Compilers Laboratory (CS39003)

Autumn 2023

Hardware

Processor: Intel(R) Core(TM) i5-4570 CPU
3.2 GHz (Max Turbo Freq: 3.6 GHz)
4 (# of cores)
4 (# of threads)

Memory: 6 MB Smart Cache
4 GB (main memory; max 32 GB)

Software

OS: GNU/Linux, 64-bit, x86_64

Software: GCC, Lex/**Flex** and Yacc/**Bison**

Language: C/C++

System

Hardware system information:

```
$ uname  –a
Linux Pralay 2.6.32-504.el6.x86_64 #1 SMP Wed Jul 13 14:27:16 UTC
2022 x86_64 x86_64 x86_64 GNU/Linux
```

CPU information:

```
$ cat  /proc/cpuinfo
processor       : 0
model name      : Intel(R) Core(TM) i5-4570 CPU @ 3.20GHz
cache size      : 6144 KB
core id         : 0
cpu cores       : 4
cache_alignment : 64
address sizes   : 36 bits physical, 48 bits virtual
```

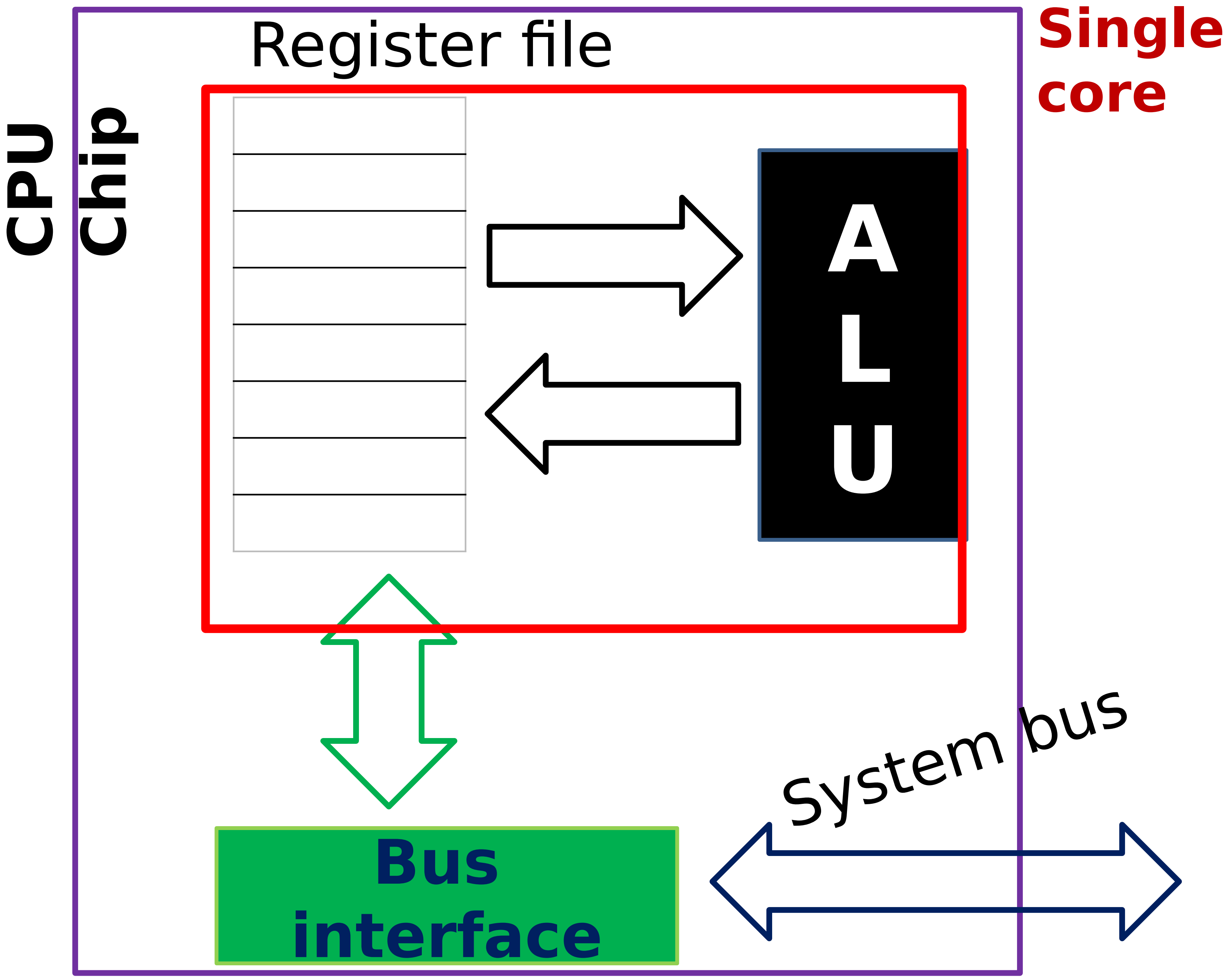
System

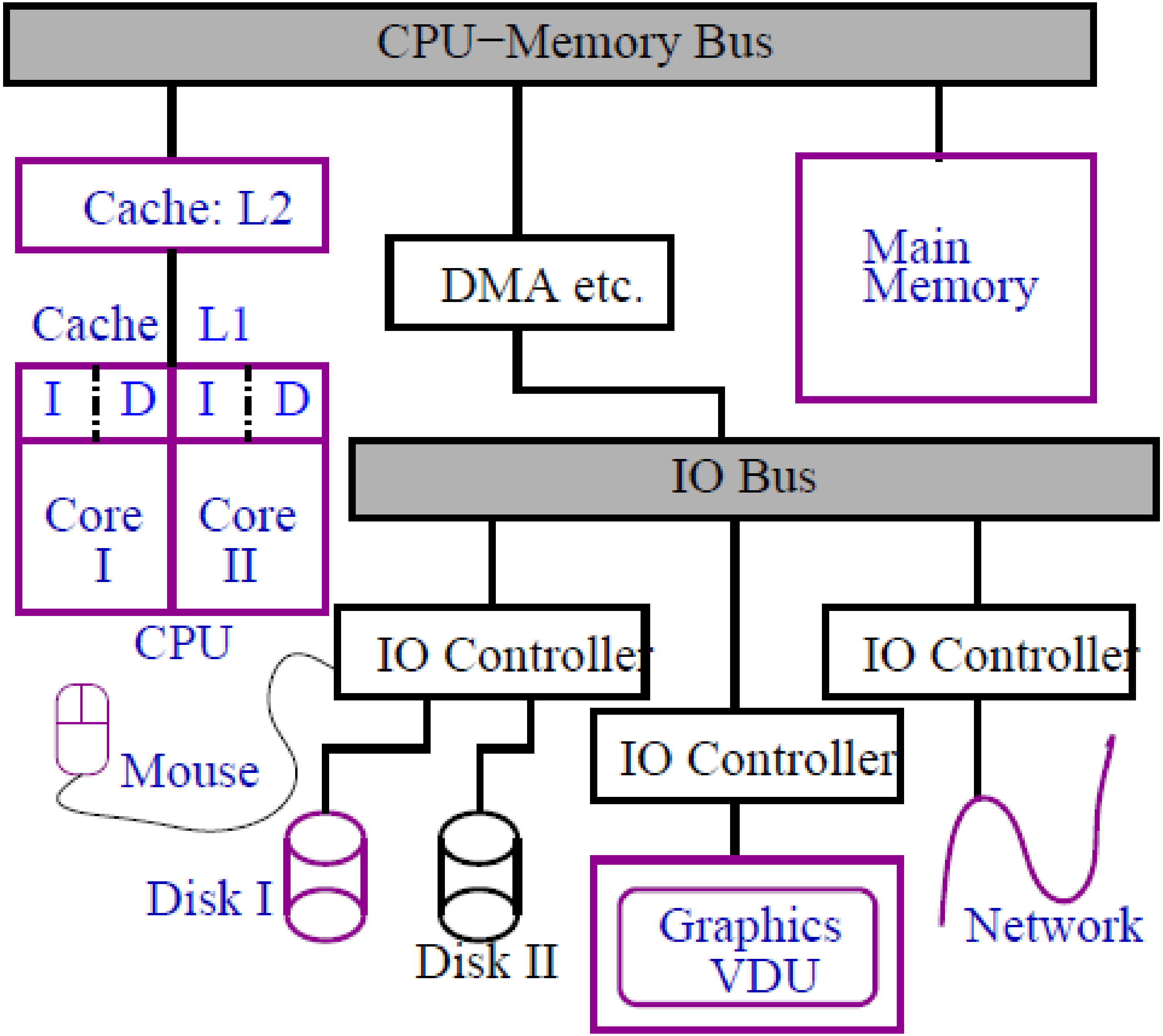
Main Memory Address

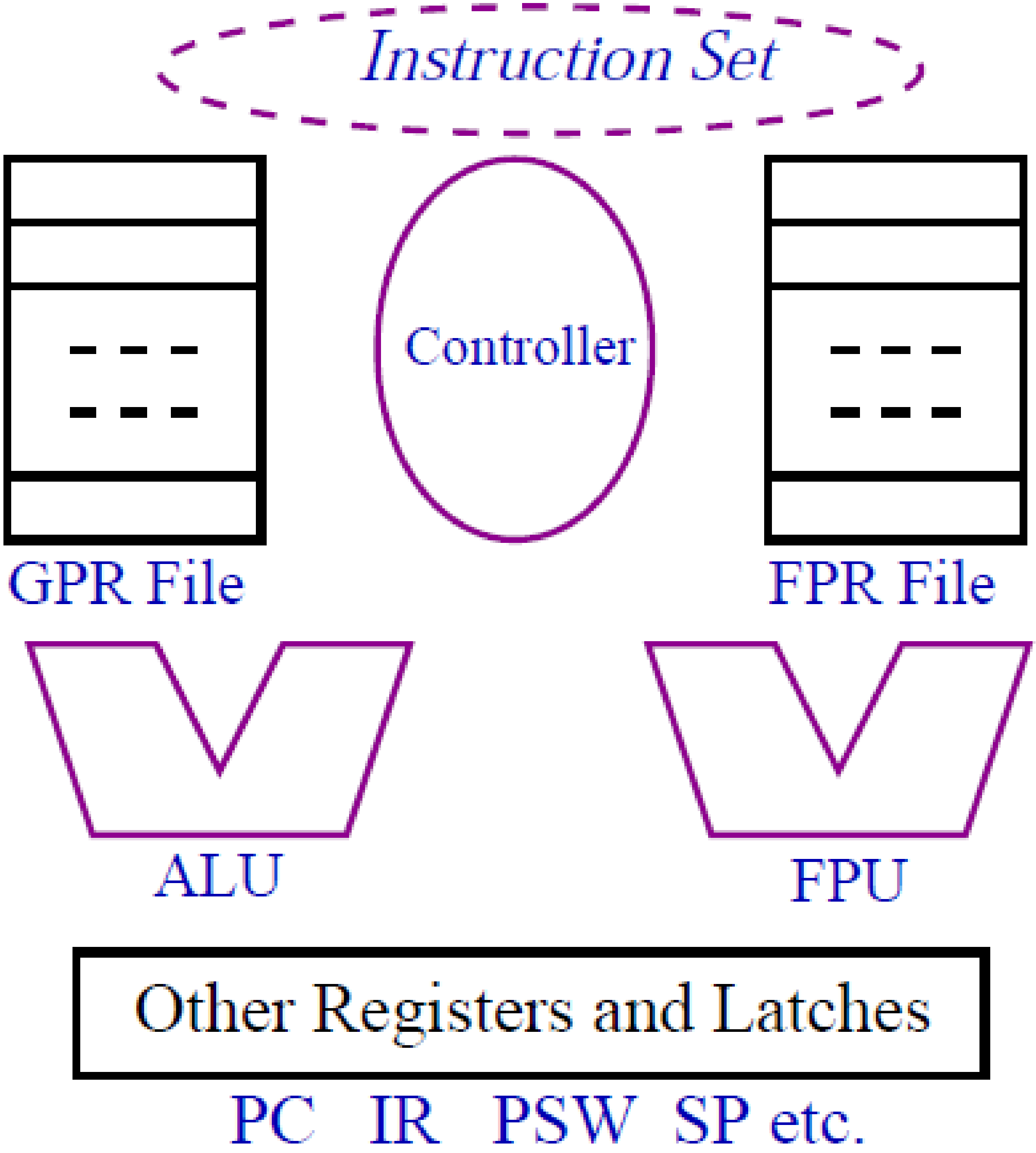
Address: 36 bits physical, 48 bits virtual/logical

The width of any X86_64 address register is 64 bit. But the most significant 17 bits are either all 1’s or all 0’s. So the logical address space of any process is 48-bits.

Depending on the model of the CPU, 48-bit logical address is translated to 36 to 40 bits of physical memory (main) address.


Register file
Single core
CPU Chip
A L U
Bus interface
System bus


CPU−Memory Bus
Cache: L2
DMA etc.
Main Memory
Cache
L1
I
D
I
D
Core I
Core II
CPU
IO Bus
IO Controller
IO Controller
IO Controller
Mouse
Disk I
Disk II
Graphics VDU
Network



Instruction Set

Controller

GPR File

FPR File

ALU

FPU

Other Registers and Latches

PC IR PSW SP etc.

Intel 64-bit Registers

GPRs: 64-bit integer registers (16)

rax, *rbx*, *rcx*, *rdx*, *rsp*, *rbp*, *rsi*, *rdi*, *r*8, .. , *r*15

FPRs: 80-bit floating point registers (8)

*r*0, .. , *r*7

MMXs: 64-bit SIMD registers (8)

*mm*0, .. , *mm*7

XMMs: 128-bit SSE registers (16)

*xmm*0, .., *xmm*15

Streaming SIMD

Special Registers

64-bit *rflags*, 64-bit *rip* (PC), segment registers, control registers, debug registers, etc.

Register Usage Convention

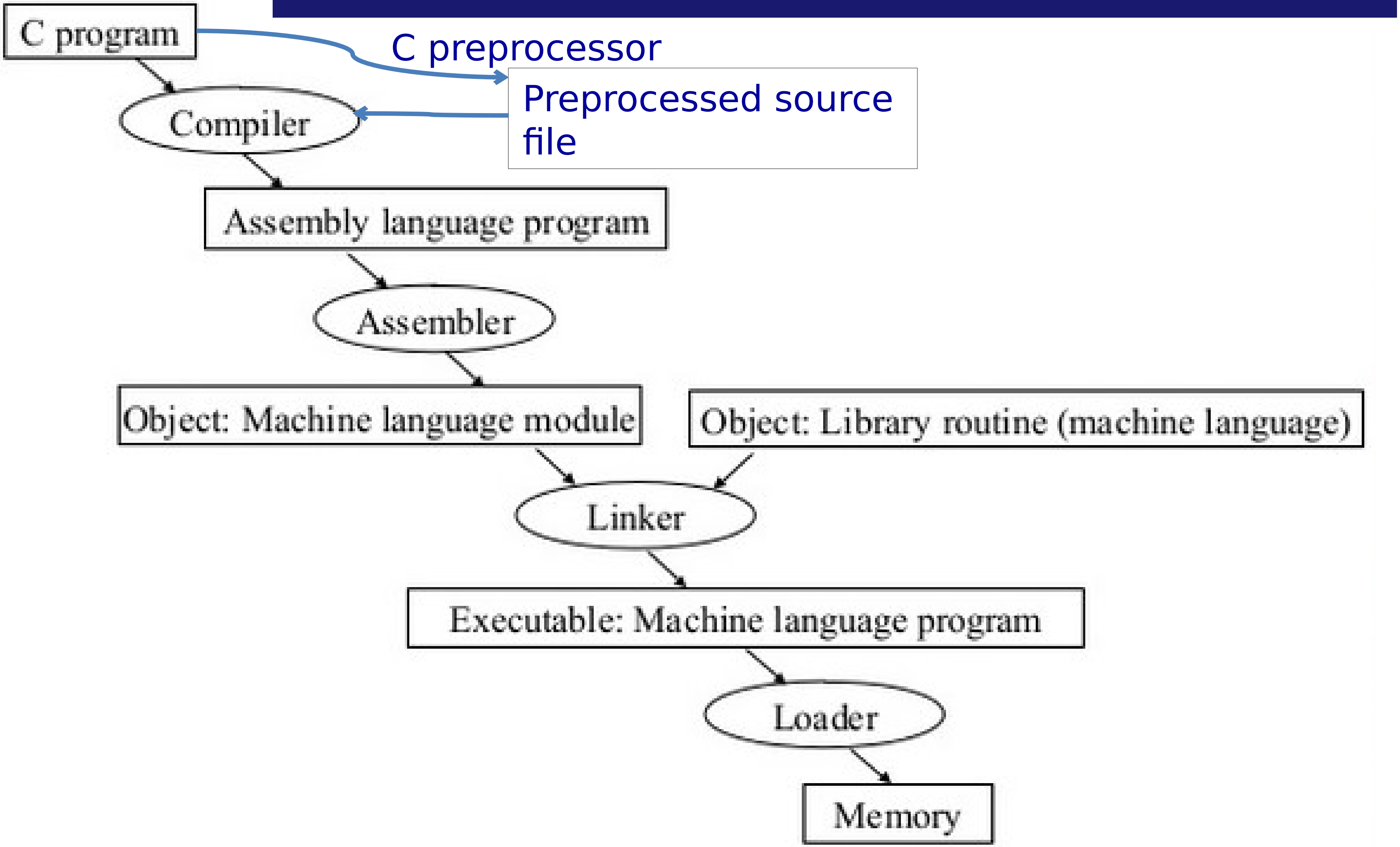
GPR (64-bit)	Usage Convention
rax	Return value from a function
rbx	Callee saved
rcx	4th argument to a function
rdx	3rd argument to a function Return value from a function
rsi	2nd argument to a function
rdi	1st argument to a function
rbp	Callee saved

Register Usage Convention

GPR (64-bit)	Usage Convention
rsp	Hardware stack pointer
r8	5th argument to a function
r9	6th argument to a function
r10	Callee saved
r11	Reserved for linker
r12	Reserved for C
r13	Callee saved
r14	Callee saved
r15	Callee saved

Function return address is at the top of the stack.

CPP → Compiler → Assembler → Linker



C program

C preprocessor

Preprocessed source file

Compiler

Assembly language program

Assembler

Object: Machine language module

Object: Library routine (machine language)

Linker

Executable: Machine language program

Loader

Memory

A simple Assembly Program

```
some_function:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $20, %esp
        movl    8(%ebp), %ebx
        movl    12(%ebp), %ecx
        movl    $0, %edx
        testl   %ecx, %ecx
        jle     .L152
        movl    $0, %eax
        movl    $0, %edx
.L153:
        addl    (%ebx,%eax,4), %edx
        addl    $1, %eax
        cmpl    %eax, %ecx
        jne     .L153
.L152:
        movl    %edx, 4(%esp)
        movl    $.LC14, (%esp)
        call    printf
        addl    $20, %esp
        popl    %ebx
        popl    %ebp
        ret
```

```
void some_function(int a[], int n) {
  int i, sum = 0;
  for (i = 0; i < n; i++) {
    sum += a[i];
  }
  printf("The sum is %d\n", sum);
}
```

Source Code

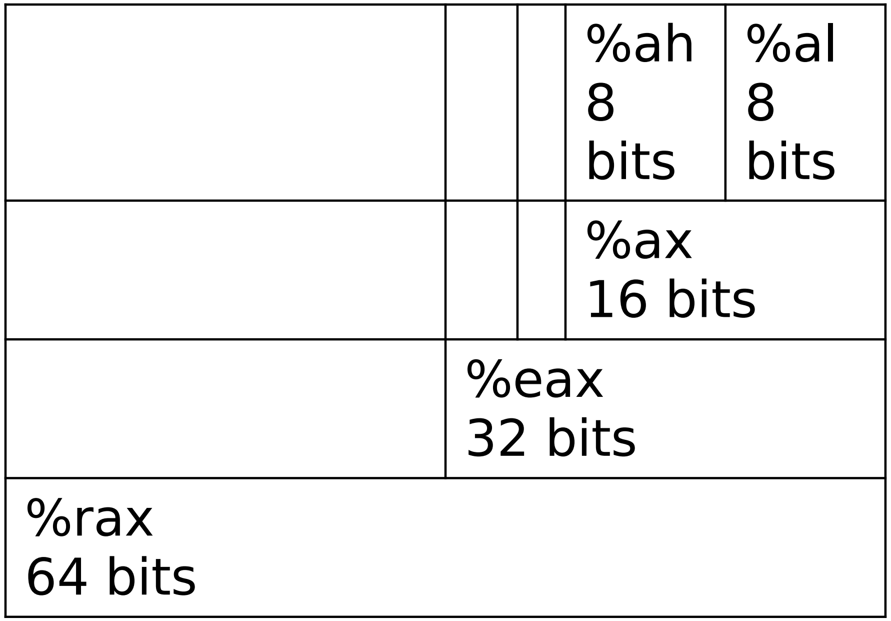
```
#include <stdio.h>

int main()
{
        int loop,terms;
        double pi,sign;

        printf("Enter the number of terms: ");
        scanf("%d",&terms);
        pi=3.0;
        sign=1.0;
        for(loop=1;loop<=terms;loop++) {
                pi+=sign*(4.0/((2.0*loop)*(2.0*loop+1)*(2.0*loop+2)));
                sign*=-1.0;
        }

        printf("\nValue of PI: %12.10lf\n",pi);
        return 0;
}
```

Compilation

```
$  cc  -Wall  -S  computePI.c            computePI.s

$  cc  -Wall  -c  computePI.c           computePI.o

$  cc  -Wall  computePI.c               a.out
```

Conventions

Suffix	**Name**	**Size**
B	BYTE	1 byte (8 bits)
W	WORD	2 bytes (16 bits)
L	LONG	4 bytes (32 bits)
Q	QUADWORD	8 bytes (64 bits)



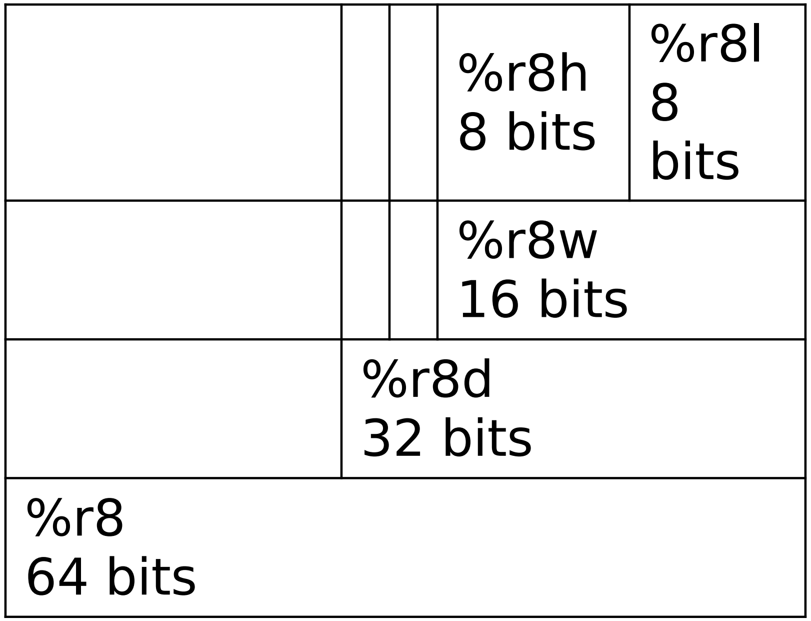
%ah
8
bits

%al
8
bits

%ax
16 bits

%eax
32 bits

%rax
64 bits



%r8h
8 bits

%r8l
8
bits

%r8w
16 bits

%r8d
32 bits

%r8
64 bits

Conventions

Mode	Example
Global Symbol	MOVQ x, %rax
Immediate	MOVQ $56, %rax
Register	MOVQ %rbx, %rax
Indirect	MOVQ (%rsp), %rax
Base-Relative	MOVQ -8(%rbp), %rax
Offset-Scaled-Base-Relative	MOVQ -16(%rbx,%rcx,8), %rax

Assembly Code

```
        .file       "computePI.c“                   # source file name
        .section    .rodata                         # read-only data section
        .align 8                                    # align with 8-byte boundary
.LC0:                                               # Label of f-string-1st printf
        .string     "Enter the number of terms: "
.LC1:                                               # Label of f-string scanf
        .string     "%d"
.LC7:                                               # Label of f-string - 2nd printf
        .string     "\nValue of PI: %12.10lf\n"
        .text                                       # Code starts
.globl main                                         # main is a global name
        .type       main, @function                 # main is a function
main:                                               # main: starts
.LFB0:
        .cfi_startproc                              # Call Frame Information
        pushq       %rbp                            # Save old base pointer
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq        %rsp, %rbp                      # rbp <-- rsp set new stack base pointer
        .cfi_def_cfa_register 6
```

Assembly Code

```
subq      $32, %rsp            # Create space for local array and variables
movl      $.LC0, %eax          # eax <-- starting of the format string, 1st param
movq      %rax, %rdi           # rdi <-- rax
movl      $0, %eax             # eax <-- 0 (?)
call      printf               # Call printf
movl      $.LC1, %eax           # eax <-- starting of the format string
leaq      -24(%rbp), %rdx      # rdx <-- (rbp - 24) (&terms)
movq      %rdx, %rsi
movq      %rax, %rdi
movl      $0, %eax             # eax <-- 0 (?)
call      __isoc99_scanf       # call scanf, return value is in eax
…..
……
……
```

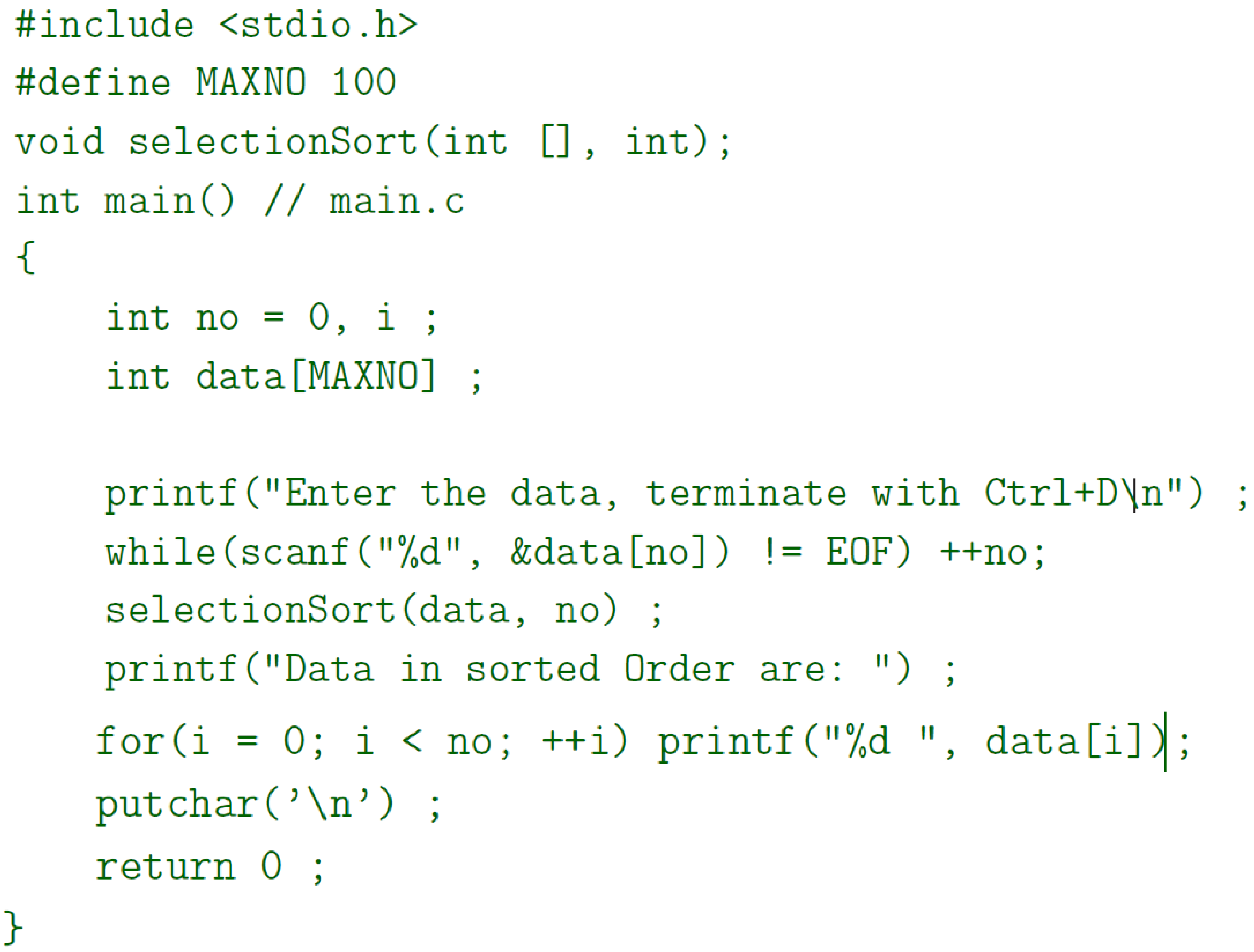
Assembly Code

```
        movsd   %xmm0, -8(%rbp)
        addl    $1, -20(%rbp)
.L2:
        movl    -24(%rbp), %eax
        cmpl    %eax, -20(%rbp)
        jle     .L3
        movl    $.LC7, %eax
        movsd   -16(%rbp), %xmm0
        movq    %rax, %rdi
        movl    $1, %eax
        call    printf
        movl    $0, %eax
        leave
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE0:
        .size   main, .-main
        .section        .rodata
        .align 8
```

Assembly Code

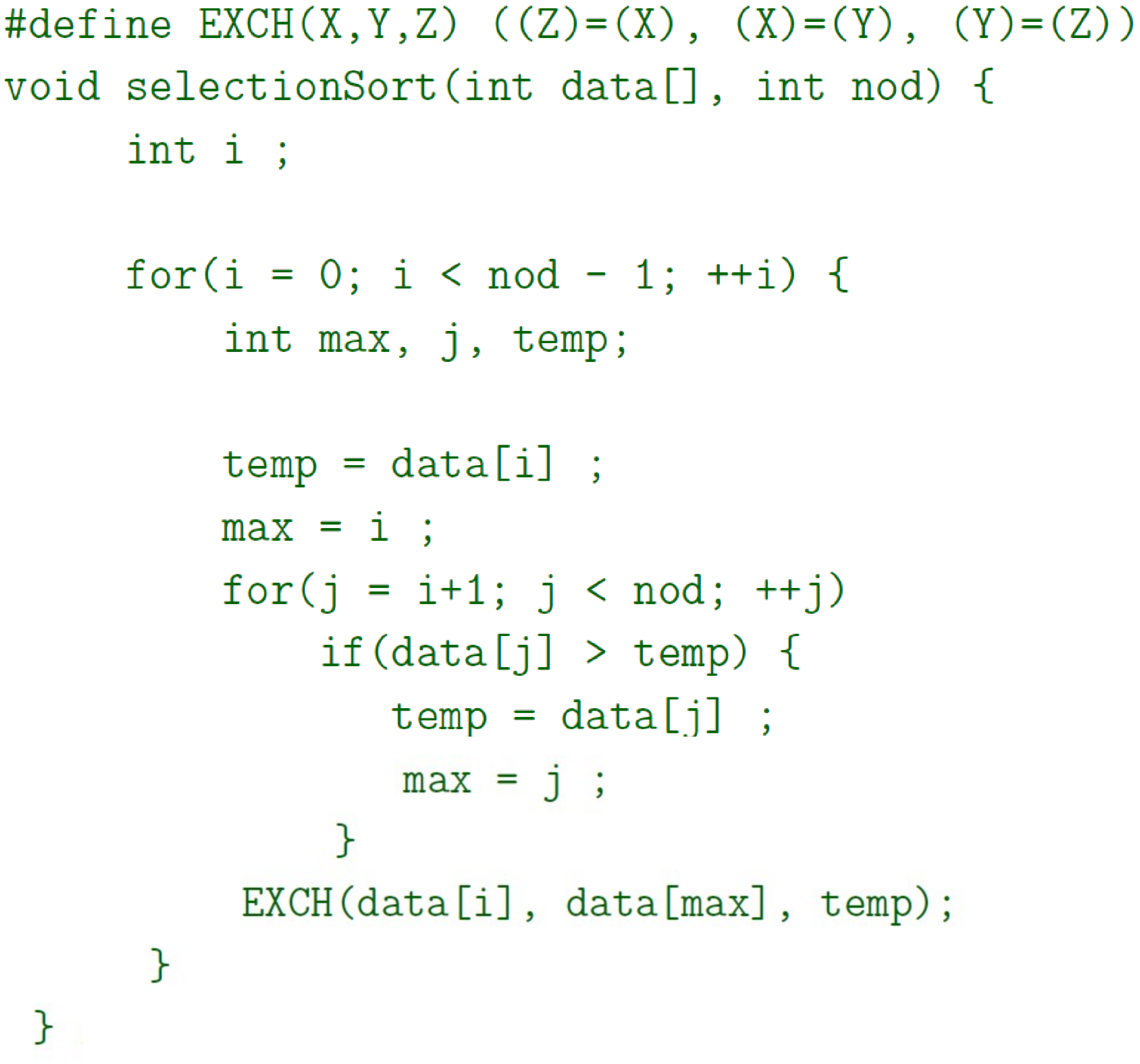
```
.LC3:
        .long       0
                    # 0000 0000 0000 0000 0000 0000 0000 0000
        .long       1072693248
        .align 8
.LC4:
        .long       0
        .long       1073741824
        .align 8
.LC5:
        .long       0
        .long       1074790400
        .align 16
.LC6:
        .long       0
        .long       -2147483648
        .long       0
        .long       0
        .ident      "GCC: (GNU) 4.4.7 20120313 (Red Hat 4.4.7-11)"
        .section    .note.GNU-stack,"",@progbits
```

Compiling a C program



```
#include <stdio.h>
#define MAXNO 100
void selectionSort(int [], int);
int main() // main.c
{
    int no = 0, i ;
    int data[MAXNO] ;

    printf("Enter the data, terminate with Ctrl+D\n") ;
    while(scanf("%d", &data[no]) != EOF) ++no;
    selectionSort(data, no) ;
    printf("Data in sorted Order are: ") ;
    for(i = 0; i < no; ++i) printf("%d ", data[i]);
    putchar('\n') ;
    return 0 ;
}
```

Compiling a C

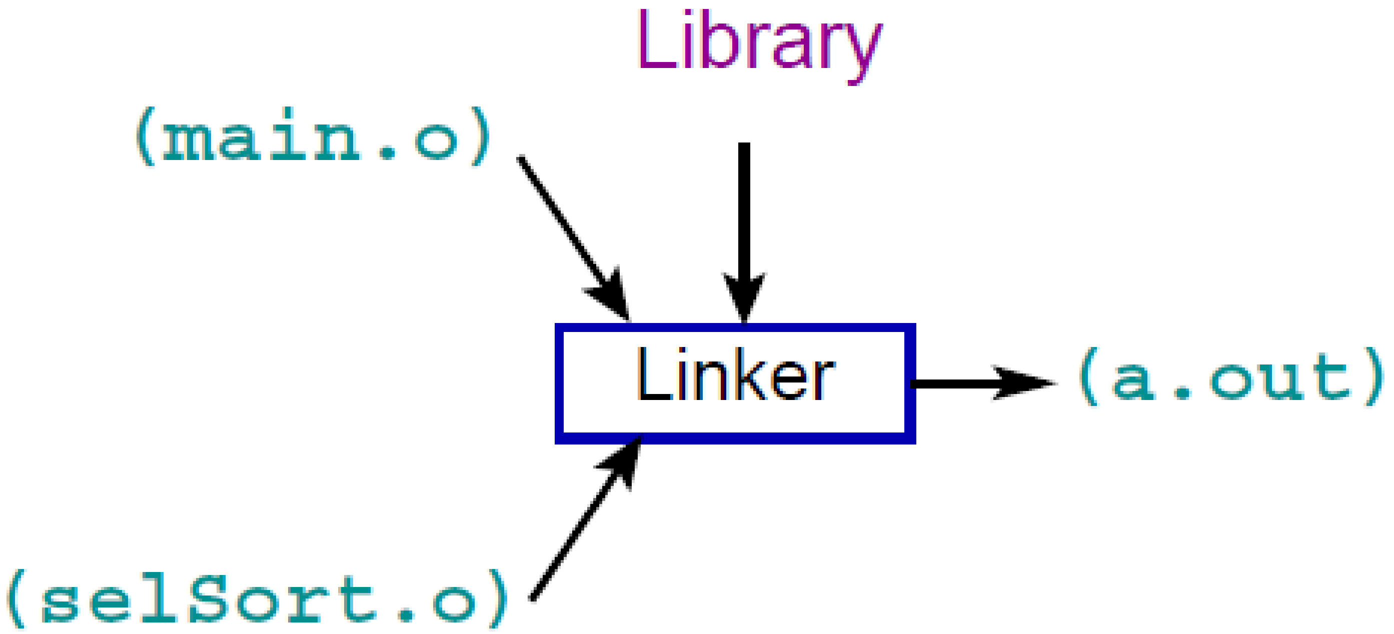


```
#define EXCH(X,Y,Z) ((Z)=(X), (X)=(Y), (Y)=(Z))
void selectionSort(int data[], int nod) {
     int i ;

     for(i = 0; i < nod - 1; ++i) {
         int max, j, temp;

         temp = data[i] ;
         max = i ;
         for(j = i+1; j < nod; ++j)
             if(data[j] > temp) {
                temp = data[j] ;
                max = j ;
             }
          EXCH(data[i], data[max], temp);
     }
  }
```

Compilation

```
$  cc  -Wall  -S  main.c          →      main.s

$  cc  -Wall  -c  main.c          →      main.o

$  cc  -Wall  -S  selSort.c       →      selSort.s

$  cc  -Wall  -c  selSort.c→      selSort.o

$  cc   main.o   selSort.o        →      a.out
```

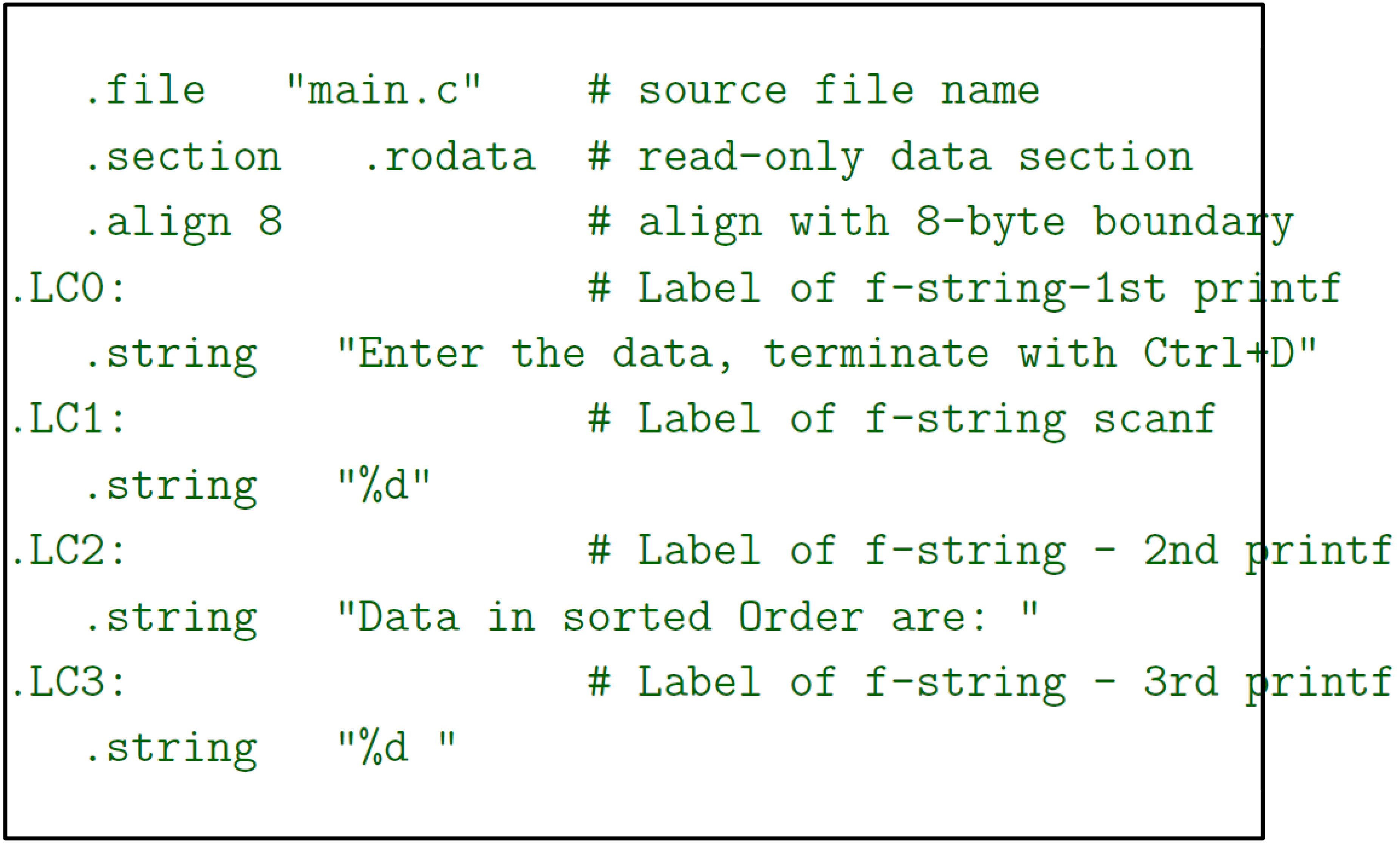
Compilation and Linking



File Types

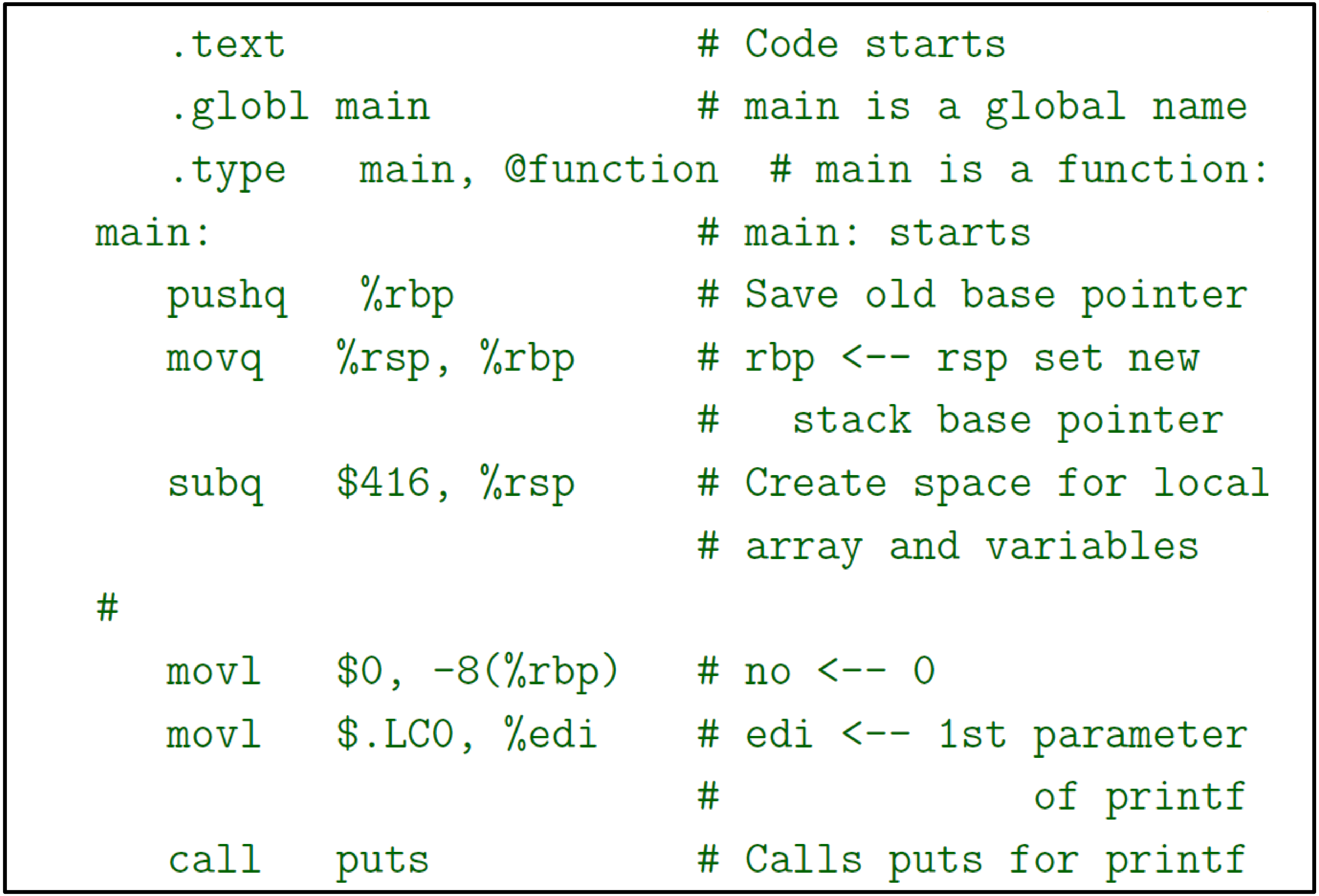
```
$  file  main.c   selSort.c
main.c:     ASCII English text
selSort.c: ASCII text

$ file   main.s   selSort.s
main.s:     ASCII English text
selSort.s: ASCII assembler program text

$ file   main.o  selSort.o
main.o:     ELF 64-bit LSB relocatable, x86-64, version 1 (SYSV), not stripped
selSort.o:  ELF 64-bit LSB relocatable, x86-64, version 1 (SYSV), not stripped

$ file   a.out
a.out:     ELF 64-bit LSB executable, x86-64, version 1 (SYSV), dynamically
           linked (uses shared libs), for GNU/Linux 2.6.18, not stripped
```

Assembly Code



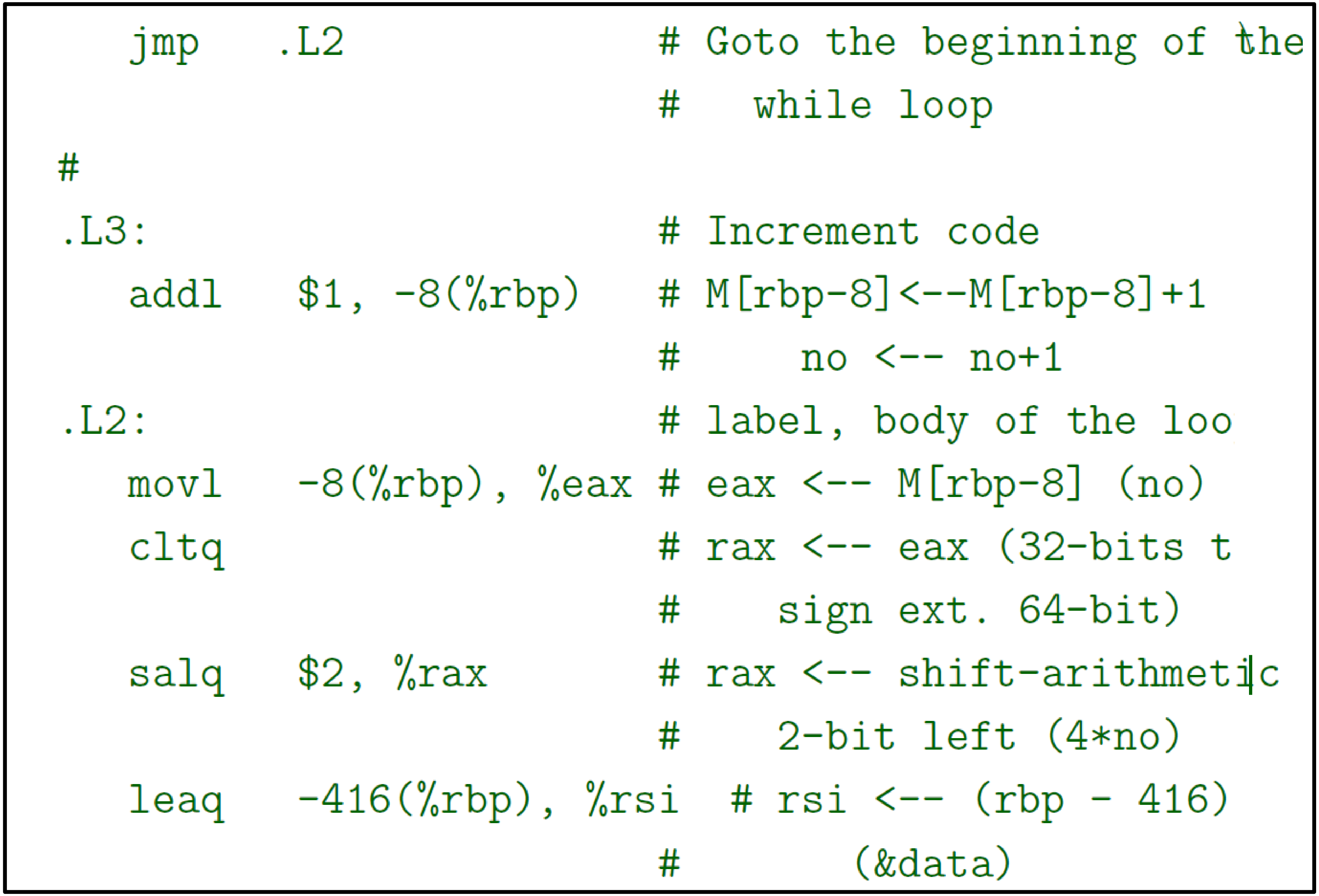
```
    .file     "main.c"     # source file name
    .section    .rodata    # read-only data section
    .align 8               # align with 8-byte boundary
.LC0:                      # Label of f-string-1st printf
    .string   "Enter the data, terminate with Ctrl+D"
.LC1:                      # Label of f-string scanf
    .string   "%d"
.LC2:                      # Label of f-string - 2nd printf
    .string   "Data in sorted Order are: "
.LC3:                      # Label of f-string - 3rd printf
    .string   "%d "
```

Assembly Code



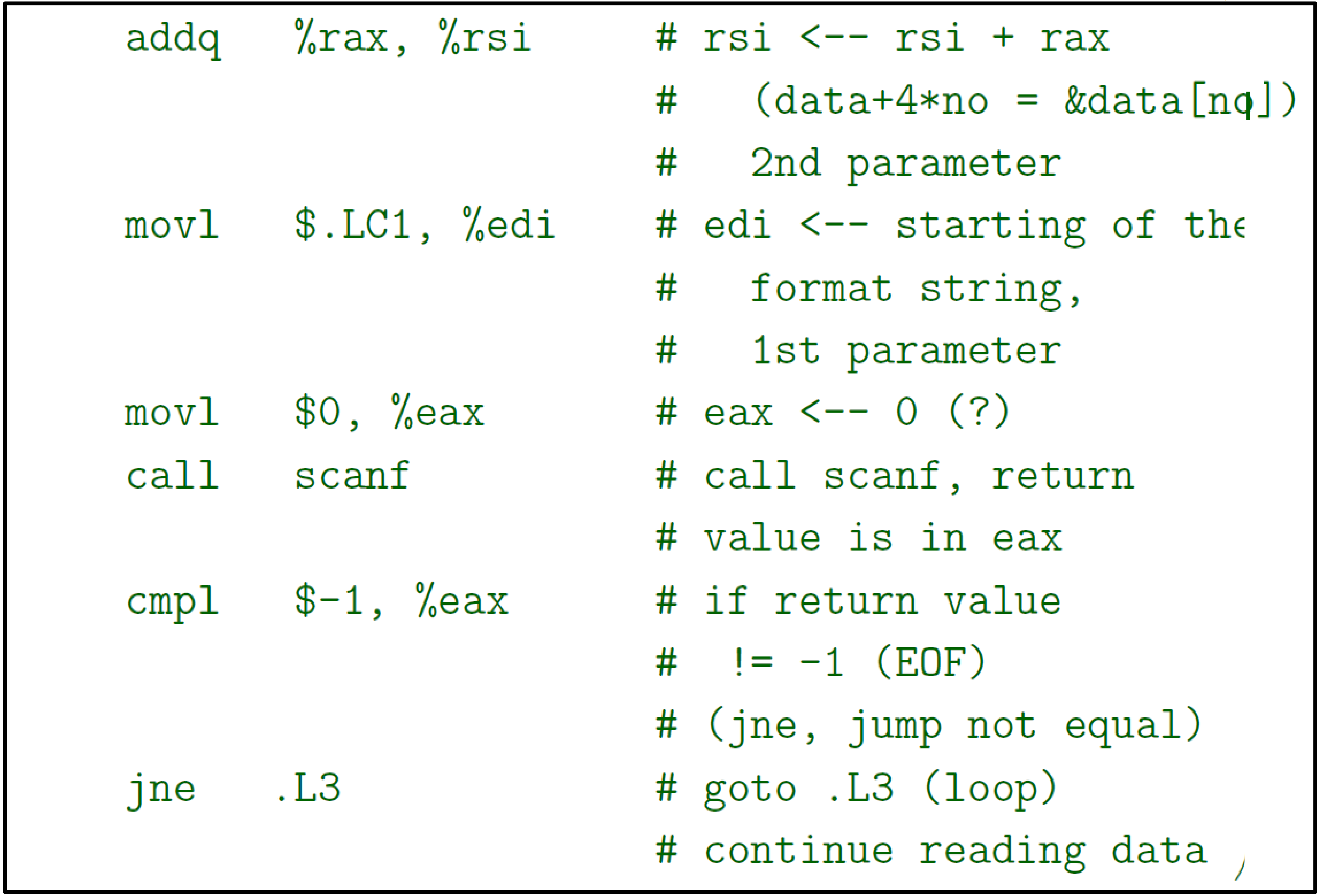
```
     .text                         # Code starts
     .globl main                   # main is a global name
     .type   main, @function   # main is a function:
  main:                            # main: starts
     pushq    %rbp                 # Save old base pointer
     movq    %rsp, %rbp            # rbp <-- rsp set new
                                   #   stack base pointer
     subq    $416, %rsp            # Create space for local
                                   # array and variables
  #
     movl    $0, -8(%rbp)          # no <-- 0
     movl    $.LC0, %edi           # edi <-- 1st parameter
                                   #             of printf
     call    puts                  # Calls puts for printf
```

Assembly Code



```
    jmp    .L2                # Goto the beginning of the
                              #   while loop
 #
 .L3:                         # Increment code
    addl   $1, -8(%rbp)       # M[rbp-8]<--M[rbp-8]+1
                              #     no <-- no+1
 .L2:                         # label, body of the loo
    movl   -8(%rbp), %eax     # eax <-- M[rbp-8] (no)
    cltq                      # rax <-- eax (32-bits t
                              #    sign ext. 64-bit)
    salq   $2, %rax           # rax <-- shift-arithmetic
                              #    2-bit left (4*no)
    leaq   -416(%rbp), %rsi    # rsi <-- (rbp - 416)
                              #       (&data)
```

Assembly Code



```
addq    %rax, %rsi      # rsi <-- rsi + rax
                        #    (data+4*no = &data[nq])
                        #    2nd parameter
movl    $.LC1, %edi     # edi <-- starting of the
                        #    format string,
                        #    1st parameter
movl    $0, %eax        # eax <-- 0 (?)
call    scanf           # call scanf, return
                        # value is in eax
cmpl    $-1, %eax       # if return value
                        #   != -1 (EOF)
                        # (jne, jump not equal)
jne    .L3              # goto .L3 (loop)
                        # continue reading data
```

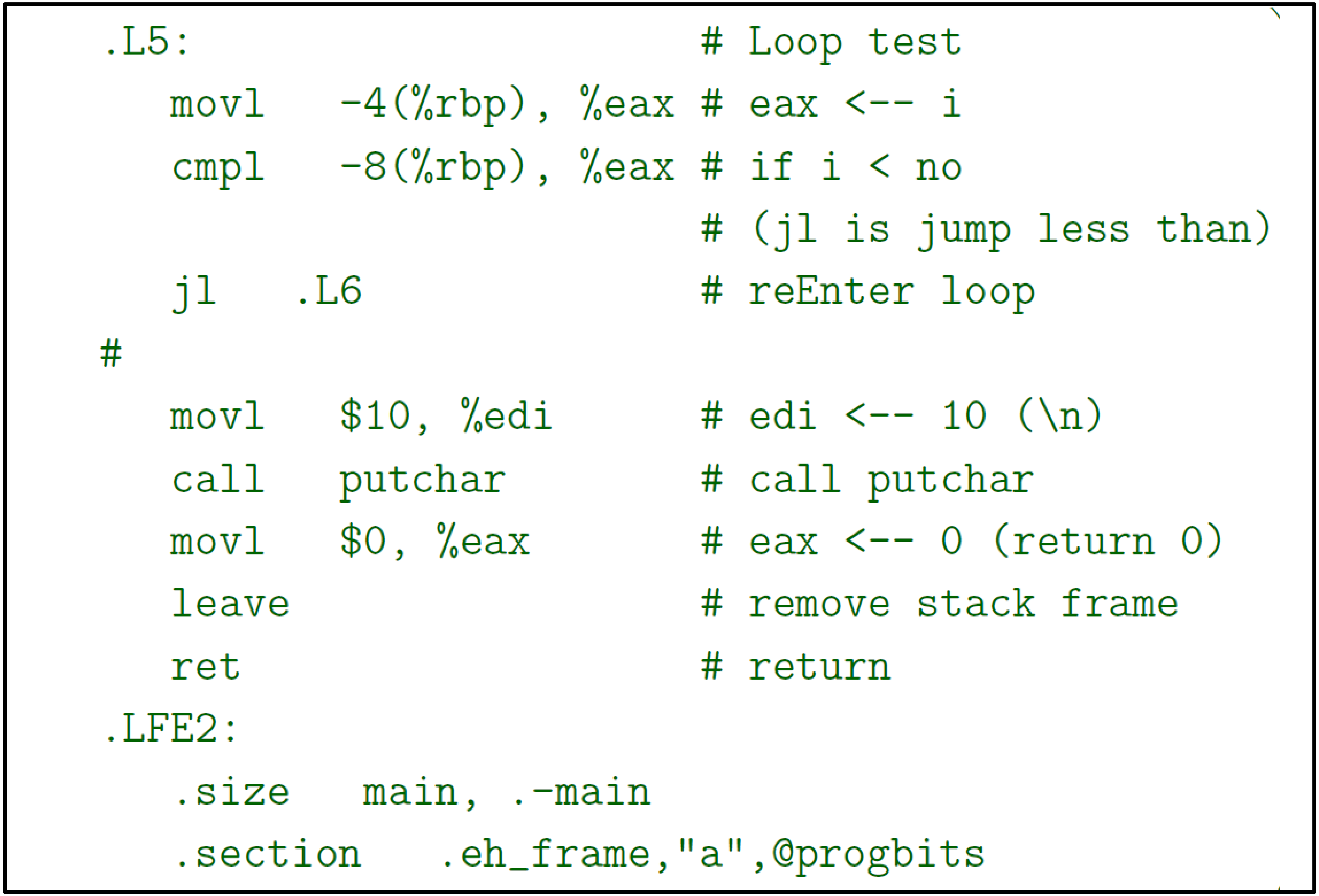
Assembly Code

```
    movl    -8(%rbp), %esi  # esi <-- no
                            #  2nd parameter
    leaq    -416(%rbp), %rdi  # rdi <-- data
                            #  1st parameter
    call    selectionSort   # call selectionSort
#
    movl    $.LC2, %edi     # edi <-- starting address
                            #  of printf format string
                            #  1st parameter
    movl    $0, %eax        # eax <-- 0 (?)
    call    printf          # Call printf (2nd call)
    movl    $0, -4(%rbp)    # M[rbp-4] <-- 0,
                            #  i <-- 0
```

Assembly Code

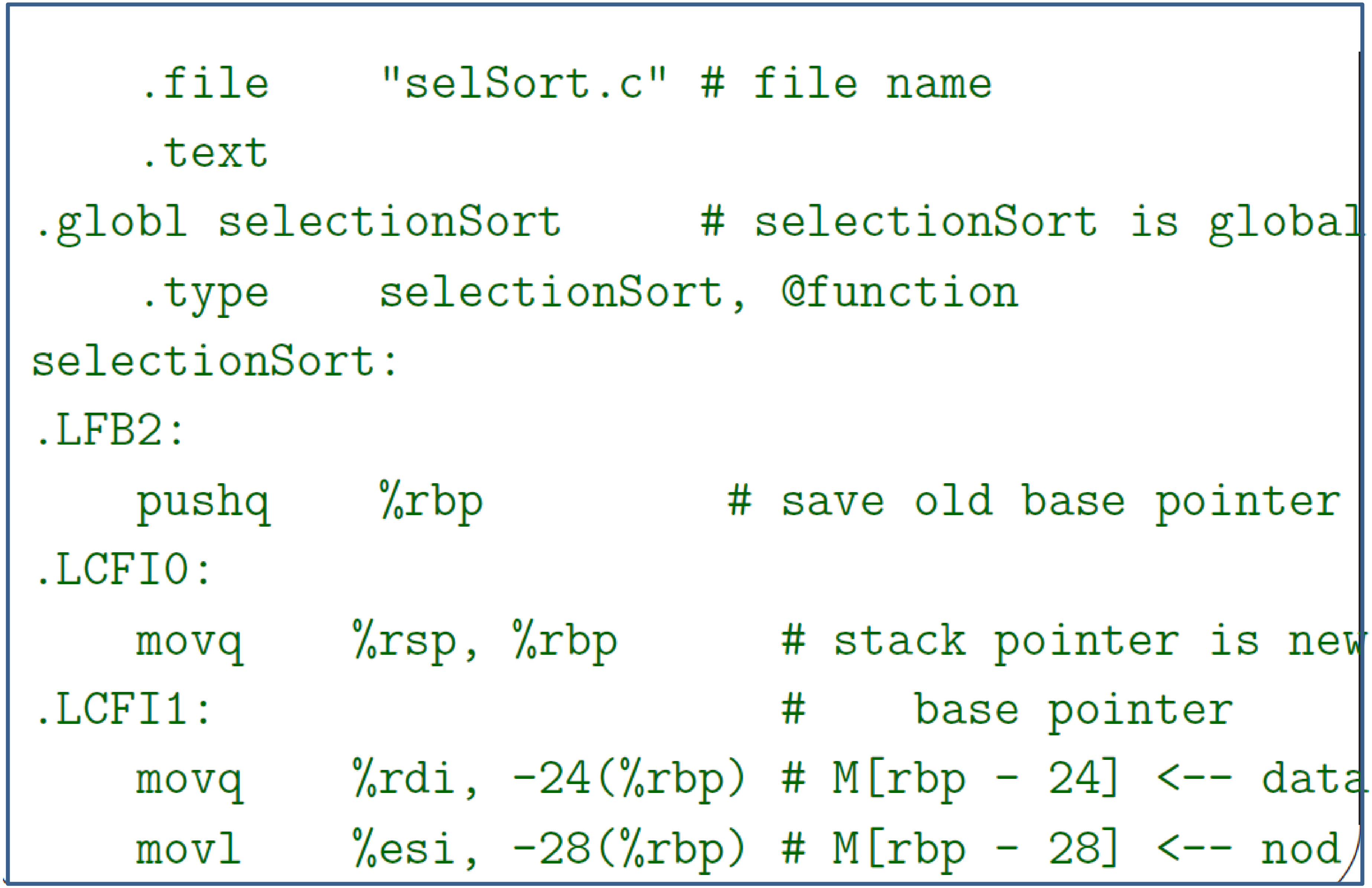
```
   jmp    .L5             # Goto loop test
#
.L6:
   movl   -4(%rbp), %eax # eax <-- i
   cltq                   # rax <-- signExt(eax)
   movl   -416(%rbp,%rax,4), %esi # esi <--
                          #  Mem[(rbp - 416)+4*rax]
                          #  esi <-- data[i], 2nd par.
   movl   $.LC3, %edi     # edi <-- addr, of format str
                          #   1st parameter
   movl   $0, %eax        # eax <-- 0
   call   printf          # Call printf
   addl   $1, -4(%rbp)    # i <-- i+1
```

Assembly Code



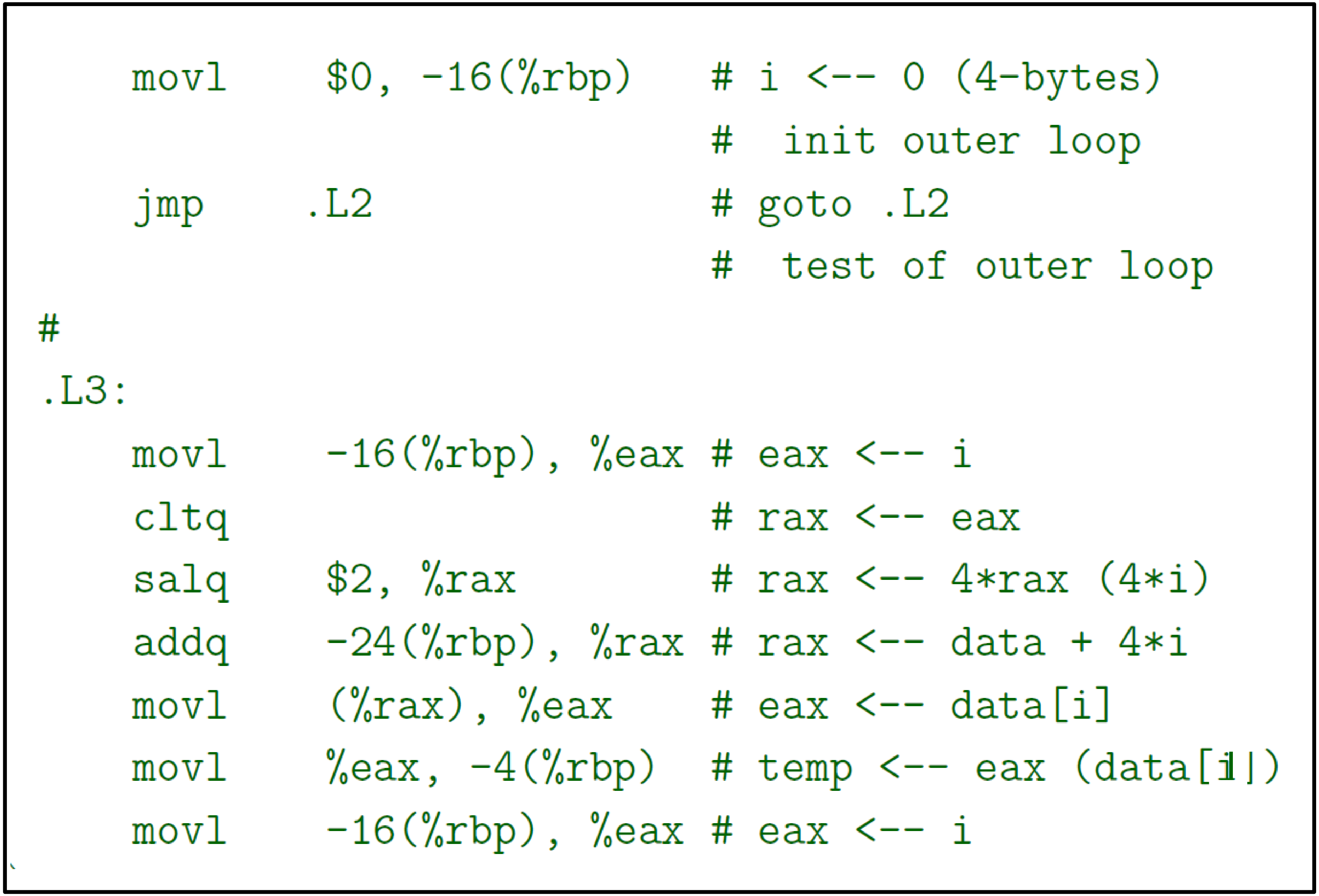
```
.L5:                     # Loop test
   movl   -4(%rbp), %eax # eax <-- i
   cmpl   -8(%rbp), %eax # if i < no
                         # (jl is jump less than)
   jl   .L6              # reEnter loop
#
   movl   $10, %edi      # edi <-- 10 (\n)
   call   putchar        # call putchar
   movl   $0, %eax       # eax <-- 0 (return 0)
   leave                 # remove stack frame
   ret                   # return
.LFE2:
   .size   main, .-main
   .section   .eh_frame,"a",@progbits
```

Assembly Code



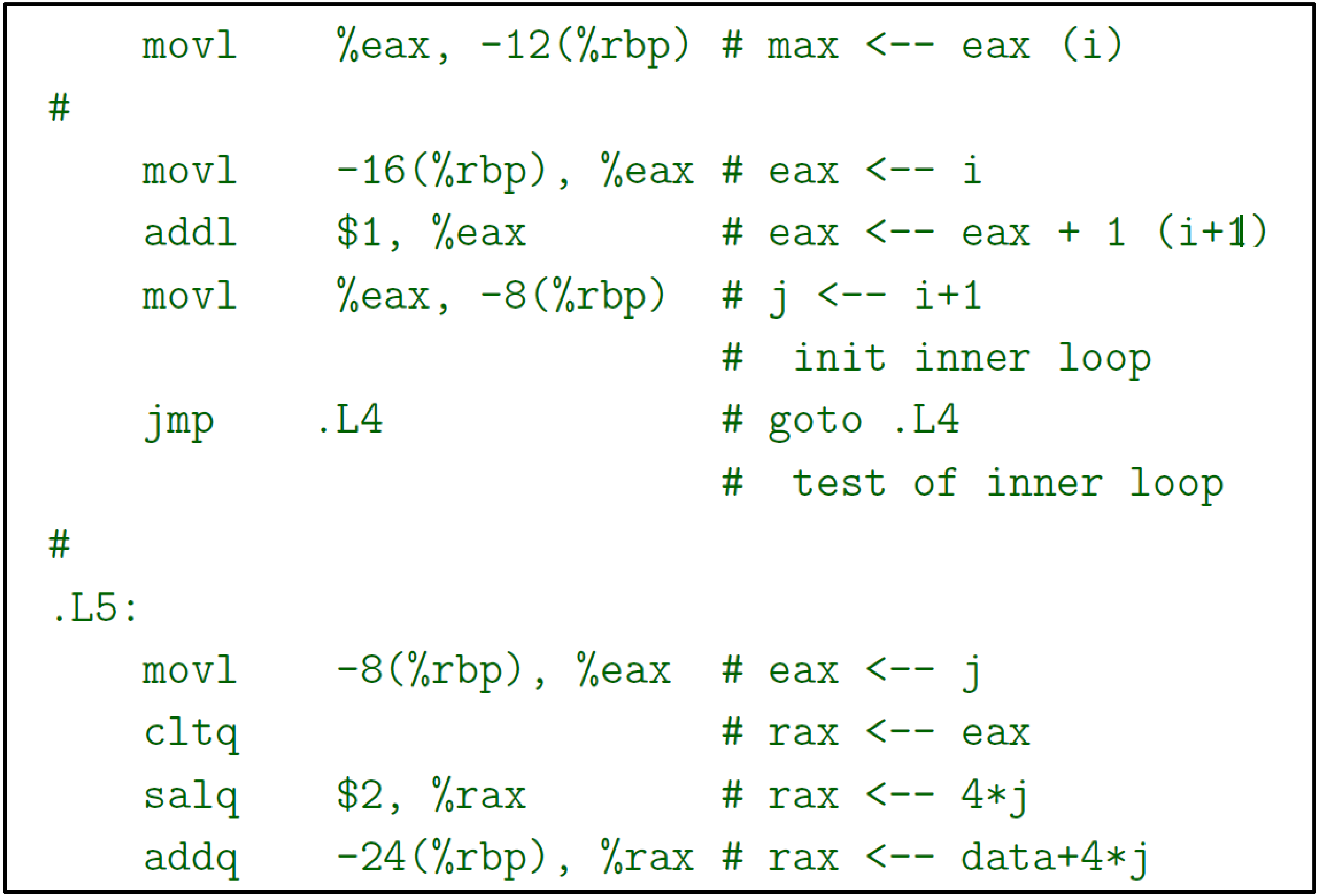
```
    .file    "selSort.c" # file name
    .text
.globl selectionSort     # selectionSort is global
    .type    selectionSort, @function
selectionSort:
.LFB2:
    pushq    %rbp         # save old base pointer
.LCFI0:
    movq    %rsp, %rbp      # stack pointer is new
.LCFI1:                     #    base pointer
    movq    %rdi, -24(%rbp) # M[rbp - 24] <-- data
    movl    %esi, -28(%rbp) # M[rbp - 28] <-- nod
```

Assembly Code



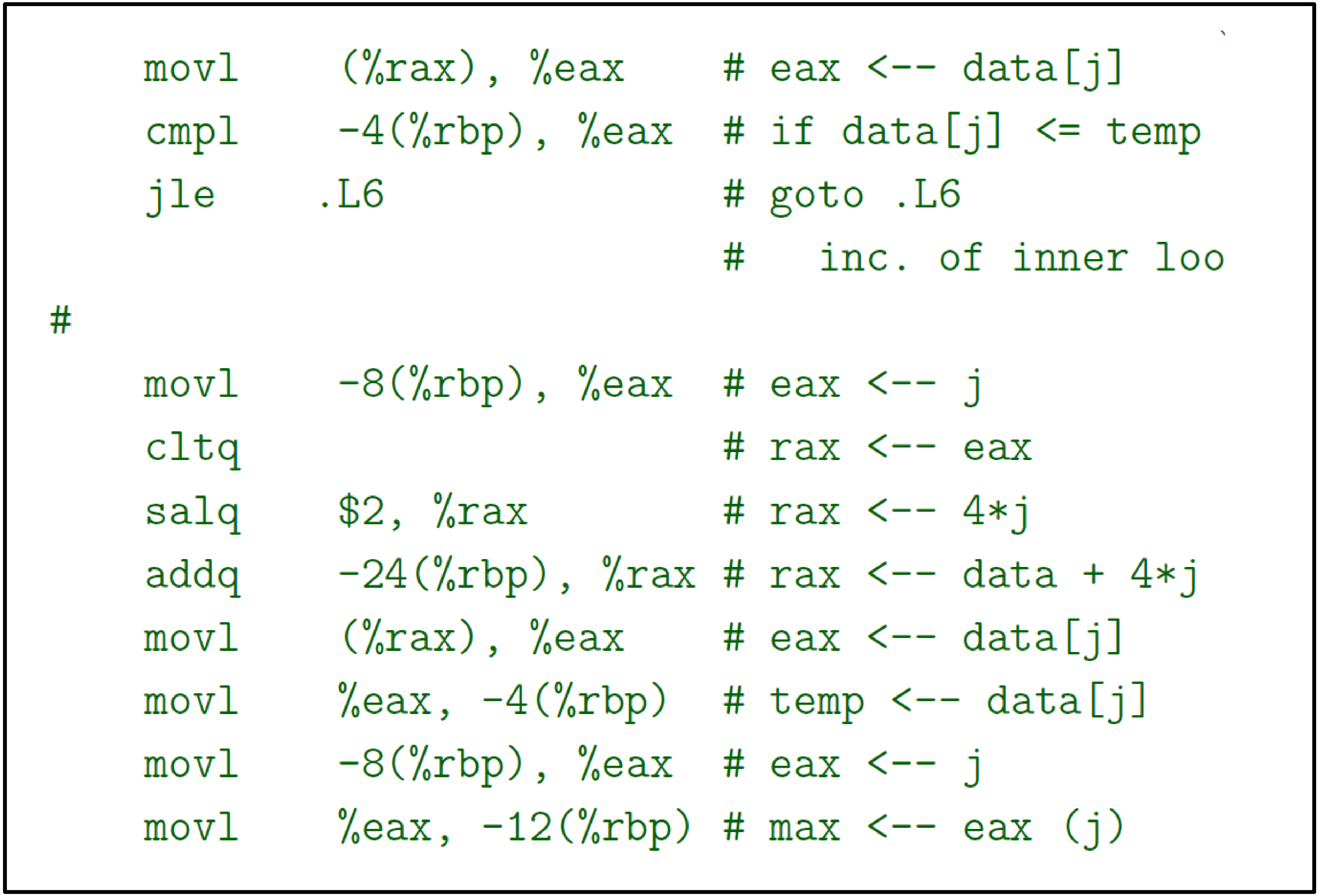
```
    movl    $0, -16(%rbp)    # i <-- 0 (4-bytes)
                             #  init outer loop
    jmp    .L2               # goto .L2
                             #  test of outer loop
#
.L3:
    movl    -16(%rbp), %eax # eax <-- i
    cltq                     # rax <-- eax
    salq    $2, %rax         # rax <-- 4*rax (4*i)
    addq    -24(%rbp), %rax # rax <-- data + 4*i
    movl    (%rax), %eax     # eax <-- data[i]
    movl    %eax, -4(%rbp)   # temp <-- eax (data[i])
    movl    -16(%rbp), %eax # eax <-- i
```

Assembly Code



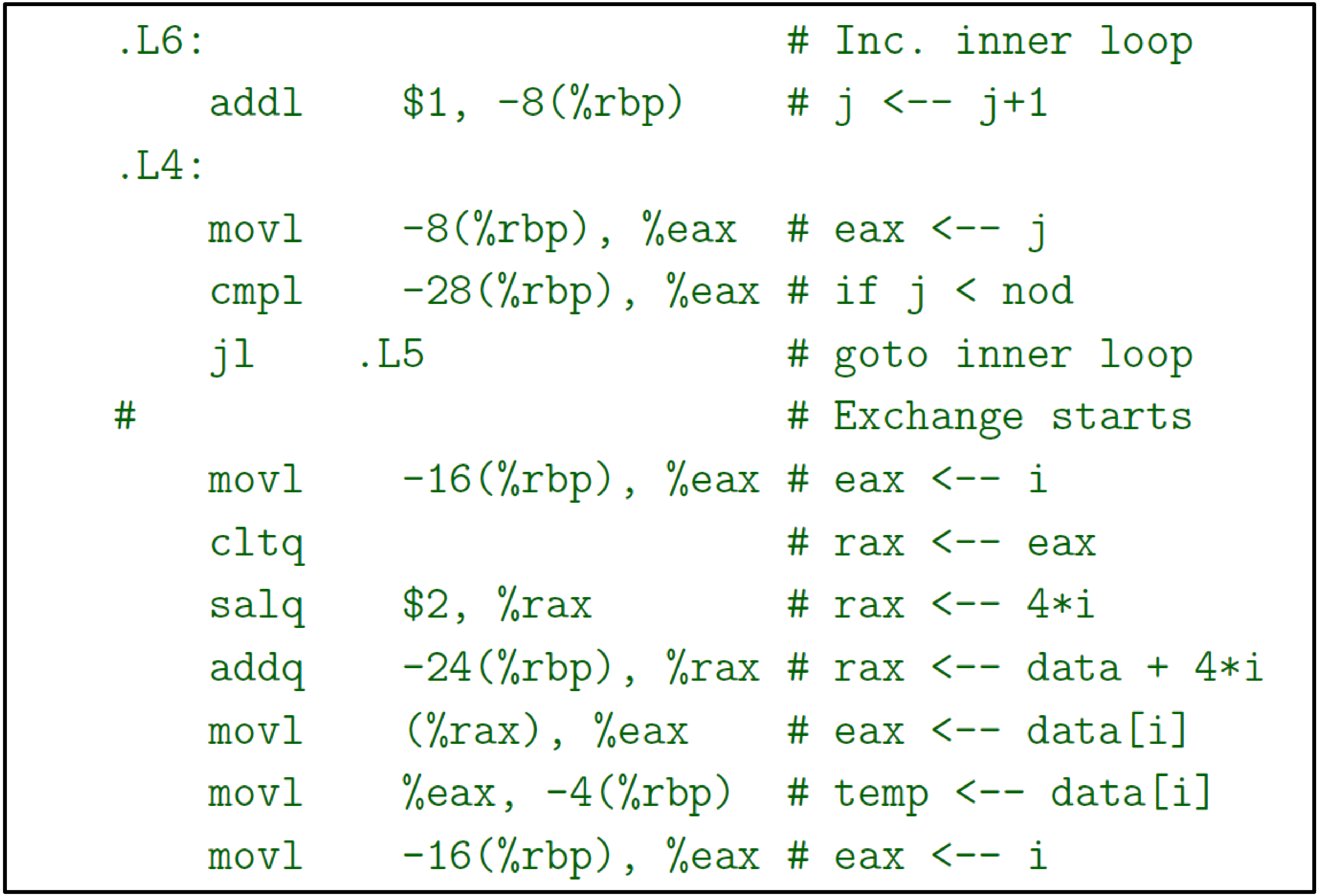
```
    movl    %eax, -12(%rbp) # max <-- eax (i)
#
    movl    -16(%rbp), %eax # eax <-- i
    addl    $1, %eax        # eax <-- eax + 1 (i+1)
    movl    %eax, -8(%rbp)  # j <-- i+1
                            #  init inner loop
    jmp    .L4              # goto .L4
                            #  test of inner loop
#
.L5:
    movl    -8(%rbp), %eax  # eax <-- j
    cltq                    # rax <-- eax
    salq    $2, %rax        # rax <-- 4*j
    addq    -24(%rbp), %rax # rax <-- data+4*j
```

Assembly Code



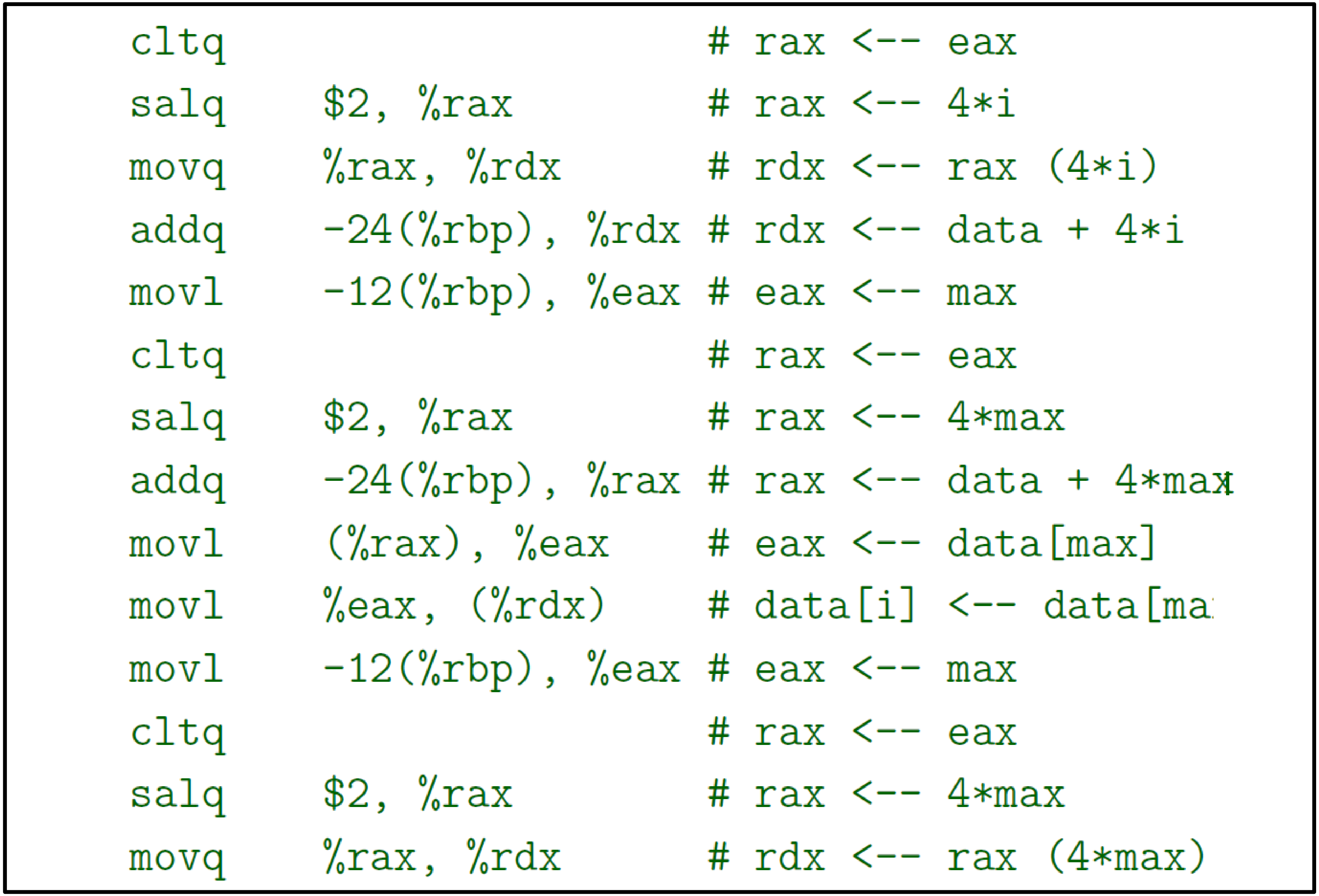
```
    movl    (%rax), %eax      # eax <-- data[j]
    cmpl    -4(%rbp), %eax    # if data[j] <= temp
    jle    .L6                # goto .L6
                              #   inc. of inner loo
#
    movl    -8(%rbp), %eax    # eax <-- j
    cltq                      # rax <-- eax
    salq    $2, %rax          # rax <-- 4*j
    addq    -24(%rbp), %rax   # rax <-- data + 4*j
    movl    (%rax), %eax      # eax <-- data[j]
    movl    %eax, -4(%rbp)    # temp <-- data[j]
    movl    -8(%rbp), %eax    # eax <-- j
    movl    %eax, -12(%rbp)   # max <-- eax (j)
```

Assembly Code



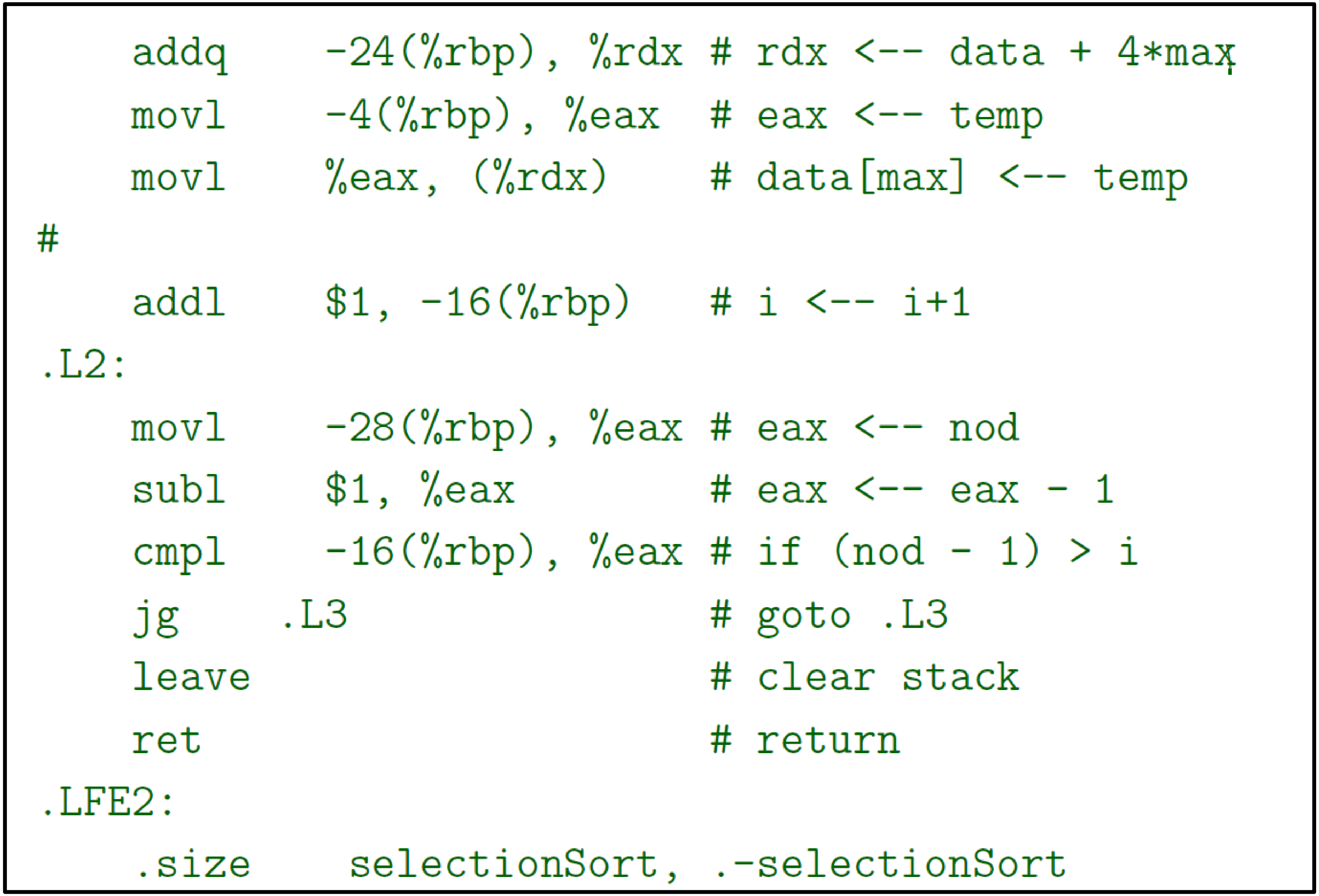
```
.L6:                                # Inc. inner loop
        addl    $1, -8(%rbp)        # j <-- j+1
.L4:
        movl    -8(%rbp), %eax      # eax <-- j
        cmpl    -28(%rbp), %eax     # if j < nod
        jl     .L5                  # goto inner loop
#                                   # Exchange starts
        movl    -16(%rbp), %eax     # eax <-- i
        cltq                        # rax <-- eax
        salq    $2, %rax            # rax <-- 4*i
        addq    -24(%rbp), %rax     # rax <-- data + 4*i
        movl    (%rax), %eax        # eax <-- data[i]
        movl    %eax, -4(%rbp)      # temp <-- data[i]
        movl    -16(%rbp), %eax     # eax <-- i
```

Assembly Code



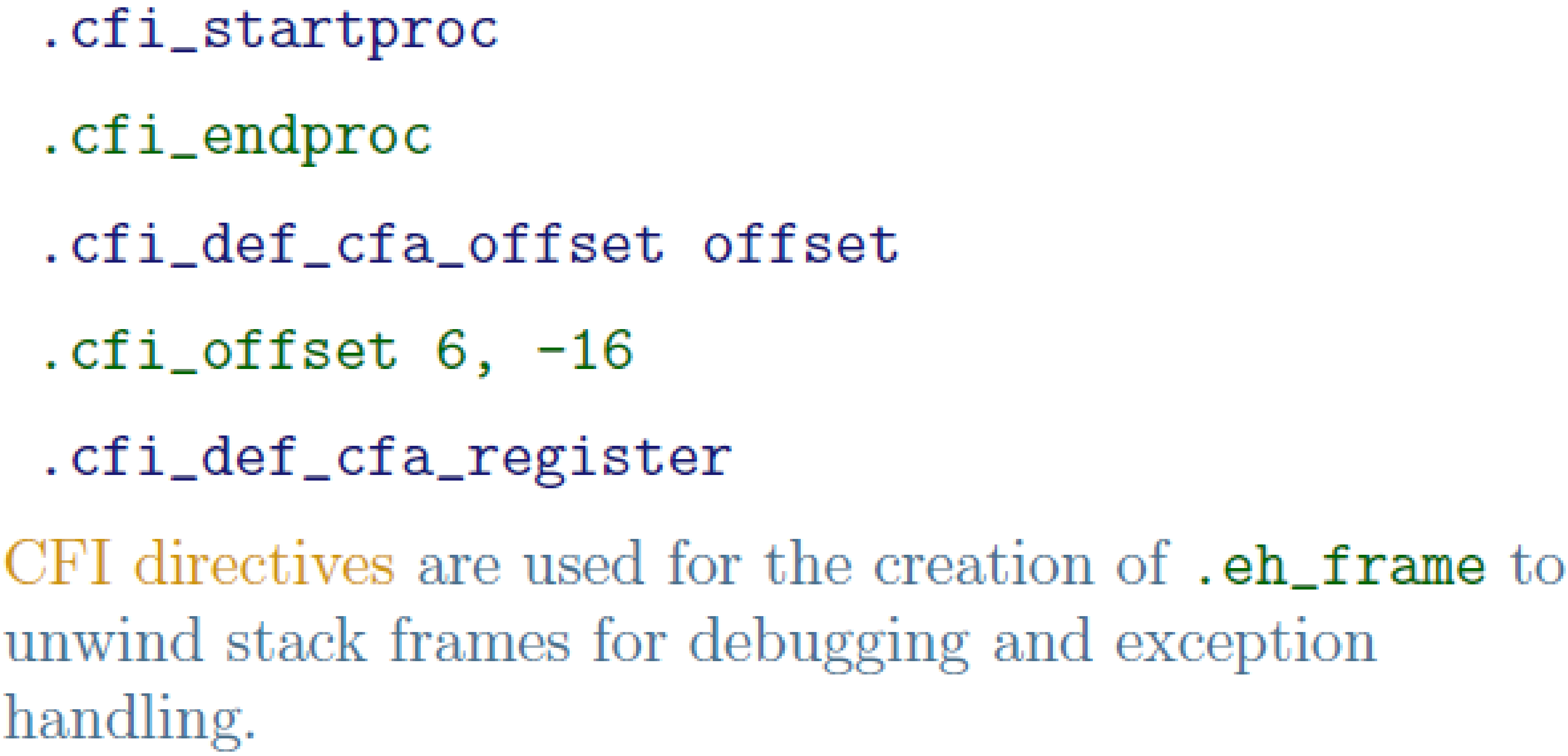
```
cltq                        # rax <-- eax
salq     $2, %rax           # rax <-- 4*i
movq     %rax, %rdx         # rdx <-- rax (4*i)
addq     -24(%rbp), %rdx    # rdx <-- data + 4*i
movl     -12(%rbp), %eax    # eax <-- max
cltq                        # rax <-- eax
salq     $2, %rax           # rax <-- 4*max
addq     -24(%rbp), %rax    # rax <-- data + 4*max
movl     (%rax), %eax       # eax <-- data[max]
movl     %eax, (%rdx)       # data[i] <-- data[ma
movl     -12(%rbp), %eax    # eax <-- max
cltq                        # rax <-- eax
salq     $2, %rax           # rax <-- 4*max
movq     %rax, %rdx         # rdx <-- rax (4*max)
```

Assembly Code



```
    addq    -24(%rbp), %rdx # rdx <-- data + 4*max
    movl    -4(%rbp), %eax  # eax <-- temp
    movl    %eax, (%rdx)    # data[max] <-- temp
#
    addl    $1, -16(%rbp)   # i <-- i+1
.L2:
    movl    -28(%rbp), %eax # eax <-- nod
    subl    $1, %eax        # eax <-- eax - 1
    cmpl    -16(%rbp), %eax # if (nod - 1) > i
    jg    .L3               # goto .L3
    leave                   # clear stack
    ret                     # return
.LFE2:
    .size    selectionSort, .-selectionSort
```

No Discussion on CFI Directives



```
.cfi_startproc

.cfi_endproc

.cfi_def_cfa_offset offset

.cfi_offset 6, -16

.cfi_def_cfa_register
```

CFI directives are used for the creation of `.eh_frame` to unwind stack frames for debugging and exception handling.