CS356 Unit 11

Linking

C LANGUAGE SPECIFICS

C Structs

- A way to group values that are related, but have different data types
- Similar to a class in C++
- Capabilities of structs changed in C++!
  - C
    - Only data members (no functions)
    - Type must include keyword 'struct'; i.e. the type is 'struct Person' not just 'Person'
  - C++
    - Like a class (data + member functions)
    - Default access is public

```
struct Person{
  char name[20];
  int age;
};
int main()
{
  // C++ decl.
  Person p1;

  // C decl.
  struct Person p1;
  struct Person *ptr = &p1;

  p1->age = 19;
  return 0;
}
```


static Keyword

- In the context of C, the keyword 'static' in front of a global variable or function prototype indicates the variable is only visible within the __________ file and should not be _______ (accessed) by other source code files
- Can be used as a sort of 'private' helper function declaration

```
// Globals
int person_count = 0;

static struct Person thePerson;

// Functions
void person_init(struct Person* p);

static void person_init_helper(
   struct Person* p);

// Definitions (code) for the
// functions
```

person.c

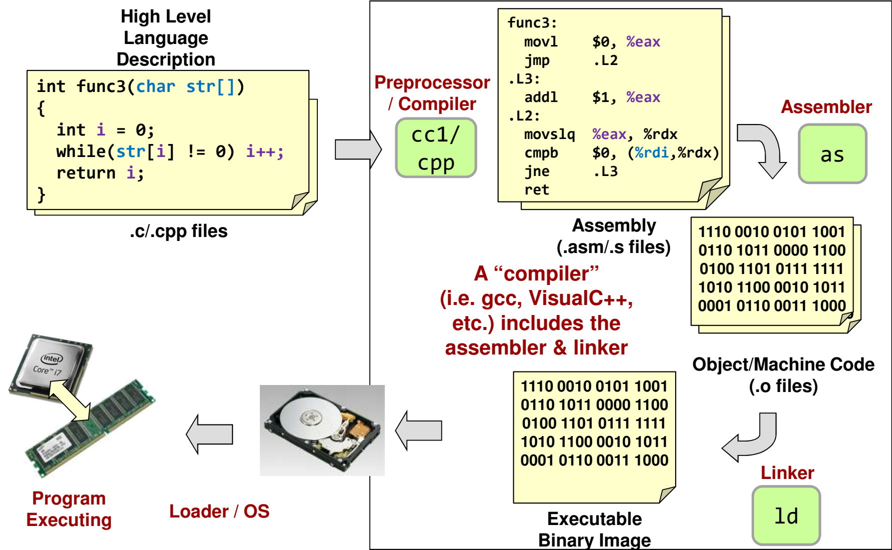
```
void person_init(struct Person*);
void person_init_helper(struct Person*);

int f1()
{  // Will compile
   person_count++;
   // Will NOT compile
   thePerson.age = 20;

   struct Person p;
   // Will compile
   person_init(&p);
   // Will NOT compile
   person_init_helper(&p);
}
```

other.c

COMPILATION REVIEW

Review

CS:APP 7.1



Compilation Units

- We want functions defined in one file to be able to be called in another
- But the compiler only compiles one file at a time…how does it know if the functions exist elsewhere?
  - It doesn't…it only checks when the ___________ runs which is the ____ step in compilation
  - But it does require a __________ to verify & know the argument/return types

```
void shuffle(int items[], int len)
{
  /* code */
}
```

shuffle.cpp

```
int main()
{
  int cards[52];
  /* Initialize cards */
  ...
  // Shuffle cards
  shuffle(cards, 52);
  return 0;
}
```

shuffle_test.cpp

```
void shuffle(int items[], int len);

int main()
{
  int cards[52];
  /* Initialize cards */
  ...

  shuffle(cards, 52);
  return 0;
}
```

shuffle_test.cpp

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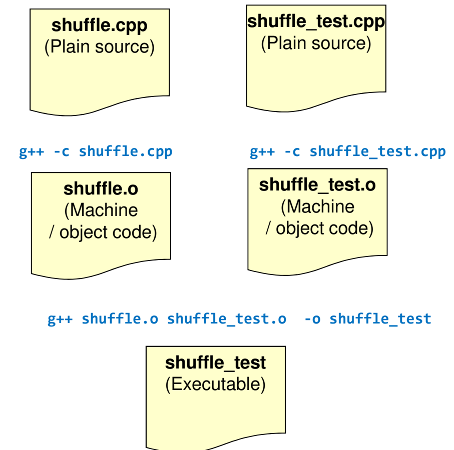
Linking

- After we compile to object code we eventually need to link all the files together and their function calls
- Without the -c, gcc/g++ will always try to link
- The linker will
  - Verify referenced functions _______ somewhere
  - ________ all the code & data together into an ___________
  - Update the machine code to tie the _______________ together



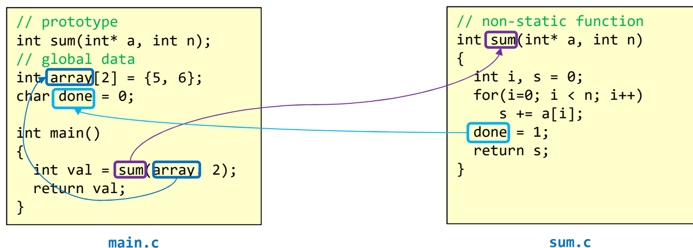
LINKING OVERVIEW

Why Study Linking

- To better understand compiler/linking error messages
  - `main.c:(.text+0x13): undefined reference to `sum'`
- To understand how large programs are built
- To avoid subtle, hard-to-find bugs
- To understand OS & other system-level concepts
  - To help with CS 350!
- To exploit shared libraries (dynamic linkage)

A First Look (1)

- Consider the example below:
  - Global variables: array and done
  - Functions: sum() and main()
- Linker needs to ensure the code references the appropriate memory locations for the code & data



A First Look (2)

- Each file can be compiled to object code separately
  - Notice the links are left blank (0) for now by the compiler

```
// prototype
int sum(int* a, int n);
// global data
int array[2] = {5, 6};
char done = 0;

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

```
$ gcc -O1 -c main.c
```

```
0000000000000000 <main>:                                    main.o
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi
   e:   e8 00 00 00 00          callq  13 <main+0x13>
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

```
// non-static function
int sum(int* a, int n)
{
  int i, s = 0;
  for(i=0; i < n; i++)
     s += a[i];
  done = 1;
  return s;
}
```

```
$ gcc -O1 -c sum.c
```

```
0000000000000000 <sum>:                                     sum.o
   0:   85 f6                   test   %esi,%esi
   2:   7e 1d                   jle    21 <sum+0x21>
   4:   48 89 fa                mov    %rdi,%rdx
   7:   8d 46 ff                lea    -0x1(%rsi),%eax
   a:   48 8d 4c 87 04          lea    0x4(%rdi,%rax,4),%rcx
   f:   b8 00 00 00 00          mov    $0x0,%eax
  14:   03 02                   add    (%rdx),%eax
  16:   48 83 c2 04             add    $0x4,%rdx
  1a:   48 39 ca                cmp    %rcx,%rdx
  1d:   75 f5                   jne    14 <sum+0x14>
  1f:   eb 05                   jmp    26 <sum+0x26>
  21:   b8 00 00 00 00          mov    $0x0,%eax
  26:   c6 05 00 00 00 00 01    movb   $0x1,0x0(%rip)
  2d:   c3                      retq
```

A First Look (3)

- The linker will produce an executable with all references resolved to their exact addresses

```
// prototype
int sum(int* a, int n);
// global data
int array[2] = {5, 6};
char done = 0;

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

```
// non-static function
int sum(int* a, int n)
{
  int i, s = 0;
  for(i=0; i < n; i++)
      s += a[i];
  done = 1;
  return s;
}
```

```
main
00000000004004d6 <sum>:
  4004d6:       85 f6                   test   %esi,%esi
  4004d8:       7e 1d                   jle    4004f7 <sum+0x21>
  4004da:       48 89 fa                mov    %rdi,%rdx
  4004dd:       8d 46 ff                lea    -0x1(%rsi),%eax
  4004e0:       48 8d 4c 87 04          lea    0x4(%rdi,%rax,4),%rcx
  4004e5:       b8 00 00 00 00          mov    $0x0,%eax
  4004ea:       03 02                   add    (%rdx),%eax
  4004ec:       48 83 c2 04             add    $0x4,%rdx
  4004f0:       48 39 ca                cmp    %rcx,%rdx
  4004f3:       75 f5                   jne    4004ea <sum+0x14>
  4004f5:       eb 05                   jmp    4004fc <sum+0x26>
  4004f7:       b8 00 00 00 00          mov    $0x0,%eax
  4004fc:       c6 05 36 0b 20 00 01    movb   $0x1,0x200b36(%rip) # 601039 <done>
  400503:       c3                      retq

0000000000400504 <main>:
  400504:       48 83 ec 08             sub    $0x8,%rsp
  400508:       be 02 00 00 00          mov    $0x2,%esi
  40050d:       bf 30 10 60 00          mov    $0x601030,%edi
  400512:       e8 bf ff ff ff          callq  4004d6 <sum>
  400517:       48 83 c4 08             add    $0x8,%rsp
  40051b:       c3                      retq
```

```
$ gcc main.o sum.o -o main
```


Linker Tasks

CS:APP 7.2

- A linker has two primary tasks:
  - ______________________: Resolve which single definition each symbol (function name, global variable, or static variable) resolves
  - ___________: Associate a _______________ to each symbol and then ______________ all code references to that location
    - Object files start at offset 0 from their text/data sections; when linking all files must be placed into a single executable and code/data relocated

Object Files

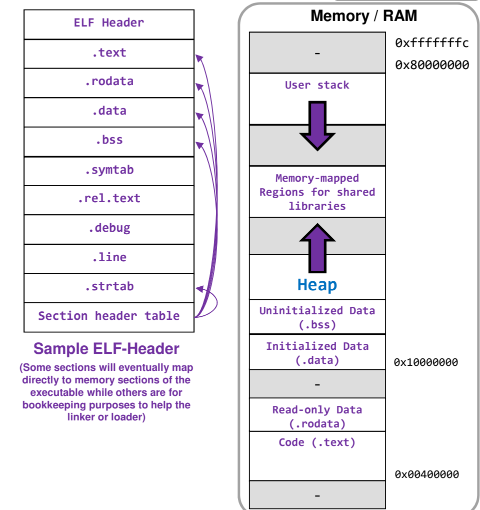
CS:APP 7.3

- 3 kinds of object files:
  - ______________ object file (typical ___ file): Code/data along with book-keeping info for the linker
  - ______________ object file (binary that can be loaded into memory by the OS loader)
  - ______________ object file (can be dynamically linked at load or run-time with some other executable)
- Each OS defines their own format
  - Windows: Portable Executable (PE) format
  - Mac OS: Mach-O format
  - Linux/Unix: ______________________________
    - We'll study this one

Relocatable Object ELF Sections

CS:APP 7.4

- Object files are made of various sections
  - Some map to actual ___________ sections when the program will execute
  - Others are for ____________ purposes to help the linker or debugger

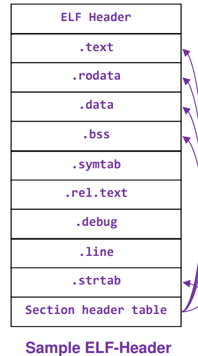


Sample ELF-Header

(Some sections will eventually map directly to memory sections of the executable while others are for bookkeeping purposes to help the linker or loader)

Section Descriptions

- **.text**: Machine code of instructions (executable code)
- **.rodata**: ___________ data such as string constants (e.g. ____________)
- **.data**: _____________ global and static variables
- **.bss**: ____________ global and static variables (no actual space in .o file)
  - Will be __________ by startup code when program is loaded
- **.symtab**: _________________ with information about functions and global variables that may exist
  - Why no local variables? They are on the _______ and cannot be accessed by other code units
- **.rel.txt & .rel.XXXX**: Relocation information about instructions in the .text section (or XXXX section) that reference outside functions or globals so that they can be modified by the linker
- **.debug & .line**: A symbol table for locals and other definitions as well as line number to instruction mappings (included when the -g flag is used to compile)
- **.strtab**: A string table of all the strings used by other headers and sections



Sample ELF-Header

STEP 1: SYMBOL RESOLUTION

Kinds of Symbols

CS:APP 7.5

- ____________ symbols
  - Non-static, global variables and functions that are defined in a compilation unit that can be referenced by other units
- ____________ global symbols
  - Symbols uses in a compilation unit that are not defined in a unit
- Local symbols
  - ________ global variables and functions
  - NOT local ____________ (i.e. these are on the stack and the linker does not need to know about them)

Examples

```
// prototype
int sum(int* a, int n);
// global data
int array[2] = {5, 6};
char done = 0;

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

```
#include <stdio.h>

int x=1, z=0;
static int y=5;

static int foo(int bar)
{
  x += bar;
  y--; z++;
  return x;
}

int main(int argc, char** argv)
{
  printf("%d\n", foo(3));
  return 0;
}
```

Global	
External	
Local	
Linker-Ignored	

Global	
External	
Local	
Linker-Ignored	

Symbol Table

- The compiler will store information about each symbol in the object file
- Fields
  - Value (relative offset in the section or absolute address of its location)
  - Bind ('local' = static defintions vs 'global')
  - Ndx (Section: 1=text, 3=data, 4=bss, UND=external)
  - Type ('object' = data, 'func' = function)

`$ gcc -c res1.c`

```
#include <stdio.h>

int x=1, z=0;
static int y=5;

static int foo(int bar)
{
  x += bar;
  y--; z++;
  return x;
}

int main(int argc, char** argv)
{
  printf("%d\n", foo(3));
  return 0;
}
```

`$ readelf -s res1.c`

```
Symbol table '.symtab' contains 15 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS res1.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    3
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    4
     5: 0000000000000004     4 OBJECT  LOCAL  DEFAULT    3 y
     6: 0000000000000000    62 FUNC    LOCAL  DEFAULT    1 foo
     7: 0000000000000000     0 SECTION LOCAL  DEFAULT    5
     8: 0000000000000000     0 SECTION LOCAL  DEFAULT    7
     9: 0000000000000000     0 SECTION LOCAL  DEFAULT    8
    10: 0000000000000000     0 SECTION LOCAL  DEFAULT    6
    11: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    3 x
    12: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    4 z
    13: 000000000000003e    49 FUNC    GLOBAL DEFAULT    1 main
    14: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND printf
```


Duplicate Symbol Resolution Rules

CS:APP 7.6

- If duplicate 'local' symbols…error
- For global symbols, the compiler defines:
  - ____________ symbols: non-static global __________ and initialized non-static global ____________
  - ____________ symbols: uninitialized, non-static global variables
- Global resolution rules:
  - ______________ 'strong' definitions of a symbol…error
  - ____ 'strong' and _____________ 'weak' definitions of a symbol…choose the 'strong' definition
  - Many duplicate 'weak' symbols: arbitrarily choose one to be *the* definition
    - Can disable this arbitrary choice and generate an error with `-fno-common` option to `gcc`

```
// strong
int error = 0;

// weak
int val;
```


Duplicate Resolution Example

`$ gcc res2a.c res2b.c -o res2`

```
// res2a.c
#include <stdio.h>

void doit(int *sum);

// better: extern int error
int error;
int val;

int main()
{
  doit(&val);
  printf("%d\n", val);
  return 0;
}
```

Strong	
Weak	

```
// res2b.c
#include <stdio.h>

int error = 0;
int val;

void doit(int *sum)
{
  int x, y;
  if(2 != scanf("%d %d", &x, &y)){
    error = 1;
    return;
  }
  *sum = x+y;
}
// would generate an error, if added
// int main() { return 0; }
```

Strong	
Weak	

```
$ gcc -fno-common res2a.c res2b.c
/tmp/ccwo7BuS.o:(.bss+0x0): multiple definition of `error'
/tmp/ccbFljfF.o:(.bss+0x0): first defined here
/tmp/ccwo7BuS.o:(.bss+0x4): multiple definition of `val'
/tmp/ccbFljfF.o:(.bss+0x4): first defined here
collect2: error: ld returned 1 exit status
```


Duplicate Resolution Example

`$ gcc res3a.c res3b.c -o res3`

```
// res3a.c
#include <stdio.h>

void doit();

int val;
int val2;

int main()
{
  val = 1;
  doit();
  val++;
  printf("val=%d\n", val);
  return 0;
}
```

Strong	
Weak	

```
// res3b.c
#include <stdio.h>

double val;


void doit(int *sum)
{
  int x;
  scanf("%d", &x);
  val += x;
}
```

Strong	
Weak	

```
$ gcc -fno-common res3a.c res3b.c
/tmp/ccHUiJtU.o:(.bss+0x0): multiple definition of `val'
/tmp/ccDcaoUE.o:(.bss+0x0): first defined here
/usr/bin/ld: Warning: size of symbol `val' changed from 4 in
/tmp/ccDcaoUE.o to 8 in /tmp/ccHUiJtU.o
collect2: error: ld returned 1 exit status
```

Global Variable Summary

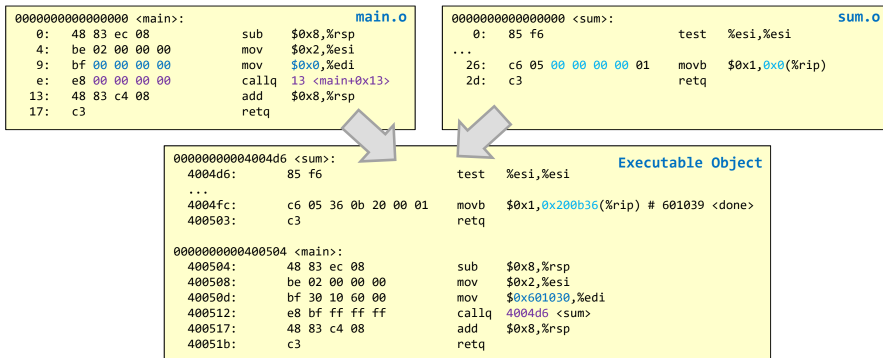
- ___________________, if you can help it
- If you must
  - Use ___________, if you can
  - If you define global variable, ___________ it (that way it will be a strong symbol and the compiler will catch duplicates)
  - If you reference a global variable from another module, use the ___________ keyword

STEP 2: RELOCATION

Executable Object File

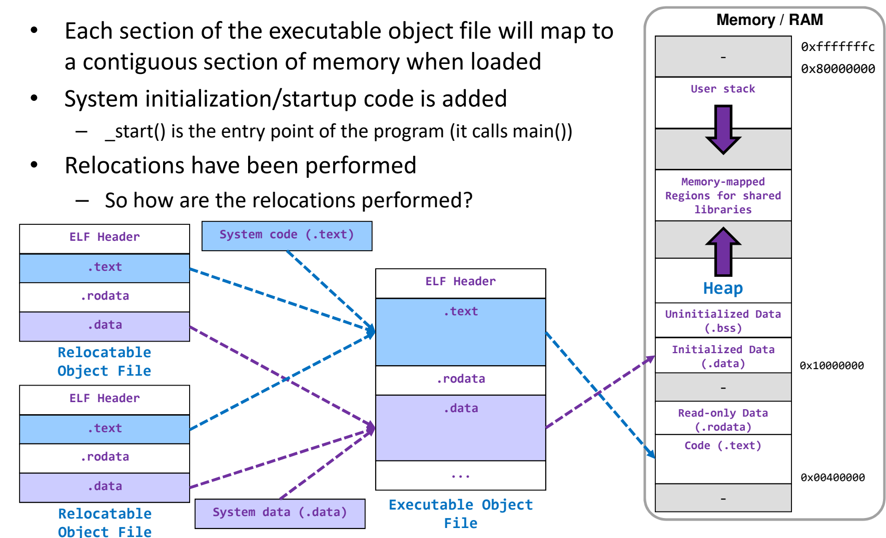
CS:APP 7.8

- When the linker runs it can create an executable by combining all the object files to resolve all symbols, decide where all code and data will be placed in memory, and then relocating all references



Executable Object File

- Each section of the executable object file will map to a contiguous section of memory when loaded
- System initialization/startup code is added
  - _start() is the entry point of the program (it calls main())
- Relocations have been performed
  - So how are the relocations performed?



Relocation Review

CS:APP 7.7

- Recall that the object files left links to global symbols blank

```
// prototype
int sum(int* a, int n);
// global data
int array[2] = {5, 6};
char done = 0;

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

$ gcc -O1 -c main.c

```
main.o
0000000000000000 <main>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi
   e:   e8 00 00 00 00          callq  13 <main+0x13>
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

```
// non-static function
int sum(int* a, int n)
{
  int i, s = 0;
  for(i=0; i < n; i++)
     s += a[i];
  done = 1;
  return s;
}
```

$ gcc -O1 -c sum.c

```
sum.o
0000000000000000 <sum>:
   0:   85 f6                   test   %esi,%esi
   2:   7e 1d                   jle    21 <sum+0x21>
   4:   48 89 fa                mov    %rdi,%rdx
   7:   8d 46 ff                lea    -0x1(%rsi),%eax
   a:   48 8d 4c 87 04          lea    0x4(%rdi,%rax,4),%rcx
   f:   b8 00 00 00 00          mov    $0x0,%eax
  14:   03 02                   add    (%rdx),%eax
  16:   48 83 c2 04             add    $0x4,%rdx
  1a:   48 39 ca                cmp    %rcx,%rdx
  1d:   75 f5                   jne    14 <sum+0x14>
  1f:   eb 05                   jmp    26 <sum+0x26>
  21:   b8 00 00 00 00          mov    $0x0,%eax
  26:   c6 05 00 00 00 00 01    movb   $0x1,0x0(%rip)
  2d:   c3                      retq
```


Relocation Entries

```
0000000000000000 <main>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi
   e:   e8 00 00 00 00          callq  13 <main+0x13>
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

```
Relocation section '.rela.text' at offset 0x208 contains 2 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
00000000000a  00090000000a R_X86_64_32       0000000000000000 array + 0
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 sum - 4
```

ELF Header
.text
.rodata
.data
.bss
.symtab
.rel.text
.debug
.line
.strtab
Section header table

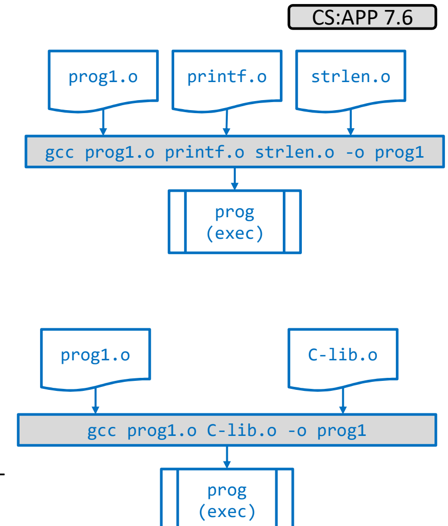
- The linker creates **relocation entries** containing:
  - Type of offset
    - **PC-Relative** (R_X86_64_PC32) or **Absolute Address** (R_X86_64_32)
  - Section offset where the relocation should be replaced
  - Symbol being referenced (and its symbol table index)

STATIC LIBRARIES

Need for Libraries

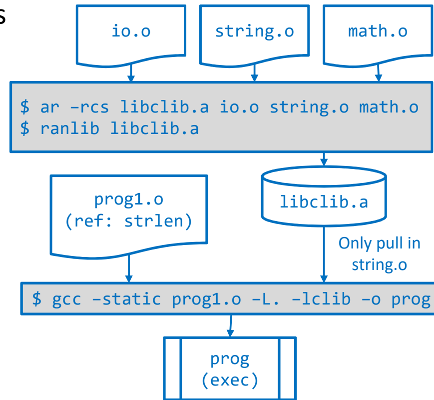
CS:APP 7.6

- Often have many related files containing commonly reused code (functions)
  - Think of the C library (I/O functions, string library, math, etc.) or related classes (and all the code of their member functions)
  - How should we compile and link these in?
- Option 1: Put each function in a ____________________
  - Painful to track and write which files are needed
- Option 2: Put all code in a __________
  - Lot of unneeded, ________ code to link in



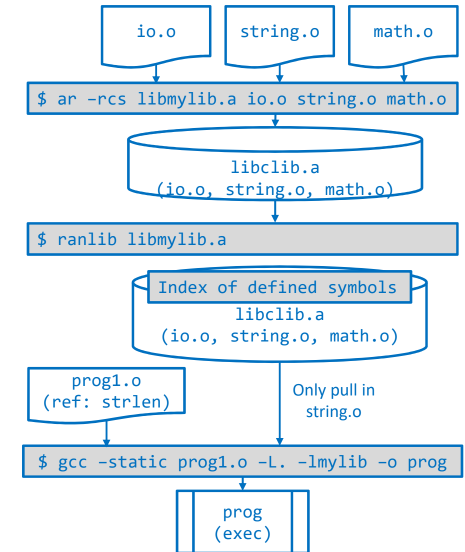
Benefits of a Library

- Compile all, possible object files and put them together into a library (_____________) file
  - Linux: Archive (.__) file
  - Windows: Portable Executable (._____) file
- When a program needs functions/data from the library, the compiler can include just the ones that are needed (by checking what undefined symbols from the program are defined in the library)



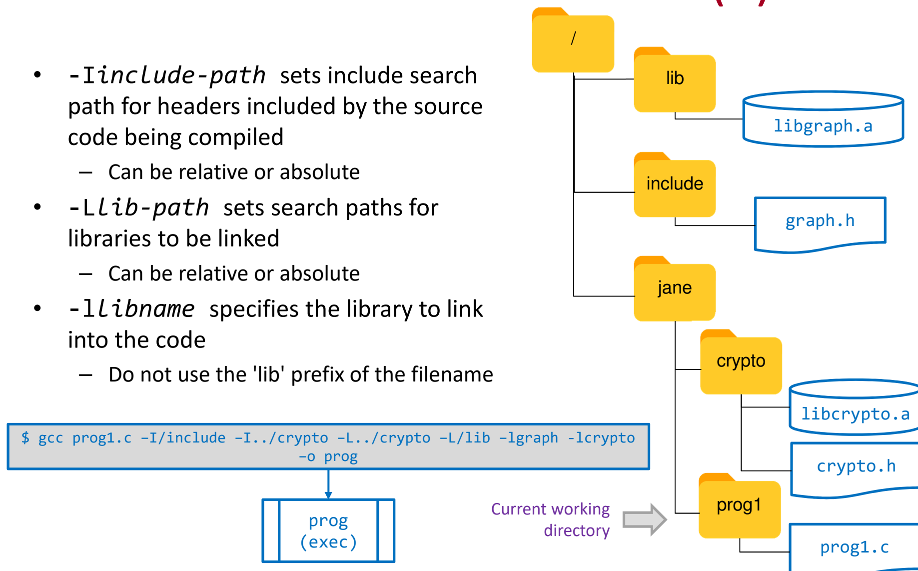
Static Libraries on Linux (1)

- ar (archiver) packs multiple object files into one
  - Output file should start with "lib" prefix
- ranlib adds an index of the symbols defined in the object files that are part of the library to enable quick determination of which object files to link in
- To link in code from a library use the `-static` option
  - -L indicates the ______________ to search for libraries
  - -l indicates the name of the library to link against (_____________ the "lib" prefix since it assumes the file will have the "lib" prefix)



Static Libraries on Linux (2)

- *-Iinclude-path* sets include search path for headers included by the source code being compiled
  - Can be relative or absolute
- *-Llib-path* sets search paths for libraries to be linked
  - Can be relative or absolute
- *-llibname* specifies the library to link into the code
  - Do not use the 'lib' prefix of the filename



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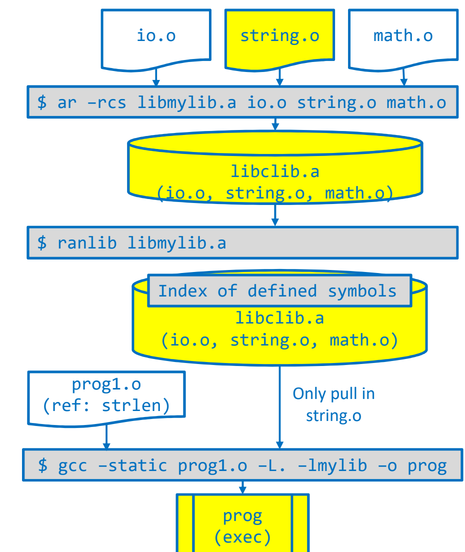
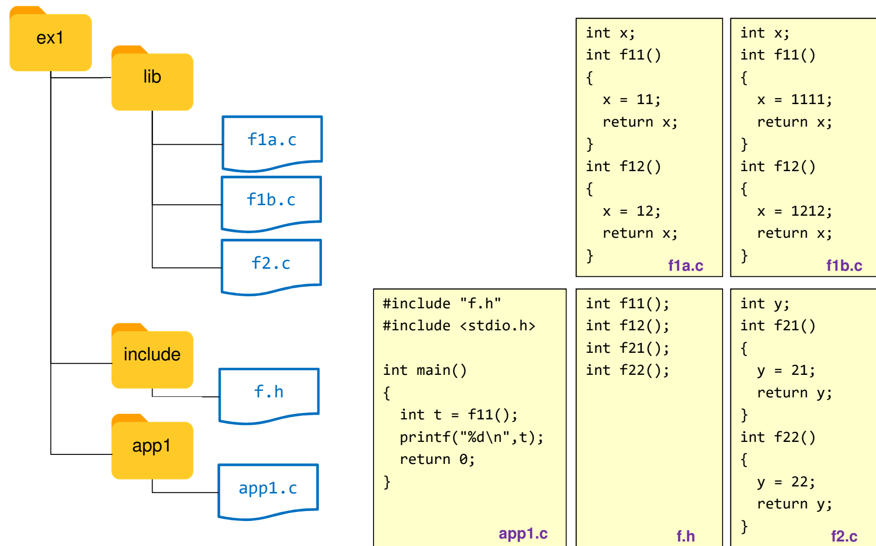
Static Library Issues

- What happens if we need to change the code in the library?
  - Need to ______ all executables that used the library
- What if multiple running programs linked against the library
  - Multiple _________ of the code in memory
- Is there a better way?
  - ________ libraries and _________ linking

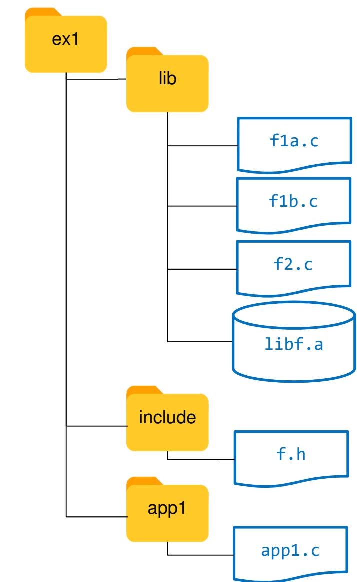


Library Example



Static Library Exercise

```
cd lib
rm libf.a
gcc -c f1a.c f2.c
ar -rcs libf.a f1a.o f2.o
ranlib libf.a
cd ../app1
gcc app1.c            # fatal error: no 'f.h'
gcc -I../include app1.c # notice 'undefined reference
# need to link in the library
gcc -I../include app1.c -L../lib -lf
./a.out       # should see '11' output
objdump -d ./a.out > a.s
subl a.s &    # notice no f21/f22 functions
cd ../lib
rm libf.a
gcc -c f1b.c
ar -rcs libf.a f1b.o f2.o
ranlib libf.a
cd ../app1
./a.out       # notice no update in output
# need to recompile app1
gcc -I../include app1.c -L../lib -lf
./a.out
# ok now we get the update
cd ..
```



Shared objects (.so) and Dynamically Linked Libraries (.dll)

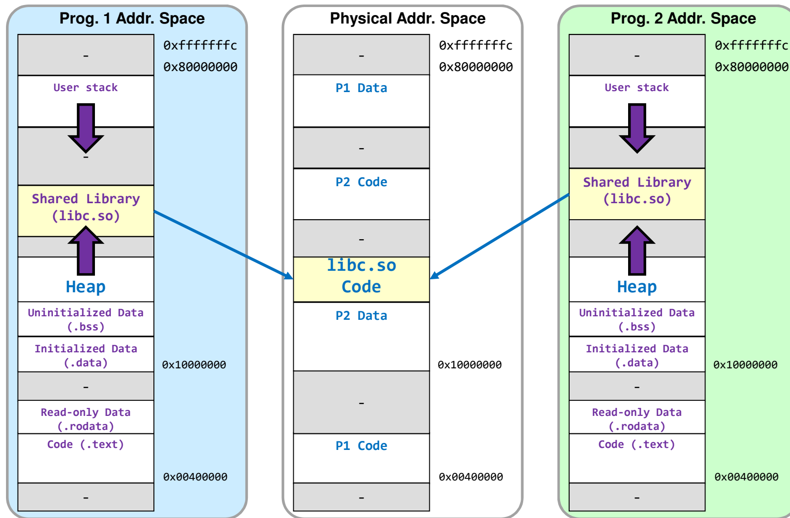
DYNAMIC/SHARED LIBRARIES

Shared Library Motivation

CS:APP 7.10

- Don't duplicate common code in physical memory
- Allow libraries to be updated (recompiled) without needing to recompile the programs that use the libraries
- Key Idea:
  - Don't hardcode the addresses of functions or data
  - Instead, use a level of indirection (a lookup table)
    - Lookup the address of the data or code at run-time and then use whatever address is found

Shared Library Motivation



Simplified View of Dynamic Linkage

- Code can reference a table (aka Global Offset Table or "GOT") in the data section that will contain the address of the desired function or global variable
- Relocation entries in the executable object file will be used by the loader and dynamic linker when the program is loaded to fill in the table with the correct address
- More details in CS:APP3e

```
          ...
0x40015 call SUB1     reference
0x4001A ...

0x40200               symbol definition
SUB1:   movl %edi,%eax
        ...
        ret
```

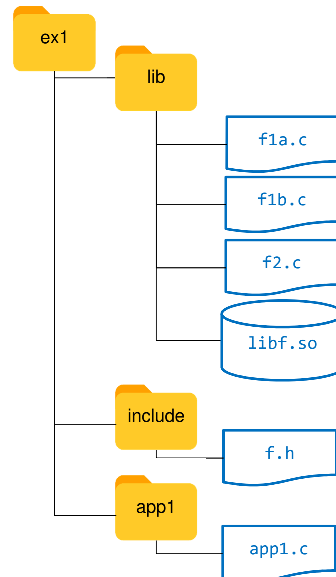
Statically Linked Code

```
0x4000e movq 0x24019(%rip), %rax
        callq *%rax
0x4001A ...

0x50e80
SUB1:   movl %edi,%eax
        ...
        ret

Jump table (Global Offset Table)
0x64020: 0x0000 0000
0x64024: 0x0000 0000
0x64028: 0x0000 0000
0x6402c: 0x0005 0e80
```

Dynamically Linked Code

Shared Library Exercise

```
cd lib
rm -f *.o *.a
gcc -c -fpic f1a.c f2.c
gcc -shared f1a.o f2.o -o libf.so
ls
cd ../app1
gcc -I../include -L../lib app1.c -lf
./a.out       # loader can't find libf.so
# set search path for libraries
export LD_LIBRARY_PATH=../lib:$LD_LIBRARY_PATH
./a.out       # should see '11' output
cd ../lib
rm libf.so
gcc -c -fpic f1b.c
gcc -I../include -shared f1b.o f2.o -o libf.so
cd ../app1
./a.out       # should se '1111' output
              # without recompile/relink
cd ..
```



APPENDIX – DETAILS OF CALCULATING RELOCATIONS

Relocation Entries

```
0000000000000000 <main>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi
   e:   e8 00 00 00 00          callq  13 <main+0x13>
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

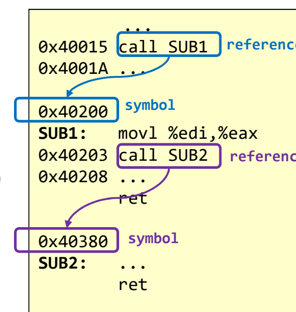
```
Relocation section '.rela.text' at offset 0x208 contains 2 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
00000000000a  00090000000a R_X86_64_32       0000000000000000 array + 0
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 sum - 4
```

ELF Header
.text
.rodata
.data
.bss
.symtab
.rel.text
.debug
.line
.strtab
Section header table

- The linker creates **relocation entries** containing:
  - Type of offset
    - **PC-Relative** (R_X86_64_PC32) or **Absolute Address** (R_X86_64_32)
  - Section offset where the relocation should be replaced
  - Symbol being referenced (and its symbol table index)

Relative Displacement Calculation

- When the linker combines all text and data into their respective sections, it will be able to determine the address of the symbol
- Then it will apply the relocation entries and ______________ the PC-relative displacements
- Formula
  - Disp = Symbol address - (reference address + addend)
  - Recall: the PC ____________ on to the next instruction by the time the instruction executes
  - addend is usually some constant (often ____) to account for the fact that the PC no longer points at the reference location
- Updated formula
  - Disp = Symbol address - (reference address + 4)
  - Disp = Symbol address + (-4) - reference address



Applying Relocation Entries (1)

```
0000000000000000 <main>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi
   e:   e8 00 00 00 00          callq  13 <main+0x13>
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

`$ readelf –r main.o`

```
Relocation section '.rela.text' at offset 0x208 contains 2 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
00000000000a  00090000000a R_X86_64_32       0000000000000000 array + 0
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 sum - 4
```

ELF Header
.text
.rodata
.data
.bss
.symtab
.rel.text
.debug
.line
.strtab
Section header table

```
Disp. = Symbol address + addend - reference address
0xffffffbf = ______________________________
```

Executable Object

```
00000000004004d6 <sum>:
  4004d6:       85 f6                   test   %esi,%esi
  ...

0000000000400504 <main>:
  400504:       48 83 ec 08             sub    $0x8,%rsp
  400508:       be 02 00 00 00          mov    $0x2,%esi
  40050d:       bf 30 10 60 00          mov    $0x601030,%edi
  400512:       e8 bf ff ff ff          callq  4004d6 <sum>
  400517:       48 83 c4 08             add    $0x8,%rsp
  40051b:       c3                      retq
```

Absolute Address Relocation:
`*(main + 0x0a) = 0x601030`

PC-Relative Relocation:
`*(main + 0x0f) = 0xffffffbf =`
____

Applying Relocation Entries (2)

```
0000000000000000 <sum>:
   0:   85 f6                   test   %esi,%esi
...
  26:   c6 05 00 00 00 00 01    movb   $0x1,0x0(%rip)
  2d:   c3                      retq
```

`$ readelf –r sum.o`

```
Relocation section '.rela.text' at offset 0x1d8 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000028  000900000002 R_X86_64_PC32     0000000000000001 done - 5
```

ELF Header
.text
.rodata
.data
.bss
.symtab
.rel.text
.debug
.line
.strtab
Section header table

```
Disp. = Symbol address + addend - reference address
0x200b36 = ______________________________
```

Executable Object

```
0000000000601039 g     O .bss   0000000000000001              done

00000000004004d6 <sum>:
  4004d6:       85 f6                   test   %esi,%esi
...
  4004fc:       c6 05 36 0b 20 00 01    movb   $0x1,0x200b36(%rip) # 601039 <done>
  400503:       c3                      retq
```

PC-Relative Relocation:
`*(sum + 0x28) = 0x00200b36`