CSE320 System Fundamentals II
Linking

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Linking

- Linking is the process of
  - collecting and combining pieces of code and data
  - into a single file that can be loaded into memory and be executed
- Benefits of doing linking
  - Separates compilation process
  - Checks missing variables, functions, libraries, incompatible library versions
- Linking can be performed at
  - Compile time, load time, and run time

Linking Example

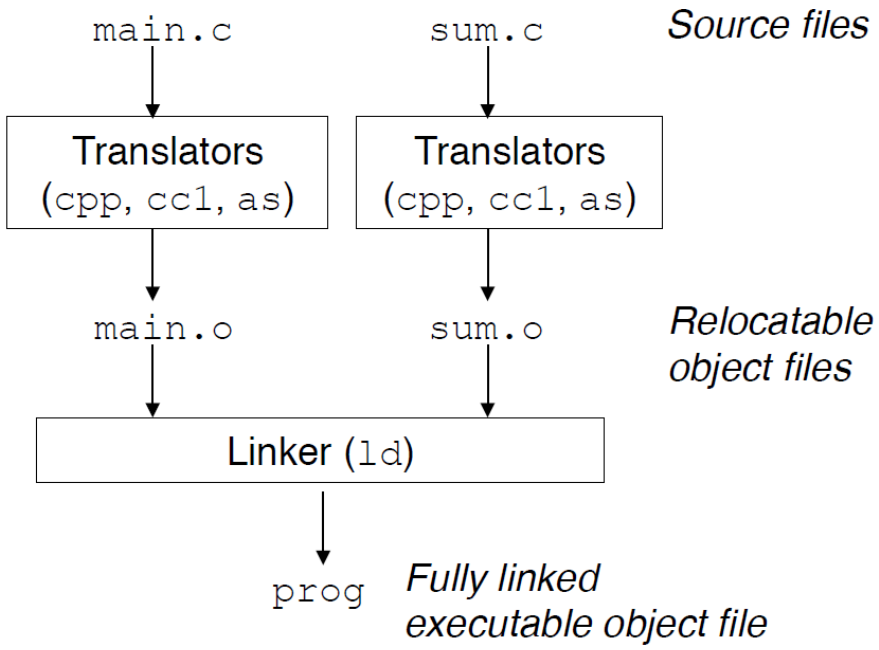
```c
/* sum.c */
int sum(int *a, int n)
{
    int i, s = 0;
    for(i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

```c
/* main.c */
int sum(int *a, int n);
int array[2] = { 1, 2 };

int main()
{
    int val = sum(array, 2);
    return val;
}
```

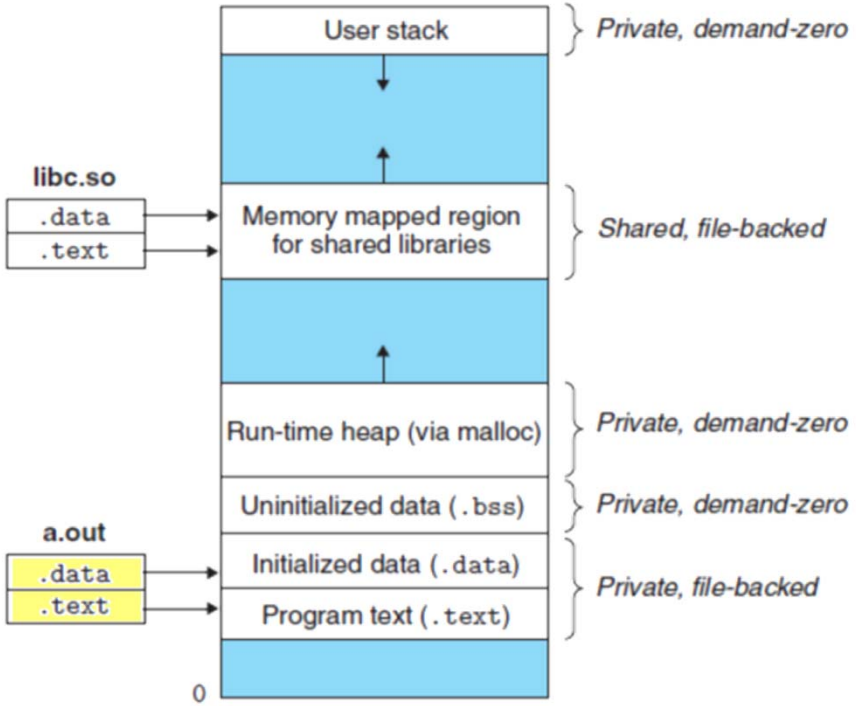
```
// gcc -c sum.c main.c
// ld [system object files and args] sum.o main.o
// gcc –o prog sum.o main.o
```

Linking



Static Linking

- Static linkers (e.g. ld)
  - Input: a collection of relocatable object files
  - Output: a fully linked executable object file



Static Linking

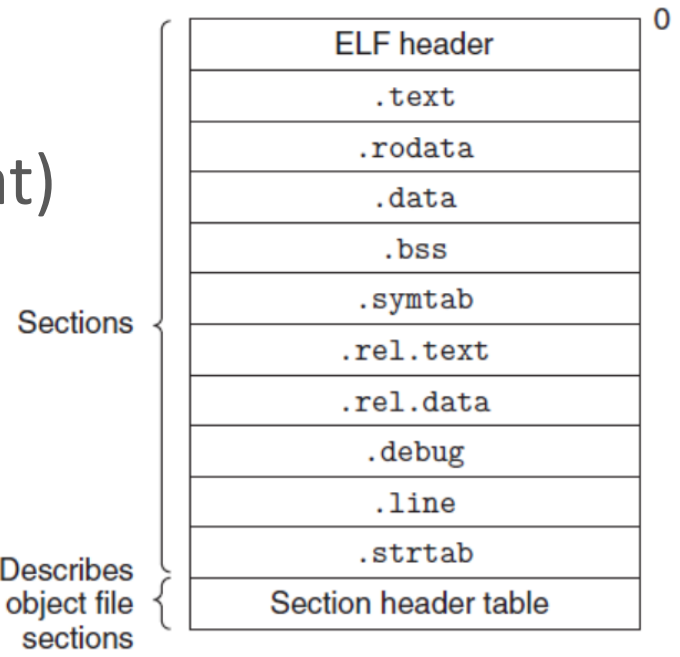
- Linking steps
  1) Symbol resolution step
     - Associate each symbol reference with exactly one symbol definition
     - Symbols: functions, global variables, static variables
  2) Relocation step
     - Compiler generates code and data sections starting at address 0
     - Allocate a memory location with each symbol definition
     - Modify all references to those symbols to memory locations

Object Files

- Relocatable object file
  - Binary code and data that can be combined with other relocatable object files at compile time to create an executable object file
- Executable object file
  - Binary code and data that can be copied directly into memory and be executed
- Shared object file
  - A special type of relocatable object file that can be loaded into memory and linked dynamically at either load time or at run time

Relocatable Object Files

ELF (Executable and Linkable Format)



.text: machine code

.rodata: read-only data

.data: initialized data

.bss: uninitialized data,
no actual space in the object file

.symtab: symbol table

.rel.text: a list of locations in .text that needs to be modified
when combined with other object files

.rel.data: relocation info for any global variables that are
referenced or defined by the module

.debug: a debugging symbol table

.line: source file line number info for codes in .text

.strtab: string table for the symbol tables in .symtab and .debug

Relocatable Object Files
readelf command

```
$ readelf -s main.o

Symbol table '.symtab' contains 17 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS main.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    3
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    4
     5: 0000000000000000     0 SECTION LOCAL  DEFAULT    5
     6: 0000000000000000     0 SECTION LOCAL  DEFAULT    7
     7: 0000000000000000     0 SECTION LOCAL  DEFAULT    8
     8: 0000000000000000     0 SECTION LOCAL  DEFAULT    9
     9: 0000000000000000     0 SECTION LOCAL  DEFAULT   11
    10: 0000000000000000     0 SECTION LOCAL  DEFAULT   13
    11: 0000000000000000     0 SECTION LOCAL  DEFAULT   15
    12: 0000000000000000     0 SECTION LOCAL  DEFAULT   16
    13: 0000000000000000     0 SECTION LOCAL  DEFAULT   14
    14: 0000000000000000     8 OBJECT  GLOBAL DEFAULT    3 array
    15: 0000000000000000    31 FUNC    GLOBAL DEFAULT    1 main
    16: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND sum
```

Relocatable Object Files
readelf command

```
$ readelf -s sum.o

Symbol table '.symtab' contains 9 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS sum.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    2
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    3
     5: 0000000000000000     0 SECTION LOCAL  DEFAULT    5
     6: 0000000000000000     0 SECTION LOCAL  DEFAULT    6
     7: 0000000000000000     0 SECTION LOCAL  DEFAULT    4
     8: 0000000000000000    62 FUNC    GLOBAL DEFAULT    1 sum
```

Symbol Resolution

- Symbol resolution
  - Associating each symbol reference with exactly one symbol definition from the symbol table of relocatable object files
  - Local and static local variables in a module
    - Compiler ensures a unique name
  - Global symbols
    - When a compiler encounters an undefined symbol, it assumes that it is defined in some other module

Symbol Resolution

- When linker cannot find a definition

```
/* undef.c */
void foo();
extern int ivar;

int main() {
    ivar = 0;
    foo();
    return 0;
}

$ gcc undef.c
/tmp/cckHPcOh.o:undef.c:function main: error: undefined reference to 'ivar'
/tmp/cckHPcOh.o:undef.c:function main: error: undefined reference to 'foo'
collect2: ld returned 1 exit status
```

Symbol Resolution

- Duplicated symbols in different modules
  - Compiler exports each symbol as either strong or weak
  - Strong Symbols: functions, initialized global variables
  - Weak Symbols: uninitialized global variables
- Resolution rules for duplicated symbols
  - Multiple strong symbols are not allowed
  - Given a strong symbol and multiple weak symbols, choose the strong symbol
  - Given multiple weak symbols, any one can be chosen

Symbol Resolution

Multiple strong symbols

```
/* dup2.c */
int foo() {
    return 2;
}

/* dup1.c */
int foo() {
    return 1;
}

int main() {
    return foo();
}

$ gcc dup1.c dup2.c
/usr/bin/ld: error: /tmp/cc5gGlfB.o: multiple definition of 'foo'
/usr/bin/ld: /tmp/ccvdInRf.o: previous definition here
collect2: ld returned 1 exit status
```

Symbol Resolution

Strong and weak symbols

```c
/* weak.c */
#include <stdio.h>
int x;
void foo();
int main() {
    printf("before: %d\n", x);
    foo();
    printf("after:  %d\n", x);
}

/* strong.c */
int x = 100;
void foo() {
    x = 200;
}
```

```
$ gcc weak.c strong.c
$ ./a.out
before: 100
after:  200
```

Symbol Resolution

Multiple weak symbols

```c
/* weak1.c */
#include <stdio.h>
int x;
void foo();
int main() {
    x = 2;
    printf("before: %d\n", x);
    foo();
    printf("after:  %d\n", x);
}
```

```c
/* weak2.c */
double x;
void foo() {
    x = 0.2;
}
```

```
$ gcc weak1.c weak2.c
$ ./a.out
before: 2
after:  -1717986918
```

Linking with Static Libraries

Different approaches

- A single relocatable module with all related functions
  - Every executable file contains a copy of all functions
  - Any changes to the module require library developers to recompile the entire source codes
  - `gcc main.c /usr/lib/libc.o`
- Separate relocatable files for each function
  - App programmers need to link each modules ⇒ time consuming and error prone
  - `gcc main.c /usr/lib/printf.o /usr/lib/scanf.o …`
- Static library
  - Related functions are compiled into separate object modules and packaged into a single file called static library
  - Linker will copy only the modules that are actually referenced
  - `gcc main.c /usr/lib/libc.a`

Creating Static Libraries

```c
/* addvec.c */
int addcnt = 0;
void addvec(int *x, int *y, int *z,
            int n) {
    int i;
    addcnt++;
    for(i = 0; i < n; i++)
        z[i] = x[i] + y[i];
}

/* mulvec.c */
int mulcnt = 0;
void mulvec(int *x, int *y, int *z,
            int n) {
    int i;
    mulcnt++;
    for(i = 0; i < n; i++)
        z[i] = x[i] * y[i];
}
```

```c
/* main2.c */
#include <stdio.h>
void addvect(int *x, int *y, int *z,
             int n);
void mulvect(int *x, int *y, int *z,
             int n);

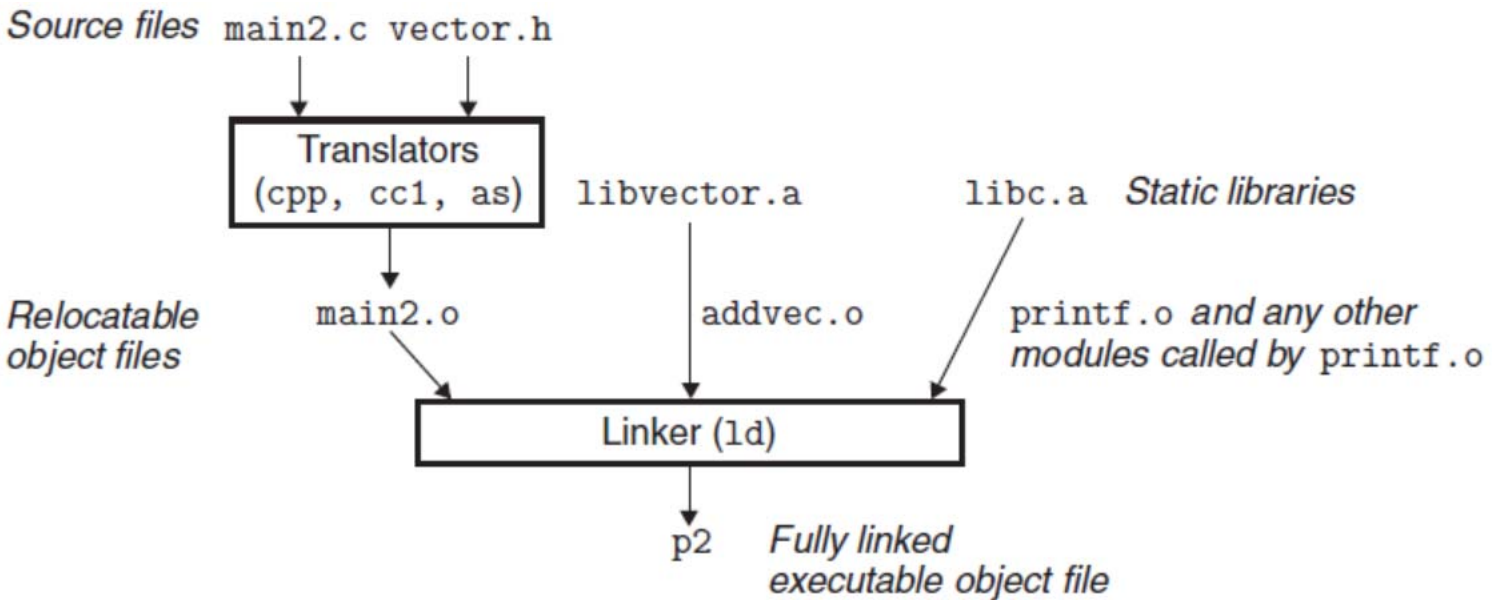
int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];
int main() {
    addvec(x, y, z, 2);
    printf("z= [%d, %d]\n", z[0], z[1]);
    return 0;
}
```

```
$ gcc -c addvec.c
$ gcc -c mulvec.c
$ ar rcs libvector.a addvec.o mulvec.o
$ gcc -static main2.c ./libvector.a
```

Creating Static Libraries

```
$ gcc main2.c ./libvector.a  (without –static option)
$ readelf -s a.out
...
Symbol table '.symtab' contains 44 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
    ...
     10: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS main2.c
     11: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS addvec.c
...
     25: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND printf
...
     27: 0000000000400524    73 FUNC    GLOBAL DEFAULT   13 main
...
     36: 0000000000402020     8 OBJECT  GLOBAL DEFAULT   24 x
     37: 0000000000402028     8 OBJECT  GLOBAL DEFAULT   24 y
     38: 0000000000402044     8 OBJECT  GLOBAL DEFAULT   25 z
     39: 0000000000400570   106 FUNC    GLOBAL DEFAULT   13 addvec
     40: 0000000000402040     4 OBJECT  GLOBAL DEFAULT   25 addcnt
...
```

Linking with Static Libraries



Relocation

- Once the symbol resolution step is done
  - Linker knows the exact sizes of code and data sections
- Relocation steps
  1) Relocating sections and symbol definitions
     - Merge all sections of the same type into an aggregate section of the same type
     - Assign run-time memory address to sections and symbols
  2) Relocating symbol references within sections
     - Modify symbol references in code and data sections so that they point to the run-time addresses

Relocating Symbol References

- ELF Relocation Entry
  - Relocation entry is generated when an assembler encounters a reference whose location is unknown.
  - Relocation entries for code and data are placed in .rel.text and .rel.data sections
  - Of many relocation types, we are interested in
    - R_X86_64_PC32: 32 bit PC relative address
    - R_X86_64_32: 32 bit absolute address type

```
typedef struct {
    long offset;    // Offset of the reference to relocate
    long type:32,   // Relocation type (R_X86_64_PC32, R_X86_64_32)
         symbol:32; // Symbol table index
    long addend;    // Constant part of relocation expression
} Elf64_Rela;
```

Relocating Symbol References

```
 1: foreach section s {
 2:    foreach relocation entry r {
 3:        refptr = s + r.offset;  // reference to be relocated
 4:
 5:        // Relocate a PC-relative reference
 6:        if (r.type == R_X86_64_PC32) {
 7:            refaddr = ADDR(s) + r.offset; // ref's run-time address
 8:            *refptr = (unsigned)(ADDR(r.symbol) - refaddr + r.addend);
 9:        }
10:
11:        // Relocate an absolute reference
12:        if (r.type == R_X86_64_32)
13:            *refptr = (unsigned)(ADDR(r.symbol) + r.addend);
14: }
```

- s: address of section
  refptr (line 3) points to the data that needs to be relocated
- ADDR(s): *run-time* address for the section s
- ADDR(r.symbol): *run-time* address for the symbol r.symbol

Relocating Symbol References

```
 0: 48 83 ec 08              sub     $0x8, %rsp
 4: be 02 00 00 00           mov     $0x2, %esi      %esi = 2

 9: bf 00 00 00 00           mov     $0x0, %edi      %edi = &array
                            a: R_X86_64_32 array     Relocation entry

 e: e8 00 00 00 00           callq   13 <main+0x13>  sum()
                            f: R_X86_64_PC32 sum-0x4 Relocation entry

13: 48 83 c4 08              add     $0x8, %rsp
17: c3                       retq
```

```
----------------------------
int main()
{
    int val = sum(array, 2);
    return val;
}
```

Code and relocation entries from main.o

Relocating PC-Relative References

- `callq 13` at address e:
  - `Relocation entry: {`
    ```
        r.offset = 0xf,
        r.symbol = sum,
        r.type = R_X86_64_PC32,
        r.addend = -4
    }
    ```
  - Mem addresses when loaded
    - `ADDR(s)` = `ADDR(.text)` = `0x4004d0`
    - `ADDR(r.symbol)` = `ADDR(sum)` = `0x4004e8`
  - Mem address of sum in call sum when loaded
    - `refaddr = ADDR(s) + r.offset = 0x4004df`
  - Update the code in the linker's data structure
    - ```
      *refptr = ADDR(r.symbol) – refaddr + r.addend
              = 0x4004e8 – 0x4004df - 4 = 0x5
      ```
      ```

Relocating PC-Relative References

- In relocatable object file (before linking)
  - `e: e8 00 00 00 00`
- In the executable object file (after linking)
  - `e: e8 05 00 00 00 ;;callq 4004e8 <sum>`
- When loaded in memory
  - `4004de: e8 05 00 00 00 ;;callq 4004e8 <sum>`
  - Push PC onto stack
  - PC ← PC + 5

Relocating Absolute References

- `mov $0x0, %edi` at address 9:
  - **Relocation entry**: {
    r.offset = 0xa,
    r.symbol = array,
    r.type = R_X86_64_32,
    r.addend = 0
    }
  - Mem addresses when loaded
    - **ADDR(r.symbol)** = ADDR(**array**) = 0x601018
  - Update the code in the linker's data structure
    - *refptr = ADDR(r.symbol) + r.addend
      = 0x601018 + 0 = 0x601018

Relocating Absolute References

- In relocatable object file (before linking)
  - `9: bf 00 00 00 00`
- In the executable object file (after linking)
  - `9: bf 18 10 60 00 ;;mov $0x601018, %edi`
- When loaded in memory
  - `4004d9: bf 18 10 60 00 ;;mov $0x601018, %edi`