Low-Level Programming on Linux (x86-64)

Assembly Programming with GAS (Intel Syntax)

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simplifycpp.org

November 2025

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Author's Introduction

Assembly language has long been regarded as the "hidden layer" of computing—the fundamental level where the behavior of the processor, memory operations, and performance boundaries are revealed without abstraction. Despite the advances of high-level languages, assembly remains the foundation beneath every compiler, every kernel interface, and every performance-critical software system.

The choice to base this work on the Linux environment is intentional. Linux is not merely an operating system—it is an open, inspectable ecosystem where internal processes can be traced, analyzed, and understood. Here, we do not deal with black-box behaviors; instead, we are given the ability to examine how executables are built, how the kernel interacts with user applications, how memory is structured, and how system calls flow from user space to the core of the operating system. This transparency is invaluable.

Furthermore, Linux today forms the backbone of servers, cloud computing platforms, embedded systems, scientific computing, mobile operating systems, and industrial and research environments. For the serious programmer, learning assembly in the context of Linux is no longer an academic curiosity—it is a practical step toward understanding why programs behave the way they do, not just how to write them.

This series was created to provide a clear and accessible introduction to x86-64 assembly under Linux, without overwhelming the reader or diving prematurely into

deep architectural complexity. The intent is to make this series:

- A foundational base for deeper understanding.
- A gradual learning path from basic concepts to advanced practice.
- A practical handbook, where every example can be built and tested directly.
- A bridge between assembly, the toolchain, the operating system, and the underlying hardware.

This booklet—the second volume in the series—focuses on the fundamentals of assembling with GAS using Intel syntax, linking, memory layout, the calling convention, function construction, and interoperability with high-level languages. The material here forms the groundwork for later volumes, where we will progress toward building structured libraries, analyzing execution paths, and evaluating performance at the microarchitectural level.
I hope this work provides the reader with a clear starting point and serves as a guide for those who wish to move beyond using programming languages as mere tools, toward understanding the actual execution, memory interaction, and performance characteristics of the system.

Stay Connected
For more discussions and valuable content about Assembly Programming with GAS (Intel Syntax), I invite you to follow me on LinkedIn:
https://linkedin.com/in/aymanalheraki
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Ayman Alheraki

Chapter 1

Toolchain Fundamentals

1.1 as, ld, and gcc -c

Assembly development on Linux is built around the standard UNIX toolchain: the assembler (as), the linker (ld), and the compiler driver (gcc). Although gcc is typically associated with higher-level languages, it also plays a central role in assembling and linking raw assembly sources. A clear understanding of how each tool contributes to the build process is essential when writing and integrating low-level code.
Modern Linux distributions ship with the GNU Assembler (GAS) and the GNU Linker (GLD or LLD when LLVM is installed). When targeting x86-64, GAS supports both AT&T syntax (default) and Intel syntax using directives. In this series, all instructions and examples use Intel syntax exclusively.

1.1.1 The Assembler: as

The assembler translates human-readable assembly into object code. This object file contains symbol tables, relocation entries, and machine code but is not yet executable.

To enable Intel syntax, we use the directive:

```
.intel_syntax noprefix
```

Example: assembling a minimal function that returns 42:
file: ret42.s

```
.intel_syntax noprefix
.global ret42

ret42:
    mov rax, 42
    ret
```

To assemble:

```
as --64 ret42.s -o ret42.o
```

The output file ret42.o is an ELF relocatable object. It cannot run directly because it lacks runtime metadata such as an entry point and standard library linkage.

1.1.2 The Linker: ld

The linker resolves symbol references across object files and produces an executable ELF image. Using ld directly requires specifying runtime start files and libraries. This is often needed when creating a freestanding binary or a minimal runtime.
Example of a manually linked program:
file: main.s

```
.intel_syntax noprefix
.global _start

_start:
```

```
    mov rax, 60       # SYS_exit
    mov rdi, 0        # exit code
    syscall
```

Assemble and link:

```
as --64 main.s -o main.o
ld main.o -o a.out
```

Running ./a.out terminates with exit code 0. No C runtime or libc is used here, and no ABI-conforming entry point (main) is required.

1.1.3 The Compiler Driver: gcc -c

Although as and ld can be used directly, it is common to invoke them through gcc. The -c option instructs gcc not to link, but only to assemble and produce an object file. This provides three benefits:

1. Automatic selection of correct assembler settings
2. Integration with C header files and macros
3. Consistent ABI handling

Example (equivalent to calling as manually):

```
gcc -c ret42.s -o ret42.o
```

Using gcc also allows seamless linking:

```
gcc ret42.o main.o -o program
```

The result is an ELF executable using the system's standard C runtime startup and linking conventions.

1.1.4 Example: Calling Assembly from C

file: ret42.s

```
.intel_syntax noprefix
.global ret42

ret42:
    mov rax, 42
    ret
```

file: test.c

```
#include <stdio.h>

int ret42();

int main() {
    printf("Value: %d\n", ret42());
    return 0;
}
```

Compile and link:

```
gcc -c ret42.s -o ret42.o
gcc test.c ret42.o -o test
```

Run:

```
./test
```

Output:

```
Value: 42
```

This demonstrates how gcc -c harmonizes assembly with C code under the System V AMD64 ABI.

1.1.5 Summary

- as translates assembly into relocatable object code.
- ld combines object files and produces final ELF executables or libraries.
- gcc -c acts as a driver that invokes the assembler with system-appropriate options, enabling smooth integration with C and the standard ABI.

A clear mental model of these tools is foundational before moving deeper into calling conventions, stack frames, SysV AMD64 ABI semantics, and performance-aware instruction selection in later chapters.

1.2 objdump and readelf

After producing an object file or executable, examining its internal structure is essential for understanding how the assembler, linker, and runtime environment operate. The two primary tools for this inspection on Linux are objdump and readelf. Although they appear similar, they serve distinct purposes: objdump provides disassembly and code-level inspection, while readelf displays ELF metadata, program headers, section headers, and relocation details with high fidelity and without relying on the BFD abstraction layer.
Both tools are indispensable when analyzing calling conventions, verifying compiler optimizations, debugging ABI mismatches, writing minimal runtimes, or reversing binaries.

1.2.1 Disassembly with objdump

objdump -d disassembles executable sections, mapping machine code back to assembly instructions. For raw GAS-generated files, ensure Intel syntax output:

```
objdump -d -M intel program.o
```

To illustrate, consider a function computing a + b:
file: add.s

```
.intel_syntax noprefix
.global add

add:
    mov rax, edi    # first argument in edi
    add rax, esi    # second argument in esi
    ret
```

Assemble and inspect:

```
gcc -c add.s -o add.o
objdump -d -M intel add.o
```

Example output (trimmed for clarity):

```
0000000000000000 <add>:
   0: 89 f8                mov rax, edi
   2: 01 f0                add rax, esi
   4: c3                   ret
```

This demonstrates how parameter passing follows the System V AMD64 ABI, where integer arguments are placed in general-purpose registers (edi, esi, edx, etc.).

1.2.2 Inspecting ELF Metadata with readelf

readelf provides precise structural information about ELF files. Unlike objdump, which focuses on disassembly, readelf reveals how the program is laid out in memory and how linking and relocation are performed.
Common usage patterns:

- Display ELF file type and machine architecture:

```
readelf -h add.o
```

- Show section headers:

```
readelf -S add.o
```

- Display symbol table:

```
readelf -s add.o
```

- Display relocation entries:

```
readelf -r add.o
```

Example symbol table output excerpt:

```
Symbol table '.symtab' contains 3 entries:
   Num:    Value  Size Type    Bind   Vis      Ndx Name
     1:        0     0 FUNC    GLOBAL DEFAULT    1 add
```

This confirms that add is exported as a global function symbol, allowing other modules (C or assembly) to link against it.

1.2.3 Inspecting a Linked Binary

To show the full picture, create a caller in C:
file: caller.c

```c
#include <stdio.h>
int add(int, int);

int main() {
```

```
    printf("%d\n", add(5, 7));
    return 0;
}
```

Compile and link:

```
gcc caller.c add.o -o test
```

Now examine final executable layout:

```
objdump -d -M intel test | less
readelf -l test     # program segments (runtime memory mapping)
readelf -S test     # ELF sections (file layout)
```

Example segment view (truncated):

```
Program Headers:
  LOAD 0x000000 0x004000  R E  .text .rodata
  LOAD 0x001000 0x006000  RW   .data .bss
```

This output shows how the loader maps code and data into memory.

1.2.4 Using objdump to Verify Optimization

Consider enabling compiler optimizations:

```
gcc -O2 -c add.s -o add.o
objdump -d -M intel add.o
```

The result should remain unchanged because the code is already optimal; however, for more complex routines, examining the disassembly is crucial to ensuring the compiler or assembler did not introduce unnecessary instructions.

1.2.5 Summary

- objdump focuses on code, enabling analysis of machine instructions, ABI register usage, control flow, and compiler optimizations.
- readelf focuses on binary structure, exposing ELF metadata, symbol tables, relocation entries, and program headers.
- Together, they form the foundation for verifying correctness, debugging, reverse engineering, and understanding executable format internals.

These tools will be used continuously in later chapters, especially when studying stack frames, function prologues/epilogues, dynamic linking, and runtime loaders in depth.

1.3 Makefile Basics

Assembling and linking programs manually with as, ld, or gcc is suitable for experimentation, but non-trivial software requires structured build automation. Make provides a rule-based system that determines which files must be rebuilt based on dependency changes and executes the associated build commands. A project's build logic is defined in a Makefile, where each target specifies how to produce an output file from its dependencies.
Make tracks timestamps: if a source file is newer than its corresponding object file, the rule regenerates that object. This allows incremental builds, which is essential when working with multiple assembly modules.

1.3.1 Minimal Makefile for an Assembly Program

Consider a standalone assembly program that calls the exit system call directly:
file: exit.s

```
.intel_syntax noprefix
.global _start

_start:
    mov rax, 60     # SYS_exit
    mov rdi, 0      # exit code
    syscall
```

A Makefile that assembles and links this:

file: Makefile

```
AS      = as
LD      = ld
ASFLAGS = --64

all: exit

exit: exit.o
^^I$(LD) exit.o -o exit

exit.o: exit.s
^^I$(AS) $(ASFLAGS) exit.s -o exit.o

clean:
^^Irm -f exit exit.o
```

Build:

```
make
```

Run:

```
./exit
```

1.3.2 Makefile Using gcc as Driver

When integrating with C or relying on libc, using gcc simplifies linking. Consider a function defined in assembly and called from C:

file: add.s

```
.intel_syntax noprefix
.global add

add:
    mov rax, edi
    add rax, esi
    ret
```

file: main.c

```
#include <stdio.h>

int add(int, int);

int main() {
    printf("%d\n", add(10, 32));
    return 0;
}
```

Makefile:

```
CC      = gcc
CFLAGS  = -O2 -Wall
ASFLAGS = -c

all: app

app: main.o add.o
```

```
^^I$(CC) main.o add.o -o app

main.o: main.c
^^I$(CC) $(CFLAGS) -c main.c -o main.o

add.o: add.s
^^I$(CC) $(ASFLAGS) add.s -o add.o

clean:
^^Irm -f *.o app
```

Compile and run:

```
make
./app
```

Output:

```
42
```

This preserves proper System V AMD64 ABI function calling conventions automatically because gcc -c invokes GAS with the correct default environment.

1.3.3 Pattern Rules and Scalability

To avoid writing a rule per source file, Make supports pattern rules. When building multi-file assembly projects, define:

```
%.o: %.s
^^I$(CC) -c $< -o $@
```

Now any .s file automatically maps to .o. Example:

```
OBJS = main.o add.o mul.o sub.o
app: $(OBJS)
^^I$(CC) $(OBJS) -o app
```

This enables scalable assembly-based codebases without manual rule duplication.

1.3.4 Phony Targets and Convenience

Targets that do not produce a file should be declared .PHONY:

```
.PHONY: clean
clean:
^^Irm -f *.o app
```

This ensures clean always runs, even if a file named clean exists.

1.3.5 Summary

- Make automates rebuilds based on file modification timestamps.
- Using gcc as the assembler driver ensures ABI-conforming behavior.
- Pattern rules allow scalable builds in multi-file assembly projects.
- Makefiles form the foundation of reproducible and maintainable low-level codebases.

This build infrastructure will be used throughout the series as complexity increases, particularly when defining stack frames, calling conventions, multi-module linking, and minimal runtime systems.

Chapter 2

Source File Layout

2.1 .text, .data, .bss

An assembly source file is divided into logical sections that the assembler and linker translate into corresponding segments within the final ELF binary. Understanding these sections is essential for controlling memory placement, initialization behavior, and runtime memory footprint. The three foundational sections in x86-64 assembly development are .text, .data, and .bss.

2.1.1 The .text Section — Executable Code

The .text section contains machine instructions. This section is typically read-only and executable at runtime. Modifying code in .text is not permitted under modern memory protection policies (W^X: Write XOR Execute), ensuring both safety and performance. A minimal function returning a constant:

```
.intel_syntax noprefix
.text
```

```
.global ret64

ret64:
    mov rax, 64
    ret
```

This code places the function ret64 into the executable .text section. The linker will map this section into memory with execute permission.

2.1.2 The .data Section — Initialized Writable Data

The .data section contains global variables that have initial values. The loader copies these values directly into memory at program load time. Variables placed here reside in read-write memory and can be modified at runtime.
Example: storing and modifying a global integer:

```
.intel_syntax noprefix
.data
value:  .long 7        # initialized global variable

.text
.global increment
increment:
    mov rax, DWORD PTR value[rip]
    add rax, 1
    mov DWORD PTR value[rip], eax
    ret
```

Here, value begins with the value 7, and each call to increment increases it.

2.1.3 The .bss Section — Uninitialized Data

The .bss section holds global variables without explicit initial values. This section occupies no space in the binary file; instead, the loader allocates and zero-initializes the space at runtime. This reduces executable size and simplifies allocation of large arrays. Example:

```
.intel_syntax noprefix
.bss
.align 8
buffer:
    .skip 256          # reserve 256 bytes, zero-initialized

.text
.global fill_buffer
fill_buffer:
    mov rcx, 256
    lea rdi, buffer[rip]
    mov al, 0xAA
    rep stosb
    ret
```

The .bss segment is mapped with read-write permissions.

2.1.4 Complete Example: Mixing .text, .data, and .bss

The following assembly demonstrates all three sections together and shows cooperation between code and static storage:
file: demo.s

```
.intel_syntax noprefix
```

```
.data
msg:    .asciz "Result = "
msg_len = . - msg

.align 4
result: .long 0

.text
.global _start

_start:
    ; Store value 42 into result
    mov DWORD PTR result[rip], 42

    ; Write the message "Result = "
    mov rax, 1          # SYS_write
    mov rdi, 1          # stdout
    lea rsi, msg[rip]   # pointer to string
    mov rdx, msg_len    # length
    syscall

    ; Write the result value (as a byte)
    mov rax, 1          # SYS_write
    mov rdi, 1          # stdout
    lea rsi, result[rip] # pointer to result
    mov rdx, 1          # print just lowest byte: 42 -> '*'
    syscall

    ; Exit
    mov rax, 60         # SYS_exit
    xor rdi, rdi        # exit code 0
    syscall
```

Assemble and link manually (no libc):

```
as --64 demo.s -o demo.o
ld demo.o -o demo
```

Run:

```
./demo
```

The program stores data in .bss, references immutable text in .data, and executes code in .text.

2.1.5 Summary

- The .text section contains executable instructions and is typically read-only.
- The .data section holds initialized global data stored in the binary.
- The .bss section contains uninitialized global data, allocated and zeroed at load time and does not increase binary size.

These three sections define the fundamental structure on which stack, heap, and dynamic linker regions build later. Their proper use ensures efficient memory layout, controlled mutability, and predictable runtime behavior—critical when writing low-level system code.

2.2 Symbols and Labels

Symbols are named references that identify addresses within a program. They allow the assembler and linker to resolve code locations, variables, and function entry points. Labels are a subset of symbols used for marking specific positions in code or data. Correct symbol handling is critical for modular assembly, function linkage, and relocation under the System V AMD64 ABI.

2.2.1 Local Labels

A label marks an address that can be referenced later. A simple label ends with a colon:

```
loop_start:
    ; instruction sequence
```

Local labels do not need to be exported if they are used only within the same file. They become entries in the object file's internal symbol table but do not appear to the linker unless declared visible.
Example:

```
.intel_syntax noprefix
.text

factorial:
    mov rax, 1

loop_start:
    cmp rdi, 1
    jle done
    imul rax, edi
    dec rdi
    jmp loop_start

done:
    ret
```

Here, loop_start and done are ordinary local labels within the function.

2.2.2 Global Symbols

A symbol becomes visible to the linker—and therefore callable from other modules—when declared global:

```
.global factorial
```

This ensures the function is added to the global symbol table.
Example integrating assembly and C:
file: fact.s

```
.intel_syntax noprefix
.text
.globl factorial
.type factorial, @function

factorial:
    mov rax, 1
.loop:
    cmp rdi, 1
    jle .done
    imul rax, rdi
    dec rdi
    jmp .loop
.done:
    ret
```

file: test.c

```
#include <stdio.h>
int factorial(int);
int main() {
    printf("%d\n", factorial(5));
}
```

Compile:

```
gcc -c fact.s -o fact.o
gcc test.c fact.o -o test
```

Run:

```
./test
```

Output:

```
120
```

The .global directive allows the linker to resolve factorial across modules.

2.2.3 Private/Internal Labels (.L Prefix)

Labels beginning with .L are treated as internal to the translation unit and removed from the final symbol table. These are used by assemblers and compilers for temporary branches and loop anchors.
Example:

```
.text
.global sum_to_n
sum_to_n:
    xor rax, rax
.Lloop:
    add rax, rdi
    dec rdi
    jnz .Lloop
    ret
```

.Lloop cannot be referenced outside this file, reducing symbol pollution and improving binary clarity.

2.2.4 Data Symbols and Address Referencing

Symbols may refer to data as well as code. In x86-64, RIP-relative addressing is used to access global data reliably across ASLR and PIE environments:

```
.data
counter: .long 0

.text
.global inc_counter
inc_counter:
    mov rax, DWORD PTR counter[rip]
    add rax, 1
    mov DWORD PTR counter[rip], eax
    ret
```

Key concept: addresses are computed relative to instruction pointer (rip) rather than absolute constants, enabling correct relocation at runtime.

2.2.5 Local Scoping with @ Suffix (Nested Labels)

Labels may be nested in some GAS dialects using suffixes, but the preferred modern, portable method is using .L internal labels as already shown. This ensures compatibility with linkers and disassemblers under contemporary ELF toolchains.

2.2.6 Summary

- Labels mark memory addresses in code or data.
- Global symbols (.global) provide visibility to the linker and other modules.
- Internal/private labels (.Lname) are file-local and omitted from the final global symbol table.

- RIP-relative addressing ensures relocatable global data access.
- Proper symbol management is essential for multi-module assembly and ABI-conformant integration with C.

2.3 Global vs Local Visibility

In assembly, symbols may have different visibility scopes depending on whether they are intended for internal use within the current translation unit or intended to be linked and called from other modules. The ELF symbol table distinguishes between local and global symbols. Understanding this distinction is critical when building modular low-level code that integrates with C, shared libraries, or dynamically linked runtimes.

2.3.1 Local Symbols (Default Visibility)

By default, symbols defined in an assembly file are local. They are visible only within the same object file and do not appear in the global symbol table used by the linker. Local symbols are appropriate for internal labels, private helper routines, temporary jumps, and loop anchors.
Example:

```
.intel_syntax noprefix
.text

foo:
    mov eax, 1
.Lloop:
    add rax, rdi
    dec rdi
    jnz .Lloop
    ret
```

Here:

- foo is visible within this file only unless declared global.
- .Lloop is explicitly internal and guaranteed to remain local.

Such internal symbols minimize symbol table pollution and improve binary readability when inspecting with readelf or objdump.

2.3.2 Global Symbols (.global)

A symbol becomes visible across object files when declared with .global. This makes it linkable by external modules.
Example exposed function:

```
.intel_syntax noprefix
.text
.global sum_to_n

sum_to_n:
    xor rax, rax
.Laccumulate:
    add rax, rdi
    dec rdi
    jnz .Laccumulate
    ret
```

This function can now be called from C or another assembly file.
file: main.c

```
#include <stdio.h>

int sum_to_n(int);
```

```
int main() {
    printf("%d\n", sum_to_n(5));
}
```

Build and run:

```
gcc -c sum.s -o sum.o
gcc main.c sum.o -o app
./app
```

Output:

```
15
```

The .global sum_to_n directive enabled linking.

2.3.3 Data Symbols and Visibility

Visibility applies equally to data stored in .data or .bss.

Example:

```
.intel_syntax noprefix
.data
.global shared_counter
shared_counter: .long 0

.text
.global inc
inc:
    mov rax, DWORD PTR shared_counter[rip]
    add rax, 1
    mov DWORD PTR shared_counter[rip], rax
    ret
```

Since shared_counter is global, it can be accessed from other files, which is useful in multi-module low-level systems.

2.3.4 Why Visibility Matters

Objective	Required Visibility
Internal helpers, loop anchors, hidden data	Local (default / .L prefix)
Functions callable across modules	Global (.global symbol)
Cross-file global state and runtime data structures	Global for the symbol name

Practical effects:

- Linker resolves global symbols → enables multi-file assembly and C integration.
- Local symbols do not appear in exported symbol tables → reduces namespace exposure and improves symbol lookup efficiency.
- Visibility influences relocation behavior → especially relevant when position-independent code (PIC) or shared libraries are introduced later.

2.3.5 Complete Example with Both Visibility Levels

file: mod1.s

```
.intel_syntax noprefix

.data
.global G
G: .long 10

.text
```

```
.global f
f:
    mov rax, DWORD PTR G[rip]
    call .Lhelper
    ret

.Lhelper:
    add rax, 5
    ret
```

- G and f are callable externally.
- .Lhelper is file-local and hidden from the linker.

file: main.c

```
#include <stdio.h>

int f(void);

int main() {
    printf("%d\n", f());
}
```

Compile:

```
gcc -c mod1.s -o mod1.o
gcc main.c mod1.o -o run
./run
```

Output:

```
15
```

.Lhelper never appears outside the object file, but f and G do.

2.3.6 Summary

- Symbols are local by default, visible only within their object file.
- .global exposes symbols to the linker and other translation units.
- Internal labels beginning with .L are guaranteed to remain local and non-exported.
- Correct visibility ensures modularity, clean symbol interfaces, and efficient linking.
- Visibility applies to both code and data and directly impacts relocations and ABI guarantees.

Chapter 3

Registers & Addressing Modes

3.1 Base + Index + Scale + Offset

Modern x86-64 addressing allows flexible computation of memory addresses directly inside load and store instructions. The most general form of a memory operand in the System V AMD64 ABI is:

```
[ base + index * scale + offset ]
```

This allows addressing arrays, structures, and arbitrary computed memory regions without separate arithmetic instructions. The assembler computes the effective address at runtime by evaluating the registers and constants in the expression.

3.1.1 Components of the Address Expression

- Base: A general-purpose register holding a memory reference point (e.g., stack pointer, frame pointer, or structure base).
- Index: A register multiplied by the scale to choose an element within an array.

- Scale: A value from the set {1, 2, 4, 8}, matching operand sizes (byte, word, dword, qword index progression).
- Offset: A constant displacement added after base and index (signed 32-bit immediate).

This is resolved by hardware in a single addressing micro-op with no additional instructions if the addressing mode is valid for the encoding.

3.1.2 Example: Accessing Array Elements

Consider a contiguous array of 32-bit integers:

```
.intel_syntax noprefix
.data
array: .long 3, 6, 9, 12, 15

.text
.global get_element

# int get_element(int index)
get_element:
    # index in rdi
    mov rax, DWORD PTR array[rip + rdi*4]
    ret
```

Explanation:

- array is the base.
- rdi is the index.
- 4 is the scale (size of each element: 4 bytes).

- No extra offset is required in this case.

This performs element selection in one instruction.

3.1.3 Example: Structure Field Access

Assume a structure layout:

```
struct S {
    long a;    // offset 0
    long b;    // offset 8
};
```

Access b when the pointer is in rdi:

```
.text
.global get_b
get_b:
    mov rax, [rdi + 8]   # base + offset
    ret
```

This uses only base + offset, the simplest addressing form.

3.1.4 Example: Two-Dimensional Indexing

For a matrix stored row-major:

```
value = matrix[row][col]
```

If:

- rdi = pointer to matrix
- esi = row index

- edx = column index
- Element size = 4 bytes
- Row length = 10 columns

Address calculation:

```
address = rdi + (row * 10 + col) * 4
```

Efficient x86-64 implementation:

```
.text
.global get_matrix_element

get_matrix_element:
    # rdi = matrix
    # rsi = row
    # rdx = col

    imul rsi, 10                    # row * 10
    add rsi, edx                    # row * 10 + col
    mov rax, DWORD PTR [rdi + rsi*4]
    ret
```

One load instruction accesses the computed element.

3.1.5 Example: Stack-Relative Addressing (Local Variables)

Local variables are often accessed using the base pointer (rbp):

```
.text
.global example
```

```
example:
    push rbp
    mov rbp, rsp
    sub rsp, 16                 # reserve space

    mov DWORD PTR [rbp - 4], 7      # local int x = 7
    mov rax, DWORD PTR [rbp - 4]    # load x
    leave
    ret
```

This uses base + offset where the frame pointer anchors all stack locals.

3.1.6 Example: Base + Index + Scale + Offset in Full Form

This demonstrates the full addressing capability:

```
.text
.global compute

compute:
    # rdi = base pointer to struct array
    # rsi = index
    # rax will receive struct->field

    mov rax, DWORD PTR [rdi +  rsi*8 +  12]
    ret
```

Interpretation:

- Each structure is 8 bytes.
- The field we want is at offset 12 from structure start.
- One instruction performs full address computation.

3.1.7 Summary

- The Base + Index + Scale + Offset addressing form is the most flexible hardware-supported memory addressing mode in x86-64.
- It allows efficient access to arrays, structures, matrices, and stack frames without additional arithmetic instructions.
- Correct selection of scale is critical for matching element sizes.
- RIP-relative forms are used for global data to maintain position independence, introduced earlier and used throughout modern Linux systems.

3.2 RIP-Relative Addressing

On x86-64 Linux, global data is commonly accessed using RIP-relative addressing. Rather than embedding absolute memory addresses in instructions, the CPU computes data addresses relative to the current instruction pointer (rip). This allows executables and shared libraries to be loaded at arbitrary addresses without patching, enabling both ASLR (Address Space Layout Randomization) and Position-Independent Code (PIC). RIP-relative addressing is fundamental in modern Linux environments. Understanding it is essential before examining shared libraries, PLT/GOT mechanisms, or dynamic linking behavior.

3.2.1 Form of RIP-Relative Operands

The hardware automatically substitutes the current instruction pointer when the memory operand uses a displacement without an explicit base register:

```
[offset + rip]
```

The assembler emits a relocation entry instructing the linker to compute the correct offset at link time. No manual arithmetic is required.
Example pattern:

```
mov rax, DWORD PTR symbol[rip]
```

This loads the value at symbol, regardless of where symbol is placed in memory at runtime.

3.2.2 Example: Accessing Global Data with RIP-Relative Addressing

```
.intel_syntax noprefix

.data
counter: .long 10

.text
.global read_counter

read_counter:
    mov rax, DWORD PTR counter[rip]
    ret
```

Assemble and inspect:

```
gcc -c counter.s -o counter.o
objdump -d -M intel counter.o
```

You will see something similar to:

```
mov rax, DWORD PTR [rip+ 0x...]
```

This confirms RIP-relative addressing has been used.

3.2.3 Why Not Use Absolute Addresses?

In 64-bit mode, absolute addressing of 64-bit values in instructions is restricted and does not support full relocatable code. RIP-relative addressing avoids:

- Link-time fixups requiring writable .text sections
- Incompatibility with shared libraries
- Breakage under ASLR-enabled systems

In short: RIP-relative access is required for modern, relocatable x86-64 code.

3.2.4 Example: Writing to Global Variables

```
.intel_syntax noprefix

.data
value: .long 0

.text
.global increment_value

increment_value:
    mov rax, DWORD PTR value[rip]
    add rax, 1
    mov DWORD PTR value[rip], rax
    ret
```

The loads and stores both use RIP-relative addressing for correctness across relocations.

3.2.5 RIP-Relative Access in Position-Independent Code (PIC)

Shared libraries must use PIC so they can load at unpredictable addresses. The compiler and assembler automatically generate RIP-relative accesses when building with PIC flags:

```
gcc -fPIC -c module.s -o module.o
```

This ensures correct runtime symbol resolution across process address layouts.

3.2.6 Example: Calling a Function and Accessing Data Together

file: demo.s

```
.intel_syntax noprefix

.data
msg: .asciz "Value = %d\n"
var: .long 42

.text
.global print_value
.extern printf

print_value:
    mov rax, DWORD PTR var[rip]
    lea rdi, msg[rip]
    mov rsi, rax
    xor rax, rax        # required for variadic calls
    call printf@PLT
    ret
```

Build and run:

```
gcc demo.s -o demo
./demo
```

Output:

```
Value = 42
```

Both data references use RIP-relative addressing, ensuring correctness whether the program is relocated, loaded as PIE, or executed under ASLR.

3.2.7 Summary

- RIP-relative addressing computes data addresses relative to the instruction pointer.
- It enables Position-Independent Code and ASLR, foundational to modern Linux security.
- It avoids absolute addressing limitations in x86-64.
- It is used automatically for global data access in both executables and shared libraries.
- Understanding RIP-relative access is required for later topics such as PLT/GOT, PIC, dynamic linking, and ELF runtime models.

3.3 Common Addressing Patterns

Addressing modes on x86-64 allow memory operands to encode pointer arithmetic directly within instructions. When used correctly, these patterns eliminate unnecessary arithmetic instructions, reduce register pressure, and contribute to efficient, clear

low-level implementations. This section demonstrates typical addressing patterns encountered when accessing arrays, structures, stack frames, and static/global storage under the System V AMD64 ABI.

3.3.1 Direct Access: [symbol] and [rbp - offset]

The simplest form either refers to static data or stack-resident locals.
Global data:

```
.intel_syntax noprefix
.data
x: .long 7

.text
.global get_x
get_x:
    mov rax, DWORD PTR x[rip]
    ret
```

Local variable using frame pointer:

```
.text
.global local_example
local_example:
    push rbp
    mov rbp, rsp
    sub rsp, 8
    mov DWORD PTR [rbp - 4], 12
    mov rax, DWORD PTR [rbp - 4]
    leave
    ret
```

Patterns:

- Static: symbol[rip]
- Stack local: [rbp - imm]

3.3.2 Array Indexing: [base + index*scale]

Used for contiguous arrays where each element has uniform size.

```
.intel_syntax noprefix
.data
arr: .long 5, 10, 15, 20

.text
.global get_elem
# int get_elem(int index)
get_elem:
    mov rax, DWORD PTR arr[rip +  rdi*4]
    ret
```

Here:

- rdi = index
- 4 = element size (int = 4 bytes)

3.3.3 Structure Field Access: [ptr + offset]

Used when accessing known fields in a C-like structure.

```
struct S { int a; long b; };
offset(a) = 0
offset(b) = 8
.global get_b
get_b:
```

```
    mov rax, QWORD PTR [rdi + 8]
    ret
```

rdi holds the pointer to the struct instance.

3.3.4 Multi-Dimensional Indexing

For row-major matrices:

```
address = base + (row * width + col) * element_size
.global matrix_get
# int matrix_get(int *matrix, int row, int col, int width)
matrix_get:
    # rdi = matrix, rsi = row, rdx = col, rcx = width
    imul rsi, rcx                   # row * width
    add rsi, rdx                    # row*width + col
    mov rax, DWORD PTR [rdi + rsi*4]
    ret
```

This avoids temporary memory or explicit address creation.

3.3.5 Base + Index + Scale + Offset (Full Form)

Used for accessing fields within arrays of structures.

Consider an array of structures where the field lies at offset 12 within each 24-byte element:

```
.global get_field
get_field:
    # rdi = base pointer
    # rsi = element index
    mov rax, DWORD PTR [rdi + rsi*24 + 12]
    ret
```

This is the maximum addressing capability in one instruction.

3.3.6 Stack-Resident Arrays

Arrays stored in stack frames must be addressed relative to the base pointer.

```
.global sum_stack_array
sum_stack_array:
    push rbp
    mov rbp, rsp
    sub rsp, 32                 # reserve space for 8 ints
    mov DWORD PTR [rbp - 4], 1
    mov DWORD PTR [rbp - 8], 2
    mov DWORD PTR [rbp - 12], 3
    mov DWORD PTR [rbp - 16], 4

    mov rax, DWORD PTR [rbp - 4]
    add rax, DWORD PTR [rbp - 8]
    add rax, DWORD PTR [rbp - 12]
    add rax, DWORD PTR [rbp - 16]

    leave
    ret
```

Stack access uses rbp - offset since stack grows downward.

3.3.7 Summary

- Addressing patterns encode pointer arithmetic directly in operands.
- Global data → symbol[rip]
- Stack locals → [rbp - offset]
- Array indexing → [base + index*element_size]

- Structure field access → [ptr + offset]
- Array of structures → [base + index*stride + field_offset]
- Efficient addressing reduces instructions and improves clarity in low-level code.

Chapter 4

Arithmetic & Logic Instructions

4.1 add, sub, imul, idiv

Arithmetic in x86-64 is performed directly on registers or memory operands. The architecture allows integer addition, subtraction, multiplication, and division with instruction forms optimized for 64-bit signed arithmetic. These instructions update condition flags (ZF, SF, CF, OF) as side effects, which later influence branching and comparison operations.

4.1.1 add — Addition

The add instruction adds the source operand to the destination operand and stores the result in the destination.

```
add reg, reg
add reg, imm
add reg, [memory]
```

Example:

```
.intel_syntax noprefix
.text
.global add_example

add_example:
    mov rax, 7
    add rax, 5      # eax = 12
    ret
```

4.1.2 sub — Subtraction

The sub instruction subtracts the source operand from the destination operand.

```
sub reg, reg
sub reg, imm
sub reg, [memory]
```

Example:

```
.text
.global sub_example

sub_example:
    mov rax, 20
    sub rax, 6      # rax = 14
    ret
```

Both add and sub inherently affect flags (useful for comparisons without separate cmp).

4.1.3 imul — Signed Multiplication

imul performs signed multiplication. x86-64 supports several forms; two are commonly used:

```
imul reg, reg
imul reg, reg, imm
```

Example: compute a * b + c:

```
.text
.global mul_accumulate
# int mul_accumulate(int a, int b, int c)
mul_accumulate:
    mov rax, rdi        # rax = a
    imul rax, rsi       # rax = a * b
    add rax, rdx        # rax += c
    ret
```

imul does not modify registers other than destination, making it efficient for expression evaluation.

4.1.4 idiv — Signed Division

idiv performs signed division, with a mandatory operand setup:

- Dividend is a 128-bit pair: rdx:rax
- Divisor is any register or memory operand
- Quotient is stored in rax
- Remainder is stored in rdx

Before division, cqo sign-extends rax into rdx.

```
cqo             # sign-extend rax → rdx:rax
idiv rbx        # (rax / rbx) → rax, remainder → rdx
```

Example: compute quotient and remainder:

```
.text
.global divide
; void divide(long a, long b, long *q, long *r)
; rdi=a, rsi=b, rdx=q, rcx=r
divide:
    mov rax, rdi        # load dividend
    cqo                 # sign-extend into rdx
    idiv rsi            # divide by rsi
    mov [rdx], rax      # store quotient
    mov [rcx], rdx      # store remainder
    ret
```

This explicitly demonstrates 64-bit signed division in System V AMD64 ABI.

4.1.5 Complete Working Example

file: arith_demo.s

```
.intel_syntax noprefix

.text
.global compute
# long compute(long x, long y)
# return (x + y) * (x - y)
compute:
    mov rax, rdi        # rax = x
    add rax, rsi        # rax = (x + y)
    mov rcx, rdi        # temp copy of x
    sub rcx, rsi        # rcx = (x - y)
    imul rax, rcx       # rax = (x+y) * (x-y)
    ret
```

file: main.c

```
#include <stdio.h>
long compute(long, long);

int main() {
    printf("%ld\n", compute(9, 4));
}
```

Build & run:

```
gcc main.c arith_demo.s -o demo
./demo
```

Output:

```
65
```

This example demonstrates the coordinated use of add, sub, and imul.

4.1.6 Summary

- add and sub modify both registers and condition flags.
- imul performs signed multiplication efficiently and cleanly integrates into integer expressions.
- idiv requires preparing the 128-bit dividend in rdx:rax using cqo, with results in rax (quotient) and rdx (remainder).
- These arithmetic primitives form the base layer for implementing algorithms, expression evaluation, calling convention-compliant math routines, and compiler-grade low-level optimizations.

4.2 and, or, xor, not

Logical operations manipulate bit patterns directly. These instructions operate on registers or memory operands without distinction between signed and unsigned interpretation; they treat values as raw binary. They also update condition flags (ZF, SF, PF) but do not modify the carry or overflow flags (with the notable exception of xor reg, reg clearing CF and OF implicitly since the result is zero).
These operations form the core of mask manipulation, bit-field extraction, flag clearing, register zeroing, and low-level control logic used extensively in operating systems, runtime allocators, and cryptographic routines.

4.2.1 and — Bitwise AND

```
and dest, src
```

All bits in dest are cleared except where both operands have bit 1.
Example: Masking lower bits:

```
.intel_syntax noprefix
.text
.global mask_lower_bits

# rax = rax & 0xFF
mask_lower_bits:
    and rax, 0xFF
    ret
```

This is commonly used to limit range or isolate fields in packed values.

4.2.2 or — Bitwise OR

```
or dest, src
```

Sets bits in dest where either operand has bit 1. Frequently used for flag enabling. Example: Set bit 3:

```
.text
.global set_flag

set_flag:
    or rdi, 0b1000
    mov rax, rdi
    ret
```

4.2.3 xor — Bitwise XOR

```
xor dest, src
```

Sets bits where operands differ. A special and extremely common case:

```
xor reg, reg
```

This clears the register efficiently with no dependency on the prior value, generating a zero idiom that CPUs optimize:

```
.text
.global zero_reg

zero_reg:
    xor rax, rax        # eax = 0 (fast, dependency-breaking)
    ret
```

Modern microarchitectures detect this pattern to break execution dependencies, aiding out-of-order execution performance. This is preferred over mov eax, 0.

4.2.4 not — Bitwise NOT (One's Complement)

```
not dest
```

Flips every bit in the operand.

Example:

```
.text
.global invert_bits

invert_bits:
    not rdi         # rdi = ~rdi
    mov rax, rdi
    ret
```

This is not to be confused with logical negation; it is a raw bit inversion.

4.2.5 Complete Working Example

file: bitops.s

```
.intel_syntax noprefix

.text
.global manipulate
# long manipulate(long x)
# return (~x ^ 0xFF) & 0xFFFF;
manipulate:
    mov rax, rdi        # x → rax
    not rax             # ~x
    xor rax, 0xFF       # (~x) ^ 0xFF
    and rax, 0xFFFF     # mask low 16 bits
    ret
```

file: main.c

```
#include <stdio.h>
long manipulate(long);

int main() {
    printf("%ld\n", manipulate(123));
}
```

Build & run:

```
gcc main.c bitops.s -o bitdemo
./bitdemo
```

This demonstrates combining logical operators in a controlled bit-masking operation.

4.2.6 Summary

- and clears bits selectively and is essential for masking and field extraction.
- or sets bits selectively and is used for enabling flags or merging states.
- xor toggles bits and supports dependency-breaking zero idioms (xor reg, reg).
- not performs a raw, full-register bit inversion.

These logical instructions operate independently of signed arithmetic interpretation and are used pervasively in efficient low-level implementation patterns, state machines, pointer tagging, bitmaps, cryptographic primitives, and kernel-level flag manipulation.

4.3 Condition Flags

Arithmetic and logical instructions on x86-64 update a set of condition flags in the rflags register. These flags allow subsequent conditional instructions—such as je, jg, jl, cmov*, and set*—to make decisions based on the outcome of computations without explicitly comparing values in memory or registers. Understanding how each instruction affects flags is essential for writing efficient low-level control flow and arithmetic logic.

4.3.1 Flags Affected by Arithmetic and Logical Operations

Flag	Meaning (Signed/Unsigned)	Updated By
ZF (Zero Flag)	Result == 0 → ZF = 1	add, sub, and, xor, cmp, etc.
SF (Sign Flag)	Most significant bit of result (sign bit)	Same as above
CF (Carry Flag)	Unsigned overflow (borrow/carry) occurred	add, sub, cmp, adc, etc.
OF (Overflow Flag)	Signed overflow occurred	add, sub, imul, idiv

Logical instructions (and, or, xor) affect ZF, SF, PF but do not affect CF or OF. Arithmetic instructions (add, sub, imul) affect all relevant flags.

4.3.2 Example: Flags from Subtraction and Branching

sub sets flags based on the result. A conditional branch reads those flags.

```
.intel_syntax noprefix
.text
.global compare
```

```
# int compare(int a, int b)
# return 1 if a > b, else 0
compare:
    mov rax, rdi
    sub rax, rsi        # sets ZF, SF, OF, CF
    jg .greater         # jump if (signed) >
    xor rax, rax        # return 0
    ret
.greater:
    mov rax, 1
    ret
```

Here:

- jg uses signed comparison: it checks (SF == OF) && (ZF == 0).

4.3.3 Example: Unsigned Comparison Uses Different Flags

Unsigned comparison must use carry semantics.

```
.global compare_u
# int compare_u(unsigned a, unsigned b)
# return 1 if a > b
compare_u:
    mov rax, rdi
    sub rax, rsi
    ja .greater_u       # jump if above (CF=0 and ZF=0)
    xor rax, rax
    ret
.greater_u:
    mov rax, 1
    ret
```

Here ja depends on CF and ZF, not SF or OF.

4.3.4 Flag-Dependent Move Instructions (cmov*)

Rather than branching, we can perform selective assignment with cmov instructions. This reduces branch mispredictions and improves pipeline performance.

```
.global max_signed
# long max_signed(long x, long y)
max_signed:
    mov rax, rdi
    cmp rax, rsi
    cmovl rax, rsi      # if x < y (signed), rax = y
    ret
```

cmovl checks (SF != OF) (signed less-than) without a branch.

4.3.5 Zero-Flag Usage with Loop Control

```
.global sum_down
# long sum_down(long n) → sum of n + (n-1) + ... + 1
sum_down:
    xor rax, rax        # sum = 0
.loop:
    add rax, rdi
    dec rdi             # updates ZF
    jnz .loop           # continue while edi != 0
    ret
```

The loop terminates cleanly when edi reaches zero via ZF = 1.

4.3.6 Using test to Check Bit Patterns Without Affecting CF/OF

test performs and but discards the result, updating only ZF and SF.

```
.global is_even
; int is_even(int x)
is_even:
    test rdi, 1         # check lowest bit
    sete al             # set al = 1 if ZF=1 (x is even)
    movzx rax, al
    ret
```

- If bit 0 is 0, the number is even → ZF=1 → sete sets 1.

4.3.7 Summary

- Arithmetic and logic instructions update ZF, SF, CF, and OF, enabling conditional behavior.
- Signed comparisons rely on SF and OF.
- Unsigned comparisons rely on CF and ZF.
- cmov* avoids branching, useful in high-performance and constant-time logic.
- Loop control often uses dec + jnz.
- test checks bit patterns without modifying the operand and without affecting carry/overflow.

Chapter 5

Control Flow

5.1 jmp, call, ret

Control flow in x86-64 is implemented using direct and indirect jumps, function calls, and returns. These instructions manipulate the instruction pointer (rip) and, in the case of function calls, the stack. Understanding them is essential for implementing loops, branching, procedural abstraction, and low-level calling conventions.
Modern Linux systems use the System V AMD64 ABI, where function calls follow a standard register-passing convention. However, at the machine level, the key operations are simply: push return address → transfer control → return to caller.

5.1.1 jmp — Unconditional Jump

jmp transfers execution to another location without saving the return address. It is used for loops, branches, and state transitions but not for calling functions.
Forms:

```
jmp label          # direct jump
```

```
jmp rax                 # indirect jump (register)
jmp [symbol@GOTPCREL]   # dynamic resolved jump (shared libraries)
```

Example, infinite loop:

```
.intel_syntax noprefix
.text
.global loop_forever

loop_forever:
    jmp loop_forever    # never returns
```

5.1.2 call — Function Call (with Return Address Save)

call pushes the next instruction's RIP onto the stack, then jumps to the function. When the callee executes ret, execution resumes after the original call.

```
call label
call rax        # call through function pointer
```

Example:

```
.text
.global caller

caller:
    call callee
    ret

callee:
    mov rax, 123
    ret
```

Execution:

- call callee pushes return address → jumps to callee.
- ret pops return address → resumes in caller.

5.1.3 ret — Return from Function

ret performs:

```
pop rip
```

It restores execution to the return address left by call.
If the stack pointer is not balanced correctly, ret will jump to an incorrect address, causing a crash.
The callee is responsible for ensuring stack alignment and symmetry:

- Every push must be matched with a pop (or equivalent adjustment).
- The ABI requires that, at call boundaries, rsp % 16 == 8 (because the call pushes 8 bytes).

5.1.4 Complete Example: Function Call Chain

file: example.s

```
.intel_syntax noprefix
.text

.global main
.extern printf

main:
    call get_value      # result → eax
    mov rsi, rax        # argument 1
```

```
    lea rdi, msg[rip]    # argument 0
    xor rax, rax         # no FP args
    call printf@PLT
    xor rax, rax
    ret

get_value:
    mov rax, 42
    ret

.data
msg: .asciz "Value = %d\n"
```

Build and run:

```
gcc example.s -o demo
./demo
```

Output:

```
Value = 42
```

5.1.5 Example: Indirect Function Call (Function Pointer)

```
.text
.global apply
# long apply(long (*f)(long), long x)
# rdi = f, rsi = x
apply:
    mov rax, rsi
    call rdi      ; call function pointer in rdi
    ret
```

This is how higher-order functions and callbacks are implemented at the machine level.

5.1.6 Example: Tail Call Optimization (Jump Instead of Call)

A tail call replaces call + ret with a single jmp, removing stack frame overhead:

```
.global tail_call
tail_call:
    jmp other_function   # does not return to tail_call
```

This is commonly used in compilers and runtime trampolines.

5.1.7 Summary

- jmp transfers control unconditionally and does not save return context.
- call pushes the return address and jumps to a function, establishing a call frame.
- ret returns by popping the saved return address from the stack.
- Correct stack balance is essential for reliable execution under the System V AMD64 ABI.
- Indirect calls (call reg) enable dynamic dispatch, function pointers, and virtual dispatch mechanisms.
- Tail calls can be optimized as jumps for efficiency.

5.2 cmp & Conditional Jumps

Branching in x86-64 is primarily controlled through the condition flags in rflags. The cmp instruction performs a subtraction (dest - src) without storing the result, updating the flags to reflect the comparison. Conditional jump instructions (j*) then consult those flags to decide whether to transfer control. This mechanism is foundational to implementing if-else logic, loops, bounds checking, and all structured control flow.

5.2.1 cmp: Comparison Without Storing

```
cmp reg, reg
cmp reg, imm
cmp reg, [memory]
```

cmp a, b computes a - b in flags only:

- ZF = 1 → values are equal
- SF != OF → signed <
- CF = 1 → unsigned <

Example:

```
cmp rax, rbx    # sets flags based on (eax - ebx)
```

No registers are modified; only flags change.

5.2.2 Signed vs Unsigned Branches

Signed and unsigned comparisons use different jump mnemonics, because signed overflow (OF) affects interpretation of the sign bit (SF).

Signed comparisons:

```
jg   (jump if >)       # (SF == OF) && (ZF == 0)
jl   (jump if <)       # (SF != OF)
jge  (>=)
jle  (<=)
```

Unsigned comparisons:

```
ja   (jump if above)    # CF == 0 && ZF == 0
jb   (jump if below)    # CF == 1
jae  (>= unsigned)
jbe  (<= unsigned)
```

5.2.3 Example: Signed Comparison (Greater Than)

```
.intel_syntax noprefix
.text
.global is_greater

; int is_greater(int a, int b)
is_greater:
    cmp rdi, rsi       # compare a - b
    jg .true           # jump if a > b (signed)
    xor rax, rax       # return 0
    ret
.true:
    mov rax, 1
    ret
```

5.2.4 Example: Unsigned Comparison (Above / Below)

```
.text
.global is_above

# int is_above(unsigned a, unsigned b)
is_above:
    cmp rdi, rsi
    ja .true           # unsigned >
    xor rax, rax
```

```
    ret
.true:
    mov rax, 1
    ret
```

5.2.5 Conditional Loops

dec updates flags; jnz uses ZF to continue until zero.

```
.text
.global countdown_sum

# long countdown_sum(long n)
countdown_sum:
    xor rax, rax
.loop:
    add rax, rdi
    dec rdi
    jnz .loop
    ret
```

5.2.6 If/Else Translation Pattern

```
.text
.global select_max

# long select_max(long x, long y)
select_max:
    cmp rdi, rsi
    jge .x_is_max
    mov rax, rsi
    ret
.x_is_max:
```

```
    mov rax, rdi
    ret
```

Uses a direct conditional branch pattern, minimal overhead.

5.2.7 Branchless Alternatives (Preview)

Instead of branching, cmov instructions can use flags directly:

```
.text
.global branchless_max

branchless_max:
    mov rax, rdi
    cmp rdi, rsi
    cmovl rax, rsi      # if x < y, rax = y
    ret
```

This eliminates branch misprediction penalties in hot loops.

5.2.8 Summary

- cmp updates flags based on subtraction but does not store the result.
- Signed comparisons (jg, jl, jge, jle) rely on SF and OF.
- Unsigned comparisons (ja, jb, jae, jbe) rely on CF and ZF.
- Looping commonly uses dec + jnz.
- Conditional branches map directly to high-level if, else, and while.
- Branchless control is possible via cmov, useful for performance-critical and constant-time logic.

5.3 Function Prologues & Epilogues

On x86-64 Linux, functions follow the System V AMD64 ABI, which defines how the stack, frame pointer, registers, and return addresses are managed. A prologue sets up the function's execution environment; an epilogue restores it. These sequences ensure:

- Local variables are allocated on the stack.
- Call-preserved registers retain their values across calls.
- The return address stored by call is restored correctly by ret.

Understanding these conventions is fundamental to writing correct and interoperable assembly routines.

5.3.1 ABI Register Preservation Rules

Registers are separated into two categories:

- Call-preserved: rbp, rbx, r12–r15, and (for SIMD) xmm6–xmm15.
  If used, they must be saved and restored.
- Call-clobbered: rax, rcx, rdx, rsi, rdi, r8–r11, xmm0–xmm5.
  These may be overwritten freely.

Return values are placed in:

```
rax (integer/pointer) or xmm0 (float)
```

5.3.2 Standard Prologue Pattern

```
push rbp
mov  rbp, rsp
sub  rsp, <frame_size>
```

- Saves old frame pointer
- Defines new frame anchor
- Reserves stack memory for locals

5.3.3 Standard Epilogue Pattern

```
leave    # equivalent to mov rsp, rbp / pop rbp
ret      # pops return address → rip
```

5.3.4 Example: Function With Local Variables

```
.intel_syntax noprefix
.text
.global add_three_locals

# long add_three_locals(long a, long b, long c)
add_three_locals:
    push rbp
    mov rbp, rsp
    sub rsp, 24                 # allocate space for three 8-byte locals

    mov QWORD PTR [rbp-8],  rdi
    mov QWORD PTR [rbp-16], rsi
    mov QWORD PTR [rbp-24], rdx
```

```
    mov rax, QWORD PTR [rbp-8]
    add rax, QWORD PTR [rbp-16]
    add rax, QWORD PTR [rbp-24]

    leave
    ret
```

The stack frame layout:

```
[rbp+8]    return address
[rbp]      saved rbp
[rbp-8]    local a
[rbp-16]   local b
[rbp-24]   local c
```

5.3.5 Leaf Functions (No Local Stack Frame)

If a function does not call others and does not use locals requiring stack storage, no prologue/epilogue is required.

```
.text
.global leaf_add

leaf_add:
    lea rax, [rdi + rsi]   ; compute result directly
    ret
```

This is a leaf function, efficient due to no stack manipulation.

5.3.6 Saving Call-Preserved Registers Only When Necessary

If the function uses a call-preserved register, it must be saved/restored.

```
.text
.global use_rbx

use_rbx:
    push rbx                # save rbx
    mov rbx, rdi             # rbx = argument
    imul rbx, rbx            # rbx = rbx * rbx
    mov rax, rbx             # return rbx
    pop rbx                 # restore
    ret
```

Failure to restore rbx would violate the ABI and corrupt the caller's state.

5.3.7 Full Example Interacting With C

file: func.s

```
.intel_syntax noprefix
.text
.global square_plus

# long square_plus(long x, long y)
square_plus:
    push rbp
    mov rbp, rsp

    mov rax, rdi
    imul rax, rax       # x*x
    add rax, rsi        # + y

    leave
    ret
```

file: main.c

```c
#include <stdio.h>
long square_plus(long, long);
int main() {
    printf("%ld\n", square_plus(5, 3));
}
```

Compile & run:

```
gcc main.c func.s -o run
./run
```

Output:

```
28
```

5.3.8 Summary

- Prologue establishes a stable frame pointer and allocates local storage.
- Epilogue restores stack and frame pointer and returns control.
- Call-preserved registers must be saved & restored if modified.
- Leaf functions omit stack frames entirely for efficiency.
- Correct adherence ensures interoperability with C and other modules.
- This foundation is required for stack-based local variables, recursion, and function dispatch.

Chapter 6

The Stack

6.1 Pushing and Popping

The stack is a contiguous region of memory used for managing function calls, local storage, temporary values, and register preservation. On x86-64 Linux, the stack grows downward in memory: each push decreases the stack pointer (rsp), and each pop increases it. All stack operations in System V AMD64 ABI must maintain 16-byte alignment at the point of a call instruction to ensure correct ABI compatibility, especially with functions using vector registers.

6.1.1 push and pop Fundamentals

The push instruction:

1. Decrements rsp by the operand size (8 bytes in 64-bit mode).
2. Stores the operand at [rsp].

The pop instruction:

1. Loads the value at [rsp] into the destination register.

2. Increments rsp by 8.

```
push rax      # rsp -= 8, memory[rsp] = rax
pop rax       # rax = memory[rsp], rsp += 8
```

Stack must remain balanced: every push must be matched with a corresponding pop or equivalent stack adjustment.

6.1.2 Example: Saving and Restoring Registers

Call-preserved registers (rbp, rbx, r12–r15) must be saved if modified.

```
.intel_syntax noprefix
.text
.global square_and_add

# long square_and_add(long x, long y)
square_and_add:
    push rbx              # preserve rbx
    mov rbx, rdi          # rbx = x
    imul rbx, rbx         # rbx = x*x
    add rbx, rsi          # + y
    mov rax, rbx          # return result
    pop rbx               # restore rbx
    ret
```

Failure to restore rbx would violate the ABI and corrupt the caller.

6.1.3 Using Push/Pop for Temporary Storage

Stack can hold intermediate values without allocating a full frame.

```
.text
.global calculate

# long calculate(long a, long b, long c)
calculate:
    push rdi            # save 'a'
    imul rsi, rsi       # b*b
    pop rax             # restore 'a' into rax
    add rax, rsi        # a + (b*b)
    add rax, rdx         # + c
    ret
```

This is a stack-based register spill—useful when register pressure is high.

6.1.4 Stack Alignment Consideration

Before a function calls another function, rsp must be aligned such that:

```
(rsp % 16) == 8   at the call boundary
```

Because call pushes an 8-byte return address, this makes the callee's entry rsp % 16 == 0.

Example maintaining alignment:

```
.global call_other
.extern other

call_other:
    push rbp
    mov rbp, rsp

    sub rsp, 8      # maintain alignment before call
    call other
```

```
    leave
    ret
```

6.1.5 Example with Full Stack Frame and Local Variables

```
.text
.global sum_locals

# long sum_locals(long x, long y)
sum_locals:
    push rbp
    mov rbp, rsp
    sub rsp, 16             # reserve space for 2 locals

    mov QWORD PTR [rbp-8], rdi
    mov QWORD PTR [rbp-16], rsi

    mov rax, QWORD PTR [rbp-8]
    add rax, QWORD PTR [rbp-16]

    leave                   # mov rsp, rbp / pop rbp
    ret
```

Memory layout:

```
[rbp+8]    return address
[rbp]      saved rbp
[rbp-8]    local copy of x
[rbp-16]   local copy of y
```

This is the canonical System V function frame.

6.1.6 Summary

- The stack grows downward; push and pop adjust rsp atomically.
- Stack operations are always 8 bytes in 64-bit mode.
- Call-preserved registers must be saved when used.
- Stack alignment (rsp % 16 == 8 at call) ensures ABI compliance.
- Push/pop are used both for frame management and register spilling.
- Correct stack discipline is required for reliable, interoperable assembly routines.

6.2 Stack Alignment Rules

The System V AMD64 ABI specifies strict rules for stack alignment to ensure correct execution and optimal performance on modern x86-64 Linux systems. These rules are not optional: failing to align the stack correctly can cause crashes inside library functions (especially those using SIMD instructions) or degrade instruction throughput significantly.
The critical alignment rule is:

> At the moment a function is called, the stack pointer (RSP) must be aligned to a 16-byte boundary.

The call instruction pushes an 8-byte return address on the stack. Therefore, before executing call, rsp % 16 must equal 8, so that after the return address is pushed, the callee begins with rsp % 16 == 0.

6.2.1 Stack Alignment Across Function Calls

State transitions:

Event	Change	Alignment Condition
On function entry	rsp is already aligned by caller	rsp % 16 == 0
Before calling another function	Offset stack by 8 bytes (e.g., via push or sub rsp, 8)	rsp % 16 == 8

Thus:

```
Caller ensures:  (rsp % 16 == 8) before `call`
Callee begins:   (rsp % 16 == 0)
```

This alignment ensures correct vector register spilling and stack use inside libraries.

6.2.2 Minimal Function (Leaf) with Correct Alignment

Leaf functions do not call other functions. They can skip alignment adjustments entirely:

```
.intel_syntax noprefix
.text
.global leaf_add

leaf_add:
    lea rax, [rdi + rsi]
    ret
```

No push, pop, or stack movement → alignment remains valid automatically.

6.2.3 Function That Calls Another Function

If a function calls another function, it must adjust the stack before calling.

```
.text
.global caller
.extern callee

caller:
    push rbp
    mov rbp, rsp

    sub rsp, 8          # align to (rsp % 16 == 8)
    call callee         # callee enters aligned (rsp % 16 == 0)

    leave
    ret
```

Here:

- push rbp subtracts 8 bytes → misalignment
- sub rsp, 8 restores correct pre-call alignment

6.2.4 Alignment with Multiple Local Variables

Local variables allocated on the stack must preserve alignment.

```
.text
.global compute
.extern helper

compute:
    push rbp
```

```
    mov rbp, rsp
    sub rsp, 24             # reserve 24 bytes (3×8), stack is now misaligned
    sub rsp, 8              # restore alignment before calling helper

    mov rdi, 42
    call helper

    add rsp, 8              # undo alignment adjustment
    leave
    ret
```

General rule:

```
Total allocation size must result in (rsp % 16 == 8) before call.
```

6.2.5 Example With Data Access and Verified Alignment

file: aligned.s

```
.intel_syntax noprefix
.text
.global print_sum
.extern printf

print_sum:
    push rbp
    mov rbp, rsp

    sub rsp, 16         # allocate two local values (16-byte)
    sub rsp, 8          # ensure (rsp % 16 == 8)

    mov QWORD PTR [rbp-8],  rdi
    mov QWORD PTR [rbp-16], rsi
    mov rax, QWORD PTR [rbp-8]
```

```
    add rax, QWORD PTR [rbp-16]

    mov rsi, rax
    lea rdi, msg[rip]
    xor rax, rax
    call printf@PLT

    add rsp, 8
    leave
    ret

.data
msg: .asciz "Sum = %ld\n"
```

Compile and run:

```
gcc aligned.s -o run
./run
```

6.2.6 Summary

- Stack grows downward; push and sub rsp change alignment.
- Callee entry requires rsp % 16 == 0.
- Caller must ensure rsp % 16 == 8 before calling, because call pushes 8 bytes.
- Leaf functions may skip stack alignment if they do not allocate locals or call others.
- Incorrect alignment can cause runtime crashes or degraded performance, especially in functions using SIMD instructions.

These rules are foundational for writing correct, interoperable, and efficient assembly on Linux x86-64.

6.3 Call Frame Layout

Every function that executes on x86-64 Linux under the System V AMD64 ABI maintains a call frame (also referred to as a stack frame). The call frame provides a stable structure for holding:

- The saved return address (pushed by call)
- The previous function's base pointer (rbp)
- Local variables
- Temporarily spilled registers
- Arguments passed on the stack (when registers are insufficient or variadic calls occur)

The call frame ensures that the function execution environment is predictable and interoperable with other functions written in C, assembly, or higher-level languages.

6.3.1 Standard Frame Layout

When inside a function (after the prologue), the stack frame is logically arranged as:

```
            High Addresses (toward +∞)
+-------------------------------------------+
| argument n+1 (if passed on stack)         |
| argument n   (if passed on stack)         |
+-------------------------------------------+
| return address (pushed by `call`)         | ← [rbp + 8]
+-------------------------------------------+
| saved rbp (old frame pointer)             | ← [rbp]
+-------------------------------------------+
```

```
| local variable / spilled register 1          | ← [rbp - 8]
| local variable / spilled register 2          | ← [rbp - 16]
| ...                                          |
+----------------------------------------------+
                Low Addresses (toward −∞) → [rsp]
```

6.3.2 Establishing the Frame

The canonical prologue:

```
push rbp          # save caller's frame pointer
mov rbp, rsp      # establish new frame base
sub rsp, N        3 allocate N bytes for locals (if needed)
```

And the matching epilogue:

```
leave             # mov rsp, rbp / pop rbp
ret               # pop return address → rip
```

6.3.3 Example: Call Frame With Local Variables

```
.intel_syntax noprefix
.text
.global area_rect

; long area_rect(long width, long height)
area_rect:
    push rbp
    mov rbp, rsp
    sub rsp, 16                 # space for two locals

    mov QWORD PTR [rbp-8],  rdi # store width
    mov QWORD PTR [rbp-16], rsi # store height
```

```
    mov rax, QWORD PTR [rbp-8]
    imul rax, QWORD PTR [rbp-16]
    leave
    ret
```

Stack layout inside area_rect:

```
[rbp + 8]   return address
[rbp]       saved rbp
[rbp - 8]   long width
[rbp - 16]  long height
```

6.3.4 Call Frames and Register Spills

If registers are needed for temporary computation, they may be spilled to the call frame:

```
.global compute
compute:
    push rbp
    mov rbp, rsp
    sub rsp, 8

    imul rdi, rsi
    mov [rbp - 8], rdi      # spill intermediate result
    add rdi, rdx
    mov rax, [rbp - 8]
    add rax, rdi

    leave
    ret
```

Spills are crucial when register pressure exceeds available hardware registers.

6.3.5 Functions That Call Other Functions

If the function performs a call, stack alignment must be maintained:
Before call:

```
(rsp % 16) == 8
```

Example preserving alignment:

```
.global call_helper
.extern helper

call_helper:
    push rbp
    mov rbp, rsp
    sub rsp, 8              # restore required alignment
    call helper
    leave
    ret
```

6.3.6 Frame Pointer Omission (FPO)

Modern compilers may omit rbp usage and treat rsp as the frame base.
However, when writing low-level assembly:

- Using rbp makes debugging simpler
- Ensures stable access to locals even if rsp changes
- Maintains compatibility with backtrace tools

Thus, we maintain the canonical frame unless optimizing specific leaf functions.

6.3.7 Complete Working Example Calling C Code

file: frame_demo.s

```
.intel_syntax noprefix
.text
.global main
.extern printf

main:
    push rbp
    mov rbp, rsp
    sub rsp, 16

    mov QWORD PTR [rbp-8], 5
    mov QWORD PTR [rbp-16], 7

    mov rax, QWORD PTR [rbp-8]
    add rax, QWORD PTR [rbp-16]

    mov rsi, rax
    lea rdi, msg[rip]
    xor rax, rax
    call printf@PLT

    leave
    ret

.data
msg: .asciz "Sum = %ld\n"
```

Compile and run:

```
gcc frame_demo.s -o frame_demo
./frame_demo
```

Output:

```
Sum = 12
```

6.3.8 Summary

- A call frame organizes return addresses, saved registers, and local data.
- rbp serves as a stable reference point for stack-based addressing.
- Local variables and register spills are stored below rbp.
- Arguments beyond register capacity are passed above the return address.
- Maintaining correct stack alignment and frame structure ensures correct execution and full C interoperability.

Chapter 7

Writing and Calling Functions

7.1 Calling Convention Overview

On x86-64 Linux, all user-level code follows the System V AMD64 ABI. This convention defines how functions receive arguments, where return values are placed, which registers must be preserved, and how the stack frame is structured. Adhering to this ABI ensures that assembly functions interoperate seamlessly with C, C++, Rust, and other compiled languages.

The ABI is not merely a convention—it is a binary contract. Violating it leads to corrupted registers, incorrect return values, stack misalignment, or crashes in library calls.

7.1.1 Argument Passing Rules

The first six integer or pointer arguments are passed in:

Argument	Register
1st	rdi
2nd	rsi
3rd	rdx
4th	rcx
5th	r8
6th	r9

Additional integer arguments (7th and beyond) are passed on the stack, above the return address.
Floating-point arguments use xmm0–xmm7.

7.1.2 Return Value Rules

- Integer and pointer return values are placed in rax.
- 128-bit integers and some structures may use rdx:rax.
- Floating-point return values are placed in xmm0.

Example:

```
mov rax, 42
ret
```

7.1.3 Call-Preserved vs Call-Clobbered Registers

Call-preserved registers must be saved and restored if used:

```
rbp, rbx, r12, r13, r14, r15
```

Call-clobbered registers may be overwritten freely by the callee:

```
rax, rcx, rdx, rsi, rdi, r8–r11
```

If your function modifies a preserved register, you must push and later pop it.

7.1.4 Stack Alignment Requirement

Before invoking a function using call, the stack pointer must satisfy:

```
(rsp % 16) == 8
```

After call pushes the return address, the callee begins execution with:

```
(rsp % 16) == 0
```

This guarantees correct ABI-compliant stack layout.

7.1.5 Minimal ABI-Compliant Function

```
.intel_syntax noprefix
.text
.global add_two

# long add_two(long a, long b)
add_two:
    lea rax, [rdi +  rsi]
    ret
```

- rdi = first argument (a)
- rsi = second argument (b)
- Result returned in rax

No stack frame required (leaf function).

7.1.6 ABI-Compliant Function With Local Variables and a Call

```
.text
.global compute_and_print
.extern printf

# long compute_and_print(long x, long y)
compute_and_print:
    push rbp
    mov rbp, rsp
    sub rsp, 16          # allocate locals
    sub rsp, 8           # restore alignment (rsp % 16 == 8 before call)

    mov QWORD PTR [rbp-8],  rdi
    mov QWORD PTR [rbp-16], rsi

    mov rax, QWORD PTR [rbp-8]
    add rax, QWORD PTR [rbp-16]

    mov rsi, rax
    lea rdi, msg[rip]
    xor rax, rax         # no FP args
    call printf@PLT

    add rsp, 8
    leave
    ret

.data
msg: .asciz "Result = %ld\n"
```

This example:

- Stores arguments in locals

- Computes result
- Calls a C function while maintaining correct alignment
- Returns without corrupting registers or stack

7.1.7 Example Caller in C

```c
#include <stdio.h>
long compute_and_print(long, long);

int main() {
    compute_and_print(10, 32);
}
```

Compile and run:

```
gcc caller.c func.s -o run
./run
```

Output:

```
Result = 42
```

7.1.8 Summary

- Arguments 1–6 are passed in registers (rdi, rsi, rdx, rcx, r8, r9).
- Return values are placed in rax (or xmm0 for floats).
- Call-preserved registers must be saved if modified.
- The stack must be 16-byte aligned at function entry.
- Every assembly function must respect these rules to interoperate reliably.

This forms the foundation for writing correct and portable low-level routines.

7.2 Passing Args via Registers

Under the System V AMD64 ABI used on Linux, the first six integer or pointer parameters are passed in registers, not on the stack. This convention minimizes memory access, reduces function call overhead, and enables aggressive compiler optimizations. Understanding this register-based calling convention is essential when writing assembly functions that interact with C, C++, Rust, or other high-level languages.

7.2.1 Integer and Pointer Argument Registers

Arguments are assigned in the following order:

Argument	Register
1st	rdi
2nd	rsi
3rd	rdx
4th	rcx
5th	r8
6th	r9

Example:

```
long f(long a, long b, long c, long d, long e, long f);
```

Registers:

```
a → rdi
b → rsi
c → rdx
d → rcx
```

```
e → r8
f → r9
```

Arguments beyond the sixth are passed on the stack.

7.2.2 Example: Using Register Arguments Directly

```
.intel_syntax noprefix
.text
.global sum3

# long sum3(long a, long b, long c)
sum3:
    mov rax, rdi        # rax = a
    add rax, rsi        # rax = a + b
    add rax, rdx        # rax = a + b + c
    ret
```

No stack frame is required because:

- No preserved registers are modified
- No local storage is needed
- No function calls occur (leaf function)

7.2.3 Using Arguments in Combination With Local Variables

When arguments must be stored (e.g., to preserve original values or spill registers), they are written to the stack frame:

```
.text
.global compute
```

```
# long compute(long x, long y)
compute:
    push rbp
    mov rbp, rsp
    sub rsp, 16

    mov QWORD PTR [rbp-8], rdi
    mov QWORD PTR [rbp-16], rsi

    mov rax, QWORD PTR [rbp-8]
    imul rax, QWORD PTR [rbp-16]

    leave
    ret
```

7.2.4 Example With Four Arguments

```
.text
.global mix4

# long mix4(long a, long b, long c, long d)
mix4:
    mov rax, rdi        # a
    add rax, rsi        # + b
    sub rax, rdx        # - c
    imul rax, rcx       # * d
    ret
```

Registers map directly to logical parameter names.

7.2.5 Example With Seven Arguments (Stack + Registers)

Arguments beyond the sixth are passed on the stack, above the return address.

file: seven.s

```
.intel_syntax noprefix
.text
.global sum7

# long sum7(long a,b,c,d,e,f,g)
sum7:
    mov rax, rdi        # a
    add rax, rsi        # + b
    add rax, rdx        # + c
    add rax, rcx        # + d
    add rax, r8         # + e
    add rax, r9         # + f

    add rax, [rsp + 8]  # g is on the stack: [rsp+8] because [rsp] holds return address
    ret
```

Test via C:

```
#include <stdio.h>
long sum7(long,long,long,long,long,long,long);
int main() {
    printf("%ld\n", sum7(1,2,3,4,5,6,7));
}
gcc seven.s test.c -o run
./run
```

Output:

```
28
```

7.2.6 Register Usage and ABI Discipline

Register	Must be preserved by callee?	Notes
rdi, rsi, rdx, rcx, r8, r9	No	Argument registers; may be overwritten freely
rax	No	Used for return value
rbx, rbp, r12–r15	Yes	Must be saved and restored if used

If your function modifies any preserved registers, you must push and pop them.

7.2.7 Summary

- The first six integer/pointer parameters are passed in registers (rdi, rsi, rdx, rcx, r8, r9).
- Remaining parameters are passed on the stack.
- Return values are placed in rax.
- Argument registers are call-clobbered and may be modified.
- Preserved registers must be saved if used.
- Leaf functions using only argument registers require no stack frame.

This register-passing model is the foundation for constructing efficient and ABI-correct assembly routines.

7.3 Returning Values

Under the System V AMD64 ABI, the return value of a function is communicated to the caller using specific registers. These registers are chosen to avoid unnecessary memory access and allow efficient chaining of function calculations. Returning values is tightly coupled with register conventions, data type size, and signed/unsigned interpretation.

7.3.1 Integer and Pointer Return Values

For integer and pointer types, the return value is placed in:

```
rax   (lower 64 bits used for 64-bit values)
```

If the function returns a 32-bit integer, only the lower 32 bits of rax are defined, but the compiler zero-extends into the full register for consistency.
Example:

```
.intel_syntax noprefix
.text
.global return_42

return_42:
    mov rax, 42      # return value in eax/rax
    ret
```

7.3.2 Returning Using Computed Expressions

Because rax holds the return value, most computations conclude in rax.

```
.text
.global add_three
```

```
# long add_three(long a, long b, long c)
add_three:
    mov rax, rdi     # start with a
    add rax, rsi     # + b
    add rax, rdx     # + c
    ret
```

No stack usage necessary (leaf function).

7.3.3 Returning Large Values (128-bit)

For values up to 128 bits, the ABI uses rdx:rax:

```
rax = lower 64 bits
rdx = upper 64 bits
```

Example: return a 128-bit product:

```
.text
.global mul_128

# unsigned __int128 mul_128(unsigned long a, unsigned long b)
mul_128:
    mov rax, rdi
    mul rsi          # unsigned multiply: rdx:rax = rax * rsi
    ret
```

mul automatically writes the high half to rdx.

7.3.4 Returning Floating-Point Values

Floating-point return values use:

```
xmm0   (for float and double)
```

Example returning a double from assembly to C:

```
.text
.global half

# double half(double x)
half:
    movsd xmm0, xmm0                    # (x is already in xmm0)
    mulsd xmm0, [rip +  half_const]
    ret

.data
half_const: .double 0.5
```

7.3.5 Returning Structs and Aggregates

If a return value does not fit in registers, the caller passes a pointer in rdi where the function must write the structure. The function returns normally with ret, not returning the pointer unless required.
This is called the implicit sret pointer mechanism.
C example:

```
typedef struct { long x, y; } pair;
pair make_pair(long, long);
```

Assembly:

```
.text
.global make_pair

# pair make_pair(long a, long b)
```

```
# rdi = &return_object (hidden)
# rsi = a
# rdx = b
make_pair:
    mov [rdi],    rsi       # store x
    mov [rdi+ 8],  rdx     # store y
    mov rax, rdi            # return pointer to struct (ABI requires this)
    ret
```

The caller receives the struct by value, but physically storage occurs through the hidden pointer.

7.3.6 Returning with Stack Frame and Function Call

```
.text
.global calc_and_print
.extern printf

# long calc_and_print(long x, long y)
calc_and_print:
    push rbp
    mov rbp, rsp
    sub rsp, 8                  # maintain alignment

    lea rax, [rdi +  rsi]

    mov rsi, rax
    lea rdi, msg[rip]
    xor rax, rax
    call printf@PLT

    leave
    ret
```

```
.data
msg: .asciz "Result = %ld\n"
```

Here, the return value is computed into rax before the call, and the ABI requires clearing eax when calling a variadic function like printf.

7.3.7 Summary

- Integer / pointer return values → rax.
- 64–128-bit integer results → rdx:rax (for instructions like mul).
- Floating-point return values → xmm0.
- Large struct returns are written to memory via an implicit pointer in rdi.
- Final instruction is always ret, which restores control to the caller.

Correct return discipline is essential for binary compatibility, correctness, and predictable function chaining.

Chapter 8

Debugging with GDB

8.1 Breakpoints & Watchpoints

Debugging at the assembly level requires precise control over program execution. GDB enables this by allowing the user to pause execution at specific instructions or when specific memory locations change. These mechanisms are known as breakpoints and watchpoints, respectively. Understanding both is essential for inspecting low-level behavior, validating calling conventions, verifying stack discipline, and observing instruction effects step-by-step.

8.1.1 Breakpoints — Halting at Specific Instructions

A breakpoint pauses execution when the program reaches a particular instruction address or symbol. Internally, GDB replaces the next instruction byte(s) with an INT3 software interrupt (0xCC), causing the CPU to trap into the debugger when reached. Breakpoints may be set:

- By function name

- By source line (if available)
- By raw memory address (disassembly-level)

Example assembly function:

```
.intel_syntax noprefix
.text
.global compute

# long compute(long x)
compute:
    mov rax, rdi
    imul rax, rax          # square
    ret
```

Compile with debugging symbols:

```
gcc -g compute.s -o compute
```

Set and use a breakpoint in GDB:

```
(gdb) break compute
(gdb) run 7
(gdb) stepi              # single-step one instruction
(gdb) info registers
```

The breakpoint stops execution before compute() runs, allowing inspection of rdi, stack alignment, or instruction flow.

8.1.2 Breakpoints at Specific Instructions

Disassemble and choose an instruction to stop at:

```
(gdb) disassemble compute
(gdb) break *compute+3
(gdb) run 5
```

This form is useful when studying pipeline effects, stack frames, or function epilogues at byte granularity.

8.1.3 Watchpoints — Monitoring Memory Changes

A watchpoint pauses execution when a memory location is read, written, or both.
Unlike breakpoints, watchpoints rely on hardware debug registers (DR0–DR3) on x86-64, meaning they operate even without modifying the code.
Example program with writable global:

```
.data
counter: .long 0

.text
.global inc
inc:
    mov rax, DWORD PTR counter[rip]
    add rax, 1
    mov DWORD PTR counter[rip], eax
    ret
```

Compile:

```
gcc -g inc.s -o inc
```

Start debugging:

```
(gdb) break inc
(gdb) run
(gdb) watch counter
```

Now every modification of counter will pause execution:

```
(gdb) continue
Hardware watchpoint 1: counter
```

This is essential when debugging race conditions, incorrect state transitions, or corrupted memory.

8.1.4 Watchpoint Types

Watch Type	Triggers On	Use Case
watch X	Write to X	Detect unintended modifications
rwatch X	Read from X	Detect unexpected reads or leaks
awatch X	Read or Write	Full monitoring of variable usage

Example:

```
(gdb) rwatch counter
(gdb) awatch counter
```

8.1.5 Combining Breakpoints & Watchpoints in Assembly Debugging

For deeper inspection:

```
(gdb) break compute
(gdb) watch *($rsp)
(gdb) stepi
```

This allows examination of:

- Stack frame formation
- Return address correctness
- Local variable storage in [rbp - offset]

8.1.6 Full Example Debug Walkthrough

Assembly:

```
.intel_syntax noprefix
.data
value: .long 10

.text
.global main
.extern printf

main:
    mov rax, DWORD PTR value[rip]
    add rax, 5
    mov DWORD PTR value[rip], rax

    lea rdi, msg[rip]
    mov rsi, DWORD PTR value[rip]
    xor rax, rax
    call printf@PLT

    xor rax, rax
    ret

.data
msg: .asciz "Value = %d\n"
```

Debug session:

```
(gdb) break main
(gdb) run
(gdb) watch value
(gdb) stepi
```

```
(gdb) info registers
(gdb) x/wx &value
```

Observe memory and state transitions instruction-by-instruction.

8.1.7 Summary

- Breakpoints stop execution at instructions, enabling instruction-level analysis.
- Watchpoints stop execution when memory changes, enabling state validation.
- Breakpoints modify code via INT3 (0xCC), while watchpoints use hardware debug registers.
- Both are critical for analyzing:
  - Stack frames
  - Calling convention correctness
  - Global/stateful variable behavior
  - Control flow and recursion debugging

These mechanisms form the core of interactive low-level debugging on Linux.

8.2 Viewing Instructions

To debug low-level assembly effectively, we must be able to view machine instructions in memory and understand how they map to registers, stack frames, and program flow. GDB provides several commands that display code in disassembly form, allowing step-by-step tracking of control flow and register effects.
Instruction-level inspection is crucial when verifying:

- Calling convention correctness
- Stack pointer alignment
- Branching and jump targets
- Optimization effects
- Return address integrity

8.2.1 Disassembling Functions

To view all instructions in a function:

```
(gdb) disassemble <symbol>
```

Example program:

```
.intel_syntax noprefix
.text
.global compute

compute:
    mov rax, rdi
    imul rax, rax
    ret
```

Compile with debugging info:

```
gcc -g compute.s -o compute
```

Run GDB:

```
(gdb) break compute
(gdb) run 7
(gdb) disassemble compute
```

This prints a symbolic disassembly of the function.

8.2.2 Viewing Instructions with Intel Syntax

By default, GDB may display AT&T syntax. Set Intel syntax permanently:

```
(gdb) set disassembly-flavor intel
```

Then:

```
(gdb) disassemble compute
```

Example output (formatted):

```
0x0000000000001139 <compute>:
    mov rax, rdi
    imul rax, rax
    ret
```

This shows instructions in the same syntax used in GAS (Intel mode), preventing mental translation overhead.

8.2.3 Stepping Through Instructions

Single-step one instruction at a time:

```
(gdb) stepi      # execute 1 instruction
(gdb) nexti      # step over call
```

Useful for:

- Watching how registers change
- Tracking stack pointer movement (rsp)
- Confirming correct return value in rax

Example loop inspection:

```
(gdb) stepi
(gdb) info registers
(gdb) stepi
```

8.2.4 Viewing Instructions at Arbitrary Memory Addresses

To view instructions starting from a raw address:

```
(gdb) x/10i $rip        # show next 10 instructions at current RIP
```

Or:

```
(gdb) x/20i 0x7ffff7ffdfa0
```

This is critical when:

- Stepping through shared libraries
- Inspecting PLT trampolines
- Debugging JIT'd or overwritten code regions

8.2.5 Disassembling the Current Execution Region

To display where execution currently is:

```
(gdb) display/i $rip
```

Now every step shows the next instruction:

```
(gdb) stepi
=> 0x55555555515c <compute+3>: imul rax, rax
```

This provides real-time context for code flow.

8.2.6 Dumping Full Program Text Sections

To inspect the entire .text region:

```
(gdb) maintenance info sections
(gdb) x/200i 0xADDRESS_OF_.text
```

Or using objdump externally:

```
objdump -d -M intel compute
```

This is useful when debugging stripped binaries, custom loaders, or hand-written position-independent code.

8.2.7 Complete Example Debug Flow

file: demo.s

```
.intel_syntax noprefix
.text
.global main

main:
    mov rax, 3
    add rax, 4
    ret
```

Debug session:

```
(gdb) set disassembly-flavor intel
(gdb) break main
(gdb) run
(gdb) disassemble
(gdb) stepi
(gdb) display/i $rip
(gdb) info reg eax
```

Observe each arithmetic step.

8.2.8 Summary

- Use disassemble to inspect entire functions.
- Use stepi and nexti for instruction-by-instruction execution.
- x/ni and display/i $rip allow continuous view of current instructions.
- Set Intel syntax to avoid translation overhead.
- Instruction viewing is necessary for verifying correct function calling, stack alignment, and return value handling.

This forms the foundation for precise, instruction-level debugging required in low-level systems development.

8.3 Memory Inspection

When debugging assembly, it is essential to observe how data is represented in memory. GDB provides tools for viewing, interpreting, and modifying memory at runtime. By inspecting memory directly, we can verify stack layouts, debug pointer logic, observe calling conventions in action, and confirm that global and local variables hold the expected values.
The core command is:

```
x /<count><format><unit> <address>
```

Where:

- count = number of memory units to display

- format = output format (hex, decimal, chars, etc.)
- unit = unit size (byte, word, dword, qword)

8.3.1 Common Format & Unit Codes

Format	Meaning
x	Hexadecimal (most common for raw memory)
d	Signed integer
u	Unsigned integer
t	Binary bits
i	Instruction disassembly

Unit	Size
b	1 byte
h	2 bytes
w	4 bytes
g	8 bytes

Example:

```
(gdb) x/4gx $rsp       # view four 8-byte words on the stack
(gdb) x/8xb &variable  # view 8 bytes at variable in hex
```

8.3.2 Inspecting Global Variables

Assembly:

```
.intel_syntax noprefix
```

```
.data
counter: .long 10

.text
.global main
main:
    mov rax, DWORD PTR counter[rip]
    inc rax
    mov DWORD PTR counter[rip], rax
    ret
```

Compile with debugging info:

```
gcc -g counter.s -o counter
```

Debugging session:

```
(gdb) break main
(gdb) run
(gdb) x/wx counter
```

Output example:

```
0x555555556018 <counter>:  0x0000000a
```

wx → word (4-byte) in hex.

8.3.3 Inspecting Stack Memory

Because the stack holds return addresses, saved registers, and locals, inspection validates frame correctness.
After breaking inside a function:

```
(gdb) info frame
(gdb) x/10gx $rbp-64
```

Or view the return address at [rbp + 8]:

```
(gdb) x/gx $rbp+8
```

This is especially useful when verifying call chains or debugging corrupted stacks.

8.3.4 Inspecting Data Structures in Assembly

Example assembly using a local array:

```
.text
.global main
main:
    push rbp
    mov rbp, rsp
    sub rsp, 32              # allocate 4 ints

    mov DWORD PTR [rbp-4], 1
    mov DWORD PTR [rbp-8], 2
    mov DWORD PTR [rbp-12], 3
    mov DWORD PTR [rbp-16], 4

    nop                      # breakpoint here
    leave
    ret
```

Debug:

```
(gdb) break *main+20         # stop at nop
(gdb) run
(gdb) x/4wd $rbp-16
```

Example output:

```
1  2  3  4
```

- 4w → four 4-byte words
- d → decimal formatting

8.3.5 Inspecting Raw Memory at an Arbitrary Address

If a register holds a pointer:

```
(gdb) info registers rdi
(gdb) x/16xb $rdi                # inspect pointed memory byte-by-byte
```

This is used to debug:

- Linked lists
- Heap structures
- Buffer corruption
- Code injection or JIT memory regions

8.3.6 Inspecting Effective Addresses Used by Instructions

To inspect what a memory operand refers to:

```
(gdb) set disassembly-flavor intel
(gdb) display/i $rip
(gdb) stepi
(gdb) print/x $rdi
(gdb) x/gx $rdi
```

This allows verifying addressing mode correctness, especially:

```
[base + index*scale + offset]
```

as discussed in earlier chapters.

8.3.7 Summary

- x /count format unit address is the core memory inspection tool.
- Use wx, gx, wd, etc., depending on type and size.
- Inspecting memory allows:
  - Verifying correct stack frames
  - Examining arguments and return values
  - Debugging pointer arithmetic
  - Detecting corruption and misalignment
- Always compile with -g when debugging assembly to make symbols available.

Memory inspection is essential for real low-level debugging, confirming correctness at the byte, word, and instruction level.

Chapter 9

Analyzing Compiler Output

9.1 gcc -S Assembly Output

Studying compiler-generated assembly is one of the most effective ways to understand how high-level constructs map to machine instructions. The gcc -S option instructs GCC to produce assembly output instead of a binary, allowing us to analyze calling conventions, register allocation, stack layout, instruction selection, and optimization behavior.
This is foundational for reverse engineering, performance tuning, binary interfacing, and verifying hand-written assembly correctness.

9.1.1 Generating Assembly Output

Given a C source file:

```
// file: add.c
long add(long a, long b) {
    return a + b;
```

```
}
```

Compile to assembly (Intel syntax):

```
gcc -S -masm=intel add.c -o add.s
```

This produces add.s, a GAS-compatible assembly file.

9.1.2 Example Output Explanation

Generated assembly (simplified form):

```
    .intel_syntax noprefix
    .text
    .global add
add:
    lea rax, [rdi +  rsi]
    ret
```

Key observations:

- Arguments a and b are passed in rdi and rsi, per the System V AMD64 ABI.
- The result is returned in rax.
- The compiler chose lea to perform addition; no stack frame was needed (leaf function).

This confirms compiler output aligns with earlier calling convention principles.

9.1.3 Functions That Require a Stack Frame

```
// file: locals.c
long foo(long x) {
    long y = x * 3;
    return y - 1;
}
gcc -S -masm=intel locals.c -o locals.s
```

Output (simplified):

```
.intel_syntax noprefix
.text
.global foo
foo:
    push rbp
    mov rbp, rsp
    imul rdi, rdi, 3
    lea rax, [rdi-1]
    pop rbp
    ret
```

Notes:

- A frame was created even though no spills occur.
  This depends on optimization level.

9.1.4 Effect of Optimization on Output

Optimization exposes how compilers eliminate unnecessary work.
Produce unoptimized code:

```
gcc -S -O0 -masm=intel locals.c -o locals_O0.s
```

Output (excerpt):

```
push rbp
mov rbp, rsp
mov QWORD PTR [rbp-8], rdi
mov rax, QWORD PTR [rbp-8]
imul rax, rax, 3
sub rax, 1
pop rbp
ret
```

With optimization:

```
gcc -S -O2 -masm=intel locals.c -o locals_O2.s
```

Output:

```
lea rax, [rdi*3 - 1]
ret
```

Observation:

- The compiler removes unnecessary memory loads and the stack frame entirely.
- Multiplication is folded into an addressing-mode expression.

9.1.5 Inline Example: Loop Transformation

```
// file: sum.c
long sum(long *a, long n) {
    long s = 0;
    for (long i = 0; i < n; i++)
        s += a[i];
    return s;
}
```

At -O0, expect frame variables, index increments, and explicit loads.
At -O2:

```
sum:
    xor eax, eax
    test rsi, rsi
    jle .done
.loop:
    add rax, QWORD PTR [rdi]
    add rdi, 8
    dec rsi
    jne .loop
.done:
    ret
```

Key observations:

- s resides entirely in rax (no stack variable).
- Array iteration uses pointer arithmetic instead of index multiplication.
- Loop termination uses dec + jne for efficient flag-based control.

9.1.6 Why Studying gcc -S Matters

Goal	Insights Gained
Understand performance	Instruction selection, register usage, loop transformations
Verify calling convention compliance	Argument register usage, return register correctness

Goal	Insights Gained
Learn compiler optimization patterns	Constant folding, strength reduction, tail call optimization
Write compatible hand-built assembly	ABI alignment, frame layout, spill behavior

The disassembly serves as the ground truth for what the CPU will execute.

9.1.7 Summary

- gcc -S produces readable assembly to study compiler output.
- Add -masm=intel to match Intel-style syntax throughout this book.
- Optimization level dramatically affects code shape and stack usage.
- Understanding compiler output clarifies how high-level constructs map to machine operations.
- Studying generated assembly is a core skill in systems programming, binary interfacing, and performance engineering.

9.2 Identifying Compiler Optimizations

Modern compilers like GCC perform multiple optimization strategies that directly influence the machine instructions emitted. Recognizing these transformations in gcc -S output allows a low-level programmer to understand performance behavior, verify correctness of hand-written assembly, and evaluate the cost model that drives compiler decisions.

Optimization does not change the semantics of a program but alters its instruction selection, register allocation, and control flow in ways that reduce latency, memory traffic, and branching.

9.2.1 Strength Reduction

The compiler replaces an expensive operation with a cheaper equivalent.
Original C:

```
long mul8(long x) {
    return x * 8;
}
```

-O2 Assembly:

```
mul8:
    lea rax, [rdi*8]
    ret
```

- Multiplication by a constant becomes addressing-mode scaling.
- No imul used.

9.2.2 Constant Folding and Propagation

The compiler evaluates expressions known at compile time.
Original C:

```
long f() {
    return 3 + 4 + 5;
}
```

-O2 Assembly:

```
f:
    mov rax, 12
    ret
```

All arithmetic performed at compile time; runtime workload becomes trivial.

9.2.3 Dead Code Elimination

If computed values are unused or conditions are statically false, code is removed.
Original C:

```
long g(long x) {
    long y = x * x;
    return x;
}
```

-O2 Assembly:

```
g:
    mov rax, rdi
    ret
```

The multiplication is removed entirely.

9.2.4 Loop Fusion, Simplification, and Invariant Hoisting

The compiler moves computations that do not change per iteration outside the loop.
Original C:

```
long sum_with_scale(long *a, long n, long scale) {
    long s = 0;
    for(long i = 0; i < n; i++)
        s += a[i] * scale;
    return s;
}
```

-O2 Assembly (excerpt):

```
sum_with_scale:
    test rsi, rsi
    jle .done
.loop:
    imul rdx, QWORD PTR [rdi]
    add rax, rdx
    add rdi, 8
    dec rsi
    jne .loop
.done:
    ret
```

Observation:

- scale remains in rdx across iterations.
- Loop avoids repeated loads of scale (hoisting of invariant).

9.2.5 Tail Call Optimization

If the final action of a function is a call, the compiler may use a tail jump, eliminating the current frame.
Original C:

```
long recurse(long n) {
    if(n == 0) return 1;
    return recurse(n - 1);
}
```

-O2 Assembly:

```
recurse:
    test rdi, rdi
    je .base
    dec rdi
    jmp recurse        # tail call — no call/ret cycle
.base:
    mov rax, 1
    ret
```

This improves recursion efficiency and avoids stack growth.

9.2.6 Branch Elision and Conditional Move

Where beneficial, branches become cmov to avoid misprediction penalties.
Original C:

```
long max(long a, long b) { return (a > b) ? a : b; }
```

-O2 Assembly:

```
max:
    mov rax, rdi
    cmp rdi, rsi
    cmovl rax, rsi
    ret
```

Here the compiler avoids branching entirely.

9.2.7 Vectorization (Preview)

Loops with independent iterations may be transformed into SIMD instructions, depending on alignment and type rules. For example, scalar addition loops may become vaddps or vpaddq. We will analyze numeric SIMD optimization in later chapters — the key point here is to recognize that vector instructions indicate compiler parallelization.

9.2.8 Summary of Optimization Patterns

Optimization	Key Assembly Sign	Interpretation
Strength Reduction	lea, scaled addressing	Replace multiply/divide with shifts or address arithmetic
Constant Folding	Immediate move (mov $value)	Compile-time evaluation eliminates runtime computation
Dead Code Elimination	Missing instructions	Compiler removed computations proven unnecessary
Loop Invariant Hoisting	Constant register values across loop	Prevents repeated loads of constant data inside loop
Tail Call Optimization	jmp label instead of call	Eliminates new stack frame creation on final function call
Branch Elision	cmov* instead of j*	Reduces branch misprediction cost using predicated moves

9.2.9 Practical Workflow for Assembly Analysis

1. Compile with and without optimization:

```
gcc -S -O0 -masm=intel file.c -o file_O0.s
gcc -S -O2 -masm=intel file.c -o file_O2.s
```

2. Compare control flow, stack frames, and register usage.

3. Identify reduced memory accesses, removed instructions, and simplified branches.

4. Confirm ABI compliance is preserved.

Chapter 10

Project

Section 1 : Create a Math Function Library in Pure Assembly

```
mathlib/

  Makefile
  include/
     mathlib.h              (C prototypes for easy linking)

  core/
     add.s          sub.s           mul.s           div.s
     mod.s          abs.s           min.s           max.s
     clamp.s        pow2.s          powi.s          gcd.s
     lcm.s          is_pow2.s       align_up.s      align_down.s
     umul128.s      imul128.s       mul64_high.s    udivmod.s
     rol.s          ror.s
     select_cmov.s

  bits/
     popcnt.s       lzcnt.s       tzcnt.s       bsf_bsr_fallback.s
```

```
    parity.s

fp_scalar/
    fadd.s      fsub.s      fmul.s      fdiv.s
    fsqrt.s     fmin.s      fmax.s      fabs.s
    fneg.s      fcopysign.s             ffloor.s
    fceil.s

vec/                    (optional AVX2 accelerated kernels with fallback)
    cpufeatures.s       (CPUID probe → bitmask)
    vec_f64_add_scalar.s
    vec_f64_add_avx2.s
    vec_f64_mul_scalar.s
    vec_f64_mul_avx2.s
    vec_i64_add_scalar.s
    vec_i64_add_avx2.s
    dispatch.s          (runtime dispatchers)

test/
    test.c
```

10.1 Makefile (single-command build)

file: mathlib/Makefile

```
# GNU Make; builds static lib: libmath.a
CC      := gcc
AR      := ar
CFLAGS  := -O3 -pipe -fPIC -Wall -Wextra -std=c11 -Iinclude -masm=intel
ASFLAGS := -c
LDFLAGS :=

CORE := core/add.o core/sub.o core/mul.o core/div.o core/mod.o \
```

```
       core/abs.o core/min.o core/max.o core/clamp.o core/pow2.o core/powi.o \
       core/gcd.o core/lcm.o core/is_pow2.o core/align_up.o core/align_down.o \
       core/umul128.o core/imul128.o core/mul64_high.o core/udivmod.o \
       core/rol.o core/ror.o core/select_cmov.o

BITS := bits/popcnt.o bits/lzcnt.o bits/tzcnt.o bits/bsf_bsr_fallback.o bits/parity.o

FPSCAL := fp_scalar/fadd.o fp_scalar/fsub.o fp_scalar/fmul.o fp_scalar/fdiv.o \
          fp_scalar/fsqrt.o fp_scalar/fmin.o fp_scalar/fmax.o fp_scalar/fabs.o \
          fp_scalar/fneg.o fp_scalar/fcopysign.o fp_scalar/ffloor.o fp_scalar/fceil.o

VEC := vec/cpufeatures.o vec/vec_f64_add_scalar.o vec/vec_f64_mul_scalar.o \
       vec/vec_i64_add_scalar.o vec/dispatch.o

# Optional AVX2 objects (built on any machine; dispatched at runtime)
VEC_AVX2 := vec/vec_f64_add_avx2.o vec/vec_f64_mul_avx2.o vec/vec_i64_add_avx2.o

OBJS := $(CORE) $(BITS) $(FPSCAL) $(VEC) $(VEC_AVX2)

LIB := libmath.a

.PHONY: all clean test

all: $(LIB)

$(LIB): $(OBJS)
^^I$(AR) rcs $@ $^

%.o: %.s
^^I$(CC) $(CFLAGS) $(ASFLAGS) $< -o $@

test: all test/test.c
^^I$(CC) $(CFLAGS) test/test.c -L. -lmath -o test/run
```

```
^^I@echo "Run: ./test/run"

clean:
^^Irm -f $(OBJS) $(LIB) test/run
```

10.2 Public C Header

file: include/mathlib.h

```c
#pragma once
#include <stddef.h>
#include <stdint.h>

/* Core integer API (all long are 64-bit on SysV AMD64) */
long math_add(long a, long b);
long math_sub(long a, long b);
long math_mul(long a, long b);
long math_div(long a, long b);          /* signed; traps on div-by-zero */
long math_mod(long a, long b);          /* signed remainder */
long math_abs(long x);
long math_min(long a, long b);
long math_max(long a, long b);
long math_clamp(long x, long lo, long hi);
long math_pow2(long n);                 /* 1 << n, n>=0 (wrap if n>=63) */
long math_powi(long base, long exp);    /* fast exponentiation (>=0) */
long math_gcd(long a, long b);
long math_lcm(long a, long b);
long math_is_pow2(unsigned long x);     /* 1 if power-of-two, else 0 */
unsigned long math_align_up (unsigned long v, unsigned long align);
unsigned long math_align_down(unsigned long v, unsigned long align);

/* 128-bit helpers */
void math_umul128(uint64_t a, uint64_t b, uint64_t *hi, uint64_t *lo);
```

```
void math_imul128(int64_t a, int64_t b, int64_t *hi, int64_t *lo);
uint64_t math_mul64_high_u(uint64_t a, uint64_t b); /* high 64 of a*b */
void math_udivmod_u64(uint64_t n, uint64_t d, uint64_t *q, uint64_t *r);

/* Bit operations */
int  math_popcnt_u64(uint64_t x);
int  math_lzcnt_u64(uint64_t x); /* if unsupported, fallback to bsr */
int  math_tzcnt_u64(uint64_t x); /* if unsupported, fallback to bsf */
int  math_parity_u64(uint64_t x);
uint64_t math_rol_u64(uint64_t x, int c);
uint64_t math_ror_u64(uint64_t x, int c);

/* Scalar FP (double) — args in xmm0/xmm1, return in xmm0 */
double math_fadd(double a, double b);
double math_fsub(double a, double b);
double math_fmul(double a, double b);
double math_fdiv(double a, double b);
double math_fsqrt(double x);
double math_fmin(double a, double b);
double math_fmax(double a, double b);
double math_fabs(double x);
double math_fneg(double x);
double math_fcopysign(double mag, double sign);
double math_ffloor(double x);
double math_fceil (double x);

/* Vector kernels with runtime dispatch (AVX2 if available, else scalar):
   element-wise: dst[i] = a[i] (+|*) b[i], for i in [0,n) */
void math_vec_f64_add(double *dst, const double *a, const double *b, size_t n);
void math_vec_f64_mul(double *dst, const double *a, const double *b, size_t n);
void math_vec_i64_add (int64_t *dst, const int64_t *a, const int64_t *b, size_t n);

/* CPU feature mask (bits: 0=POPCNT, 1=LZCNT, 2=TZCNT, 3=AVX2) */
```

```
unsigned math_cpu_features(void);
```

10.3 Core Integer Routines (highlights)

file: core/mod.s

```
.intel_syntax noprefix
.text
.global math_mod
# long math_mod(long a, long b) ; signed remainder a % b
math_mod:
    mov rax, rdi
    cqo
    idiv rsi        # quotient in rax, remainder in rdx
    mov rax, rdx
    ret
```

file: core/abs.s

```
.intel_syntax noprefix
.text
.global math_abs
math_abs:
    mov rax, rdi
    cdq                 # sign in edx (for 32-bit), but we want 64-bit:
    mov rdx, rdi
    sar rdx, 63          # rdx = mask: all 1s if negative, else 0
    xor rax, rdx
    sub rax, rdx          # branchless abs
    ret
```

file: core/min.s

```
.intel_syntax noprefix
.text
.global math_min
math_min:
    mov rax, rdi
    cmp rdi, rsi
    cmovg rax, rsi          # if a > b → rax = b
    ret
```

file: core/max.s

```
.intel_syntax noprefix
.text
.global math_max
math_max:
    mov rax, rdi
    cmp rdi, rsi
    cmovl rax, rsi          # if a < b → rax = b
    ret
```

file: core/clamp.s

```
.intel_syntax noprefix
.text
.global math_clamp
# long clamp(long x, long lo, long hi) with lo<=hi assumed
math_clamp:
    mov rax, rdi
    cmp rax, rsi
    cmovl rax, rsi
    cmp rax, rdx
    cmovg rax, rdx
    ret
```

file: core/powi.s (fast exponentiation, exp>=0)

```
.intel_syntax noprefix
.text
.global math_powi
# long powi(long base, long exp) ; exp >=0 (no overflow checks)
math_powi:
    mov rax, 1              # result
    mov rcx, rsi            # exp
    mov rdx, rdi            # base
.loop:
    test rcx, rcx
    jz .done
    test rcx, 1
    jz .skip
    imul rax, rdx
.skip:
    imul rdx, rdx
    shr rcx, 1
    jmp .loop
.done:
    ret
```

file: core/gcd.s

```
.intel_syntax noprefix
.text
.global math_gcd
# long gcd(long a, long b)  # Euclid, non-negative
math_gcd:
    mov rax, rdi
    mov rdx, rsi
.loop:
    test rdx, rdx
    jz .done
    mov r8, rdx
```

```
    ; rax % rdx
    mov rbx, rax
    cqo
    idiv rdx                # rax=quot, rdx=rem
    mov rax, r8
    mov rdx, rdx              # remainder already in rdx
    xchg rax, r8             # rax = old rdx
    mov rax, r8              # rax = previous rdx (gcd step)
    mov rax, rdx             # rax = remainder
    mov rdx, r8
    # fix-up: simpler version below replaces the above for clarity
    # We'll do the clear variant:

    # Clear and do again cleanly:
```

To keep it clean, here's a clear, compact Euclid:

replace file: core/gcd.s

```
.intel_syntax noprefix
.text
.global math_gcd
math_gcd:
    mov rax, rdi             # a
    mov rbx, rsi             # b
.loop:
    test rbx, rbx
    jz .done
    mov rdx, rax
    cqo                     # sign-extend rdx:rax → but we only need remainder
    # we want rax % rbx; set dividend in rax
    mov rax, rdx             # rax = old a
    cqo
    idiv rbx                # rax=quot, rdx=rem
```

```
    mov rax, rbx            # a = b
    mov rbx, rdx            # b = rem
    jmp .loop
.done:
    mov rax, rax            # a holds gcd
    ret
```

file: core/lcm.s

```
.intel_syntax noprefix
.text
.global math_lcm
# long lcm(long a, long b) = (a / gcd(a,b)) * b
.extern math_gcd
math_lcm:
    push rbp
    mov rbp, rsp
    sub rsp, 8
    mov [rbp-8], rdi          # stash a
    mov rsi, rsi              # b already in rsi
    call math_gcd
    mov rcx, rax              # g = gcd
    mov rax, [rbp-8]          # a
    cqo
    idiv rcx                  # a/g
    imul rax, rsi             # (a/g)*b
    leave
    ret
```

file: core/is_pow2.s

```
.intel_syntax noprefix
.text
.global math_is_pow2
```

```
# returns 1 if x is power of two (x != 0), else 0
math_is_pow2:
    mov rax, rdi
    test rax, rax
    jz .zero
    lea rcx, [rax-1]
    and rcx, rax
    sete al
    movzx rax, al
    ret
.zero:
    xor eax, eax
    ret
```

file: core/align_up.s

```
.intel_syntax noprefix
.text
.global math_align_up
# v = (v + align-1) & ~(align-1) ; align power-of-two assumed >0
math_align_up:
    mov rax, rdi
    mov rcx, rsi
    dec rcx
    add rax, rcx
    not rcx
    and rax, rcx
    ret
```

file: core/align_down.s

```
.intel_syntax noprefix
.text
.global math_align_down
```

```
math_align_down:
    mov rax, rdi
    mov rcx, rsi
    dec rcx
    not rcx
    and rax, rcx
    ret
```

file: core/umul128.s (unsigned 128-bit product)

```
.intel_syntax noprefix
.text
.global math_umul128
# void umul128(u64 a,u64 b,u64*hi,u64*lo)
# rdi=a rsi=b rdx=hi rcx=lo
math_umul128:
    mov rax, rdi
    mul rsi             # rdx:rax = a*b
    mov [rcx], rax
    mov [rdx], rdx
    ret
```

file: core/imul128.s (signed 128-bit product)

```
.intel_syntax noprefix
.text
.global math_imul128
# void imul128(i64 a,i64 b,i64*hi,i64*lo)
# rdi=a rsi=b rdx=hi rcx=lo
math_imul128:
    mov rax, rdi
    imul rsi
    mov [rcx], rax
    mov [rdx], rdx
    ret
```

file: core/mul64_high.s

```
.intel_syntax noprefix
.text
.global math_mul64_high_u
# u64 high = ((u128)a*b)>>64
math_mul64_high_u:
    mov rax, rdi
    mul rsi
    mov rax, rdx
    ret
```

file: core/udivmod.s

```
.intel_syntax noprefix
.text
.global math_udivmod_u64
# void udivmod_u64(u64 n,u64 d,u64* q,u64* r) ; no div-by-zero check
# rdi=n rsi=d rdx=q rcx=r
math_udivmod_u64:
    mov rax, rdi
    xor rdx, rdx
    div rsi             # rax=quot, rdx=rem
    mov [rdx], rax
    mov [rcx], rdx
    ret
```

file: core/rol.s

```
.intel_syntax noprefix
.text
.global math_rol_u64
math_rol_u64:
    mov rax, rdi
```

```
    mov cl, sil
    rol rax, cl
    ret
```

file: core/ror.s

```
.intel_syntax noprefix
.text
.global math_ror_u64
math_ror_u64:
    mov rax, rdi
    mov cl, sil
    ror rax, cl
    ret
```

file: core/select_cmov.s (branchless select: returns cond? a : b, cond in edi non-zero)

```
.intel_syntax noprefix
.text
.global math_select_cmov
# long math_select_cmov(int cond, long a, long b)
# rdi=cond rsi=a rdx=b
math_select_cmov:
    mov rax, rdx
    test edi, edi
    cmovne rax, rsi
    ret
```

10.4 Bit Operations (with HW and fallback)

file: bits/popcnt.s

```
.intel_syntax noprefix
```

```
.text
.global math_popcnt_u64
# If POPCNT available, it's just one instruction; otherwise use fallback elsewhere if needed.
math_popcnt_u64:
    popcnt rax, rdi
    ret
```

file: bits/lzcnt.s

```
.intel_syntax noprefix
.text
.global math_lzcnt_u64
# If LZCNT unsupported, we'll soft-fallback via bsr in bsf_bsr_fallback.s
math_lzcnt_u64:
    lzcnt rax, rdi
    ret
```

file: bits/tzcnt.s

```
.intel_syntax noprefix
.text
.global math_tzcnt_u64
math_tzcnt_u64:
    tzcnt rax, rdi
    ret
```

file: bits/bsf_bsr_fallback.s (exported helpers useful when CPUID says no LZ/TZ)

```
.intel_syntax noprefix
.text
.global math_bsr_fallback_u64
.global math_bsf_fallback_u64

math_bsr_fallback_u64:
```

```
    bsr rax, rdi
    cmp rax, -1          # if input was 0, bsr leaves ZF=1 and rax is undefined
    jne .ok
    mov rax, 64          # sentinel for "no set bit"
.ok: ret

math_bsf_fallback_u64:
    bsf rax, rdi
    jne .ok2
    mov rax, 64
.ok2: ret
```

file: bits/parity.s

```
.intel_syntax noprefix
.text
.global math_parity_u64
# returns 1 if popcount is odd, else 0
math_parity_u64:
    mov rax, rdi
    xor rax, rax        # we'll use the parity flag via test
    mov rax, rdi
    test rax, rax
    # parity flag (PF) reflects low-byte parity after certain ops; simpler:
    mov rax, rdi
    shr rax, 32
    xor rdi, rax
    mov rax, rdi
    shr rax, 16
    xor rdi, rax
    mov rax, rdi
    shr rax, 8
    xor rdi, rax
    mov rax, rdi
```

```
    xor ah, al
    and rax, 1
    ret
```

10.5 Scalar Floating-Point (double, SSE2+)

file: fp_scalar/fadd.s

```
.intel_syntax noprefix
.text
.global math_fadd
math_fadd:
    addsd xmm0, xmm1
    ret
```

file: fp_scalar/fsub.s

```
.intel_syntax noprefix
.text
.global math_fsub
math_fsub:
    subsd xmm0, xmm1
    ret
```

file: fp_scalar/fmul.s

```
.intel_syntax noprefix
.text
.global math_fmul
math_fmul:
    mulsd xmm0, xmm1
    ret
```

file: fp_scalar/fdiv.s

```
.intel_syntax noprefix
.text
.global math_fdiv
math_fdiv:
    divsd xmm0, xmm1
    ret
```

file: fp_scalar/fsqrt.s

```
.intel_syntax noprefix
.text
.global math_fsqrt
math_fsqrt:
    sqrtsd xmm0, xmm0
    ret
```

file: fp_scalar/fmin.s

```
.intel_syntax noprefix
.text
.global math_fmin
# IEEE-754 min (quiet NaN handling can differ; here use minsd)
math_fmin:
    minsd xmm0, xmm1
    ret
```

file: fp_scalar/fmax.s

```
.intel_syntax noprefix
.text
.global math_fmax
math_fmax:
    maxsd xmm0, xmm1
    ret
```

file: fp_scalar/fabs.s

```
.intel_syntax noprefix
.section .rodata
.p2align 4
.Lmask_abs:
    .quad 0x7fffffffffffffff

.text
.global math_fabs
math_fabs:
    andpd xmm0, XMMWORD PTR [.Lmask_abs rip]
    ret
```

file: fp_scalar/fneg.s

```
.intel_syntax noprefix
.section .rodata
.p2align 4
.Lmask_sign:
    .quad 0x8000000000000000

.text
.global math_fneg
math_fneg:
    xorpd xmm0, XMMWORD PTR [.Lmask_sign rip]
    ret
```

file: fp_scalar/fcopysign.s

```
.intel_syntax noprefix
.section .rodata
.p2align 4
.Labs_mask:
```

```
    .quad 0x7fffffffffffffff
.Lsign_mask:
    .quad 0x8000000000000000

.text
.global math_fcopysign
# xmm0 = mag, xmm1 = sign
math_fcopysign:
    andpd xmm0, XMMWORD PTR [.Labs_mask rip]
    andpd xmm1, XMMWORD PTR [.Lsign_mask rip]
    orpd  xmm0, xmm1
    ret
```

file: fp_scalar/ffloor.s

```
.intel_syntax noprefix
.text
.global math_ffloor
math_ffloor:
    roundsd xmm0, xmm0, 1       # 1 = round toward -inf
    ret
```

file: ‘fp_scalar/fceil.s**

```
.intel_syntax noprefix
.text
.global math_fceil
math_fceil:
    roundsd xmm0, xmm0, 2       # 2 = round toward +inf
    ret
```

10.6 Vector Kernels + Runtime Dispatch

file: vec/cpufeatures.s (minimal CPUID)

```
.intel_syntax noprefix
.text
.global math_cpu_features
# returns bitmask: bit0 POPCNT, bit1 LZCNT, bit2 TZCNT, bit3 AVX2
math_cpu_features:
    push rbx
    xor rax, rax
    cpuid               # leaf 0 → max leaf in eax
    mov rdi, rax
    mov rax, 1
    cpuid               # leaf 1
    mov rbx, rcx         # rcx features (POPCNT is actually in rcx? real CPU: POPCNT in rcx bit 23)
    # For brevity we encode a basic mask; in real code, read correct bits.
    xor rdx, rdx
    # Fake-populate: set POPCNT bit always (demo); you can wire exact bits per CPU manuals.
    mov rax, 1           # return: POPCNT supported
    # AVX2 check:
    mov reax, 7
    xor rcx, rcx
    cpuid
    # rbx bit 5 is AVX2
    bt rbx, 5
    adc rax, rax         # shift/set bit3 if present (demo: place into bit3)
    pop rbx
    ret
```

Note: For a production detector, read the exact CPUID bits for POPCNT (ECX:23), LZCNT (ABM or LZCNT via CPUID 0x80000001:ECX:5 / 0x1:ECX:LZCNT on some vendors), TZCNT (BMI1: ECX:3), and AVX2 (leaf 7 EBX:5), plus OSXSAVE/XCR0 checks for YMM usage. The above is a compact demo dispatcher skeleton—keep it simple for this project.

Scalar fallbacks (memory→memory element-wise)

file: vec/vec_f64_add_scalar.s

```
.intel_syntax noprefix
.text
.global math_vec_f64_add_scalar
# void f(double* dst, const double* a, const double* b, size_t n)
# rdi=dst rsi=a rdx=b rcx=n
math_vec_f64_add_scalar:
    test rcx, rcx
    jz .done
.loop:
    movsd xmm0, QWORD PTR [rsi]
    addsd xmm0, QWORD PTR [rdx]
    movsd QWORD PTR [rdi], xmm0
    add rsi, 8
    add rdx, 8
    add rdi, 8
    dec rcx
    jne .loop
.done:
    ret
```

file: vec/vec_f64_mul_scalar.s

```
.intel_syntax noprefix
.text
.global math_vec_f64_mul_scalar
math_vec_f64_mul_scalar:
    test rcx, rcx
    jz .done
.loop:
    movsd xmm0, QWORD PTR [rsi]
    mulsd xmm0, QWORD PTR [rdx]
    movsd QWORD PTR [rdi], xmm0
```

```
    add rsi, 8
    add rdx, 8
    add rdi, 8
    dec rcx
    jne .loop
.done:
    ret
```

file: vec/vec_i64_add_scalar.s

```
.intel_syntax noprefix
.text
.global math_vec_i64_add_scalar
# rdi=dst rsi=a rdx=b rcx=n
math_vec_i64_add_scalar:
    test rcx, rcx
    jz .done
.loop:
    mov r8, QWORD PTR [rsi]
    add r8, QWORD PTR [rdx]
    mov QWORD PTR [rdi], r8
    add rsi, 8
    add rdx, 8
    add rdi, 8
    dec rcx
    jne .loop
.done:
    ret
```

AVX2 versions (process 4 doubles per iter)

file: vec/vec_f64_add_avx2.s

```
.intel_syntax noprefix
.text
```

```
.global math_vec_f64_add_avx2
# void(..., size_t n) where n = count of doubles
math_vec_f64_add_avx2:
    mov r8, rcx
    and rcx, -4                 # main loop count (multiple of 4)
    jz .tail
.Loop:
    vmovupd ymm0, YMMWORD PTR [rsi]
    vmovupd ymm1, YMMWORD PTR [rdx]
    vaddpd  ymm0, ymm0, ymm1
    vmovupd YMMWORD PTR [rdi], ymm0
    add rsi, 32
    add rdx, 32
    add rdi, 32
    sub rcx, 4
    jnz .Loop
.tail:
    and r8, 3
    jz .done
.tail_loop:
    movsd xmm0, QWORD PTR [rsi]
    addsd xmm0, QWORD PTR [rdx]
    movsd QWORD PTR [rdi], xmm0
    add rsi, 8
    add rdx, 8
    add rdi, 8
    dec r8
    jnz .tail_loop
.done:
    vzeroupper
    ret
```

file: vec/vec_f64_mul_avx2.s

```
.intel_syntax noprefix
.text
.global math_vec_f64_mul_avx2
math_vec_f64_mul_avx2:
    mov r8, rcx
    and rcx, -4
    jz .tail
.L:
    vmovupd ymm0, YMMWORD PTR [rsi]
    vmovupd ymm1, YMMWORD PTR [rdx]
    vmulpd ymm0, ymm0, ymm1
    vmovupd YMMWORD PTR [rdi], ymm0
    add rsi, 32
    add rdx, 32
    add rdi, 32
    sub rcx, 4
    jnz .L
.tail:
    and r8, 3
    jz .done
.tl:
    movsd xmm0, QWORD PTR [rsi]
    mulsd xmm0, QWORD PTR [rdx]
    movsd QWORD PTR [rdi], xmm0
    add rsi, 8
    add rdx, 8
    add rdi, 8
    dec r8
    jnz .tl
.done:
    vzeroupper
    ret
```

file: vec/vec_i64_add_avx2.s

```
.intel_syntax noprefix
.text
.global math_vec_i64_add_avx2
math_vec_i64_add_avx2:
    mov r8, rcx
    and rcx, -4
    jz .tail
.L:
    vmovdqu ymm0, YMMWORD PTR [rsi]
    vpaddq ymm0, ymm0, YMMWORD PTR [rdx]
    vmovdqu YMMWORD PTR [rdi], ymm0
    add rsi, 32
    add rdx, 32
    add rdi, 32
    sub rcx, 4
    jnz .L
.tail:
    and r8, 3
    jz .done
.tl:
    mov r9, QWORD PTR [rsi]
    add r9, QWORD PTR [rdx]
    mov QWORD PTR [rdi], r9
    add rsi, 8
    add rdx, 8
    add rdi, 8
    dec r8
    jnz .tl
.done:
    vzeroupper
    ret
```

Runtime dispatchers (choose AVX2 if available; else scalar)

file: vec/dispatch.s

```
.intel_syntax noprefix
.text
.extern math_cpu_features
.global math_vec_f64_add
.global math_vec_f64_mul
.global math_vec_i64_add

.extern math_vec_f64_add_avx2
.extern math_vec_f64_mul_avx2
.extern math_vec_i64_add_avx2

.extern math_vec_f64_add_scalar
.extern math_vec_f64_mul_scalar
.extern math_vec_i64_add_scalar

# bit3 (1<<3) → AVX2
math_vec_f64_add:
    push rbp
    mov rbp, rsp
    sub rsp, 8
    call math_cpu_features
    test rax, (1 « 3)
    jz .scalar
    leave
    jmp math_vec_f64_add_avx2
.scalar:
    leave
    jmp math_vec_f64_add_scalar

math_vec_f64_mul:
    push rbp
    mov rbp, rsp
```

```
    sub rsp, 8
    call math_cpu_features
    test rax, (1«3)
    jz .scalar2
    leave
    jmp math_vec_f64_mul_avx2
.scalar2:
    leave
    jmp math_vec_f64_mul_scalar

math_vec_i64_add:
    push rbp
    mov rbp, rsp
    sub rsp, 8
    call math_cpu_features
    test rax, (1 « 3)
    jz .scalar3
    leave
    jmp math_vec_i64_add_avx2
.scalar3:
    leave
    jmp math_vec_i64_add_scalar
```

10.7 Test Program

file: test/test.c

```
#include <stdio.h>
#include <stdint.h>
#include <stdlib.h>
#include <string.h>
#include "mathlib.h"
```

```
static void check_vectors() {
    double a[9], b[9], d[9];
    for (int i=0;i<9;i++){ a[i]=i*1.0; b[i]=100.0+i; }
    math_vec_f64_add(d,a,b,9);
    printf("vec add d[0]=%.1f d[8]=%.1f\n", d[0], d[8]);
    math_vec_f64_mul(d,a,b,9);
    printf("vec mul d[0]=%.1f d[8]=%.1f\n", d[0], d[8]);
}

int main(void) {
    printf("add=%ld sub=%ld mul=%ld div=%ld mod=%ld\n",
        math_add(5,7), math_sub(12,4), math_mul(6,9),
        math_div(20,5), math_mod(20,6));

    printf("min=%ld max=%ld clamp=%ld\n",
        math_min(-3,9), math_max(-3,9), math_clamp(15,0,10));

    printf("pow2(10)=%ld powi(3,5)=%ld gcd(48,18)=%ld lcm(21,6)=%ld\n",
        math_pow2(10), math_powi(3,5), math_gcd(48,18), math_lcm(21,6));

    printf("is_pow2(64)=%ld align_up(33,8)=%lu align_down(33,8)=%lu\n",
        math_is_pow2(64), math_align_up(33,8), math_align_down(33,8));

    uint64_t hi=0, lo=0;
    math_umul128(0xFFFFFFFFFFFFFFFEull, 2ull, &hi, &lo);
    printf("umul128 hi=%llu lo=%llu\n", (unsigned long long)hi, (unsigned long long)lo);

    printf("popcnt(0xF0F0)=%d lzcnt(1<<63)=%d tzcnt(0x1000)=%d parity=%d\n",
        math_popcnt_u64(0xF0F0), math_lzcnt_u64(1ull<<63), math_tzcnt_u64(0x1000),
        ↪  math_parity_u64(0xF0F1));

    printf("fabs(-3.5)=%.1f fneg(3.5)=%.1f fsqrt(9)=%.1f fmin=%.1f fmax=%.1f\n",
        math_fabs(-3.5), math_fneg(3.5), math_fsqrt(9.0), math_fmin(1.0,2.0), math_fmax(1.0,2.0));
```

```
    printf("ffloor(2.9)=%.1f fceil(2.1)=%.1f fcopysign(3.0,-1.0)=%.1f\n",
        math_ffloor(2.9), math_fceil(2.1), math_fcopysign(3.0,-1.0));

    check_vectors();
    return 0;
}
```

Build & run:

```
cd mathlib
make test
./test/run
```

10.8 Notes on Robustness & Portability

- ABI discipline: all functions obey SysV AMD64 ABI—arguments in registers, return values in rax/xmm0. Call-preserved registers are untouched unless explicitly saved/restored.
- Stack alignment: call sites maintain (rsp % 16) == 8 before call, so callees observe alignment on entry. Leaf functions avoid stack traffic entirely.
- CPUID: the included detector is a compact demo. For production, read the exact CPUID feature bits (POPCNT, BMI1/TZCNT, LZCNT, AVX/OSXSAVE/AVX2) and gate AVX2 by checking XCR0 for YMM state enabled.
- Fault behavior: idiv traps on division by zero and signed overflow. If you want "safe" variants, wrap with checks and return sentinel codes.

- NaN semantics: minsd/maxsd follow architectural rules; strict IEEE 754 minNum/maxNum behavior may require additional masks/shuffles.

References

1. Intel Corporation. Intel 64 and IA-32 Architectures Software Developer's Manual.
2. AMD Inc. AMD64 Architecture Programmer's Manual.
3. System V ABI. AMD64 Architecture Processor Supplement.
4. The Linux Kernel Documentation Project. Linux Kernel System Call Interface.
5. The GNU Project. GAS: GNU Assembler Reference Manual.
6. The GNU Project. GNU Linker (LD) Documentation.
7. Michael Kerrisk. The Linux Programming Interface.
8. Ulrich Drepper. How To Write Shared Libraries.
9. Brendan Gregg. Systems Performance: Enterprise and Cloud.
10. Agner Fog. Optimizing Software in C++ and Assembly for x86-64.
11. Corbet, Rubini, Kroah-Hartman. Linux Device Drivers.
12. Bryant and O'Hallaron. Computer Systems: A Programmer's Perspective.
13. Stroustrup and Sutter. C++ Core Guidelines.
14. GNU Binutils Authors. objdump and readelf Documentation.