

CSCI 2021: ELF Files, Linking, and Loading

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Logistics

Reading Bryant/O'Hallaron

- ▶ Ch 9: Virtual Mem
- ▶ Ch 7: ELF / Linking

Goals

- ▶ Finish Virtmem
- ▶ ELF Files
- ▶ Linking/Loading

P4

- ▶ Due Mon 01-May
- ▶ Unified OH: 01-May
- ▶ Lab 14: Help on P4
- ▶ Video later today (maybe)

Date	Event
Mon 24-Apr	Virtmem Wrap Obj Code/Linking
Tue 25-Apr	Lab/HW 13 Due
Wed 26-Apr	Obj Code/Linking Lab 14: P4 + Feedback
Fri 28-Apr	Obj Code/Linking
Mon 01-May	Last Lecture, Review SRTs due by 1:25pm Unified OH in Lind 325 P4 Due
Fri 05-May	10:30a-12:30pm Final Exam for 1:25pm Lec 001
Sat 06-May	10:30a-12:30pm Final Exam for 3:35pm Lec 010

Course Feedback

Course Exit Survey on Canvas

- ▶ Opens on Canvas Wed 24-Apr, Due Tue 02-May
- ▶ 1 Engagement Point for Completing it

Official Student Rating of Teaching (SRTs)

- ▶ Official UMN Evals are done online this semester
- ▶ Available here: <https://srt.umn.edu/blue>
- ▶ **EVALUATE YOUR LECTURE SECTION: 001 or 010**
Optionally evaluate lab section
- ▶ **Due** Mon 01-May by 1:25pm
- ▶ Response Rate $\geq 80\%$ in **both sections** → One Final Exam Question Revealed

Final Exam Logistics

- ▶ Final Exam in person, normal lecture location
 - ▶ ~1.5 pages F/B Virtual Memory / Linking / Object Files / P5
 - ▶ ~1.5 page F/B Comprehensive Review
(F/B = Front/Back)
- ▶ 2 hours to take Final Exam in person
- ▶ Review during last lecture

Overview

- ▶ Review building programs
- ▶ Executable and Linkable Format (ELF) Files
- ▶ Linker: Merging ELF files
- ▶ Loading: Creating running Problems
- ▶ Relocation
- ▶ Static vs Dynamic Linking
- ▶ Static/Dynamic Libraries

May not have time to cover all these topics and whatever we don't get to won't appear on any exams.

The Immense Journey (apologies to Loren Eisley)

From C source file to running process involves a variety of tools, formats, software and hardware, summarized for Linux below

1. *Compilation*: gcc preprocesses prog.c file, converts to internal representation, optimizes, produces assembly code (stop at this stage with -S)
2. *Assembly*: gas invoked by gcc to turn a prog.s file to a prog.o ELF file, may be other .o files involved for multiple .c files
3. *Linking*: ld invoked by gcc to link multiple .o files to single executable or library, copy in any statically linked library code, indicates if executable has dynamic library dependencies
4. *Stored Program*: Now have an executable program in ELF format stored on disk waiting to be run; call it prog.out
5. *Loading*: ld-linux.so invoked by shell to load prog.out into memory, sets up virtual memory map for .data / .text / heap / stack, initializes .bss sections to 0, resolves any dynamic library links required at load time, sets %rip to first program instruction
6. *Running*: OS handles remaining behavior of executing program (**process**), running, sleeping, exiting, killing on segfaults

Exercise: Separate Compilation

COMPILATION 1

```
> gcc -c func_01.c  
> gcc -c main_func.c  
> gcc -o main_func main_func.o func_01.o
```

COMPILATION 2

```
> gcc -o main_func main_func.c func_01.c
```

- ▶ Describe differences between compilations above
- ▶ What is the result in each case?
- ▶ How are they different: any *artifacts* created in one but not the other?
- ▶ Any advantages/disadvantages to them?

Answers: Separate Compilation

COMPILATION 1

```
> gcc -c func_01.c  
> gcc -c main_func.c  
> gcc -o main_func main_func.o func_01.o
```

COMPILATION 2

```
> gcc -o main_func main_func.c func_01.c
```

Compilation 1: Separate Compilation

- ▶ Separately compile `func_01.c` and `main_func.c` to binary
- ▶ Results in 2 **.o object files**
- ▶ Final step is to **link** two objects together to create an executable

Compilation 2: “Together” Compilation

- ▶ Compile all the C files at once to produce an executable
- ▶ Still likely to internally do separate compilation BUT no `.o` files will be produced, only executable

Advantages of Separate Compilation described at the end of this presentation, primarily efficiency: changing 1 file means recompiling 1 file and re-linking, NOT recompiling all files

Object Files and ELF

- ▶ Binary files can't be random so will usually adhere to some standard
- ▶ **Executable and Linkable Format (ELF)** is standard for the results of compilation on Unix systems
- ▶ Stores program data in a variety of **sections** in binary
- ▶ Explicitly designed to allow binary objects to be
 - ▶ Executed (programs)
 - ▶ Merged with other objects (linked)

Historically, ELF was preceded by a dated format called `a.out`: still default name of gcc output programs

ELF header
Segment header table (required for executables)
.text section
.rodata section
.data section
.bss section
.symtab section
.rel.text section
.rel.data section
.debug section
Section header table

Brief Tour of ELF Sections

- ▶ ELF defines sections that are used in specific circumstances
 - ▶ Always ELF Header at the beginning
 - ▶ Always Program (Segment) Header Table for executable
 - ▶ Always Section Header Table for linkable objects
- ▶ Some sections like `.debug` are common but don't appear in ELF specification (have their own DWARF spec)

Section	Brief Description
ELF Header	Global Info (32- or 64-bit, Executable?, Byte ordering, etc.)
Program Header Table	For executable programs, virtual address space info
Section Header Table	Descriptions of sections and positions in file
<code>.text</code>	Opcodes (binary assembly) that can be executed
<code>.rodata</code>	Read Only data like string constants
<code>.data</code>	Initialized global variables, space for values
<code>.bss</code>	Un-initialized global variables, no space for values
<code>.symtab</code>	Table of publicly available symbols for funcs/vars
<code>.strtab</code>	Null-terminated strings, names of things in <code>.symtab</code>
<code>.shstrab</code>	Null-terminated strings, names in section headers
<code>.debug</code>	Debug info from gcc <code>-g</code> in DWARF format
<code>.rel.text</code>	Relocation information for <code>.text</code> section
<code>.rel.data</code>	Relocation information for <code>.data</code> section

ELF is a Binary Format

- ▶ ELF is a binary format so it is NOT easy on the eyes
- ▶ Make use of utilities like `readelf` to examine sections
- ▶ Can view bytes yourself but it is not usually intelligible

ELF Header									
1st program header		.text							
00000000	7F454C46	01020100	00000000	00000000	00020014	00000001	0ELF.....4. ... (
00000018	10000054	00000034	00000184	00000000	00340020	00010028	...b..... ...!яа		
00000030	00050002	00000001	00000000	10000000	10000000	00000162	...N...и...Е.х...<оГyx		
00000048	00000162	00000005	00010000	7C0802A6	90010004	9421FFE8	...N... ...yA...о.гх8.и		
00000060	BF810008	48000005	7FE802A6	83C50278	801E003C	7FC3F378	...N... ...yA...о.гх8.и		
00000078	7C0903A6	4E800421	389F00DC	38A00032	801E01A8	7FC3F378	...N... ...yA...о.гх8.и		
00000090	7C0903A6	4E800421	7C7C1B79	41820080	7F84E378	38BF00E8	...N... ...yA...о.гх8.и		
000000A8	38C00001	38E00000	801E01C0	7FC3F378	7C0903A6	4E800421	...N... ...yA...о.гх8.и		
000000C0	7C7D1B79	41820044	801D0060	7FA3EB78	7C0903A6	4E800421	...N... ...yA...о.гх8.и		
000000D8	7C641B78	38BF00ED	38C00000	801D0058	7FA3EB78	7C0903A6	...N... ...yA...о.гх8.и		
000000F0	4E800421	7FA4EB78	801E01C8	7FC3F378	7C0903A6	4E800421	...N... ...yA...о.гх8.и		
00000108	7F84E378	801E01AC	7FC3F378	7C0903A6	4E800421	801E0040	...N... ...yA...о.гх8.и		
00000120	7FC3F378	7C0903A6	4E800421	38600000	8B810008	38210020	...N... ...yA...о.гх8.и		
00000140	80010004	7C0803A6	4E800020	646F732E	6C96272	61727908	...N... ...yA...о.гх8.и		
00000160	6D61696E	0048656C	6C6F2057	6F726C64	2100002E	73796D74	...N... ...yA...о.гх8.и		
.shstrtab	00000168	6162002E	73747274	6162002E	73687374	72746162	...N... ...yA...о.гх8.и		
1st section header (NULL)	00000180	78740038	00000000	00000000	00000000	00000000	...N... ...yA...о.гх8.и		
2nd section header (.text)	00000198	00000000	00000000	00000000	00000000	00000018	...N... ...yA...о.гх8.и		
3rd section header (.shstrtab)	000001B0	00000001	00000000	10000054	00000054	0000010E	...N... ...yA...о.гх8.и		
4th section header (.syntab)	000001C8	00000000	00000001	00000000	00000011	00000003	...N... ...yA...о.гх8.и		
5th section header (.strtab)	000001E0	00000000	00000162	00000021	00000000	00000000	...N... ...yA...о.гх8.и		
	000001F0	00000000	00000001	00000002	00000000	00000000	...N... ...yA...о.гх8.и		
	00000210	00000030	00000004	00000002	00000004	00000010	...N... ...yA...о.гх8.и		
	00000228	00000003	00000000	00000000	0000027C	00000008	...N... ...yA...о.гх8.и		
	00000240	00000000	00000001	00000000	00000000	00000000	...N... ...yA...о.гх8.и		
	00000258	00000000	00000000	10000054	00000000	03000001	...N... ...yA...о.гх8.и		
	00000270	10000054	00000000	10000001	005F7374	61727400	...N... ...yA...о.гх8.и		
.syntab							...N... ...yA...о.гх8.и		
.strtab							...N... ...yA...о.гх8.и		

Linking: Merging Binary Files to One

Linking: merge multiple `.o` into one `.o` OR executable file

- ▶ Merge `.text` section with instructions
- ▶ Merge `.data` section with global variables
- ▶ Merge `.symtab` modifying positions of where things exist, etc.

Symbol Resolution

- ▶ Multiple object files define a symbol, must resolve which definition to use
- ▶ Some tricky bugs can arise in resolution

Relocation

- ▶ Adjust offsets of things in symbol table
- ▶ Change any instructions which use locations that have changed

Linkers must deal with a lot of details; we will only touch on a few important principles and how they relate C/Assembly programs

Linker: Multiple .o to Single/Executable

- ▶ A linker converts multiple .o files to...
 - ▶ An executable (default)
 - ▶ Single .o file (-r option)
- ▶ gcc automatically invokes the linker when creating executables
- ▶ Can also manually play with linker: command 'ld'
 - ▶ SO: Why is the Unix linker called 'ld'?
- ▶ Rarely use ld by hand: difficult to generate executables properly
- ▶ gcc invokes ld with *many* additional options / libraries to create executables

```
# Demo merging two .o files with ld
```

```
> nm func_01.o # names in .o file
0000000000000000 T func_01
                  U puts
```

```
> nm func_02.o # names in .o file
0000000000000000 T func_02
                  U puts
```

```
# manually link to create combined .o
```

```
> ld -r func_01.o func_02.o \
    -o funcs_12.o
```

```
> nm funcs_12.o # names in .o file
0000000000000000 T func_01
0000000000000013 T func_02
                  U puts
```

```
# can't create executable with
# undefined symbols and no main()
```

```
> ld func_01.o func_02.o \
    -o executable.o
```

```
ld: warning: cannot find
entry symbol _start;
defaulting to 00000000004000e8
func_01.o: In function 'func_01':
func_01.c:(.text+0xc): 'puts' undefined
func_02.o: In function 'func_02':
func_02.c:(.text+0xc): 'puts' undefined
```

Symbol Resolution by the Linker

- ▶ Linker must resolve **symbols** when merging relocatable objects (.o files)
- ▶ Only global stuff qualify as symbols: **functions, global variables**. These can be seen / used from outside a C file
- ▶ Local variables inside functions will NOT have symbols associated
- ▶ A few rules apply during symbol resolution
 1. .o files can have undefined symbols but executables cannot (for the most part) cannot
 2. Symbols are classified as **strong and weak**; can only have one **strong** definition but many weak definitions
 3. Strong definitions are mostly named functions and global variables with initial values
 4. Weak definitions are mostly uninitialized global variables and extern declarations for global variables, function prototypes

Exercise: Linking Trouble

Consider these two C files

```
// FILE: x_int.c
int x=0;           // global vars
int y=0;           // strongly defined

void x_to_neg8(); // in different .o

#include <stdio.h>
int main(){
    x_to_neg8(); // set x only
    printf("x: %d\n",x);
    printf("y: %d\n",y);
    return 0;
}
```

```
// FILE: x_long.c
long x; // global var
           // weakly defined
void x_to_neg8(){
    x = -8; // set global var
}
```

Compile + Run

```
> gcc -fcommon x_int.c x_long.c
/usr/bin/ld: Warning: ...
> ./a.out
x: -8
y: -1   # WTF^M??
```

Why is this output unexpected?

What might be the cause?

Answers: Linking Trouble

- ▶ Two files define the sizes of global variable x differently

```
// FILE: x_long.c
long x;           // uninitialized, weak symbol
// FILE: x_int.c
int x = 0;        // initialized, strong symbol, prevails
int y = 0;
```

- ▶ Linker warns of this during compilation (see below)

```
> gcc -fcommon x_int.c x_long.c
/usr/bin/ld: Warning: alignment 4 of symbol 'x'
in /tmp/ccs1zLtj.o is smaller than 8 in /tmp/cc37ZX9Q.o
```

- ▶ Variable y in x_int.c, adjacent to 4-byte x in memory
- ▶ Function void x_to_neg8() is in x_long.c
- ▶ Writes 8 bytes to location x clobbering y

INITIAL MEMORY

GLOBALS	#2044	y	0	0x00000000	
	#2040	x	0	0x00000000	

movq \$-8, 2040 # 8-byte write for a long

GLOBALS	#2044	y	-1	0xFFFFFFFF	
	#2040	x	-8	0xFFFFFFFF8	

- ▶ Message: Global variables are dangerous in linking (and for code design in general) [but you knew that already]

Version Note

GCC Version 10 (Rel May 7, 2020) prevents global variable linking problems better by NOT mapping uninitialized C vars to “Common” (weak) symbols.

*GCC now defaults to -fno-common. As a result, global variable accesses are more efficient on various targets. In C, **global variables with multiple tentative definitions now result in linker errors**. With -fcommon such definitions are silently merged during linking.*

– *GCC 10 Release Series, Changes, New Features, and Fixes*

```
> gcc --version
gcc (GCC) 10.2.0
```

```
> gcc x_long.c x_int.c
/usr/bin/ld: /tmp/ccEBD0n.o:
multiple definition of 'x';
collect2: error: ld returned
1 exit status
```

```
> file a.out
a.out: cannot open 'a.out'
(No such file or directory)
```

```
vvvvvvvvv
> gcc -fcommon x_long.c x_int.c
/usr/bin/ld: warning:
size of symbol 'x' changed from 8
in /tmp/ccSWBZ.o to 4 in /tmp/ccENzS.o
```

```
> file a.out
a.out: ELF 64-bit LSB pie executable
```

The Value of Headers and extern declarations

- ▶ Headers (.h) declare global symbols for all C files that will use them

- ▶ May declare *external* variables which are defined in another file

```
// FILE: x_to_neg8.h
extern long x;
void x_to_neg8();
-----
// FILE: x_to_neg8.c
#include "x_to_neg8.h"
long x; // actual global var
void x_to_neg8(){
    x = -8;
}
-----
// FILE: x_main.c
#include "x_to_neg8.h"
// there will be an x var
// and x_to_neg8() func
...
```

- ▶ Proper use of headers allow compiler to warn of conflicting definitions

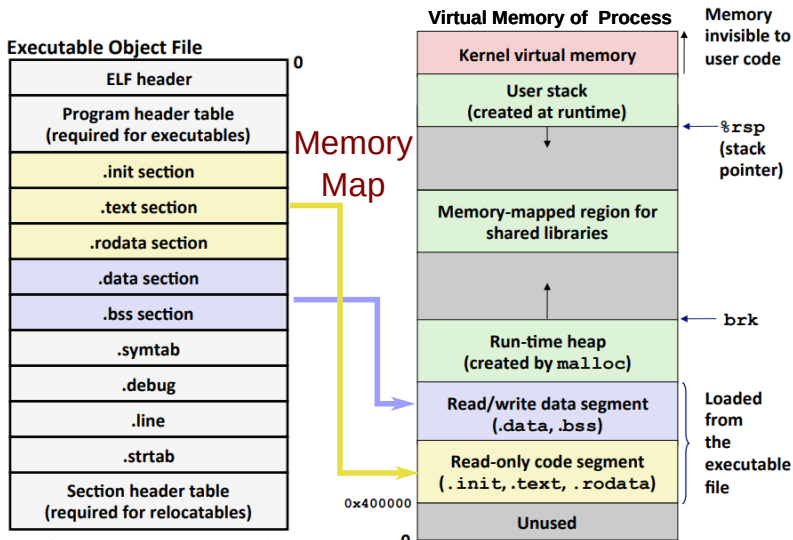
```
// FILE: x_main.c
#include "x_to_neg8.h"
int x = 0; // !!!
...

> gcc -c x_main_bad.c
x_main_bad.c:4:5: error:
conflicting types for 'x'
    int x = 0; // !!!
    ^
x_to_neg8.h:7:13: note:
previous declaration of
'x' was here
    extern long x;
    ^
```

- ▶ Without using .h header files, compiler can't help as much

Loading ELF: Stored Program becomes Running Process

- ▶ Loader maps ELF file Text/Globals into virtual memory
- ▶ Loader maps Stack/Heap into virtual memory



Linker and Loader

Traditional: Static Linking

- ▶ Linker merges .o files to create executable
- ▶ All global symbols must be resolved: copy text for functions into the executable from libraries
- ▶ **Loader** copies executable into memory, set %rip to first instruction address, notifies OS to schedule it for execution
- ▶ All code/data for running program is in its own memory image

Modern: Dynamic Linking

- ▶ Linker merges .o files to create executable
- ▶ Global symbols from Dynamic Libraries are left Undefined (U)
- ▶ Loader copies executable into memory, sets %rip but..
- ▶ Creates a virtual memory map to definitions for library functions **dynamically linking** to definitions
- ▶ Code for running program is spread across its memory image and shared libraries

gcc: Statically vs Dynamically Linked Executables

- ▶ By default gcc produces 'mixed' executables
 - ▶ Use as many dynamic libraries (.so) as possible
 - ▶ Use a static version (.a) of library ONLY if no dynamic version is available
- ▶ With the -static option, use all static libraries
- ▶ Note the differences reported by the file command below

```
> cat hello.c
```

```
#include <stdio.h>
int main(int argc, char *argv[]){
    printf("Hello world! I'm a program\n");
    return 0;
}
```

```
# compile static dynamically linked vs statically linked
```

```
> gcc -o hello_dynamic hello.c
```

```
> gcc -o hello_static hello.c -static
```

```
# examine file types
```

```
> file hello_static
```

```
hello_static: ELF 64-bit LSB executable, x86-64, statically linked
```

```
> file hello_dynamic
```

```
hello_dynamic: ELF 64-bit LSB shared object, x86-64, dynamically linked,
interpreter /lib64/ld-linux-x86-64.so.2
```

Exercise: Static/Dynamic Program Sizes

- ▶ Examine file sizes of two programs below reported by du
- ▶ Which program is bigger on disk in number of bytes?
- ▶ **Why** is there a size difference?

```
# compile static dynamically linked vs statically linked
> cat hello.c
#include <stdio.h>
int main(int argc, char *argv[]){
    printf("Hello world! I'm a program\n");
    return 0;
}

> gcc -o hello_dynamic hello.c
> gcc -o hello_static hello.c -static

# examine size of executables in bytes
> du -b hello_*
 9664 hello_dynamic
721424 hello_static
```

Answers: Static/Dynamic Program Sizes

```
# examine size of executables in bytes
> du -b hello_*
 9664  hello_dynamic  # 9,664 bytes
721424 hello_static   # 721,424 bytes
```

- ▶ All libc.a functions needed (printf/puts/malloc/etc.) copied into statically linked version
- ▶ Dynamically linked version has undefined references to functions like puts() which will be resolved at load/run time

```
# examine symbols/functions
# in static/dynamic executables
```

```
> nm hello_static
```

```
...
00000000004009dd T main
# T: defined "strong" symbol
...
0000000000408460 W puts
# W: defined "weak" symbol
...
```

```
> nm hello_dynamic
```

```
...
000000000000064a T main
# T: defined "strong" symbol
...
```

```
U puts@@GLIBC_2.2.5
# U: undefined
# your funciont is in
# a different castle
```

Libraries Required at Load/Runtime

- ▶ Most executables know ahead of time which dynamic libraries will be needed at run time
- ▶ Can examine this with the `ldd` command: print shared object dependencies

```
> gcc -o hello_dynamic hello.c
```

```
> gcc -o hello_static hello.c -static
```

```
# examine which libraries will be dynamically linked
```

```
# compile static dynamically linked vs statically linked
```

```
> ldd hello_static
```

```
not a dynamic executable
```

```
> ldd hello_dynamic
```

```
linux-vdso.so.1 (0x00007ffe9b0fb000)
```

```
libc.so.6 => /usr/lib/libc.so.6 (0x00007f6a8c295000) #printf!
```

```
/lib64/ld-linux-x86-64.so.2 =>
```

```
/usr/lib64/ld-linux-x86-64.so.2 (0x00007f6a8c84e000)
```


Linking Against Standard Libraries

- ▶ At link time, linker must know about library dependencies
- ▶ gcc option `-l` will link against a library
 - > `gcc do_math.c -lm` # link to math library
 - > `gcc do_pthreads.c -lpthread` # link to threads library
- ▶ Default Convention: `-lmystuff` tries linking files
 - ▶ `libmystuff.so` (dynamic lib) THEN
 - ▶ `libmystuff.a` (static lib)
- ▶ Force use of ONLY static libraries with `-static` option
- ▶ GCC **always** links `libc` (unless using `-nostdlib`)
- ▶ Compiler/Linker searches known directories for headers and libraries

```
> gcc -v do_math.c -lm          # -v: verbose output
...
#include <...> search starts here:
/usr/lib/gcc/x86_64-pc-linux-gnu/7.2.1/include
/usr/local/include
/usr/lib/gcc/x86_64-pc-linux-gnu/7.2.1/include-fixed
/usr/include
...
LIBRARY_PATH=/lib/./usr/lib/...
```

Creating/Linking Statically Linked Libraries

- ▶ Statically Linked Libraries are **archives** with `.a` extension
- ▶ Traditional form of program libraries, comprised of a bunch of `.o` files
- ▶ Utility `ar` allows creation, modification, inspection of `.a` files
- ▶ Most systems include `/lib/libc.a` to allow creation statically linked programs
- ▶ System `.a` archives are identical in structure to user-created libraries

```
> gcc -g -Wall -c tree.c
> gcc -g -Wall -c array.c
> gcc -g -Wall -c list.c
> gcc -g -Wall -c util.c
```

```
# create archive with ar
> ar rcs libds_search.a \
    tree.o array.o list.o util.o
```

```
> file libds_search.a
libds_search.a: current ar archive
```

```
# show .o files in archive
> ar t libds_search.a
tree.o array.o list.o util.o
```

```
> ar t /lib/libc.a | grep printf.o
vfprintf.o vprintf.o reg-printf.o
fprintf.o printf.o snprintf.o
...
```

Linking Against User Libraries

- ▶ Final Exam review exercises will discuss linking against user-libraries NOT in standard library directories

```
> ls ds_search_static/  
libds_search.a  
ds_search.h
```

PROBLEM 1

```
> gcc do_search.c -lds_search  
do_search.c:8:10: fatal error:  
  ds_search.h: No such file or directory  
    #include "ds_search.h"  
           ^~~~~~  
compilation terminated.
```

PROBLEM 2

```
> gcc do_search.c -lds_search ...  
/usr/bin/ld: cannot find -lds_search  
collect2: error: ld returned 1 exit status
```

- ▶ Compilers have options to resolve these two problems

Directing Compiler to non-standard Locations

```
> ls ds_search_static/  
libds_search.a  
ds_search.h
```

```
# PROBLEM 1
```

```
# Use -I to give "includes" directory with header
```

```
> gcc do_search.c -lds_search \  
    -I ds_search_static/    # header directory for ds_search.h  
/usr/bin/ld: cannot find -lds_search  
collect2: error: ld returned 1 exit status
```

```
# PROBLEM 2
```

```
# Use -L to add a directory to search for libraries
```

```
> gcc do_search.c -lds_search \  
    -I ds_search_static/    # header directory for ds_search.h  
    -L ds_search_static/    # library directory with libds_search.a  
> file a.out
```

```
a.out: ELF 64-bit LSB shared object, x86-64
```

Creating Dynamic Libraries

- ▶ Dynamically Libraries are **shared objects** with .so extension (or .dll if you are a Windows user)
- ▶ Created by invoking compiler linker with appropriate options
 - ▶ Compile option fPIC for **position independent code**
 - ▶ Link option -shared for a shared object
- ▶ Dynamic libraries may depend on other dynamic libraries

```
> gcc -g -Wall -fpic -c tree.c
> gcc -g -Wall -fpic -c array.c
> gcc -g -Wall -fpic -c list.c
> gcc -g -Wall -fpic -c util.c
```

```
# create shared object with gcc
> gcc -shared -o libds_search.so \
    tree.o array.o list.o util.o
```

```
> file libds_search.so
libds_search.so: ELF 64-bit LSB
shared object, x86-64, ...
```

```
# show dependencies
> ldd libds_search.so
    linux-vdso.so.1 (0x00007ffce291e000)
    libc.so.6 => /usr/lib/libc.so.6 (0x00007f8e4d1b1000)
    /usr/lib64/ld-linux-x86-64.so.2 (0x00007f8e4d1b1000)
```

Exercise: A Dynamic Hitch

Consider the below hitch which hinders the convenience of dynamic libraries

```
> gcc do_search.c -lds_search \
    -I ds_search_dynamic/ \
    -L ds_search_dynamic/

> ./a.out
a.out: error while loading shared libraries:
libds_search.so: cannot open shared object file:
No such file or directory

> ldd a.out
linux-vdso.so.1
libds_search.so => not found    !!!!
libc.so.6 => /usr/lib/libc.so.6
/lib64/ld-linux-x86-64.so.2 => /usr/lib64/ld-linux-x86-64.so.2
```

- ▶ What went wrong?
- ▶ Thoughts on how to resolve?
- ▶ Why didn't this happen in the statically linked case?

Answers: A Dynamic Hitch

- ▶ Compiler informed that `libds_search.so` was in a non-standard directory
- ▶ **Loader** NOT informed of this
- ▶ Loader searched `/lib/` and other places, didn't find `libds_search.so` gave up on loading the program
- ▶ Must inform loader of non-standard directories for libraries with `LD_LIBRARY_PATH`
- ▶ An **environment variable** honored by loader, directories to search aside from standard locations
- ▶ Environment variables can be set in most shells and are looked for by programs to modify their behaviour
- ▶ Default command shell on many Unixes is `bash` with env't var syntax `export VAR=some_value`
- ▶ Often set vars in initialization files like `.bashrc` or `.bash_init` in your home directory

```
export PAGER=less           # a better 'more'
export EDITOR=emacs         # major improvement
export BROWSER=google-chrome # hog my RAM!
```

Answers: A Dynamic Hitch

Below is a complete session which fixes the loading problem

```
> ./a.out
a.out: error while loading shared libraries:
libds_search.so: cannot open shared object file:
No such file or directory

> export LD_LIBRARY_PATH="ds_search_dynamic"

> ldd a.out
linux-vdso.so.1
libds_search.so => ds_search_dynamic/libds_search.so  :-)
libc.so.6 => /usr/lib/libc.so.6
/lib64/ld-linux-x86-64.so.2 => /usr/lib64/ld-linux-x86-64.so.2

> ./a.out
Searching 2048 elem array, 10 repeats: 1.6470e-01 seconds
```

If distributing a .so, either

- ▶ Install it in a standard location like /usr/lib/ (admin access)
- ▶ Notify users of library to adjust LD_LIBRARY_PATH

Exercise: Dynamic Loading Tricks

Consider the following strange session

```
> gcc hello.c
> ./a.out
Hello World!
My favorite int is 32 and float is 1.234000

> gcc -shared -fPIC -Wl,-soname -Wl,libsamy_printf.so \
    -o libsamy_printf.so samy_printf.c -ldl
> export LD_PRELOAD=$PWD/libsamy_printf.so

> ./a.out
Hello World!
... but most of all, Samy is my hero.
My favorite int is 32 and float is 1.234000
... but most of all, Samy is my hero.
```

Why would compiling another piece of code change the behavior of an **already compiled program**?

Answers: Dynamic Loading Tricks

- ▶ One can **interpose** library calls: ask dynamic loader to link a function to a different definition
- ▶ Only possible with dynamic linking but a powerful technique
- ▶ In this case, re-define `printf()`, similar tricks by `valgrind` for `malloc()` / `free()`

```
> gcc hello.c
> a.out
> ldd a.out
    linux-vdso.so.1
    libc.so.6 => /usr/lib/libc.so.6
    /lib64/ld-linux-x86-64.so.2 => /usr/lib64/ld-linux-x86-64.so.2

> export LD_PRELOAD=$PWD/libsamy_printf.so
> ldd a.out
    linux-vdso.so.1 (0x00007fff591d6000)
    ./libsamy/libsamy_printf.so !!!!!
    libc.so.6 => /usr/lib/libc.so.6
    libdl.so.2 => /usr/lib/libdl.so.2
    /lib64/ld-linux-x86-64.so.2 => /usr/lib64/ld-linux-x86-64.so.2
```

Valgrind and Your own Malloc

- ▶ Valgrind replaces normal `malloc()` / `free()` with its own version which is slower but allows error checking
- ▶ Uses dynamic loading tricks for this so you don't need to recompile your program
- ▶ If you complete `el_malloc.c`, you could extend it to a full allocator (would need `realloc()`, use of `sbrk()` for heap management, define `malloc()` / `free()`)
- ▶ Use **library interposition** with `LD_PRELOAD` dynamically link in your own programs
- ▶ [Brief Instructions in the GNU libc manual](#) on how to do this

Recall: Globals in Assembly

- ▶ A long time ago in an assembly project far, far away...
- ▶ Used a weird syntax to access global variables in assembly

```
movl  SOME_GLOBAL_VAR(%rip), %edi
```

- ▶ Load is based on an offset from the Instruction Pointer `rip`
- ▶ Similarly, will often see in decompiled code the following

```
> objdump -d clock_update.o
```

```
2f2:  e8 00 00 00 00      callq  2f7 <set_tod_from_secs>
```

```
...
```

```
31c:  e8 00 00 00 00      callq  321 <set_display_from_tod>
```

- ▶ Why are both call instructions `e8 00 00 ...`?
- ▶ Both these deserve some explanation

Relocation and PC-Relative Address

- ▶ Linker merges global symbols from multiple `.o` files into single output sections
 - ▶ Functions into single `.text`
 - ▶ Global vars into `.data` / `.bss` sections
- ▶ Historically, linker would just assign a virtual memory address to each symbol / section (simple, easy to implement)
- ▶ **Problem:** forces program to be loaded at a fixed virtual memory address, decreases options available to loader/dynamic linker
- ▶ gcc now generates **relocatable** code by default: all instructions must be independent of exact memory position where program is loaded (trickier but flexible/safer)
- ▶ Loader guarantees: **distance between sections is constant**
 - ▶ `.text` might be loaded at `0x9000` or at `0x9100` by OS
 - ▶ `.text` and `.data` always `0x1000` bytes apart
 - ▶ `.text` loaded contiguously at some start address
- ▶ Addressing relative to PC allows flexibility in code placement, requires extra linker work

Relocation Entries

- ▶ ELF files contain **relocation entries**, spots with unknown address that must be “filled in” at link time
- ▶ Relocation entries are created for **function calls** and **global variable use** in ELF sections
 - ▶ `.rel.text`: Relocation info for `.text` section
 - ▶ `.rel.data`: Relocation info for `.data` section
- ▶ Compiler notes byte locations that require insertion of info at link time
 - ▶ Position where the fix is needed (“fill this in”)
 - ▶ What symbol is needed
 - ▶ Extra arithmetic stuff
- ▶ Interested in two types of relocation entries
 - ▶ `R_X86_64_PC32`: insert address of something relative to `rip`; used for global vars, functions in same C file
 - ▶ `R_X86_64_PLT32`: insert address of a **procedure linkage table entry**; used for functions not in same C file
- ▶ Linker **inserts addresses** at positions indicated by relocation entries

Example of Relocation Entries

ORIGINAL SOURCE CODE

```
// file: glob.c
int glob_arr[128];
void glob_func1(int scale){ ... }

void glob_func2(int scale, inty[])
{
    glob_func1(scale);           // 66
    for(int i=0; i<128; i++){
        glob_arr[i] += y[i];     // 83
        printf("%d\n",glob_arr[i]); // e0
    }
}
```

RELEVANT DISASSEMBLED CODE

```
> objdump -dx glob.o
0000000000000051 <glob_func2>:
   65:  e8 00 00 00 00      callq  6a                # call function
               ^^ 66: R_X86_64_PC32      glob_func1-0x4          # in same file

   80:  48 8d 05 00 00 00 00  lea     0x0(%rip),%rax    # use global var
               ^^ 83: R_X86_64_PC32      glob_arr-0x4           # in same file

   df:  e8 00 00 00 00      callq  e4                # call function
               ^^ e0: R_X86_64_PLT32      printf-0x4            # in another file
```

RELOCATION ENTRIES

```
> readelf -r glob.o
Off Type          Sym + Addend
66 R_X86_64_PC32   glob_func1 - 4
83 R_X86_64_PC32   glob_arr - 4
e0 R_X86_64_PLT32   printf - 4
```

Above byte positions must have addresses inserted by the linker at link time. Currently those position have 00's as placeholders until the linker fills them in.

End Result: Relocatable Code

- ▶ Most ELF programs have **no load time constant addresses**
- ▶ All functions and variables (locals/globals) are referenced relative to the rip (program counter)
- ▶ ELF image can be loaded at an starting Virtual Memory Address and run successfully
- ▶ Will notice memory address of functions/variables change from run to run but the **difference between locations is constant**

```
> gcc -o glob_main glob_main.c glob.c
```

```
> ./glob_main
```

```
ADDRESSES
```

```
0x5637e3bc6060: glob_arr variable
```

```
0x5637e3bc3159: main func
```

```
0x5637e3bc32aa: glob_func1
```

```
0x5637e3bc32fa: glob_func2
```

```
ADDRESS DIFFERENCES
```

```
2f07: glob_arr - main
```

```
2db6: glob_arr - glob_func1
```

```
151: glob_func1 - main
```

```
50: glob_func2 - glob_func1
```

```
> ./glob_main
```

```
ADDRESSES
```

```
0x5642d3feb060: glob_arr variable
```

```
0x5642d3fe8159: main func
```

```
0x5642d3fe82aa: glob_func1
```

```
0x5642d3fe82fa: glob_func2
```

```
ADDRESS DIFFERENCES
```

```
2f07: glob_arr - main
```

```
2db6: glob_arr - glob_func1
```

```
151: glob_func1 - main
```

```
50: glob_func2 - glob_func1
```


Wait, what about that PLT thing?

- ▶ Minor performance hit for dynamically linked libraries, use of program linkage table (PLT) and global offset table (GOT)
- ▶ First call to `printf()` is expensive when it is dynamically linked
- ▶ Dynamic linker delays determining address of `printf()` until it is called
- ▶ Pseudo-code representing gcc / Linux approach to the right: clever use of 1 level of indirection and GOT table of function pointers

```
void main(){
    ...
    printf(...); // compiled to call_printf()
    ...
}

void *GOT[];    // has addresses of funcs

void call_printf(...){
    int (*func_ptr) = GOT[3]; // get func ptr
    func_ptr(...);           // call func
}

void link_printf(...){    // 1st call only
    void *printf_addr =    // use linker to
        dlsym("printf");   // find printf
    GOT[3] = printf_addr;  // save ptr later
    printf_addr(...);      // call printf
}

void *GOT[] = {    // global table
    ...
    &link_printf,  // for first printf call
    ..
}
```

Exercise: Separate Compilation Time

- ▶ Mack is building a large application
- ▶ Has a `main_func.c` and `func_01.c`, `func_02.c` ... that define application, up to `func_20.c`
- ▶ During build process notices that it takes about 10s for to compile each C file and 20s to link the C files
- ▶ After editing files to add features, Mack usually compiles to project like this
 - > `gcc -o main_func *.c`
- ▶ **Estimate** his typical build time in seconds
- ▶ **Suggest** a way that he might reduce his build time if he has edited only a small number of files

Answers: Separate Compilation Time

Total Build Time `gcc -o main_func *.c`

Item	Example	Build	Tot
Library C files	func_01.c	20 x 10s	200s
Main C file	main_func.c	1 x 10s	10s
Linking	all .o files	1 x 20s	20s
Total Time	~ 4min	22 steps	230s

- ▶ Explicitly recompiling all C files to object code despite many not changing
- ▶ Spends valuable human time waiting to redo the same task as has been done many before

Answers: Separate Compilation Time

Exploit Separate Compilation

- ▶ Assume already compiled all files, have `func_01.o`, `func_02.o`
- ▶ Edit `func_08.c` to add a new feature
- ▶ **Don't** recompile C files that haven't changed
- ▶ Compile like this
 - > `gcc -c func_08.c`
 - > `gcc -o main_func *.o`

Item	Example	Build	Time
Library .o files	<code>func_01.o</code>	19 x 0s	0s
Main .o file	<code>main_func.o</code>	1 x 0s	0s
Changed .c files	<code>func_08.c</code>	1 x 10s	10s
Linking	all .o files	1 x 20s	20s
Total Time	~ 30 seconds	2 steps	30s

Build Systems Exploit Separate Compilation

- ▶ Build Systems like make / Makefile exploit separate compilation
- ▶ Build system establishes a dependency structure
- ▶ **Targets** are usually files to create
- ▶ **Dependencies** are other files/targets that must be up to date to create a given target
- ▶ Only rebuild a target if a dependency **changes**

```
# Typical Makefile gives targets, dependencies,  
# commands to create target using dependencies  
# TARGET : DEPENDENCIES  
#      COMMANDS / ACTIONS
```

```
main_func : main_func.o func_01.o func_02.o  
    gcc -o main_funcs main_func.o func_01.o func_02.o
```

```
main_func.o : main_func.c  
    gcc -c main_funcs.c
```

```
func_01.o : func_01.c  
    gcc -c funcs_01.c
```

Example Builds from big-compile/

```
> make clean
rm -f *.o main_func

# first compiles, no object files built, build everything
> make main_func
gcc -c main_func.c
gcc -c func_01.c
gcc -c func_02.c
...
gcc -c func_20.c
gcc -o main_func main_func.o func_01.o func_02.o...

# edit func_08.c

# 1 file changed, recompile it and re-link
> make main_func
gcc -c func_08.c      # ONLY NEED TO RECOMPILE THIS
gcc -o main_func main_func.o func_01.o func_02.o...

# no edits, no need to rebuild
> make main_func
make: Nothing to be done for 'main_func'.
```

Exercise: Initialized vs Uninitialized Data Matters

Some interesting engineering tricks are baked into the ELF file format. Observe:

```
// FILE: big_data.c
long arr[20000] = {1,2,3};
int main(){
    for(int i=0; i<1024; i++){
        arr[i] = i;
    }
    return 0;
}

> gcc -c big_data.c # compile to object
> du -b big_data.o # print number of bytes
161384 big_data.o

// FILE: big_bss.c
long arr[20000] = {};
int main(){
    for(int i=0; i<1024; i++){
        arr[i] = i;
    }
    return 0;
}

> gcc -c big_bss.c # compile to object
> du -b big_bss.o # print number of bytes
1384 big_bss.o
```

- ▶ What is the difference between the two files above?
- ▶ Why is there such a size difference in the object files

Answers: Initialized vs Uninitialized Data Matters

- ▶ ELF .data section tracks global variables that is initialized with non-zero values
- ▶ Must record every value in global variable so it can be properly set when loaded to run

- ▶ big_data.o will have a large .data section as the line
`long arr[20000] = {1,2,3};`

initializes the first few array values, rest will be 0

```
> readelf -S big_data.o
```

There are 12 section headers, starting at offset 0x27368:

Section Headers:

[Nr]	Name	Type	Address	Offset	
	Size	EntSize	Flags Link Info Align		
...					
[3]	.data	PROGBITS	0000000000000000	00000080	<--
----	> 00000000000027100	0000000000000000	WA 0 0 32		
[4]	.bss	NOBITS	0000000000000000	00027180	<--
	0000000000000000	0000000000000000	WA 0 0 1		
...					

- ▶ 0x27100 = 160000 bytes: entire arr array stored in file

Answers: Initialized vs Uninitialized Data Matters

- ▶ ELF .bss section tracks global variables that are not initialized or initialized to all 0's
- ▶ No specific values need be recorded, just instructions on how much space to allocate on starting the program
- ▶ big_bss.o will have a miniscule .data section as the line `long arr[20000] = {};` initializes to all 0's so .bss section

```
> readelf -S big_bss.o
```

There are 12 section headers, starting at offset 0x268:

Section Headers:

[Nr]	Name Size	Type EntSize	Address Flags Link Info	Offset Align
...				
[3]	.data 0000000000000000	PROGBITS 0000000000000000	0000000000000000 WA 0 0	0000007f 1
[4]	.bss 00000000000027100	NOBITS 0000000000000000	0000000000000000 WA 0 0	00000080 <-- 32

[5]	.comment 0000000000000012	PROGBITS 0000000000000001	0000000000000000 MS 0 0	00000080 <-- 1
...				

- ▶ arr array NOT stored in file, significantly smaller .o file

— END SPRING 2023 CONTENT —

The remaining slides are informative but optional. Their content will not be part of the SPRING 2022 final exam.