Symbolic Links Considered Harmful

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Opening Windows to a Wider World

What are symbolic links ?

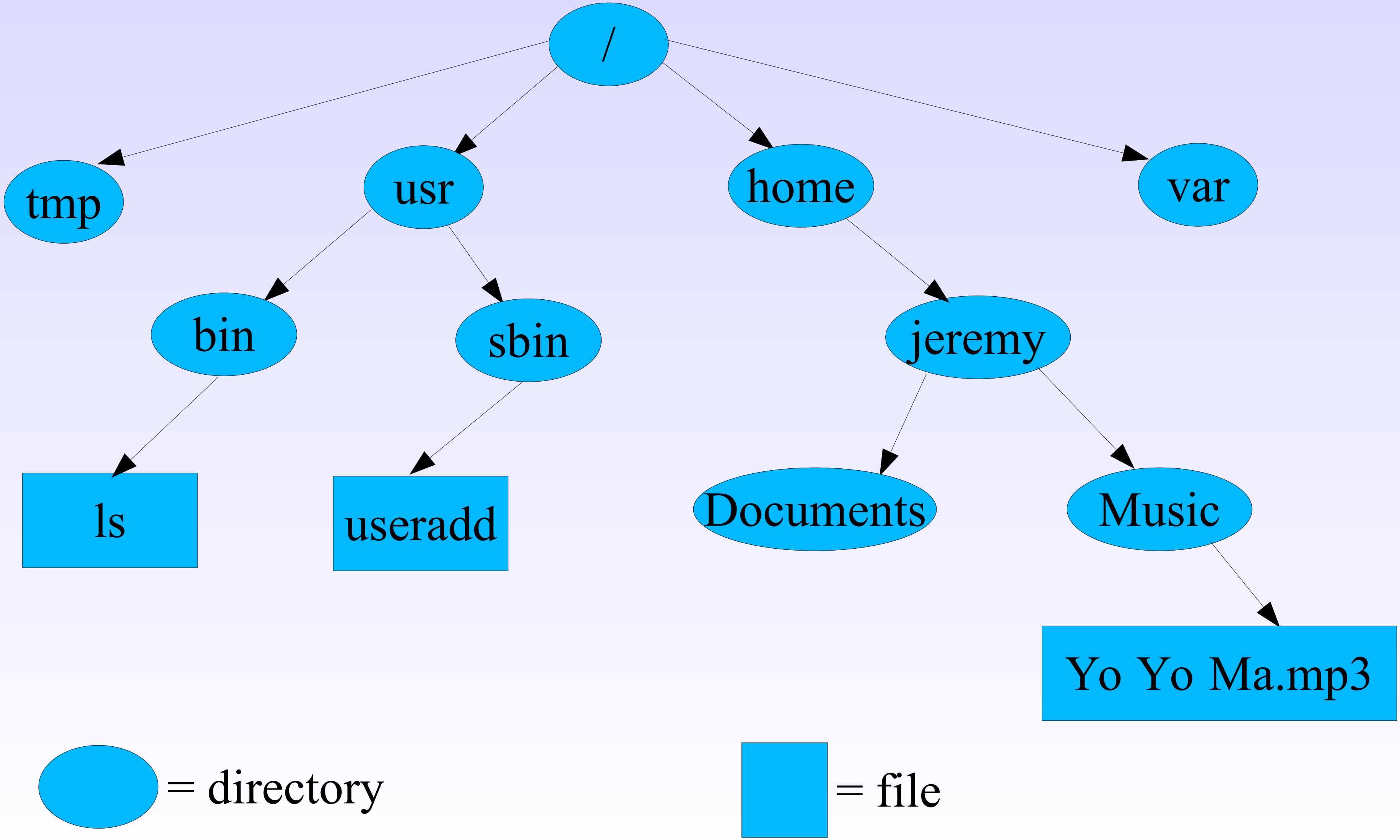
- Strange to have to explain this in a file system conference, but..
- Most computer users these days have no contact with a file system.
  - iPhone and Android users have no concept of a file system on their device. Each application only handles its own kind of data storage.
    - Possibly to enforce data “silos” to keep users tied to an application.
  - Students no longer know where a file is stored: https://www.theverge.com/22684730/students-file-folder-directory-structure-education-gen-z
  - Users only search for “objects” by name.
- I have to help my family move “objects” around from phone to file server.

Opening Windows to a Wider World

Step back – What is a file system ?

A file system visualized.

Path = /home/jeremy/Music/Yo Yo Ma.mp3



The original UNIX file system C API dealing with paths

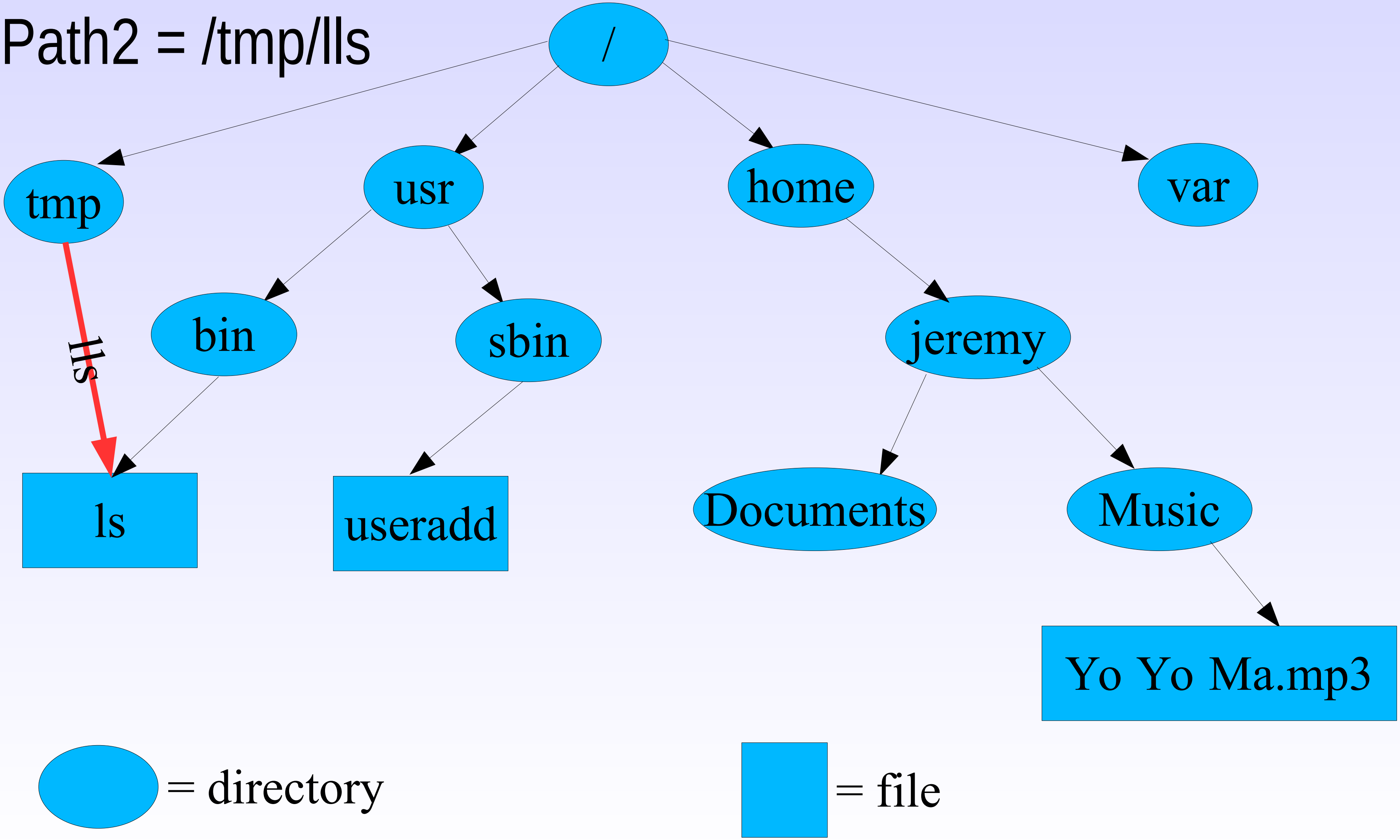
- open(“/home/jeremy/Music/Yo Yo Ma.mp3”, int flags, mode_t mode)
- unlink(“/path/to/file”)
- mkdir(“/new/directory/name”)
- rmdir(“/directory/name”)
- stat(“Yo Yo Ma.mp3”, struct stat *st) ($cwd is “/home/jeremy/Music”)
- chmod(“/path/to/file”, int mode)
- chown(“/path/to/file”, uid_t owner, gid_t group)
- chdir(“/path/to/new/working/directory”)
- etc..
- Note the “path” may be specified from the root (starts with ‘/’) or relative to the current working directory (doesn’t start with ‘/’).

Hard links:

ln /usr/bin/ls /tmp/lls
link("/usr/bin/ls", "/tmp/lls")

Path1 = /usr/bin/ls

Path2 = /tmp/lls



Hard link details

- Hard links create a new directory entry (name) which points to the *same* file data and metadata.
- Hard links cannot be made to directories.
- Hard links simply create a new absolute path to the *same* file.
- Useful to allow a single file to be referenced by many names.
    - Underlying data is only removed once last link has gone.
- First use of hard links seems to be in the Incompatible Timesharing System (ITS) in 1969.

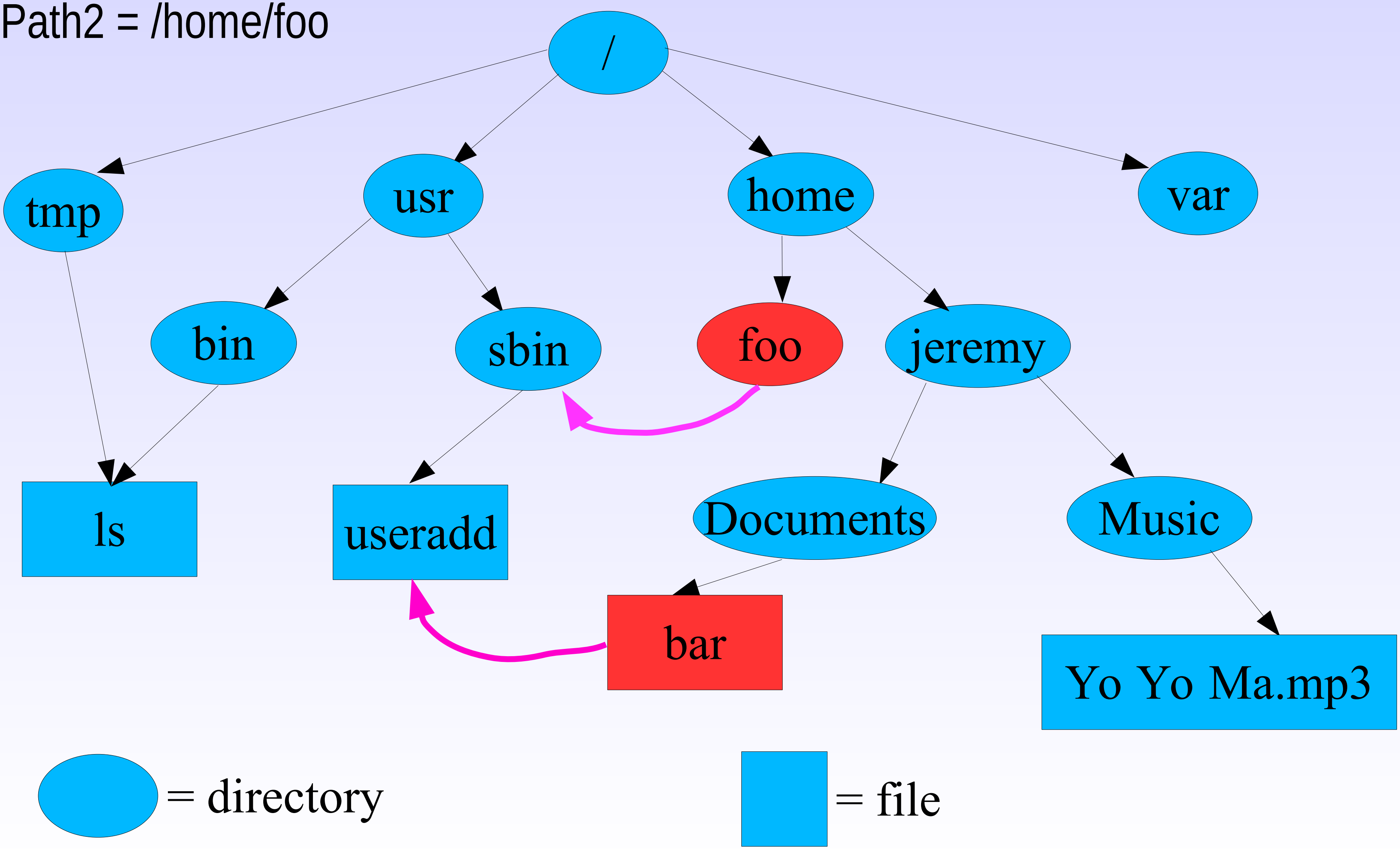
Symbolic links:

ln -s /usr/sbin /home/foo

symlink("/home/foo", "/usr/sbin")

Path1 = /usr/sbin

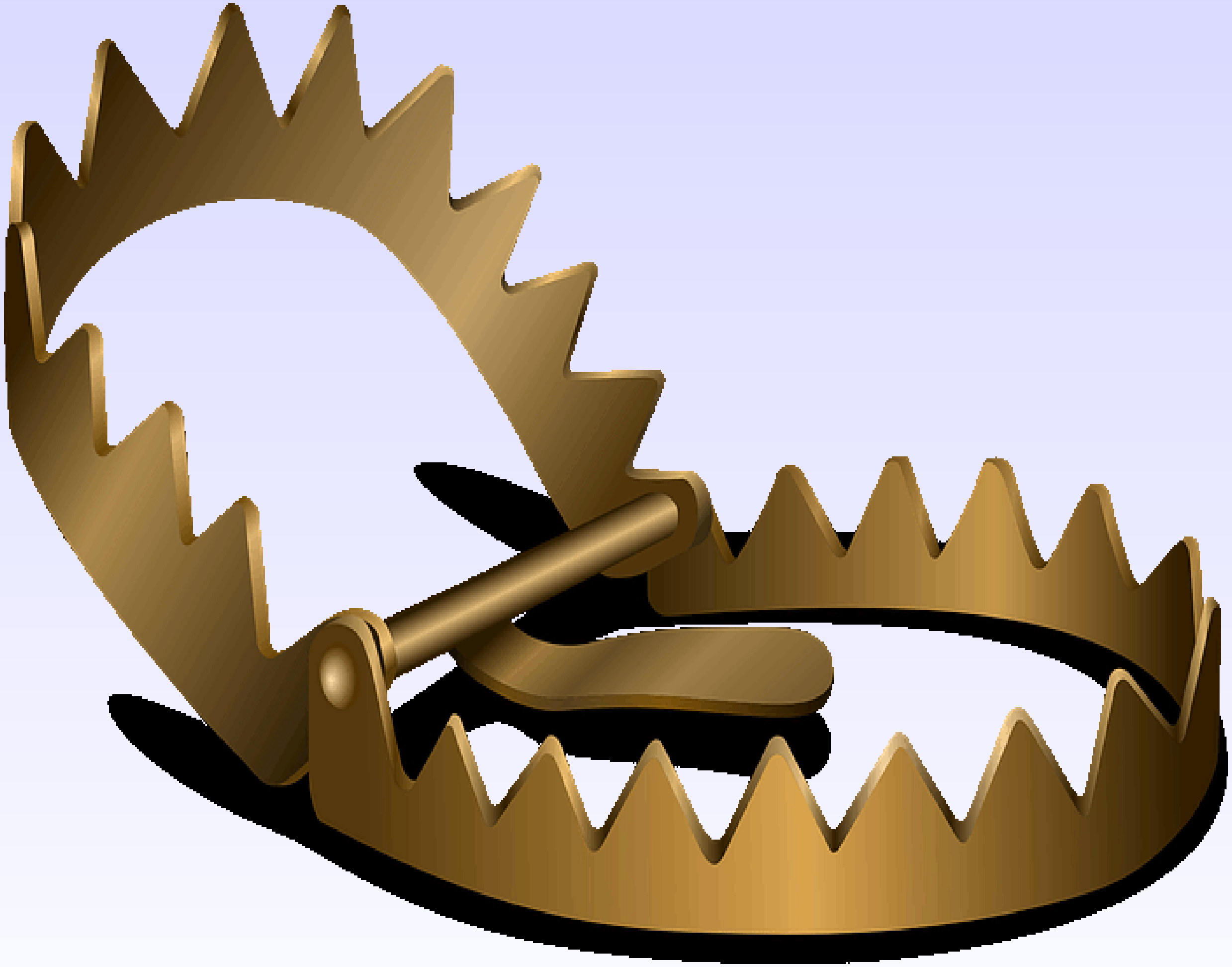
Path2 = /home/foo



Symbolic link details

- Symbolic links allow the creation of a new object in the file system that causes any process accessing it to follow it to an arbitrary target somewhere else on the file system.
  - Not only files, but directories too.
  - Loops can be created.
    - This should have been a warning sign to file system designers that they were doing something wrong.
- First reference to them is from MULTICS in 1965.
  - But added to 4.2 BSD Unix.
  - “..symbolic links have been added to release 4.2 of Berkeley Unix. This feature frees the user from the constraints of the strict hierarchy that a tree structure imposes. This flexibility is essential for good name space management.”

Symbolic links for application developers



Why are symlinks so bad ?

- Symlinks allow paths to change on the fly, creating a whole class of time-of-check, time-of-use (TOCTOU) race condition security problems.
- Symlinks are not restricted to privileged users, but can be created by anyone with write access anywhere in a path.
- Symlinks break the beautiful “tree” abstraction of a POSIX file system.
- Symlinks break the beautiful simplicity of the POSIX file system API.

The evolution of the API to deal with symlinks

- First change was introduction of lstat
  - lstat(const char *path, struct stat *st)
  - Original “stat()” API silently and transparently follows symlinks.
  - Allows calling application to detect if the terminal component of a path is a symlink.
  - Does not detect symlinks other than the terminal component.
- Ended up in unsafe code such as:

```
lstat(dangerous_path, &sbuf);
if (!S_ISLNK(sbuf.st_mode)) {
    do_dangerous_operation_on(dangerous_path);
}
```

Go Speed Racer Go !

- Race condition exists between:

```
lstat(dangerous_path, &sbuf);
-------race starts here----
if (!S_ISLNK(sbuf.st_mode)) {
    ------race ends here----
    do_dangerous_operation_on(dangerous_path);
}
```

- If an attacker can rename dangerous_path, and replace it with a symlink to somewhere else before do_dangerous_operation_on(dangerous_path) is called, the dangerous operation is applied to the attackers chosen path.

Surely these races are too narrow for me to care about ?

- https://cve.mitre.org/cgi-bin/cvekey.cgi?keyword=symbolic+link
  - There are 1361 CVE Records that match your search.
- This does not just include “old” applications that were written before symlink mitigation API’s were added to POSIX.
  - This includes symlink race condition security holes in the Rust language standard library (from 2022).
- The API’s added to mitigate symlink errors are impossible for application developers to use safely.
  - Similar to the care needed for “atomic” files data and meta-data updates, the POSIX API changes are too complex for safe use.

POSIX Symlink API mitigations

- First was an additional flag, O_NOFOLLOW to the open() system call.
  - Looks perfect, in practice doesn’t do what applications need.
  - O_NOFOLLOW prevents the terminal component in a pathname passed to open() being a symlink.
  - If completely ignores symlinks in non-terminal components.
- Example of an exploit:
  - (Application running as root – checks /data/mydir is safe)

    Attacker renames “/data/mydir” → “/data/out-of-the-way”

    symlink(“/data/mydir”, “/etc”);

    int fd = open(“/data/mydir/passwd”, O_WRONLY|O_NOFOLLOW..);

    ret = write(fd, data, size);
  - Application now writes into /etc/passwd

More POSIX API mitigations

- To solve the previous O_NOFOLLOW problem applications have to chdir() into the parent directory. Check it hasn't been symlink raced and then use O_NOFOLLOW, then chdir back.
  - Samba did this prior to 4.17.
- open() → openat(int dirfd, const char *path, int flags, mode_t mode)
  - This actually works. The 'dirfd' parameter here is a handle of a containing (parent) directory.
  - So long as "path" has no "/" characters and flags contains O_NOFOLLOW, then this cannot be raced.
- Of course, getting the handle on the parent directory also has to be protected against symlink races.

XXXXat’s for everyone !

- Based on openat(), **ALL** path-based operations must have an XXXXat() variant to avoid symlink races in the same way.
- Oh look, lots of new system calls.

openat(), mkdirat(), unlinkat(), linkat(), renameat(), symlinkat(), fstatat(), fchmodat(), fchownat(), futimesat(), mknodat(), faccessat(), readlinkat(), utimensat(), scandirat(), execveat()

- The original clean and simple POSIX filesystem API doesn’t look so clean and simple anymore.
  - And on Linux, one of these calls doesn’t work – fchmodat() will still always follow symlinks in the target path.

Pathnames are now broken.

- Any application that allows more than one component in a path without splitting the last component off and using the XXXXat() functions can be symlink raced.
- Still not enough for a feature complete application.
  - Extended attribute calls are missing, no getxattrat(), setxattrat() etc.
  - For extended attribute pathname operations the chdir()/realpath()/getxattr()/chdir() dance must still be done.
- I know, let’s add more open() flags !
  - Linux added O_PATH.
  - Allows a handle to be taken on a file or directory, usually meant to be passed as the file descriptor argument to the XXXXat() functions.
  - O_PATH handles cannot be used to read/write data.

Extended attributes revisited

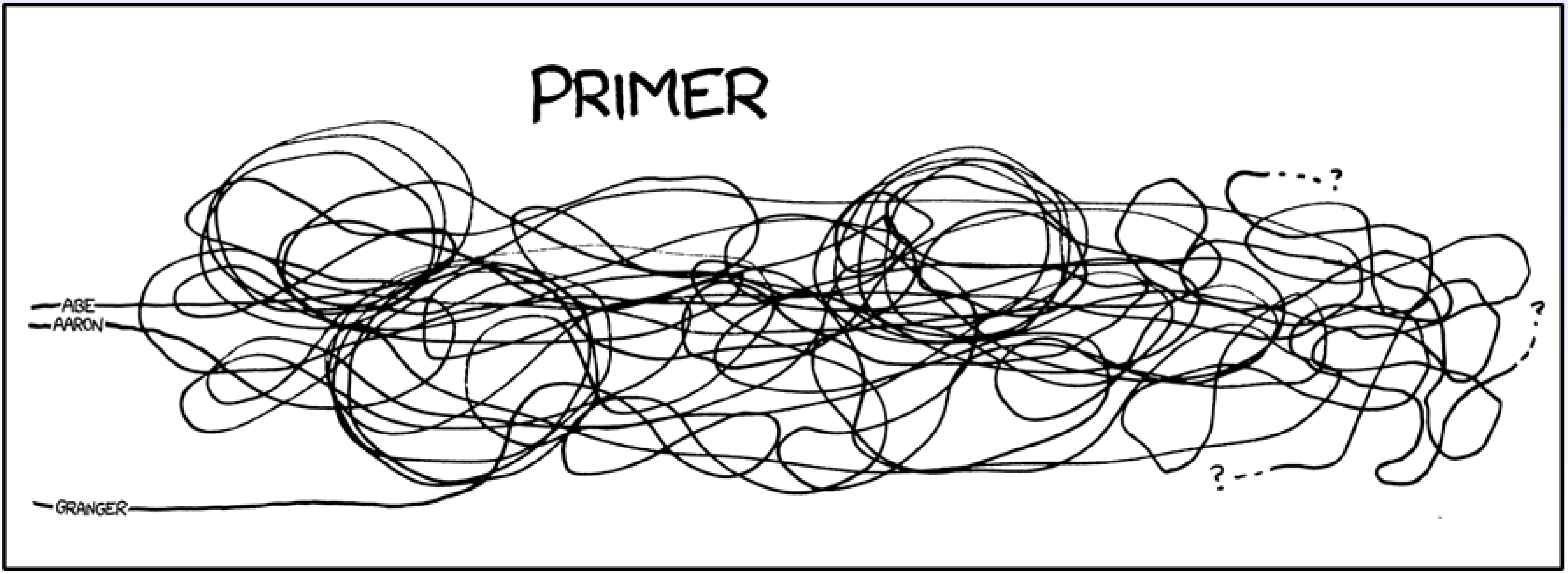
- Having an O_PATH handle would be a great solution for getting/setting extended attributes where you don’t want to open the file for modification.
  - Unfortunately O_PATH prohibits reading or writing extended attributes.
- “Hack” solution, invented by a Red Hat engineer.
  - int fd = openat(dirfd, “file”, O_PATH|O_NOFOLLOW);

    sprintf(buf, “/proc/self/fd/%d”, fd);

    getxattr(buf, ea_name, value, size);
- Depends on Linux-only semantics of /proc file system.
  - Insanity, pure insanity.

Symlinks turn this:

Into this
("Primer" timeline credit xkcd):



I assert that pathnames are now unusable for “mortal” application developers on POSIX

- I claim that for a non-trivial application, it is impossible for application developers to avoid symlink races.
- It’s not just their own code – all library code they call that uses path names must be aware of multi-path-component symlink races.
- Spoiler alert – even security library code is not symlink race aware.

Example #1

- Given a directory hierarchy:

```
foo/
    bar/
        baz/
            bibble
```

- $ strace setfacl -R -m u:gdm:r foo

```
setxattr("foo", "system.posix_acl_access", "...", 44, 0) = 0
getxattr("foo/bar", "system.posix_acl_access", 0x7ffc474a4c00, 132) = -1 ENODATA
setxattr("foo/bar", "system.posix_acl_access", "...", 44, 0) = 0
getxattr("foo/bar/baz", "system.posix_acl_access", 0x7ffc474a4b70, 132) = -1 ENODATA
setxattr("foo/bar/baz", "system.posix_acl_access", “...", 44, 0) = 0
getxattr("foo/bar/baz/bibble", "system.posix_acl_access", 0x7ffc474a4ae0, 132) = -1
ENODATA
setxattr("foo/bar/baz/bibble", "system.posix_acl_access", "...", 44, 0) = 0
```

Example #2

- In one of the patches for git CVE-2022-24765

```
+#ifndef is_path_owned_by_current_user
+static inline int is_path_owned_by_current_uid(const char *path)
+{
+	struct stat st;
+	if (lstat(path, &st))
+		return 0;
+	return st.st_uid == geteuid();
+}
+
+#define is_path_owned_by_current_user is_path_owned_by_current_uid
+#endif
```

- Called from ensure_valid_ownership(const char *path), also added for CVE-2022-24765.

Example #3

- Rust language standard library CVE-2022-21658.

The Rust Security Response WG was notified that the std::fs::remove_dir_all standard library function is vulnerable to a race condition enabling symlink following (CWE-363). An attacker could use this security issue to trick a privileged program into deleting files and directories the attacker couldn't otherwise access or delete.

Overview

Let's suppose an attacker obtained unprivileged access to a system and needed to delete a system directory called sensitive/, but they didn't have the permissions to do so. If std::fs::remove_dir_all followed symbolic links, they could find a privileged program that removes a directory they have access to (called temp/), create a symlink from temp/foo to sensitive/, and wait for the privileged program to delete foo/. The privileged program would follow the symlink from temp/foo to sensitive/ while recursively deleting, resulting in sensitive/ being deleted.

To prevent such attacks, std::fs::remove_dir_all already includes protection to avoid recursively deleting symlinks, as described in its documentation:

This function does not follow symbolic links and it will simply remove the symbolic link itself.

Unfortunately that check was implemented incorrectly in the standard library, resulting in a TOCTOU (Time-of-check Time-of-use) race condition. Instead of telling the system not to follow symlinks, the standard library first checked whether the thing it was about to delete was a symlink, and otherwise it would proceed to recursively delete the directory.

This exposed a race condition: an attacker could create a directory and replace it with a symlink between the check and the actual deletion. While this attack likely won't work the first time it's attempted, in our experimentation we were able to reliably perform it within a couple of seconds.

How can we fix this mess #1 ?

- Learn from Windows.
  - Yes, Windows implemented this **RIGHT**.
- The Windows NTFS file system has application followed symlinks, called reparse points.
- Symbolic links on NTFS by default can only be created by an Administrator (root).
  - This fixes the problem perfectly. No code is safe from root anyway.
- Unfortunately this will break many existing applications (systemd user services for one).

How can we fix this mess #2 ?

- New system call (yes ! The Linux way).
- Linux system call openat2() has a flags field:
  - RESOLVE_BENEATH
  - RESOLVE_IN_ROOT
  - RESOLVE_NO_SYMLINKS
- All restrict symlink following in different ways (see the man page).
  - No glibc wrapper (yet).
  - Only fixes the problem for open().
  - All applications need to be re-written.
  - Promising for the future though.
  - Samba 4.17 now uses RESOLVE_NO_SYMLINKS.

How can we fix this mess #3 ?

- Suggested by lwn user “willy”.
- Add a prctl() (process control) option that causes any system call traversing a symlink to return ELOOP.
- This will break existing applications, but in the “right” way (i.e. they individually have to ask for it, and then cope “correctly”).
- No one is currently planning on implementing this.

How can we fix this mess #4 ?

- Suggested by lwn user “nix”
- Change symlink semantics such that symlinks owned by non-root are only followed by a process with a token containing the uid that created them.
    - More subtle protection, but would still break existing applications.
    - Probably too confusing for administrators, symlinks “randomly” breaking.
    - Still doesn’t fix the “restricted share” problem when exporting a file system (may be a Samba / NFS specific problem).
- Again, no one is currently planning on implementing this.

How can we fix this mess #5 ?

- Linux has a little known mount option MNT_NOSYMFOLLOW.
  - This does **exactly** what we need !
  - Allows symlinks to be created and read on a mounted filesystem, but any attempt to traverse a path containing a symlink returns ELOOP.
- Breaks applications in the “right” way.
- Allows application vendors to declare – “This application is only secure if run on a file system mounted with MNT_NOSYMFOLLOW.
- New option for mount command - option -o nosymfollow

How can we fix this mess #6 ?

- Ex-Samba Team member Simo Sorce came up with the following:
  - 1. Create /var/lib/samba/mounts
  - 2. Parse smb.conf - share [fooshare] path = /somewhere/foo
  - 3. mount -o nosymfollow,bind /somewhere/foo /var/lib/samba/mounts/fooshare
  - 4. Enjoy race free, performant, file server code. :-).
- Elegant and simple !
  - Unfortunately doesn’t work on latest Ubuntu LTS 22.04 (mount option missing).
  - Linux only. Samba 4.17 now has support for RESOLVE_NO_SYMLINKS as an optimization.
  - We still need the slow path for other OS’s (FreeBSD).

Conclusion

- Short term (on Linux) MNT_NOSYMFOLLOW is my preferred choice – and works in Samba 4.17.
- Keeps existing symlink requirements for normal apps (systemd, kernel name links etc.)
- Allows specific applications to opt out of symlink insanity.
  - Still allows symlinks to be stored and followed manually if the application is coded that way.
  - Turns symlinks into Windows “shortcuts”.
- Proselytize the “no more symlinks” creed !
- Let’s eliminate symlink race CVEs by 2032 !

Questions and Comments ?

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Slides available at: