Week 5. Linking, Loading and Code Optimization

18-342: Fundamentals of Embedded Systems

Rajeev Gandhi
INI & ECE
Carnegie Mellon University

Carnegie Mellon

Electrical & Computer ENGINEERING

Overview of this Week

- Linking and Loading
  - Statically linked executable
  - Dynamically linked executable
- ELF File Format
- Code Optimization
  - Processor independent code optimization techniques
  - ARM specific code optimization techniques
- Announcement:
  - Quiz next Thursday
  - Same policies as Quiz 1
  - Syllabus will include everything covered up to next Tuesday's lecture from Friday's lecture after Quiz 1

Linkers

- Compilers and assemblers generate re-locatable object files
  - References to external symbols are not resolved
  - Compilers generate object files in which code starts at address 0
  - Cannot execute a compiler produced object file
- Executable files are created from individual object files and libraries through the linking process
- Linker performs two tasks
  - Symbol resolution: Object files define and reference symbols, linker tries to resolve each symbol reference with one symbol definition
  - Relocation: Linker tries to relocate code and data from different object files so that different sections start at different addresses and all the references are updated

Example: Compiling `main.c` and `square.c`

main.c

```
int counter=3;
int tmp;
static int sum(int x,
int y);
extern int square(int
x);

int main()
{
        int x=5, y=10;
        int a, b;
        tmp=sum(x,y);
        a=square(x);
        b=square(y);
        tmp=sum(a,b);
        return;
}

int sum(int x, int y)
{
        int result;
        result=x+y;
        return result;
}
```

compiler

main.o

```
00000000 <sum>:
 0:  add    r0, r0, r1          ; sum=x+y
 4:  bx     lr                  ; return
00000008 <main>:
 8:   push  {r4, r5, lr}        ;save registers
 c:   sub   sp, sp, #4          ; sp <- sp- 0x4
 10:  mov   r0, #5  ; 0x5       ; x=5;
 14:  mov   r1, #10 ; 0xa       ; y=10
 18:  bl    0 <sum>             ; compute sum(x,y)
 1c : ldr   r5, [pc, #48]       ; r5 <= &tmp (54)
 20:  str   r0, [r5]            ; tmp=r0=sum(x,y)
 24:  mov   r0, #5              ; x=5;
 28:  bl    0 <square>          ; compute  square(5)
 2c:  mov   r4, r0              ; r4=r0= 25;
 30:  mov   r0, #10 ; 0xa       ; r0=10;
 34:  bl    0 <square>          ; compute  square(10)
 38:  mov   r1, r0              ; r1=100;
 3c:  mov   r0, r4              ; r0=r4=25
 40:  bl    0 <sum>             ; compute sum(25, 100)
 44:  str   r0, [r5]            ; tmp = r0 = 125;
 48:  add   sp, sp, #4          ; sp <= sp + 4
 4c:  pop   {r4, r5, lr}        ; restore registers
 50:  bx    lr                  ; jump back
 54:  .word  0x00000000

00000000 <counter>:
 0:   .word  0x00000003     ; address 0x00 of data
section contains 3
```

square.c

```
extern int counter;
int square(int x)
{
  int result;
  if(counter >= 0)
      result=x*x;
  else
      result=0;
  counter--;
  return result;
}
```

compiler

square

```
0:   ldr    r3, [pc, #32]   ; 28 <square
+0x28>
 4:  ldr    r2, [r3]
 8:  cmp    r2, #0  ; 0x0
 c:  movlt  r0, #0  ; 0x0
 10: mulge  r3, r0, r0
 14: movge  r0, r3
 18: sub    r2, r2, #1      ; 0x1
 1c: ldr    r3, [pc, #4]    ; 28 <square
+0x28>
 20: str    r2, [r3]
 24: bx     lr
 28: 00000000       .word
0x00000000
```

Example: After Linking `main.o` and `square.o`

```
00008338 <sum>:
  8338:   add   r0, r0, r1
  833c:   bx    lr
00008340 <main>:
  8340:   push  {r4, r5, lr}
  8344:   sub   sp, sp, #4     ; 0x4
  8348:   mov   r0, #5  ; 0x5
  834c:   mov   r1, #10 ; 0xa
  8350:   bl    8338 <sum>
  8354:   ldr   r5, [pc, #48]; r5 <= 0x0001056c = &tmp
  8358:   str   r0, [r5]       ; *0x0001056c = tmp = 15
  835c:   mov   r0, #5  ; 0x5
  8360:   bl    8390 <square>  ;
  8364:   mov   r4, r0
  8368:   mov   r0, #10 ; 0xa
  836c:   bl    8390 <square>
  8370:   mov   r1, r0
  8374:   mov   r0, r4
  8378:   bl    8338 <sum>
  837c:   str   r0, [r5]       ; *0x0001056c = tmp = 125
  8380:   add   sp, sp, #4     ;
  8384:   pop   {r4, r5, lr}
  8388:   bx    lr
  838c:   .word 0x0001056c
```

```
00008390 <square>:
  8390: ldr    r3, [pc, #32]   ; r3 = &counter (83b8)
  8394  ldr    r2, [r3]        ; r2 = counter
  8398 cmp     r2, #0  ; 0x0   ; counter > 0 ?
  839c: movlt  r0, #0  ; 0x0   ; if(counter < 0) then r0<=0x0
  83a0:   mulge  r3, r0, r0    ; else r3 = r0*r0
  83a4:   movge  r0, r3        ; else r0 = r3 =r0 * r0
  83a8:   sub    r2, r2, #1    ; counter--
  83ac:   ldr    r3, [pc, #4]  ; r3 = 0x00010564 = &counter (83b8)
  83b0:   str    r2, [r3]      ; counter = r2 = counter-1
  83b4:   bx     lr            ; return back
  83b8:   .word  0x00010564

00010564 <counter>:
  10564:   .word  0x00000003

.bss
0001056c <tmp>:
  1056c:   .word  0x00000000
```

linker adds the actual address of symbol *square*

linker relocates the code to a different memory location

Library Functions

- What happens when the source files use library functions like `printf`, `scanf`, etc.?
- Compiler produces a symbol (in the same way as the `square` function in the previous example) in the object file
- Linker
  - Attempts to resolve these references by matching them to definitions found in other object files
  - If the symbol is not resolved, the linker searches for the symbol definition in library files
- What are library files?
  - Collection of object files that provide related functionality
  - Example: The standard C library `libc.a` is a collection of object files `printf.o`, `scanf.o`, `fprintf.o`, `fscanf.o`…

Library Functions

- How does the linker know where to find the library?
  - User defined libraries can be specified as a command line argument
  - The environment variable LD_LIBRARY_PATH holds the path that is searched to find the specific library
- Linker does a search to see whether the symbol is defined in the specified libraries
  - The order in which this search is performed is determined by the order in which the libraries are specified
  - If the symbol is defined in more than 1 library, the first library in the path is selected
    - Linker then extracts the specific .o file that defines the symbol in the library and processes this .o file with all the other object files
  - If the symbol is not defined in any of the library, linker throws an error

Kinds of Linking Models

- Different kinds of linking models
  - ***Static:*** Set of object files, system libraries and library archives are statically bound, references are resolved, and a *self-contained executable file* is created
    - Problem: If multiple programs are running on the processor simultaneously, and they require some common library module (say, `printf.o`), multiple copies of this common module are included in the executable file and loaded into memory (waste of memory!)
  - ***Dynamic:*** Set of object files, libraries, system shared resources and other shared libraries are linked together to create an executable file
    - When this executable is loaded, *other shared resources and dynamic libraries must be made available* in the system for the program to run successfully
    - If multiple programs running on a processor need the same object module, only one copy of the module needs to be loaded in the memory

Dynamic Linking

- Dynamically linked executable or shared object undergoes final linking when
  - Loaded into memory by a program loader
- An executable or shared object to be linked dynamically might
  - List one or more shared objects (shared libraries) with which it should be linked
- Other advantages of dynamic linking
  - Updating of libraries
- The size on disk of an executable that uses dynamically linked modules may be less than its size in memory (during run-time)
  - Why?

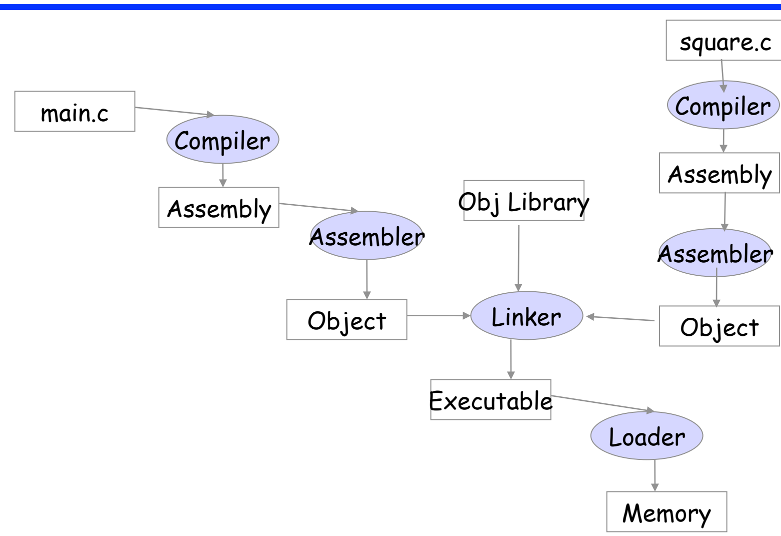
Kinds of Object Files

- Three main types of object files
  - **Re-locatable file**: Code and data suitable for linking with other object files to create an executable or a shared object file
  - **Executable file**: Program suitable for execution
  - **Shared object file (also called "Dynamically linked library")**: Special type of re-locatable object file that can be loaded into memory and linked dynamically
    - First, the linker may process it with other re-locatable and shared object files to create another object file
    - Second, the dynamic linker combines it with an executable file and other shared objects to create a process image
- Compilers and assemblers generate re-locatable object files
- Linkers generate executable object files

Executable and Linking Format (ELF)

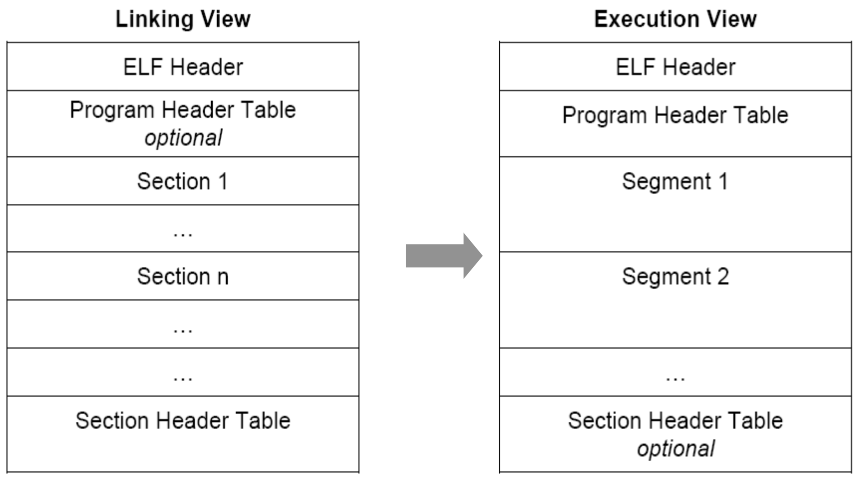
- Object files need to be in a specific format to facilitate linking and loading
- Executable and Linkable Format (ELF) is the popular format of an object file
- Supported by many vendors and tools
  - Diverse processors, multiple data encodings and multiple classes of machines
- ELF specifies the layout of the object files and not the contents of code or data
- ELF object files consist of
- ELF Header
  - Beginning of ELF file
  - Holds a road map of file's organization
  - How to interpret the file, independent of the processor
- Program header table
  - Tells the system how to create a process image
  - Files used to build a process image (execute a program) must have a program header table
  - Re-locatable files do not need one
- Sections

Program Translation

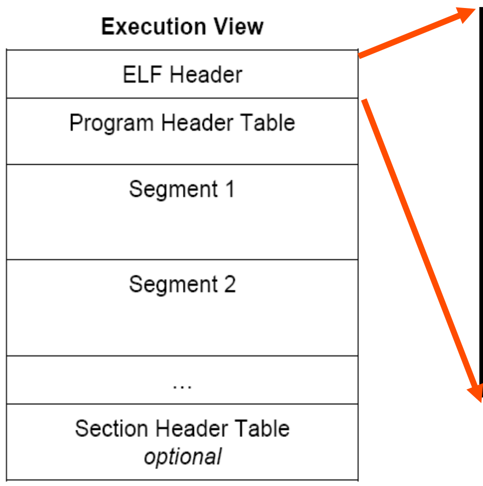


Source : D. Patterson,J. Hennessey *Computer Organization & Design*

Linking & Execution Views



ELF Execution View




```
typedef struct {
    unsigned char e_ident[EI_NIDENT];
    Elf32_Half e_type;
    Elf32_Half e_machine;
    Elf32_Word e_version;
    Elf32_Addr e_entry;
    Elf32_Off  e_phoff;
    Elf32_Off  e_shoff;
    Elf32_Word e_flags;
    Elf32_Half e_ehsize;
    Elf32_Half e_phentsize;
    Elf32_Half e_phnum;
    Elf32_Half e_shentsize;
    Elf32_Half e_shnum;
    Elf32_Half e_shstrndx;
} Elf32_Ehdr;
```

ELF Header

- All ELF files contain a header in the beginning of the file
  - Determines whether the file is an ELF file, whether it is in big/little endian format, the target processor, offsets to the program header table and/or section header table…
- Format of the ELF header

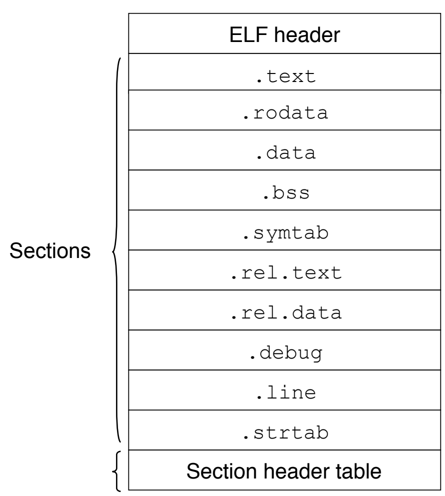
```
#define EI_NIDENT 16
typedef struct {
    unsigned char e_ident[EI_NIDENT];  // file info (object file or not)
    Elf32_Half e_type;       // type of file (relocatable, executable, etc.)
    Elf32_Half e_machine;    // target processor (Intel x86, ARM, SPARC etc.)
    Elf32_Word e_version;    /  version # (to allow for future versions of ELF)
    Elf32_Addr e_entry;      // program entry point (0 if no entry point)
    Elf32_Off  e_phoff;      // offset of program header (in bytes)
    Elf32_Off  e_shoff;      // offset of section header table
    Elf32_Word e_flags;      // processor-specific flags
    Elf32_Half e_ehsize;     // ELF header's size
    Elf32_Half e_phentsize;  // entry size in pgm header tbl
    Elf32_Half e_phnum;      // # of entries in pgm header
    Elf32_Half e_shentsize;  // entry size in sec header tbl
    Elf32_Half e_shnum;      // # of entries in sec header tbl
    Elf32_Half e_shstrndx;   // sec header tbl index of str tbl
} Elf32_Ehdr;
```

See Section 3.2 of ARM ELF Specification document

ELF Sections

Relocatable files must have a section header table

Locations and size of sections are described by the section header table

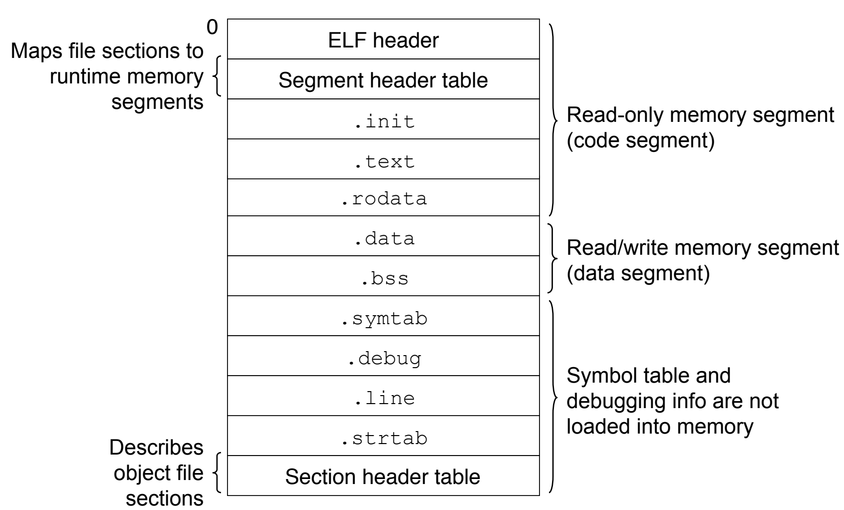


Source: "Computer Systems: A Programmer's Perspective", R. E. Bryant and D. O'Hallaron

Description of Various Sections

- `.text`: program instructions and literal data
- `.rodata`: Read-only data such as the format strings in printf statements
- `.data`: initialized global data
- `.bss`: un-initialized global data (set to zero when program image is created)
  - This section does not occupy any space in the object file
- `.symtab`: this section holds the symbol table information
  - All global variables and functions that are defined and referenced in the program
- `.rel.text`: list of locations in the `.text` section that will need to be modified when linker combines this object files with others
- `.rel.data`: relocation information for any global variables that are referenced or defined in a module
- `.debug`: debugging information (present only if code is compiled to produce debug information)
- `.line`: mapping between line numbers in C program and machine code instructions (present only if code is compiled to produce debug information)
- `.strtab`: string table for symbols defined in `.symtab` and `.debug` sections

Executable Object Files



Source: *"Computer Systems: A Programmer's Perspective", R. E. Bryant and D. O'Hallaron*

ELF Program Header

- Executable ELF files must have a program header table
  - The program header table is used to load the program (called "creating program image")
  - Each segment has its own entry in the program header table
    - e_*phnum* in ELF Header holds the number of program header entries
  - All program header entries have the same size (*e_phentsize* in ELF header)

- Program header entry for each segment

```
typedef struct {
    Elf32_Word p_type; //type of segment - loadable, dll,...
    Elf32_Off  p_offset;       //offset in bytes from the start of file
    Elf32_Addr p_vaddr;        //virtual address in memory of segment
    Elf32_Addr p_paddr;        //physical address in memory of segment
    Elf32_Word p_filesz;       //number of bytes in the file of the segment
    Elf32_Word p_memsz;        //number of bytes in memory of the process
                               //image of the segment
    Elf32_Word p_flags;        //indicates whether segment is executable
    Elf32_Word p_align;        //alignment information
} Elf32_Phdr;
```

- What happens if `p_memsz > p_filesz?`
  - The remaining bytes `(p_memsz-p_filesz)` are initialized with 0

Useful Tools

- You can use many command line tools to parse ELF files
- ARM provides `readelf` command line utility that can display information about an ELF file
  - You can disassemble ELF files, look at symbol table information, etc.
- Example: `readelf main.o`

  ** ELF Header Information
  File Name: main.c
  Machine class: ELFCLASS32 (32-bit)
  Data encoding: ELFDATA2MSB (Big endian)
  Header version: EV_CURRENT (Current version)
  File Type: ET_REL (Relocatable object) (1)
  Machine: EM_ARM (ARM)
  Header size: 52 bytes (0x34)
  Program header entry size: 32 bytes (0x20)
  Section header entry size: 40 bytes (0x28)
  Program header entries: 0
  Section header entries: 25
  Program header offset: 0 (0x00000000)
  Section header offset: 4512 (0x000011a0)
  …and more

Useful Tools (contd.)

- Look at the symbol table information in `main.o`
- Example: `nm main.o`

D (global, initialized, data)	counter
T (global text)	main
U (global undefined)	square
t (local, static, text)	sum
C (global, uninitialized)	tmp

- **You can also use other switches to print information on each segment, section, print relocation information …**

References

- Linking
  - How linking works
  - Static & Dynamic Linking
- Loading
  - ELF file format
  - Executable & Linking Format Header

  - References:
- Chapter 7 of "*Computer Systems: A Programmer's perspective*" by R. E. Bryant and D. R. O' Hallaron
  - Read sections 3.1, 3.2 and 3.7 of the *ARM ELF Specification* (on Blackboard in *Course Documents* ➔ *Manuals* folder)

Improving Program Performance

- Compiler writers try to apply several standard optimizations
  - Do **not** always succeed
  - Have to ensure that the program will produce the same output for *all* cases

```
void t1(int *x, int *y)
{
  *x+=*y;
  *x+=*y;
}
```

```
void t2(int *x, int *y)
{
        *x += ((*y)<<1);
}
```

Source: "Computer Systems: A Programmer's Perspective"

- Optimizations based on specific architecture/implementation characteristics can be very helpful

- How can one help?
  - Re-organize code to help compiler find opportunities for improvement

Processor Independent Compiler Optimizations (1)

- Common Sub-expression Elimination
  - Formally, "An occurrence of an expression E is called a *common sub-expression* if E was previously computed, and the values of variables in E have not changed since the previous computation."
  - You can avoid re-computing the expression if we can use the previously computed one.
  - **Benefit**: less code to be executed

Before

```
b:
        t6 = 4 * i
        x  = a[t6]
        t7 = 4 * i
        t8 = 4 * j
        t9 = a[t8]
        a[t7]  = t9
        t10    = 4 * j
        a[t10] = x
        goto b
```

After

```
b:
        t6 = 4* i
        x  = a[t6]
        t8 = 4 * j
        t9 = a[t8]
        a[t6] = t9
        a[t8] = x
        goto b
```

Processor Independent Compiler Optimizations (2)

- Dead-Code Elimination
  - If code is definitely *not* going to be executed during *any* run of a program, then it is called dead code and can be removed.
  - Example:

```
debug = 0;
...
if (debug){
   print .....
}
```

  - **You** can help by using `#ifdefs` to tell the compiler about dead code
    - It is often difficult for the compiler to identify dead code itself

Processor Independent Compiler Optimizations (3)

- Induction Variables and Strength Reduction
  - A variable X is called an *induction variable* of a loop L if every time the variable X changed value, it is incremented or decremented by some constant
  - When there are 2 or more induction variables in a loop, it may be possible to get rid of all but one
  - It is also frequently possible to perform strength reduction on induction variables
    - the strength of an instruction corresponds to its execution cost
  - Benefit: fewer and less expensive operations

```
    j = 0
label_XXX
    j  = j + 1
    t4 = 11 * j
    t5 = a[t4]
    if (t5 > v) goto label_XXX
```

Before

```
    t4 = 0
label_XXX
    t4 += 11
    t5 = a[t4]
    if (t5 > v) goto label_XXX
```

After

Processor Independent Compiler Optimizations (4)

- Loop Unrolling
  - Doing multiple iterations of work in each iteration is called "loop unrolling"
  - Benefit: reduction in looping overheads and opportunity for more code opts.
  - **Danger**: increased code size and *non-integral loop div*.
  - Appropriate when loops are small

```
int checksum(int *data, int N)
{
        int i, sum=0;
        for(i=0;i<N;i++)
        {
               sum += *data++;
        }
        return sum;
}
```

Before loop unrolling

```
int checksum(int *data, int N)
{
     int i, sum=0;
     for(i=0;i<N;i+=4)
     {
        sum += *data++;
        sum += *data++;
        sum += *data++;
        sum += *data++;
     }
     return sum;
}
```

Loop is unrolled 4 times

After unrolling the loop

Processor Independent Compiler Optimizations (4)

```
int checksum(int *data, int N)
{
        int i, sum=0;
        for(i=0;i<N;i++)
        {
               sum += *data++;
        }
        return sum;
}
```

```
0x00:    MOV      r3,#0        ; sum =0
0x04:    MOV      r2,#0        ; i= 0
0x08:    CMP      r2,r1        ; (i < N) ?
0x0c:    BGE      0x20         ; go to 0x20 if i >= N
0x10:    LDR      r12,[r0],#4  ; r12 <- data++
0x14:    ADD      r3,r12,r3    ; sum = sum + r12
0x18:    ADD      r2,r2,#1     ; i=i+1
0x1c:    B        0x8          ; jmp to 0x08
0x20:    MOV      r0,r3        ; sum = r3
0x24:    MOV      pc,r14       ; return
```

Loop Unrolling

Original loop

```
0x00:   MOV     r3,#0        ; sum =0
0x04:   MOV     r2,#0        ; i= 0
0x08:   CMP     r2,r1        ; (i < N) ?
0x0c:   BGE     0x20         ; go to 0x20 if i >= N
0x10:   LDR     r12,[r0],#4  ; r12 <- data++
0x14:   ADD     r3,r12,r3    ; sum = sum + r12
0x18:   ADD     r2,r2,#1     ; i=i+1
0x1c:   B       0x8          ; jmp to 0x08
0x20:   MOV     r0,r3        ; sum = r3
0x24:   MOV     pc,r14       ; return
```

loop overhead computed N times

After unrolling the loop 4 times

```
0x00:   MOV     r3,#0        ; sum = 0
0x04:   MOV     r2,#0        ; i = 0
0x08:   B       0x30         ; jmp to 0x30
0x0c:   LDR     r12,[r0],#4  ; r12 <- data++
0x10:   ADD     r3,r12,r3    ; sum = sum + r12
0x14:   LDR     r12,[r0],#4  ; r12 <- data++
0x18:   ADD     r3,r12,r3    ; sum = sum + r12
0x1c:   LDR     r12,[r0],#4  ; r12 <- data++
0x20:   ADD     r3,r12,r3    ; sum = sum + r12
0x24:   LDR     r12,[r0],#4  ; r12 <- data++
0x28:   ADD     r3,r12,r3    ; sum = sum + r12
0x2c:   ADD     r2,r2,#4     ; i = i + 4
0x30:   CMP     r2,r1        ; (i < N) ?
0x34:   BLT     0xc          ; go to 0x0c if i < N
0x38:   MOV     r0,r3        ; r0 <- sum
0x3c:   MOV     pc,r14       ; return
```

loop overhead computed N/4 times

Processor Independent Compiler Optimizations (5)

- In-lining of functions
  - Replacing a call to a function with the function's code is called “in-lining”
  - Benefit: reduction in procedure call overheads and opportunity for additional code optimizations
  - Danger: increased code size (possibly)
  - Appropriate when small and/or called from a small number of sites

```
void t(int x, int y)
{
    int a1=max(x,y);
    int a2=max(x+1,y);

    return max(a1+1,a2);
}
__inline int max(int a, int b)
{
    int x;
    x=(a>b ? a:b);
    return x;
}
```

Without Function Inlining

```
void t(int x, int y)
{
    int a1=max(x,y);
    int a2=max(x+1,y);

    return max(a1+1,a2);
}
int max(int a, int b)
{
    int x;
    x=(a>b ? a:b);
    return x;
}
```

```
max
$a
0x00:   CMP     r0,r1;  (x > y) ?
0x04:   BGT     0x0c;   return if (x > y)
0x08:   MOV     r0,r1;  else r0 <- y
0x0c:   MOV     pc,r14  return
t
0x10:   STMFD   r13!,{r4,r14}; save registers
0x14:   MOV     r2,r0;          r2 <- x
0x18:   MOV     r3,r1;          r3 <- y
0x1c:   MOV     r1,r3;          r1 <- y
0x20:   MOV     r0,r2;          r0 <- x
0x24:   BL      max  ;          r0 <- max(x,y)
0x28:   MOV     r4,r0;          r4 <- a1
0x2c:   MOV     r1,r3;          r1 <- y
0x30:   ADD     r0,r2,#1;       r0 <- x+1
0x34:   BL      max  ;         r0 <- max(x+1,y)
0x38:   MOV     r1,r0 ;        r1 <- a2
0x3c:   ADD     r0,r4,#1 ;      r0 <- a1+1
0x40:   LDMFD   r13!,{r4,r14} ; restore
0x44:   B       max  ;
```

With Function Inlining

```
void t(int x, int y)
{
    int a1=max(x,y);
    int a2=max(x+1,y);

    return max(a1+1,a2);
}
__inline int max(int a, int b)
{
    int x;
    x=(a>b ? a:b);
    return x;
}
```

```
0x00:   CMP     r0,r1 ; (x<= y) ?
0x04:   BLE     0x10  ; jmp to 0x10 if true
0x08:   MOV     r2,r0 ; a1 <- x
0x0c:   B       0x14  ; jmp to 0x14
0x10:   MOV     r2,r1 ; a1 <- y if x <= y
0x14:   ADD     r0,r0,#1; generate r0=x+1
0x18:   CMP     r0,r1    ;    (x+1 > y) ?
0x1c:   BGT     0x24     ;jmp to 0x24 if true
0x20:   MOV     r0,r1    ; r0 <- y
0x24:   ADD     r1,r2,#1 ; r1 <- a1+1
0x28:   CMP     r1,r0 ; (a1+1 <= a2) ?
0x2c:   BLE     0x34  ; jmp to 0x34 if true
0x30:   MOV     r0,r1 ; else r0 <- a1+1
0x34:   MOV     pc,r14
```

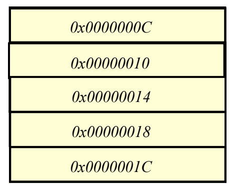
Negative Instruction-Cache Effects

- Negative instruction cache effects
  - Loop unrolling and function in-lining can cause performance degradation in systems with caches

```
int checksum(int *data, int N)
{
        int i;
        for(i=N;i>=0;i--)
        {
            sum += *data++ ;
        }
        return sum;
}
```

Before unrolling the loop

```
0x0000000c:   LDR   r3,[r2],#4
0x00000010:   ADD   r0,r3,r0
0x00000014:   SUB   r1,r1,#1
0x00000018:   CMP   r1,#0
0x0000001c:   BGE   0xc
```



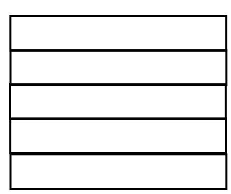
instruction cache

Negative Instruction-Cache Effects (contd)

After unrolling the loop

```
int checksum(int *data, int N)
{
        int i;
        for(i=N;i>=0;i-=4)
        {

            sum += *data++;
            sum += *data++;
            sum += *data++;
            sum += *data++;

        }



return sum;
}
```

```
0x00000008:   LDR   r3,[r0],#4
0x0000000c:   ADD   r2,r3,r2
0x00000010:   LDR   r3,[r0],#4
0x00000014:   ADD   r2,r3,r2
0x00000018:   LDR   r3,[r0],#4
0x0000001c:   ADD   r2,r3,r2
0x00000020:   LDR   r3,[r0],#4
0x00000024:   ADD   r2,r3,r2
0x00000028:   SUB   r1,r1,#4
0x0000002c:   CMP   r1,#0
0x00000030:   BGE   0x8
```



instruction cache

ARM Specific Code Optimization Techniques

- Often, it is important to understand the architecture's implementation in order to effectively optimize code

- One example of this is the ARM barrel shifter
  - Can convert Y * Constant into series of adds and shifts
    - Y * 9 = Y * 8 + Y * 1
    - Assume R1 holds Y and R2 will hold the result
      - ADD R2, R1, R1, LSL #3 ; LSL #3 is same as * by 8

- Use of conditional execution of instructions can reduce the code size as well as reduce the number of execution cycles

Writing Efficient C for ARM Processors (1)

- Use loops that count down to zero, instead of counting upwards
- Example

```
int checksum(int *data)
{
   unsigned i;
   int sum=0;

   for(i=0;i<64;i++)
       sum += *data++;

   return sum;
}
```

Count-up loop

```
int checksum (int *data)
{
   unsigned i;
   int sum=0;

   for(i=63;i >= 0;i--)
       sum += *data++;

   return sum;
}
```

Count-down loop

- Counting upwards needs an `ADD` instruction, a `CMP` to check if index less than 64, and a conditional branch if index is less than 64
  - Counting downwards needs a SUBS instruction (which sets the CPSR flags), and a conditional branch instruction BGE to handle the end of the looping

Count-Down Loops

Example

```
int checksum_v1(int *data)
{
    unsigned i;
    int sum=0;

    for(i=0;i<64;i++)
        sum += *data++;

    return sum;
}
```

```
int checksum_v2(int *data)
{
    unsigned i;
    int sum=0;

    for(i=63;i >= 0;i--)
        sum += *data++;

    return sum;
}
```

```
     MOV   r2, r0;        r2=data
     MOV   r0, #0;        sum=0
     MOV   r1, #0;        i=0
L1   LDR   r3,[r2],#4;    r3=*data++
     ADD   r1, r1, #1;    i=i+1
     CMP   r1, 0x40;      cmp r1, 64
     ADD   r0, r3, r0;    sum +=r3
     BCC   L1;         if i < 64, goto L1
     MOV   pc, lr;     return sum
```

```
     MOV   r2, r0;        r2=data
     MOV   r0, #0;        sum=0
     MOV   r1, #0x3f;     i=63
L1   LDR   r3,[r2],#4;    r3=*data++
     ADD   r0, r3, r0;    sum +=r3
     SUBS  r1, r1, #1;    i--, set flags
     BGE   L1;  if i >= 0, goto L1
     MOV   pc, lr;        return sum
```

Writing Efficient C for ARM Processors (2)

- These are things you can keep in mind, rather than expecting the compiler to do all the work for you
- ARM processors uses 32-bit data types in their data processing instructions
- Example

```
void t3(void)
{
        char c;
        int x=0;
        for(c=0;c<63;c++)
                x++;
}
```

```
void t4(void)
{
        int c;
        int x=0;
        for(c=0;c<63;c++)
                x++;
}
```

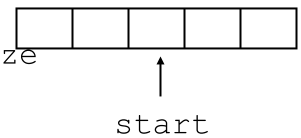
```
        MOV       r0,#0;         x=0
        MOV       r1,#0;         c=0
L1      CMP       r1,#0x3f;      cmp c with 63
        BCS       L2;            if c>= 63, goto L2
        ADD       r0,r0,#1;      x++;
        ADD       r1,r1,#1;      c++
        AND       r1,r1,#0xff;   c=(char) r1
        B         L1;            branch to L1
L2      MOV       pc,r14
```

Writing Efficient C for ARM Processors (3) – Avoid Divisions or Remainder Operation

- ARM does not have a divide instruction
- Divisions are implemented by calling software routines in C library
- Can take between 20-100 cycles
- In many cases, it might be possible to avoid divisions and/or remainder operation

  Example: Circular Buffers (assuming `increment <= size`)

```
start=(start+increment) % size
```




```
start+= increment;
if (start >= size)
    start -= size;
```

- If you cannot avoid a division, try to arrange the numerator and denominator to be unsigned integers

Writing Efficient C for ARM Processors (4)

- Efficiently using global variables: Global variables are stored in memory, load and store instructions are typically used to access the variable when they are used or modified
  - Register accesses are more efficient than memory accesses
- In some cases a global variable is used frequently, it may be better to store it in a local variable
- Example

```
int f(void);
int g(void);
int errs;

void test_v1(void)
{
   errs += f();
   errs += g();
}
```

```
int f(void);
int g(void);
int errs;

void test_v2(void)
{
   int local_errs=errs;
   local_errs += f();
   local_errs += g();
   errs=local_errs;
}
```

Efficient Use of Global Variables

```
test_v1
 0x00:     STMFD     r13!,{r4,r14}    ; save registers
 0x04:     BL        f                          ; compute f()
 0x08:     LDR       r4,0x84                    ; r4 <- address of errs
 0x0c:     LDR       r1,[r4,#0]       ; r1 <- errs
 0x10:     ADD       r0,r0,r1                   ; r1 <- r1 + r0
 0x14:     STR       r0,[r4,#0]                 ; store r1 at mem loc address of errs
 0x18:     BL        g                          ; compute g()
 0x1c:     LDR       r1,[r4,#0]                 ; r1 <- errs
 0x20:     ADD       r0,r0,r1
 0x24:     STR       r0,[r4,#0]                 ; store r0 in errs
 0x28:     LDMFD     r13!,{r4,pc}     ; exit from function
```

```
test_v2
 0x00:     STMFD     r13!,{r3-r5,r14}           ; save registers
 0x04:     LDR       r5,0x84                    ; r5 <- address of errs
 0x08:     LDR       r4,[r5,#0]                 ; r4 = local_errs = errs
 0x0c:     BL        f                          ; compute f()
 0x10:     ADD       r4,r0,r4                   ; r4 = r4 + f()
 0x14:     BL        g                          ; compute g()
 0x18:     ADD       r0,r0,r4                   ; r0 = r0 + r4;
 0x1c:     STR       r0,[r5,#0]                 ; store r0 at mem loc address of errs
 0x20:     LDMFD     r13!,{r3-r5,pc}            ; exit from function
```

Writing Efficient C for ARM Processors (5)

- Local variables are typically stored in registers
- In some cases, local variables need to be stored in memory
  - Example – when the address of a local variable is taken
- If a local variable is stored in memory, load and store are used to access the variable
- Example

```
int f(int *a);
int g(int b);

void test_v1(void)
{
   int i=0;
   f(&i);
   i += g(i);
   i += g(i);
   /* lots of access to i */
   return i;
}
```

```
int f(int *a);
int g(int b);

void test_v2(void)
{
   int dummy=0, i;
   f(&dummy);
    i = dummy;
   i += g(i);
   i += g(i);
    /* lots of access to i */
    return i;
}
```

Writing Efficient C for ARM Processors (6)

- Avoid *register spilling*
  - When the number of local variables in use in a function exceeds the number of registers available
  - Causes the compiler to place certain variables in memory
- You should limit the number of live variables in a function
  - Subdividing large functions into multiple small functions may help (keep in mind that there you increase the function call overhead)
  - Use the `register` keyword to tell the compiler which variables have to be stored in registers in case of register spilling

Optimizing Function Calls

- Can the compiler optimize multiple calls to the same function?
- Example: Will the compiler convert

```
void test(int x)
   return(square(x*x) + square(x*x));
```

into

```
void test(int x)
   return(2*square(x*x));
```

?

Writing Efficient C for ARM Processors (7) – Optimizing Function Calls

- Pure functions: Function whose output depends only upon the input parameters (and not the value of any other global variables) and do not have any side-effects

- Can tell a compiler that a function is a pure function by using the keyword `__pure` in the declaration of the function
  - This allows the compiler to optimize calls to pure functions regardless of where the function is defined
- Example:

```
__pure int square(int x);

int test(int x)
{
   return (square(x*x) + square(x*x));
}
```

```
__pure int square(int x);

int test(int x)
{
   return (2*square(x*x));
}
```

Optimization for Code Size – Optimizing Structures

- Which of the two structures would be better?

```
struct
{
        char a;
        int b;
        char c;
        short d;
}
```

12 bytes

```
struct
{
        char a;
        char c;
        short d;
        int b;
}
```

8 bytes

More Space Optimization

- Can use the `__packed` key word to instruct the compiler to remove all padding

```
__packed struct
{
        char a;
        int b;
        char c;
        short d;
}
```

8 bytes

- Packed structures are slow and inefficient to access
- ARM Compiler emulates unaligned load and store by using several aligned accesses and using several byte-by-byte operations to get the data
- Use `__packed` only if space is more important than speed and you cannot reduce padding by rearrangement

Summary of Lecture

- Improving program performance
  - Processor independent compiler optimizations
    - Common sub-expression elimination
    - Dead-code elimination
    - Induction variables
    - In-lining of functions
    - Loop unrolling
- ARM specific optimizations
- Writing efficient C for running programs on ARM processors