Linking

15-213 / 18-213: Introduction to Computer Systems
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Today

- Linking
- Case study: Library interpositioning
Example C Program

**main.c**

```c
int buf[2] = {1, 2};

int main()
{
    swap();
    return 0;
}
```

**swap.c**

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
    int temp;

    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```
Static Linking

- Programs are translated and linked using a compiler driver:
  - unix> gcc -O2 -g -o p main.c swap.c
  - unix> ./p
Why Linkers?

- **Reason 1: Modularity**
  
  - Program can be written as a collection of smaller source files, rather than one monolithic mass.
  
  - Can build libraries of common functions (more on this later)
    - e.g., Math library, standard C library
Why Linkers? (cont)

- **Reason 2: Efficiency**
  
  - Time: Separate compilation
    - Change one source file, compile, and then relink.
    - No need to recompile other source files.
  
  - Space: Libraries
    - Common functions can be aggregated into a single file...
    - Yet executable files and running memory images contain only code for the functions they actually use.
What Do Linkers Do?

■ Step 1. Symbol resolution

□ Programs define and reference symbols (variables and functions):
  □ void swap() {...} /* define symbol swap */
  □ swap(); /* reference symbol swap */
  □ int *xp = &x; /* define symbol xp, reference x */

□ Symbol definitions are stored in object file (by compiler) in symbol table.
  □ Symbol table is an array of structs
  □ Each entry includes name, size, and location of symbol.

□ Linker associates each symbol reference with exactly one symbol definition.
What Do Linkers Do? (cont)

- **Step 2. Relocation**
  - Merges separate code and data sections into single sections
  - Relocates symbols from their relative locations in the .o files to their final absolute memory locations in the executable.
  - Updates all references to these symbols to reflect their new positions.
Three Kinds of Object Files (Modules)

- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
  - Each `.o` file is produced from exactly one source (`.c`) file

- **Executable object file (`.out` file)**
  - Contains code and data in a form that can be copied directly into memory and then executed.

- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries (DLLs)* by Windows
Executable and Linkable Format (ELF)

- Standard binary format for object files

- One unified format for
  - Relocatable object files (.o),
  - Executable object files (a.out)
  - Shared object files (.so)

- Generic name: ELF binaries
ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.

- **Segment header table**
  - Page size, virtual addresses memory segments (sections), segment sizes.

- **.text section**
  - Code

- **.rodata section**
  - Read only data: jump tables, ...

- **.data section**
  - Initialized global variables

- **.bss section**
  - Uninitialized global variables
  - “Block Started by Symbol”
  - “Better Save Space”
  - Has section header but occupies no space

<table>
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<tr>
<th>ELF header</th>
<th>Segment header table (required for executables)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>.text section</td>
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<tr>
<td></td>
<td>.rodata section</td>
</tr>
<tr>
<td></td>
<td>.data section</td>
</tr>
<tr>
<td></td>
<td>.bss section</td>
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<td>.rel.txt section</td>
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<tr>
<td></td>
<td>.rel.data section</td>
</tr>
<tr>
<td></td>
<td>.debug section</td>
</tr>
</tbody>
</table>

Section header table
ELF Object File Format (cont.)

- **.symtab section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations

- **.rel.text section**
  - Relocation info for `.text` section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.

- **.rel.data section**
  - Relocation info for `.data` section
  - Addresses of pointer data that will need to be modified in the merged executable

- **.debug section**
  - Info for symbolic debugging (gcc -g)

- **Section header table**
  - Offsets and sizes of each section
Linker Symbols

- **Global symbols**
  - Symbols defined by module $m$ that can be referenced by other modules.
  - E.g.: non-`static` C functions and non-`static` global variables.

- **External symbols**
  - Global symbols that are referenced by module $m$ but defined by some other module.

- **Local symbols**
  - Symbols that are defined and referenced exclusively by module $m$.
  - E.g.: C functions and variables defined with the `static` attribute.
  - Local linker symbols are *not* local program variables
# Resolving Symbols

**main.c**

```c
int buf[2] = {1, 2};
int main()
{
    swap();
    return 0;
}
```

**swap.c**

```c
extern int buf[];
int *bufp0 = &buf[0];
static int *bufp1;
void swap()
{
    int temp;
    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

- **Global**: `int buf[2] = {1, 2};`
- **External**: `
extern int buf[];
int *bufp0 = &buf[0];
static int *bufp1;`
- **Local**: `
void swap()
{
    int temp;
    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}`

Linker knows nothing of `temp`.
Relocating Code and Data

Relocatable Object Files

- System code
- System data

main.o

- main()
- int buf[2]={1,2}

swap.o

- swap()
- int *bufp0=&buf[0]
- static int *bufp1

Executable Object File

- Headers
- System code
- main()
- swap()
- More system code
- System data
- int buf[2]={1,2}
- int *bufp0=&buf[0]
- int *bufp1
- .symtab
- .debug

Even though private to swap, requires allocation in .bss
Relocation Info (main)

main.c

int buf[2] = {1,2};

int main()
{
    swap();
    return 0;
}

main.o

Disassembly of section .data:

Source: objdump -r -d

Carnegie Mellon
Relocation Info (swap, .text)

**swap.c**

```c
extern int buf[];

int *bufp0 = &buf[0];

static int *bufp1;

void swap()
{
    int temp;
    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

**swap.o**

Disassembly of section .text:

```
00000000 <swap>:
  0: 8b 15 00 00 00 00   mov  0x0,%edx
  2: R_386_32       buf
  6: a1 04 00 00 00   mov  0x4,%eax
  7: R_386_32       buf
  b: 55              push %ebp
  c: 89 e5           mov %esp,%ebp
  e: c7 05 00 00 00 00 04 movl $0x4,0x0
  15: 00 00 00
  10: R_386_32       .bss
  14: R_386_32       buf
  18: 8b 08           mov (%eax),%ecx
  1a: 89 10           mov %edx,%eax
  1c: 5d              pop %ebp
  1d: 89 0d 04 00 00 00 00 mov %ecx,0x4
  1f: R_386_32       buf
  23: c3              ret
```
Relocation Info (swap, .data)

**swap.c**

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
    int temp;

    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

Disassembly of section .data:

```
00000000 <bufp0>:
  0:  00 00 00 00

  0: R_386_32 buf
```
Executable Before/After Relocation (.text)

00000000 <main>:
  ...
  e: 83 ec 04  sub  $0x4,%esp
  11: e8 fc ff ff ff  call  12 <main+0x12>
      12: R_386_PC32 swap
  16: 83 c4 04  add  $0x4,%esp
      ...

08048380 <main>:
  8048380: 8d 4c 24 04  lea   0x4(%esp),%ecx
  8048384: 83 e4 f0  and   $0xfffffffff0,%esp
  8048387: ff 71 fc  pushl  0xfffffffffc(%ecx)
  804838a: 55  push   %ebp
  804838b: 89 e5  mov    %esp,%ebp
  804838d: 51  push   %ecx
  804838e: 83 ec 04  sub    $0x4,%esp
  8048391: e8 1a 00 00 00  call  80483b0 <swap>
  8048396: 83 c4 04  add    $0x4,%esp
  8048399: 31 c0  xor    %eax,%eax
  804839b: 59  pop     %ecx
  804839c: 5d  pop     %ebp
  804839d: 8d 61 fc  lea    0xfffffffffc(%ecx),%esp
  80483a0: c3  ret

0x80483b0 + (-4) = 0x8048392 = 0x1a
0x8048396 + 0x1a = 0x80483b0
Before relocation

0:  8b 15 00 00 00 00  mov 0x0,%edx

2: R_386_32        buf

6:  a1 04 00 00 00  mov 0x4,%eax

7: R_386_32        buf

...  c7 05 00 00 00 00 04  movl $0x4,0x0

15:  00 00 00

10: R_386_32        .bss

14: R_386_32        buf

...  89 0d 04 00 00 00  mov %ecx,0x4

1f: R_386_32        buf

23:  c3  ret

After relocation

080483b0 <swap>:
80483b0:  8b 15 20 96 04 08  mov 0x8049620,%edx
80483b6:  a1 24 96 04 08  mov 0x8049624,%eax
80483bb:  55            push %ebp
80483bc:  89 e5         mov %esp,%ebp
80483be:  c7 05 30 96 04 08 24  movl $0x8049624,0x8049630
80483c5:  96 04 08
80483c8:  8b 08         mov (%eax),%ecx
80483ca:  89 10         mov %edx,(%eax)
80483cc:  5d            pop %ebp
80483cd:  89 0d 24 96 04 08  mov %ecx,0x8049624
80483d3:  c3            ret
Executable After Relocation (.data)

Disassembly of section .data:

08049620 <buf>:
  8049620:   01 00 00 00 02 00 00 00

08049628 <bufp0>:
  8049628:   20 96 04 08
**Strong and Weak Symbols**

- Program symbols are either strong or weak
  - **Strong**: procedures and initialized globals
  - **Weak**: uninitialized globals

```c
int foo=5;
p1() {
}
p2() {
}
```

```
int foo;
p1() {
}
p2() {
}
```
Linker’s Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error

- **Rule 2: Given a strong symbol and multiple weak symbol, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol

- **Rule 3: If there are multiple weak symbols, pick an arbitrary one**
  - Can override this with `gcc -fno-common`
# Linker Puzzles

<table>
<thead>
<tr>
<th><code>int x;</code></th>
<th><code>p1() {}</code></th>
<th><code>p1() {}</code></th>
<th><strong>Link time error: two strong symbols (p1)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><code>int x;</code></td>
<td><code>int x;</code></td>
<td><code>p2() {}</code></td>
<td><strong>References to x will refer to the same uninitialized int. Is this what you really want?</strong></td>
</tr>
<tr>
<td><code>int x;</code></td>
<td><code>double x;</code></td>
<td><code>p2() {}</code></td>
<td><strong>Writes to x in p2 might overwrite y!</strong></td>
</tr>
<tr>
<td><code>int x=7;</code></td>
<td><code>double x;</code></td>
<td><code>p2() {}</code></td>
<td><strong>Writes to x in p2 will overwrite y!</strong></td>
</tr>
<tr>
<td><code>int y=5;</code></td>
<td><code>int x;</code></td>
<td><code>p2() {}</code></td>
<td><strong>References to x will refer to the same initialized variable.</strong></td>
</tr>
</tbody>
</table>

## Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.
Role of .h Files

c1.c

```c
#include "global.h"

int f() {
    return g+1;
}
```

c2.c

```c
#include <stdio.h>
#include "global.h"

int main() {
    if (!init) {
        g = 37;
        int t = f();
        printf("Calling f yields %d\n", t);
    } else {
        int g;
        static int init = 1;
        int t = f();
        printf("Calling f yields %d\n", t);
    }
    return 0;
}
```

global.h

```c
#ifndef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```
Running Preprocessor

c1.c

#include "global.h"

int f() {
    return g+1;
}

-DINITIALIZE

int g = 23;
static int init = 1;
int f() {
    return g+1;
}

no initialization

int g;
static int init = 0;
int f() {
    return g+1;
}

global.h

#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif

#include causes C preprocessor to insert file verbatim (Use gcc -E to view result)
Global Variables

- Avoid if you can

- Otherwise
  - Use `static` if you can
  - Initialize if you define a global variable
  - Use `extern` if you use external global variable
Packaging Commonly Used Functions

How to package functions commonly used by programmers?
- Math, I/O, memory management, string manipulation, etc.

Awkward, given the linker framework so far:
- **Option 1:** Put all functions into a single source file
  - Programmers link big object file into their programs
  - Space and time inefficient
- **Option 2:** Put each function in a separate source file
  - Programmers explicitly link appropriate binaries into their programs
  - More efficient, but burdensome on the programmer
Solution: Static Libraries

- Static libraries (.a archive files)
  - Concatenate related relocatable object files into a single file with an index (called an archive).
  
  - Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.
  
  - If an archive member file resolves reference, link it into the executable.
Creating Static Libraries

- Archiver allows incremental updates
- Recompile function that changes and replace .o file in archive.
Commonly Used Libraries

**libc.a (the C standard library)**
- 8 MB archive of 1392 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

**libm.a (the C math library)**
- 1 MB archive of 401 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```bash
% ar -t /usr/lib/libc.a | sort
... fork.o
... fprintf.o
fputc.o
fpu_control.o
freopen.o
fscanf.o
fseek.o
fstab.o
...

% ar -t /usr/lib/libm.a | sort
... e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
e_asinl.o
...```
Linking with Static Libraries

Translators (cpp, cc1, as)

main2.c  vector.h

Archiver (ar)

libvector.a  libc.a

addvec.o  multvec.o

Linker (1d)

main2.o  addvec.o  printf.o

Static libraries

printf.o and any other modules called by printf.o

Relocatable object files

Fully linked executable object file
Using Static Libraries

- **Linker’s algorithm for resolving external references:**
  - Scan `.o` files and `.a` files in the command line order.
  - During the scan, keep a list of the current unresolved references.
  - As each new `.o` or `.a` file, `obj`, is encountered, try to resolve each unresolved reference in the list against the symbols defined in `obj`.
  - If any entries in the unresolved list at end of scan, then error.

- **Problem:**
  - Command line order matters!
  - Moral: put libraries at the end of the command line.

- `unix> gcc -L. libtest.o -lmine`
- `unix> gcc -L -lmine libtest.o`
- `libtest.o: In function `main'
  libtest.o(.text+0x4): undefined reference to `libfun'`
# Loading Executable Object Files

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<th>Executable Object File</th>
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<td>Program header table</td>
<td>(created at runtime)</td>
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<tr>
<td>(required for executables)</td>
<td></td>
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<tr>
<td>.init section</td>
<td>Memory-mapped region</td>
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<td></td>
</tr>
<tr>
<td>.data section</td>
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<td>.bss section</td>
<td>(created by malloc)</td>
</tr>
<tr>
<td>.symtab</td>
<td></td>
</tr>
<tr>
<td>.debug</td>
<td>Read/write segment</td>
</tr>
<tr>
<td>.line</td>
<td>(.data, .bss)</td>
</tr>
<tr>
<td>.strtab</td>
<td>Read-only segment</td>
</tr>
<tr>
<td>Section header table</td>
<td>(init, text, rodata)</td>
</tr>
<tr>
<td>(required for relocatables)</td>
<td>Unused</td>
</tr>
</tbody>
</table>

- **Memory outside 32-bit address space**: Memory outside 32-bit address space
- **%esp**: (stack pointer)
- **brk**: Loaded from the executable file

Memory-mapped region for shared libraries

- **User stack**: (created at runtime)
- **Run-time heap**: (created by malloc)
- **Read/write segment**: (.data, .bss)
- **Read-only segment**: (.init, .text, .rodata)
- **Unused**
Shared Libraries

- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function needs std libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **Modern solution: Shared Libraries**
  - Object files that contain code and data that are loaded and linked into an application *dynamically*, at either *load-time* or *run-time*
  - Also called: dynamic link libraries, DLLs, `.so` files
Shared Libraries (cont.)

- Dynamic linking can occur when executable is first loaded and run (load-time linking).
  - Common case for Linux, handled automatically by the dynamic linker (`ld-linux.so`).
  - Standard C library (`libc.so`) usually dynamically linked.

- Dynamic linking can also occur after program has begun (run-time linking).
  - In Linux, this is done by calls to the `dlopen()` interface.
    - Distributing software.
    - High-performance web servers.
    - Runtime library interpositioning.

- Shared library routines can be shared by multiple processes.
  - More on this when we learn about virtual memory
Dynamic Linking at Load-time

main2.c  vector.h

Translators (cpp, cc1, as)

main2.o

Linker (ld)

p2

Loader (execve)

Dynamic linker (ld-linux.so)

unix> gcc -shared -o libvector.so \ addvec.c multvec.c

libc.so

libvector.so

Relocation and symbol table info

Code and data
Dynamic Linking at Run-time

```c
#include <stdio.h>
#include <dlfcn.h>

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
    void *handle;
    void (*addvec)(int *, int *, int *, int);
    char *error;

    /* Dynamically load the shared lib that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
```
Dynamic Linking at Run-time

... 

/* Get a pointer to the addvec() function we just loaded */
addvec = dlsym(handle, "addvec");
if ((error = dlerror()) != NULL) {
    fprintf(stderr, "%s
", error);
    exit(1);
}

/* Now we can call addvec() just like any other function */
addvec(x, y, z, 2);
printf("z = [%d %d]
", z[0], z[1]);

/* unload the shared library */
if (dlclose(handle) < 0) {
    fprintf(stderr, "%s
", dlerror());
    exit(1);
}
return 0;
Today

- Linking
- Case study: Library interpositioning
Case Study: Library Interpositioning

Library interpositioning: powerful linking technique that allows programmers to intercept calls to arbitrary functions

Interpositioning can occur at:

- Compile time: When the source code is compiled
- Link time: When the relocatable object files are statically linked to form an executable object file
- Load/run time: When an executable object file is loaded into memory, dynamically linked, and then executed.
Some Interpositioning Applications

- **Security**
  - Confinement (sandboxing)
    - Interpose calls to libc functions.
  - Behind the scenes encryption
    - Automatically encrypt otherwise unencrypted network connections.

- **Monitoring and Profiling**
  - Count number of calls to functions
  - Characterize call sites and arguments to functions
  - Malloc tracing
    - Detecting memory leaks
    - **Generating address traces**
Example program

```c
#include <stdio.h>
#include <stdlib.h>
#include <malloc.h>

int main()
{
    free(malloc(10));
    printf("hello, world\n");
    exit(0);
}

hello.c
```

- **Goal:** trace the addresses and sizes of the allocated and freed blocks, without modifying the source code.

- **Three solutions:** interpose on the `lib malloc` and `free` functions at compile time, link time, and load/run time.
Compile-time Interpositioning

```c
#ifdef COMPILETIME
/* Compile-time interposition of malloc and free using C preprocessor. A local malloc.h file defines malloc (free) as wrappers mymalloc (myfree) respectively. */

#include <stdio.h>
#include <malloc.h>

/*
 * mymalloc - malloc wrapper function
 */
void *mymalloc(size_t size, char *file, int line)
{
    void *ptr = malloc(size);
    printf("%s:%d: malloc(%d)=%p\n", file, line, (int)size, ptr);
    return ptr;
}
```

mymalloc.c
Compile-time Interpositioning

```c
#define malloc(size) mymalloc(size, __FILE__, __LINE__ )
#define free(ptr) myfree(ptr, __FILE__, __LINE__ )

void *mymalloc(size_t size, char *file, int line);
void myfree(void *ptr, char *file, int line);
```

```
linux> make helloc
gcc -O2 -Wall -DCOMPILETIME -c mymalloc.c
gcc -O2 -Wall -I. -o helloc hello.c mymalloc.o
linux> make runc
./helloc
hello.c:7: malloc(10)=0x501010
hello.c:7: free(0x501010)
hello, world
```
#ifdef LINKTIME
/* Link-time interposition of malloc and free using the static linker's (ld) "--wrap symbol" flag. */

#include <stdio.h>

void *__real_malloc(size_t size);
void __real_free(void *ptr);

/*
 * __wrap_malloc - malloc wrapper function
 */
void *__wrap_malloc(size_t size)
{
    void *ptr = __real_malloc(size);
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}

mymalloc.c
The “-Wl” flag passes argument to linker

Telling linker “--wrap,malloc” tells it to resolve references in a special way:

-Refs to malloc should be resolved as __wrap_malloc
-Ref to __real_malloc should be resolved as malloc

```bash
linux> make hellol
gcc -O2 -Wall -DLINKTIME -c mymalloc.c
gcc -O2 -Wall -Wl,--wrap,malloc -Wl,--wrap,free \
-o hellol hello.c mymalloc.o
linux> make runl
./hellol
malloc(10) = 0x501010
free(0x501010)
hello, world
```
#ifdef RUNTIME
  /* Run-time interposition of malloc and free based on *
  * dynamic linker's (ld-linux.so) LD_PRELOAD mechanism */
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

void *malloc(size_t size)
{
  static void *(*mallocp)(size_t size);
  char *error;
  void *ptr;

  /* get address of libc malloc */
  if (!mallocp) {
    mallocp = dlsym(RTLD_NEXT, "malloc");
    if ((error = dlerror()) != NULL) {
      fputs(error, stderr);
      exit(1);
    }
  }
  ptr = mallocp(size);
  printf("malloc(%d) = %p\n", (int)size, ptr);
  return ptr;
}
Load/Run-time Interpositioning

- The `LD_PRELOAD` environment variable tells the dynamic linker to resolve unresolvedrefs (e.g., to `malloc`) by looking in `libdl.so` and `mymalloc.so` first.
  - `libdl.so` necessary to resolve references to the `dlopen` functions.

```
linux> make hellor
gcc -O2 -Wall -DRUNTIME -shared -fPIC -o mymalloc.so mymalloc.c
gcc -O2 -Wall -o hellor hello.c
linux> make runr
(LD_PRELOAD="/usr/lib64/libdl.so ./mymalloc.so" ./hellor)
malloc(10) = 0x501010
free(0x501010)
hello, world
```
Interpositioning Recap

■ Compile Time
  ▪ Apparent calls to malloc/free get macro-expanded into calls to mymalloc/myfree

■ Link Time
  ▪ Use linker trick to have special name resolutions
    ▪ malloc \rightarrow \texttt{\_\_wrap\_malloc}
    ▪ \texttt{\_\_real\_malloc} \rightarrow \texttt{malloc}

■ Compile Time
  ▪ Implement custom version of malloc/free that use dynamic linking to load library malloc/free under different names