Compilers Laboratory (CS39003)

Autumn 2022

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++

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

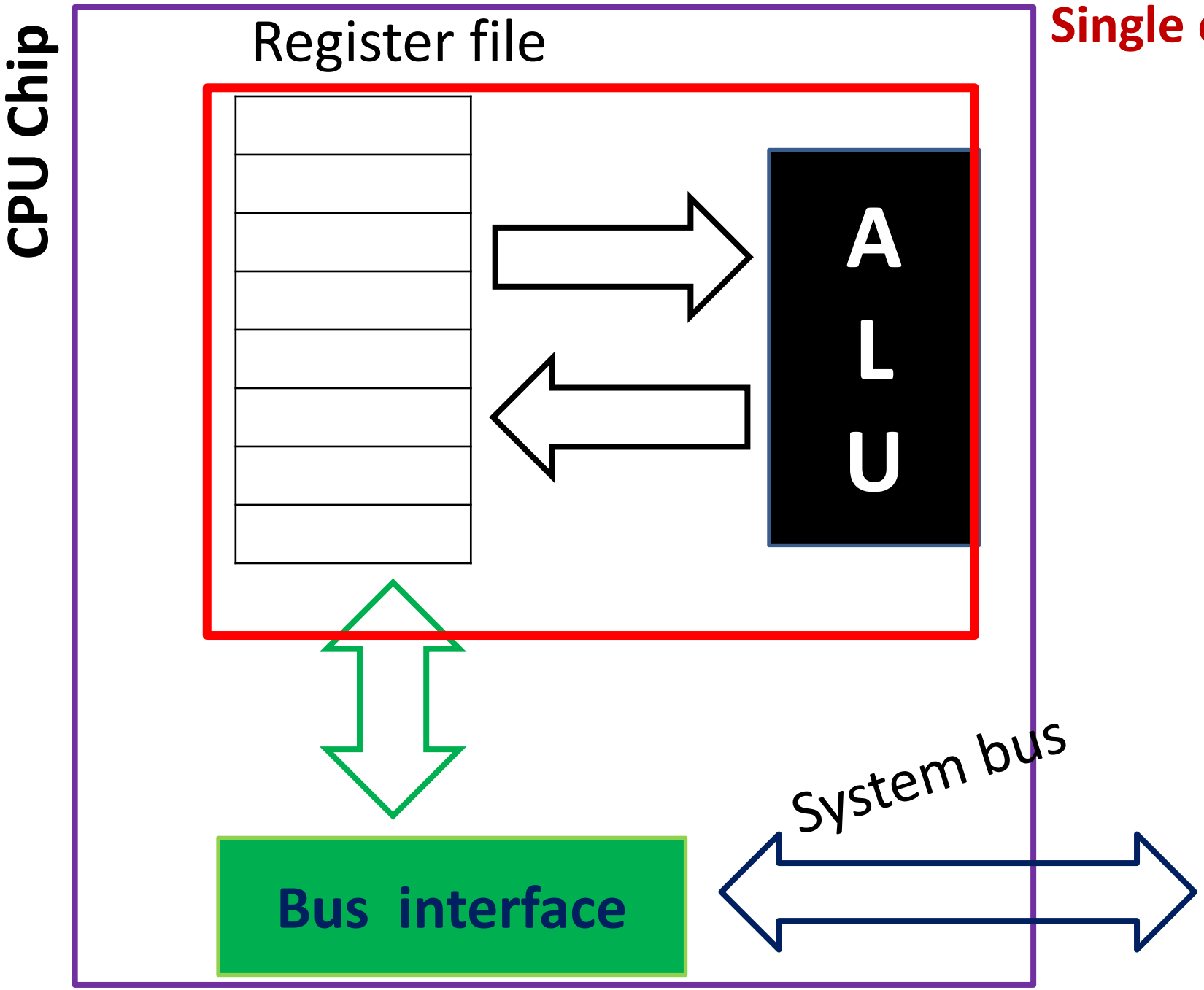
System

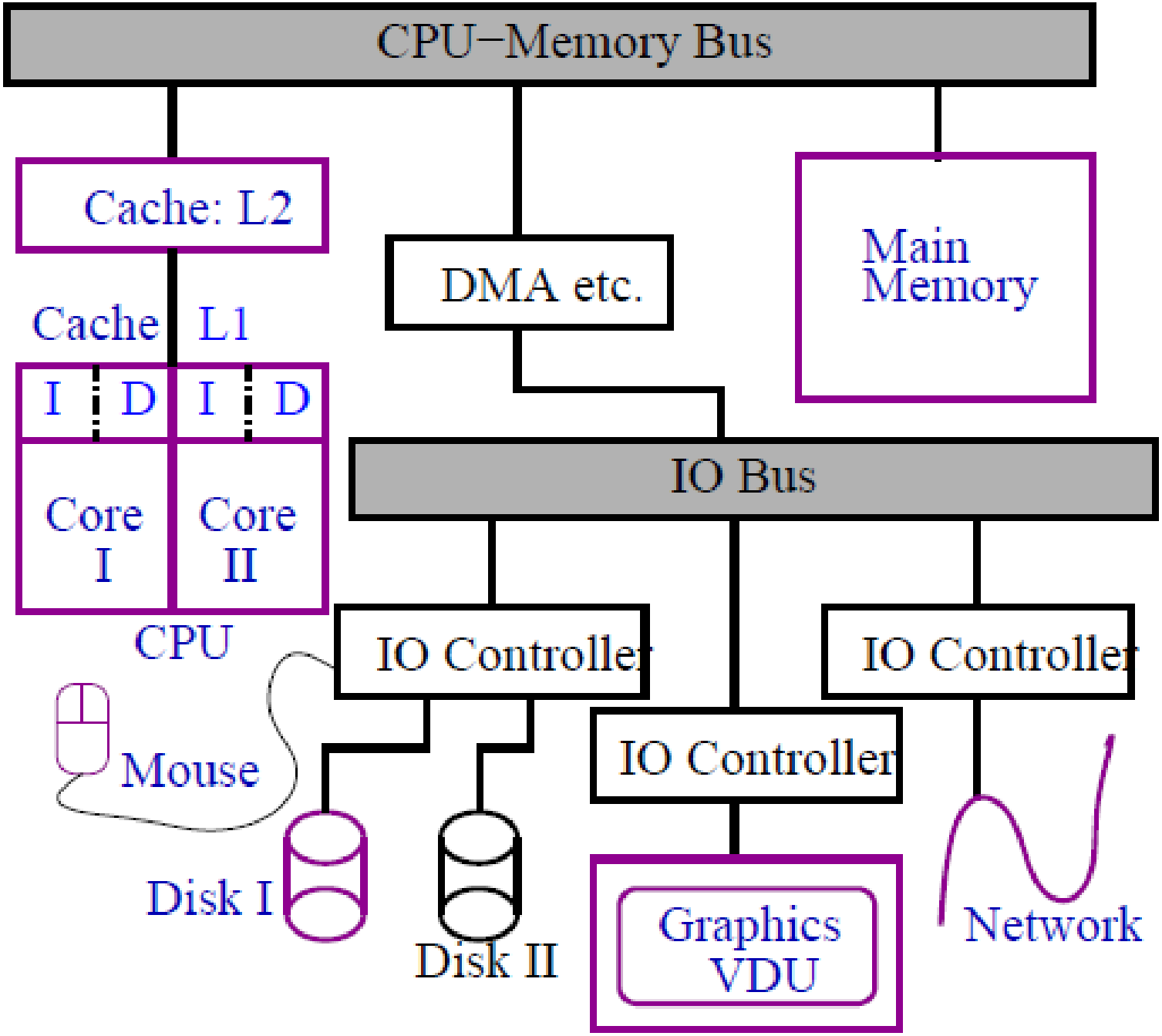
Main Memory Address

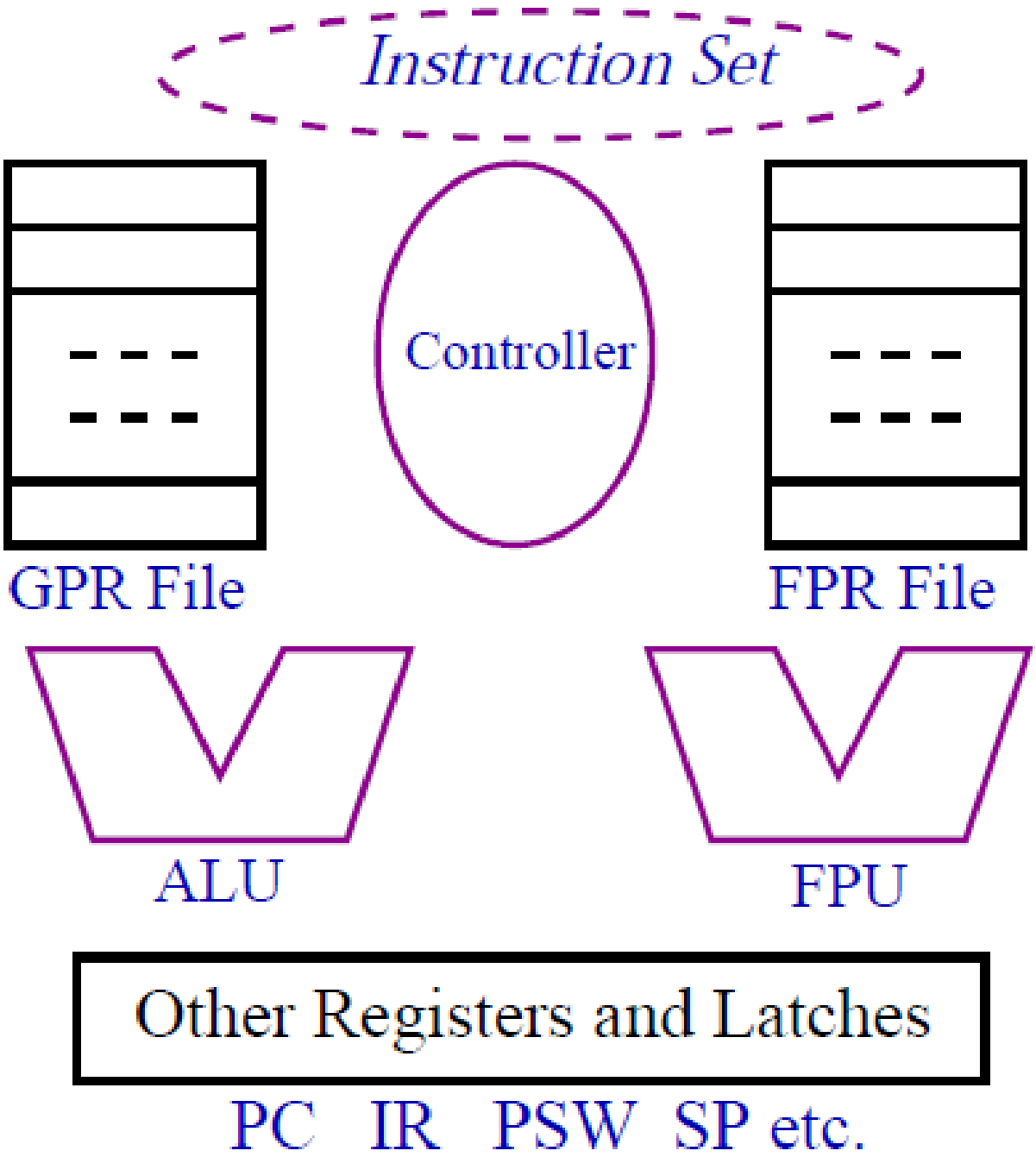
Address: 36 bits physical, 48 bits virtual/logical

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.


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


CPU–Memory Bus
Cache: L2
Cache L1
I D I D
Core I
Core II
CPU
DMA etc.
Main Memory
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

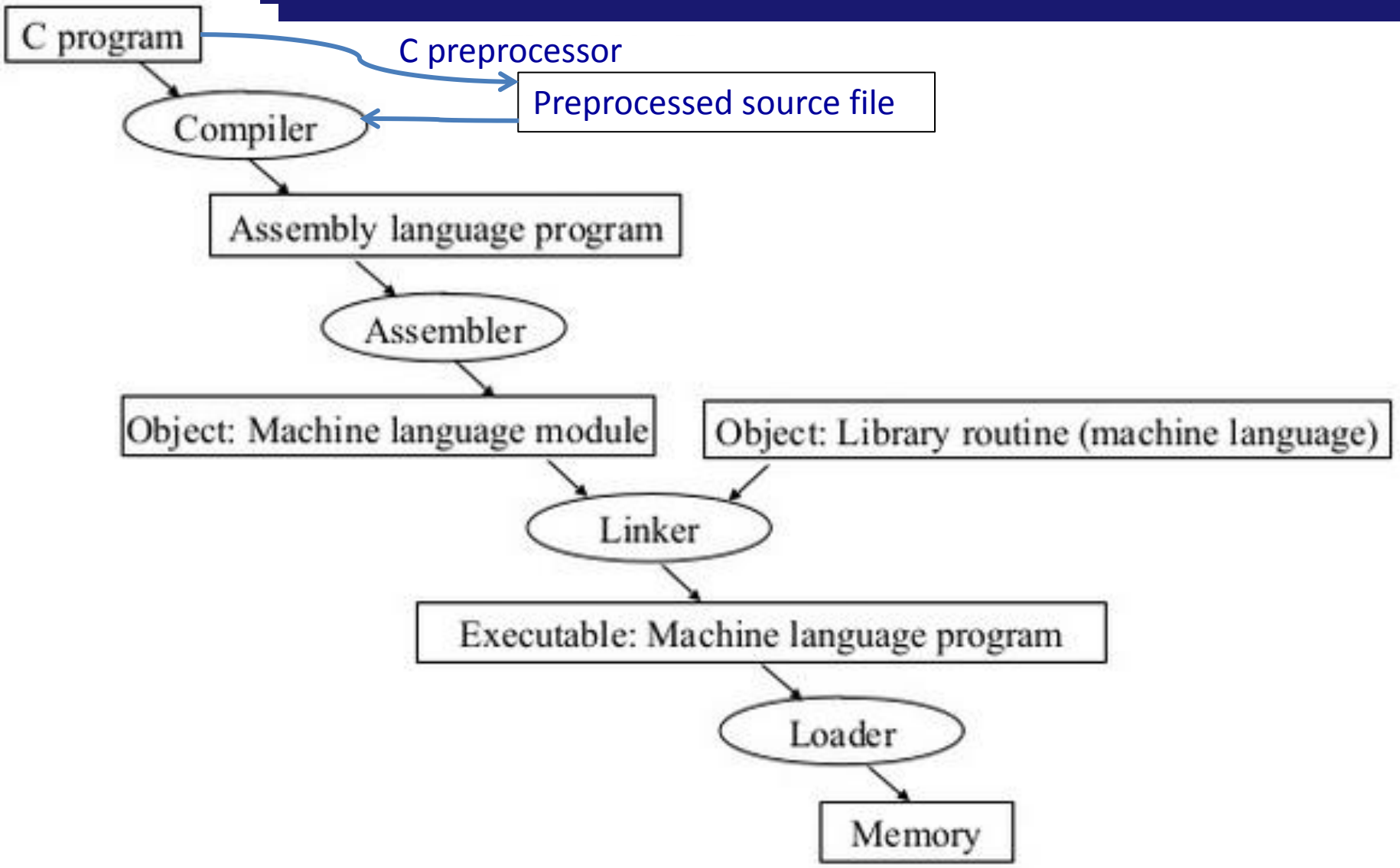
GPR (64-bit)	Usage Convention
rax	Return value from a function
rbx	Callee saved
rcx	4th argument to a function
rdx	3rd argument to a function Return value from a function
rsi	2nd argument to a function
rdi	1st argument to a function
rbp	Callee saved

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



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

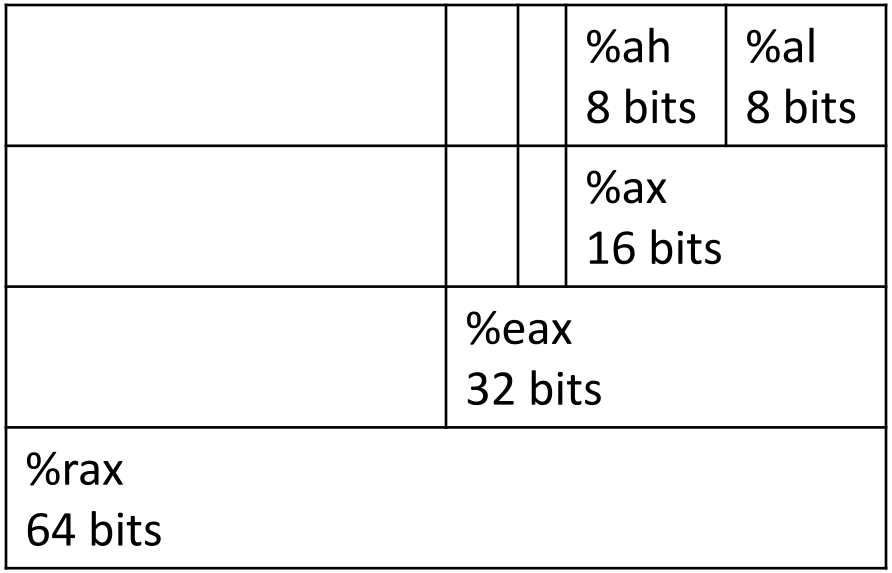
$ cc -Wall -S computePI.c → computePI.s

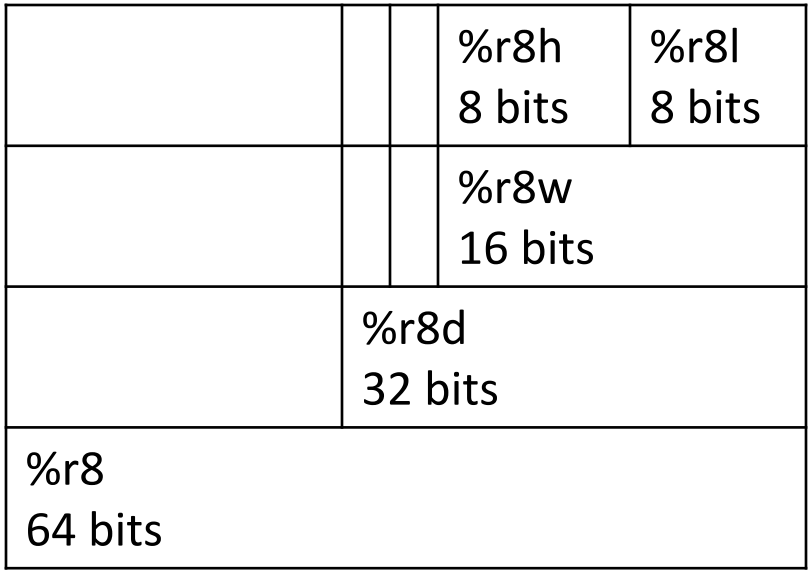
$ cc -Wall -c computePI.c → computePI.o

$ 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)





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

```
cvtsi2sd   -20(%rbp), %xmm0
addsd      %xmm0, %xmm0
movsd      .LC3(%rip), %xmm2
addsd      %xmm2, %xmm0
mulsd      %xmm0, %xmm1
cvtsi2sd   -20(%rbp), %xmm0
addsd      %xmm0, %xmm0
movsd      .LC4(%rip), %xmm2
addsd      %xmm2, %xmm0
mulsd      %xmm1, %xmm0
movsd      .LC5(%rip), %xmm1
movapd     %xmm1, %xmm2
divsd      %xmm0, %xmm2
movapd     %xmm2, %xmm0
mulsd      -8(%rbp), %xmm0
movsd      -16(%rbp), %xmm1
addsd      %xmm1, %xmm0
movsd      %xmm0, -16(%rbp)
movsd      -8(%rbp), %xmm1
movsd      .LC6(%rip), %xmm0
xorpd      %xmm1, %xmm0
```

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 program

```
#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

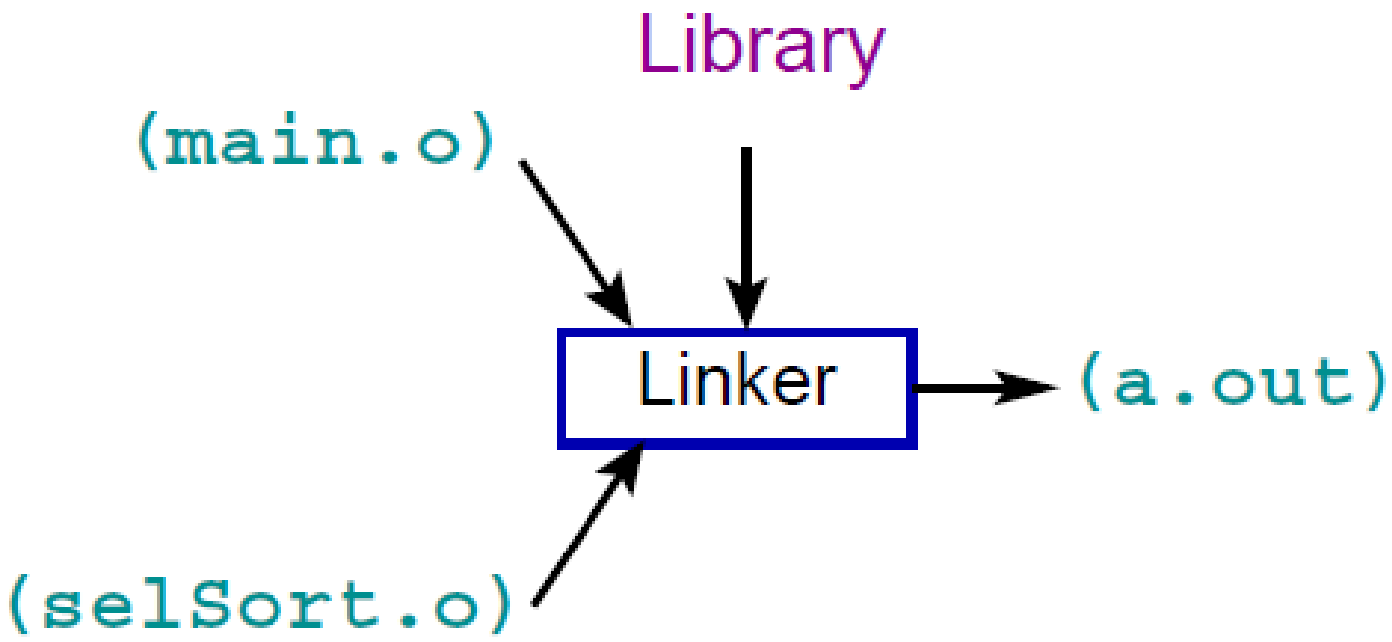
$ cc -Wall -c main.c → main.o

$ 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[no])
                        #   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.