Building and Using Shared Libraries on Linux

Shared Libraries: The Dynamic Linker

Michael Kerrisk, man7.org © 2023

February 2023

mtk@man7.org

Outline

Rev: # e2bf8f005a44

Outline

Specifying library search paths in an object

- So far, we have two methods of informing the dynamic linker (DL) of location of a shared library:
  - `LD_LIBRARY_PATH`
  - Installing library in one of the standard directories
- Third method: during static linking, we can **insert a list of directories into the executable**
  - A "run-time library path (**rpath**) list"
  - At run time, DL will search listed directories to resolve dynamic dependencies
  - Useful if libraries will reside in locations that are fixed, but not in standard list

[TLPI §41.10]

Defining an rpath list when linking

- To embed an rpath list in an executable, use the *–rpath* linker option (*cc –Wl,–rpath,path-to-lib-dir*)
  - Multiple *–rpath* options can be specified ⇒ ordered list
  - Alternatively, multiple directories can be specified as a colon-separated list in a single *–rpath* option
- Example:

```
$ cc -g -Wall -Wl,-rpath,$PWD -o prog prog.c libdemo.so
$ objdump -p prog | grep 'R[UN]*PATH'
  RPATH                /home/mtk/tlpi/code/shlibs
$ ./prog
Called mod1-x1
Called mod2-x2
```

  - Embeds current working directory in rpath list
  - *objdump* command allows us to inspect rpath list
  - Executable now "tells" DL where to find shared library

An rpath improvement: DT_RUNPATH

There are **two types of rpath list**:

- Differ in precedence relative to `LD_LIBRARY_PATH`
- Original (and default) rpath list has higher precedence
  - `DT_RPATH` ELF entry
- Original rpath behavior was a **design error**
  - User should have full control when using `LD_LIBRARY_PATH`

An rpath improvement: DT_RUNPATH

- **Newer rpath type has lower precedence**
  - **Gives user possibility to override rpath** at runtime using LD_LIBRARY_PATH usually what we want)
  - DT_RUNPATH ELF entry
    - Supported in DL since 1999
  - Use: *cc –Wl,–rpath,some-dir-path –Wl,--enable-new-dtags*
    - Since *binutils* 2.24 (2013): inserts only DT_RUNPATH entry
    - Some distros (Ubuntu) default to *–Wl,--enable-new-dtags*
    - Before *binutils* 2.24, inserted DT_RUNPATH **and** DT_RPATH (to allow for old DLs that didn't understand DT_RUNPATH)
- If both types of rpath list are embedded in an object, **DT_RUNPATH has precedence** (i.e., DT_RPATH is ignored)

Shared libraries can have rpath lists

- Shared libraries can themselves have dependencies
  - ⇒ can use *–rpath* linker option to embed rpath lists when building shared libraries

An object's rpath list is private to the object

- Each object (the main program or a shared library) can have an rpath...
- An object's (DT_RUNPATH) rpath is used for resolving only its own immediate dependencies
  - One object's rpath doesn't affect search for any other object's dependencies
    - See example in shlibs/rpath_independent
- ⚠ Old style rpath (DT_RPATH) behaves differently
  - One object's DT_RPATH can be used for resolving dependencies of another object

Outline

Dynamic string tokens

- DL understands certain special strings in rpath list
  - **Dynamic string tokens**
  - Written as `$NAME` or `${NAME}`
- `$ORIGIN`: expands to directory containing program or library
  - Write turn-key applications!
  - Installer unpacks tarball containing application with library in (say) a subdirectory; application can be linked with:

```
cc -Wl,-rpath,'$ORIGIN/lib'
```

    - ⚠ ⚠ Note use of quotes to prevent interpretation of $ by shell!

Dynamic string tokens

- `$LIB`: expands to `lib` or `lib64`, depending on architecture
  - E.g., useful on multi-arch platforms to supply 32-bit or 64-bit library, as appropriate
- `$PLATFORM`: expands to string corresponding to processor type (e.g., `x86_64`)
  - Rpath entry can include arch-specific directory component
- DL also understands these names in some other contexts
  - `LD_LIBRARY_PATH`, `LD_PRELOAD`, `LD_AUDIT`, and *dlopen()*; see *ld.so(8)*

Outline

Finding shared libraries at run time

When resolving dependencies in dynamic dependency list, DL deals with each dependency string as follows:

- If the string contains a slash ⇒ interpret dependency as a relative or absolute pathname
- Otherwise, search for shared library using these rules
  1. If calling object has `DT_RPATH` list and does **not** have `DT_RUNPATH` list, search directories in `DT_RPATH` list
  2. If `LD_LIBRARY_PATH` defined, search directories it specifies
     - For security reasons, `LD_LIBRARY_PATH` is ignored in "secure" mode (set-UID and set-GID programs, etc.)
  3. If calling object has `DT_RUNPATH` list, search directories in that list
  4. Check `/etc/ld.so.cache` for a corresponding entry
  5. Search `/lib` and `/usr/lib` (in that order)
     - Or `/lib64` and `/usr/lib64`

[TLPI §41.11]

Exercises

1. The directory `shlibs/mysleep` contains two files:
   - `mysleep.c`: implements a function, *mysleep(nsecs)*, which prints a message and calls *sleep()* to sleep for *nsecs* seconds.
   - `mysleep_main.c`: takes one argument that is an integer string. The program calls *mysleep()* with the numeric value specified in the command-line argument.

   Using these files, perform the following steps to create a shared library and executable in the same directory:
   - Build a shared library from `mysleep.c`. (You do **not** need to create the library with a soname or to create the linker and soname symbolic links.)
   - Compile and link `mysleep_main.c` against the shared library to produce an executable that embeds an rpath list with the run-time location of the shared library (specified as an absolute path, e.g., use the value of *$PWD*).
     [Exercise continues on next slide]

Exercises

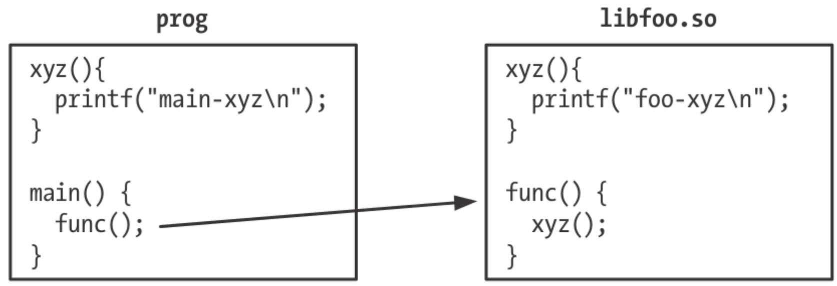
   - Verify that you can successfully run the executable without the use of `LD_LIBRARY_PATH`.
   - Try **moving** (not copying!) both the executable and the shared library to a different directory. What now happens when you try to run the executable? Why?

2. Now employ an rpath list that uses the `$ORIGIN` string:
   - Modify the previous example so that you create an executable with an rpath list containing the string `$ORIGIN/sub`.
     ⚠ Remember to use single quotes around `$ORIGIN`!
   - Copy the executable to some directory, and copy the shared library to a subdirectory, `sub`, under that directory. Verify that the program runs successfully.
   - If you move both the executable and the directory `sub` (which still contains the shared library) to a different location, is it still possible to run the executable?

Outline

Run-time symbol resolution

- Suppose main program and shared library both define a function *xyz()*, and another function inside library calls *xyz()*



- To which symbol does reference to *xyz()* resolve?
- The results may seem a little surprising:

```
$ cc -g -c -fPIC -Wall foo.c
$ cc -g -shared -o libfoo.so foo.o
$ cc -g -o prog prog.c libfoo.so
$ LD_LIBRARY_PATH=. ./prog
main-xyz
```

  - Definition in main program overrides version in library!

Symbol interposition

- When a symbol definition inside an object is overridden by an outside definition, we say symbol has been **interposed**
  - **Interposition** can occur for both functions and variables
- Surprising, but good historical reason for this behavior
- Shared libraries are designed to mirror traditional static library semantics:
  - Definition of global symbol in main program overrides version in library
  - Global symbol appears in multiple libraries?
    - ⇒ reference is resolved to first definition when **scanning libraries in left-to-right order as specified in static link command line**
- Interposition behavior made transition from static to shared libraries easier

Interposition vs libraries as self-contained subsystems

- Symbol interposition semantics **conflict with model of shared library as a self-contained subsystem**
  - Shared library can't guarantee that reference to its own global symbols will bind to those symbols at run time
  - Properties of shared library may change when it is aggregated into larger system
- Can sometimes be desirable to force symbol references within a shared library to resolve to library's own symbols
  - I.e., prevent interposition by outside symbol definition

Forcing global symbol references to resolve inside library

- *–Bsymbolic* linker option causes references to global symbols within shared library to resolve to library's own symbols

```
$ cc -g -c -fPIC -Wall foo.c
$ cc -g -shared -Wl,-Bsymbolic -o libfoo.so foo.o
$ cc -g -o prog prog.c libfoo.so
$ LD_LIBRARY_PATH=. ./prog
foo-xyz
```

  - ELF `DT_SYMBOLIC` tag
- ⚠ Affects **all** symbols in shared library! ☹
- Other techniques can provide this behavior on a per-symbol basis ☺
  - (Described later)

Symbol resolution and library load order

```
         .......main_prog.......
       /          |             \
libx1.so       liby1.so          libz1.so
   |              | abc(){...}      |  call abc()
   |              |                 |
libx2.so       liby2.so          libz2.so
  abc(){...}     xyz(){...}         |
  xyz(){...}                     libz3.so
                                   xyz(){...}
```

- Main program has three dynamic dependencies
- Some libraries on which main has dependencies in turn have dependencies
  - **Note**: main program has no direct dependencies other than `libx1.so`, `liby1.so`, and `libz1.so`
    - Likewise, `libz1.so` has no direct dependency on `libz3.so`

Symbol resolution and library load order

```
       .......main_prog.......
      /         |           \
libx1.so      liby1.so         libz1.so
   |            | abc(){...}     |  call abc()
   |            |                |
libx2.so      liby2.so         libz2.so
  abc(){...}    xyz(){...}       |
  xyz(){...}                   libz3.so
                                 xyz(){...}
```

- libx2.so and liby1.so both define public function *abc()*
- When *abc()* is called from inside libz1.so, which instance of *abc()* is invoked?
  - Call to *abc()* resolves to definition in liby1.so

Symbol resolution and library load order

```
       .......main_prog.......
      /         |           \
libx1.so      liby1.so         libz1.so
   |            | abc(){...}     |  call abc()
   |            |                |
libx2.so      liby2.so         libz2.so
  abc(){...}    xyz(){...}       |
  xyz(){...}                   libz3.so
                                 xyz(){...}
```

- Dependent libraries are added in **breadth-first order**
  - Immediate dependencies of main program are loaded first
  - Then dependencies of those dependencies, and so on
    - Libraries that are already loaded are skipped (but are reference counted)
- Symbols are resolved by searching libraries in load order

Symbol resolution and library load order

```
       .......main_prog.......
      /         |             \
libx1.so      liby1.so         libz1.so
   |            | abc(){...}      |   call abc()
   |            |                 |   call xyz()
libx2.so      liby2.so         libz2.so
  abc(){...}    xyz(){...}        |
  xyz(){...}                   libz3.so
                                 xyz(){...}
```

- A quiz...
- `libx2.so`, `liby2.so`, and `libz3.so` all define public function *xyz()*
- When *xyz()* is called from inside `libz1.so`, which instance of *xyz()* is invoked?
  - Call to *xyz()* resolves to definition in `libx2.so`

Link-map lists ("namespaces")

- Set of shared objects that have been loaded by application is recorded on a **link-map list** (AKA "namespace")
  - Doubly linked list that is arranged in library load order
  - See definition of `struct link_map` in `<link.h>`
  - *dl_iterate_phdr(3)* can be used to iterate through link map
    - (Manual page has an example program)
  - See also *dlinfo(3)*, which obtains info about a dynamically loaded object

Outline

The LD_DEBUG environment variable

- LD_DEBUG can be used to monitor operation of dynamic linker
  - LD_DEBUG="*value*" prog
  - To list LD_DEBUG options, without executing program:

```
$ LD_DEBUG=help ./prog
Valid options for the LD_DEBUG environment variable are:

  libs        display library search paths
  reloc       display relocation processing
  files       display progress for input file
  symbols     display symbol table processing
  bindings    display information about symbol binding
  versions    display version dependencies
  scopes      display scope information
  all         all previous options combined
  statistics  display relocation statistics
  unused      determined unused DSOs
  help        display this help message and exit

To direct the debugging output into a file instead of
standard output a filename can be specified using the
LD_DEBUG_OUTPUT environment variable.
```

  - TLPI §42.6

Exercises

The files in the directory `shlibs/sym_res_load_order` set up the scenario shown earlier under the heading *Symbol resolution and library load order* (slide 4-27). (You can inspect the source code used to build the various shared libraries to verify this.) The `main` program uses *dl_iterate_phdr()* to display the link-map order of the loaded shared objects.

1. Use *make(1)* to build the shared libraries and the main program, and use the following command to run the program in order to verify the link-map order and also to see which versions of *abc()* and *xyz()* are called from inside `libz1.so`:

```
LD_LIBRARY_PATH=. ./main
```

2. Run the program using `LD_DEBUG=libs` and use the dynamic linker's debug output to verify the order in which the shared libraries are loaded.

[Exercise continues on the next slide]

Exercises

3. Run the program using `LD_DEBUG=symbols` and use the dynamic linker's debug output to discover which definitions the calls to *abc()* and *xyz()* bind to.

4. The order in which the immediate dependencies of `main` are loaded into the link map is determined by the order that the libraries are specified in the link command that is used to build `main`. Verify this as follows:
   - Modify the `Makefile` to rearrange the order in which the libraries are specified in the command that builds `main` to be: `libz1.so liby1.so libx1.so`
   - Remove the executable using `make clean`.
   - Rebuild the executable using `make`.
   - Run the executable again, and note the difference in the link-map order that is displayed by *dl_iterate_phdr()*.