Towards oblivious sandboxing

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For those playing along at home: **https://github.com/trombonehero/sandbox-examples**, **https://github.com/freebsd/freebsd**

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Background: Capsicum

- framework for *principled*, *coherent* compartmentalization
- compartmentalization: application subdivision

Principled:

- draws on rich history of computer security concepts and literature
- monotonic reduction of authority

Coherent:

- clear, simple policies
- uniform application across applications

Background: capability mode

No access to global namespaces:

- PIDs
- file paths, filesystem IDs
- NFS file handles
- socket protocol addresses
- sysctl MIBs
- POSIX, SysV IPC names
- system clocks
- jails, CPU sets

Hotel California

Strong isolation

Alternative syscall filter: `seccomp(2)`

- filter system calls with BPF programs
- easy: check syscall number (on same arch)
- hard: check arguments (e.g., filenames)
- impossible: check arguments *meaningfully* (just like `systrace`)

```
#define Allow(syscall) \
    BPF_JUMP(BPF_JMP+BPF_JEQ+BPF_K, SYS_##syscall, 0, 1), \
    BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_ALLOW)

struct sock_filter filter[] = {
    // Check architecture: syscall numbers arch-dependent!
    BPF_STMT(BPF_LD+BPF_W+BPF_ABS, ArchField),
    BPF_JUMP(BPF_JMP+BPF_JEQ+BPF_K, AUDIT_ARCH_X86_64, 1, 0),
    BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_KILL),

    // Check syscall:
    BPF_STMT(BPF_LD+BPF_W+BPF_ABS, SYSCALL_NUM_OFFSET),
    Allow(brk),             // allow stack extension
    Allow(close),           // allow closing files!
    /* ... */
    Allow(openat),          // to permit openat(config_dir), etc.
    BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_TRAP),    // or die
```

Thanks: https://eigenstate.org/notes/seccomp

Alternative syscall filter: `pledge(2)`

- *much* simpler filters
  - e.g., `stdio` limits to `clock_getres(2)`, `close(2)`, `dup(2)`, `fchdir(2)`, `read(2)`…
  - `rpath` allows read-only effects on the filesystem: `chdir(2)`, `getcwd(3)`, `openat(2)`, …
- optional path whitelisting

Still insufficient!

```
// Enter sandbox!
if (pledge("stdio rpath cpath flock", NULL) < 0)
{
    err(-1, "error in pledge()");
}
```

```
// Or we could've whitelisted a few specific paths
// (assuming we know them all in advance).
const char *paths[] =
{
    "foo.lock",
    "bar.lock!",
    NULL,
};
```

pledge(2) and seccomp(2): the good news

Can sandbox trivial applications trivially

If your application only needs `read(2)`, `write(2)`, `close(2)`, etc.:

```
+if (prctl(PR_SET_SECCOMP, SECCOMP_MODE_STRICT) != 0)
+{
+     err(-1, "error inpledge()");
+}
+
 if (excite_file(STDIN_FILENO, // ...
```

```
+if (pledge("stdio", NULL) != 0)
+{
+     err(-1, "error in pledge()");
+}
+
 if (excite_file(STDIN_FILENO, // ...
```

Demo!

pledge(2) and paths

Slightly more interesting program:

```
[openbsd-vm jon]$ ./do_stuff ../conf `mktemp -d [...]`
hello!
package conf
locked.
[openbsd-vm jon]$ ls
Makefile        do_stuff.c      p0wnd!
do_stuff        do_stuff.o      scratch.MIwnTP
```

- escape from scratch directory

With path whitelist:

```
const char *known_paths[] =
{
    "foo.lock",
    "bar.lock!",
    NULL,
};
```

- enumerate all possible paths
- shallow filtering (e.g., symlinks)
- concurrency leads to TOCTTOU

It's the same story with `seccomp(2)`, just with more complex pattern matching. MacOS Sandbox is... interesting.

Authorizing security-sensitive operations

It's not enough to:

- filter on system call numbers/names
- filter on system call arguments

Authorization must be done:

- atomically with authorized operations
- deep within the kernel (not a wrapper)

Fundamental limitation for:

- systrace
- seccomp w/BPF
- pledge

Background: capabilities

Historic idea:

identifier for an object + *operations* that can be performed on it

Dennis and Van Horn (1966): index into supervisor-maintained *C-list*

Historic capabilities ⇨ PSOS ⇨ Multics ⇨ Unix

Background: file descriptors

Like capabilities:

- index into supervisor-maintained list of objects
- identifiers with operations: `read(2)`, `write(2)`, etc.

Unlike capabilities:

- lots of implicit rights
- lack of monotonic reduction

```
int fd = open("my-data.dat", O_RDONLY);
if (fchmod(fd, 0777) < 0)
    err(-1, "unable to chmod"); // usually doesn't run
```

Background: capabilities

Rigorous focus on allowed operations

proc ⇒ filedesc ⇒ fdescenttbl ⇒ filedescent ⇒ filecaps ⇒ {cap_rights_t fc_rights, fc_ioctls, fc_fcntls}

```c
struct filedescent {
  struct file     *fde_file;
  struct filecaps  fde_caps;
  uint8_t          fde_flags;
  seq_t            fde_seq;
}
```

- allowed syscalls, ioctls, fcntls
- CAP_READ, CAP_FTRUNCATE, CAP_MMAP, CAP_FCHMOD...
- `fget(td, fd, cap_rights_init(&rights, CAP_FSTAT), &fp);`

`open(2)` gives all rights, `cap_rights_limit(2)` limits, `*at(2)`, `accept(2)` derive from others

Background: Capsicum in practice

```
--- a/true/true.c
+++ b/true/true.c
@@ -28,7 +28,11 @@
 #include <sys/cdefs.h>
 __FBSDID("$FreeBSD$");

+#include <sys/capsicum.h>
+
+#include <capsicum_helpers.h>
 #include <err.h>
+#include <errno.h>
 #include <stdbool.h>

 #include <true.h>
```

(see zxombie/libtrue:#5)

```
@@ -37,6 +41,12 @@ int
 main(int argc, char *argv[])
 {

+	if (caph_limit_stdio() != 0)
+		errx(1, "Failed to limit std{in,out,err}");
+
+	if (cap_enter() != 0 && errno != ENOSYS)
+		errx(1, "Failed to enter capability mode");
+
	if (!get_true())
		errx(1, "Bad true value");
```

But more seriously…

Background: Capsicum in practice

- limitation: requires **voluntary** self-compartmentalization

```
 if (lpc_bootrom())
     fwctl_init();

+#ifndef WITHOUT_CAPSICUM
+caph_cache_catpages();
+
+if (caph_limit_stdout() == -1 || caph_limit_stderr() == -1)
+    errx(EX_OSERR, "Unable to apply rights for sandbox");
+
+if (cap_enter() == -1 && errno != ENOSYS)
+    errx(EX_OSERR, "cap_enter() failed");
+#endif

 /*
  * Change the proc title to include the VM name.
  */
 setproctitle("%s", vmname);
```

Long-term goals:

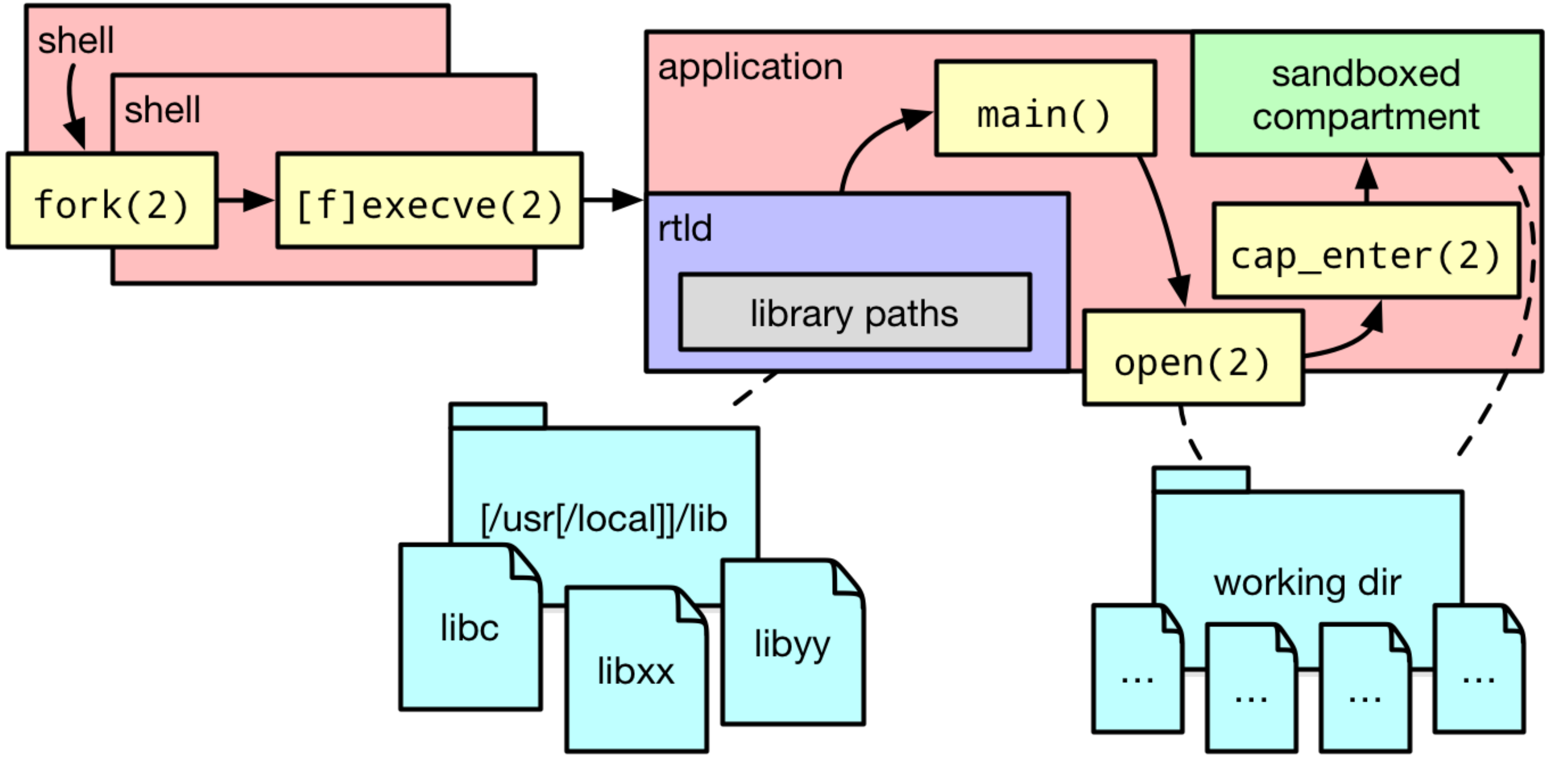
- compartmentalization without modification
- protecting ourselves from vulnerable applications **whether they like it or not**

Sandboxing as she is played today

1. open resources
2. `cap_enter(2)`
3. compute
4. (profit???)

Resources are:

statically-enumerable
or
externally-provided



Resource dependencies

Explicit resources

- files, directories, sockets...
- can pre-open files or directories (for `openat(2)`)
  - pre-opened file descriptors are preserved across `exec(2)` boundary
  - parent process can `fork(2)`, open directory descriptors, `setenv(3)`, `cap_enter(2)`...
- external services (e.g., libcasper, powerbox service*, ...)

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* Ka-Ping **Yee**, "Aligning security and usability", *IEEE Security and Privacy 2(5)*, 2004 , "App Sandbox in Depth", *Apple Developer Guides*, 2016
.

Resource dependencies (2)

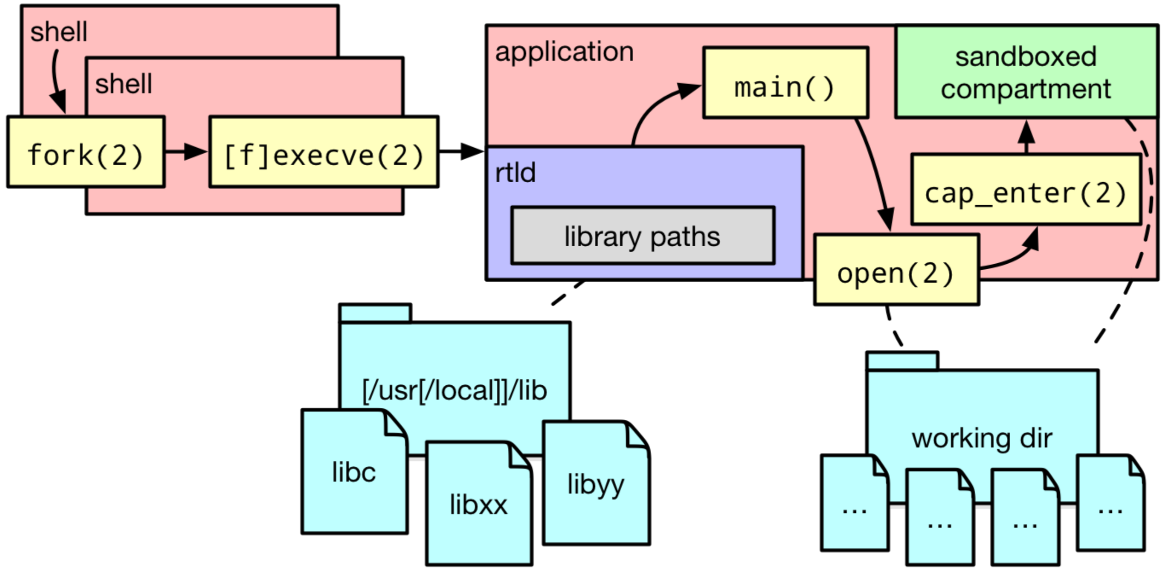
Implicit resources

- locale data (can be pre-cached; see Mariusz' r306657)
- shared libraries: even `cat(1)` and `echo(1)` need `libc`
- but neither `exec(2)` nor run-time linking work in capability mode!

`exec(2)` without a name

Traditional approach:

- `fork(2)` child process
- `exec(2)` binary
  - cleans up memory mappings, closes `O_CLOEXEC` files
  - preserves other open files, environment variables
  - finds binary **by name**, mmap's, transfers control to linker



`exec(2)` without a name (2)

Problematic line:

> finds binary **by name**, mmap's, transfers control to linker

- first problem: "finds binary **by name**"
  - solution: `fexecve(2)` takes already-open file descriptor for binary*
  - `fexecve(binary /* pre-opened? */, args, environ)`
- next problem: "mmap's"
  - but wait... isn't `mmap(2)` allowed in capability mode?
  - yes, but **what are we mapping**?

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* ask me about `fexecve` on Linux, it's **kind of funny**.

How do we `exec(2)` binaries?

`exec(2)`, `execve(2)`, `fexecve(2)` ⇒ `kern_execve()`
(supports lots of binary *image* formats)

- try process-specific image activator (`p_sysent`)
- try each `execsw[i]->ex_imgact` in turn (a.out, ELF, …)
- ELF: `exec_elfXX_imgact` @ `sys/kern/imgact_elf.c`:

```
static int
__CONCAT(exec_, __elfN(imgact))(struct image_params *)
{
    /* ... */
}
```

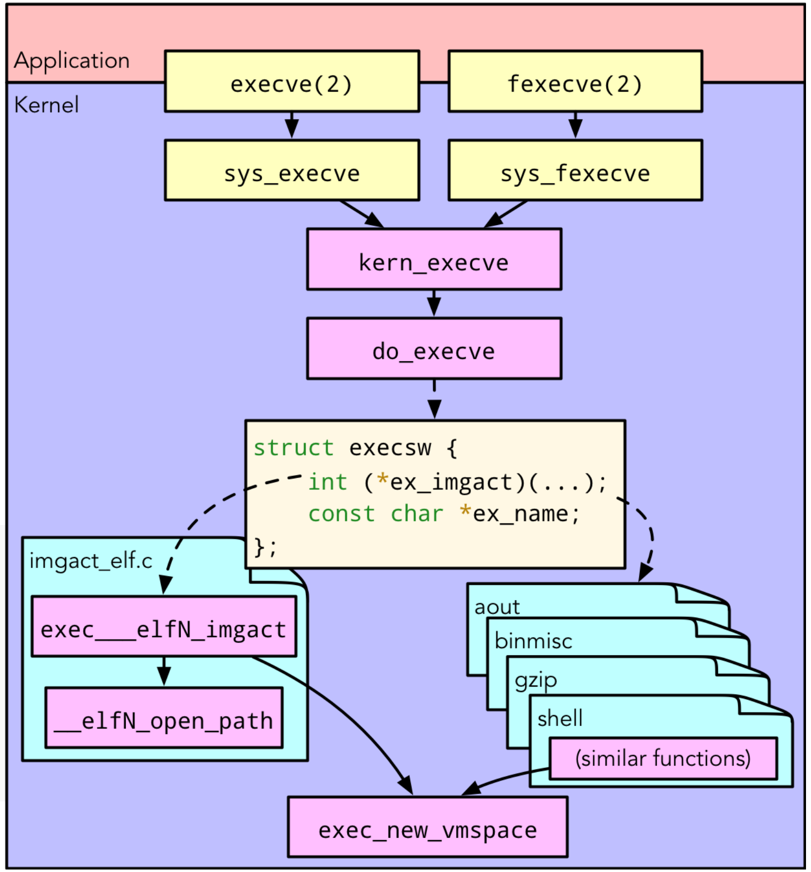
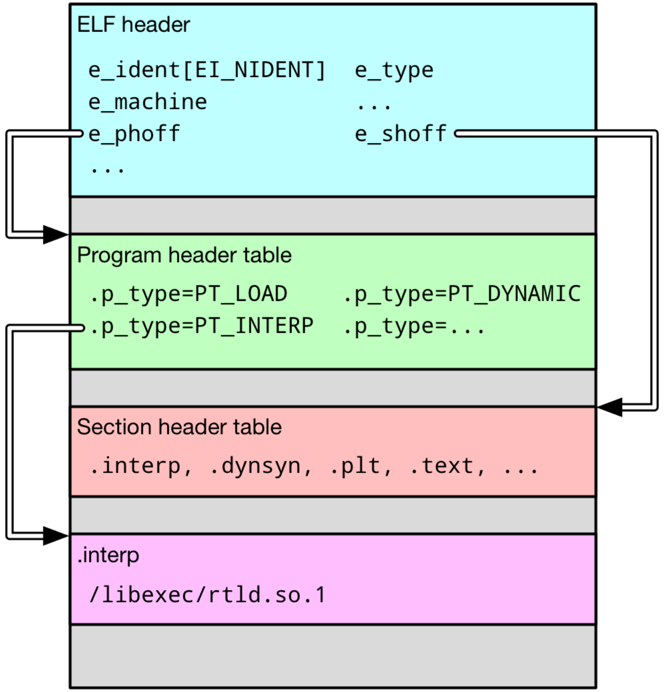


Image activation

- ELF image activator encodes knowledge of run-time linker (a.k.a., run-time "interpreter")
- binaries can also encode a run-time linker path: `PT_INTERP` field in ELF program header table
- ELF image activator **maps both interpreter and binary** into memory, starts running the interpreter
- what's the problem?



Linker always specified by path!

Finding the linker

- in capability mode, `open(2)` syscall disallowed
- more fundamentally, **all name lookups** in capability mode are restricted in `namei()`

see `sys/kern/vfs_lookup.c:350`:

```
if (error == 0 && IN_CAPABILITY_MODE(td) &&
    (cnp->cn_flags & NOCAPCHECK) == 0) {
     ndp->ni_lcf |= NI_LCF_STRICTRELATIVE;
```

```
if (cnp->cn_flags & ISDOTDOT) {
    if ((ndp->ni_lcf & (NI_LCF_STRICTRELATIVE |
        == NI_LCF_STRICTRELATIVE) {
            error = ENOTCAPABLE;
            goto bad;
    }
```

- `NI_LCF_STRICTRELATIVE`
  - don't allow `'/'`, `AT_FDCWD` or `".."`
  - explicit kernel override: `NOCAPCHECK` flag (only used for coredumps)
- **desirable property** of Capsicum's deep-in-the-kernel approach

Finding the linker (2)

The problem:

- can't look up the default RTLD path
- can't use the `PT_INTERP` path
- where can we get a run-time linker?

The solution:

- **punt!***

"Dear user, **you tell me** what linker to use! kthxbye."

Finding the linker (3)

- applications that launch binaries from sandboxes need **some knowledge of ABIs**
  - library? ("dear binutils, what sort of binary is this?")
  - system service? ("what linker should this binary use?")

Future work☺

- initial approach: `ffexecve(2)` (specify linker, binary by FD)
- final approach: **directly-executable linker**

Directly-executable linker

```
Usage: /libexec/ld-elf.so.1 [-h] [-f <FD>] [--] <binary> [<args>]

Options:
  -h        Display this help message
  -f <FD>   Execute <FD> instead of searching for <binary>
  --        End of RTLD options
  <binary>  Name of process to execute
  <args>    Arguments to the executed process
```

as before: `fork(2)`, open directory descriptors, `setenv(3)`, `cap_enter(2)`

the new bit: `fexecve(the_linker, args + [ "-f", the_binary ], environ)`

```
r319135 | kib      | 2017-05-29 MFC direct execution mode for rtld.
r318431 | jonathan | 2017-05-17 Allow rtld direct-exec to take a file descriptor.
r318380 | kib      | 2017-05-16 Pretend that there is some security when executing in direct mode.
r318313 | kib      | 2017-05-15 Make ld-elf.so.1 directly executable.
```

Demo: run(1)

The opposite of sudo(8)

- find the ELF interpreter
- find a binary
- execute it in a sandbox

This solves all our problems... right?

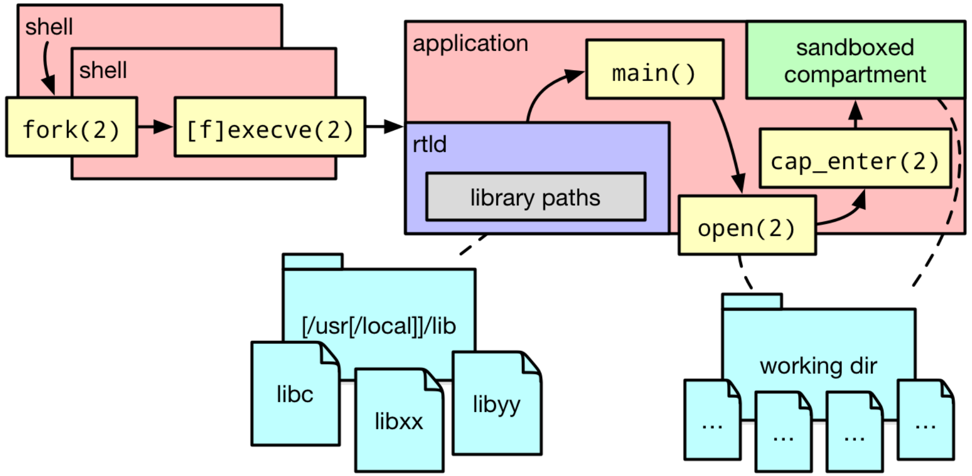
Er, not quite.

```
int rtld = open("/libexec/ld-elf.so.1", O_RDONLY);
int binary = open(name, O_RDONLY);

char *args[argc + 4];
args[0] = strdup(name);
args[1] = "-f";
asprintf(args + 2, "%d", binary);
args[3] = "--";
args[argc + 3] = NULL;

for (int i = 0; i < argc - 1; i++)
    args[i + 4] = argv[i + 1];

fexecve(rtld, args, environ);
```

note: error handling removed for space reasons

Linking within compartments

The story so far:



- most applications need dynamic libraries*
- run-time linker is "just" code in a process
  - same address space / security domain
  - runs before `main`, opens needed libraries

Actual linking can happen at run-time, even in capability mode...
but libraries cannot be `open(2)`'ed from capability mode!

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* Other than the FreeBSD-derived MacOS, which doesn't support statically-linked binaries...

Finding libraries

How it normally works:

(see `find_library` at `libexec/rtld-elf/rtld.c:1586`)

- `DT_RPATH` (with rules about DSO, `DT_RUNPATH`...)
- `LD_LIBRARY_PATH`
- `DT_RUNPATH`
- ldconfig hints (with rules aroudn `-z nodefaultlib`)
- `STANDARD_LIBRARY_PATH` (`/lib32:/usr/lib32`, `/lib/casper:/lib:/usr/lib`...)

... followed by `open(2)` ... which isn't allowed in capability mode!

Shared libraries in capability mode

- r267678: `LD_LIBRARY_PATH_FDS`
  - like `LD_LIBRARY_PATH`, but with file descriptors
  - directory descriptors for `/lib`, `/usr/lib`, `/usr/local/share/myapp/plugins`…
  - then `openat(2)`, then `fstat(2)`…

The story so far

We can run RTLD

RTLD can find libraries

RTLD can run binaries

Profit???

Not quite!

```
int rtld = open("/libexec/ld-elf.so.1", O_RDONLY);
int binary = open(name, O_RDONLY);

char *args[argc + 4];
args[0] = strdup(name);
args[1] = "-f";
asprintf(args + 2, "%d", binary);
args[3] = "--";
args[argc + 3] = NULL;

for (int i = 0; i < argc - 1; i++)
    args[i + 4] = argv[i + 1];

fexecve(rtld, args, environ);
```

note: error handling removed for space reasons

The story so far (2)

Libraries are not enough:

```
$ cc run.c -o run && ./run /bin/cat /etc/passwd
cat: /etc/passwd: Not permitted in capability mode
```

Also need support for traditional resource access

Accessing file resources

Existing applications like to use:

- `access(2)`
- `stat(2)`
- `open(2)`

… none of which are allowed!

We could rewrite the application to assume it will be given a directory descriptor and use `openat(2)`, etc. … but that wouldn't be very oblivious!

libpreopen

Transparent filesystem proxying

- libpreopen's `struct po_map` maps virtual paths to capabilities
- `libc` wrappers provide Capsicum-aware versions of, e.g., `open(2)`:
  - `LD_PRELOAD` libpreopen* to take precedence over system calls†
  - take given (absolute) path, search through `struct po_map`:
    - on success: translate `"/usr/local/share/my_app/foo.conf"` ⇒ `(FD 3,"foo.conf")`; these can be passed to `accessat(2)`, `openat(2)`, `statat(2)`…
    - no suitable pre-opened path: translate to `(FD -1,NULL)`, return error

---

* This works in capability mode iff `libpreopen.so` is reachable via `LD_LIBRARY_PATH_FDS` — if not, we **always fail closed**.
† System calls are defined as *weak symbols* in libc to allow overriding.

libpreopen (2)

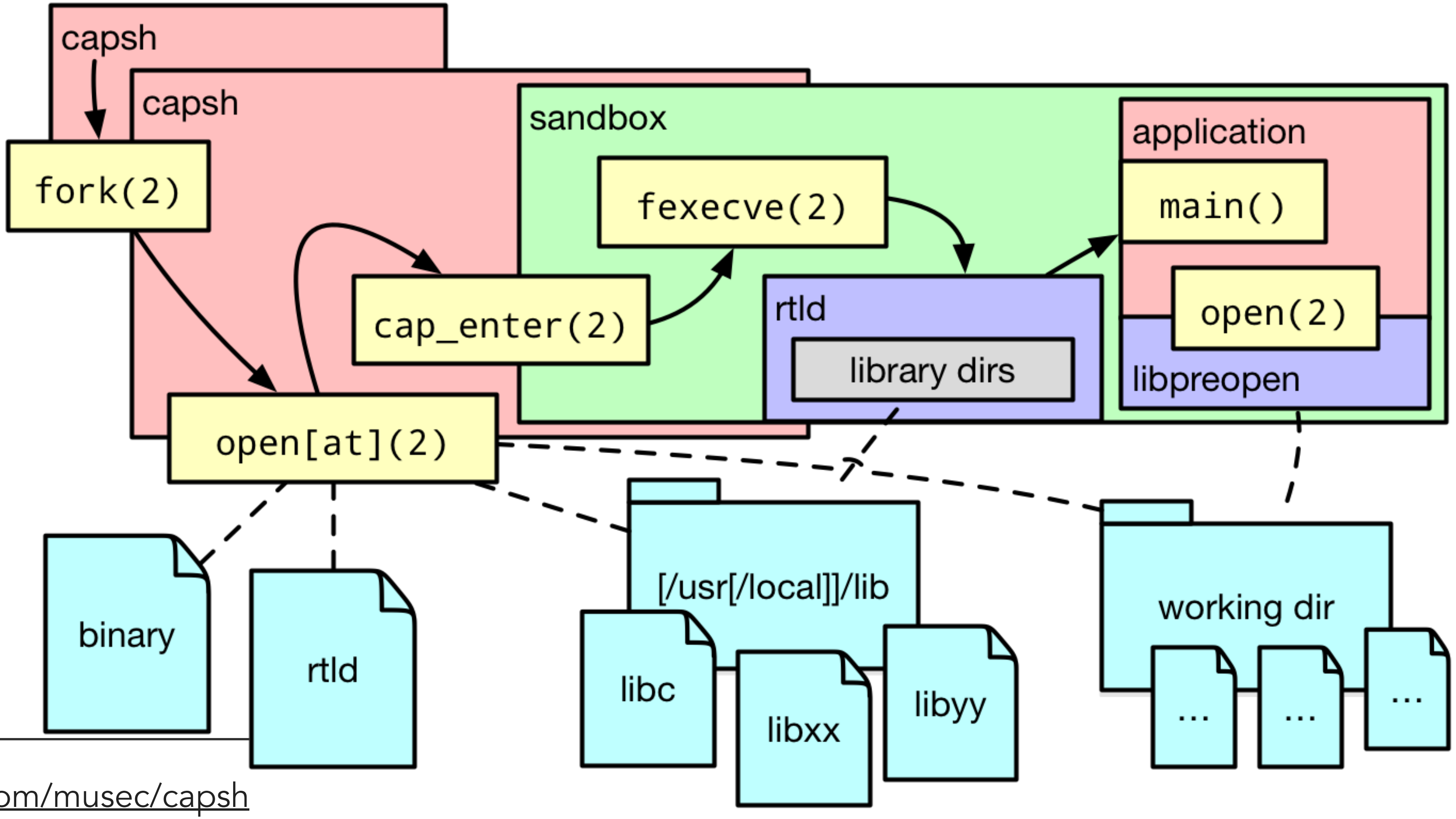
But where does a `po_map` come from?

Our overall objective: **launch an unmodified application from a sandbox**

Who pre-opens files and directories?
It's the responsibility of the thing (process) doing the launching.

- (in most cases) `fork(2)`
- pre-open any required resources
- populate a `struct po_map`
- pack the `po_map` into POSIX SHM
- set `LD_LIBRARY_PATH_FDS`, `LD_PRELOAD`
- set `LIB_PO_MAP`
- `fexecve(2)` the linker
- let `libc` wrappers unwrap/use `LIB_PO_MAP`

capsh: a capability-enhanced shell



Available from github.com/musec/capsh

capsh **status**

Where are we today?

Not a real shell: only usable as `capsh <args>` for direct execution.

Not very sophisticated: we can do a little more than `echo`, but not much*!

But: it does execute execute **unmodified software**.

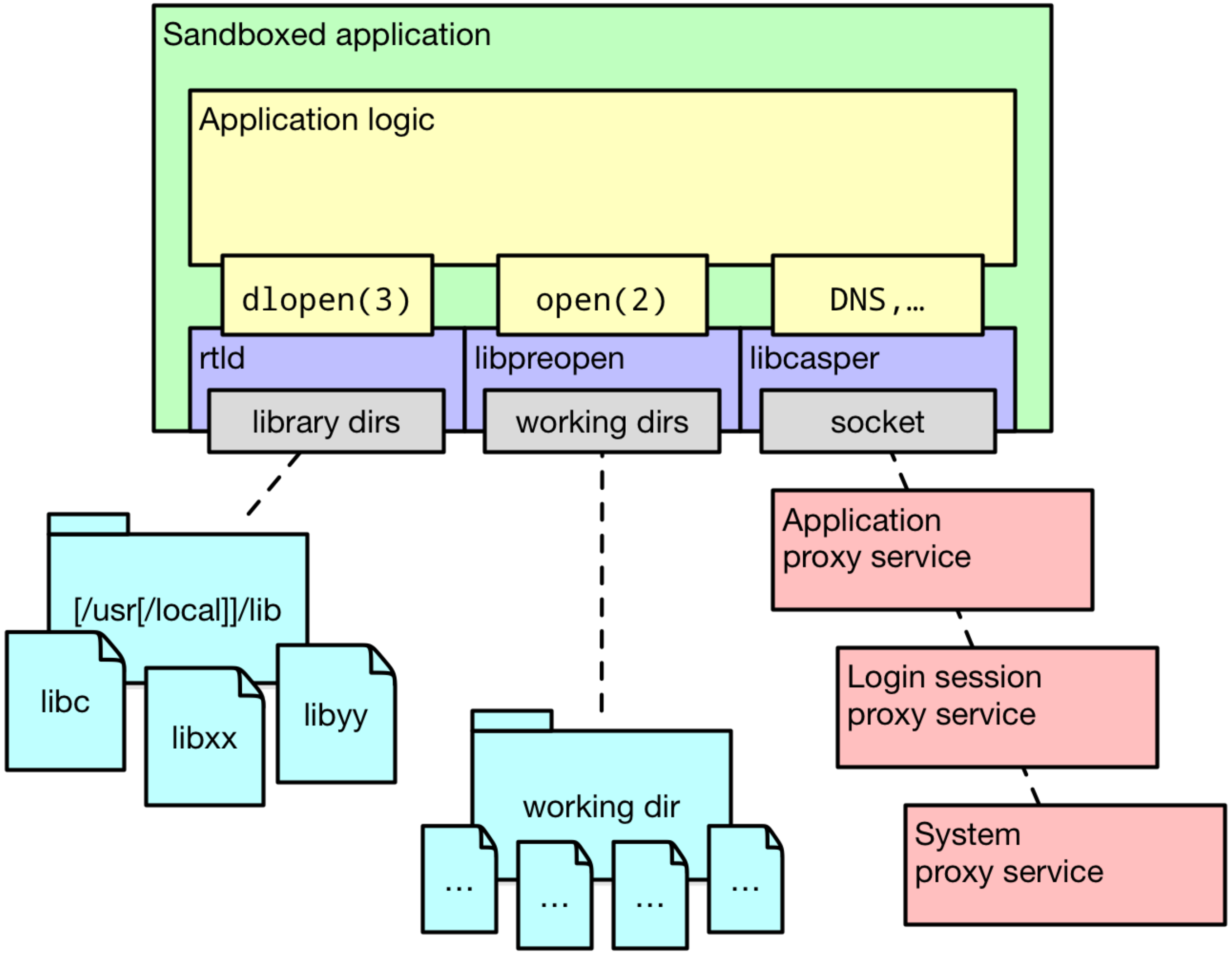
We can run `/usr/bin/true`, `banner`, `pom`, `primes`...

The goal

Sandboxing programs by default

Services required:

- static pre-opened files:
  - CLI arguments
  - package policies
- dynamic provisioning:
  - UI interaction
  - user/system policies

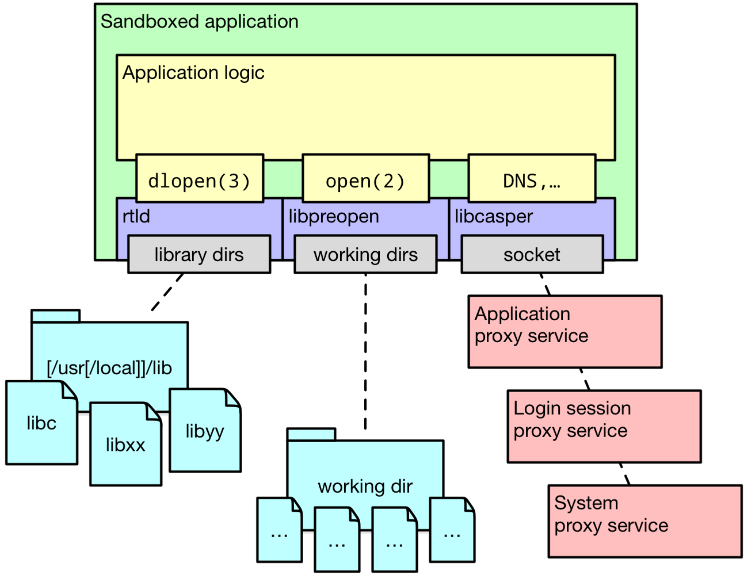


Static policies*

```
services:
  exec:
    paths: [ /usr/local/llvm39, /bin, /usr/bin ]

  filesystem:
    - root: /usr/local/llvm39
      preopen: true        # we always need the llvm39 dir
      rights: [ read, seek, lookup ]
    - root: /usr/local/bin
      globs: [ "clang*", "ll*" ]
      rights: [ read, seek, exec ]

  network:
    https:
      hostname: llvm-crashreporter.freebsd.org
      certificate-policy: # ...
```



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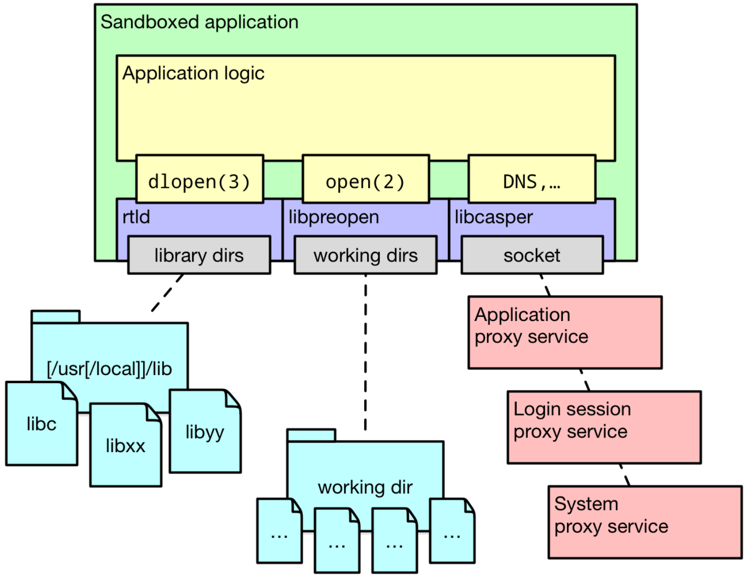
* Policy syntax is **suggestive of future directions**: this stuff **doesn't exist yet**.

Dynamic services

- application-level services
  - TLS handling
  - worker processes
- session-level services
  - D-Bus
  - UI powerboxes
  - user data provisioning
- system-level services
  - names, syslog..
  - shared data and configuration



Towards oblivious sandboxing

From a Capsicum sandbox, we can:

- pre-open libraries and resources
- run RTLD directly
  - use library directory FDs
  - map, run binary
- wrap ambient-authority system calls
  - retrieve FDs from anonymous shared memory
  - convert `access(2)` to `accessat(2)`, `open(2)` to `openat(2)`…
- provide access to **named system services**

Conclusion

- Capsicum provided kernel-level foundation for **principled, coherent compartmentalization**
- new work provides application-level foundation for:
  - running **unmodified** applications
  - providing application services
- stage set for deeper exploration of **oblivious sandboxing**
- movement towards applications that **just work** and are **secure by default**