

CSE 401/M501 – Compilers

x86-64 Lite for Compiler Writers

A quick (a) introduction or (b) review

[pick one]

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Agenda

- Overview of x86-64 architecture
 - Core part only, a bit beyond what we need for the project, but not too much
- Upcoming lectures...
 - Mapping source language constructs to x86
 - Code generation for MiniJava project
- Rest of the quarter...
 - Survey of compiler optimizations
 - More sophisticated back-end algorithms

Some x86-64 References

(All linked on course project web page - **, * = most useful)

- **x86-64 Instructions and ABI
 - Handout for University of Chicago CMSC 22620, Spring 2009, by John Reppy
- *x86-64 Machine-Level Programming
 - Earlier version of sec. 3.13 of Computer Systems: A Programmer's Perspective, 2nd ed. by Bryant & O'Hallaron (CSE 351 textbook)
- Intel architecture processor manuals
 - Undoubtedly way more than we'll need

x86-64 Main features

- 16 64-bit general registers; 64-bit integers (but int is 32 bits usually; long is 64 bits)
- 64-bit address space; pointers are 8 bytes
- 16 SSE registers for floating point, SIMD
- Register-based function call conventions
- Additional addressing modes (pc relative)
- 32-bit legacy mode
- Some pruning of old features

x86-64 Assembler Language

- Target for our compiler project

But, the nice thing about standards...

- Two main assembler languages for x86-64
 - Intel/Microsoft version – what’s in the Intel docs
 - AT&T/GNU assembler – what we’re generating and what’s in the linked handouts and 351 book
 - Use `gcc -S` to generate asm code from C/C++ code for more examples
- Slides use `gcc/AT&T/GNU` syntax

Intel vs. GNU Assembler

- Main differences between Intel docs and gcc assembler

	Intel/Microsoft	AT&T/GNU as
Operand order: op a,b	a = a op b (dst first)	b = a op b (dst last)
Memory address	[baseregister+offset]	offset(baseregister)
Instruction mnemonics	mov, add, push, ...	movq, addq, pushq [explicit operand size added to end]
Register names	rax, rbx, rbp, rsp, ...	%rax, %rbx, %rbp, %rsp, ...
Constants	17, 42	\$17, \$42
Comments	; to end of line	# to end of line or /* ... */

- Intel docs include many complex, historical instructions and artifacts that aren't commonly used by modern compilers – and we won't use them either

x86-64 Memory Model

- 8-bit bytes, byte addressable
- 16-, 32-, 64-bit words, double words and quad words (Intel terminology)
 - That’s why the ‘q’ in 64-bit instructions like `movq`, `addq`, etc.
- Data should normally be aligned on “natural” boundaries for performance, although unaligned accesses are generally supported – but with a big performance penalty on many machines
- Little-endian – address of a multi-byte integer is address of low-order byte

x86-64 registers

- 16 64-bit general registers
 - %rax, %rbx, %rcx, %rdx, %rsi, %rdi, %rbp, %rsp, %r8-%r15
- Registers can be used as 64-bit integers or pointers, or as 32-bit ints
 - Also possible to reference low-order 16- and 8-bit chunks – we won't for the most part
- To simplify our project we'll use only 64-bit data (ints, pointers, even booleans!)

Instruction Format

- Typical data manipulation instruction
opcode src,dst # comment
- Meaning is
 $dst \leftarrow dst \text{ op } src$
- Normally, one operand is a register, the other is a register, memory location, or integer constant
 - Can't have both operands in memory – can't encode two memory addresses in a single instruction (e.g., cmp, mov)
- Language is free-form, comments and labels may appear on lines by themselves (and can have multiple labels per line of code)

x86-64 Memory Stack

- Register `%rsp` points to the “top” of stack
 - Dedicated for this use; don’t use otherwise
 - Points to the last 64-bit quadword pushed onto the stack (not next “free” quadword)
 - Should always be quadword (8-byte) aligned
 - It will start out this way, and will stay aligned unless your code does something bad
 - Should normally be 16-byte aligned on function calls
 - Stack grows *down* (towards lower addresses)

Stack Instructions

pushq src

$\%rsp \leftarrow \%rsp - 8$; $\text{memory}[\%rsp] \leftarrow \text{src}$
(e.g., push src onto the stack)

popq dst

$\text{dst} \leftarrow \text{memory}[\%rsp]$; $\%rsp \leftarrow \%rsp + 8$
(e.g., pop top of stack into dst and logically remove it from the stack)

Stack Frames

- When a method is called, a stack frame is normally allocated on the logical “top” of the stack to hold its local variables
 - Stack actually grows down towards lower memory addresses when a new stack frame is pushed (allocated)
- Frame is popped on method return
- By convention, `%rbp` (base pointer) points to a known offset into the current active stack frame
 - Local variables referenced relative to `%rbp`
 - Base pointer common in 32-bit x86 code; less so in x86-64 code where push/pop used less & stack frame normally has fixed size so locals can be referenced from `%rsp` easily
 - We will use `%rbp` in our project – simplifies addressing of local variables and compiler bookkeeping

Operand Address Modes (1)

- These should cover most of what we'll need

```
movq $17,%rax      # store 17 in %rax
```

```
movq %rcx,%rax     # copy %rcx to %rax
```

```
movq 16(%rbp),%rax # copy memory to %rax
```

```
movq %rax,-24(%rbp) # copy %rax to memory
```

- References to object fields work similarly – put the object's memory address in a register and use that address plus an offset
- Remember: can't have two memory addresses in a single instruction

Operand Address Modes (2)

- A memory address can combine the contents of two registers (with one optionally multiplied by 2, 4, or 8) plus a constant:

$\text{basereg} + \text{indexreg} * \text{scale} + \text{constant}$

- Main use of general form is for array subscripting or small computations - if the compiler is clever
- Example: suppose we have an array **A** of 8-byte ints with address of the array in %rcx and subscript **i** in %rax. Code to store %rbx in **A[i]**:

`movq %rbx, (%rcx, %rax, 8)`

Basic Data Movement and Arithmetic Instructions

`movq src,dst`

$\text{dst} \leftarrow \text{src}$

`addq src,dst`

$\text{dst} \leftarrow \text{dst} + \text{src}$

`subq src,dst`

$\text{dst} \leftarrow \text{dst} - \text{src}$

`incq dst`

$\text{dst} \leftarrow \text{dst} + 1$

`decq dst`

$\text{dst} \leftarrow \text{dst} - 1$

`negq dst`

$\text{dst} \leftarrow -\text{dst}$

(2's complement
arithmetic negation)

Integer Multiply and Divide

`imulq src,dst`

$\text{dst} \leftarrow \text{dst} * \text{src}$

dst must be a register

`cqto`

$\%rdx:\%rax \leftarrow$ 128-bit sign
extended copy of $\%rax$

(why??? To prep
numerator for `idivq`!)

`idivq src`

Divide $\%rdx:\%rax$ by `src`
($\%rdx:\%rax$ holds sign-
extended 128-bit value;
cannot use other registers
for division!!)

$\%rax \leftarrow$ quotient

$\%rdx \leftarrow$ remainder

(no division in MiniJava!)

Bitwise Operations

`andq src,dst`

$\text{dst} \leftarrow \text{dst} \& \text{src}$

`orq src,dst`

$\text{dst} \leftarrow \text{dst} | \text{src}$

`xorq src,dst`

$\text{dst} \leftarrow \text{dst} \wedge \text{src}$

`notq dst`

$\text{dst} \leftarrow \sim \text{dst}$

(logical or 1's complement)

Shifts and Rotates

`shlq dst,count`

`dst` ← `dst` shifted left
count bits

`shrq dst,count`

`dst` ← `dst` shifted right
count bits (0 fill)

`sarq dst,count`

`dst` ← `dst` shifted right
count bits (sign bit fill)

`rolq dst,count`

`dst` ← `dst` rotated left
count bits

`rorq dst,count`

`dst` ← `dst` rotated right
count bits

Uses for Shifts and Rotates

- Can often be used to optimize multiplication and division by small constants
 - If you're interested, look at "Hacker's Delight" by Henry Warren, A-W, 2nd ed, 2012
 - Lots of very cool bit fiddling and other algorithms
 - But be careful – be sure semantics are OK
 - Example: right shift is not the same as Java/C/C++/etc. integer divide for negative numbers (why?)
- There are additional instructions that shift and rotate double words, use a calculated shift amount instead of a constant, etc.

Load Effective Address

- The unary `&` operator in C/C++

`leaq src,dst` # `dst` ← address of `src`

- `dst` must be a register
- Address of `src` includes any address arithmetic or indexing
- Useful to capture addresses for pointers, reference parameters, etc.
- Also useful for computing arithmetic expressions that match `r1+scale*r2+const`

Control Flow - GOTO

- At this level, all we have is goto and conditional goto
- Loops and conditional statements are synthesized from these
- Note: random jumps play havoc with pipeline efficiency; much work is done in modern compilers and processors to minimize this impact

Unconditional Jumps

`jmp dst`

`%rip ← address of dst`

- `dst` is usually a label in the code (which can be on a line by itself)
- `dst` address can also be indirect using the address in a register or memory location (`*reg` or `*(reg)`) – use for method calls, switch

Conditional Jumps

- Most arithmetic instructions set “condition code” bits to record information about the result (zero, non-zero, >0, etc.)
 - True of `addq`, `subq`, `andq`, `orq`; but not `imulq`, `idivq`, `leaq`
- Other instructions that set condition codes
 - `cmpq src,dst` # compare dst to src (e.g., `dst-src`)
 - `testq src,dst` # calculate `dst & src` (logical and)
 - These do not alter `src` or `dst`

Conditional Jumps Following Arithmetic Operations

jz	label	# jump if result == 0
jnz	label	# jump if result != 0
jg	label	# jump if result > 0
jng	label	# jump if result <= 0
jge	label	# jump if result >= 0
jnge	label	# jump if result < 0
jl	label	# jump if result < 0
jnl	label	# jump if result >= 0
jle	label	# jump if result <= 0
jnle	label	# jump if result > 0

- Obviously, the assembler is mapping multiple opcode mnemonics to some of the actual instructions

Compare and Jump Conditionally

- Want: compare two operands and jump if a relationship holds between them
- Would like to have this instruction

```
    jmpcond op1,op2,label
```

but can't, because 3-operand instructions can't be encoded in x86-64

(also true of most other machines)

cmp and jcc

- Instead, we use a 2-instruction sequence

```
    cmpq  op1,op2    # compute op2-op1  
    jcc   label
```

where j_{cc} is a conditional jump that is taken if the result of the comparison matches the condition cc

Conditional jumps after `cmpq op1,op2` (subtract `op2-op1` and compare to 0)

<code>je</code>	<code>label</code>	<code># jump if op1 == op2</code>
<code>jne</code>	<code>label</code>	<code># jump if op1 != op2</code>
<code>jg</code>	<code>label</code>	<code># jump if op2 > op1</code>
<code>jng</code>	<code>label</code>	<code># jump if op2 <= op1</code>
<code>jge</code>	<code>label</code>	<code># jump if op2 >= op1</code>
<code>jnge</code>	<code>label</code>	<code># jump if op2 < op1</code>
<code>jl</code>	<code>label</code>	<code># jump if op2 < op1</code>
<code>jnl</code>	<code>label</code>	<code># jump if op2 >= op1</code>
<code>jle</code>	<code>label</code>	<code># jump if op2 <= op1</code>
<code>jnle</code>	<code>label</code>	<code># jump if op2 > op1</code>

- Again, the assembler is mapping more than one mnemonic to some of the machine instructions

Aarrrg – this slide has had comparisons backwards for years! – fixed(?) 21sp
(please check and report if still messed up – sigh 🤔)

Function Call and Return

- The x86-64 instruction set itself only provides for transfer of control (jump) and return
- Stack is used to capture return address and recover it
- Everything else – parameter passing, stack frame organization, register usage – is a matter of software convention and not defined by the hardware
 - Follow the conventions even if you write all the code!
 - Helps anyone reading your code figure out what's happening
 - Lets standard tools like gdb work successfully with your code (in the unlikely 😊 event that you have to debug something...)

call and ret Instructions

call label

- Push address of next instruction and jump
- $\%rsp \leftarrow \%rsp - 8$; $\text{memory}[\%rsp] \leftarrow \%rip$
 $\%rip \leftarrow \text{address of label}$
- Address can also be in a register or memory as with `jmp` – we'll use these for dynamic dispatch of method calls (more later)

ret

- Pop address from top of stack and jump
- $\%rip \leftarrow \text{memory}[\%rsp]$; $\%rsp \leftarrow \%rsp + 8$
- **WARNING!** The word on the top of the stack had better be the address we want and not some leftover data

enter and leave

- Complex instructions for languages with nested procedures
 - enter is often slow on current processors – best avoided – i.e., don't use it in your project
 - leave is equivalent to

```
mov %rbp,%rsp
pop %rbp
```

and is generated by many compilers. Fits in 1 byte, saves space. Not clear if it's any faster.

x86-64-Register Usage

- `%rax` – function result
- Arguments 1-6 passed in these registers in order
 - `%rdi, %rsi, %rdx, %rcx, %r8, %r9`
 - For Java/C++ “`this`” pointer is first argument, in `%rdi`
 - More about “`this`” later
- `%rsp` – stack pointer; value must be 8-byte aligned always and 16-byte aligned when calling a function
- `%rbp` – frame pointer (optional use)
 - We’ll use it

x86-64 Register Save Conventions

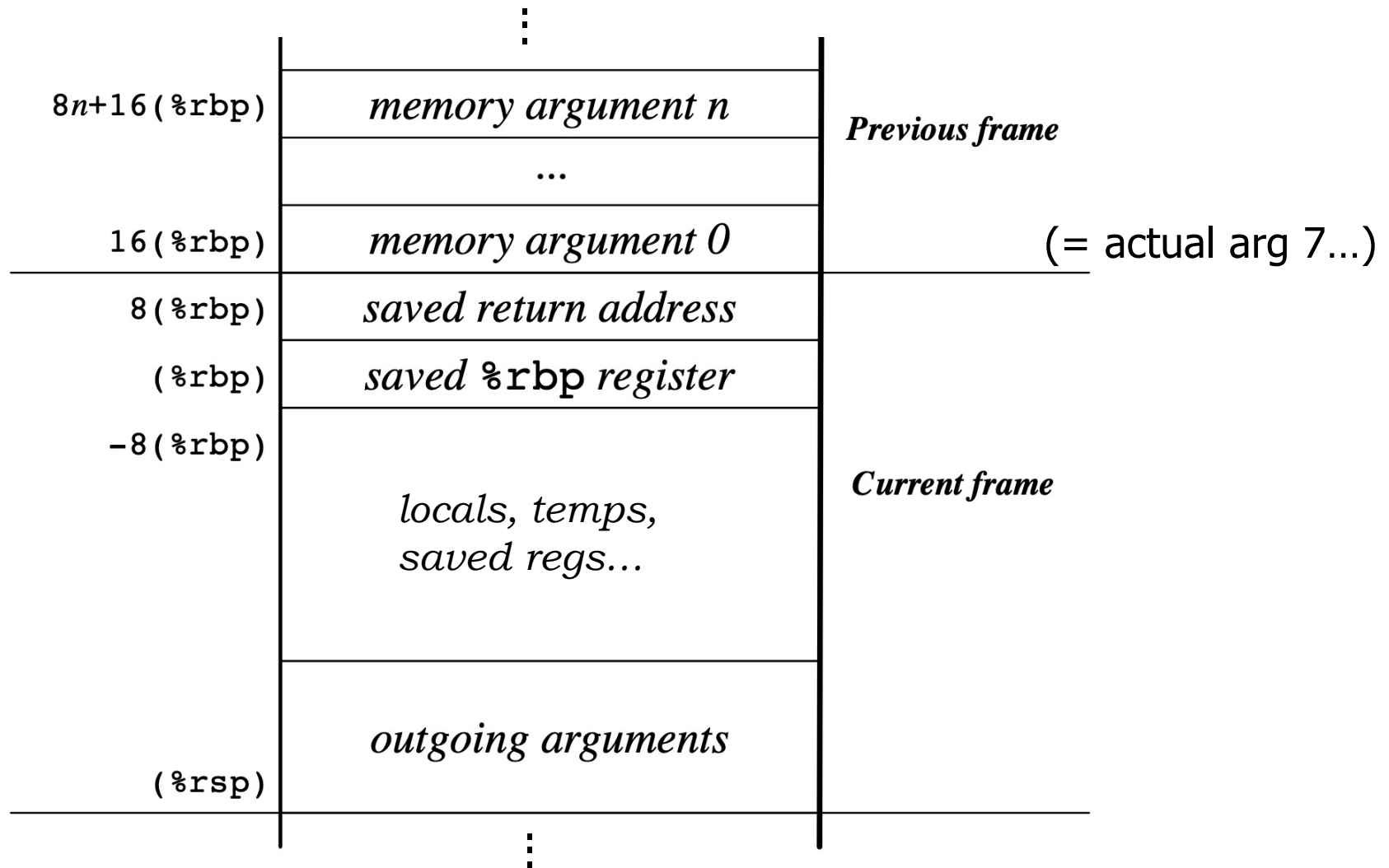
- A called function must preserve these registers (or save/restore them if it wants to use them)
 - `%rbx, %rbp, %r12-%r15`
- `%rsp` isn't on the “callee save list”, but needs to be properly restored for return
- All other registers can change across a function call
 - Debugging/correctness note: always assume every called function will change all registers it is allowed to
 - (including registers containing function parameters!)
 - (for debugging, maybe *deliberately* clobber them!)

x86-64 Function Call

- Caller places up to 6 arguments in registers, rest on stack, then executes call instruction (which pushes 8-byte return address)
- On entry, called function prologue sets up the stack frame:

```
pushq %rbp           # save old frame ptr
movq  %rsp,%rbp     # new frame ptr is top of
                    # stack after ret addr and
                    # old rbp pushed
subq  $framesize,%rsp # allocate stack frame
                    # (size should be multiple
                    # of 16 normally)
```

Stack Frame Layout



x86-64 Function Return

- Called function puts result (if any) in %rax and restores any callee-save registers if needed
- Called function returns with:

```
    movq %rbp,%rsp    # or use leave instead
    popq %rbp         #   of movq/popq
    ret
```
- If caller allocated space for arguments (beyond the 6 in regs) it deallocates as needed

Caller Example

- $n = \text{sumOf}(17, 42)$

```
movq    $42,%rsi    # load arguments in
movq    $17,%rdi    # either order, but use
                        # correct registers
call    sumOf       # jump & push ret addr
movq    %rax,offset_n(%rbp) # store result
```

Example Function

- Source code

```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

Assembly Language Version

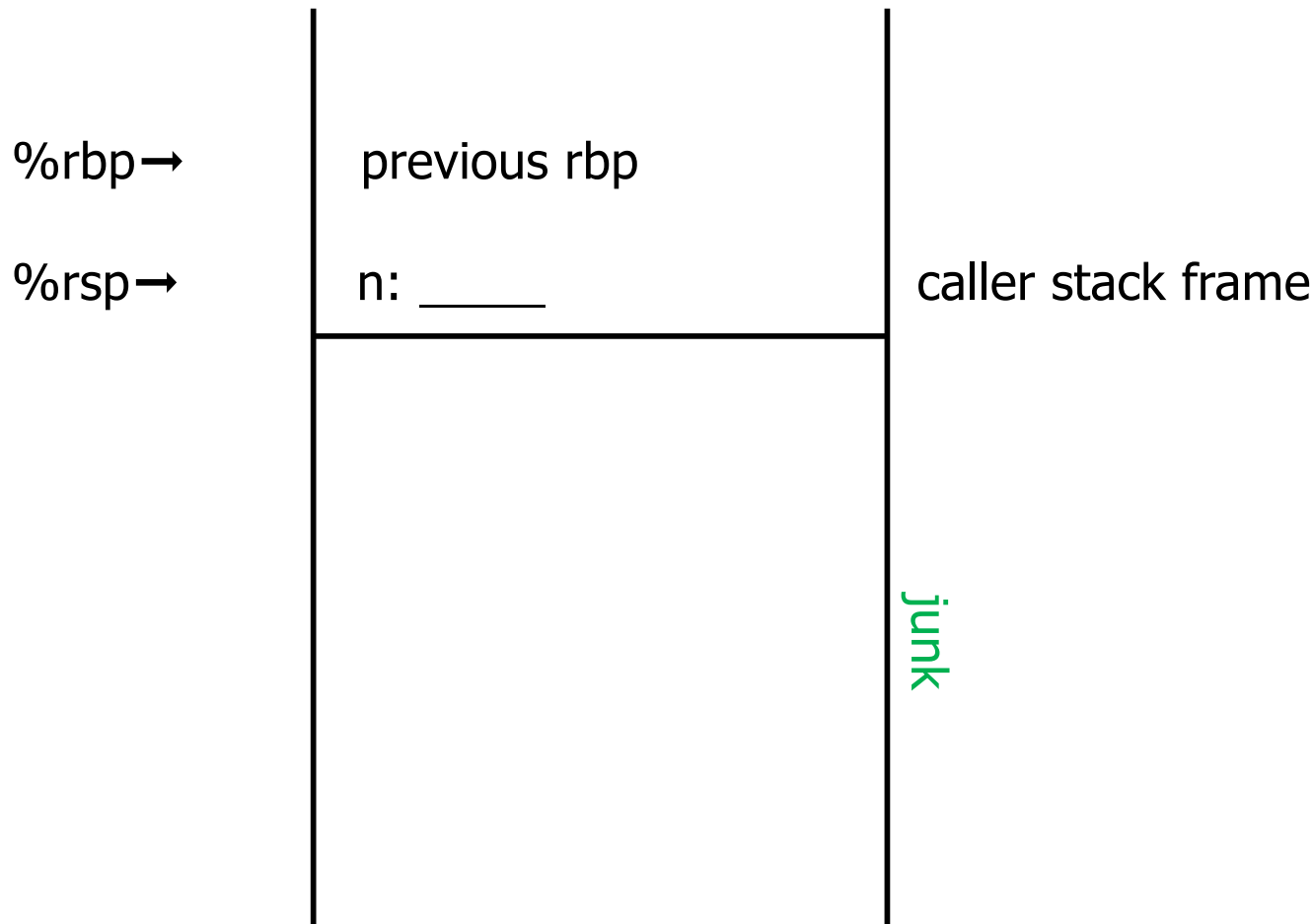
```
# int sumOf(int x, int y) {
#   int a, int b;
sumOf:
    pushq   %rbp   # prologue
    movq    %rsp,%rbp
    subq    $16,%rsp
#   a = x;
    movq    %rdi,-8(%rbp)
#   b = a + y;
    movq    -8(%rbp),%rax
    addq    %rsi,%rax
    movq    %rax,-16(%rbp)
#   return b;
    movq    -16(%rbp),%rax
    movq    %rbp,%rsp
    popq    %rbp
    ret
# }
```

Stack Frame for sumOf

```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

Stack Frame for sumOf

registers: %rax _____ %rdi _____ %rsi _____

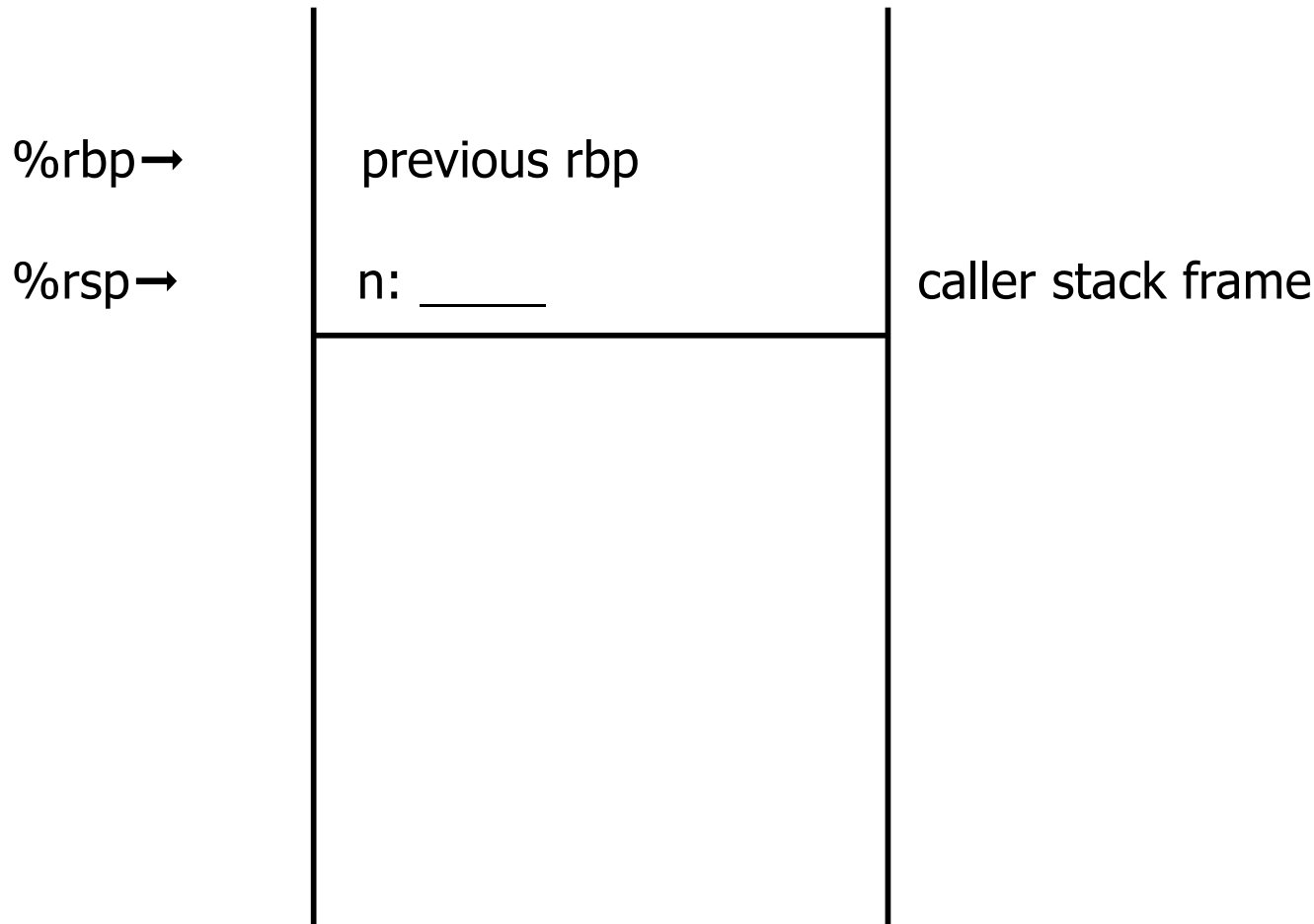


```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

```
sumOf:  
# prologue  
    pushq %rbp  
    movq  %rsp,%rbp  
    subq  $16,%rsp  
# a = x;  
    movq  %rdi,-8(%rbp)  
# b = a + y;  
    movq  -8(%rbp),%rax  
    addq  %rsi,%rax  
    movq  %rax,-16(%rbp)  
# return b;  
    movq  -16(%rbp),%rax  
    movq  %rbp,%rsp  
    popq  %rbp  
    ret  
# }
```


Stack Frame for sumOf

registers: %rax _____ %rdi 17 %rsi 42



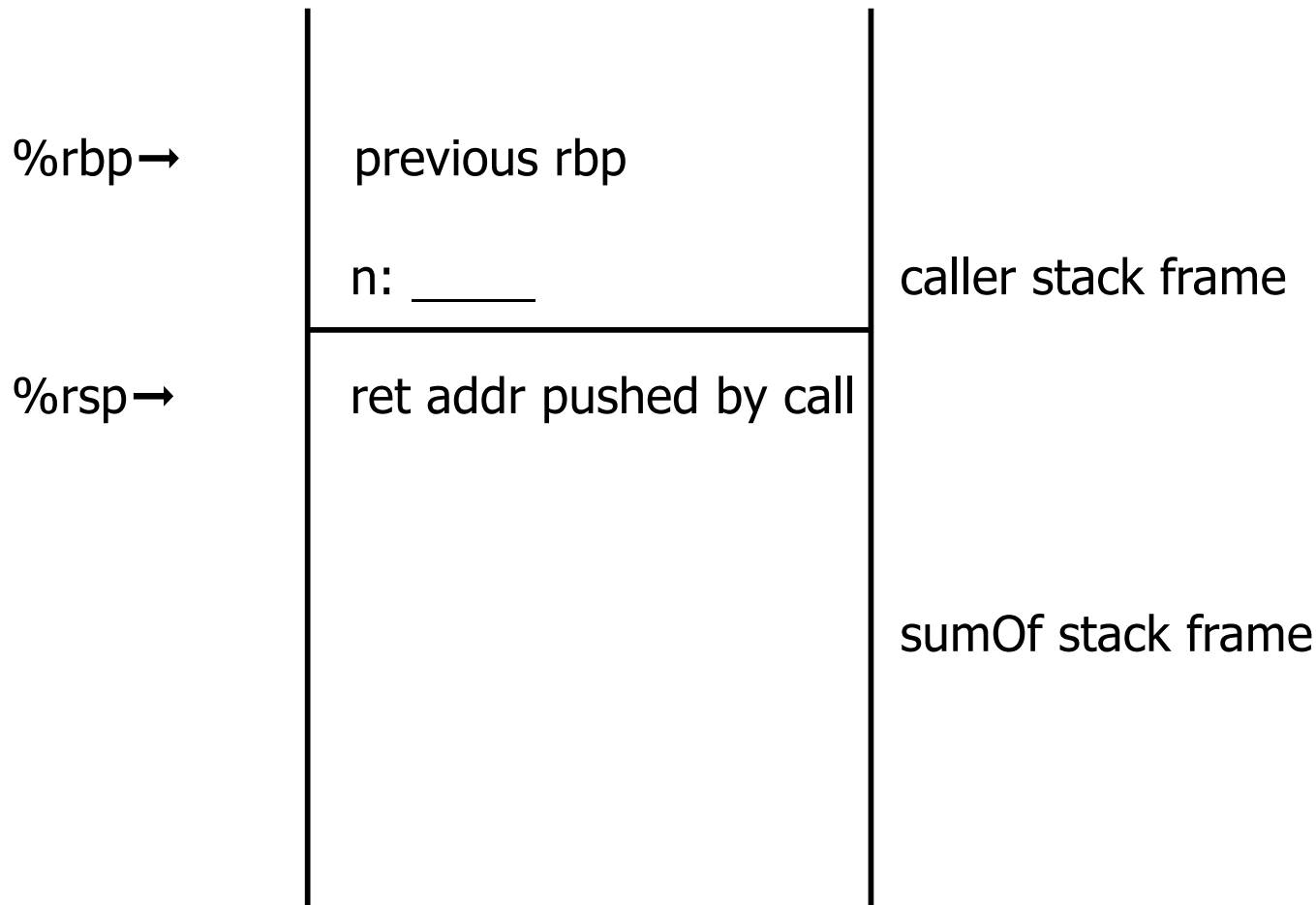
```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

👉 (Caller loads arg regs)

```
sumOf:  
# prologue  
    pushq %rbp  
    movq  %rsp,%rbp  
    subq  $16,%rsp  
# a = x;  
    movq  %rdi,-8(%rbp)  
# b = a + y;  
    movq  -8(%rbp),%rax  
    addq  %rsi,%rax  
    movq  %rax,-16(%rbp)  
# return b;  
    movq  -16(%rbp),%rax  
    movq  %rbp,%rsp  
    popq  %rbp  
    ret  
# }
```

Stack Frame for sumOf

registers: %rax _____ %rdi 17 %rsi 42



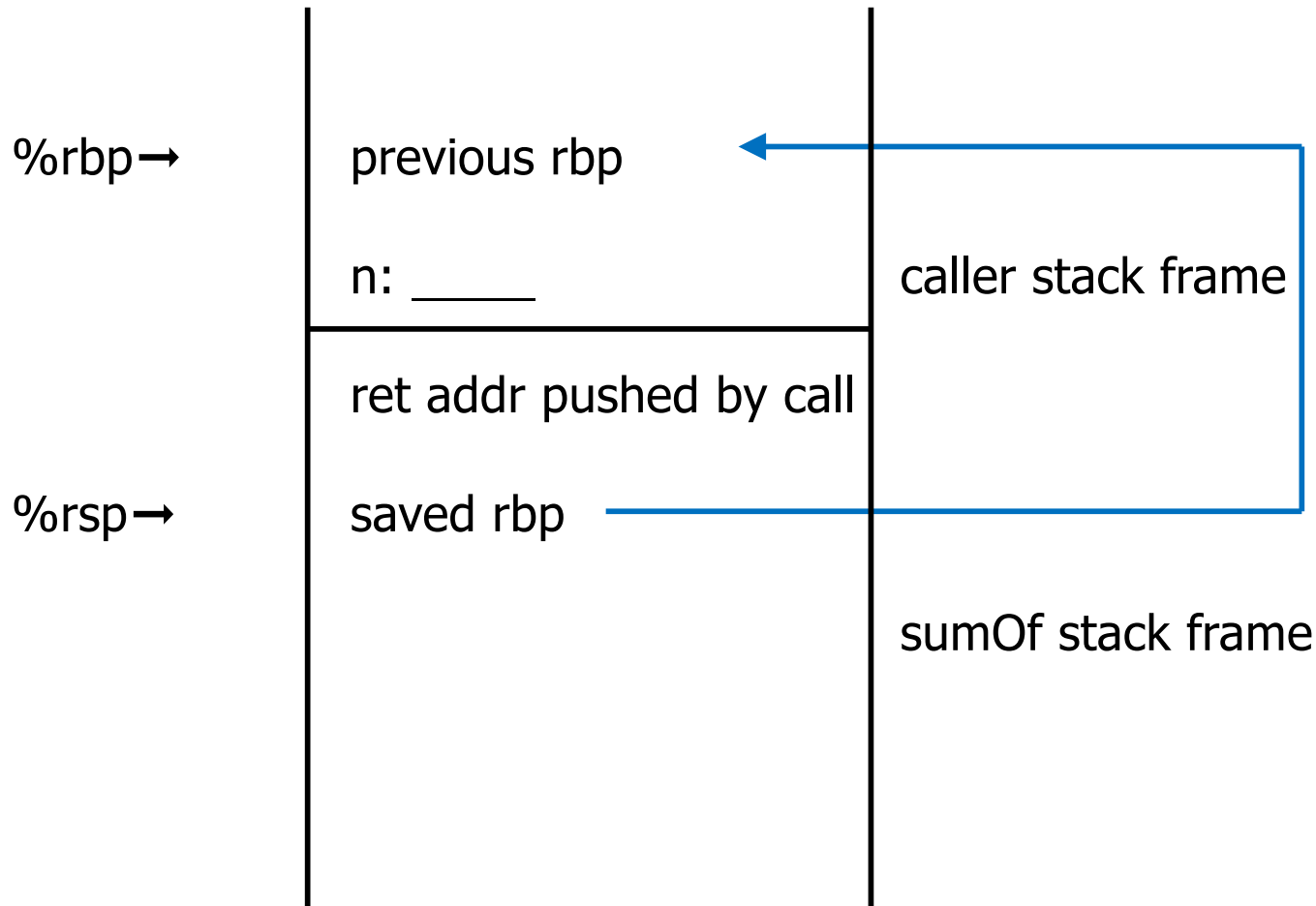
```
int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
}
```

 (Caller calls)

```
sumOf:
# prologue
    pushq %rbp
    movq  %rsp,%rbp
    subq  $16,%rsp
# a = x;
    movq  %rdi,-8(%rbp)
# b = a + y;
    movq  -8(%rbp),%rax
    addq  %rsi,%rax
    movq  %rax,-16(%rbp)
# return b;
    movq  -16(%rbp),%rax
    movq  %rbp,%rsp
    popq  %rbp
    ret
# }
```

Stack Frame for sumOf

registers: %rax _____ %rdi 17 %rsi 42

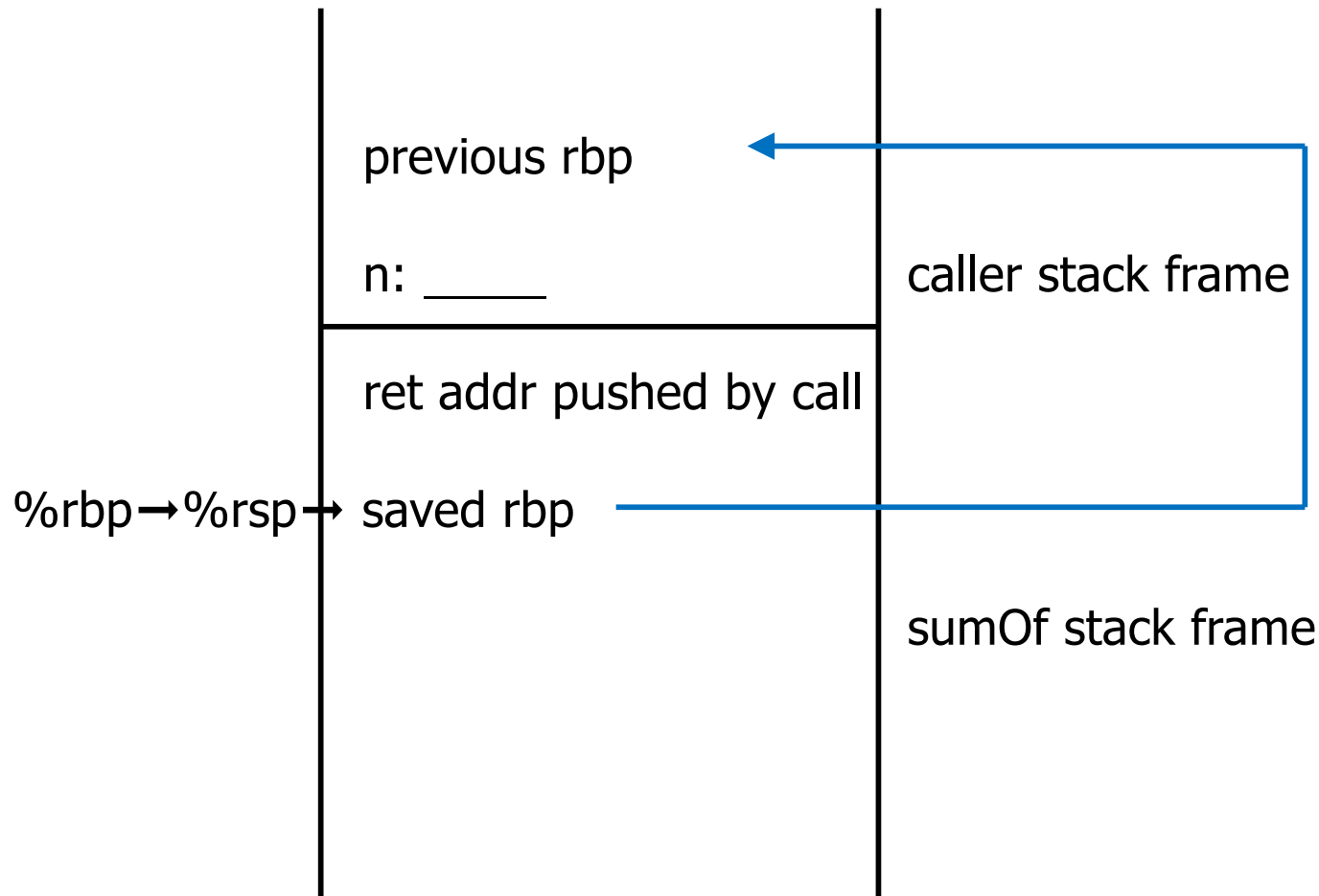


```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

```
sumOf:  
# prologue  
pushq %rbp  
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subq $16,%rsp  
# a = x;  
movq %rdi,-8(%rbp)  
# b = a + y;  
movq -8(%rbp),%rax  
addq %rsi,%rax  
movq %rax,-16(%rbp)  
# return b;  
movq -16(%rbp),%rax  
movq %rbp,%rsp  
popq %rbp  
ret  
# }
```

Stack Frame for sumOf

registers: %rax _____ %rdi 17 %rsi 42

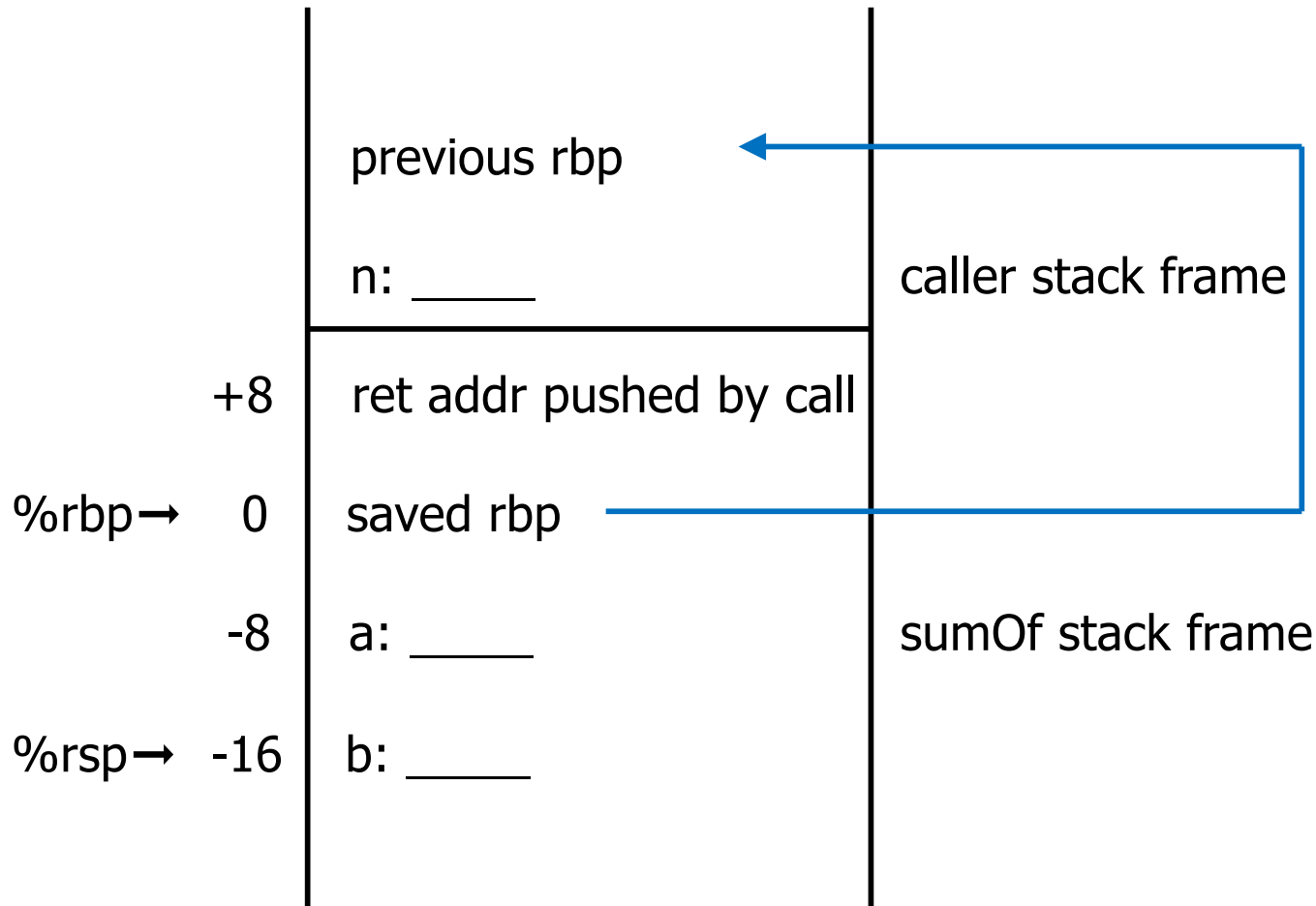


```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

```
sumOf:  
# prologue  
pushq %rbp  
movq %rsp,%rbp  
subq $16,%rsp  
# a = x;  
movq %rdi,-8(%rbp)  
# b = a + y;  
movq -8(%rbp),%rax  
addq %rsi,%rax  
movq %rax,-16(%rbp)  
# return b;  
movq -16(%rbp),%rax  
movq %rbp,%rsp  
popq %rbp  
ret  
# }
```

Stack Frame for sumOf

registers: %rax _____ %rdi 17 %rsi 42

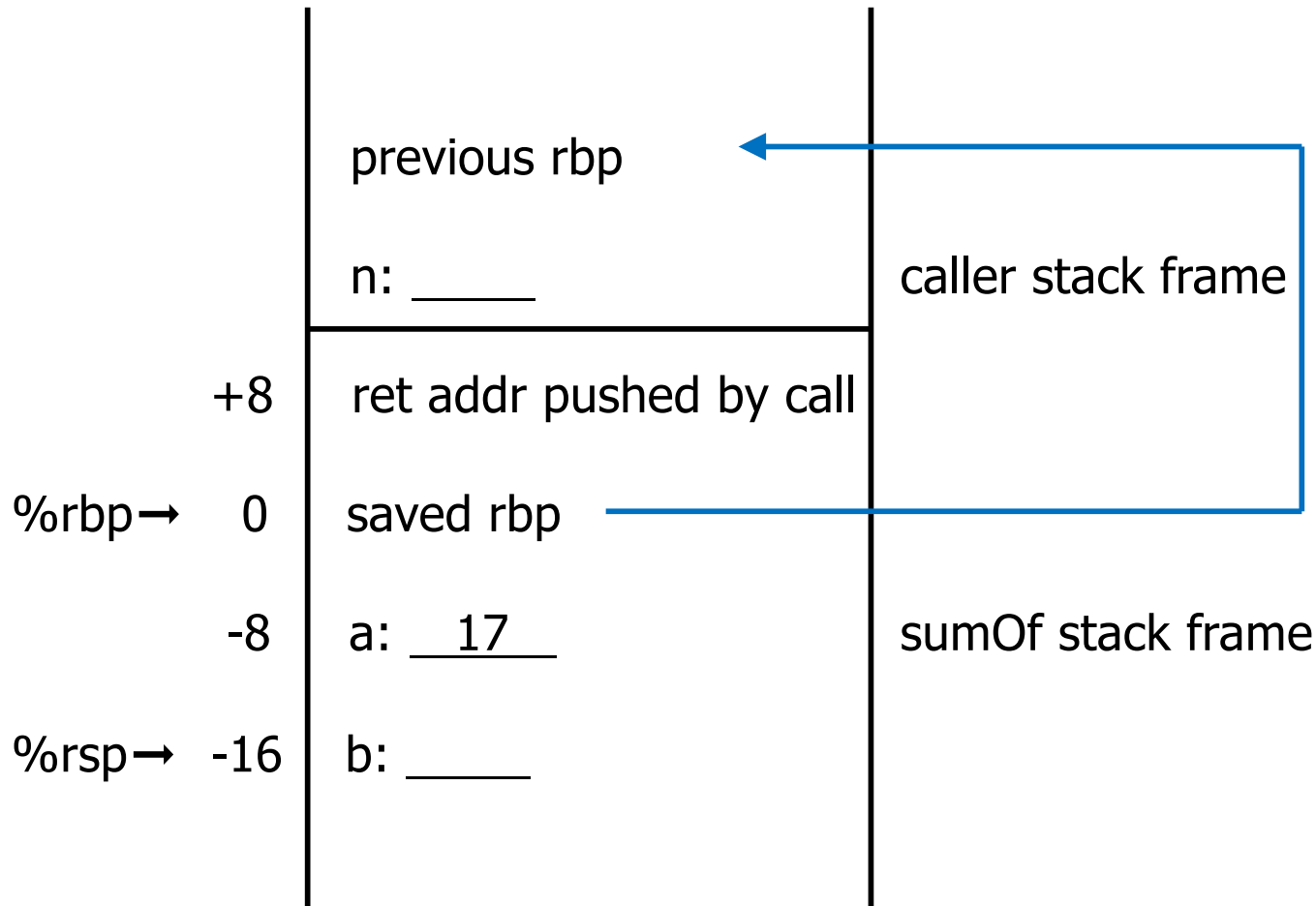


```
int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
}
```

```
sumOf:
# prologue
pushq %rbp
movq %rsp,%rbp
subq $16,%rsp
# a = x;
movq %rdi,-8(%rbp)
# b = a + y;
movq -8(%rbp),%rax
addq %rsi,%rax
movq %rax,-16(%rbp)
# return b;
movq -16(%rbp),%rax
movq %rbp,%rsp
popq %rbp
ret
# }
```

Stack Frame for sumOf

registers: %rax _____ %rdi 17 %rsi 42

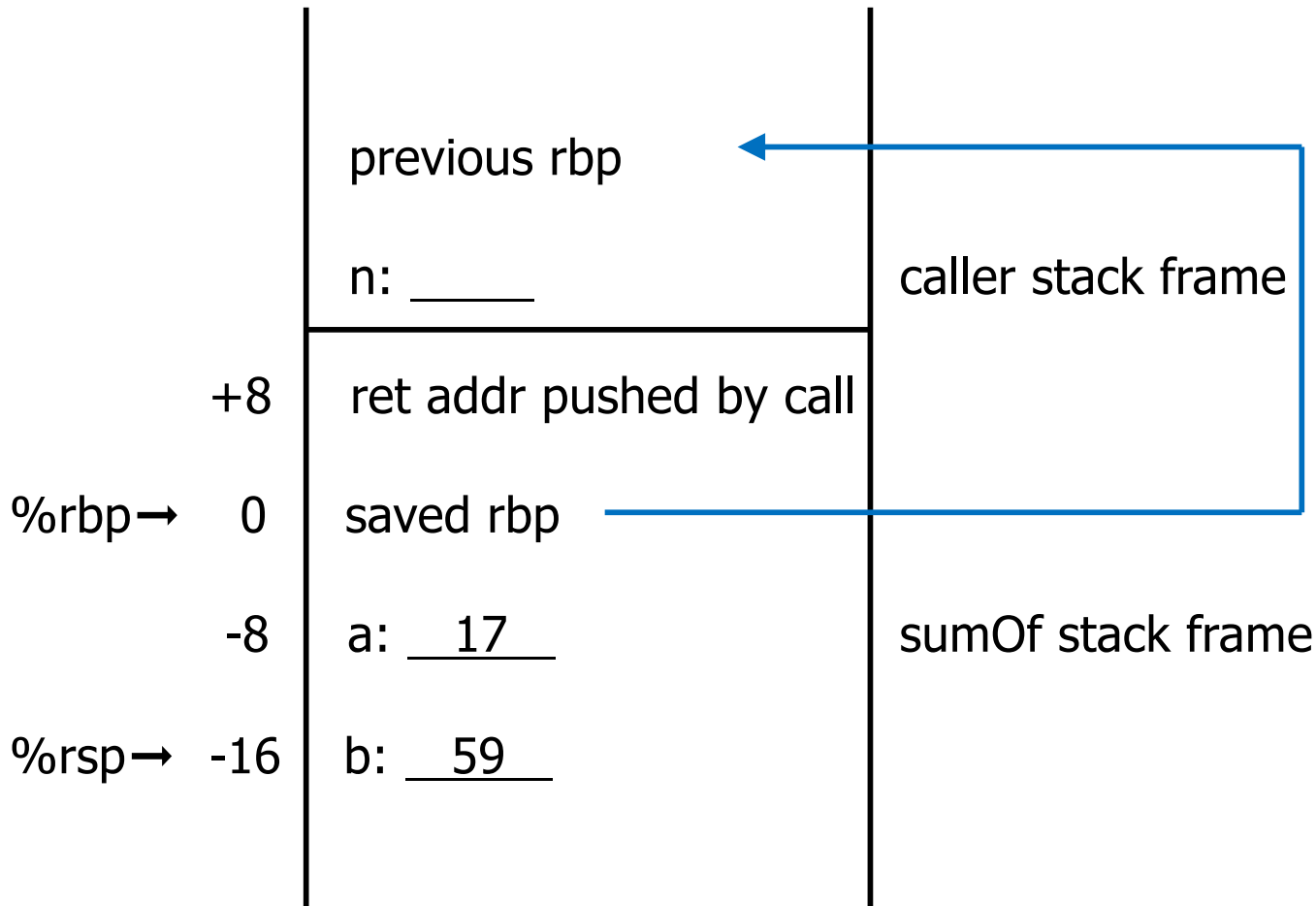


```
int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
}
```

```
sumOf:
# prologue
pushq %rbp
movq %rsp,%rbp
subq $16,%rsp
# a = x;
movq %rdi,-8(%rbp)
# b = a + y;
movq -8(%rbp),%rax
addq %rsi,%rax
movq %rax,-16(%rbp)
# return b;
movq -16(%rbp),%rax
movq %rbp,%rsp
popq %rbp
ret
# }
```

Stack Frame for sumOf

registers: %rax 17 59 %rdi 17 %rsi 42

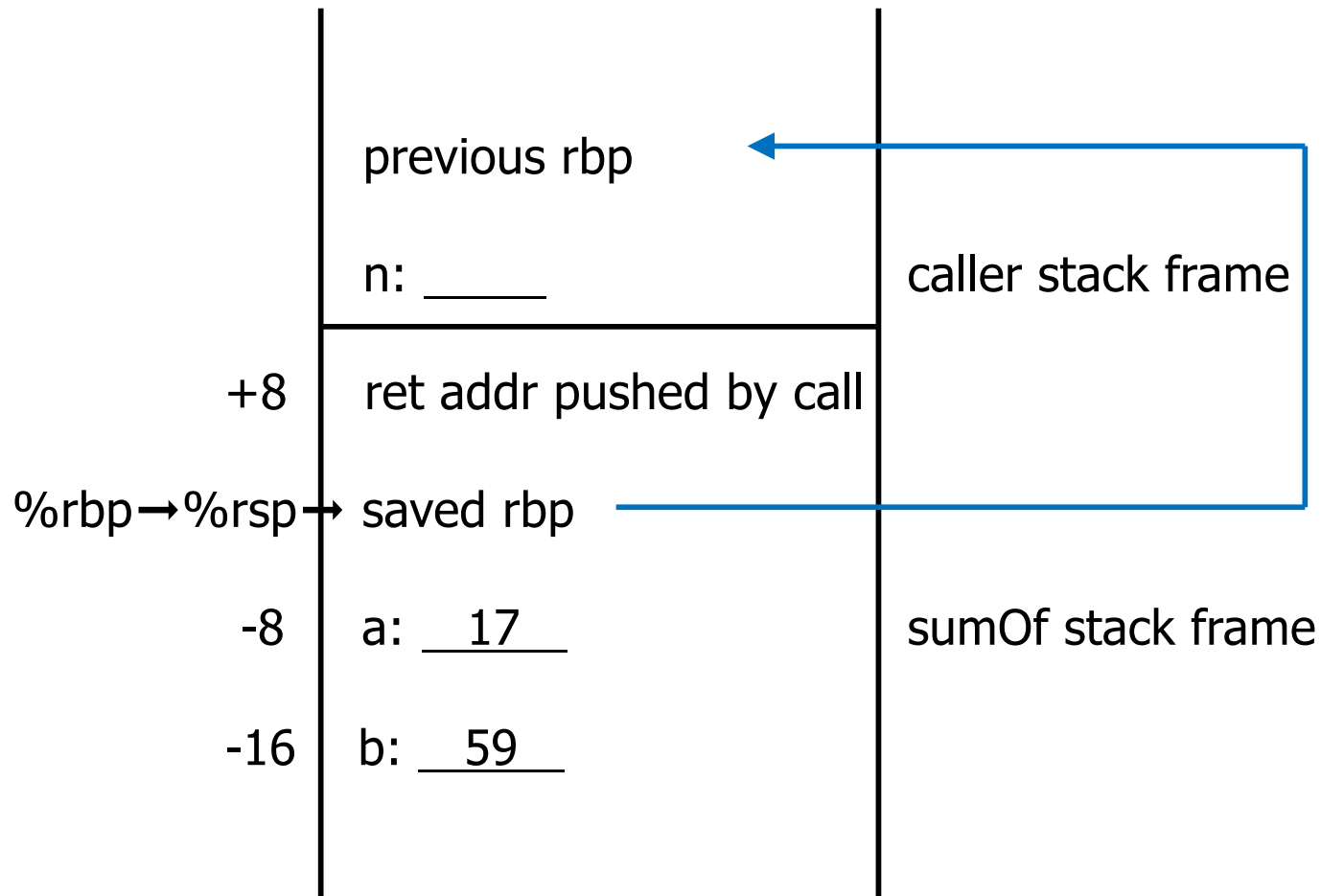


```
int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
}
```

```
sumOf:
# prologue
pushq %rbp
movq %rsp,%rbp
subq $16,%rsp
# a = x;
movq %rdi,-8(%rbp)
# b = a + y;
movq -8(%rbp),%rax
addq %rsi,%rax
movq %rax,-16(%rbp)
# return b;
movq -16(%rbp),%rax
movq %rbp,%rsp
popq %rbp
ret
# }
```

Stack Frame for sumOf

registers: %rax 59 %rdi 17 %rsi 42

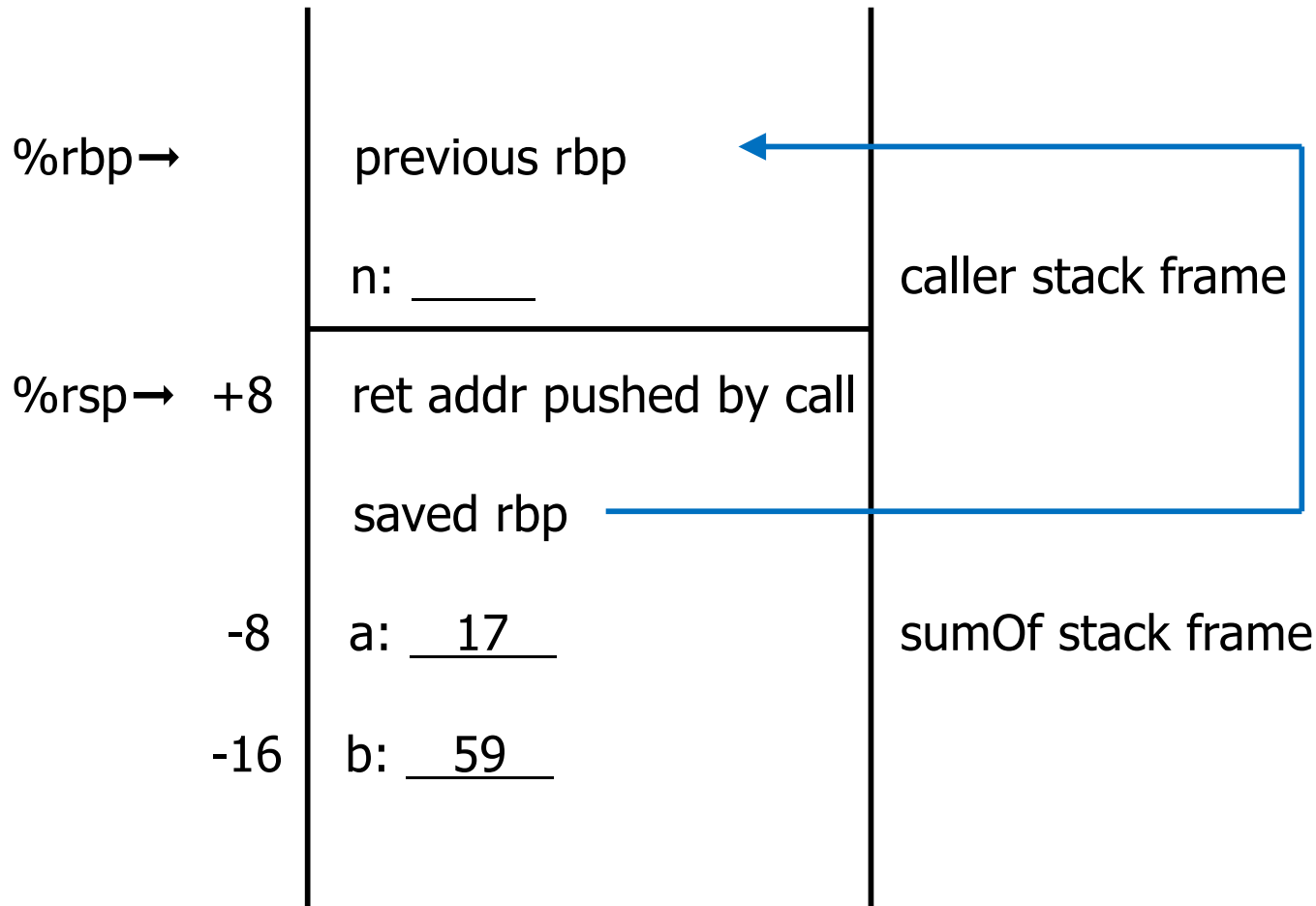


```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

```
sumOf:  
# prologue  
    pushq %rbp  
    movq  %rsp,%rbp  
    subq  $16,%rsp  
# a = x;  
    movq  %rdi,-8(%rbp)  
# b = a + y;  
    movq  -8(%rbp),%rax  
    addq  %rsi,%rax  
    movq  %rax,-16(%rbp)  
# return b;  
    movq  -16(%rbp),%rax  
    movq  %rbp,%rsp  
    popq  %rbp  
    ret  
# }
```


Stack Frame for sumOf

registers: %rax 59 %rdi 17 %rsi 42

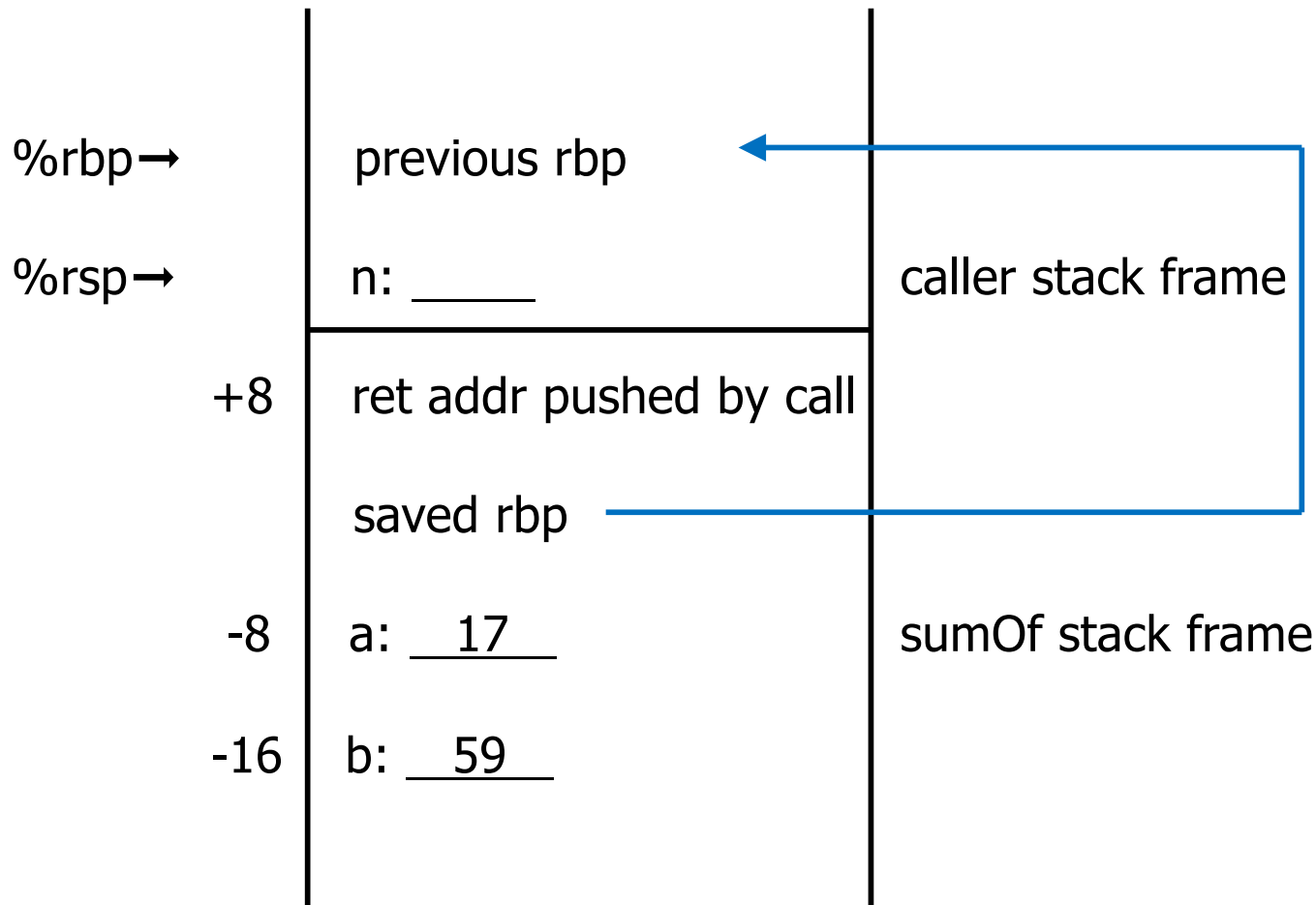


```
int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
}
```

```
sumOf:
# prologue
pushq %rbp
movq %rsp,%rbp
subq $16,%rsp
# a = x;
movq %rdi,-8(%rbp)
# b = a + y;
movq -8(%rbp),%rax
addq %rsi,%rax
movq %rax,-16(%rbp)
# return b;
movq -16(%rbp),%rax
movq %rbp,%rsp
popq %rbp
ret
# }
```

Stack Frame for sumOf

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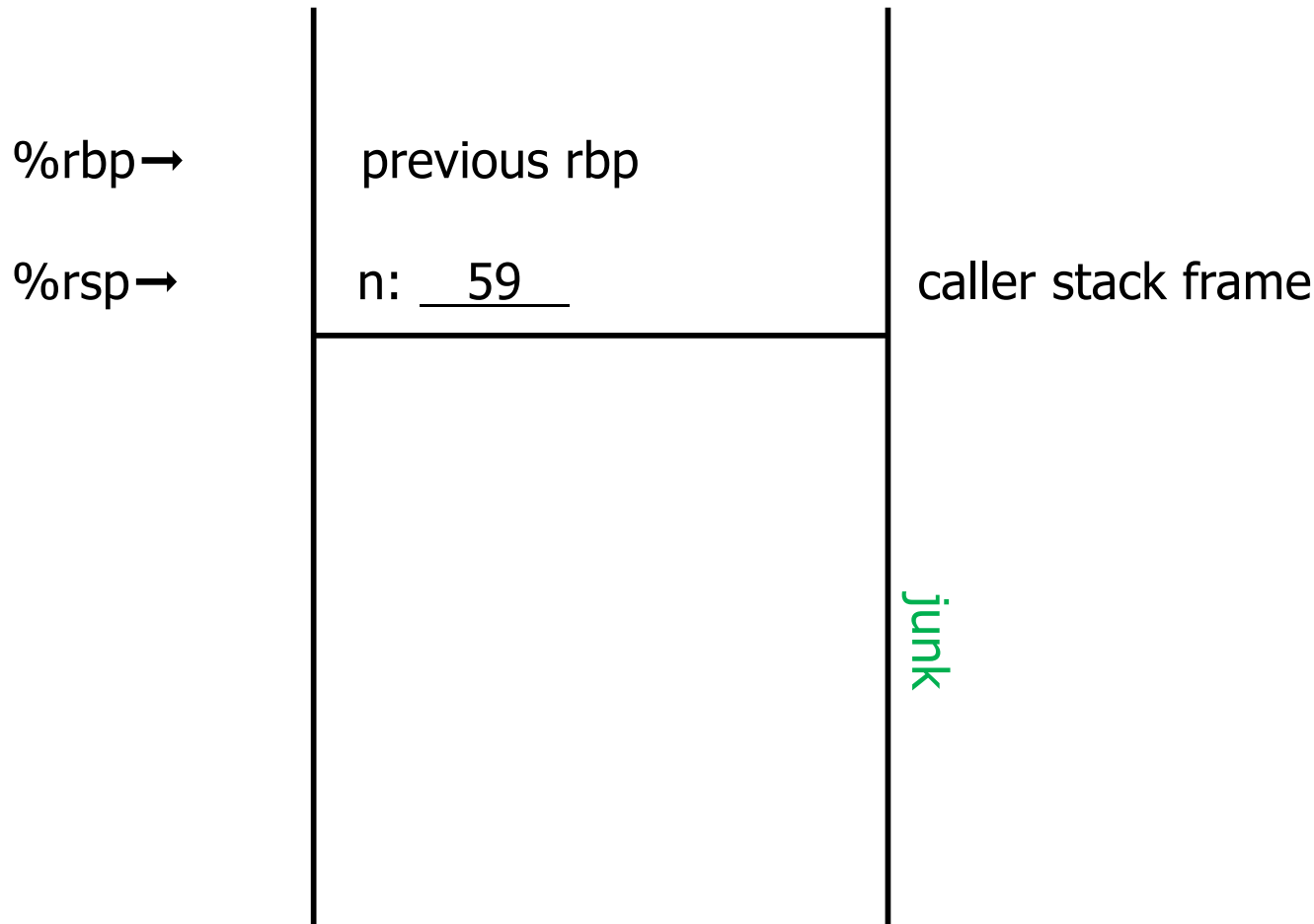


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int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
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```
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addq %rsi,%rax
movq %rax,-16(%rbp)
# return b;
movq -16(%rbp),%rax
movq %rbp,%rsp
popq %rbp
ret
# }
```

Stack Frame for sumOf

registers: %rax 59 %rdi 17 %rsi 42



```
int sumOf(int x, int y) {  
    int a, int b;  
    a = x;  
    b = a + y;  
    return b;  
}
```

👉 (Caller sets $n \leftarrow \%rax$)

```
sumOf:  
# prologue  
    pushq %rbp  
    movq  %rsp,%rbp  
    subq  $16,%rsp  
# a = x;  
    movq  %rdi,-8(%rbp)  
# b = a + y;  
    movq  -8(%rbp),%rax  
    addq  %rsi,%rax  
    movq  %rax,-16(%rbp)  
# return b;  
    movq  -16(%rbp),%rax  
    movq  %rbp,%rsp  
    popq  %rbp  
    ret  
# }
```

The Nice Thing About Standards...

- The above is the System V/AMD64 ABI convention (used by Linux, MacOS X)
- Microsoft's x64 calling conventions are slightly different (sigh...)
 - First four parameters in registers %rcx, %rdx, %r8, %r9; rest on the stack
 - Called function stack frame must include empty space for called function to save values passed in parameter registers if desired
- Not relevant for us, but worth being aware of it
 - (except that providing space in each stack frame to save parameter registers will be handy for our simple code gen)

Coming Attractions

- Now that we've got a basic idea of the x86-64 instruction set, we need to map language constructs to x86-64
 - Code Shape
- Then need to figure out how to get compiler to generate this and how to bootstrap things to run our compiled programs