



CS 240

Foundations of Computer Systems



x86 Basics

Translation tools: C -> assembly <-> machine code

x86 registers, data movement instructions, memory addressing, arithmetic instructions

CSAPP book is **highly useful** and well-aligned with class for the remainder of the course.

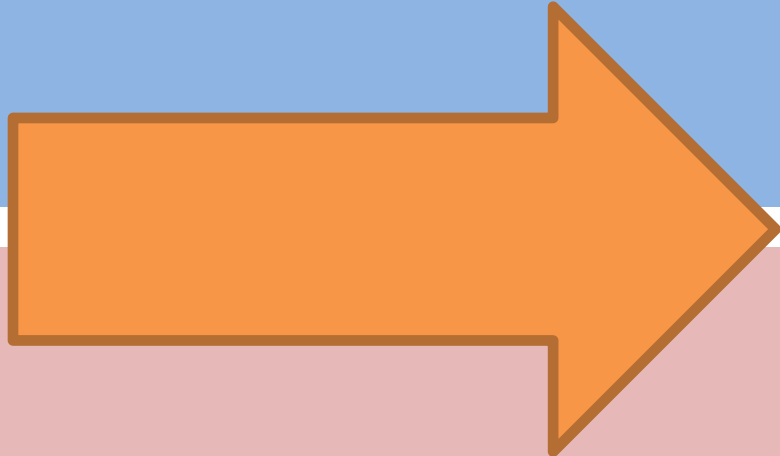
Software

- Program, Application
- Programming Language
- Compiler/Interpreter
- Operating System



Hardware

- Instruction Set Architecture**
- Microarchitecture
- Digital Logic
- Devices (transistors, etc.)
- Solid-State Physics



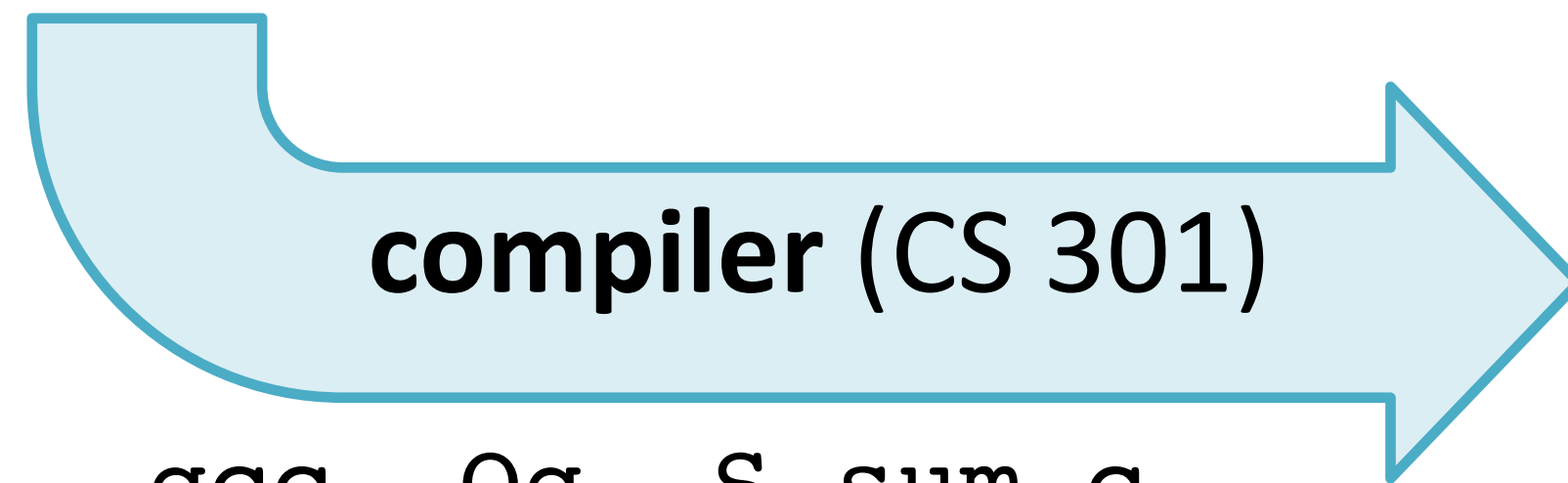
Turning C into *Actual* Machine Code



Real-world security & performance implications

```
void sumstore(long x, long y,  
              long *dest) {  
    long t = x + y;  
    *dest = t;  
}
```

sum.c



gcc -Og -S sum.c

Generated x86 Assembly Code

Human-readable language close to machine code.

```
sum:  
    addq %rdi,%rsi  
    movq %rsi,(%rdx)  
    retq
```

sum.s

assembler

Object Code

```
01010101100010011110010110  
00101101000101000011000000  
00110100010100001000100010  
01111011000101110111000011
```

sum.o

linker

Executable: sum

Resolve references between object files,
libraries, (re)locate data

Machine Instruction Example

```
*dest = t;
```

```
movq %rsi, (%rdx)
```

```
0x400539: 48 89 32
```

C Code

Store value t where indicated by dest

Assembly Code

Move 8-byte value to memory

t: Register %rsi

dest: Register %rdx

*dest: Memory **M**[%rdx]

Object Code

3-byte instruction encoding

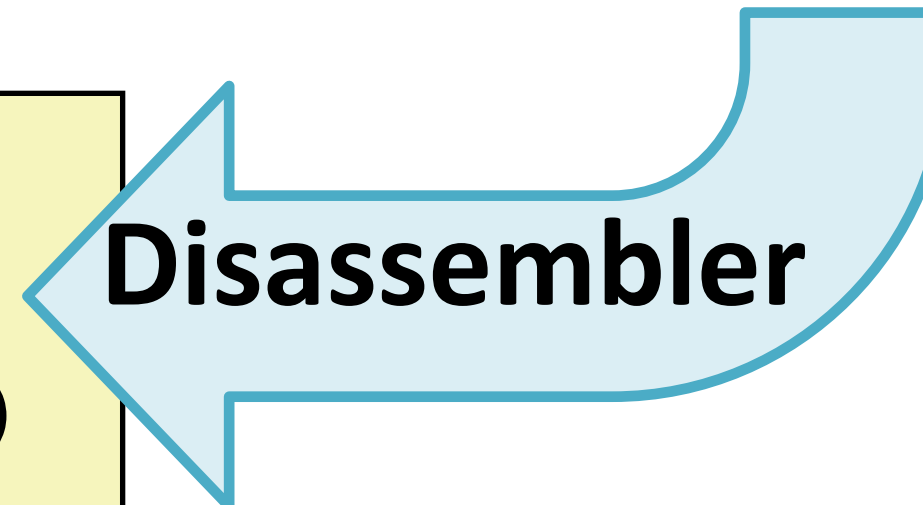
Stored at address 0x400539

Disassembling Object Code

```
00101101000101000011000000  
00110100010100001000100010  
01111011000101110111000011  
...
```

Disassembled by `objdump -d sum`

```
0000000000400536 <sumstore>:  
400536: 48 01 fe add %rdi,%rsi  
400539: 48 89 32 mov %rsi,(%rdx)  
40053c: c3      retq
```



Object

```
0x00400536:  
0x48  
0x01  
0xfe  
0x48  
0x89  
0x32  
0xc3
```

Disassembled by GDB

```
0x0000000000400536 <+0>: add %rdi,%rsi  
0x0000000000400539 <+3>: mov %rsi,(%rdx)  
0x000000000040053c <+6>: retq
```

```
$ gdb sum  
(gdb) disassemble sumstore  
      (disassemble function)  
(gdb) x/7b sum
```

(examine the 13 bytes starting at sum)

CISC vs. RISC

x86: real ISA, widespread

CISC: maximalism

Complex Instruction Set Computer

Many instructions, specialized.

Variable-size encoding,
complex/slow decode.

Gradual accumulation over time.

Original goal:

- humans program in assembly
- or simple compilers generate assembly by template
- hardware supports many patterns as single instructions
- fewer instructions per SLOC

Usually fewer registers.

We will stick to a small subset.

HW: toy, but based on real MIPS ISA

RISC: minimalism

Reduced Instruction Set Computer

Few instructions, general.

Regular encoding,
simple/fast decode.

1980s+ reaction to bloated ISAs.

Original goal:

- humans use high-level languages
- smart compilers generate highly optimized assembly
- hardware supports fast basic instructions
- more instructions per SLOC

Usually many registers.

a brief history of x86

Word
Size

16

ISA

8086

First

Intel 8086

Year

1978

First 16-bit processor. Basis for IBM PC & DOS
1MB address space

IA32

Intel 386

1985

First 32-bit ISA.
Flat addressing, improved OS support

Since 2016: most laptops,
desktops, servers.

240 now:

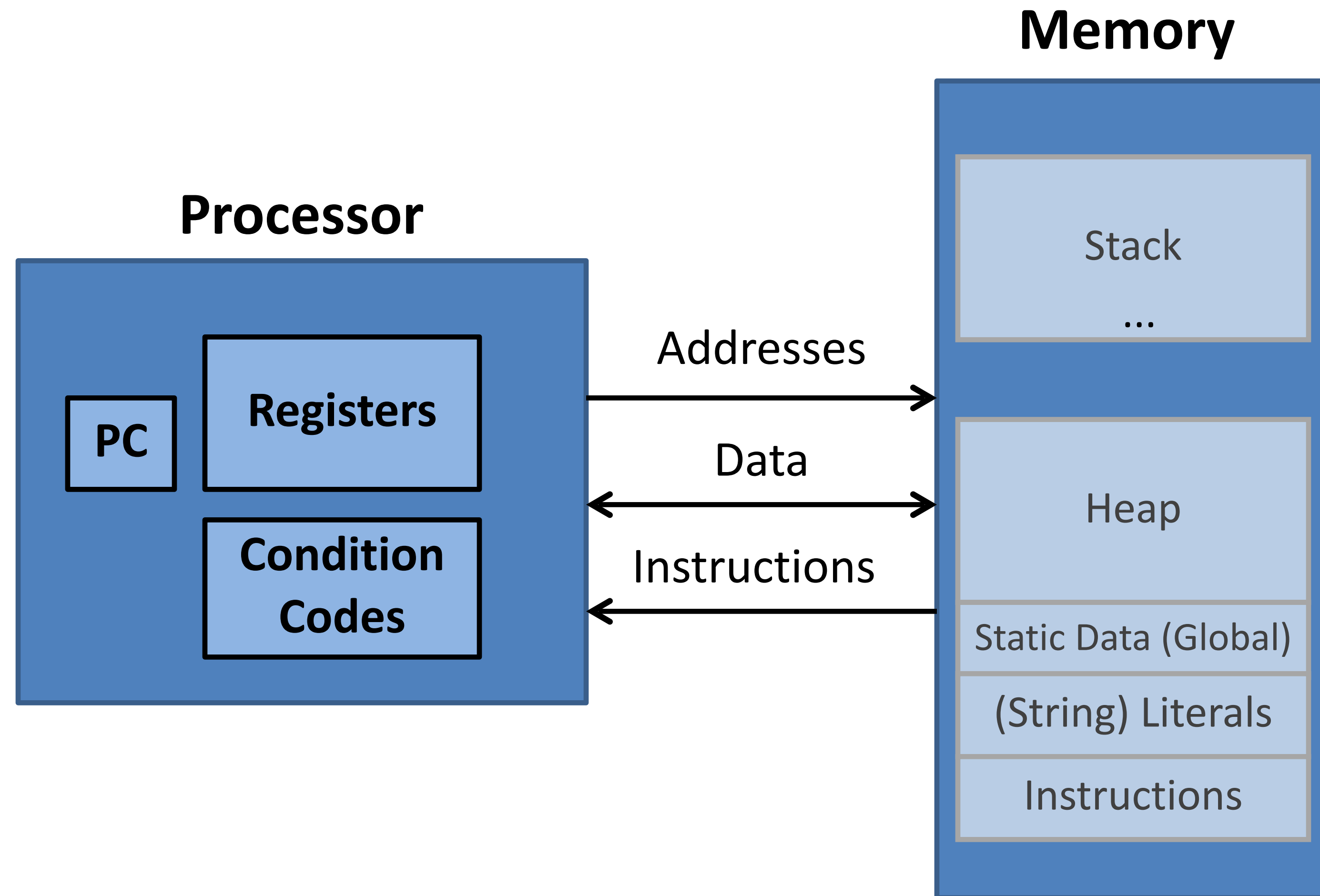
64

x86-64

AMD Opteron 2003*

Slow AMD/Intel conversion, slow adoption.
*Not actually x86-64 until few years later.
Mainstream only after ~10 years.

ISA View



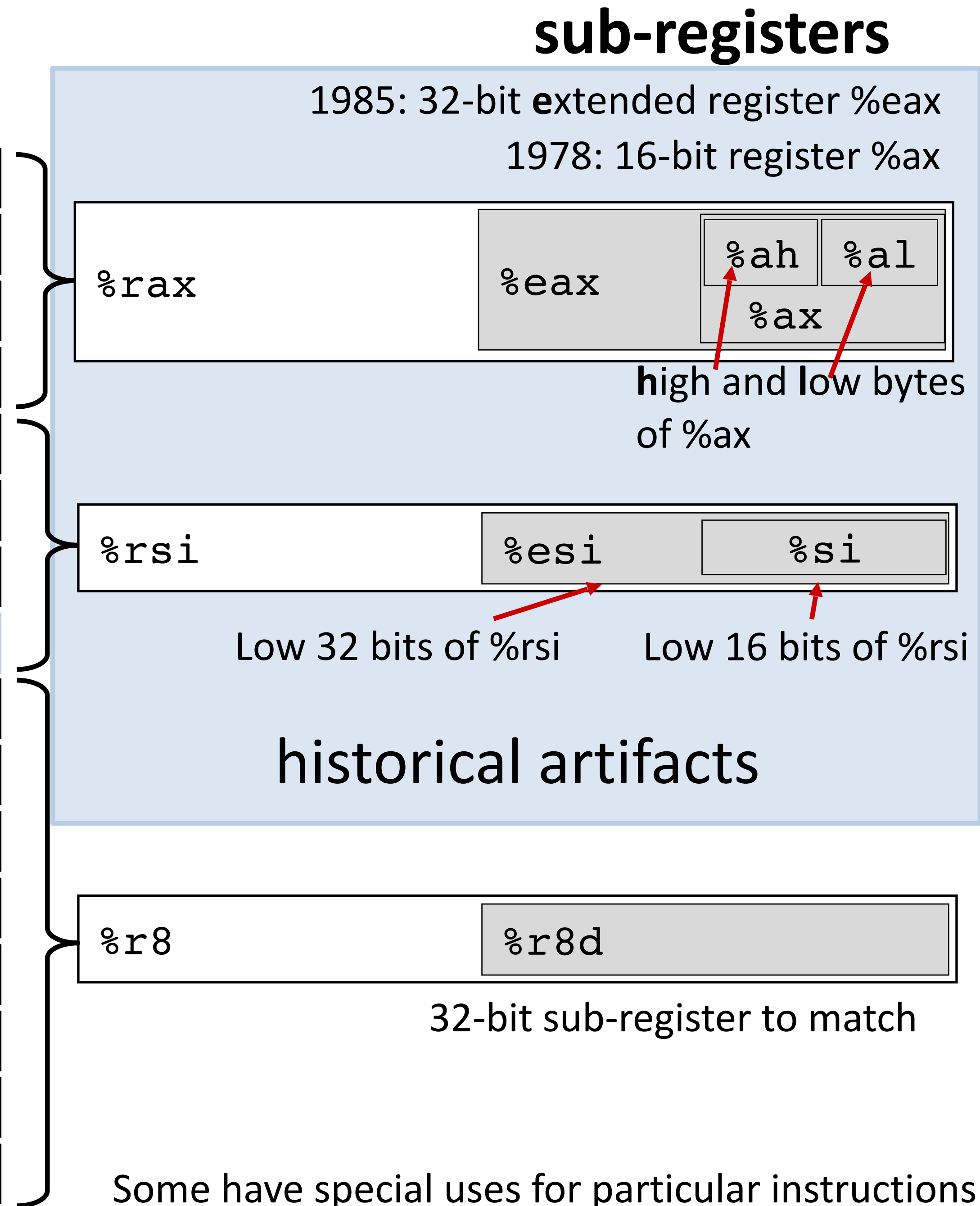
x86-64 registers

16 named registers

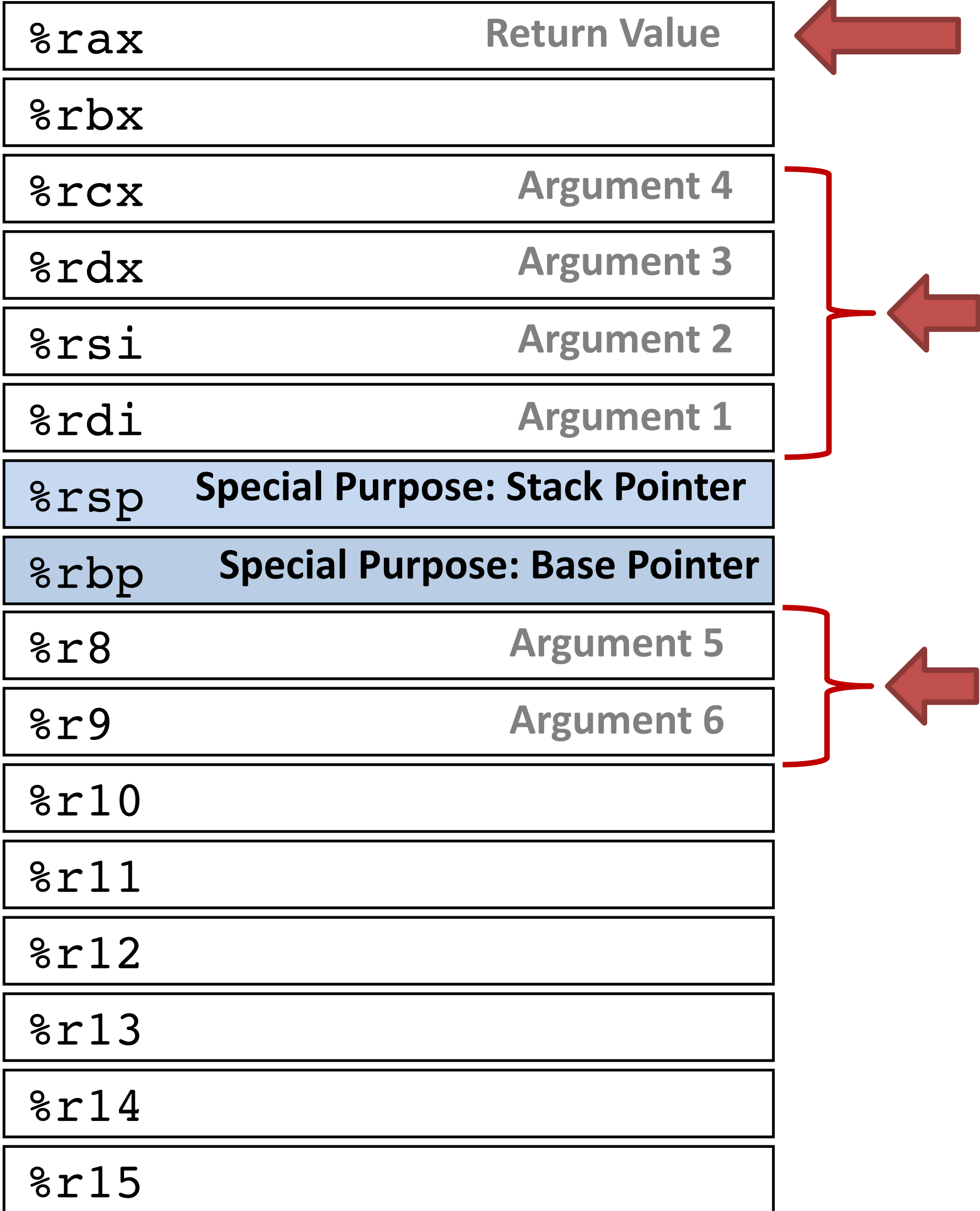
Each 64 bits (8 bytes)

<code>%rax</code>	Return Value
<code>%rbx</code>	
<code>%rcx</code>	Argument 4
<code>%rdx</code>	Argument 3
<code>%rsi</code>	Argument 2
<code>%rdi</code>	Argument 1
<code>%rsp</code>	Special Purpose: Stack Pointer
<code>%rbp</code>	Special Purpose: Base Pointer
<code>%r8</code>	Argument 5
<code>%r9</code>	Argument 6
<code>%r10</code>	
<code>%r11</code>	
<code>%r12</code>	
<code>%r13</code>	
<code>%r14</code>	
<code>%r15</code>	

64-bits / 8 bytes



x86-64 registers: function arguments and return value



64-bits / 8 bytes

Mnemonic:

	register
Diana's	%rdi
silk	%rsi
dress	%rdx
costs	%rcx
\$89	%r8
	%9

Arguments 7 and above are passed via stack, not in registers.

x86: Three Basic Kinds of Instructions

1. Data movement between memory and register

Load data from memory into register

$\%reg \leftarrow \text{Mem}[\text{address}]$

Store register data into memory

$\text{Mem}[\text{address}] \leftarrow \%reg$

Memory is conceptually
an array[] of bytes!

2. Arithmetic/logic on register or memory data

$c = a + b;$ $z = x \ll y;$ $i = h \& g;$

3. Comparisons and Control flow to choose next instruction

Unconditional jumps to/from procedures

Conditional branches

Data movement instructions

(Like LW and SW in the HW ISA)

mov __ *Source, Dest*

*“copy the contents of **source** operand into **dest** operand”*

data size __ is one of {b, w, l, q}

movq: move 8-byte “quad word”

movl: move 4-byte “long word”

movw: move 2-byte “word”

movb: move 1-byte “byte”

Historical terms based on the 16-bit days,
not the current machine word size (64 bits)

Source, Dest operand types:

Immediate: Literal integer data

Examples: \$0x400 \$-533

Register: One of 16 registers

Examples: %rax %rdx

Memory: consecutive bytes in memory, at address held by register

Direct addressing: (%rax)

With displacement/offset: 8(%rsp)

mov Operand Combinations

	Source	Dest	Src, Dest	C Analog
movq	Imm	Reg	movq \$0x4, %rax	a = 0x4;
		Mem	movq \$-147, (%rax)	*p = -147;
	Reg	Reg	movq %rax, %rdx	d = a;
		Mem	movq %rax, (%rdx)	*q = a;
	Mem	Reg	movq (%rax), %rdx	d = *p;

Cannot do memory-memory transfer with a single instruction.

How would you do it?

Memory Addressing Modes

Indirect (R) Mem[Reg[R]]

Register R specifies memory address: `movq (%rcx), %rax`

Displacement D(R) Mem[Reg[R]+D]

Register R specifies **base** memory address (e.g. base of an object)

Displacement D specifies literal **offset** (e.g. a field in the object)

`movq %rdx, 8(%rsp)`

General Form: D(Rb,Ri,S) Mem[Reg[Rb] + S*Reg[Ri] + D]

D: Literal “displacement” value represented in 1, 2, or 4 bytes

Rb: Base register: Any register

Ri: Index register: Any except %rsp

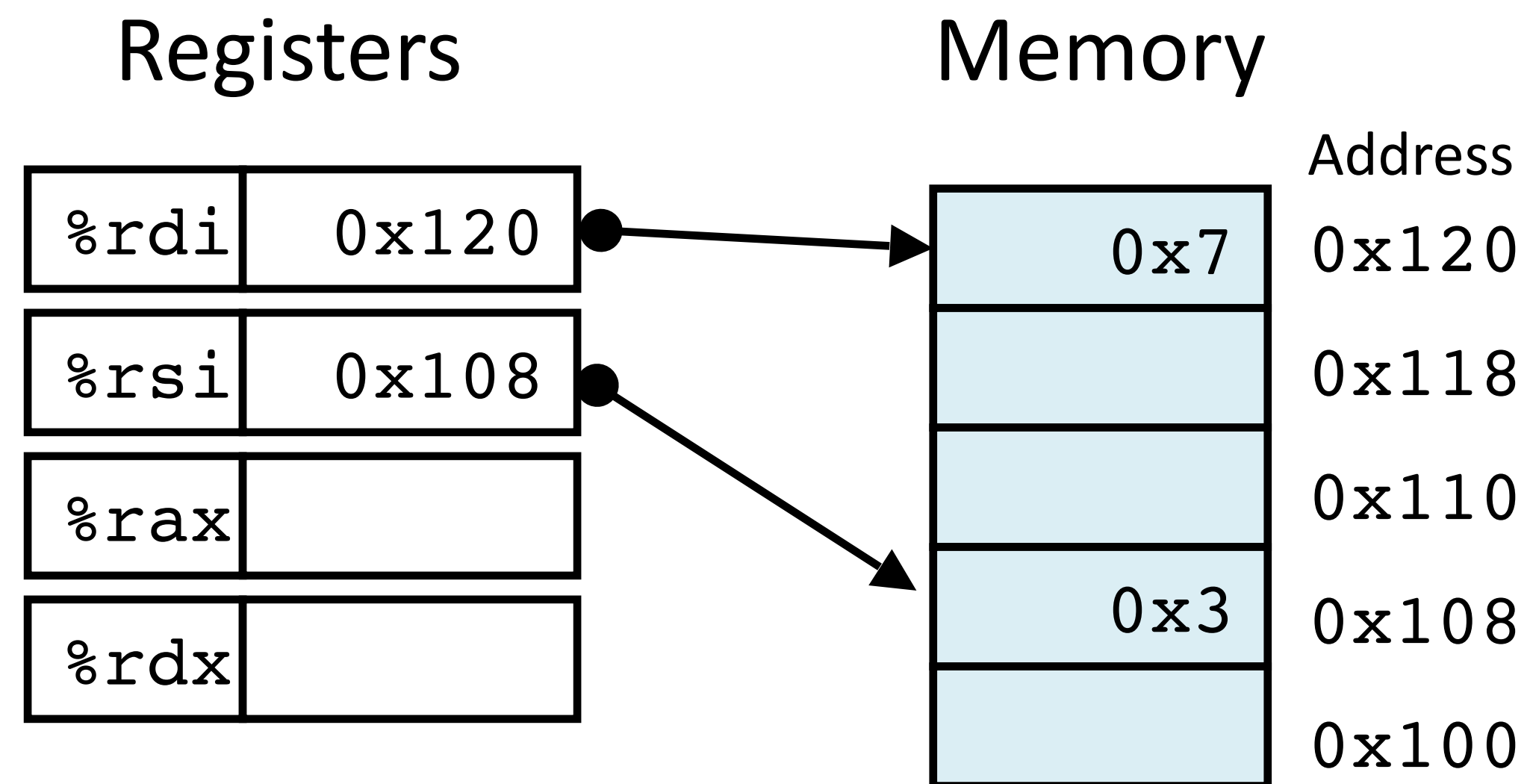
S: Scale: 1, 2, 4, or 8

Pointers and Memory Addressing

```
void swap(long* xp, long* yp){  
    long t0 = *xp;  
    long t1 = *yp;  
    *xp = t1;  
    *yp = t0;  
}
```

```
swap:  
    movq (%rdi),%rax  
    movq (%rsi),%rdx  
    movq %rdx,(%rdi)  
    movq %rax,(%rsi)  
    retq
```

<u>Register</u>		<u>Variable</u>
%rdi	↔	xp
%rsi	↔	yp
%rax	↔	t0
%rdx	↔	t1

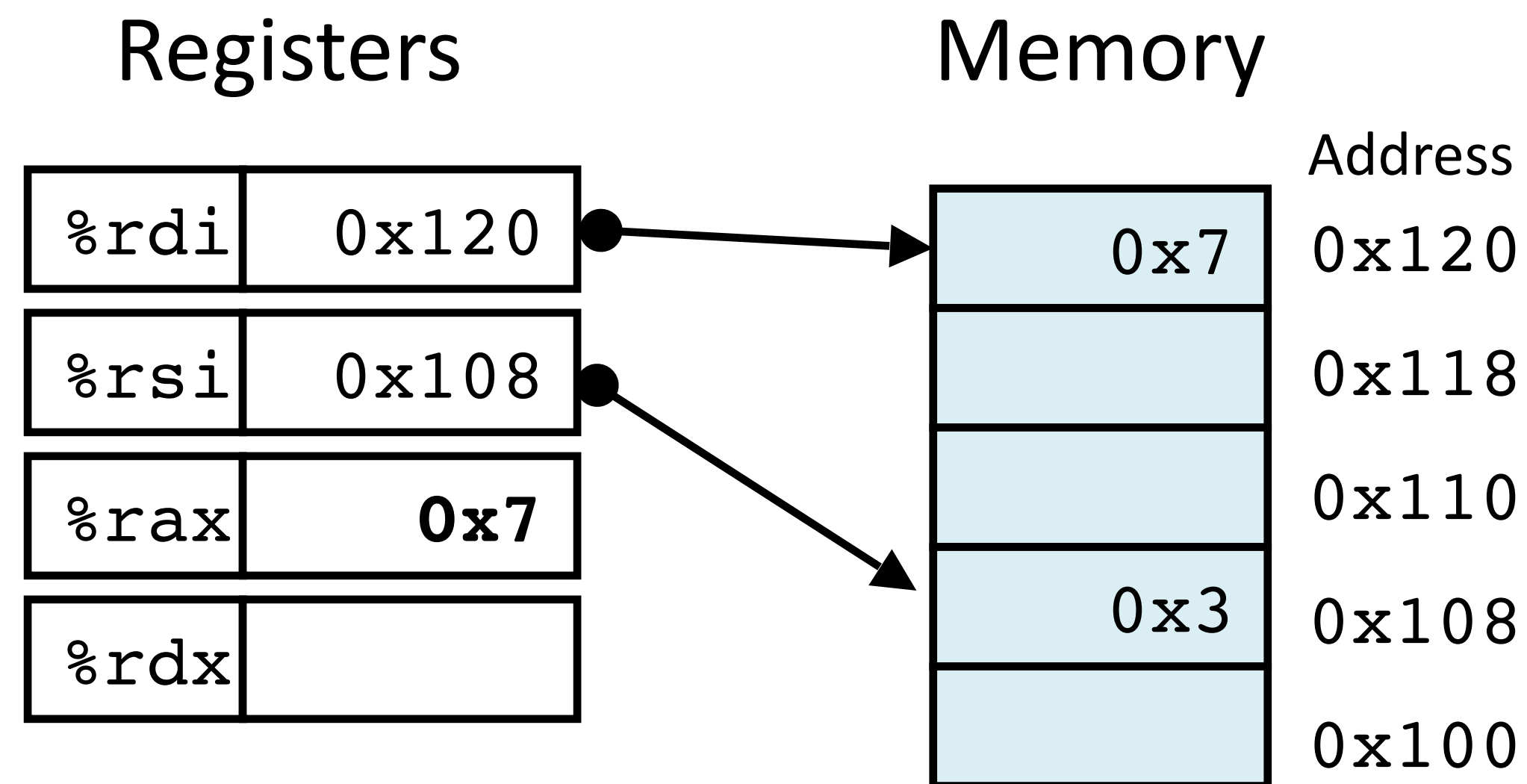


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```

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    movq %rax,(%rsi)
    retq
```

<u>Register</u>		<u>Variable</u>
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%rax	↔	t0
%rdx	↔	t1

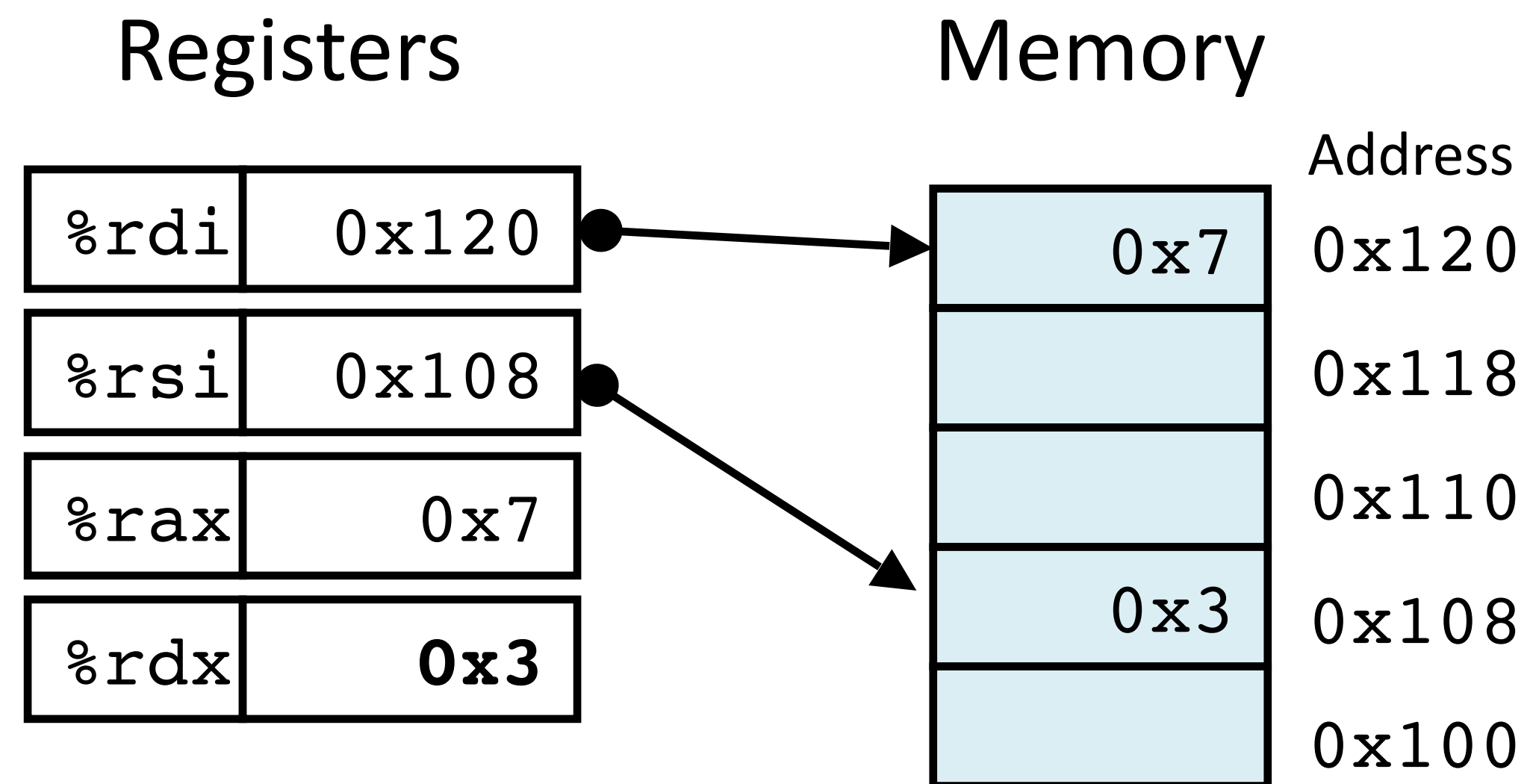


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    movq %rdx, (%rdi)  
    movq %rax, (%rsi)  
    retq
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Pointers and Memory Addressing

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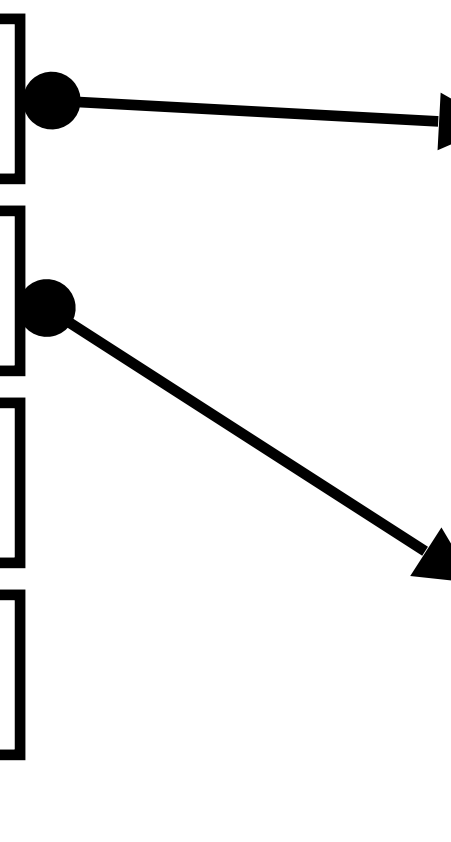
<u>Register</u>		<u>Variable</u>
%rdi	↔	xp
%rsi	↔	yp
%rax	↔	t0
%rdx	↔	t1

Registers

%rdi	0x120
%rsi	0x108
%rax	0x7
%rdx	0x3

Memory

Address
0x120
0x118
0x110
0x108
0x100

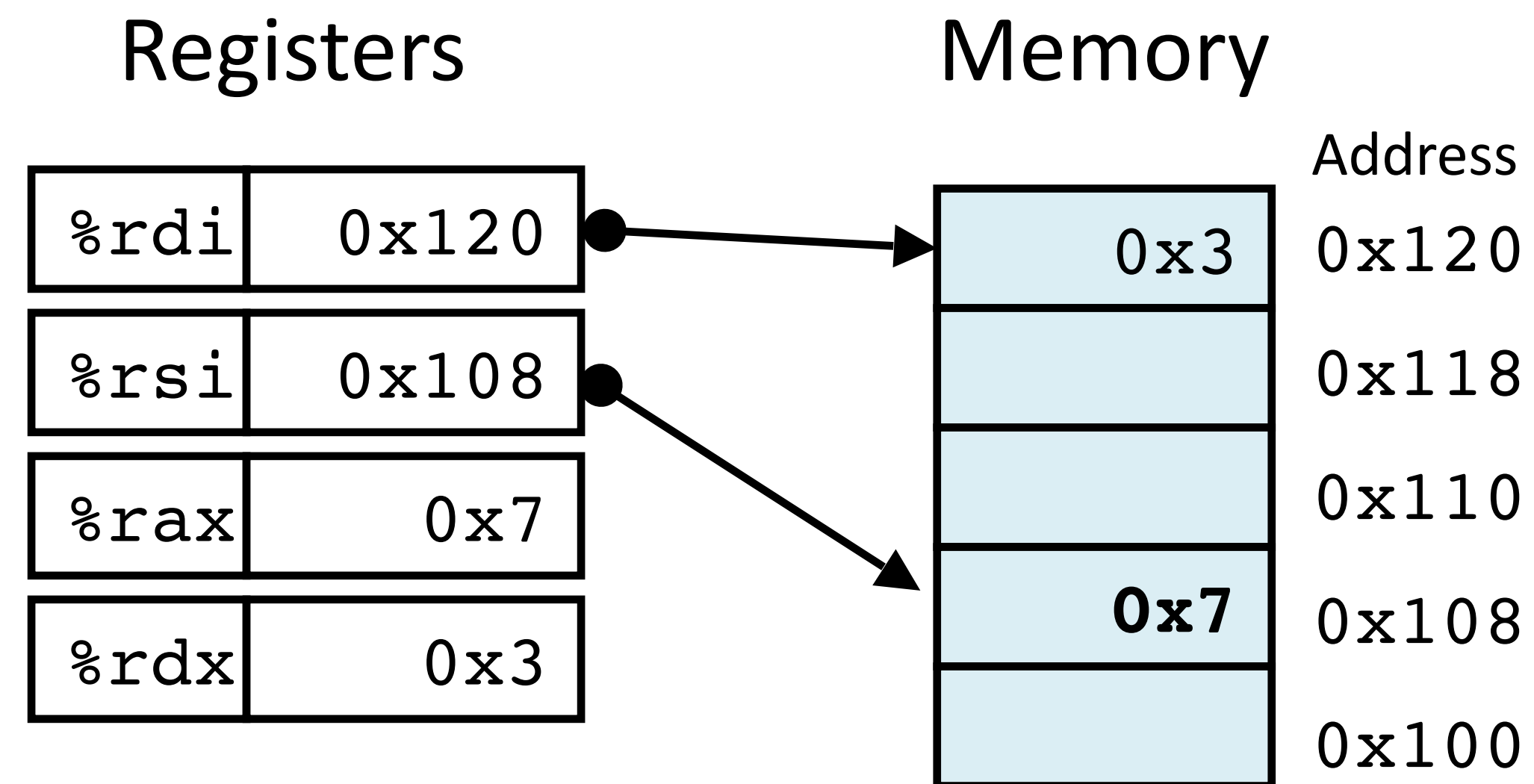


Pointers and Memory Addressing

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<u>Register</u>		<u>Variable</u>
%rdi	↔	xp
%rsi	↔	yp
%rax	↔	t0
%rdx	↔	t1



Address Computation Examples



General Addressing Modes

Register contents

<code>%rdx</code>	<code>0xf000</code>
<code>%rcx</code>	<code>0x100</code>

$$D(Rb, Ri, S) \quad \text{Mem}[\text{Reg}[Rb] + S * \text{Reg}[Ri] + D]$$

Special Cases:

(Rb, Ri)	$\text{Mem}[\text{Reg}[Rb] + \text{Reg}[Ri]]$	Implicitly: $(S=1, D=0)$
$D(Rb, Ri)$	$\text{Mem}[\text{Reg}[Rb] + \text{Reg}[Ri] + D]$	$(S=1)$
(Rb, Ri, S)	$\text{Mem}[\text{Reg}[Rb] + S * \text{Reg}[Ri]]$	$(D=0)$

Address Expression	Address Computation	Address
<code>0x8(%rdx)</code>	<code>0x8 + 0xf000</code>	
<code>(%rdx,%rcx)</code>		
<code>(%rdx,%rcx,4)</code>		
<code>0x80(,%rdx,2)</code>		

Address Computation Examples

ex

General Addressing Modes

Register contents

<code>%rdx</code>	<code>0xf000</code>
<code>%rcx</code>	<code>0x100</code>

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Address Expression	Address Computation	Address
<code>0x8(%rdx)</code>	<code>0x8 + 0xf000</code>	<code>0xf008</code>
<code>(%rdx,%rcx)</code>	<code>0xf000 + 0x100 * 1</code>	<code>0xf100</code>
<code>(%rdx,%rcx,4)</code>	<code>0xf000 + 0x100 * 4</code>	<code>0xf400</code>
<code>0x80(,%rdx,2)</code>	<code>0x80 + 0x0 + 0xf000 * 2</code>	<code>0x1e080</code>

What memory address will the following access? 0x1(%rdx,%rcx,2)

Register contents

<code>%rdx</code>	0x03
<code>%rcx</code>	0x04

General Addressing Modes

$D(Rb, Ri, S) \text{ Mem}[\text{Reg}[Rb] + S * \text{Reg}[Ri] + D]$

Special Cases:

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(Rb, Ri, S)	$\text{Mem}[\text{Reg}[Rb] + S * \text{Reg}[Ri]]$	(D=0)

0x8 (8)

0xA (10)

0xB (11)

0xC (12)

0xD (13)

0xE (14)

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0x8 (8)

0%

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0xC (12)

0%

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0%

0xE (14)

0%

Load effective address



Compute address given by this addressing mode expression and store it here.

`leaq Src, Dest`

DOES NOT ACCESS MEMORY

Uses: "address of" "Lovely Efficient Arithmetic"

`p = &x[i];` $x + k * l$, where $k = 1, 2, 4, \text{ or } 8$

leaq vs. movq

Registers	Memory	Address	Assembly Code																						
<table border="1"><tr><td>%rax</td><td></td></tr><tr><td>%rbx</td><td></td></tr><tr><td>%rcx</td><td>0x4</td></tr><tr><td>%rdx</td><td>0x100</td></tr><tr><td>%rdi</td><td></td></tr><tr><td>%rsi</td><td></td></tr></table>	%rax		%rbx		%rcx	0x4	%rdx	0x100	%rdi		%rsi		<table border="1"><tr><td>0x400</td></tr><tr><td>0xf</td></tr><tr><td>0x8</td></tr><tr><td>0x10</td></tr><tr><td>0x1</td></tr></table>	0x400	0xf	0x8	0x10	0x1	<table><tr><td>0x120</td></tr><tr><td>0x118</td></tr><tr><td>0x110</td></tr><tr><td>0x108</td></tr><tr><td>0x100</td></tr></table>	0x120	0x118	0x110	0x108	0x100	<pre>leaq (%rdx,%rcx,4), %rax movq (%rdx,%rcx,4), %rbx leaq (%rdx), %rdi movq (%rdx), %rsi</pre>
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<code>%rdi</code>		0x1	0x100	
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<code>%rdx</code>	0x100	0x10	0x108	<code>movq (%rdx), %rsi</code>
<code>%rdi</code>	0x100	0x1	0x100	
<code>%rsi</code>				

Load effective address



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`leaq Src, Dest`

DOES NOT ACCESS MEMORY

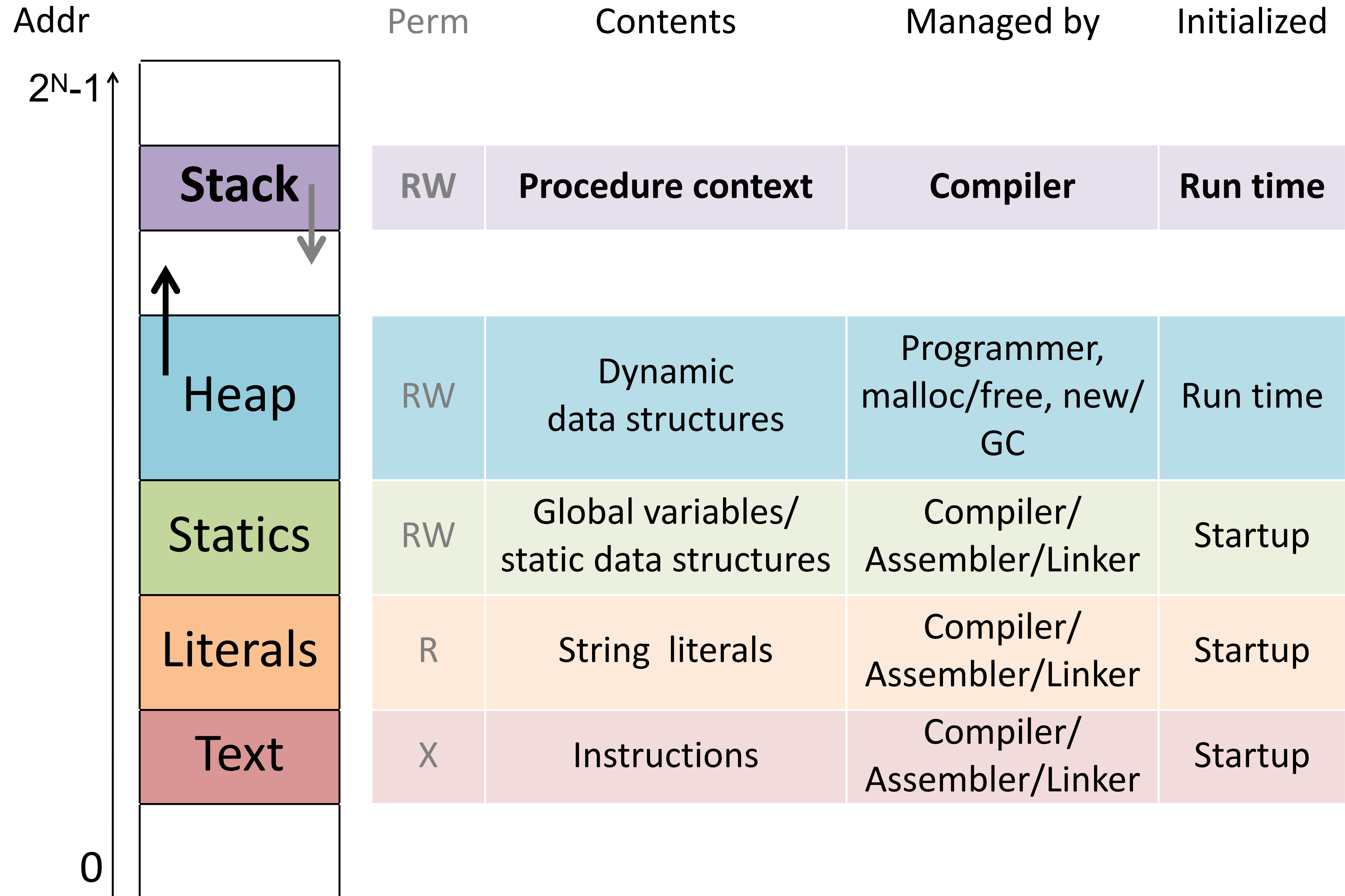
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<code>%rsi</code>	<code>0x1</code>	<code>0x1</code>	<code>0x100</code>	

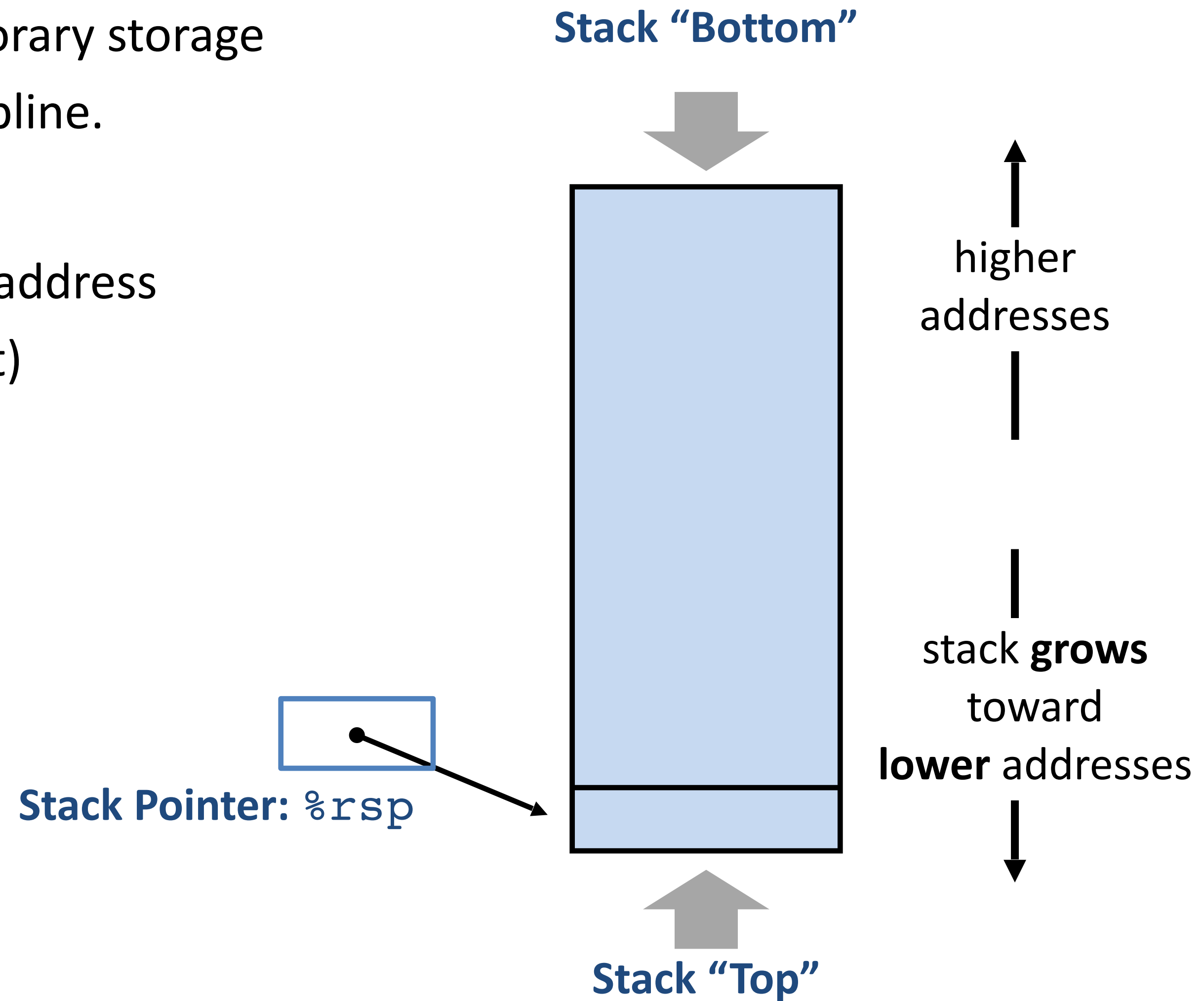
Memory address-space layout



Call Stack

Memory region for temporary storage managed with stack discipline.

`%rsp` holds lowest stack address (address of "top" element)



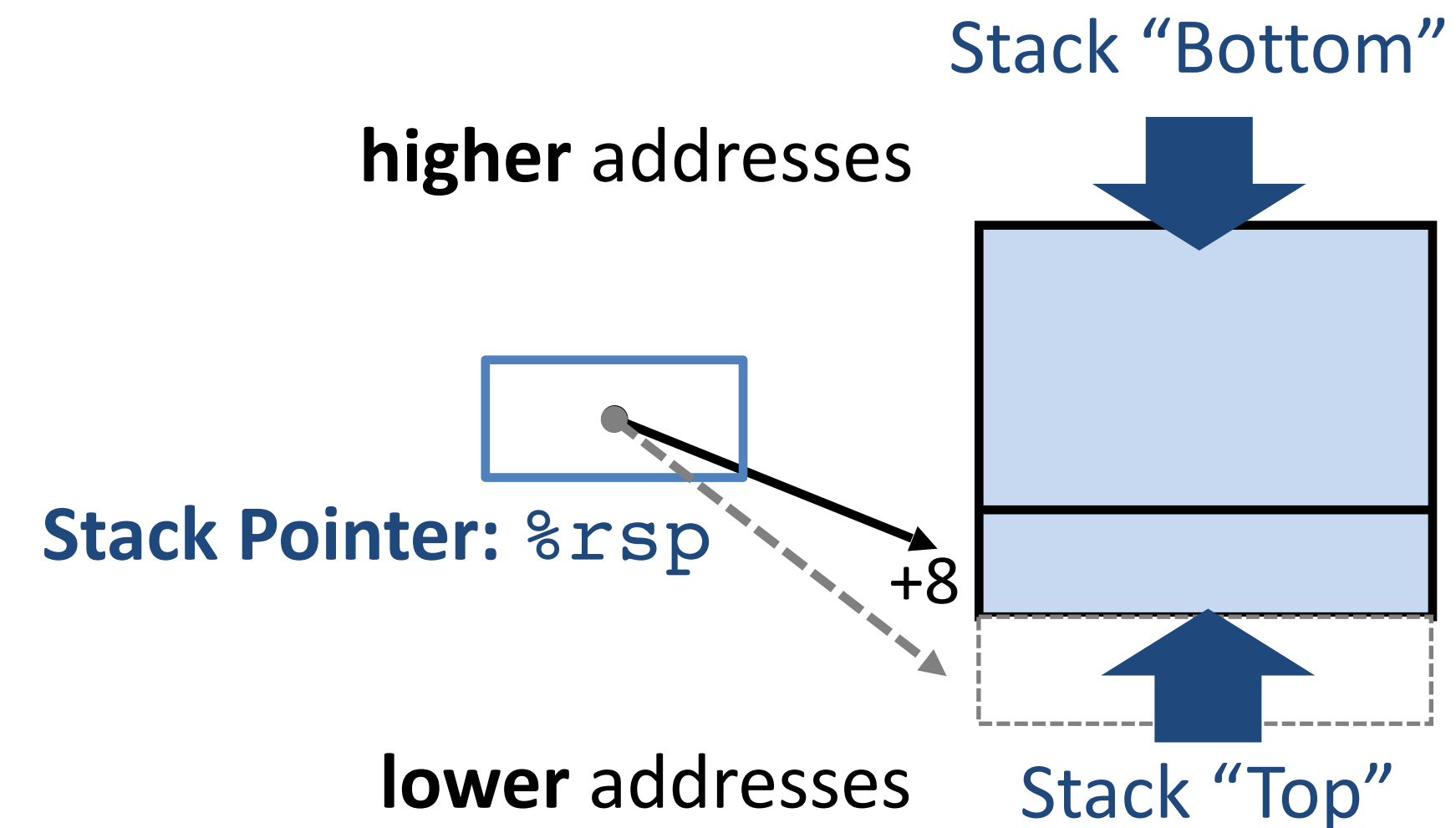
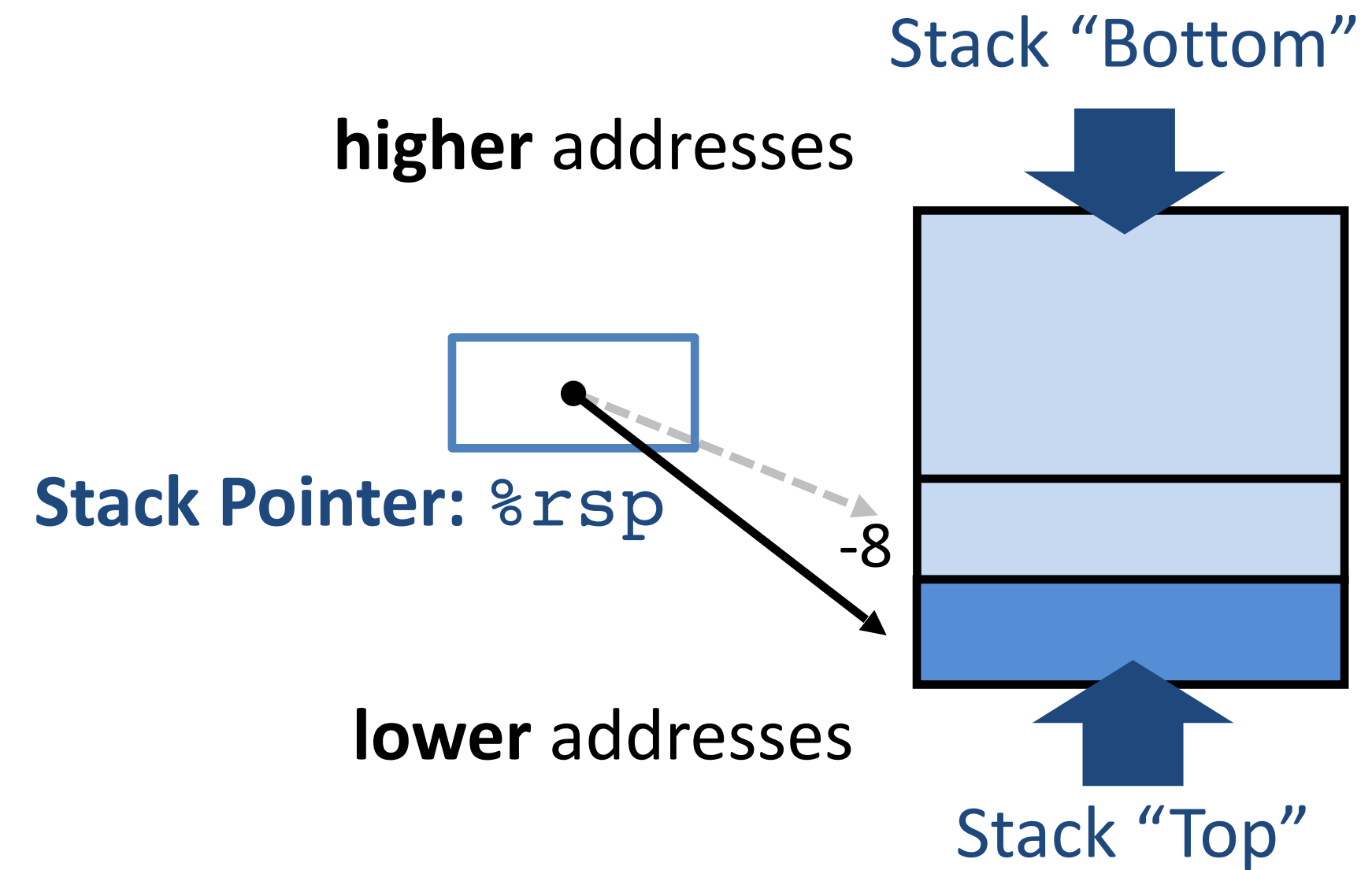
Call Stack: Push, Pop

`pushq Src`

1. Fetch value from *Src*
2. Decrement `%rsp` by 8 (*why 8?*)
3. Store value at new address given by `%rsp`

`popq Dest`

1. Load value from address `%rsp`
2. Write value to *Dest*
3. Increment `%rsp` by 8



Procedure Preview (more soon)

call, ret, push, pop

Procedure arguments passed in 6 registers:

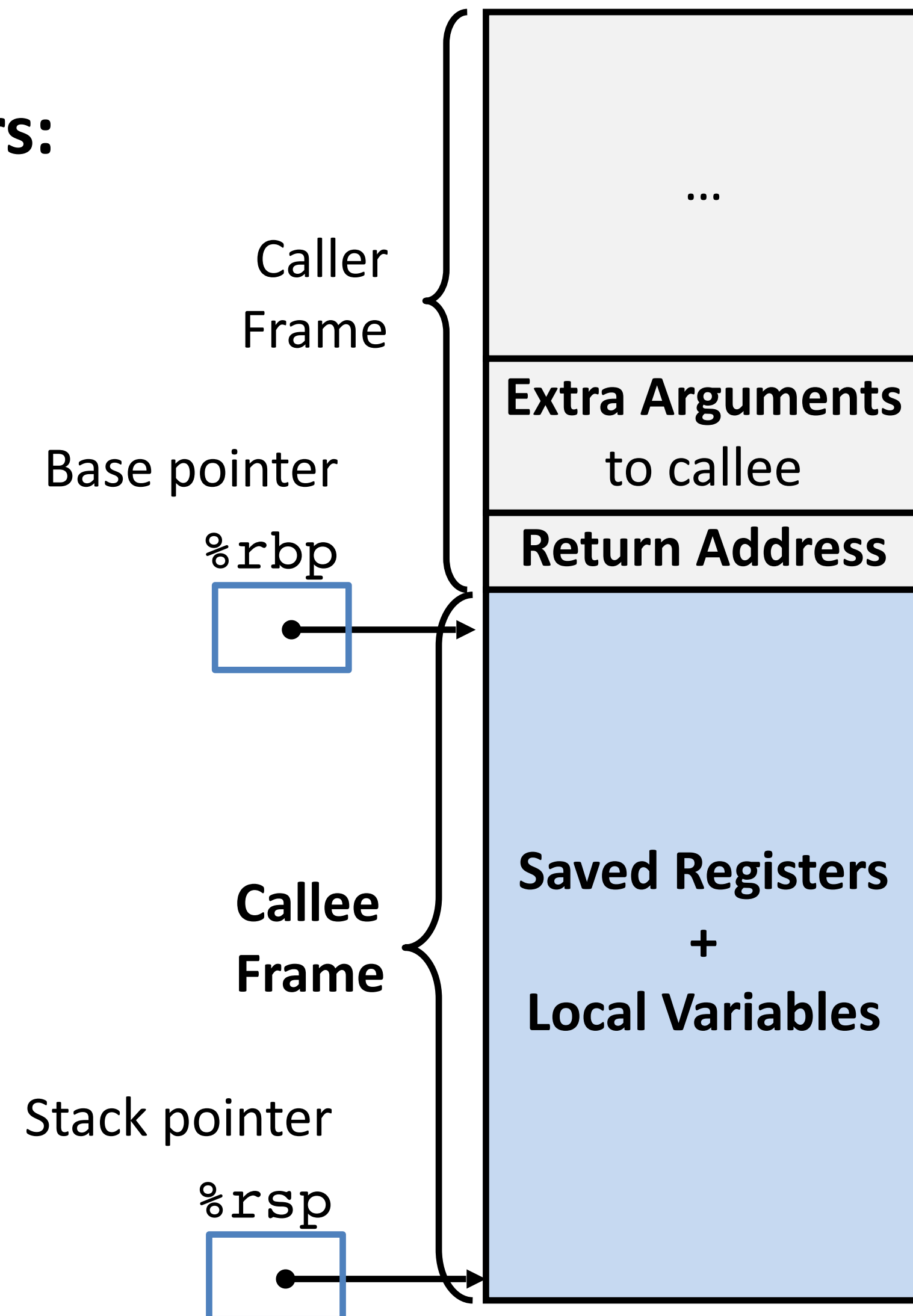
%rax	Return Value	%r8	Argument 5
%rbx		%r9	Argument 6
%rcx	Argument 4	%r10	
%rdx	Argument 3	%r11	
%rsi	Argument 2	%r12	
%rdi	Argument 1	%r13	
%rsp	Stack pointer	%r14	
%rbp	Base pointer	%r15	

Return value in %rax.

Allocate/push new *stack frame*
for each procedure call.

Some local variables,
saved register values, extra arguments

Deallocate/pop frame before return.



x86: Three Basic Kinds of Instructions

1. Data movement between memory and register

Load data from memory into register

$\%reg \leftarrow \text{Mem}[\text{address}]$

Store register data into memory

$\text{Mem}[\text{address}] \leftarrow \%reg$

Memory is an
array[] of bytes!

2. Arithmetic/logic on register or memory data

$c = a + b;$ $z = x \ll y;$ $i = h \& g;$

3. Comparisons and Control flow to choose next instruction

Unconditional jumps to/from procedures

Conditional branches

Arithmetic Operations

(Unlike the HW ISA, combines 1 operand and the destination)

Two-operand instructions:

Format

`addq Src, Dest`

`subq Src, Dest`

`imulq Src, Dest`

`shlq Src, Dest`

`sarq Src, Dest`

`shrq Src, Dest`

`xorq Src, Dest`

`andq Src, Dest`

`orq Src, Dest`

Computation

$Dest = Dest + Src$

$Dest = Dest - Src$

$Dest = Dest * Src$

$Dest = Dest \ll Src$

$Dest = Dest \gg Src$

$Dest = Dest \gg Src$

$Dest = Dest \wedge Src$

$Dest = Dest \& Src$

$Dest = Dest | Src$



note the unexpected argument order

a.k.a salq

Arithmetic

Logical

One-operand (unary) instructions

`incq Dest`

`decq Dest`

`negq Dest`

`notq Dest`

$Dest = Dest + 1$

$Dest = Dest - 1$

$Dest = -Dest$

$Dest = \sim Dest$

increment

decrement

negate

bitwise complement

See CSAPP 3.5.5 for: `mulq`, `cqto`, `idivq`, `divq`

leaq for arithmetic

```
long arith(long x, long y,  
           long z){  
    long t1 = x+y;  
    long t2 = z+t1;  
    long t3 = x+4;  
    long t4 = y * 48;  
    long t5 = t3 + t4;  
    long rval = t2 * t5;  
    return rval;  
}
```

```
arith:  
    leaq    (%rdi,%rsi), %rax  
    addq   %rdx, %rax  
    leaq   (%rsi,%rsi,2), %rdx  
    salq   $4, %rdx  
    leaq   4(%rdi,%rdx), %rcx  
    imulq  %rcx, %rax  
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	
%rcx	

leaq for arithmetic

```
long arith(long x, long y,  
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    leaq   4(%rdi,%rdx), %rcx  
    imulq  %rcx, %rax  
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	t1
%rcx	

leaq for arithmetic

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long arith(long x, long y,
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Register	Use(s)
%rdi	Argument x
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%rax	t1 t2
%rcx	

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arith:
    leaq    (%rdi,%rsi), %rax
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    leaq   (%rsi,%rsi,2), %rdx
    salq   $4, %rdx
    leaq   4(%rdi,%rdx), %rcx
    imulq  %rcx, %rax
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z 3*y
%rax	t1 t2
%rcx	

leaq for arithmetic

```
long arith(long x, long y,
           long z){
    long t1 = x+y;
    long t2 = z+t1;
    long t3 = x+4;
    long t4 = y * 48;
    long t5 = t3 + t4;
    long rval = t2 * t5;
    return rval;
}
```

```
arith:
    leaq    (%rdi,%rsi), %rax
    addq    %rdx, %rax
    leaq    (%rsi,%rsi,2), %rdx
    salq    $4, %rdx
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    imulq   %rcx, %rax
    ret
```

Register	Use(s)
%rdi	Argument x
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leaq for arithmetic

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    leaq    (%rdi,%rsi), %rax
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    salq   $4, %rdx
    leaq   4(%rdi,%rdx), %rcx
    imulq  %rcx, %rax
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z 3*y t4
%rax	t1 t2
%rcx	4+x+t4 = t5

leaq for arithmetic

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long arith(long x, long y,  
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    return rval;  
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```

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    leaq   4(%rdi,%rdx), %rcx  
    imulq  %rcx, %rax  
    ret
```

Register	Use(s)
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leaq for arithmetic

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```
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    salq    $4, %rdx
    leaq    4(%rdi,%rdx), %rcx
    imulq   %rcx, %rax
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z 3*y t4
%rax	t1 t2 rval
%rcx	4+x+t4 = t5

- Instructions in different order from C code
- Some expressions require multiple instructions
- Some instructions cover multiple expressions
- Same x86 code by compiling:
 $(x+y+z) * (x+4+48*y)$

Compiler optimization example

```
long logical(long x, long y){
    long t1 = x^y;
    long t2 = t1 >> 17;
    long mask = (1<<13) - 7;
    long rval = t2 & mask;
    return rval;
}
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	

logical:

```
movq %rdi,%rax
xorq %rsi,%rax
sarq $17,%rax
andq $8185,%rax
retq
```

Compiler optimization example

```
long logical(long x, long y){
    long t1 = x^y;
    long t2 = t1 >> 17;
    long mask = (1<<13) - 7;
    long rval = t2 & mask;
    return rval;
}
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	x

logical:

```
movq %rdi,%rax
xorq %rsi,%rax
sarq $17,%rax
andq $8185,%rax
retq
```

Compiler optimization example

```
long logical(long x, long y){
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    long rval = t2 & mask;
    return rval;
}
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	* t1

logical:

```
movq %rdi,%rax
xorq %rsi,%rax
sarq $17,%rax
andq $8185,%rax
retq
```

Compiler optimization example

```
long logical(long x, long y){
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}
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	* t1 t2

logical:

```
movq %rdi,%rax
xorq %rsi,%rax
sarq $17,%rax
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Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	* t1 t2 rval

```
logical:
    movq %rdi,%rax
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Next lecture:

3. Comparisons and Control flow to choose next instruction

Unconditional jumps to/from procedures

Conditional branches