6.172
Performance
Engineering
of Software
Systems

LECTURE 5

C to Assembly

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Review: Why Assembly?

Why look at the assembly of your program?

- Assembly is more precise than C and can reveal program details such as type-cast operations and usage of registers and memory.
- The assembly reveals what the compiler did and did not do, e.g., to optimize basic operations.
- Bugs can arise at a low level. For example, a bug in the code might only have an effect when compiling at `-O3`. Bugs might also be caused by the compiler!
- You can modify the assembly by hand to make it run fast.
- Reverse engineering: You can decipher what a program does when you only have access to its binary.

Where We Stand

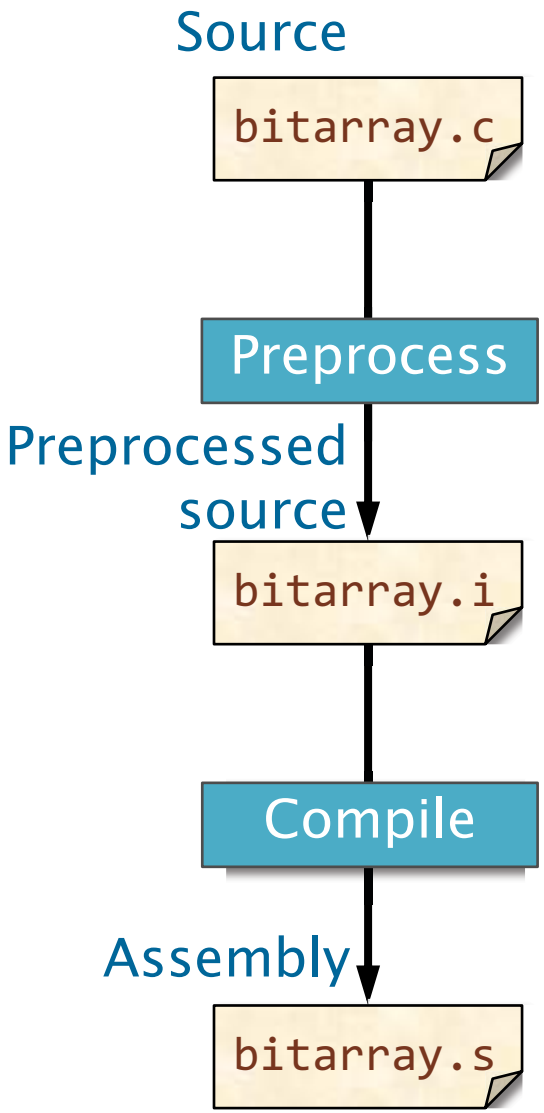
Lecture 4: Computer Architecture

- Basics of the x86-64 assembly language: instructions, registers, data types, memory addressing modes, the RFLAGS register, and condition codes.

This lecture:

- How C code is implemented in x86-64 assembly.

How Does C Code Become Assembly?



The compiler does a lot of stuff to translate C code to assembly:

- Choose assembly instructions to implement C operations.
- Implement C conditionals and loops using jumps and branches.
- Choose registers and memory locations to store data.
- Move data among the registers and memory to satisfy dependencies.
- Coordinate function calls.
- Try to make the assembly fast.

Example: fib.s

As a result, the mapping from C to assembly is not always obvious.

C code fib.c

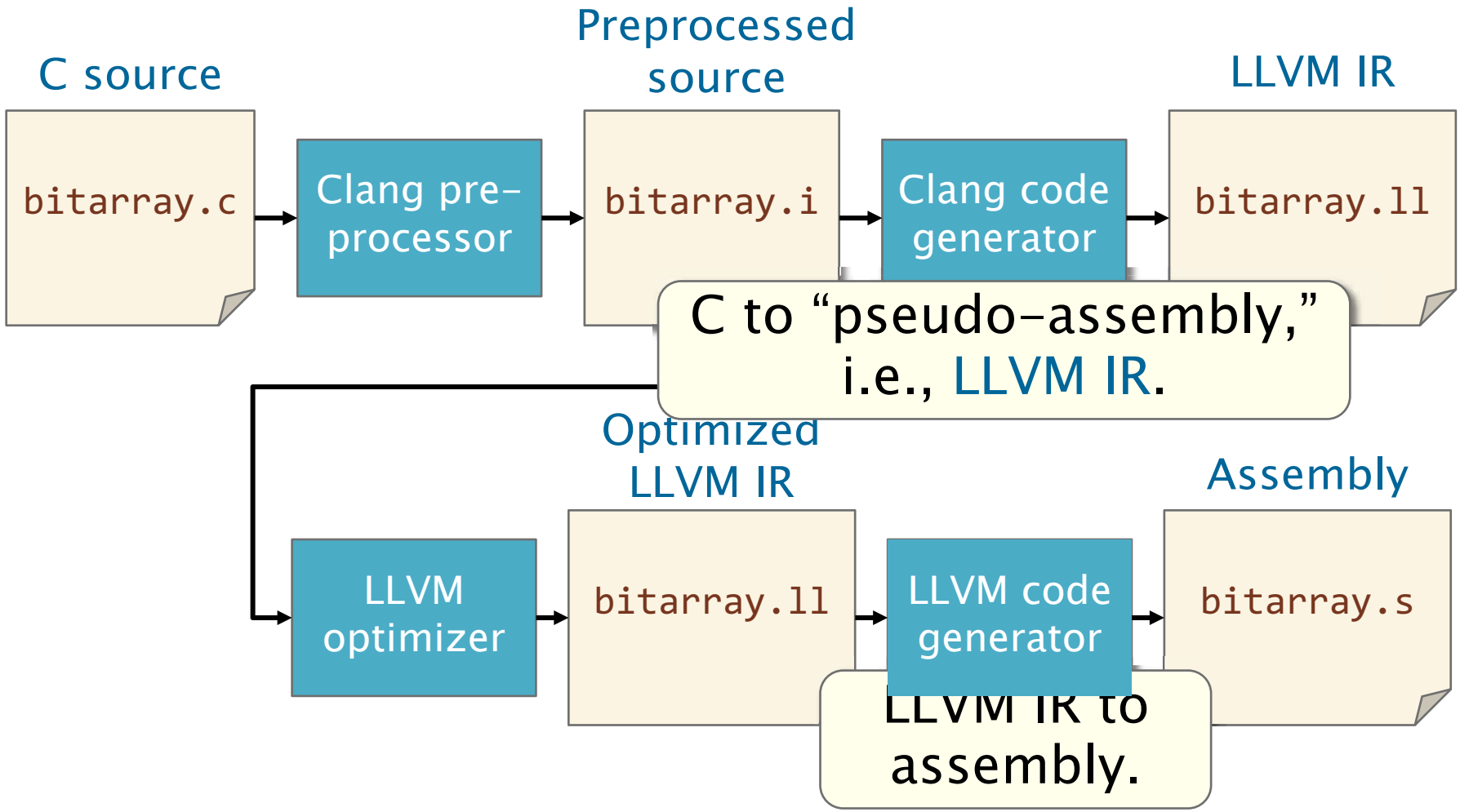
```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  return (
    fib(n-1)
    +
    fib(n-2));
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align 4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Clang/LLVM Compilation Pipeline

To understand this translation process, let us see how the compiler reasons about it.



Viewing LLVM IR

You can see what the `clang` compiler does by looking at the LLVM IR.

Source code `fib.c`

```
int64_t fib(int64_t n) {
  if (n < 2) return n;
  return (fib(n-1) + fib(n-2));
}
```

```
$ clang -O3 fib.c \
> -S -emit-llvm
```

Clang flags:

- "`-S`" produces assembly.
- "`-S -emit-llvm`" produces LLVM IR.

LLVM IR code `fib.ll`

```
define i64 @fib(i64) local_unnamed_addr #0 {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                                ; preds = %1
  ret i64 %0
}
```

Compiling LLVM IR

LLVM IR can be translated directly into assembly.

LLVM IR code `fib.ll`

```
define i64 @fib(i64) local_unnamed_addr #0 {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                                ; preds = %1
  ret i64 %0
}
```

```
$ clang fib.ll -S
```

Assembly code `fib.s`

```
        .globl  _fib
        .p2align 4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Outline

LLVM IR Primer

C to LLVM IR

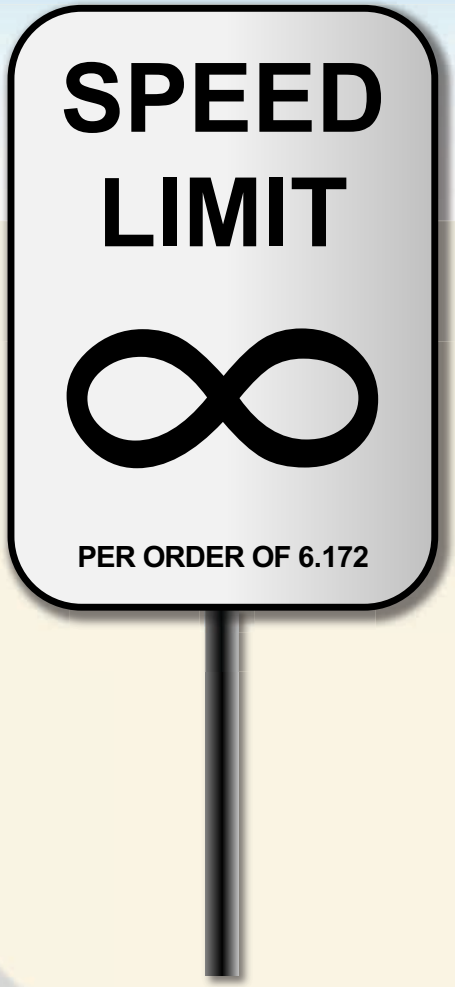
- Straight-Line C Code to LLVM IR
- C Functions to LLVM IR
- C Conditionals (e.g., If-Then-Else) to LLVM IR
- C Loops to LLVM IR
- LLVM IR Attributes

LLVM IR to Assembly

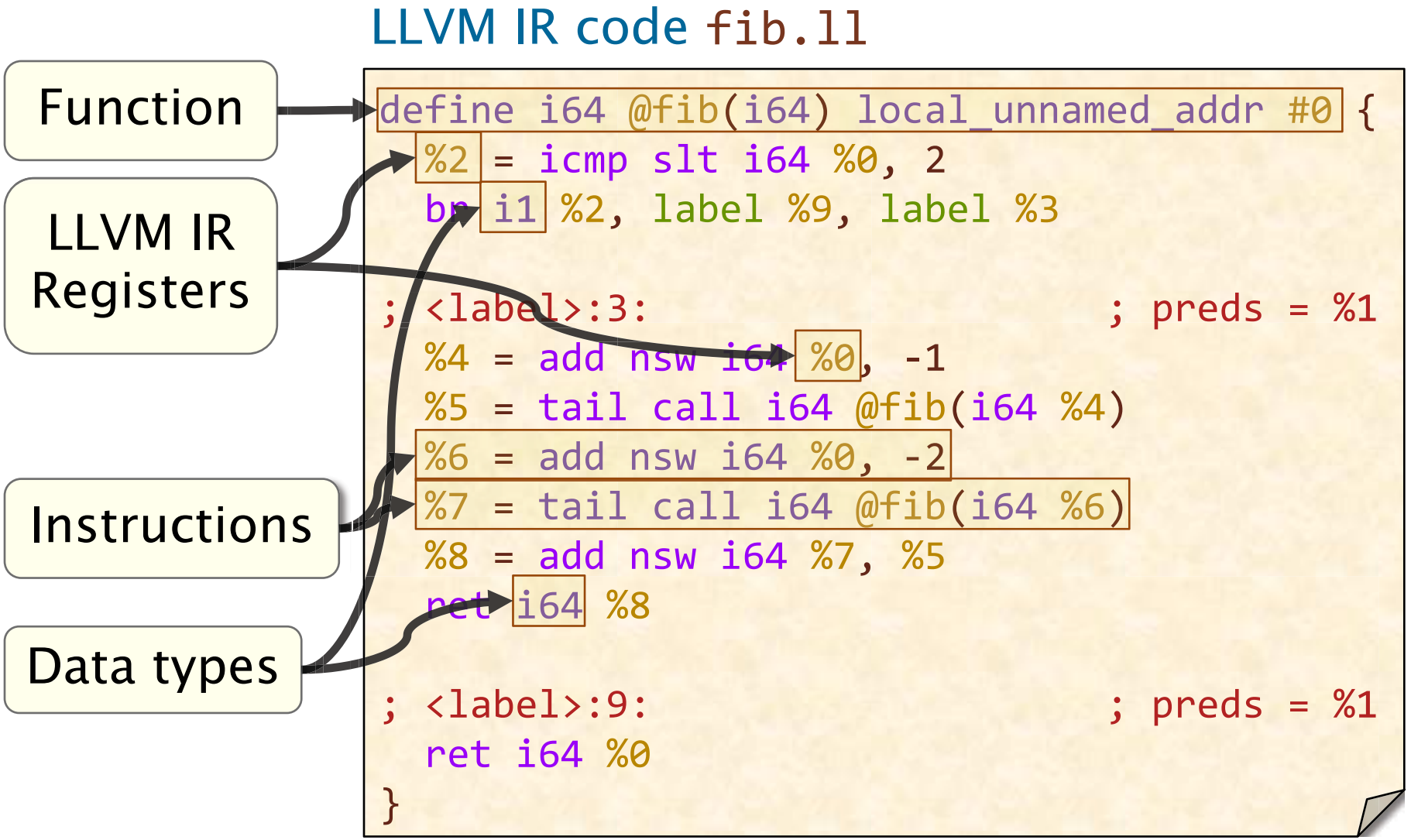
- Linux x86-64 Calling Convention

Case Study: Fib

LLVM IR Primer



Components of LLVM IR



LLVM IR Versus Assembly

LLVM IR is *similar* to assembly.

- LLVM IR uses a simple instruction format, i.e., ⟨destination operand⟩ = ⟨opcode⟩ ⟨source operands⟩
- LLVM IR code adopts a similar structure to assembly code.
- Control flow is implemented using conditional and unconditional branches.

LLVM IR is *simpler* than assembly.

- Smaller instruction set.
- Infinite LLVM IR registers, similar to variables in C.
- No implicit FLAGS register or condition codes.
- No explicit stack pointer or frame pointer.
- C-like type system.
- C-like functions.

LLVM IR Registers

LLVM IR stores values variables, called ***registers***.

- Syntax: %<name>
- LLVM registers are like C variables: LLVM supports an infinite number of registers, each distinguished by name.
- Register names are local to each LLVM IR function.

Registers in an LLVM IR snippet.

```
%4 = add nsw i64 %0, -1
%5 = tail call i64 @fib(i64 %4)
%6 = add nsw i64 %0, -2
%7 = tail call i64 @fib(i64 %6)
%8 = add nsw i64 %7, %5
ret i64 %8
```

One catch: We shall see that LLVM hijacks its syntax for registers to refer to "basic blocks."

LLVM IR Instructions

LLVM-IR code is organized into *instructions*.

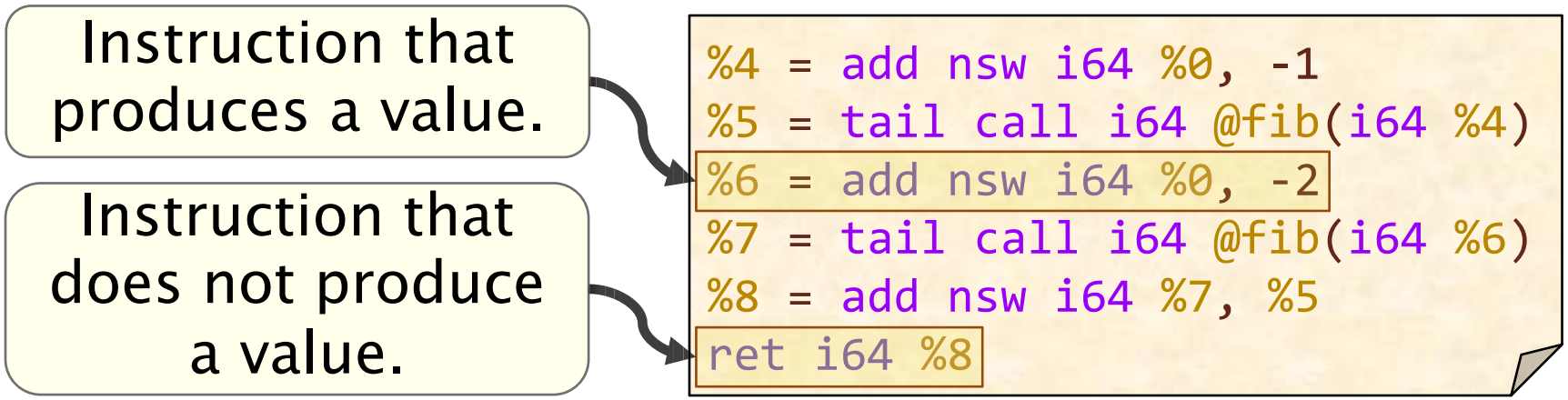
- Syntax for instructions that produce a value:

  `%<name> = <opcode> <operand list>`

- Syntax for other instructions:

  `<opcode> <operand list>`

- Operands are registers, constants, or "basic blocks."



Common LLVM IR Instructions

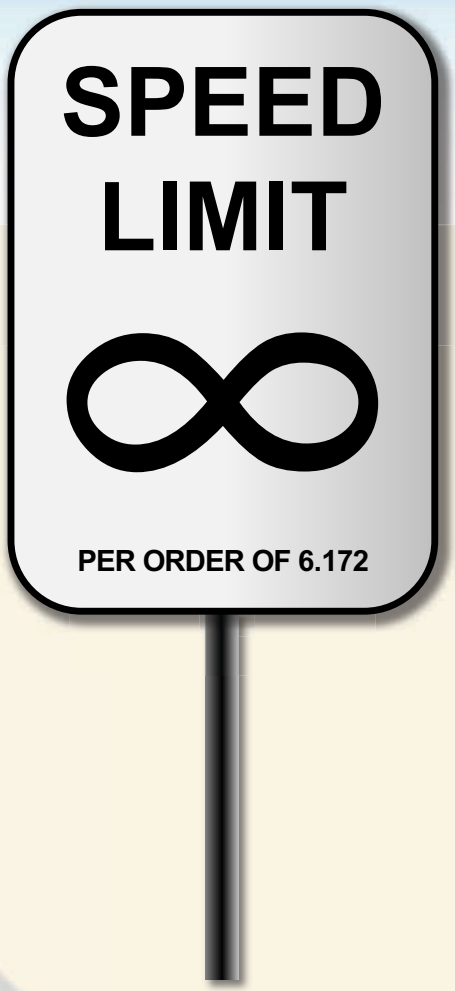
Type or operation		Example(s)
Data movement	Stack allocation	alloca
	Memory read	load
	Memory write	store
	Type conversion	bitcast, ptrtoint
Arithmetic and logic	Integer arithmetic	add, sub, mul, div, shl, shr
	Floating-point arithmetic	fadd, fmul
	Binary logic	and, or, xor, not
	Boolean logic	icmp
	Address calculation	getelementptr
Control flow	Unconditional jump	br <location>
	Conditional jump	br <condition>, <true>, <false>
	Subroutines	call, ret
	Maintaining SSA form	phi

LLVM IR Data Types

LLVM IR supports a variety of ***data types***.

- Integers: `i<number>`
  - Example: A 64-bit integer: `i64`
  - Example: A 1-bit integer: `i1`
- Floating-point values: `double`, `float`
- Arrays: `[<number> x <type>]`
  - Example: An array of 5 `int`'s: `[5 x i32]`
- Structs: `{ <type>, … }`
- Vectors: `< <number> x <type> >`
- Pointers: `<type>*`
  - Example: A pointer to an 8-bit integer: `i8*`
- Labels (i.e., basic blocks): `label`

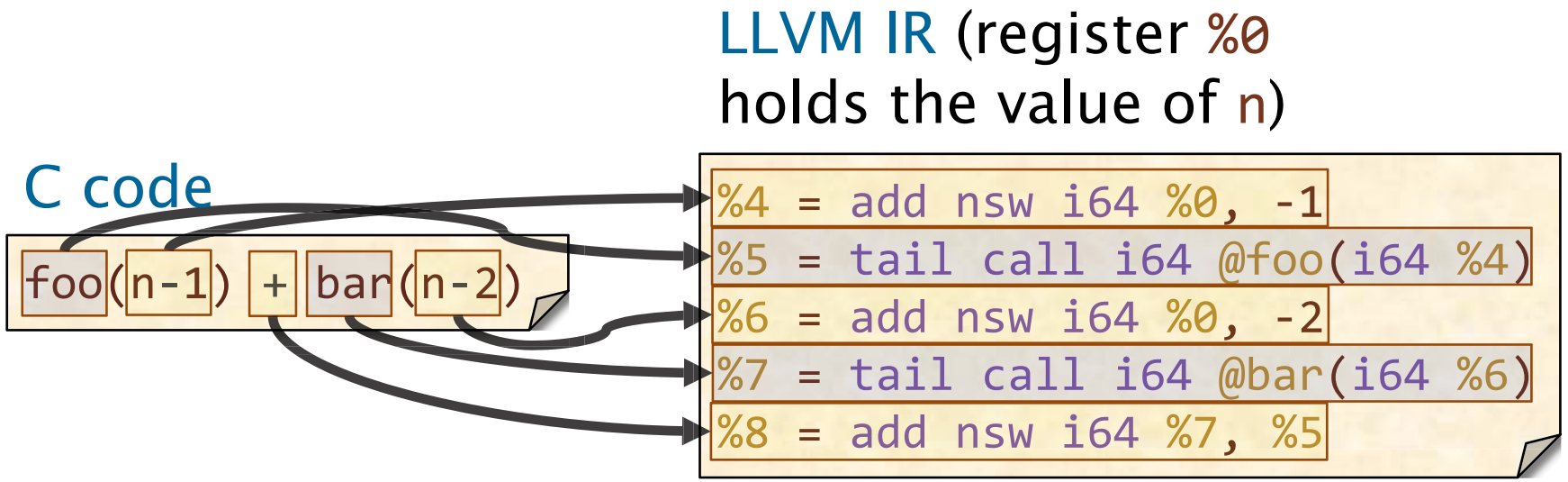
Straight-Line C Code to LLVM IR



Straight-Line C Code in LLVM IR

Straight-line C code (i.e., containing no conditionals or loops) becomes a sequence of LLVM IR instructions.

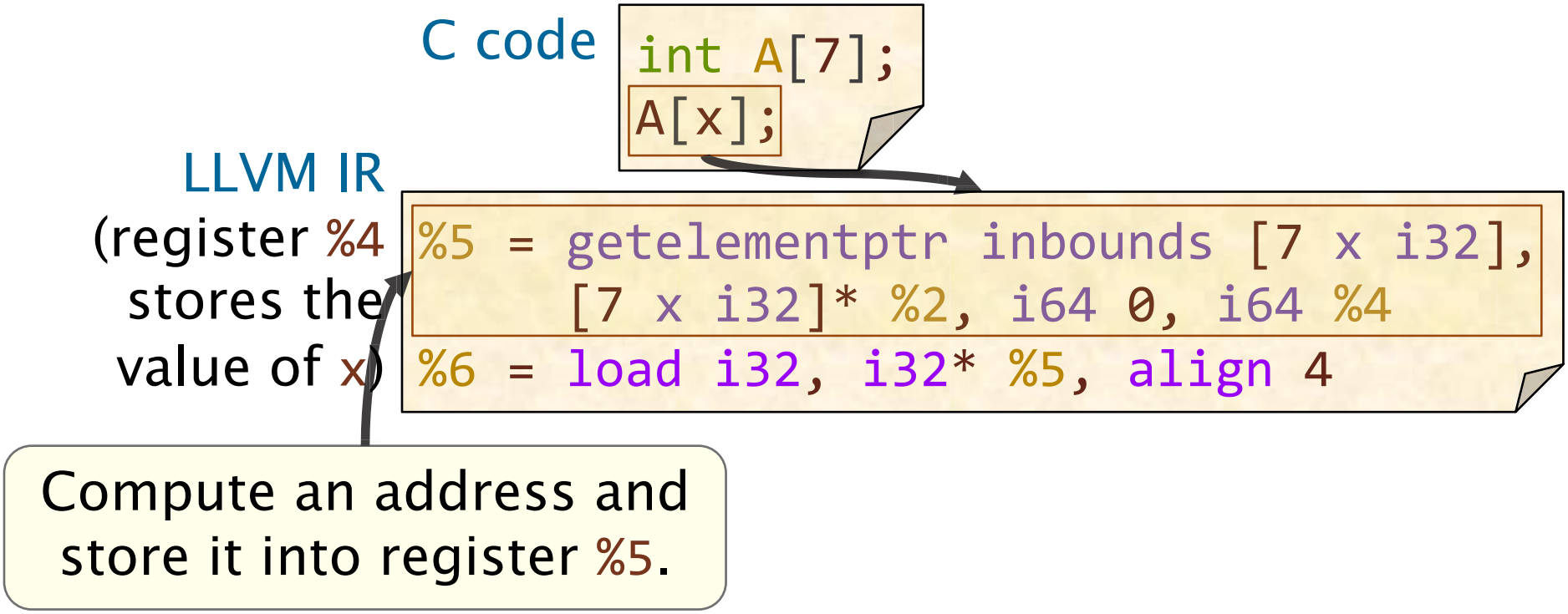
- Arguments are evaluated before the C operation.
- Intermediate results are stored in registers.



Aggregate Types

A variable with an aggregate type (i.e., an array or a struct) is typically stored in memory.

Accessing the aggregate type involves computing an address and then reading or writing memory.



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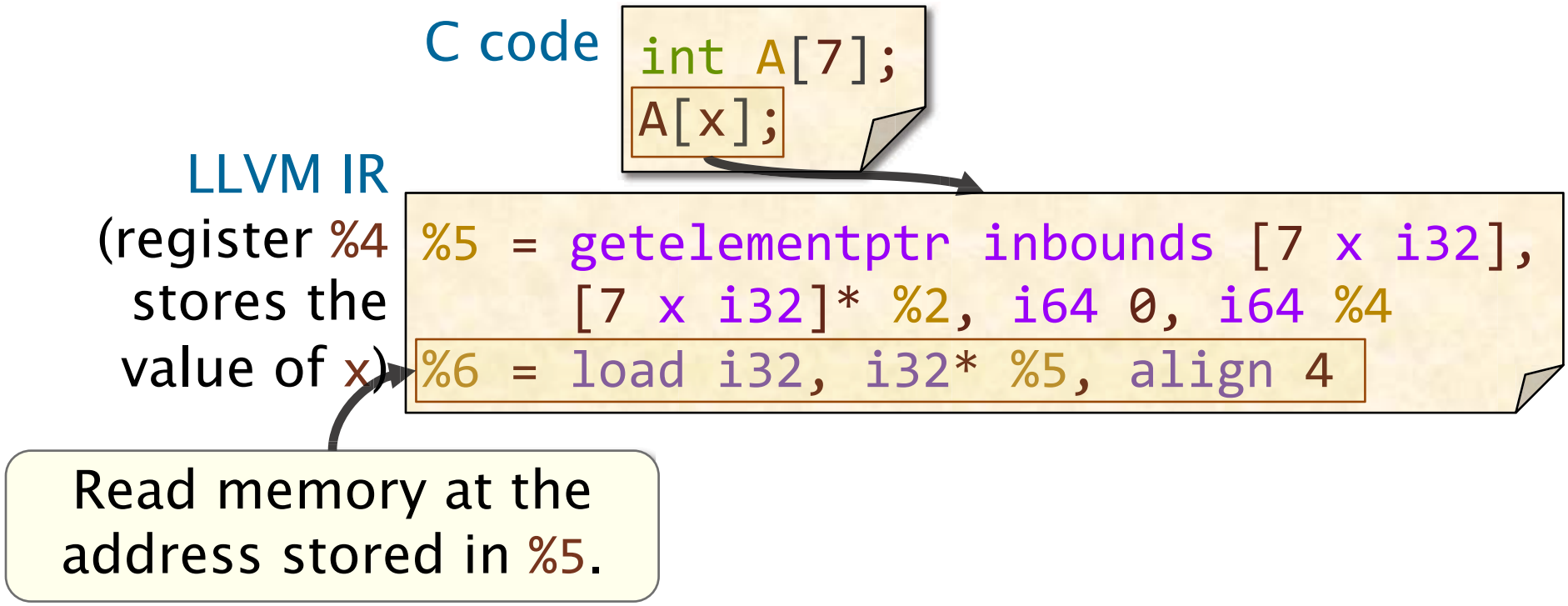
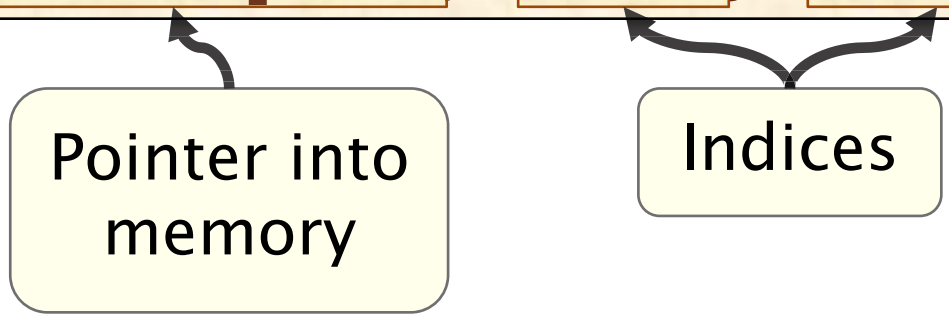


The getelementptr Instruction

The `getelementptr` instruction computes a memory address from a pointer and a list of indices.

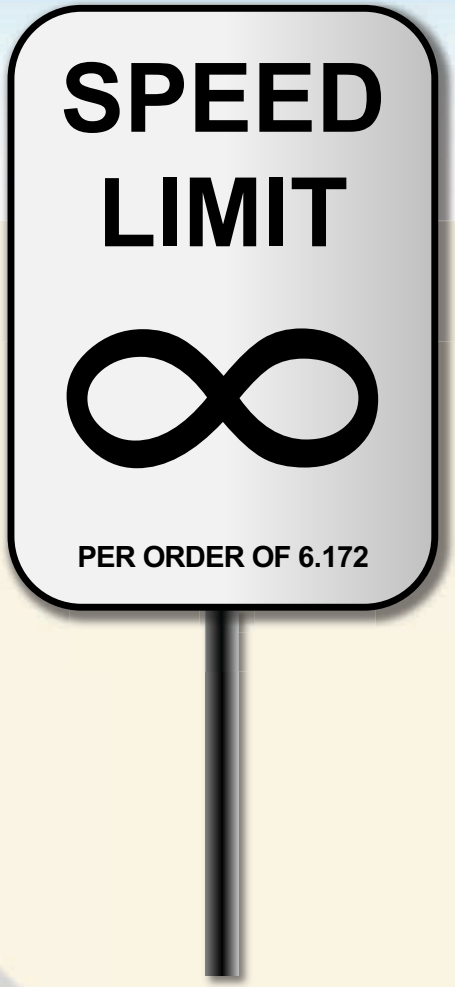
Example: Compute the address `%2 + 0 + %4`

```
%5 = getelementptr inbounds [7 x i32],
     [7 x i32]* %2, i64 0, i64 %4
```



See https://llvm.org/docs/GetElementPtr.html

C Functions to LLVM IR



LLVM IR Functions

Functions in LLVM IR resemble functions in C.

C code `fib.c`

```
int64_t fib(int64_t n) {
  …
  return n;
  …
}
```

LLVM IR `fib.ll`

```
define i64 @fib(i64) local_unnamed_addr #0 {
  …
  ret i64 %0
}
```

Function declarations and definitions are C-like.

A `ret` instruction terminates the function, just like a `return` statement in C.

Function Parameters

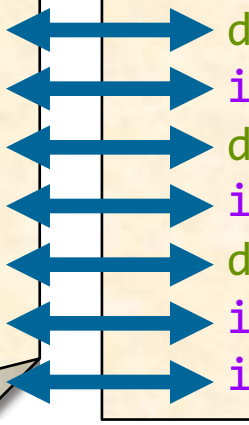
LLVM IR function parameters map directly to their C counterparts.

C code `mm.c`

```
void mm_base(
    double *restrict C,
    int n_C,
    double *restrict A,
    int n_A,
    double *restrict B,
    int n_B,
    int n) { … }
```

LLVM IR: `mm.ll`

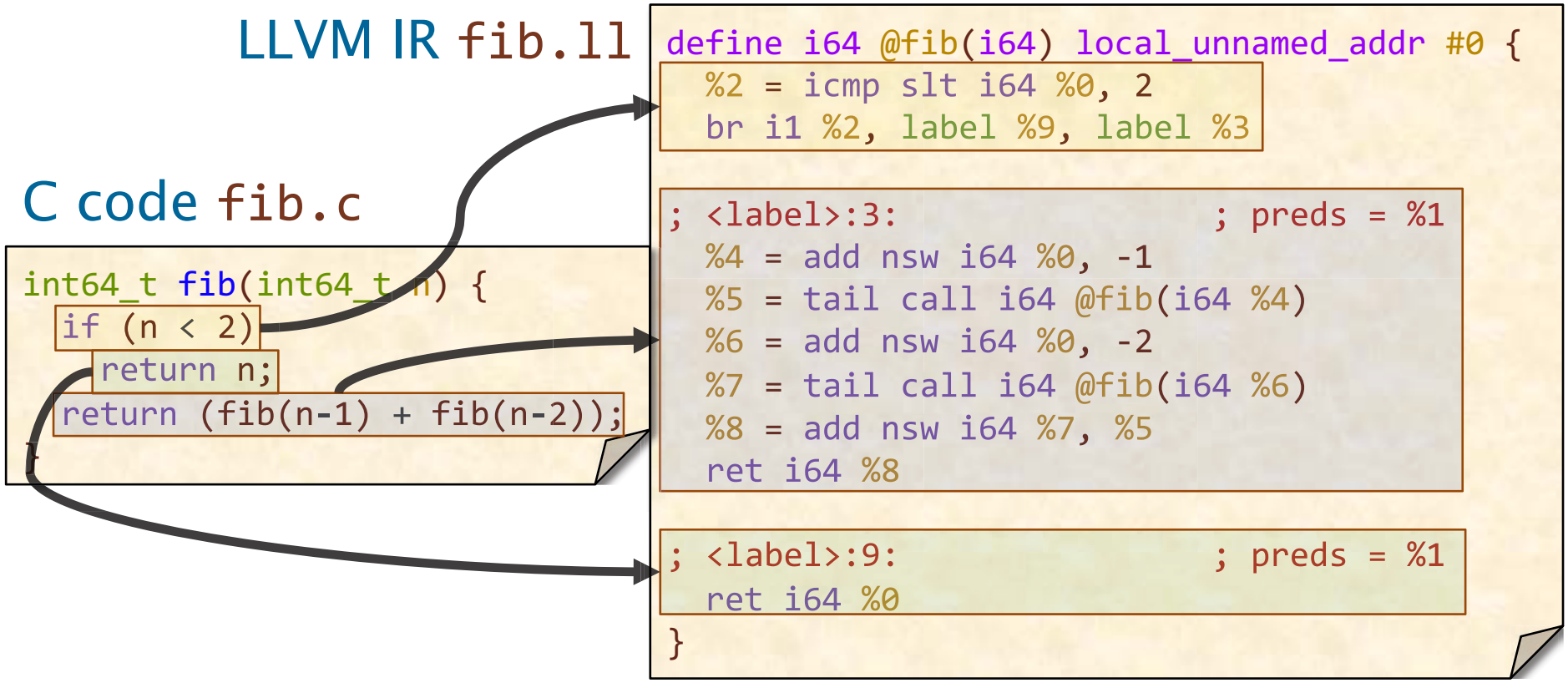
```
define void @mm_base(
    double* noalias nocapture,
    i32,
    double* noalias nocapture readonly,
    i32,
    double* noalias nocapture readonly,
    i32,
    i32) local_unnamed_addr #0 { … }
```



Function parameters are automatically named %0, %1, %2, etc.

Basic Blocks

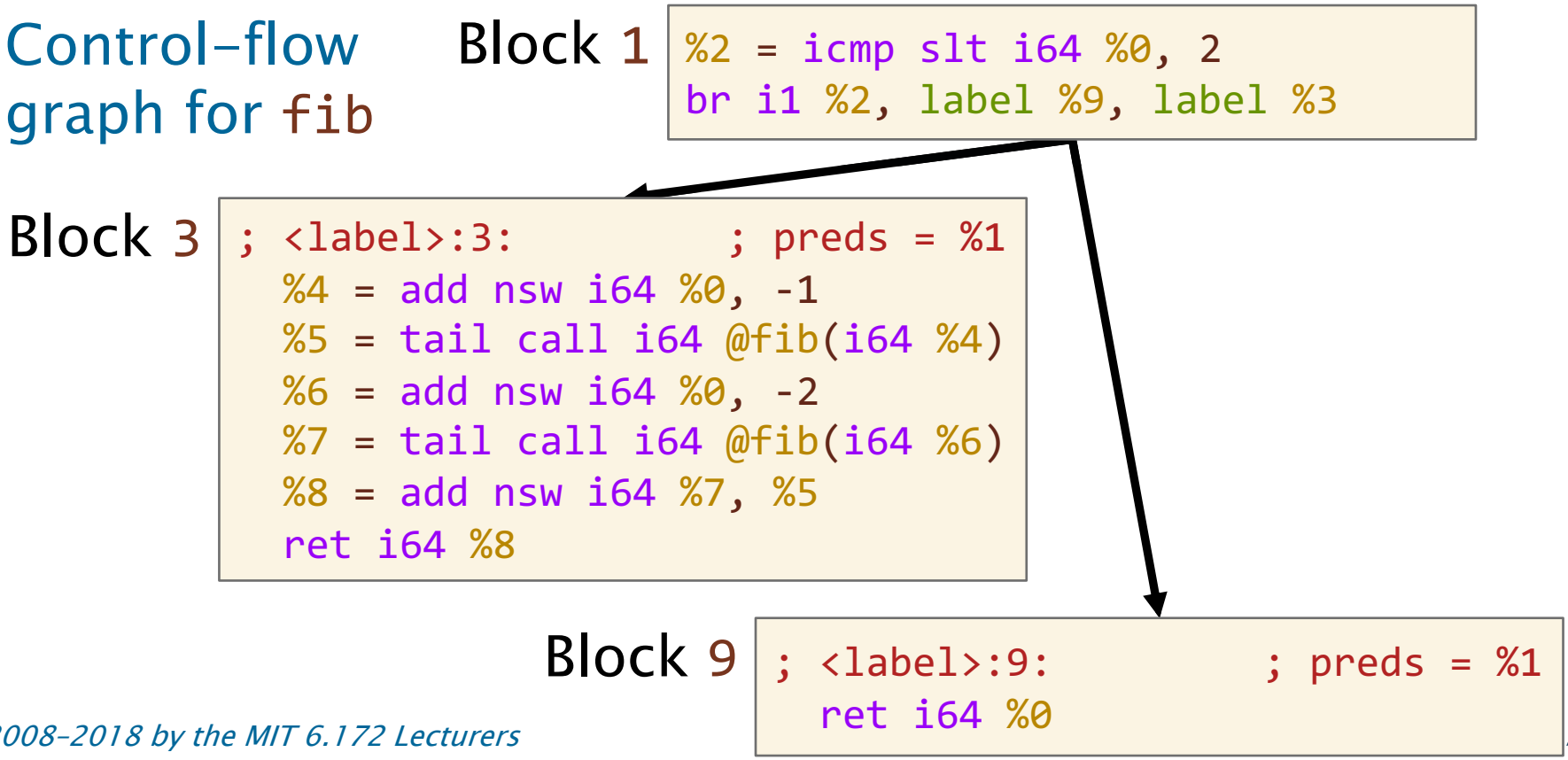
The body of a function definition is partitioned into *basic blocks:* sequences of instructions (i.e., straight-line code) where control only enters through the first instruction and only exits from the last.



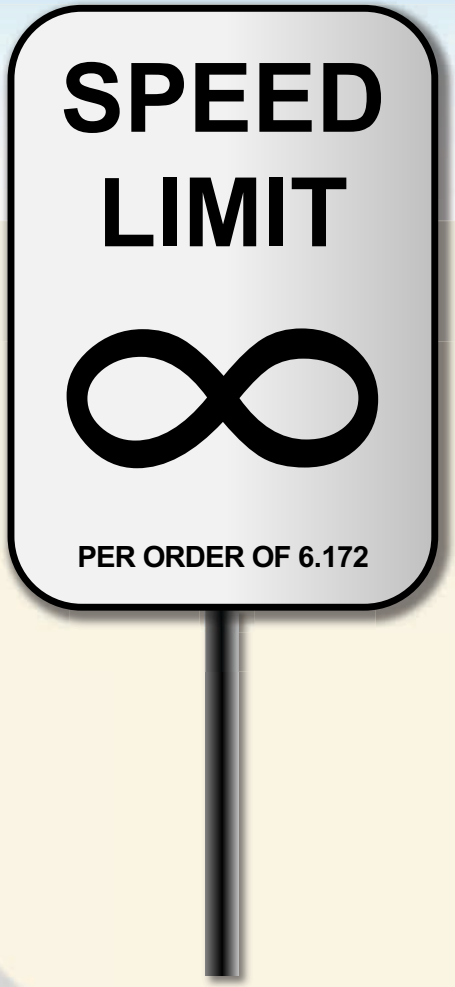
Control-Flow Graphs

Control-flow instructions (e.g., `br` instructions) induce control-flow edges between the basic blocks of a function, creating a control-flow graph (CFG).

Control-flow graph for `fib`



C Conditionals (e.g., If-Then-Else) to LLVM IR



C Conditionals

A conditional in C is translated into a *conditional branch instruction*, `br`, in LLVM IR.

C code `fib.c`

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  return (fib(n-1) + fib(n
}
```

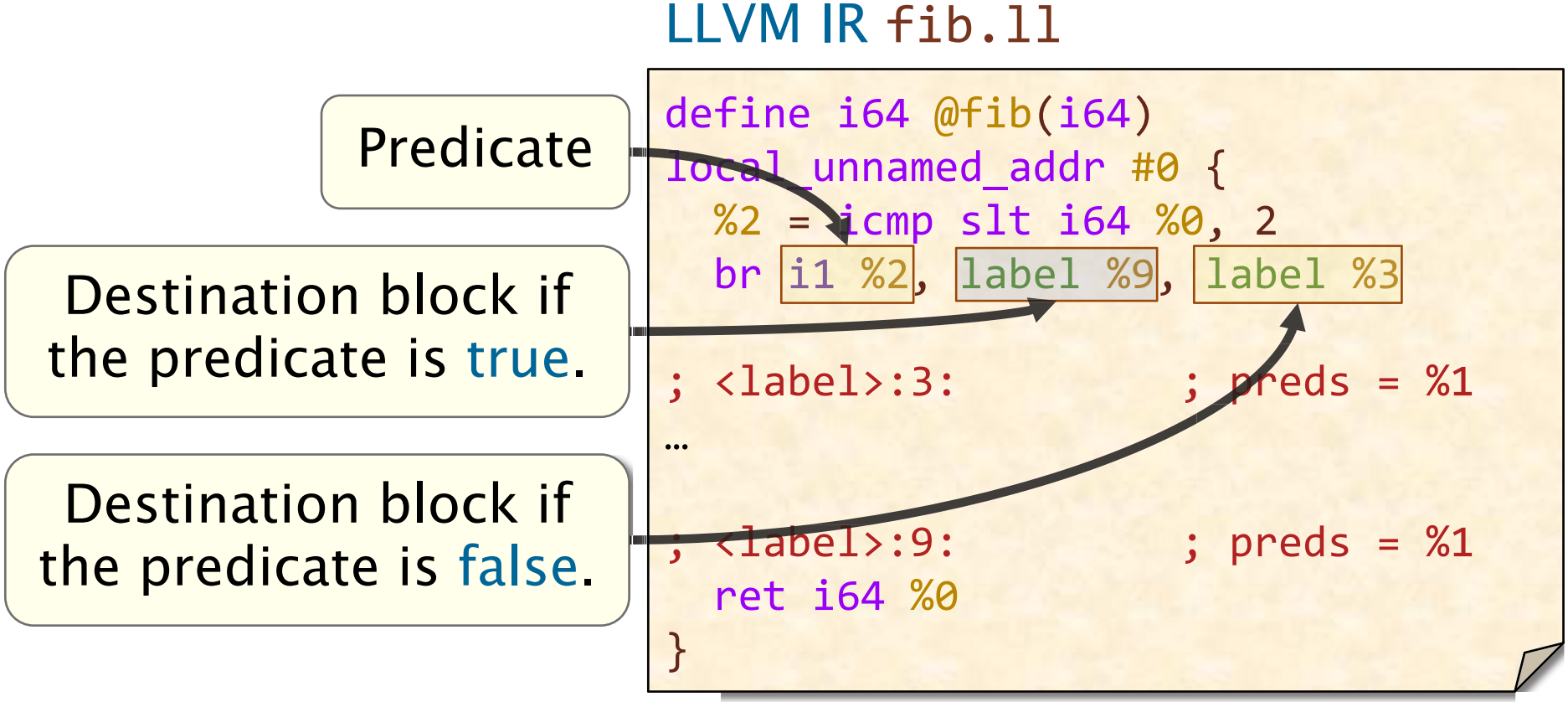
LLVM IR `fib.ll`

```
define i64 @fib(i64)
local_unnamed_addr #0 {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
…

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

The comparison in C becomes an `icmp` instruction.

Arguments of a Conditional Branch

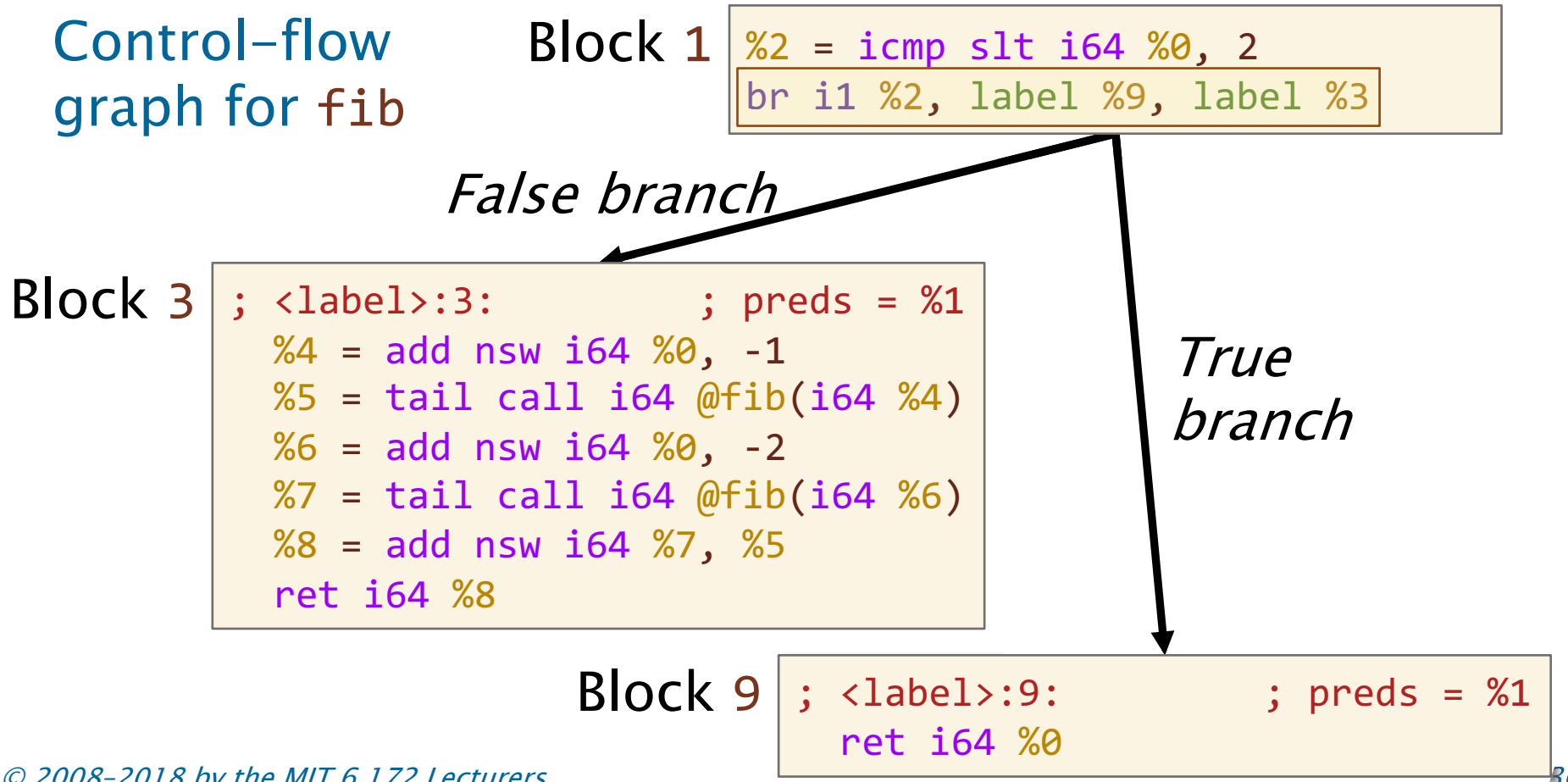
The conditional branch in LLVM IR takes as arguments a 1-bit integer and two basic-block labels.



Conditional Branches in the CFG

A conditional branch terminates its basic block and creates 2 outgoing control-flow edges in the CFG.

Control-flow graph for `fib`



Unconditional Branches

If a `br` instruction has just one operand, it is an *unconditional branch*.

LLVM IR

```
; <label>:4:                    ; preds = %1
  tail call void @foo() #2
  br label %6
```

Unconditional branch to block 6.

An unconditional branch terminates its basic block and produces 1 outgoing control-flow edge.

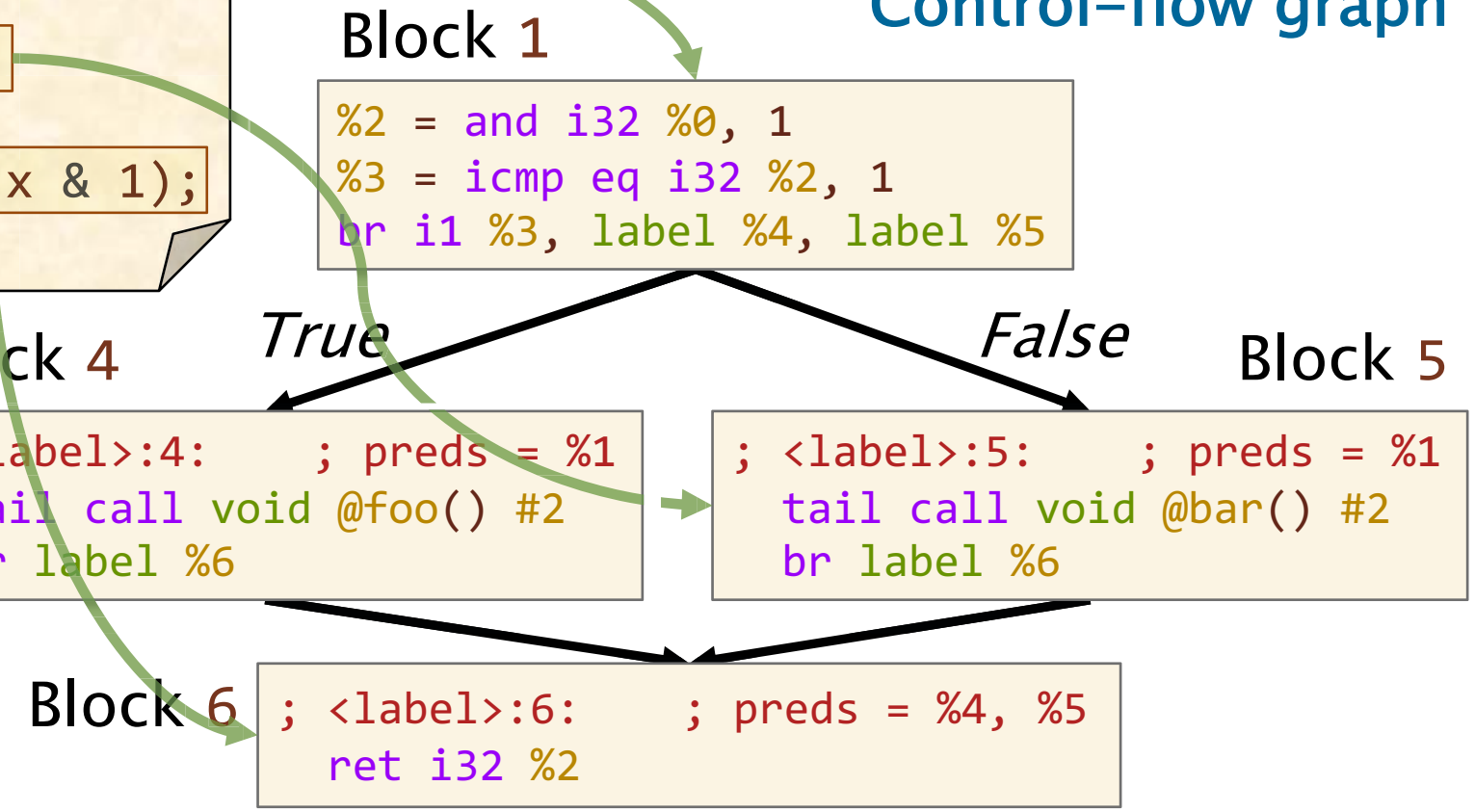
C Conditionals in CFG Form

C code

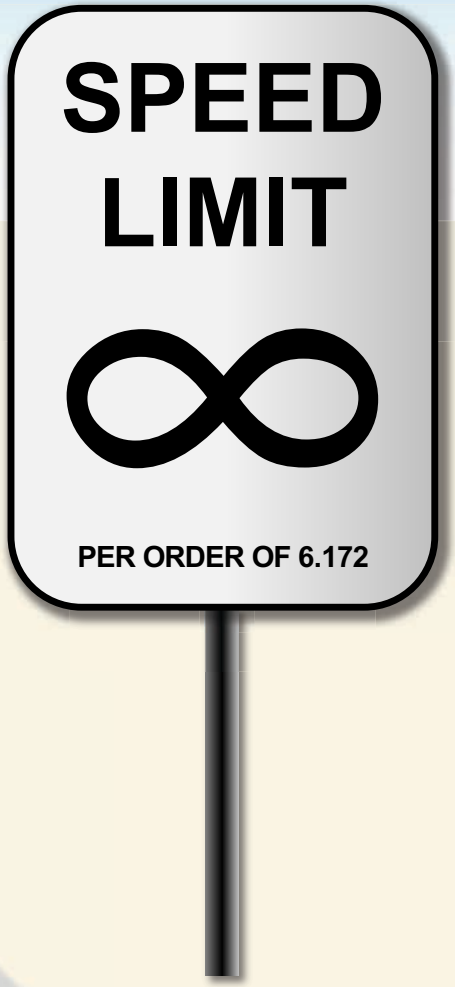
```
int baz(int x) {
  if (x & 1) {
    foo();
  } else {
    bar();
  }
  return (x & 1);
}
```

In general, a C conditional typically creates a ***diamond pattern*** in the CFG.

Control-flow graph



C Loops to LLVM IR



Components of a C Loop

```
void dax(
    double *restrict y, double a,
    const double *restrict x,
    int64_t n) {
  for (int64_t i = 0; i < n; ++i)
    y[i] = a * x[i];
}
```

C code

A C loop involves a *loop body* and *loop control*.

LLVM IR snippet

```
; <label>:8:                                ; preds = %6, %8
%9 = phi i64 [ %14, %8 ], [ 0, %6 ]
%10 = getelementptr inbounds double,
       double* %2, i64 %9
%11 = load double, double* %10, align 8
%12 = fmul double %11, %1
%13 = getelementptr inbounds double,
       double* %0, i64 %9
store double %12, double* %13, align 8
%14 = add nuw nsw i64 %9, 1
%15 = icmp eq i64 %14, %3
br i1 %15, label %7, label %8
```

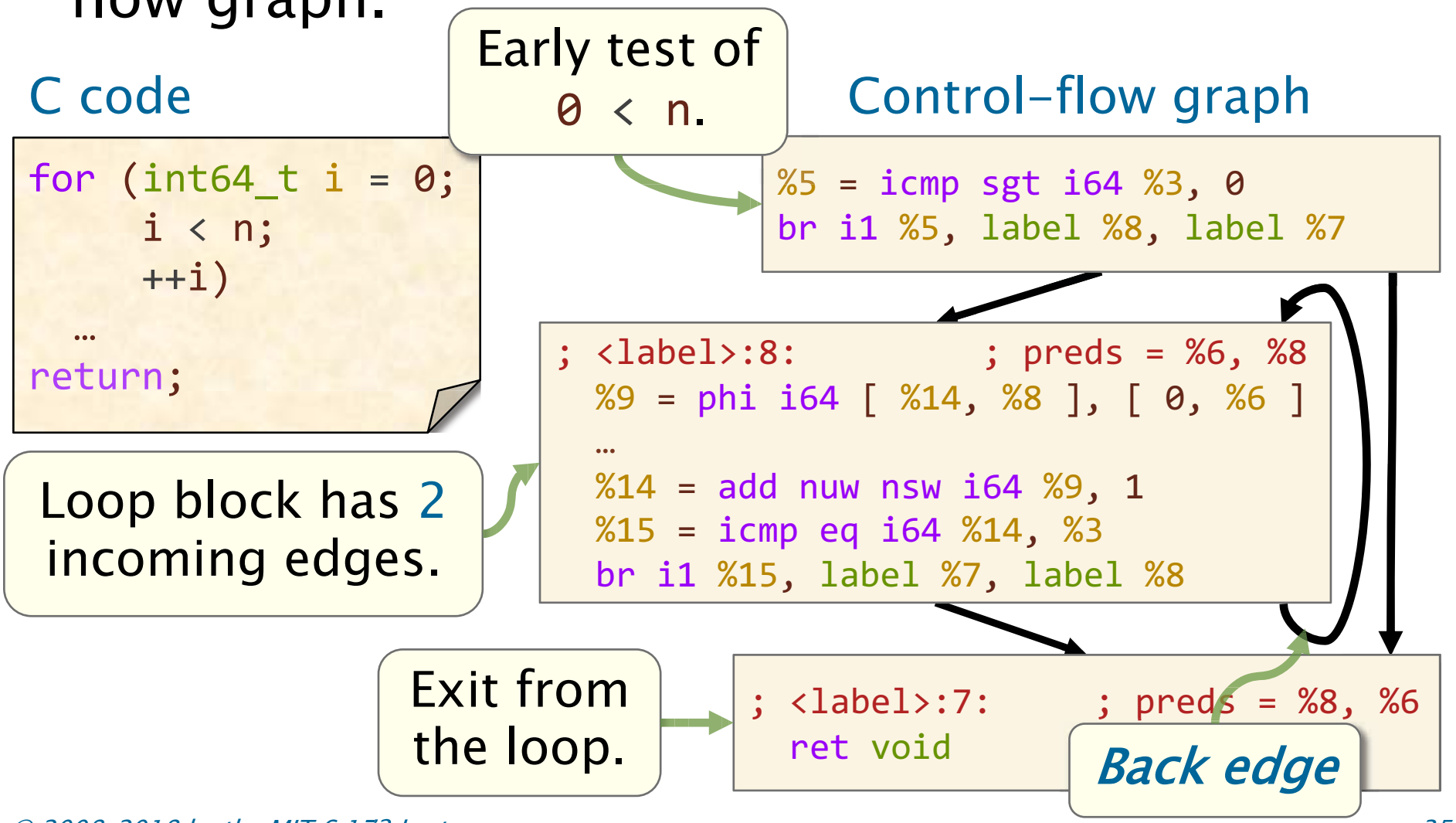
Loop body

Loop control

We'll look at the `phi` instruction soon.

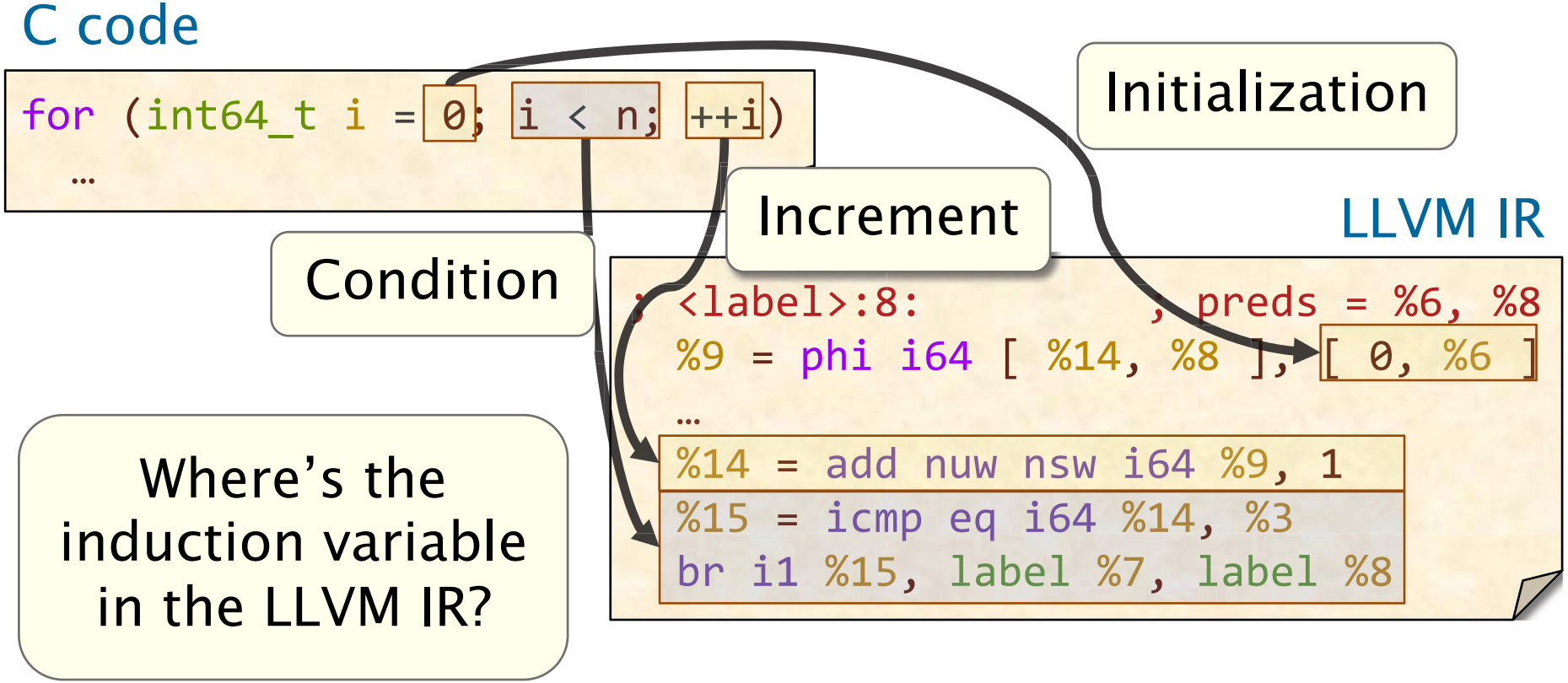
Loops in the CFG

A C loop produces a *loop pattern* in the control-flow graph.



Loop Control

The *loop control* for a C loop consists of a loop induction variable, an initialization, a condition, and an increment.



Loop Induction Variables

The induction variable changes registers at the code for the loop increment.

```
for (int64_t i = 0; i < n; ++i)
  y[i] = a * x[i];
```

C code

LLVM IR

```
; <label>:8:                    ; preds = %6, %8
  %9 = phi i64 [ %14, %8 ], [ 0, %6 ]
  %10 = getelementptr inbounds double,
        double* %2, i64 %9
  %11 = load double, double* %10, align 8
  %12 = fmul double %11, %1
  %13 = getelementptr inbounds double,
        double* %0, i64 %9
  store double %12, double* %13, align 8
  %14 = add nuw nsw i64 %9, 1
  %15 = icmp eq i64 %14, %3
  br i1 %15, label %7, label %8
```

Why change registers?

Because the loop increment redefines its value.

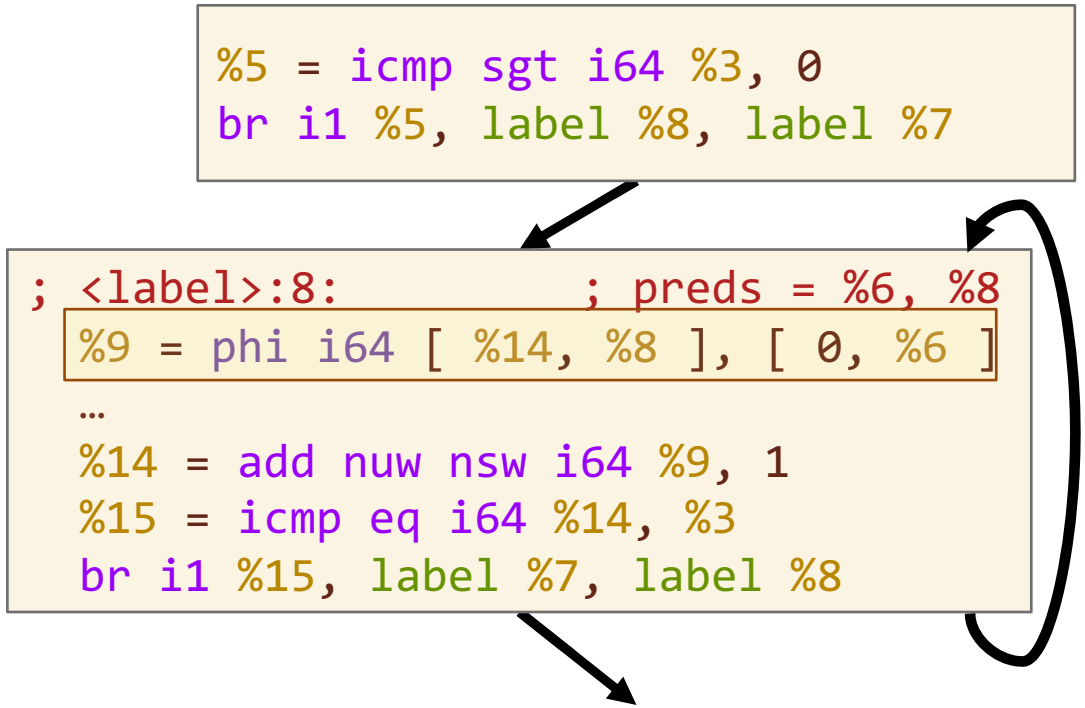
Static Single Assignment

LLVM IR maintains the *static single assignment (SSA)* invariant: a register is defined by at most one instruction in a function.

PROBLEM: What happens when control flow merges, e.g., at the entry point of a loop?

SOLUTION: The `phi` instruction.

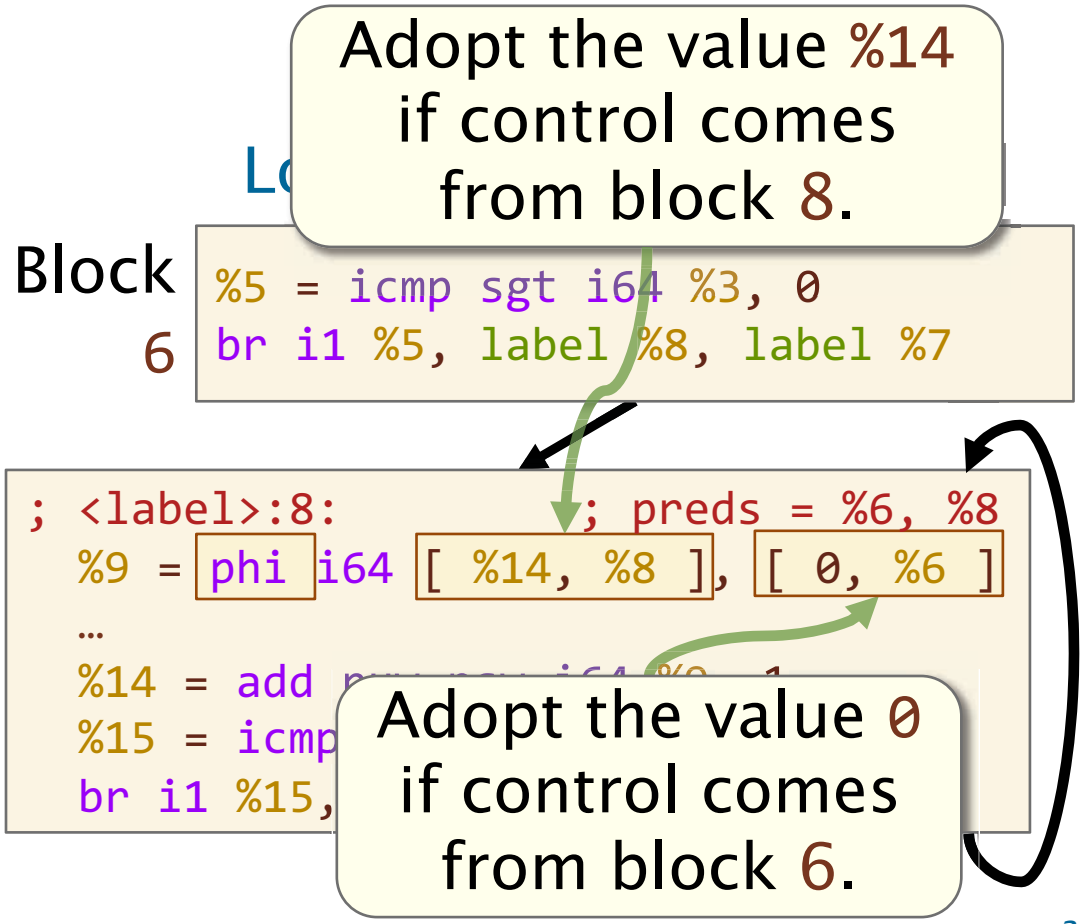
Loop control-flow graph



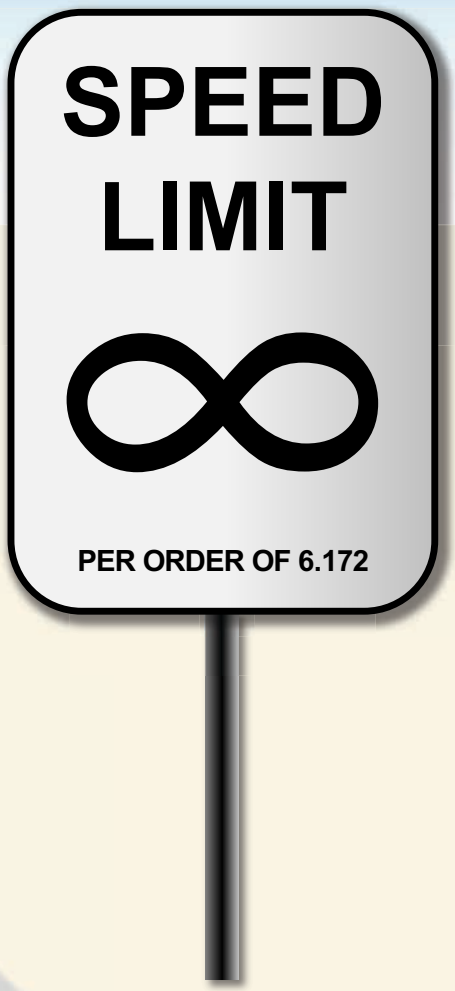
The Phi Instruction

The phi instruction specifies, for each predecessor P of a basic block B, the value of the destination register if control enters B via P.

- A block with multiple incoming edges may have phi instructions.
- The phi instruction is not a real instruction.



LLVM IR Attributes



Attributes

LLVM IR constructs (e.g., instructions, operands, functions, and function parameters) might be decorated with *attributes*.

C code

```
const uint64_t deBruijn = 0x022fdd63cc95386d;
const int convert[64] = { … };
int r = convert[(x * deBruijn) >> 58];
```

LLVM IR

```
%4 = getelementptr inbounds [64 x i32],
[64 x i32]* @convert, i64 0, i64 %3
%5 = load i32, i32* %4, align 4, !tbaa !2
```

Attribute describing the alignment of the read from memory.

Where Do Attributes Come From?

Some attributes are derived from the source code.

C code saxpy.c

```
void saxpy(…
           const double *restrict x,
           …)
```

LLVM IR saxpy.ll

```
define void @saxpy(
  …
  double* noalias nocapture readonly,
  …)
```

Other attributes are determined by compiler analysis.

Analysis determined the alignment of this read.

LLVM IR

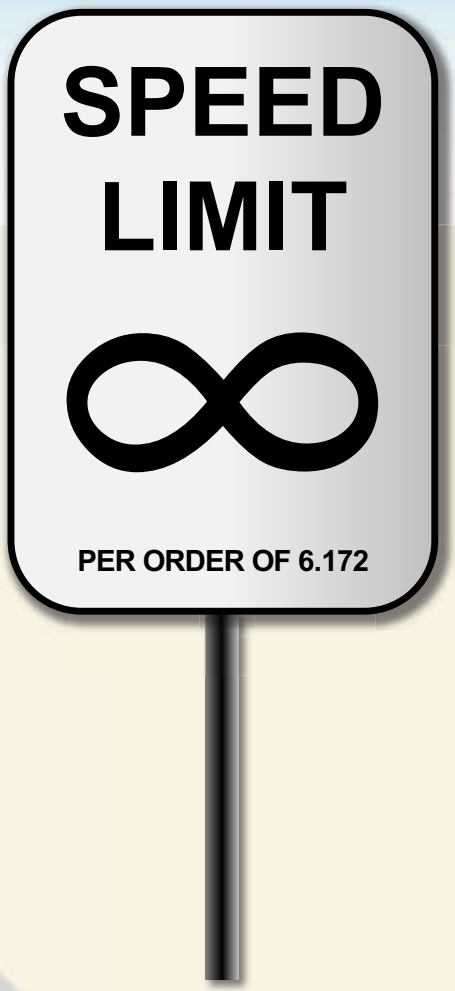
```
%15 = load double, double* %14, align 8
```

Summary of LLVM IR

LLVM IR is similar to assembly, but simpler.

- All computed values are stored in *registers*.
- *Static single assignment:* Each register name is written on at most one line of IR.
- A function is modeled as a *control-flow graph*, whose nodes are *basic blocks*, and whose edges denote control flow between basic blocks.
- Compared to C, all operations are explicit.
  - All integer sizes are apparent.
  - There are no implicit operations, e.g., type casts.

LLVM IR to Assembly



Mapping LLVM IR To Assembly

LLVM IR is structurally similar to assembly.

LLVM IR code `fib.ll`

```
define i64 @fib(i64) local_unnamed_addr #0
{
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                                ; preds = %1
  ret i64 %0
}
```

Assembly code `fib.s`

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

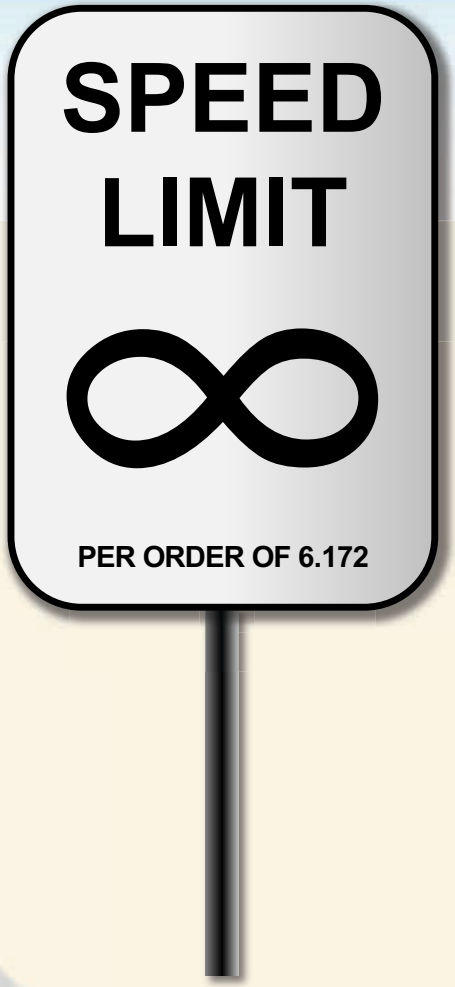
Translating LLVM IR to Assembly

The compiler must perform three tasks to translate LLVM IR into x86-64 assembly.

- Select assembly instructions to implement LLVM IR instructions.
- Allocate x86-64 general-purpose registers to hold values.
- Coordinate function calls.

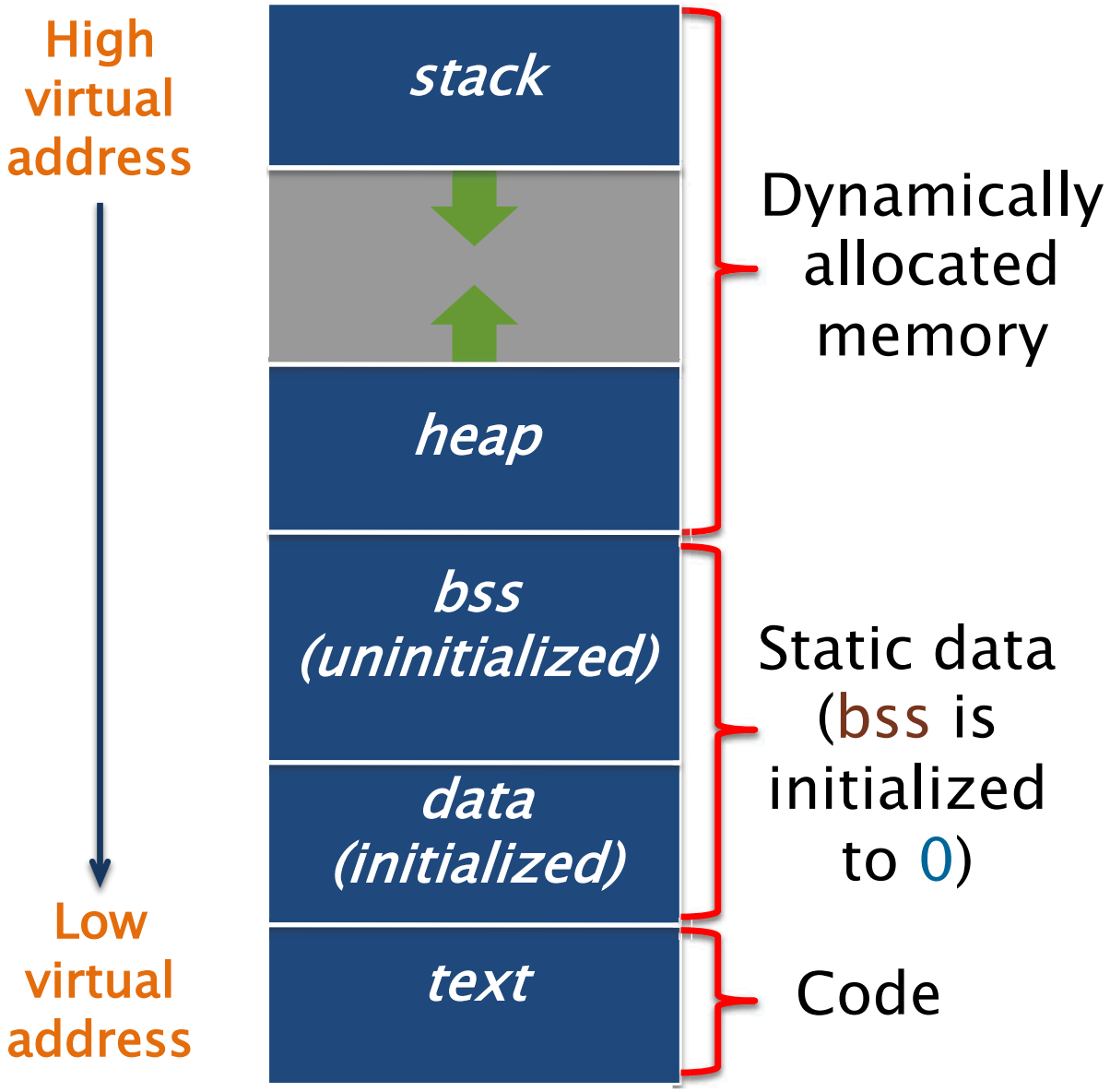
Our main focus

The Linux x86-64 Calling Convention



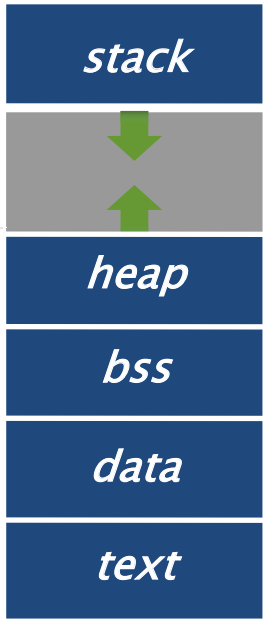
Layout of a Program in Memory

When a program executes, virtual memory is organized into *segments*.



Assembler Directives

Assembly code contains *directives* that refer to and operate on sections of assembly.



- *Segment directives* organize the contents of an assembly file into segments.
  - "`.text`": Identifies the text segment.
  - "`.bss`": Identifies the bss segment.
  - "`.data`": Identifies the data segment.
- *Storage directives* store content into the current segment.

  Examples:

```
x: .space 20
y: .long 172
z: .asciz "6.172"
   .align 8
```

  Allocates 20 bytes at location x.
  Stores the constant 172L at location y.
  Stores the string "6.172\0" at location z.
  Align the next content to an 8-byte boundary.

- *Scope and linkage directives* control linking.

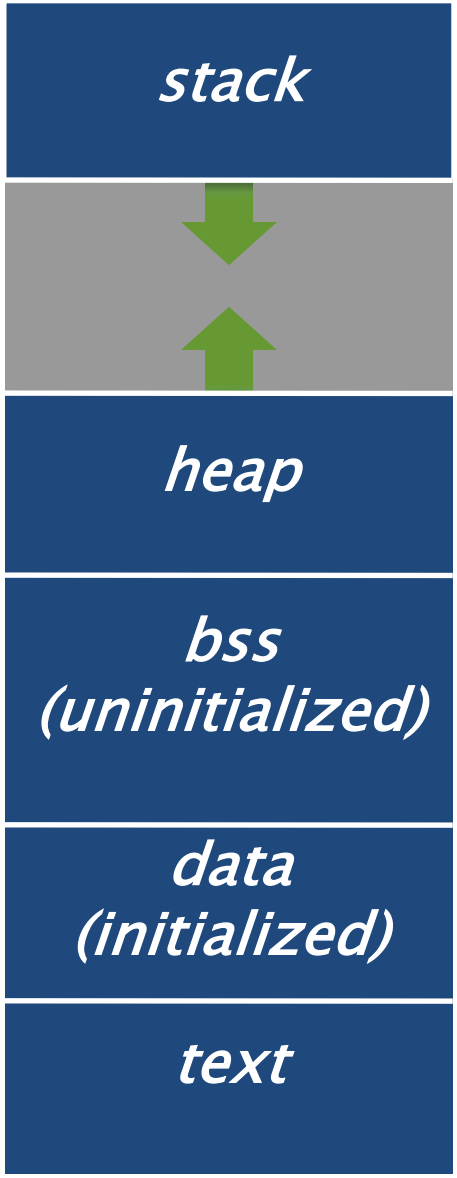
  Example: "`.globl fib`": Makes "`fib`" visible to other object files.

The Call Stack

The *stack* segment stores data in memory to manage function calls and returns.

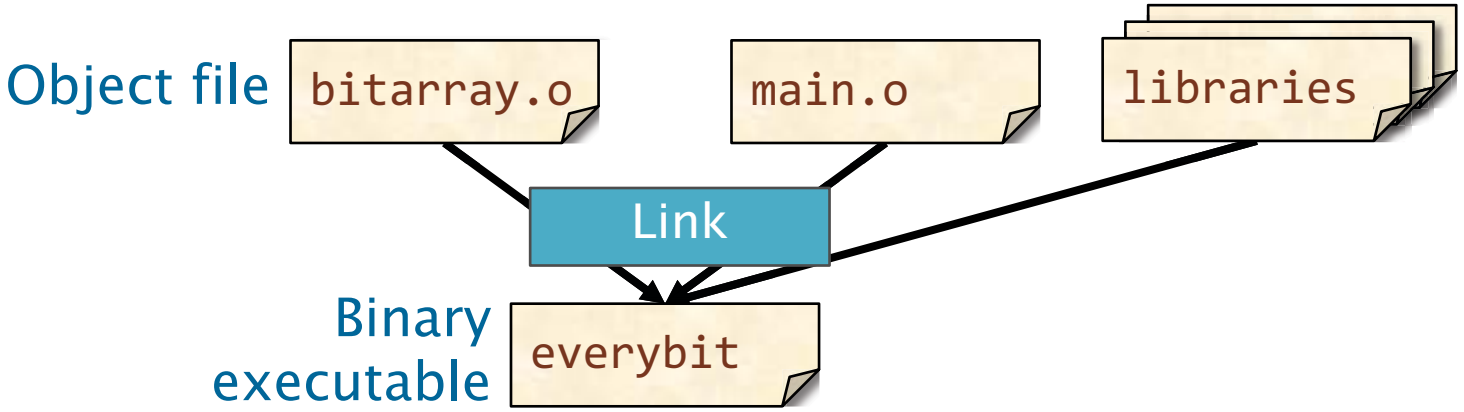
More specifically, what data is stored on the stack?

- The return address of a function call.
- Register state, so different functions can use the same registers.
- Function arguments and local variables that don't fit in registers.



Coordinating Function Calls

PROBLEM: How do functions in different object files coordinate their use of the stack and of register state?



ANSWER: Functions abide by a *calling convention*.

Linux x86-64 Calling Convention

The Linux x86-64 calling convention organizes the stack into *frames*, where each function instantiation gets a single frame of its own.

- The `%rbp` register points to the top of the current stack frame.
- The `%rsp` register points to the bottom of the current stack frame.

The call and ret instructions use the stack and the instruction pointer, `%rip`, to manage the return address of each function call.

- A call instruction in x86-64 pushes `%rip` onto the stack and jumps to the operand, which is the address of a function.
- A ret instruction in x86-64 pops `%rip` from the stack and returns to the caller.

Maintaining Registers Across Calls

PROBLEM: Who's responsible for preserving the register state across a function call and return?

- The *caller* might waste work saving register state that the callee doesn't use.
- The *callee* might waste work saving register state that the caller wasn't using.

ANSWER: The Linux x86-64 calling convention does a bit of both.

- *Callee-saved registers:* %rbx, %rbp, %r12-%r15.
- All other registers are *caller-saved*.

C Linkage for x86-64 GPR's

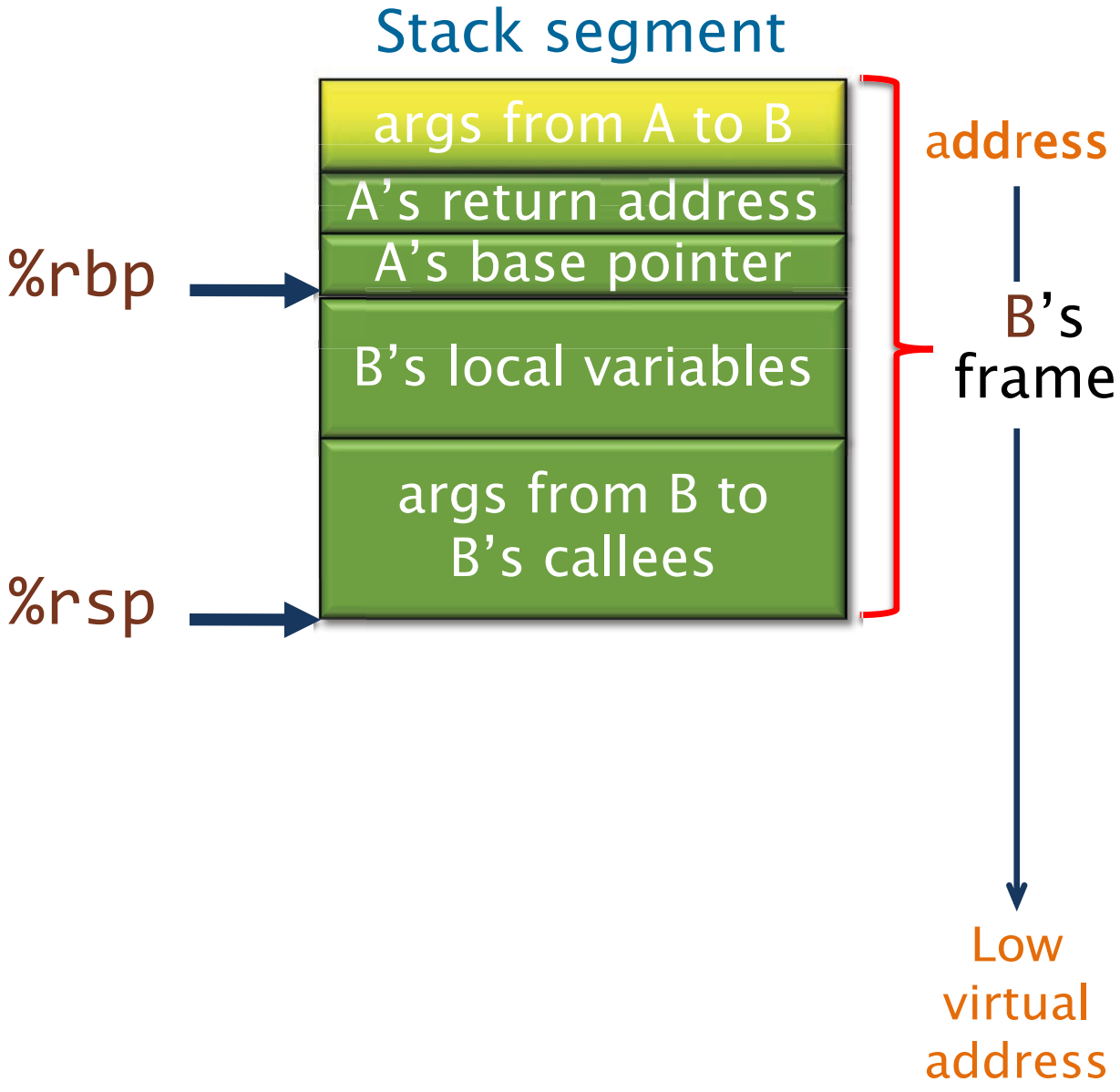
C linkage	64-bit name	32-bit name	16-bit name	8-bit name(s)
Return value	%rax	%eax	%ax	%ah, %al
Callee saved	%rbx	%ebx	%bx	%bh, %bl
4th argument	%rcx	%ecx	%cx	%ch, %cl
3rd argument	%rdx	%edx	%dx	%dh, %dl
2nd argument	%rsi	%esi	%si	%sil
1st argument	%rdi	%edi	%di	%dil
Base pointer	%rbp	%ebp	%bp	%bpl
Stack pointer	%rsp	%esp	%sp	%spl
5th argument	%r8	%r8d	%r8w	%r8b
6th argument	%r9	%r9d	%r9w	%r9b
Callee saved	%r10	%r10d	%r10w	%r10b
For linking	%r11	%r11d	%r11w	%r11b
Callee saved	%r12			
Callee saved	%r13			
Callee saved	%r14			
Callee saved	%r15			

The registers %xmm0–%xmm7 are used to pass floating-point arguments.

Example: Linux C Subroutine Linkage

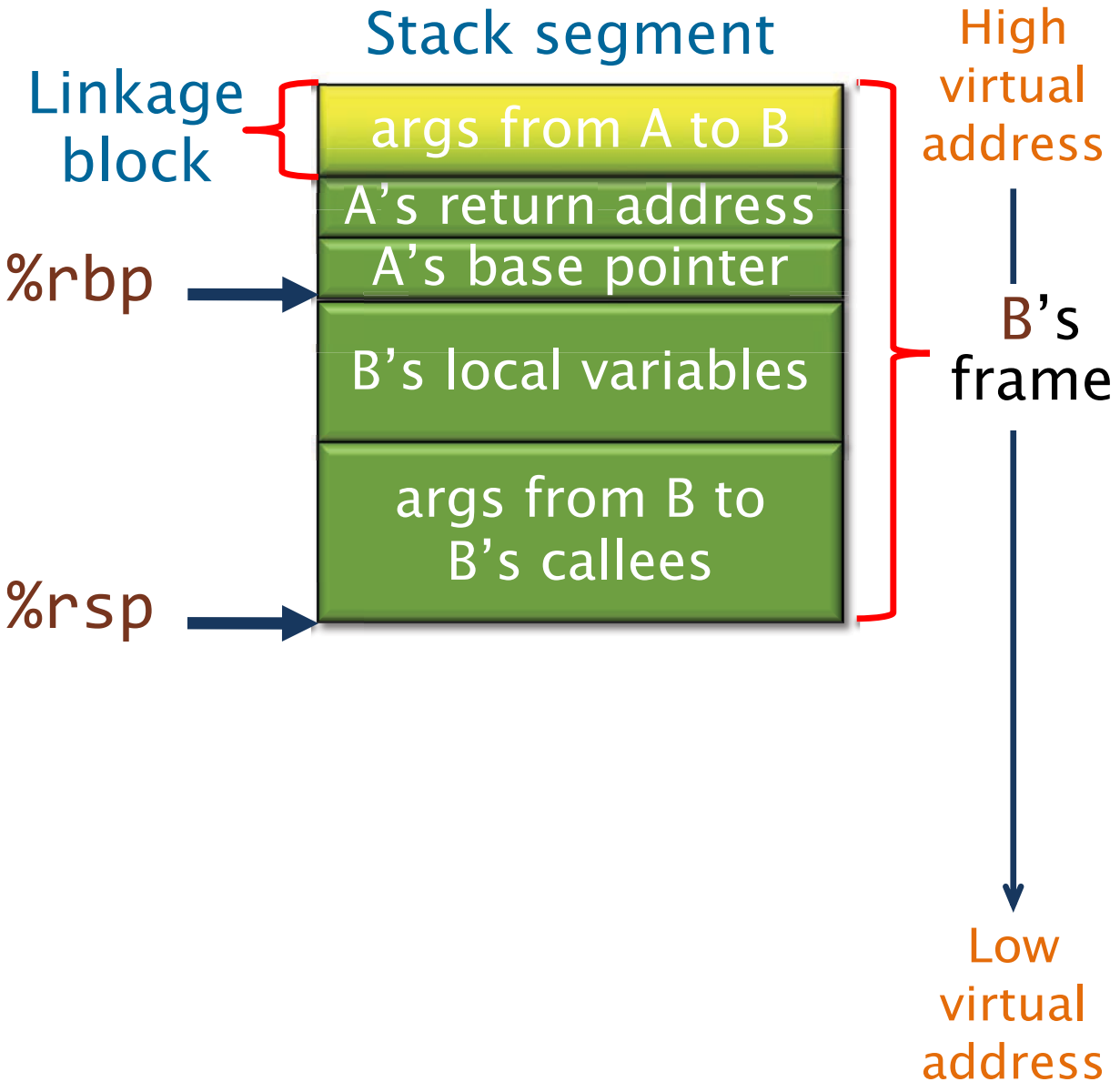
Let's work through an example function call in action.

SETUP: Function B was called from function A and is about to call function C.



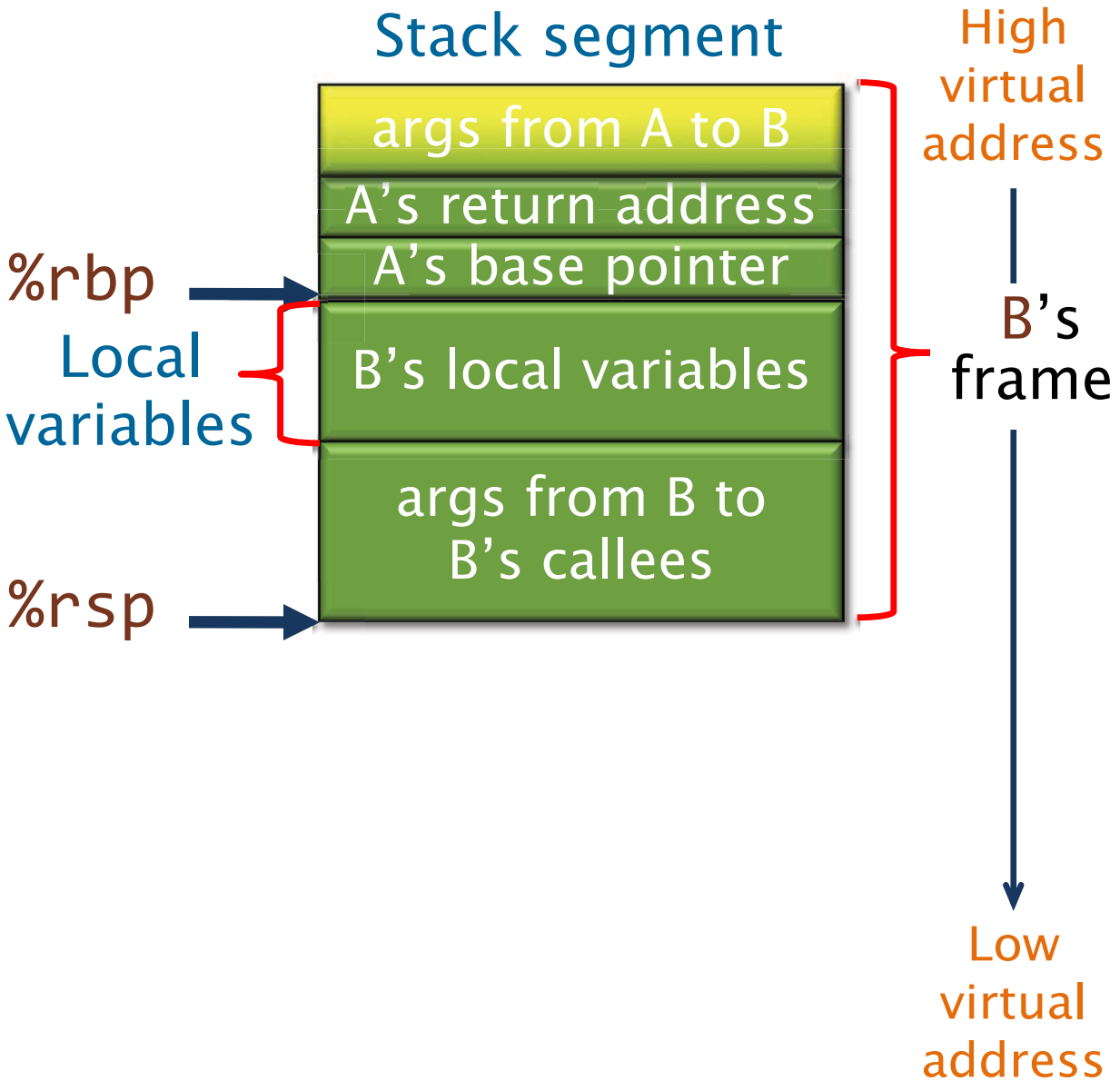
Example: Linux C Subroutine Linkage

Function B accesses its nonregister arguments from A, which lie in a *linkage block*, by indexing %rbp with positive offsets.



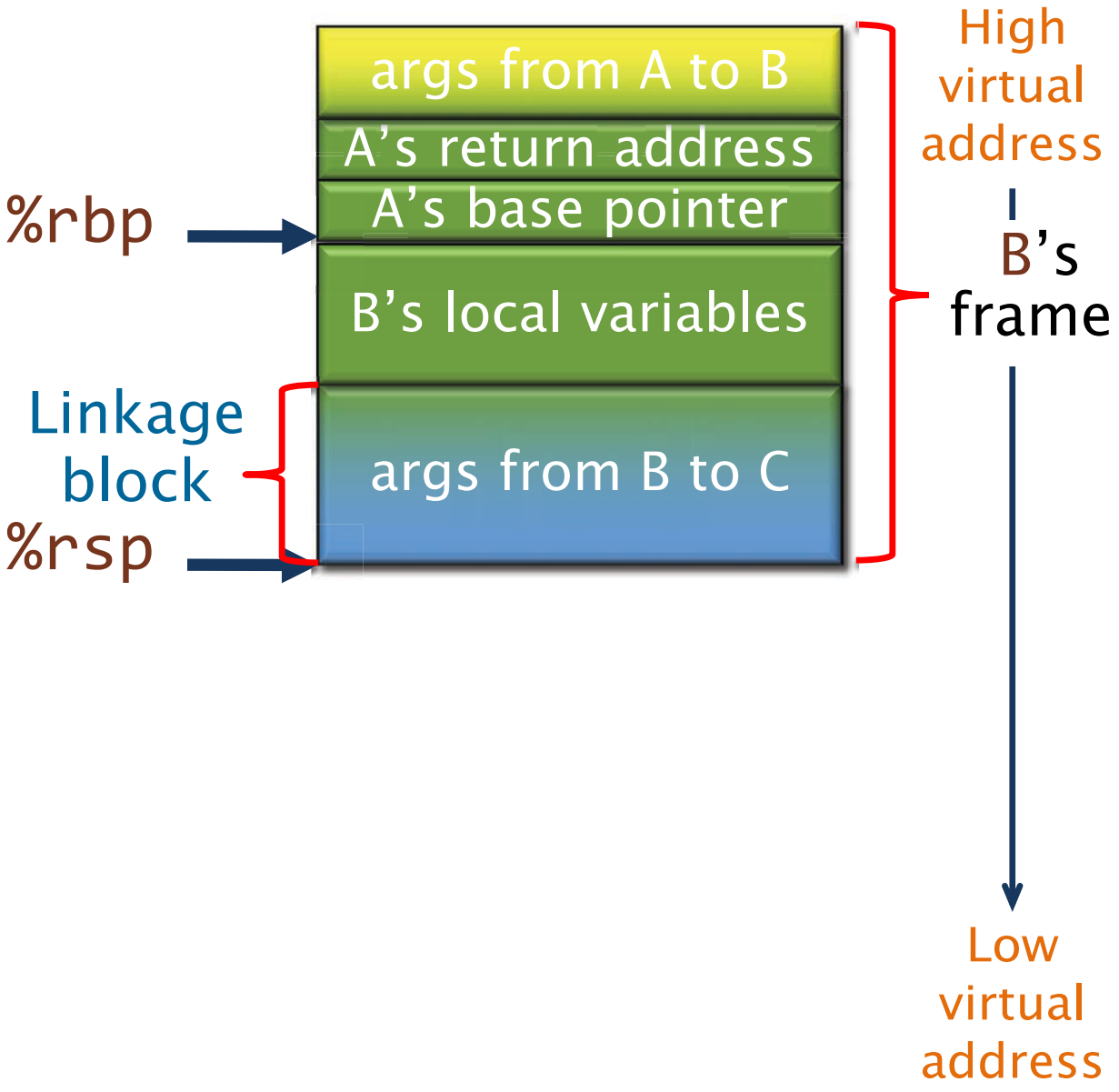
Example: Linux C Subroutine Linkage

Function B accesses its local variables by indexing %rbp with negative offsets.



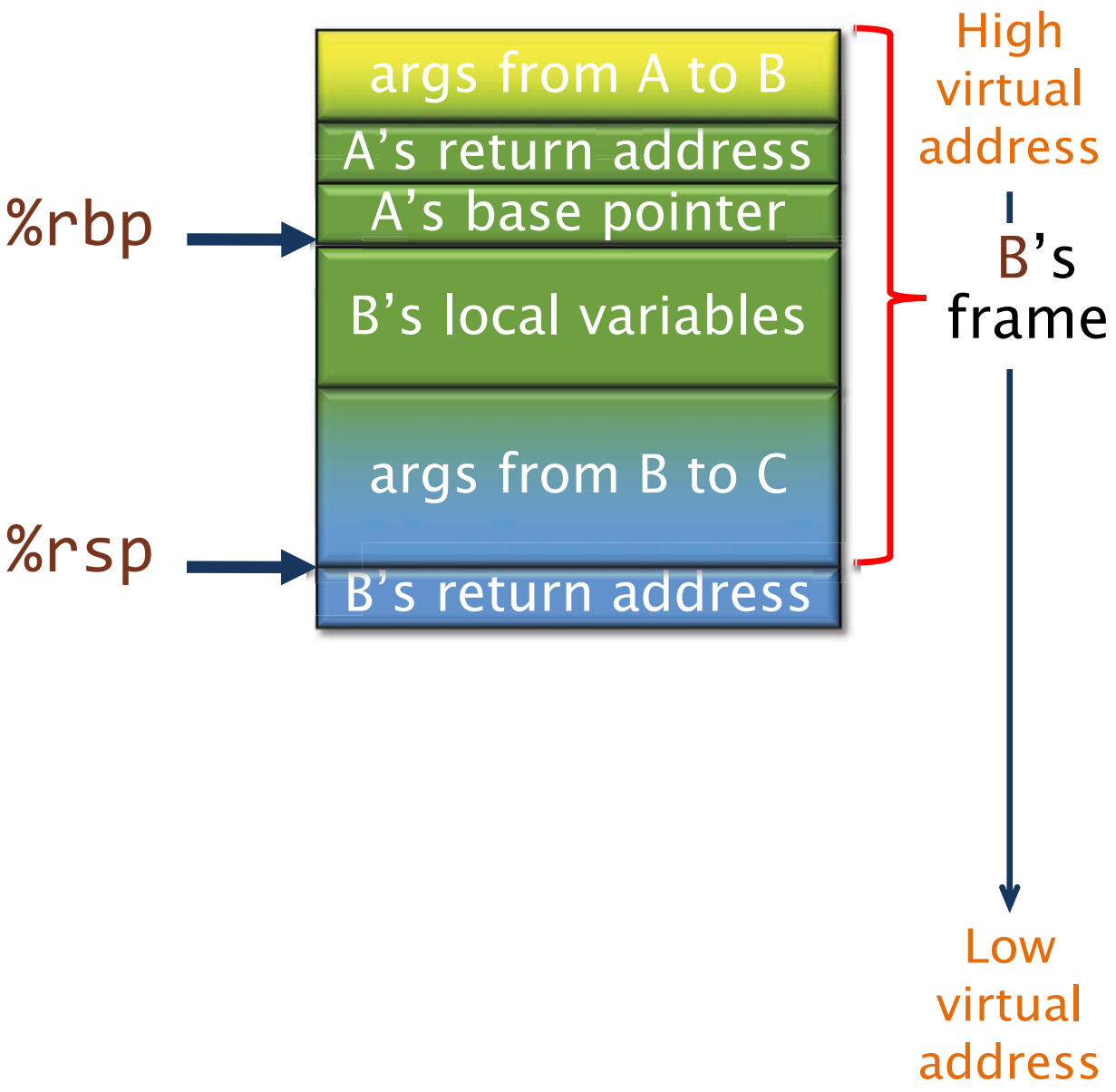
Example: Linux C Subroutine Linkage

Before calling C, B places the nonregister arguments for C into the reserved linkage block it will share with C, which B accesses by indexing %rbp with negative offsets.



Example: Linux C Subroutine Linkage

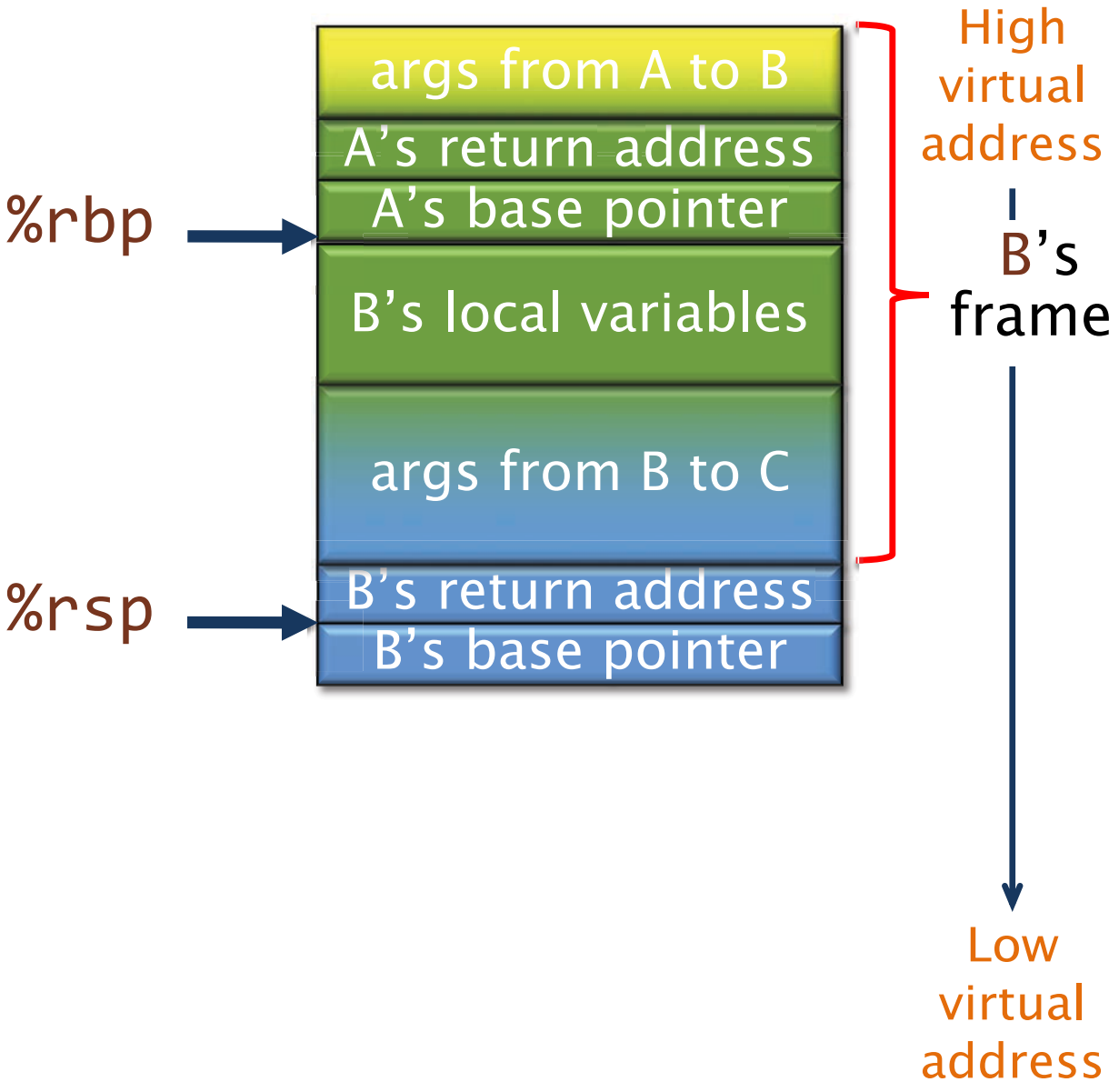
B calls C, which saves the return address for B on the stack and transfers control to C.



Example: Linux C Subroutine Linkage

When function C starts, it executes a function prologue:

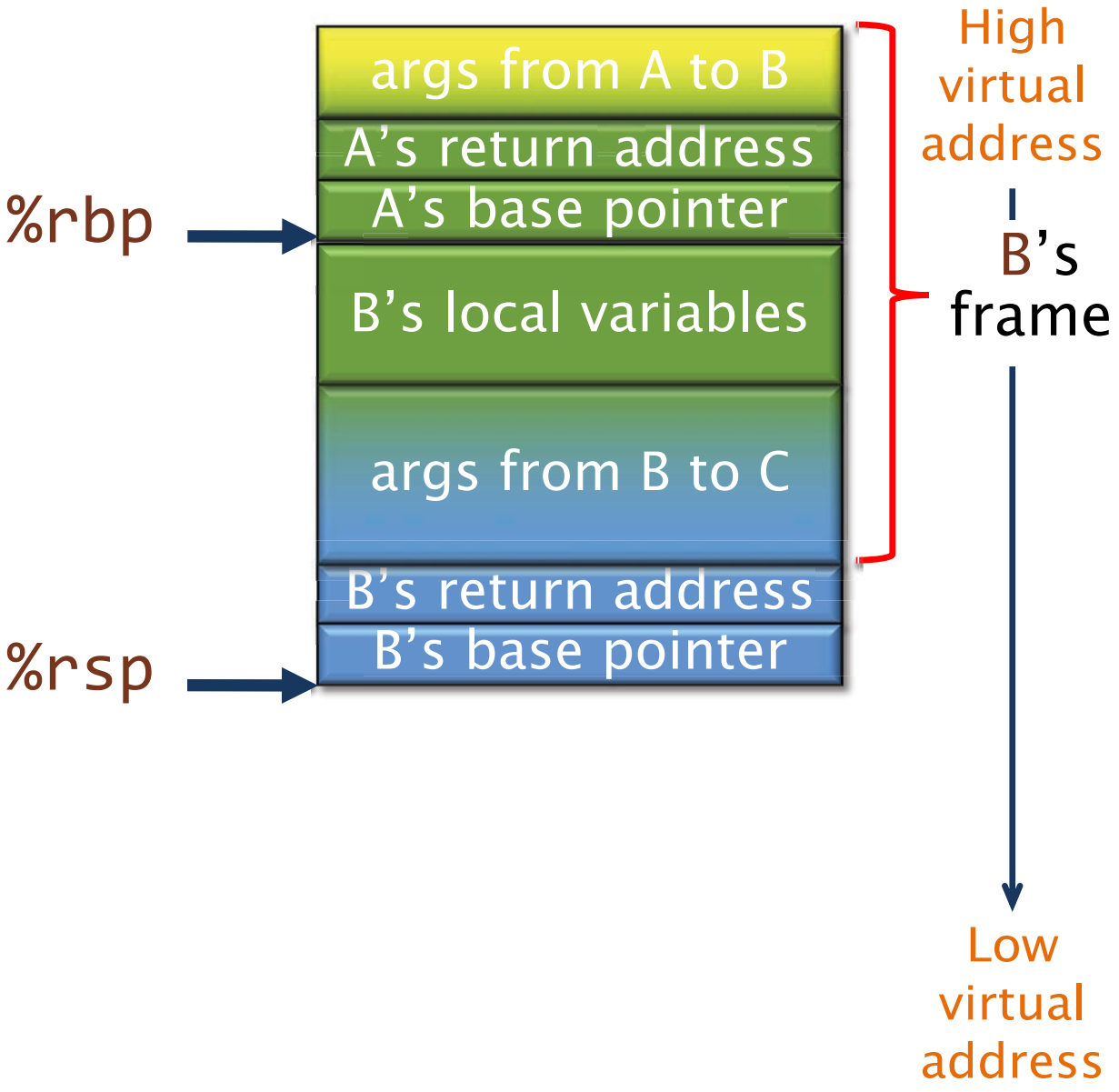
1. Save B's base pointer on the stack,



Example: Linux C Subroutine Linkage

When function C starts, it executes a function prologue:

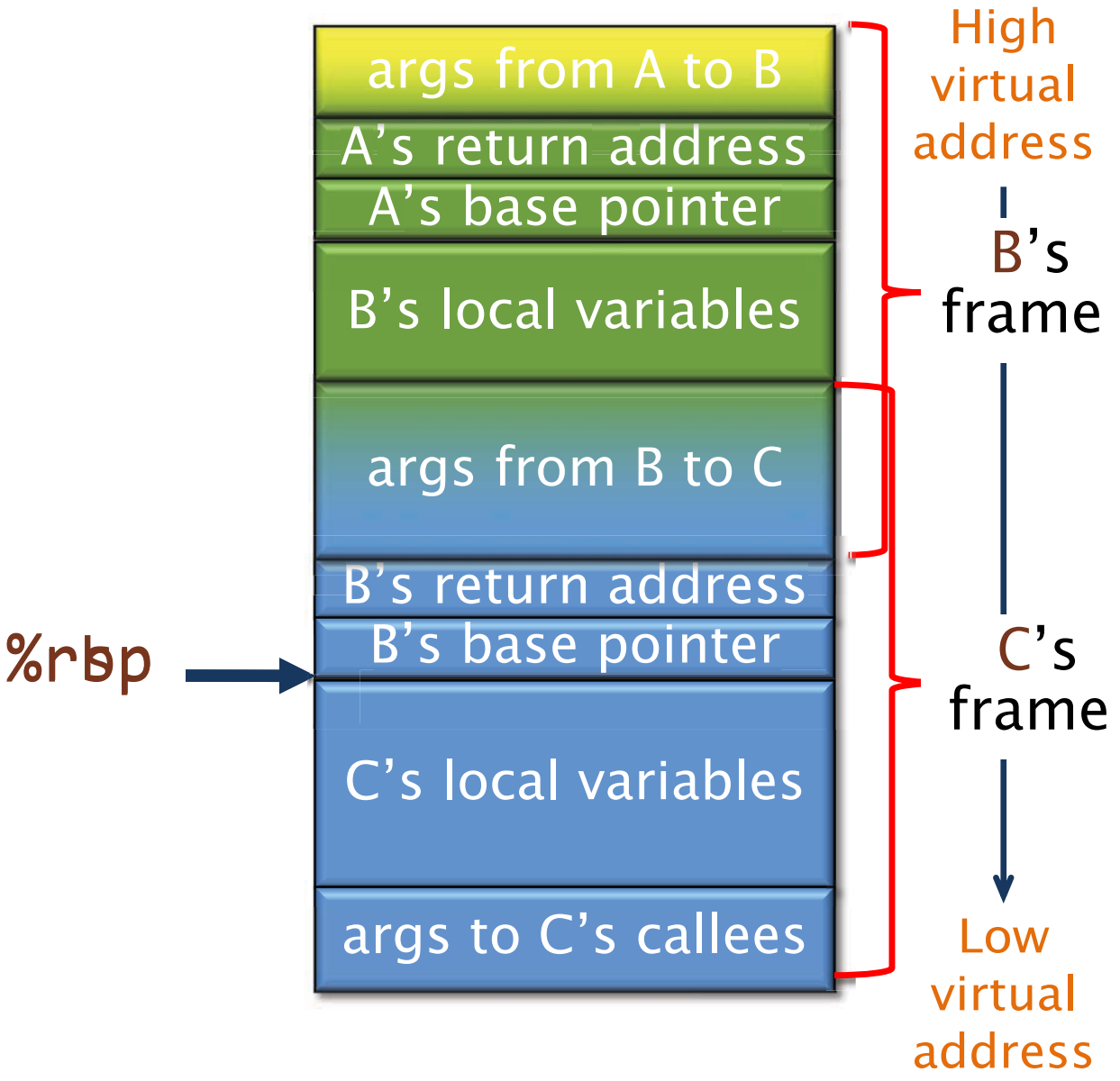
1. Save B's base pointer on the stack,
2. Set `%rbp=%rsp`,



Example: Linux C Subroutine Linkage

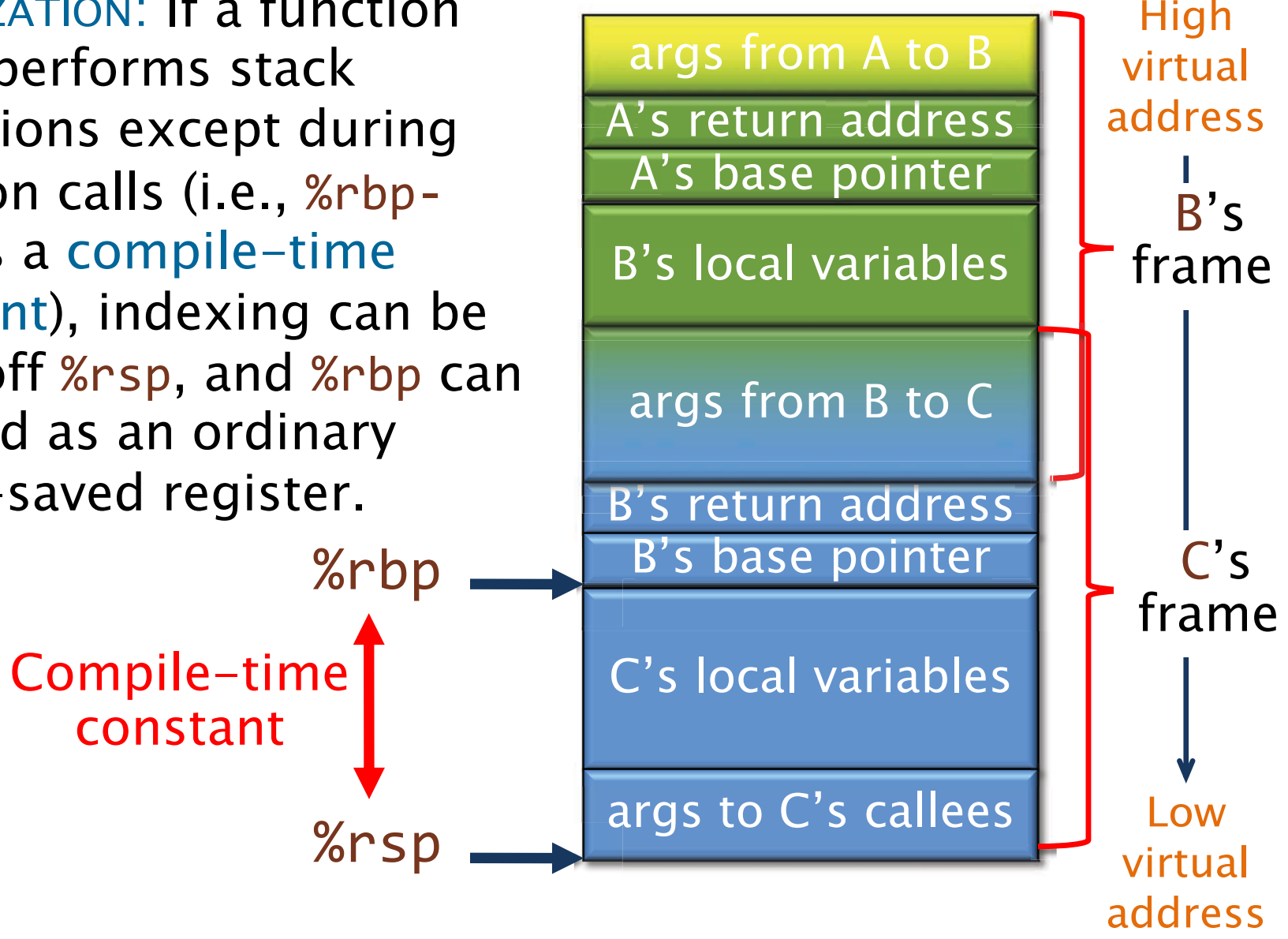
When function C starts, it executes a function prologue:

1. Save B's base pointer on the stack,
2. Set `%rbp=%rsp`,
3. Advance `%rsp` to allocate space for C's local variables and linkage block.



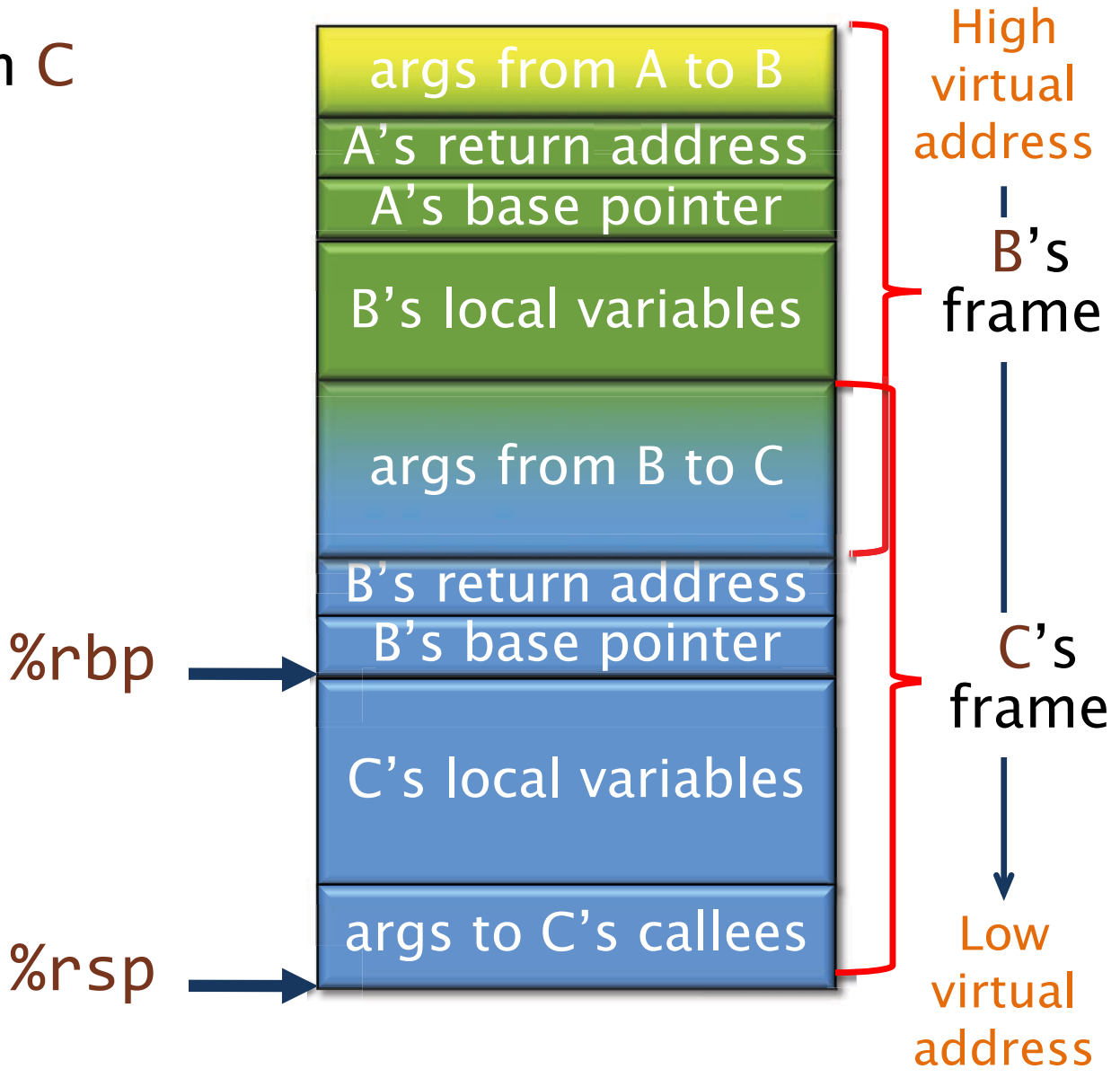
Example: Linux C Subroutine Linkage

OPTIMIZATION: If a function never performs stack allocations except during function calls (i.e., `%rbp-%rsp` is a compile-time constant), indexing can be done off `%rsp`, and `%rbp` can be used as an ordinary callee-saved register.

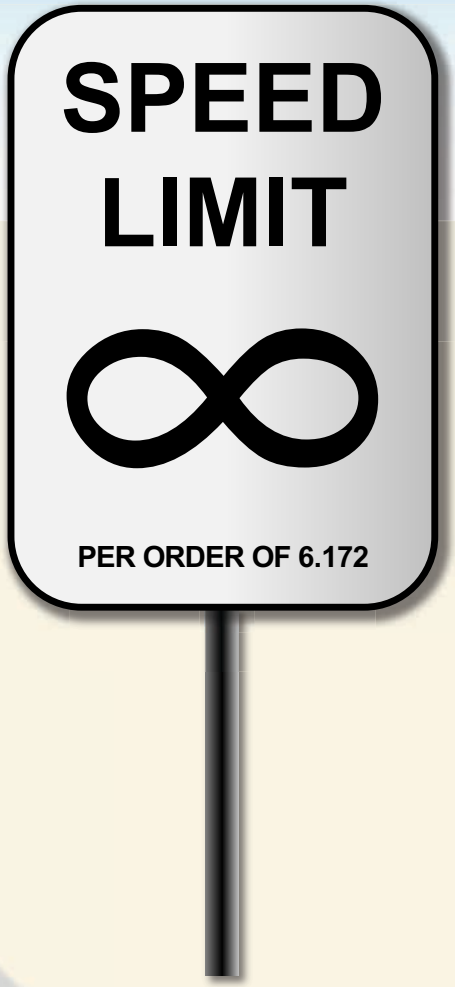


Example: Linux C Subroutine Linkage

For more details on C linkage, see the System V ABI.



Case Study: Fib



Starting Point: `fib.c`

The C function `fib` computes the nth Fibonacci number F(n) recursively using the formula:

$$F(n) = \begin{cases} n & \text{if } n \in \{0,1\} \\ F(n-1) + F(n-2) & \text{otherwise.} \end{cases}$$

C code `fib.c`

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  return (fib(n-1) + fib(n-2));
}
```

From fib.c to fib.ll

C code fib.c

```
int64_t fib(int64_t n)
{
  if (n < 2)
    return n;
  return (
    fib(n-1)
    +
    fib(n-2));
}
```

LLVM IR fib.ll

```
define i64 @fib(i64) local_unnamed_addr #0 {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                                ; preds = %1
  ret i64 %0
}
```

From fib.c to fib.ll

C code fib.c

```
int64_t fib(int64_t n)
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}
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}
```

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}
```

Compiling LLVM IR To Assembly

LLVM IR code `fib.ll`

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{
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>
  ret i64
}
```

Assembly code `fib.s`

```
        .globl  _fib
        .p2align 4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Roughly speaking, we can translate LLVM IR into assembly line by line.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:                   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
```

```
        .globl  _fib
        .p2align  4, 0x90
_fib:                   ## @fib
```

Declare the _fib label to be global.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
```

```
pushq   %rbp
movq    %rsp, %rbp
```

Function prologue:
Save %rbp and sets %rbp = %rsp.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

```
pushq   %r14
pushq   %rbx
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
```

Save any callee-saved registers that fib will use.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        popq    %rbx
```

```
movq    %rdi, %rbx
```

Register %rdi stores the function argument n.

Copy the incoming argument n into %rbx.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
```

```
cmpq    $2, %rbx
```

Compare n against 2.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

```
jge     LBB0_1
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
```

False side of LLVM branch: If `n >= 2`, jump to label `LBB0_1`.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
```

```
movq    %rbx, %rax
jmp     LBB0_3
```

True side of LLVM branch: If n < 2, move n into %rax, and jump to label LBB0_3.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
```

LBB0_1:

Label for the false side of the LLVM branch.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
```

```
leaq -1(%rbx), %rdi
```

Compute n-1. Store the result in %rdi.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
```

```
callq  _fib
```

Call fib. The argument n-1 has already been stored in %rdi.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                  ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                  ; preds = %1
  ret i64 %0
}
```

```
movq    %rax, %r14
```

Assembly code fib.s

```
        .globl      _fib
        .p2align    4, 0x90
_fib:                ## @fib
...
LBB0_1:
        leaq        -1(%rbx), %rdi
        callq       _fib
        movq        %rax, %r14
        addq        $-2, %rbx
        movq        %rbx, %rdi
        callq       _fib
        addq        %r14, %rax
```

Register %rax stores the result of the last function call.

Save the result of calling fib into %r14.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
```

```
addq    $-2, %rbx
movq    %rbx, %rdi
```

Compute n–2, then move the result into %rdi.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
_fib:   ## @fib
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r14
        pushq   %rbx
        movq    %rdi, %rbx
        cmpq    $2, %rbx
        jge     LBB0_1
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
```

```
callq  _fib
```

Call `fib`. The argument `n-2` is in `%rdi`.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
        movq    %rdi, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Add the results of `fib(n-1)` and `fib(n-2)`. Save the sum in `%rax`.

```
addq  %r14, %rax
```

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

LBB0_3:

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Label for the true side of the LLVM branch.

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Function epilogue:
Restore the callee-saved registers that `fib` used.

```
popq    %rbx
popq    %r14
popq    %rbp
```

From fib.ll to fib.s

LLVM IR code fib.ll

```
define i64 @fib(i64) {
  %2 = icmp slt i64 %0, 2
  br i1 %2, label %9, label %3

; <label>:3:                ; preds = %1
  %4 = add nsw i64 %0, -1
  %5 = tail call i64 @fib(i64 %4)
  %6 = add nsw i64 %0, -2
  %7 = tail call i64 @fib(i64 %6)
  %8 = add nsw i64 %7, %5
  ret i64 %8

; <label>:9:                ; preds = %1
  ret i64 %0
}
```

retq

Assembly code fib.s

```
        .globl  _fib
        .p2align  4, 0x90
        movq    %rbx, %rax
        jmp     LBB0_3
LBB0_1:
        leaq    -1(%rbx), %rdi
        callq   _fib
        movq    %rax, %r14
        addq    $-2, %rbx
        movq    %rbx, %rdi
        callq   _fib
        addq    %r14, %rax
LBB0_3:
        popq    %rbx
        popq    %r14
        popq    %rbp
        retq
```

Return from the function.

Summary: From C to Assembly

We can reason through the mapping from C code to assembly in two steps: C to LLVM IR, and then LLVM IR to assembly.

- LLVM IR organizes a C function into a *control-flow graph*.
  - Nodes are *basic blocks*, which correspond to straight-line code in C.
  - C control-flow constructs (i.e., conditionals and loops) induce *control-flow edges*.
- Assembly implements the LLVM IR code using ISA registers and the stack, according to a *calling convention*.

References

Quick reference on assembly instructions:
http://en.wikipedia.org/wiki/X86_instruction_listings

LLVM IR language reference
https://llvm.org/docs/LangRef.html

6.172 Performance Engineering of Software Systems

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