CS 241: Systems Programming
Lecture 30. Dynamic Libraries

Fall 2025

Prof. Stephen Checkoway

Announcements

- Monday’s lecture is a project work day
- Tuesday’s lab is a project work day
- There is no scheduled class/lab. Please use the time to work on your final projects.

Review - Static Libraries

Static libraries (or archives) are a way of bundling a collection of object files together

The object files are linked together into a program at compile time

Today

Dynamic libraries

- Very commonly used in C, C++
- Rust can use dynamic libraries written in C, and produce dynamic libraries that can be used by C programs

Dynamic libraries

Like static libraries, dynamic libraries start as a collection of object files (`.o`)

- When linking an executable against a static library, the **program linker** copies the relevant library code/data into the output

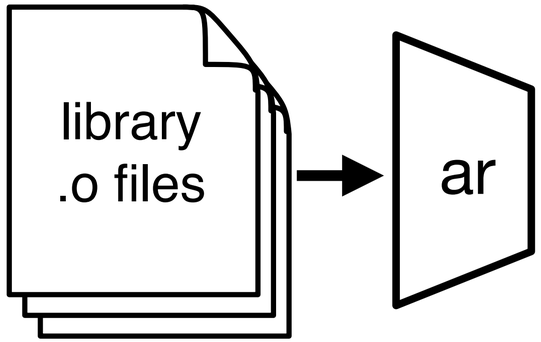
Unlike static libraries, dynamic libraries are produced by the linker

- When linking an executable against a dynamic library, the **program linker** inserts references to the library into the output, but does not copy the library code/data into the output

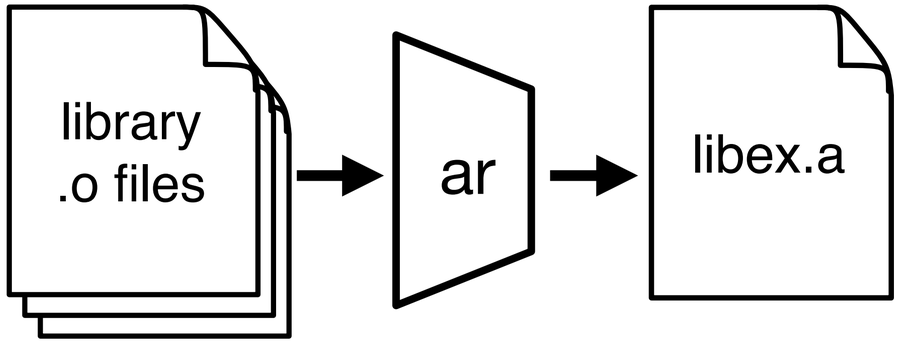
At run time the **dynamic linker** (the loader) loads the executable and all of its required libraries into memory

Static library

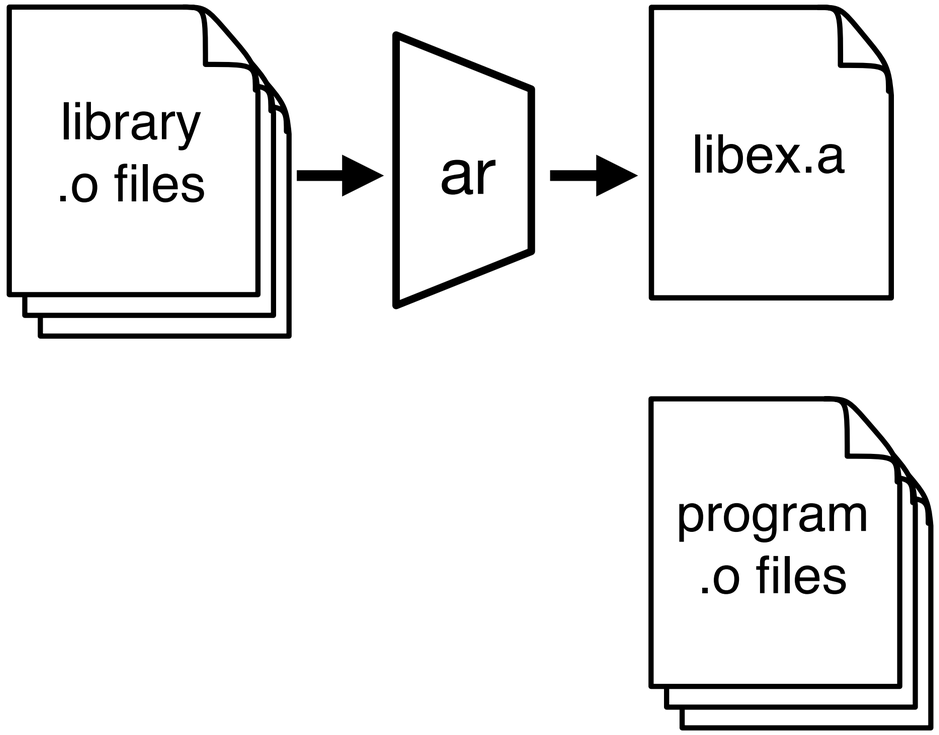
Static library



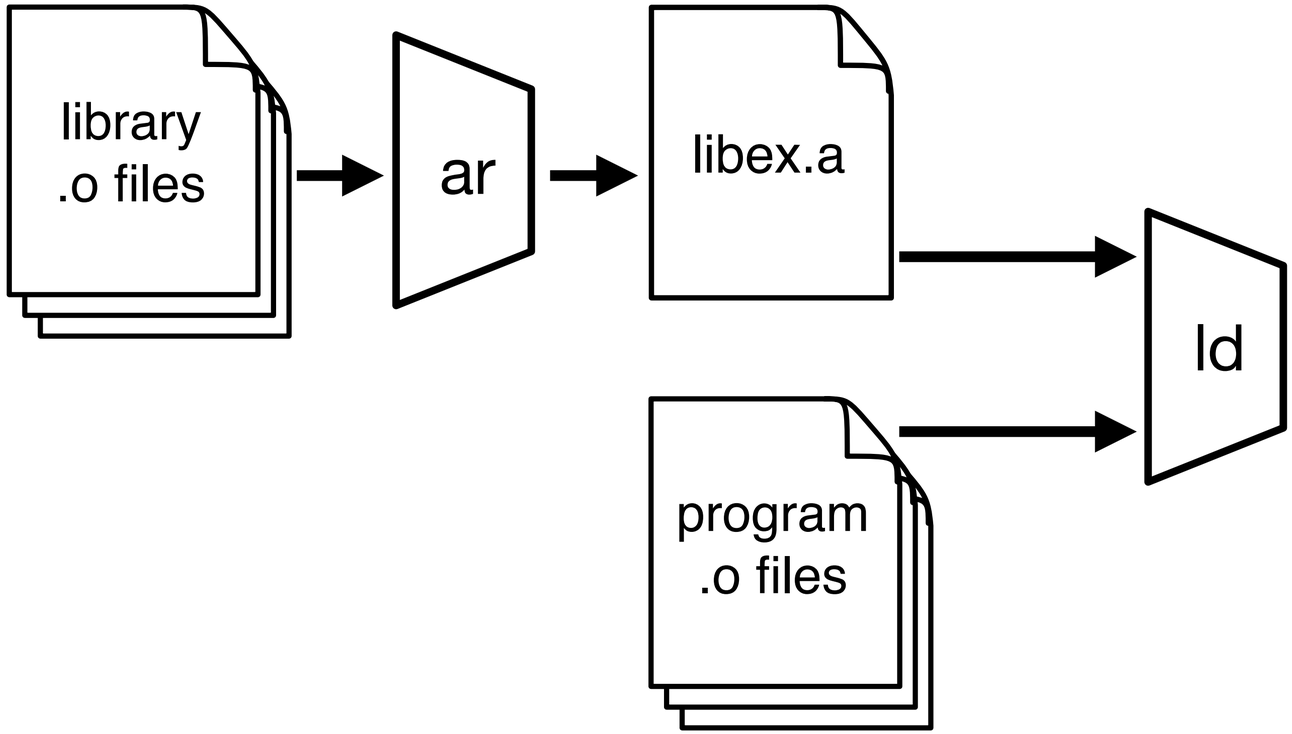
Static library



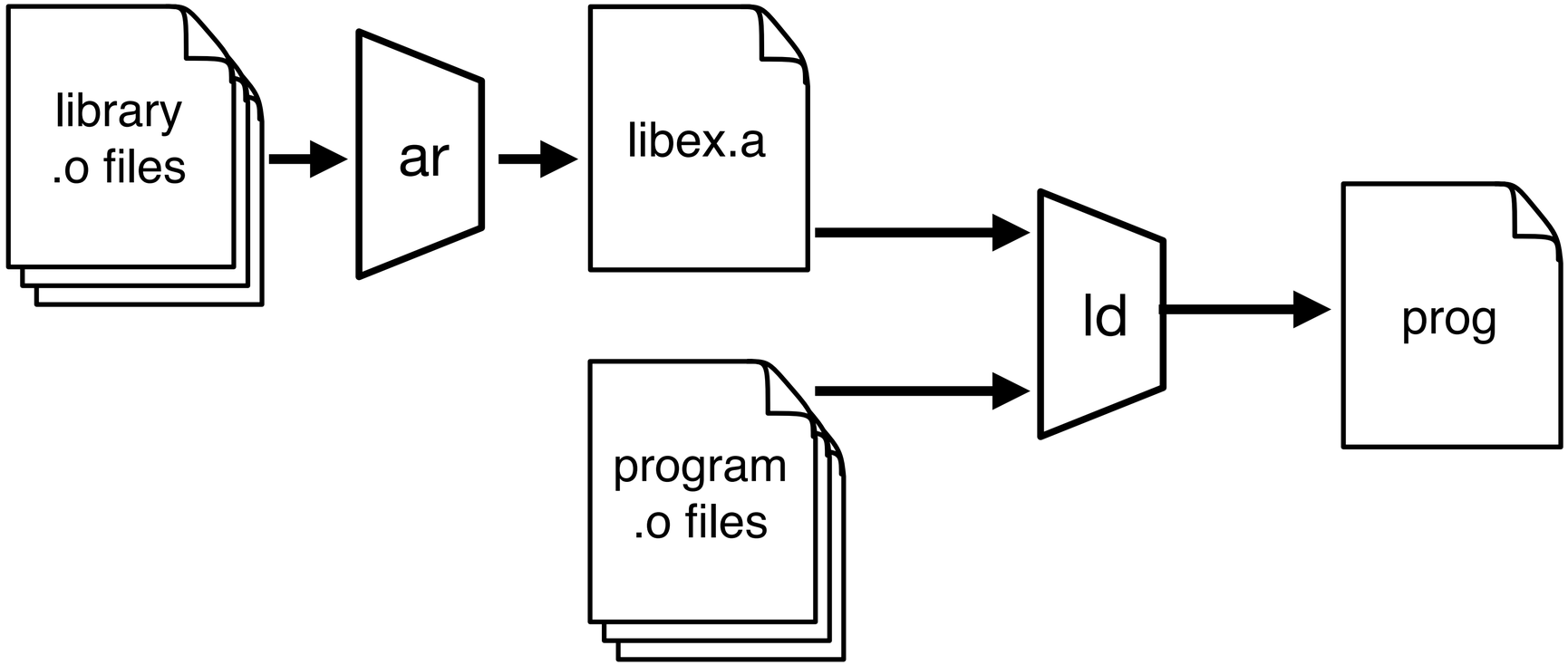
Static library



Static library



Static library



Dynamic library

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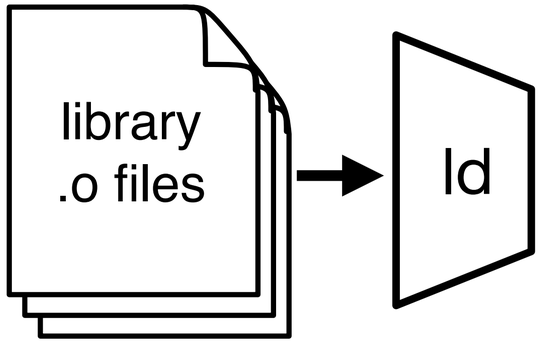
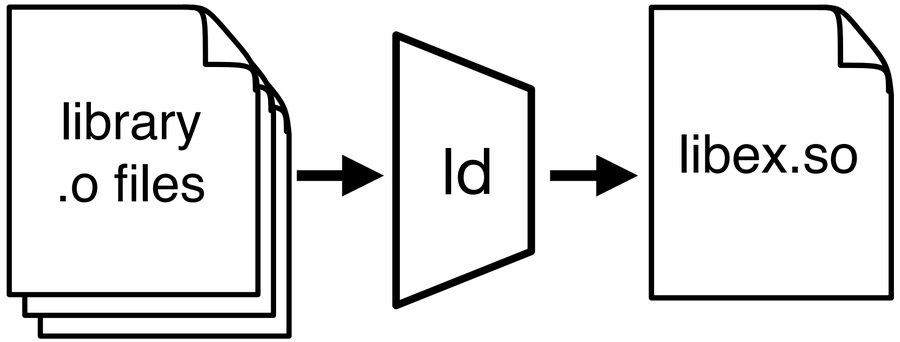
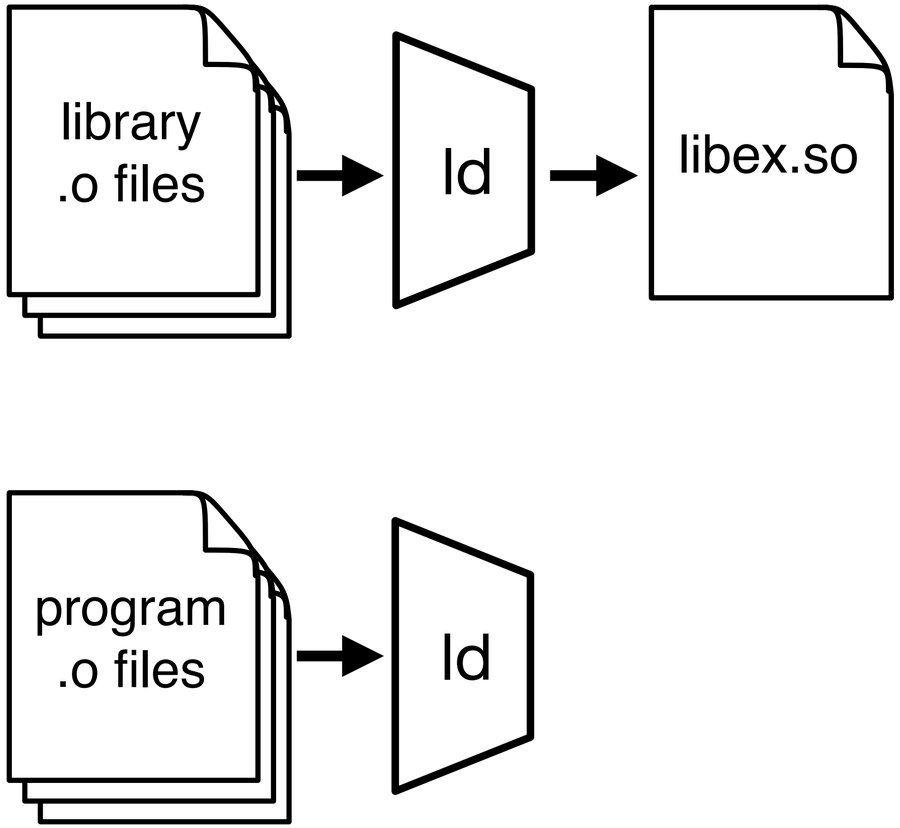


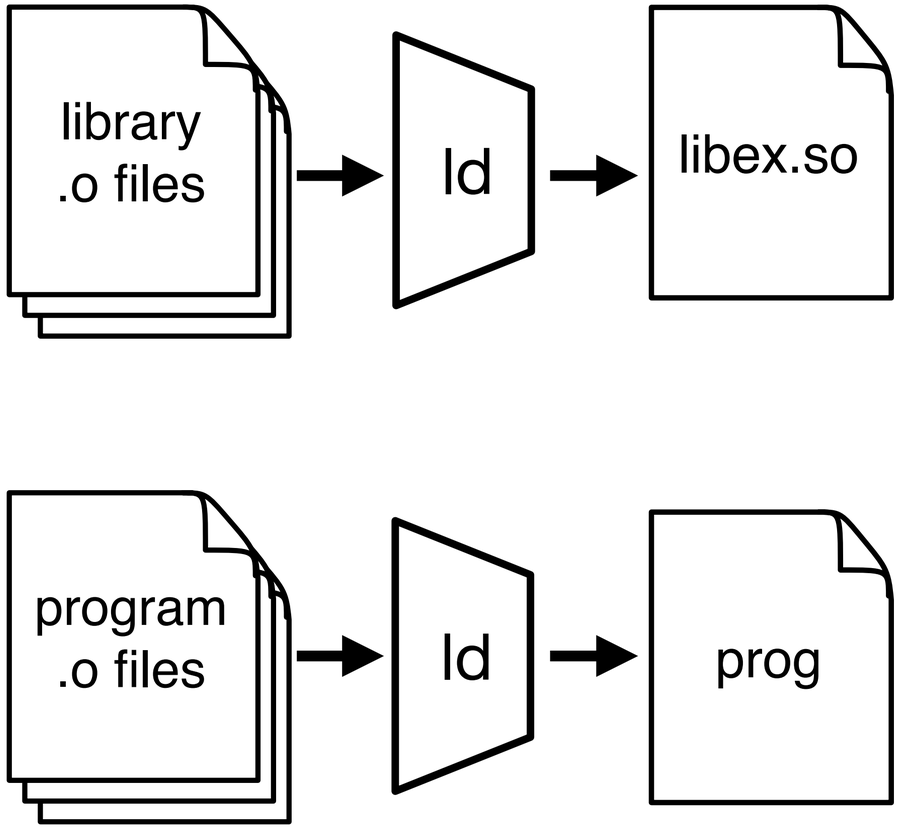
Dynamic library



Dynamic library



Dynamic library



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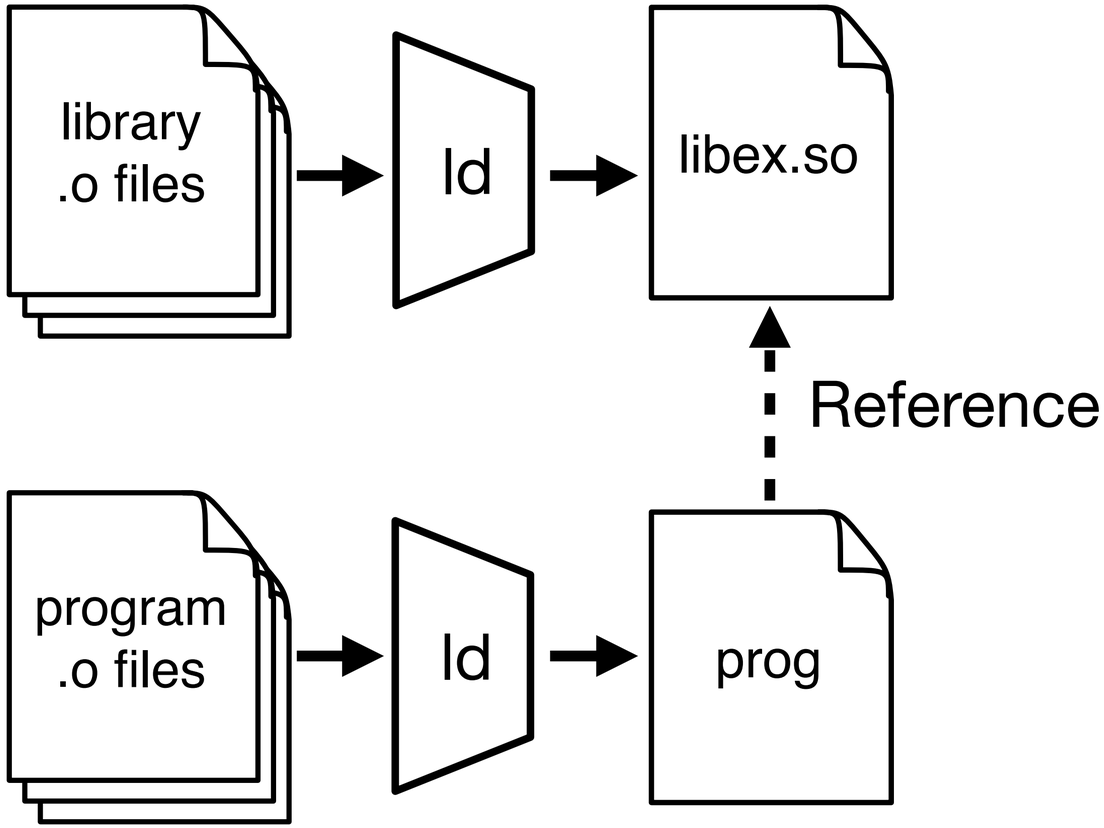

Differences at runtime

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Programs linked to static libraries

- Library code/data is part of the program
- Only the object files needed are included
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Programs linked to dynamic libraries

- Library code/data is loaded into memory separately
- The whole library is included, not just the needed bits
- Library code/data is loaded at a semi-arbitrary address
- Multiple programs can share a single copy of library code and read-only data; they need their own copy of the writable data
- The program loader needs to perform more work at program start up

When a library is used by many applications (e.g., libc), which of the following is **not** a benefit of using a **dynamic** library as compared to using a static library?

A. Smaller memory usage for an individual application

B. Smaller total memory usage across multiple applications

C. Smaller total disk usage across multiple applications

D. Faster program linking

When a library is used by only one application, which of the following is **not** a benefit of using a **static** library as compared to a dynamic library?

A. Smaller memory usage for the application

B. Smaller disk usage for the application

C. Faster program startup

D. Better program performance (it runs faster) separate from its start up speed

E. Bugs in the library can be fixed independently of the application

soname (ELF-based systems)

Each dynamic library has a **soname** (shared object name)

- `lib⟨name⟩.so.⟨ABI version⟩`
- ABI is application binary interface
- The soname specifies the name of the library and its ABI version
- Multiple versions of a library with a compatible ABI have the same soname
- Versions of a library with incompatible ABIs (different functions or parameters) have a different soname
  - `libc.so.5`
  - `libc.so.6`

soname vs. file name (Linux)

Example sonames

- zlib (a compression library) has the soname `libz.so.1`
- libc's soname is `libc.so.6`
- PCRE's library's soname is `libpcre.so.3`

On the file system the soname is a symbolic link to the actual library

- The file name is *usually* `lib⟨name⟩.so.⟨major⟩.⟨minor⟩.⟨patch⟩`
- The major version number is often the ABI version
  - `libz.so.1 -> libz.so.1.2.11`
  - `libpcre.so.3 -> libpcre.so.3.13.3`
  - `libc.so.6 -> libc-2.27.so` <- Nonstandard name!

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The two need not be in the same directory

- `/usr/lib/x86_64-linux-gnu/libz.so -> /lib/x86_64-linux-gnu/libz.so.1.2.11`
- `/lib/x86_64-linux-gnu/libz.so.1 -> libz.so.1.2.11`
- `/lib/x86_64-linux-gnu/libz.so.1.2.11`

Linking to a .so

We specify a library using a command line option: `-l`

- `$ clang -o prog main.o -lblah`

`libblah.so` is a symlink to `libblah.so.1.3.2` which has a soname of `libblah.so.1`

- The compiler records `libblah.so.1` in the output `prog`

At run time, the loader will look for `libblah.so.1` (which will be a symlink) and follow that link to the actual library which could be `libblah.so.1.4.0`

Wait, why might the library loaded at runtime, `libblah.so.1.4.0`, be different from that at compile time, `libblah.so.1.3.2`? (next slide)

Why might the library used at compile time differ from the library used at run time? And is that a problem?

A. Vote for A when you've come up with one

B. Vote for B if you can't think of a reason

Example: bash

We can see the library sonames recorded in a binary using the `--dynamic` (`-d`) option to `readelf`

```
mhogan@mcnulty:~$ readelf -d /bin/bash | grep NEEDED
 0x0000000000000001 (NEEDED)             Shared library: [libtinfo.so.6]
 0x0000000000000001 (NEEDED)             Shared library: [libdl.so.2]
 0x0000000000000001 (NEEDED)             Shared library: [libc.so.6]
```

Compiler search paths

When the compiler searches for files, it looks in a variety of paths

- Header files (for C or C++) come from the header search path
- Library files come from the library search path
- macOS has “Frameworks” which are like packaged libraries, headers, and data; the compiler has a search path for Frameworks

We can add a directory to a specific search path via command line arguments to the compiler

- The particular arguments depend on the types of files and on the compiler

Runtime search paths

When the program starts, the dynamic linker looks at the sonames recorded in the binary and looks for a file with a matching name (which is usually a symlink) and loads that library

Actual library paths for bash

We can print the paths of the libraries that will be loaded

```
mhogan@mcnulty:~$ ldd /bin/bash
  linux-vdso.so.1 (0x00007fff295db000)
  libtinfo.so.6 => /lib/x86_64-linux-gnu/libtinfo.so.6 (0x00007fbbd50ee000)
  libdl.so.2 => /lib/x86_64-linux-gnu/libdl.so.2 (0x00007fbbd50e8000)
  libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007fbbd4ef6000)
  /lib64/ld-linux-x86-64.so.2 (0x00007fbbd525f000)
```

`linux-vdso.so.1` is a virtual dynamic library (see `$ man 7 vdso` for details)
`ld-linux-x86-64.so.2` is the actual dynamic linker (loads everything else into memory)