straightforward implementation

    inflexible -- hard to reload generated code
  - Used in interrupt handlers and device drivers

Assembly example

```
                          .section
                 .LC0:
0000 6572726F7200            .string "error"
                          .text
                 .globl fact
                  fact:
0000 55                   pushq   %rbp
0001 4889E5                       %rsp, %rbp
0004 4883EC10                     $16, %rsp
0008 897DFC                       %edi, -4(%rbp)
000b 837DFC00
000f 7911
0011 BF00000000           movl $0, -4(%rbp)
                                  $.LC0, %edi
0016 B800000000
001b E800000000
0020 EB22                      $0, %eax
                 .L2:          printf
0022 837DFC00
0026 7509                 jne .L3   L4
0028 C745F801000000
002f EB13                      .
                 .L4:          $1, -8(%rbp)
0031 8B7DFC                       -4(%rbp), %edi
0034 FFCF                     .L3
0036 E800000000   movl          ll    fact
003b 0FAF45FC                     -4(%rbp), %eax
003f 8945F8                       %eax, -8(%rbp)
0042 EB00
                 .L3:
0044 8B45F8                       -8(%rbp), %eax
0047 C9
0048 C3
```

movl

Composition of an Object File

- We use the ELF file format

- The object file has:
  - Multiple Segments
  - Symbol Information
  - Relocation Information

- Segments
  - Global Offset Table
  - Procedure Linkage Table
  - Text (code)
  - Data
  - Read Only Data

```
 .file
       "test2"
        .section
.LC0:
        .string "error %d"

        .section    .text
.globl fact
fact:
        pushq   %rbp
        movq    %rsp, %rbp
        subq    $16, %rsp
        movl    -8(%rbp), %eax
        leave
        ret
.
        .comm   bar,4,4
        .comm   a,1,1
        .comm   b,1,1

        .section
        .long   .LECIE1-.LSCIE1
        .long   0x0
                .eh_frame,"a",@progbits
        .byte   0x1
        .string ""
        .uleb128 0x1
```

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- Memory Layout
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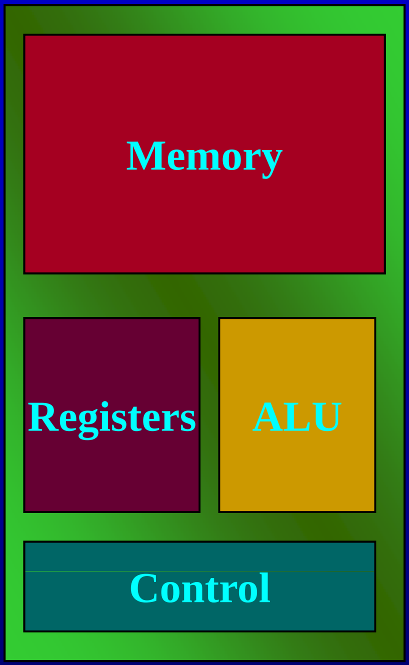
Overview of a modern processor

- ALU
- Control
- Memory
- Registers

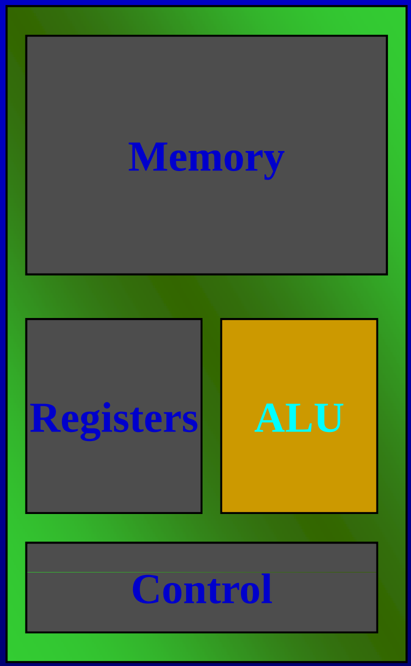


Arithmetic and Logic Unit

- Performs most of the data operations
- Has the form:
  OP <oprnd$_1$>, <oprnd$_2$>
  - <oprnd$_2$> = <oprnd$_1$> OP <oprnd$_2$>

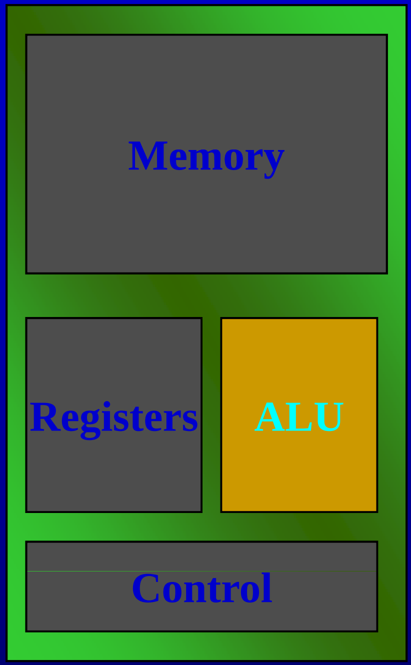
  Or

  OP <oprnd$_1$>
- Operands are:
  - Immediate Value $25
  - Register %rax
  - Memory 4(%rbp)
- Operations are:
  - Arithmetic operations (add, sub, imul)
  - Logical operations (and, sal)
  - Unitary operations (inc, dec)



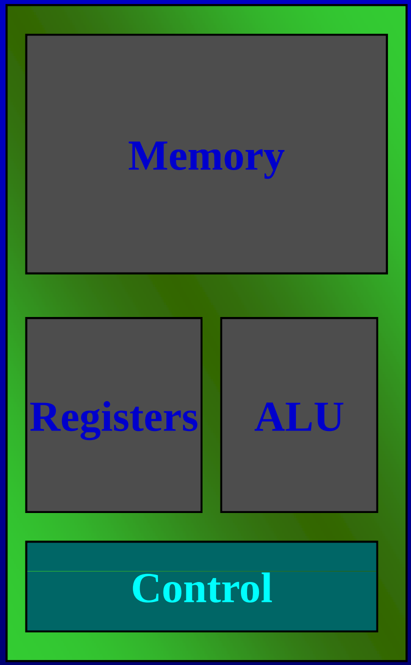
Arithmetic and Logic Unit

- Many arithmetic operations can cause an exception
  - overflow and underflow
- Can operate on different data types
  - addb 8 bits
  - addw 16 bits
  - addl 32 bits
  - addq 64 bits (Decaf is all 64 bit)
  - signed and unsigned arithmetic
  - Floating-point operations (separate ALU)



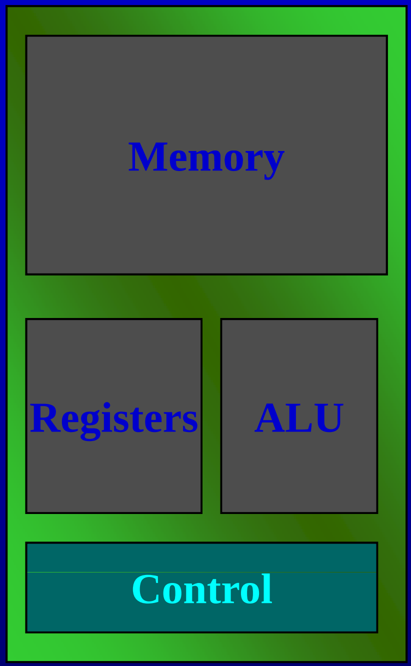
Control

- Handles the instruction sequencing
- Executing instructions
  - All instructions are in memory
  - Fetch the instruction pointed by the PC and execute it
  - For general instructions, increment the PC to point to the next location in memory



Control

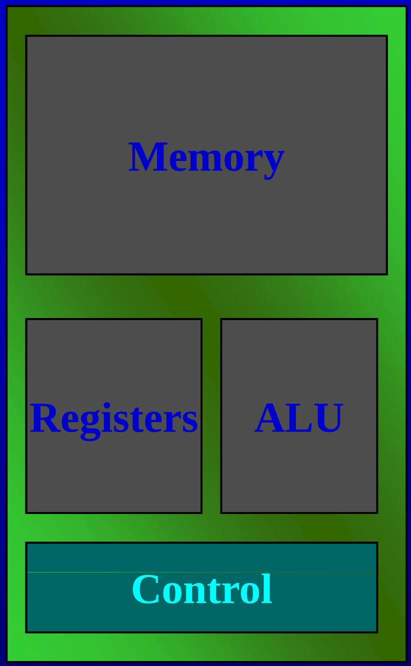
- Unconditional Branches
  - Fetch the next instruction from a different location
  - Unconditional jump to an address
    jmp .L32
  - Unconditional jump to an address in a register
    jmp %rax
  - To handle procedure calls
    call fact   call %r11



Control

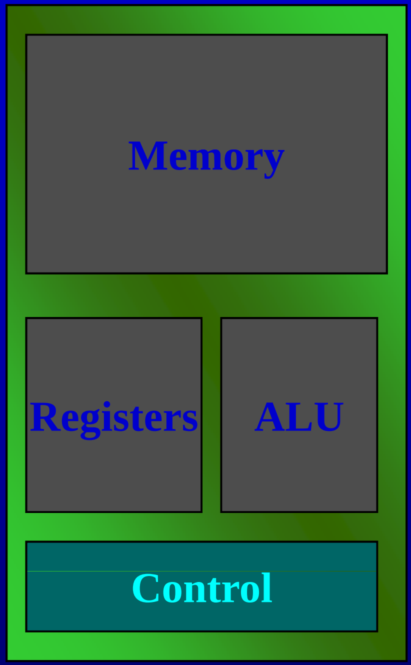
- All arithmetic operations update the condition codes (rFLAGS)

- Compare explicitly sets the rFLAGS
  - cmp $0, %rax
- Conditional jumps on the rFLAGS
  - Jxx .L32   Jxx 4(%rbp)
  - Examples:
    - JO   Jump Overflow
    - JC   Jump Carry
    - JAE   Jump if above or equal
    - JZ   Jump is Zero
    - JNE   Jump if not equal



Control

- Control transfer in special (rare) cases
  - traps and exceptions
  - Mechanism
    - Save the next(or current) instruction location
    - find the address to jump to (from an exception vector)
    - jump to that location

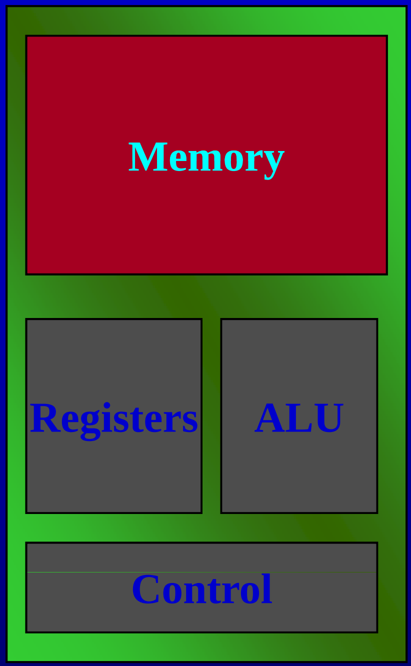


When to use what?

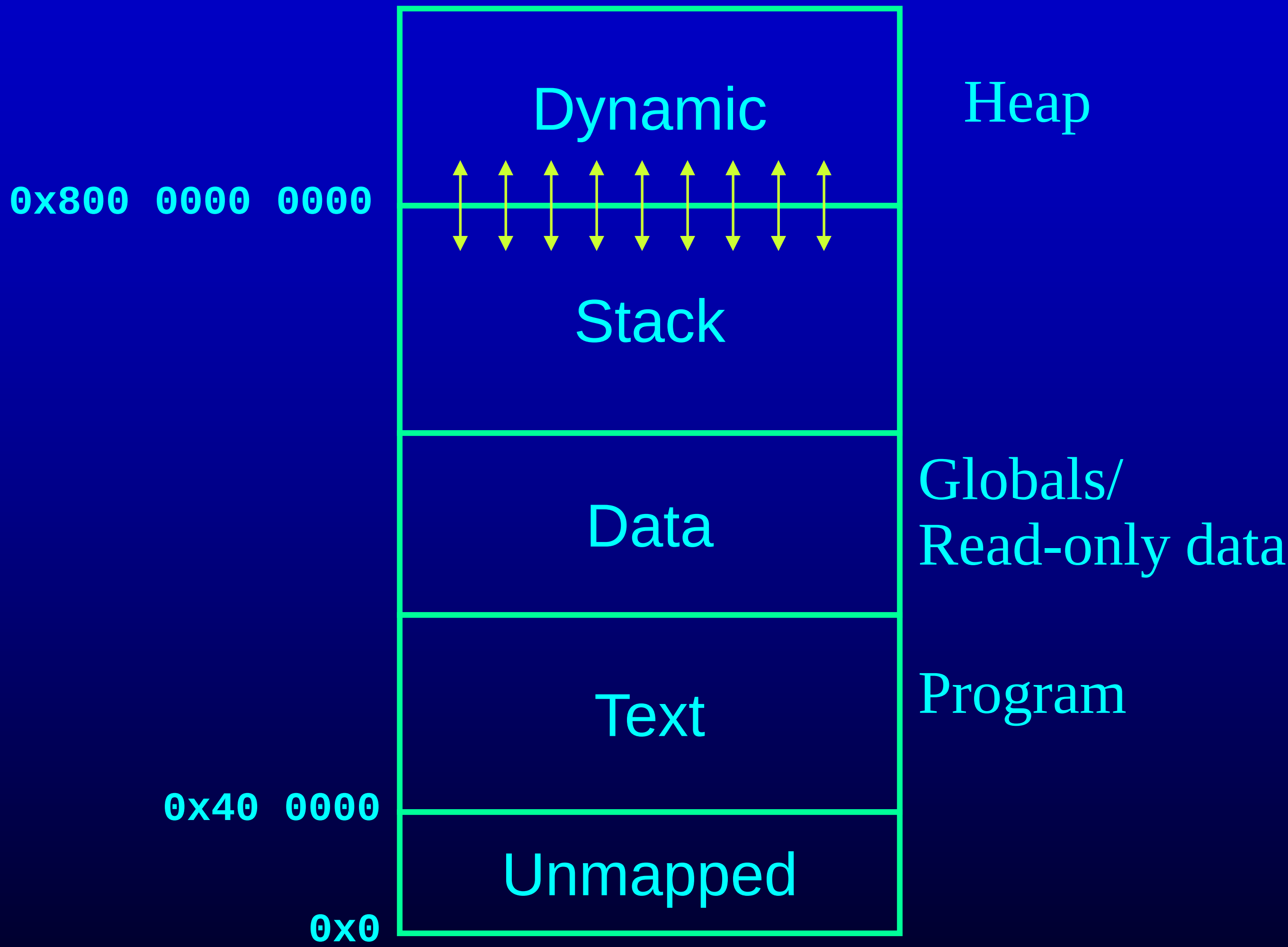
- Give an example where each of the branch instructions can be used
  1. jmp L0
  2. call L1
  3. jmp %rax
  4. jz -4(%rbp)
  5. jne L1

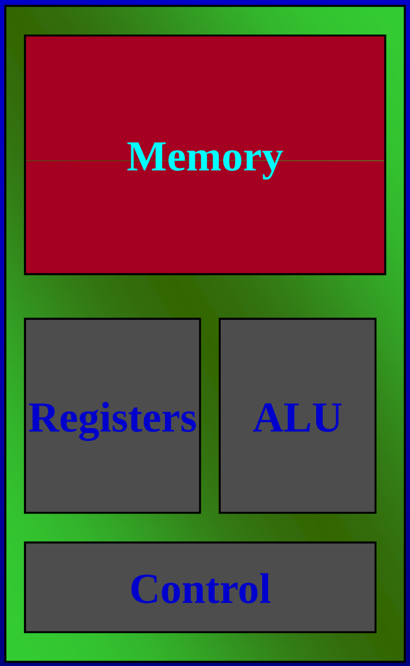
Memory

- Flat Address Space
  - composed of words
  - byte addressable
- Need to store
  - Program
  - Local variables
  - Global variables and data
  - Stack
  - Heap



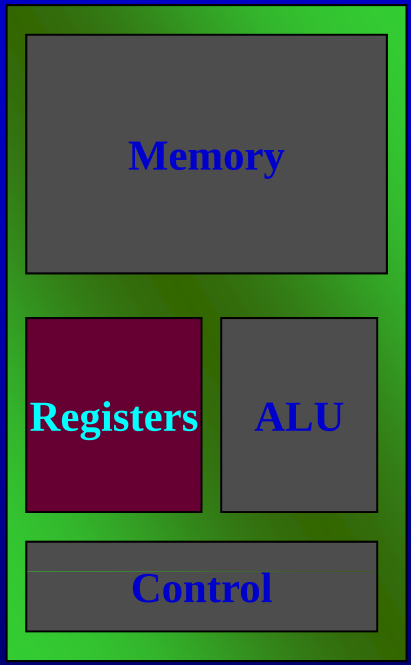
Memory


Dynamic
0x800 0000 0000
Stack
Data
Text
0x40 0000
Unmapped
0x0
Heap
Globals/
Read-only data
Program


Memory
Registers
ALU
Control

Registers

- Instructions allow only limited memory operations
  - ~~add   -4(%rbp), -8(%rbp)~~
    add   %r10, -8(%rbp)
- Important for performance
  - limited in number
- Special registers
  - %rbp   base pointer
  - %rsp   stack pointer

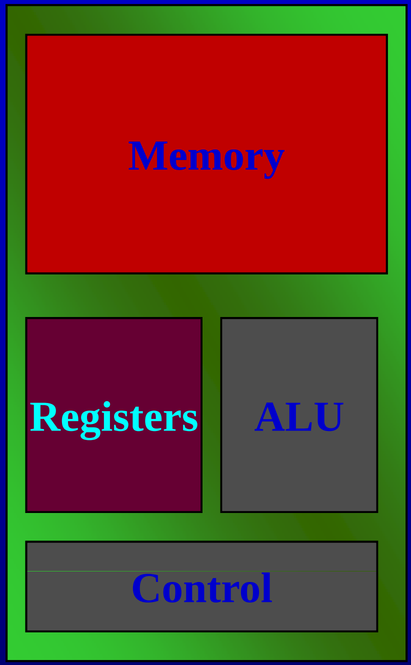


Moving Data

– mov *source* *dest*
  - Moves data
    – from one register to another
    – from registers to memory
    – from memory to registers

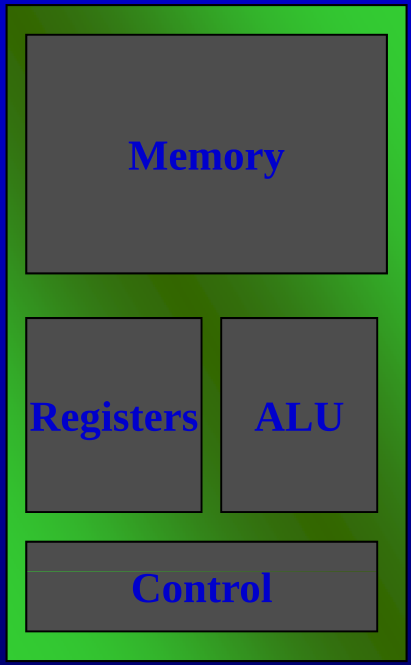
– push *source*
  - Pushes data into the stack

– pop *dest*
  - Pops data from the stack to *dest*



Other interactions

- Other operations
  - Input/Output
  - Privilege / secure operations
  - Handling special hardware
    - TLBs, Caches etc.



- Mostly via system calls
  - hand-coded in assembly
  - compiler can treat them as a normal function call

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Components of a High Level Language

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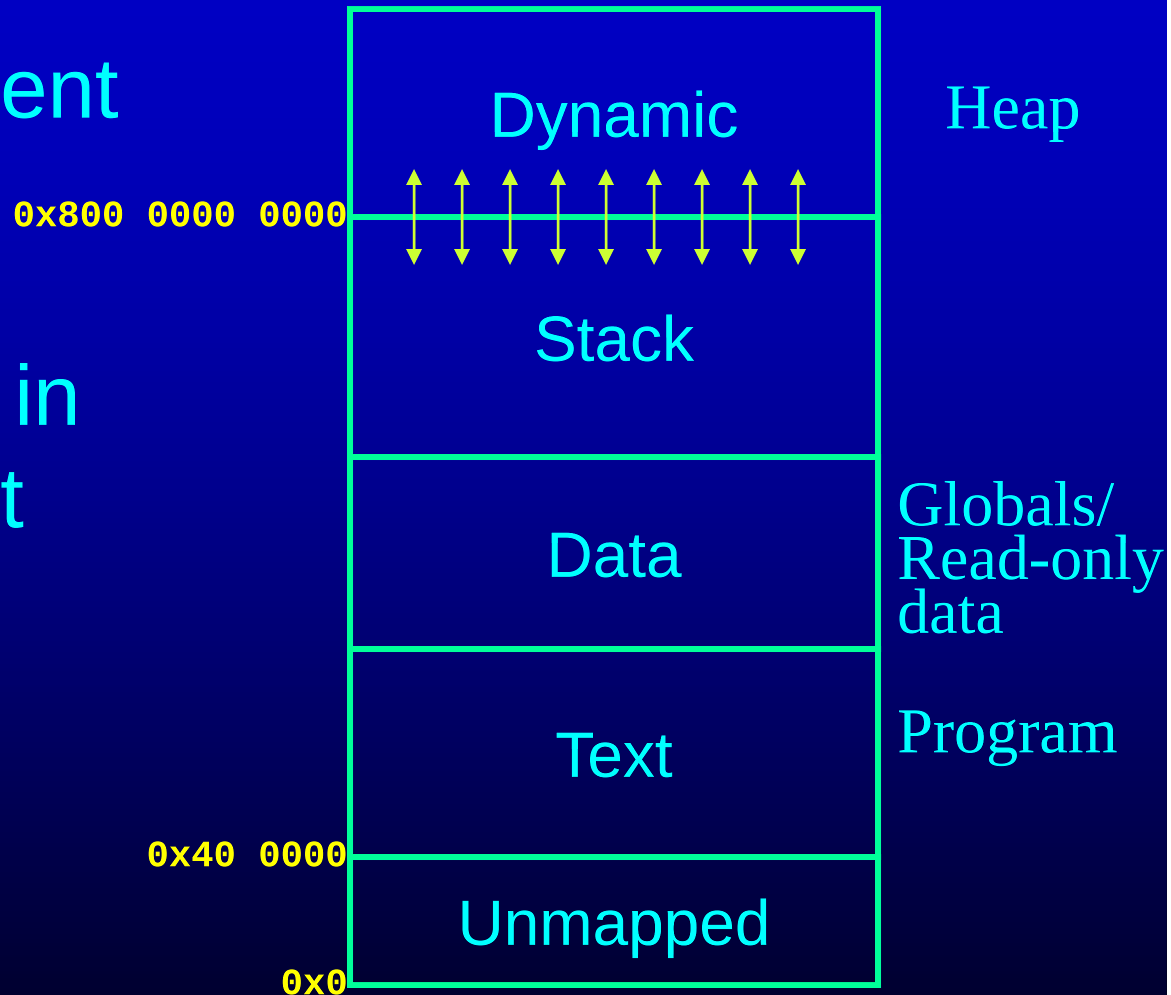
- Control Flow
- Procedures
- Statements
- Data Access

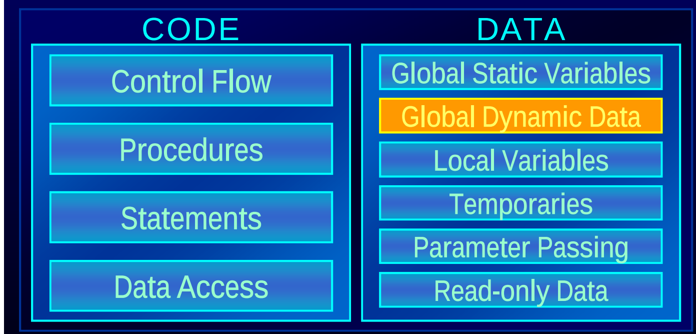
DATA

- Global Static Variables
- Global Dynamic Data
- Local Variables
- Temporaries
- Parameter Passing
- Read-only Data

Memory Layout

- Heap management
  - – free lists
- starting location in the text segment



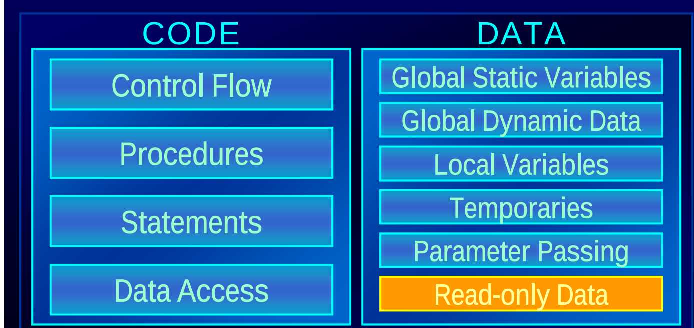


Allocating Read-Only Data

- All Read-Only data in the text segment
- Integers
  - use load immediate
- Strings
  - use the .string macro

```
    .section  .text
    .globl main
main:
    enter     $0, $0
    movq      $5, x(%rip)
    push      x(%rip)
    push      $.msg
    call      printf_035
    add       $16, %rsp
    leave
    ret

.msg:
    .string "Five: %d\n"
```



Global Variables

- Allocation: Use the assembler's .comm directive

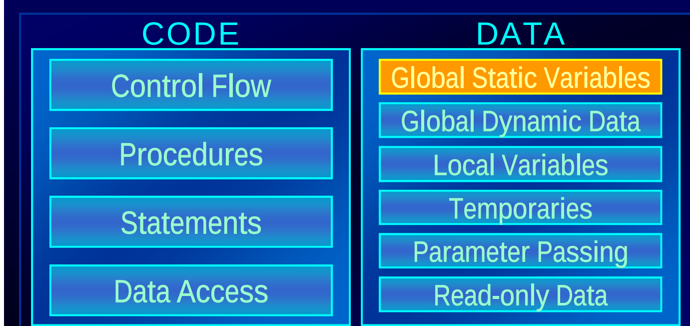
- Use PC relative addressing
  - %rip is the current instruction address
  - X(%rip) will add the offset from the current instruction location to the space for x in the data segment to %rip
  - Creates easily recolatable binaries

```
      .section   .text
      .globl main
main:
      enter         $0, $0
      movq          $5, x(%rip)
      push          x(%rip)
      call          printf_035
      add           $16, %rsp
      leave
      ret

      .comm         x, 8
```

.comm *name*, *size*, *alignment*

The .comm directive allocates storage in the data section. The storage is referenced by the identifier *name*. *Size* is measured in bytes and must be a positive integer. *Name* cannot be predefined. *Alignment* is optional. If *alignment* is specified, the address of *name* is aligned to a multiple of *alignment*



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Procedure Abstraction

- Requires system-wide compact
  - Broad agreement on memory layout, protection, resource allocation calling sequences, & error handling
  - Must involve architecture (ISA), OS, & compiler
- Provides shared access to system-wide facilities
  - Storage management, flow of control, interrupts
  - Interface to input/output devices, protection facilities, timers, synchronization flags, counters, …
- Establishes the need for a private context
  - Create private storage for each procedure invocation
  - Encapsulate information about control flow & data abstractions

The procedure abstraction is a *social contract* (Rousseau)

Procedure Abstraction

- In practical terms it leads to...
  - multiple procedures
  - library calls
  - compiled by many compilers, written in different languages, hand-written assembly
- For the project, we need to worry about
  - Parameter passing
  - Registers
  - Stack
  - Calling convention

Parameter passing disciplines

- Many different methods
  - call by reference
  - call by value
  - call by value-result (copy-in/copy-out)

Parameter Passing Disciplines

```
Program {
   int A;
   foo(int B) {
      B = B + 1
      B = B + A
   }
   Main() {
      A = 10;
      foo(A);
   }
}
```

- Call by value A is ???
- Call by reference A is ???
- Call by value-result A is ???

Parameter Passing Disciplines

```
Program {
   int A;
   foo(int B) {
      B = B + 1
      B = B + A
   }
   Main() {
      A = 10;
      foo(A);
   }
}
```

- Call by value A is 10
- Call by reference A is 22
- Call by value-result A is 21

Parameter passing disciplines

- Many different methods
  - call by reference
  - call by value
  - call by value-result
- How do you pass the parameters?
  - via. the stack
  - via. the registers
  - or a combination
- In the Decaf calling convention, the first 6 parameters are passed in registers.
  - The rest are passed in the stack

Registers

- What to do with live registers across a procedure call?
  - Caller Saved
  - Calliee Saved

Question:

- What are the advantages/disadvantages of:
  - Calliee saving of registers?
  - Caller saving of registers?
- What registers should be used at the caller and calliee if half is caller-saved and the other half is calliee-saved?

Registers

- What to do with live registers across a procedure call?
  – Caller Saved
  – Calliee Saved

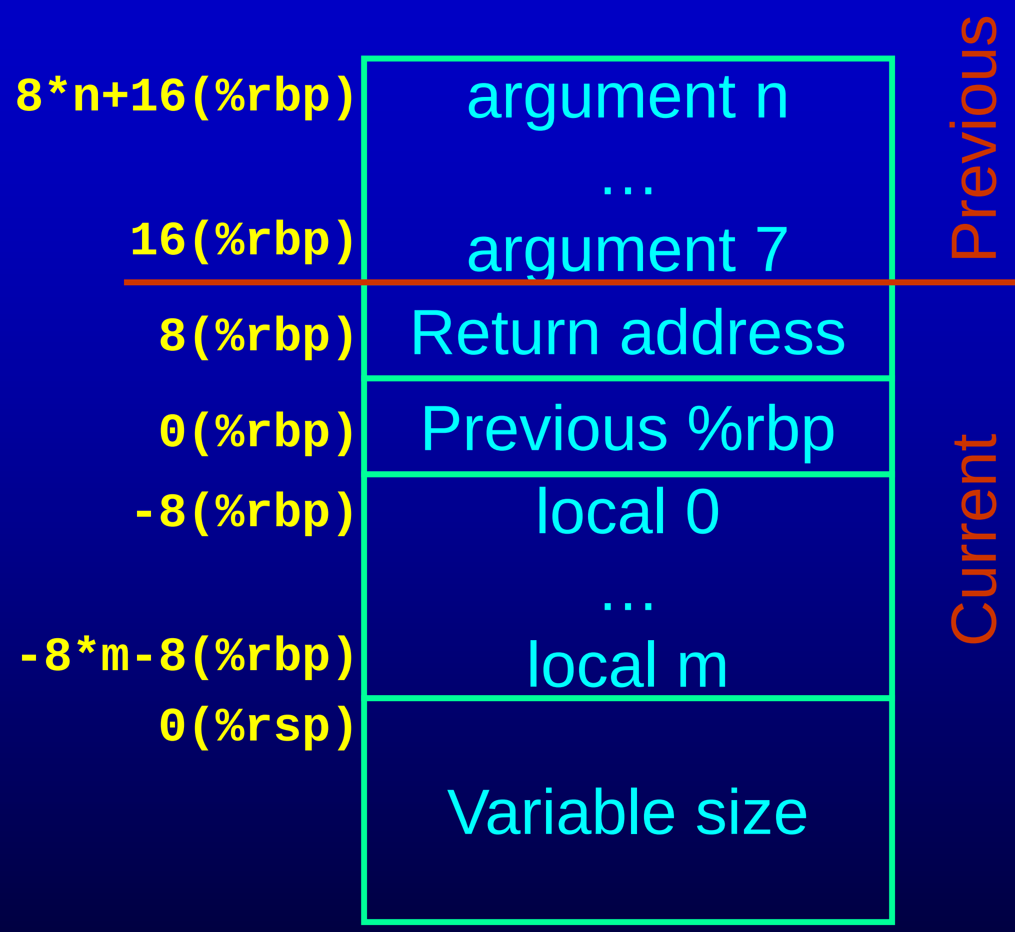
- In this segment, use registers only as short-lived temporaries

```
mov    -4(%rbp), %r10
mov    -8(%rbp), %r11
add    %r10, %r11
mov    %r11, -8(%rbp)
```

  – Should not be live across procedure calls
  – Will start keeping data in the registers for performance in Segment V

The Stack

- Arguments 0 to 6 are in:
  - %rdi, %rsi, %rdx, %rcx, %r8 and %r9



Question:

- Why use a stack? Why not use the heap or pre-allocated in the data segment?

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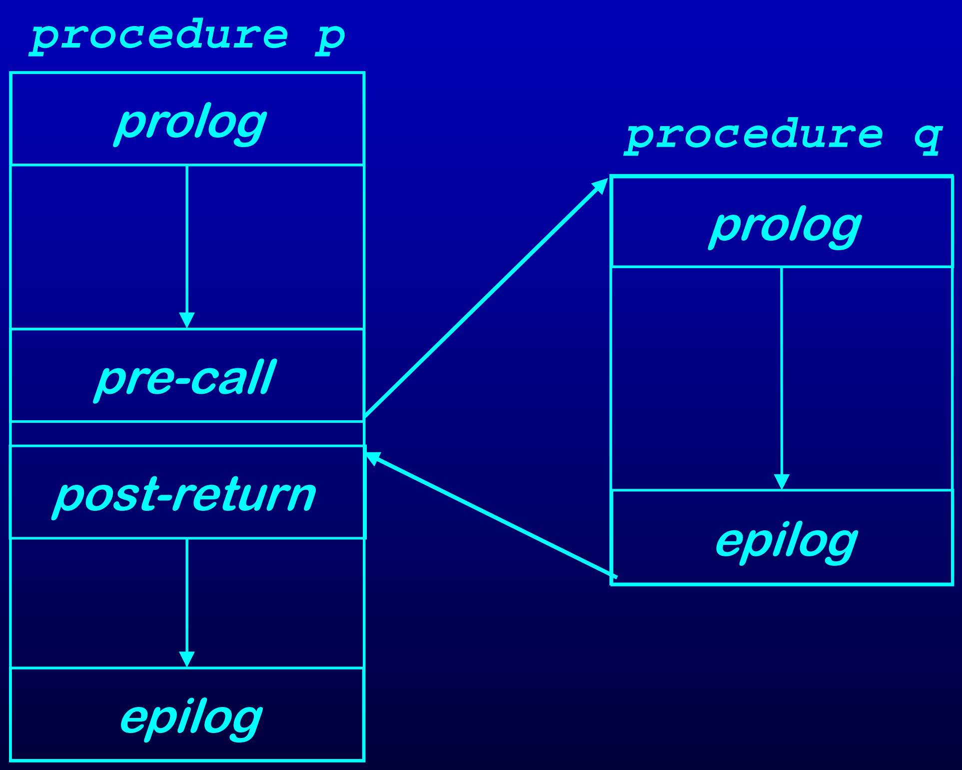
Procedure Linkages

Standard procedure linkage



Procedure has

- **standard prolog**
- **standard epilog**

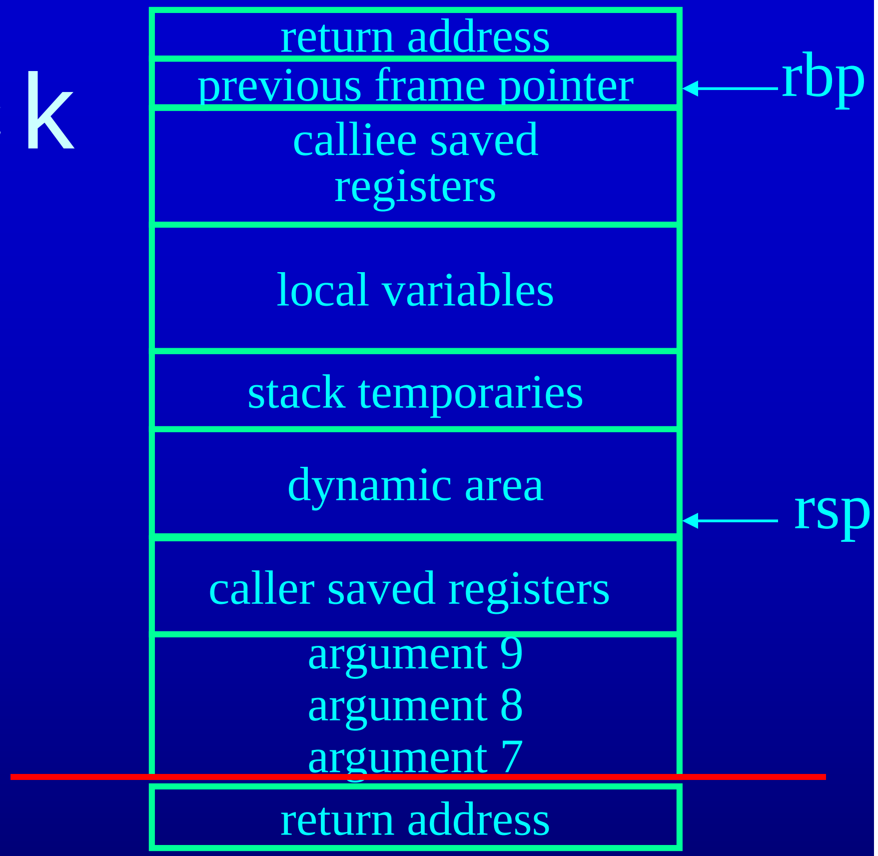
Each call involves a

- **pre-call sequence**
- **post-return sequence**

Stack

- Calling: Caller
  - Assume %rcx is live and is caller save
  - Call foo(A, B, C, D, E, F, G, H, I)
    - A to I are at -8(%rbp) to -72(%rbp)

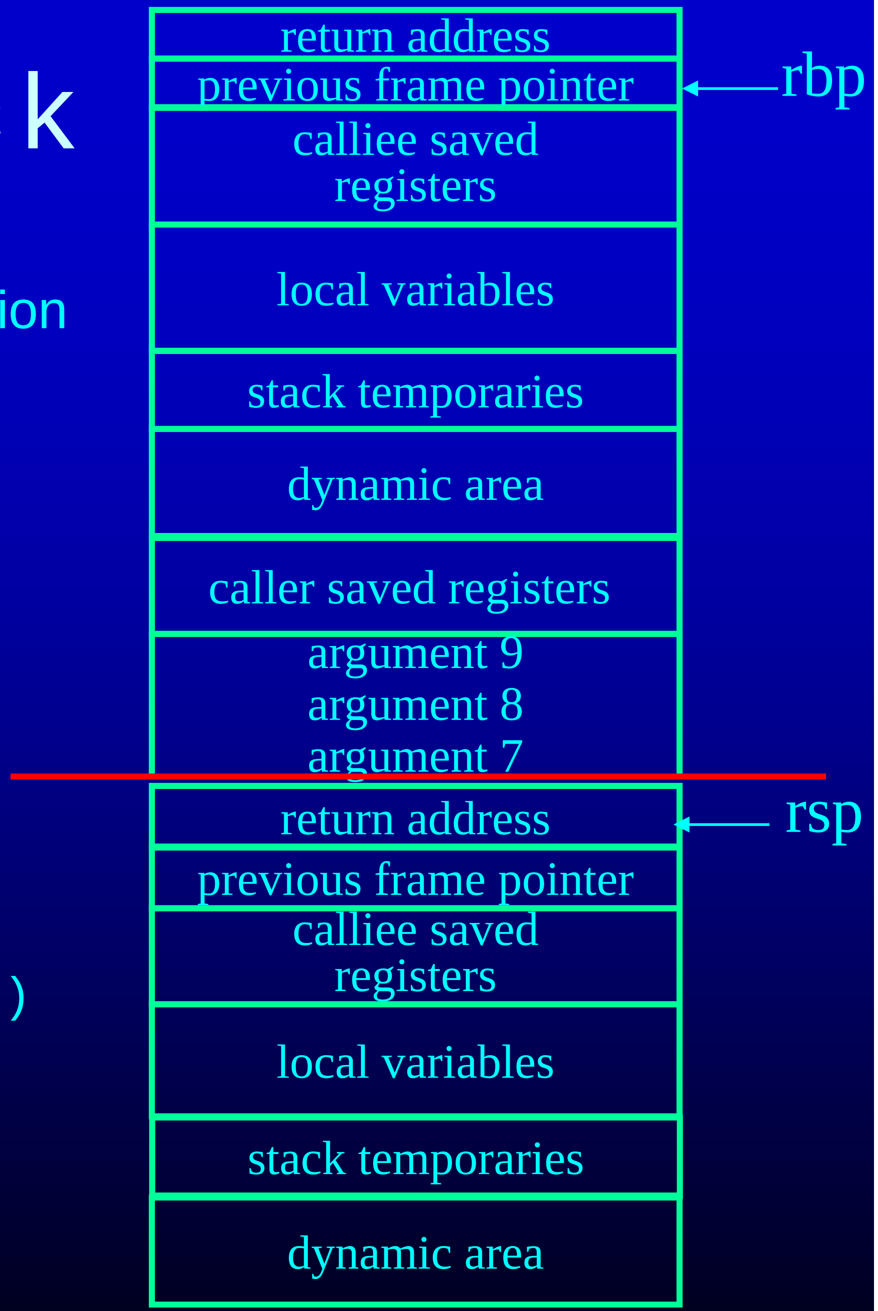
```
push        %rcx
push        -72(%rbp)
push        -64(%rbp)
push        -56(%rbp)
mov          -48(%rbp), %r9
mov          -40(%rbp), %r8
mov          -32(%rbp), %rcx
mov          -24(%rbp), %rdx
mov          -16(%rbp), %rsi
mov          -8(%rbp), %rdi
call        foo
```



Stack

- Calling: Calliee
  - Assume %rbx is used in the function and is calliee save
  - Assume 40 bytes are required for locals

```
foo:
    push    %rbp
    enter   $48, $0
    mov     %rsp, %rbp
    sub     $48, %rsp
    mov     %rbx, -8(%rbp)
```



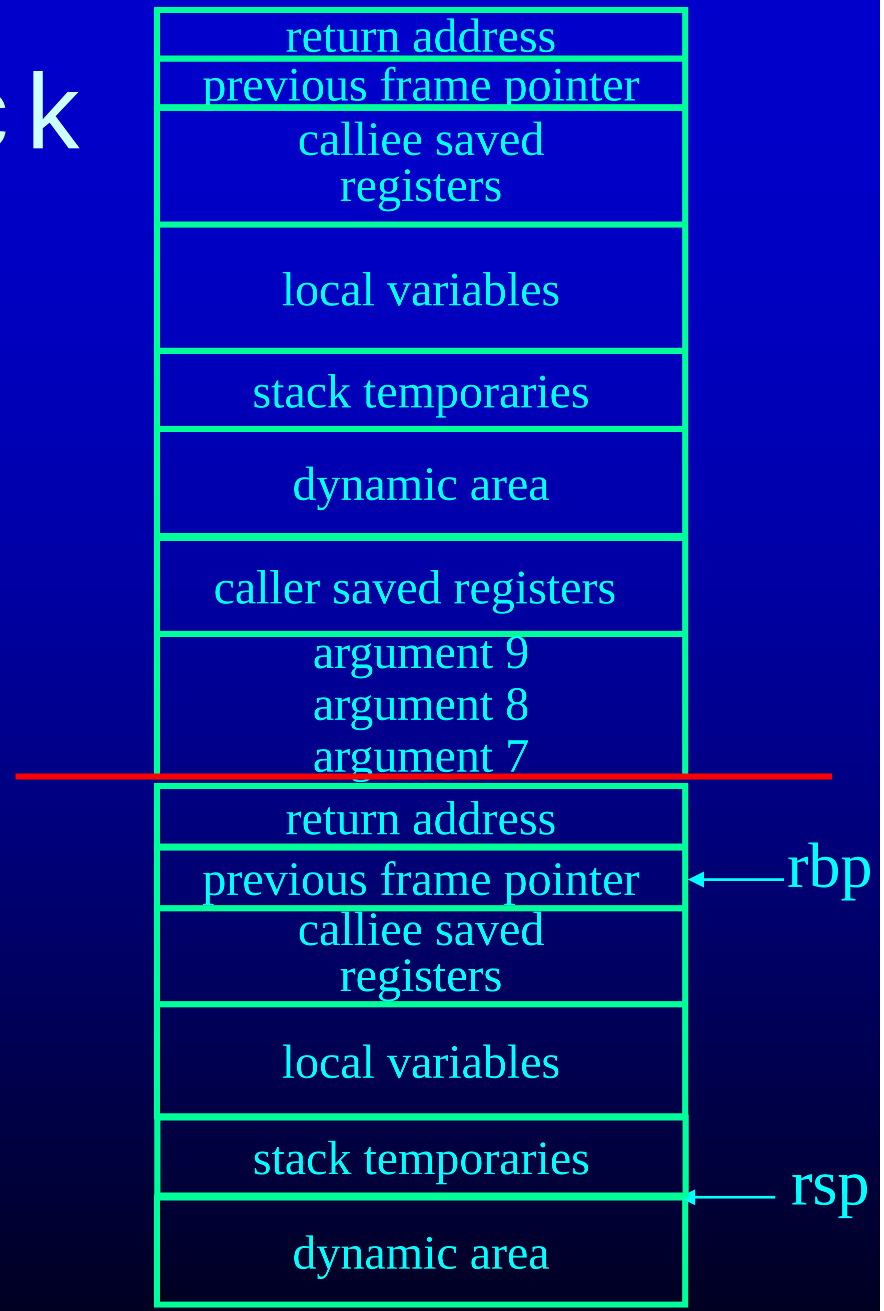
Stack

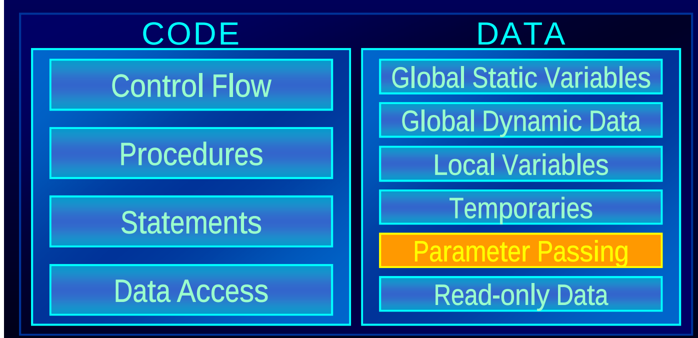
- Arguments
- Call foo(A, B, C, D, E, F, G, H, I)
  - Passed in by pushing before the call

```
push      -72(%rbp)
push      -64(%rbp)
push      -56(%rbp)
mov       -48(%rbp), %r9
mov       -40(%rbp), %r8
mov       -32(%rbp), %rcx
mov       -24(%rbp), %rdx
mov       -16(%rbp), %rsi
mov       -8(%rbp), %rdi
call      foo
```

  - Access A to F via registers
    - or put them in local memory
  - Access rest using 16+xx(%rbp)

```
mov       16(%rbp), %rax
mov       24(%rbp), %r10
```





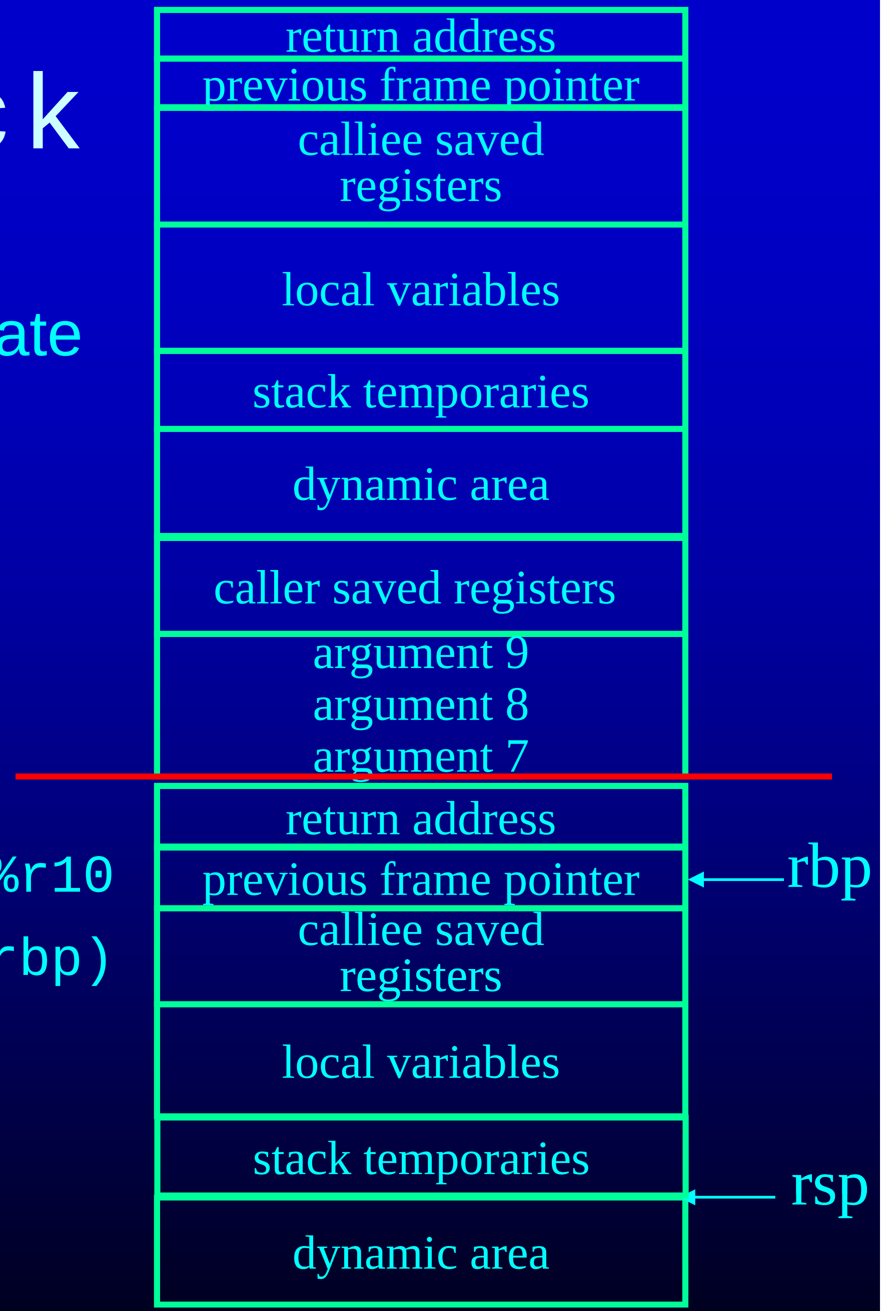
Stack

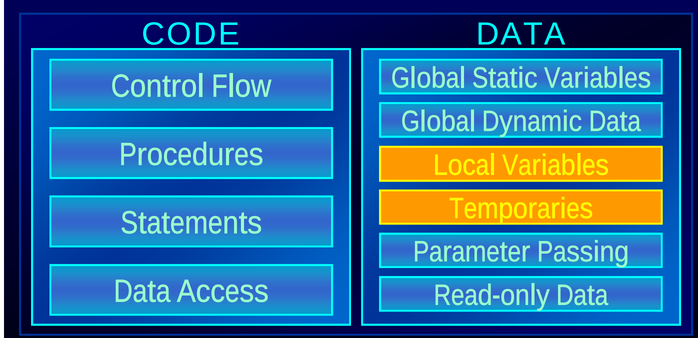
- Locals and Temporaries
  - Calculate the size and allocate space on the stack

```
    sub      $48, %rsp
or  enter    $48, 0
```

  - Access using -8-xx(%rbp)

```
    mov      -28(%rbp), %r10
    mov      %r11, -20(%rbp)
```

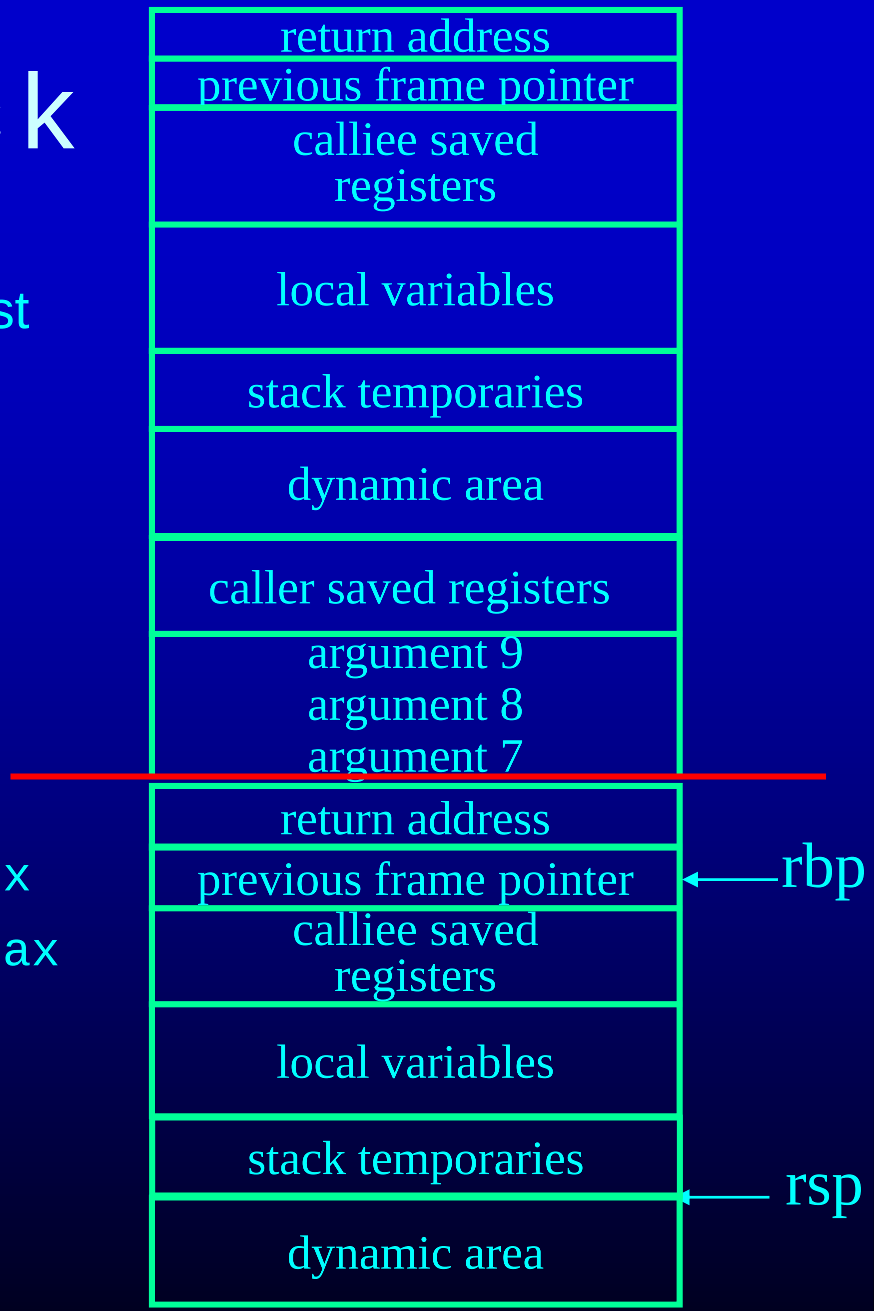




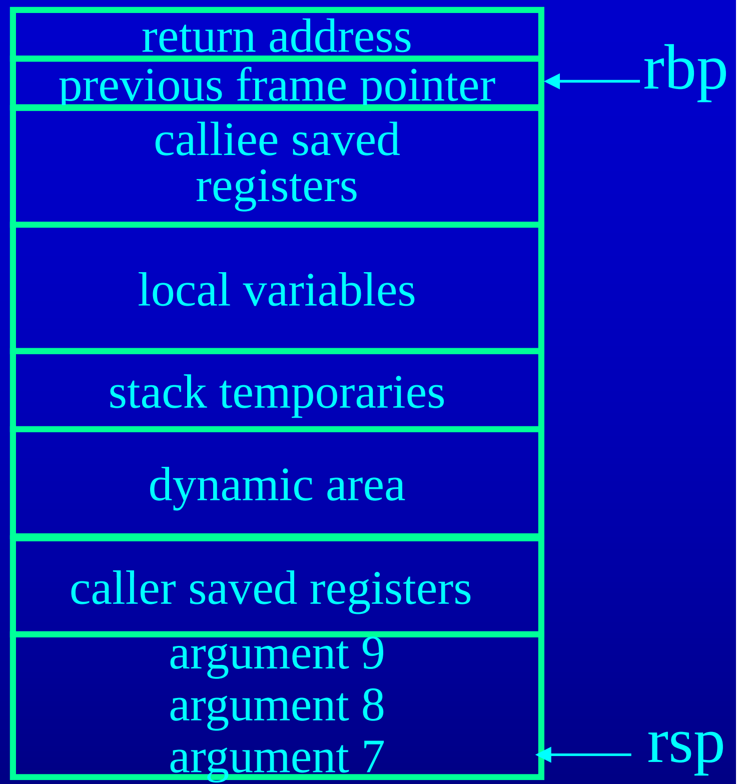
Stack

- Returning Calliee
  - Assume the return value is the first temporary
  - Restore the caller saved register
  - Put the return value in %rax
  - Tear-down the call stack

```
mov      -8(%rbp), %rbx
mov      -16(%rbp), %rax
mov      %rbp, %rsp
pop      %rbp
leave
ret
```

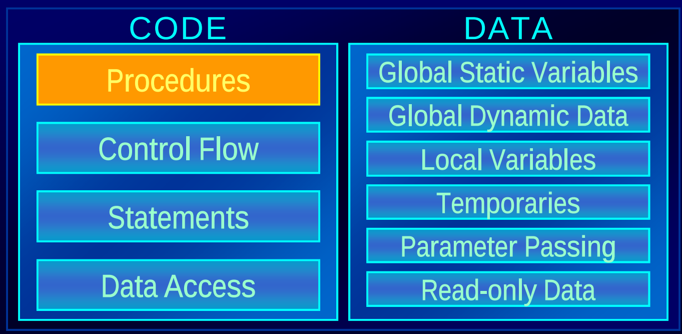


Stack



- Returning Caller
  - Assume the return value goes to the first temporary
  - Restore the stack to reclaim the argument space
  - Restore the caller save registers

```
call    foo
add     $24, %rsp
pop     %rcx
mov     %rax, 8(%rbp)
…
```



Question:

- Do you need the $rbp?
- What are the advantages and disadvantages of having $rbp?

Outline

- Introduction
- Machine Language
- Overview of a modern processor
- Memory Layout
- Procedure Abstraction
- Procedure Linkage
- **Guidelines in Creating a Code Generator**

What We Covered Today..

CODE

- Procedures
- Control Flow
- Statements
- Data Access

DATA

- Global Static Variables
- Global Dynamic Data
- Local Variables
- Temporaries
- Parameter Passing
- Read-only Data

Guidelines for the code generator

- Lower the abstraction level slowly
  - Do many passes, that do few things (or one thing)
    - Easier to break the project down, generate and debug
- Keep the abstraction level$_{cons}$ istent
  - IR should have ‘correct’ semantics at all time
    - At least you should know the semantics
  - You may want to run some of the optimizations between the passes.
- Use assertions liberally
  - Use an assertion to check your assumption

Guidelines for the code generator

- Do the simplest but dumb thing
  - it is ok to generate 0 + 1*x + 0*y
  - Code is painful to look at, but will help optimizations

- Make sure you know want can be done at…
  - Compile time in the compiler
  - Runtime using generated code

Guidelines for the code generator

- Remember that optimizations will come later
  - Let the optimizer do the optimizations
  - Think about what optimizer will need and structure your code accordingly
  - Example: Register allocation, algebraic simplification, constant propagation

- Setup a good testing infrastructure
  - regression tests
    - If a input program creates a bug, use it as a regression test
  - Learn good bug hunting procedures
    - Example: binary search

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