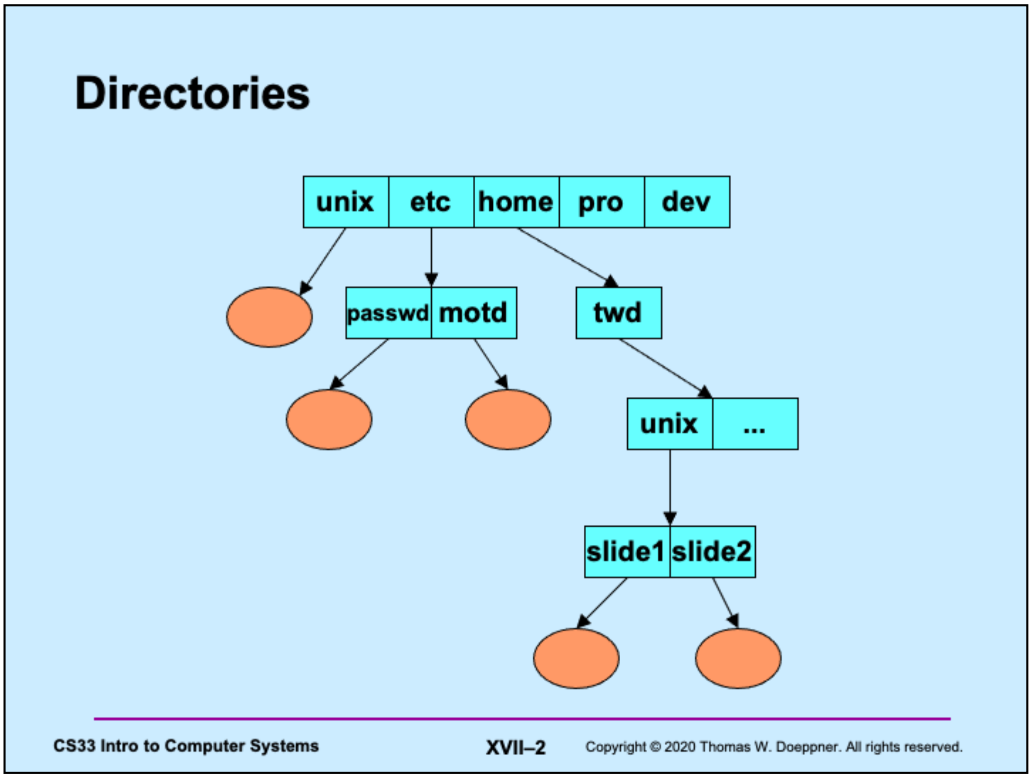
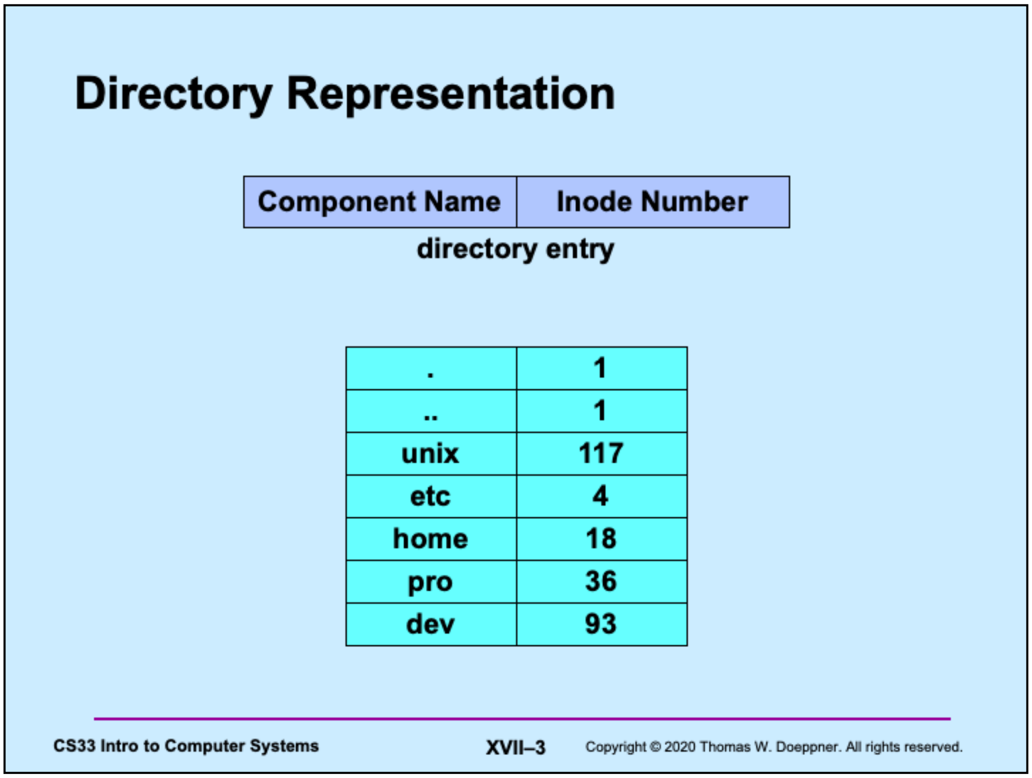
CS 33

Files Part 2

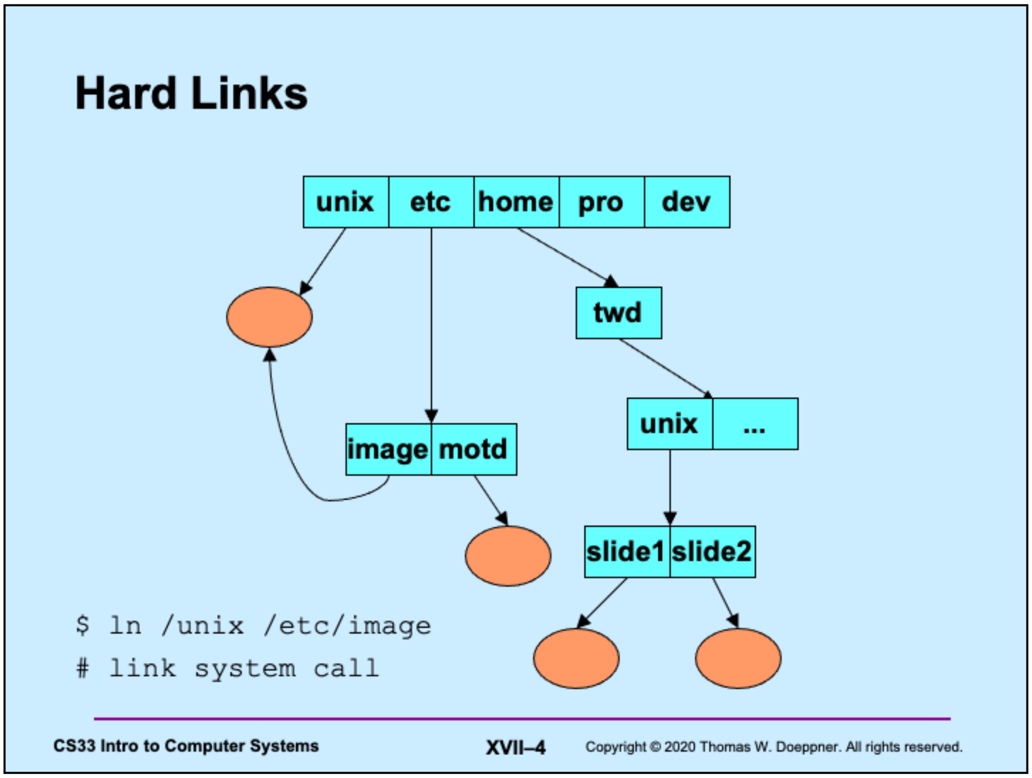


Here is a portion of a Unix directory tree. The ovals represent files, the rectangles represent directories (which are really just special cases of files).



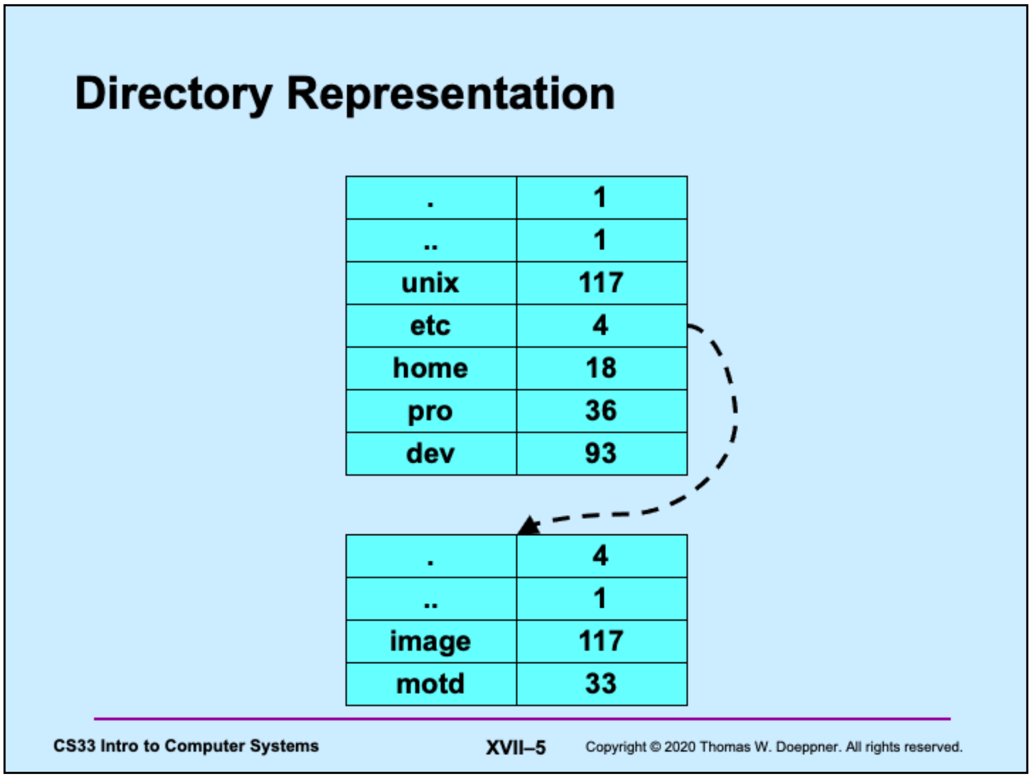
A simple implementation of a directory consists of an array of pairs of *component name* and *inode number*, where the latter identifies the target file's *inode* to the operating system (an inode is data structure maintained by the operating system that represents a file). Note that every directory contains two special entries, "." and "..". The former refers to the directory itself, the latter to the directory's parent (in the case of the slide, the directory is the root directory and has no parent, thus its ".." entry is a special case that refers to the directory itself).

While this implementation of a directory was used in early file systems for Unix, it suffers from a number of practical problems (for example, it doesn't scale well for large directories). It provides a good model for the semantics of directory operations, but directory implementations on modern systems are more complicated than this (and are beyond the scope of this course).



Here are two directory entries referring to the same file. This is done, via the shell, through the *ln* command which creates a (hard) link to its first argument, giving it the name specified by its second argument.

The shell's "ln" command is implemented using the link system call.

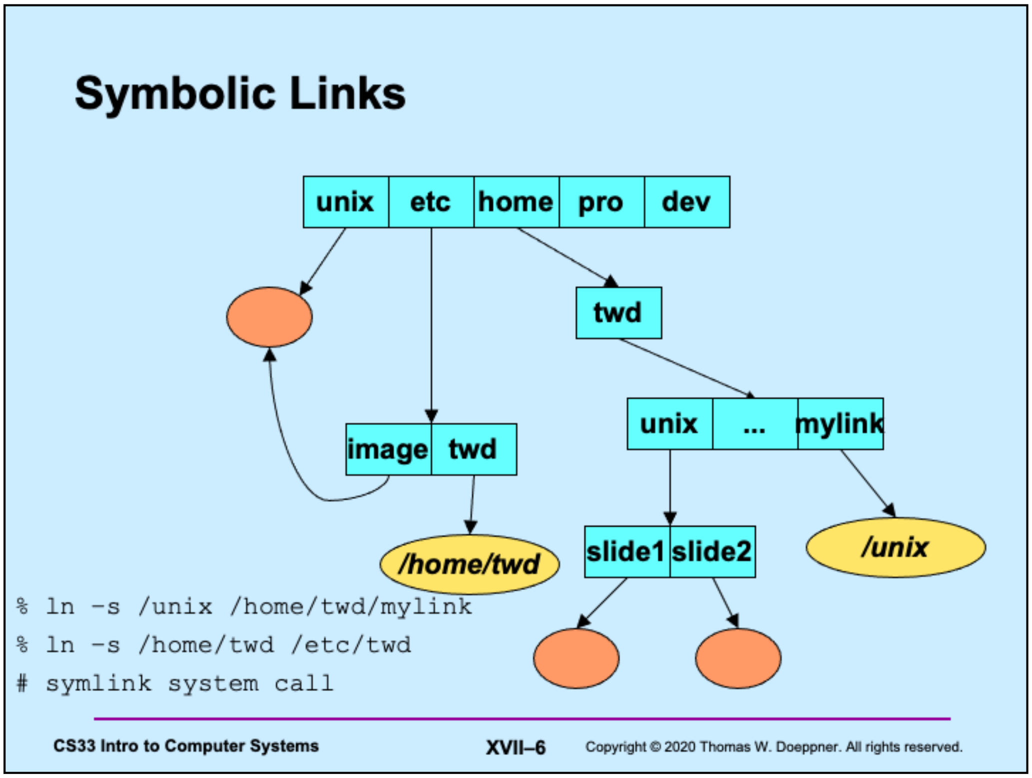


Here are the (abbreviated) contents of both the *root* (/) and */etc* directories, showing how */unix* and */etc/image* are the same file. Note that if the directory entry */unix* is deleted (via the shell's "rm" command), the file (represented by inode 117) continues to exist, since there is still a directory entry referring to it. However if */etc/image* is also deleted, then the file has no more links and is removed. To implement this, the file's inode contains a link count, indicating the total number of directory entries that refer to it. A file is actually deleted only when its inode's link count reaches zero.

Note: suppose a file is open, i.e. is being used by some process, when its link count becomes zero. Rather than delete the file while the process is using it, the file will continue to exist until no process has it open. Thus the inode also contains a reference count indicating how many times it is open: in particular, how many system file table entries point to it. A file is deleted when and only when both the link count and this reference count become zero.

The shell's "rm" command is implemented using the *unlink* system call.

Note that */etc/..* refers to the root directory.



Differing from a hard link, a symbolic link (often called soft link) is a special kind of file containing the name of another file. When the kernel processes such a file, rather than simply retrieving its contents, it makes use of the contents by replacing the portion of the directory path that it has already followed with the contents of the soft-link file and then following the resulting path. Thus referencing */home/twd/mylink* results in the same file as referencing */unix*. Referencing */etc/twd/unix/slide1* results in the same file as referencing */home/twd/unix/slide1*.

The shell's "ln" command with the "-s" flag is implemented using the *symlink* system call.

Working Directory

- Maintained in kernel for each process
  - paths not starting from "/" start with the working directory
  - changed by use of the *chdir* system call
    - » *cd* shell command
  - displayed (via shell) using "pwd"
    - » how is this done?

The *working directory* is maintained in the kernel for each process. Whenever a process attempts to follow a path that doesn't start with "/", it starts at its working directory (rather than at "/").

Open

```
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
int open(const char *path, int options [, mode_t mode])
```

- options
  - » O_RDONLY — open for reading only
  - » O_WRONLY — open for writing only
  - » O_RDWR — open for reading and writing
  - » O_APPEND — set the file offset to *end of file* prior to each *write*
  - » O_CREAT — if the file does not exist, then create it, setting its mode to *mode* adjusted by *umask*
  - » O_EXCL — if O_EXCL and O_CREAT are set, then *open* fails if the file exists
  - » O_TRUNC — delete any previous contents of the file

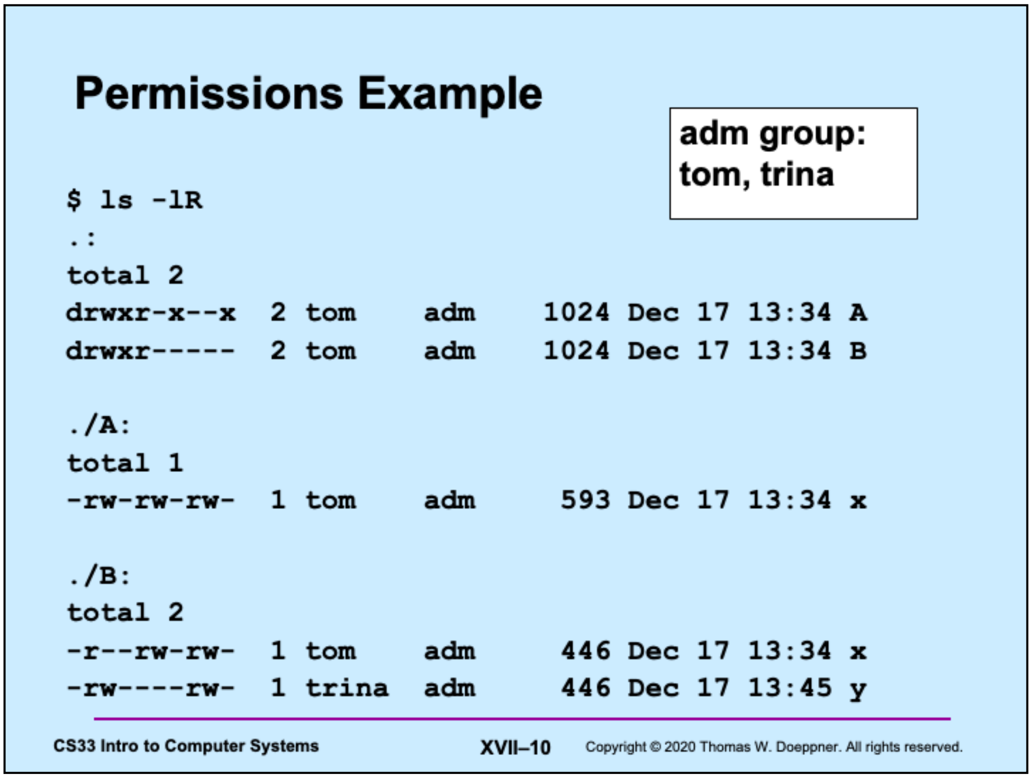
Here's a partial list of the options available as the second argument to open. (Further options are often available, but they depend on the version of Unix.) Note that the first three options are mutually exclusive: one, and only one, must be supplied. We discuss the third argument to *open*, mode, in the next few slides.

File Access Permissions

- **Who's allowed to do what?**
  - who
    - » user (owner)
    - » group
    - » others (rest of the world)
  - what
    - » read
    - » write
    - » execute

Each file has associated with it a set of access permissions indicating, for each of three classes of principals, what sorts of operations on the file are allowed. The three classes are the owner of the file, known as *user*, the group owner of the file, known simply as *group*, and everyone else, known as *others*. The operations are grouped into the classes *read*, *write*, and *execute*, with their obvious meanings. The access permissions apply to directories as well as to ordinary files, though the meaning of execute for directories is not quite so obvious: one must have *execute* permission for a directory file in order to follow a path through it.

The system, when checking permissions, first determines the smallest class of principals the requester belongs to: user (smallest), group, or others (largest). It then, within the chosen class, checks for appropriate permissions.



In the current directory are two subdirectories, *A* and *B*, with access permissions as shown in the slide. Note that the permissions are given as a string of characters: the first character indicates whether or not the file is a directory, the next three characters are the permissions for the owner of the file, the next three are the permissions for the members of the file's group's members, and the last three are the permissions for the rest of the world.

Quiz: the users *tom* and *trina* are members of the *adm* group; *andy* is not.

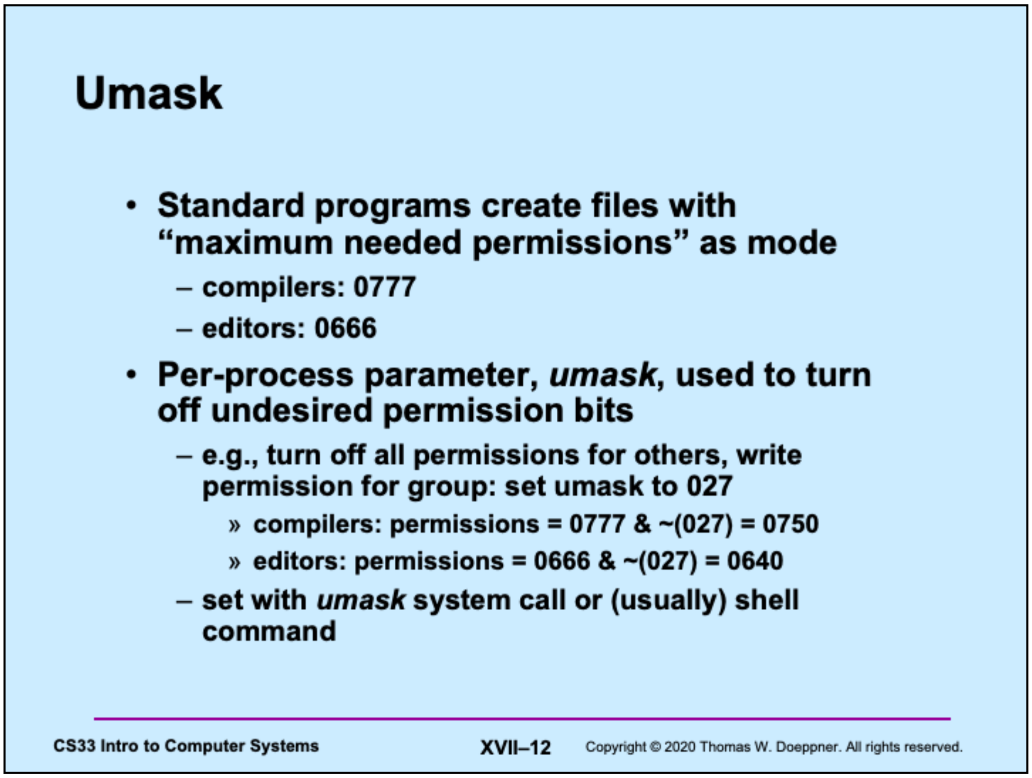
- May *andy* list the contents of directory *A*?
- May *andy* read *A/x*?
- May *trina* list the contents of directory *B*?
- May *trina* modify *B/y*?
- May *tom* modify *B/x*?
- May *tom* read *B/y*?

Setting File Permissions

```
#include <sys/types.h>
#include <sys/stat.h>
int chmod(const char *path, mode_t mode)
```

- **sets the file permissions of the given file to those specified in *mode***
- **only the owner of a file and the superuser may change its permissions**
- **nine combinable possibilities for *mode* (*read/write/execute* for *user*, *group*, and *others*)**
  - » `S_IRUSR (0400), S_IWUSR (0200), S_IXUSR (0100)`
  - » `S_IRGRP (040), S_IWGRP (020), S_IXGRP (010)`
  - » `S_IROTH (04), S_IWOTH (02), S_IXOTH (01)`

The *chmod* system call (and the similar *chmod* shell command) is used to change the permissions of a file. Note that the symbolic names for the permissions are rather cumbersome; what is often done is to use their numerical equivalents instead. Thus the combination of read/write/execute permission for the user (0700), read/execute permission for the group (050), and execute-only permission for others (01) can be specified simply as 0751.



The *umask* (often called the "creation mask") allows programs to have wired into them a standard set of maximum needed permissions as their file-creation modes. Users then have, as part of their environment (via a per-process parameter that is inherited by child processes from their parents), a limit on the permissions given to each of the classes of security principals. This limit (the *umask*) looks like the 9-bit permissions vector associated with each file, but each one-bit indicates that the corresponding permission is not to be granted. Thus, if *umask* is set to 022, then, whenever a file is created, regardless of the settings of the mode bits in the *open* or *creat* call, write permission for *group* and *others* is not to be included with the file's access permissions.

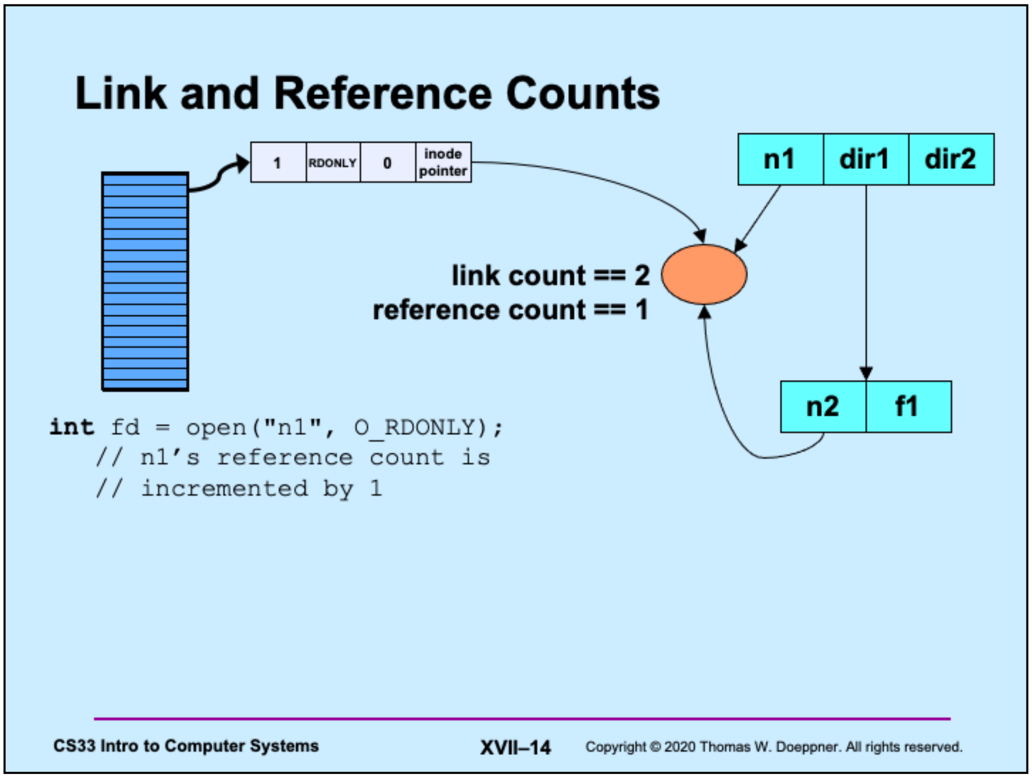
You can determine the current setting of *umask* by executing the *umask* shell command without any arguments.

Creating a File

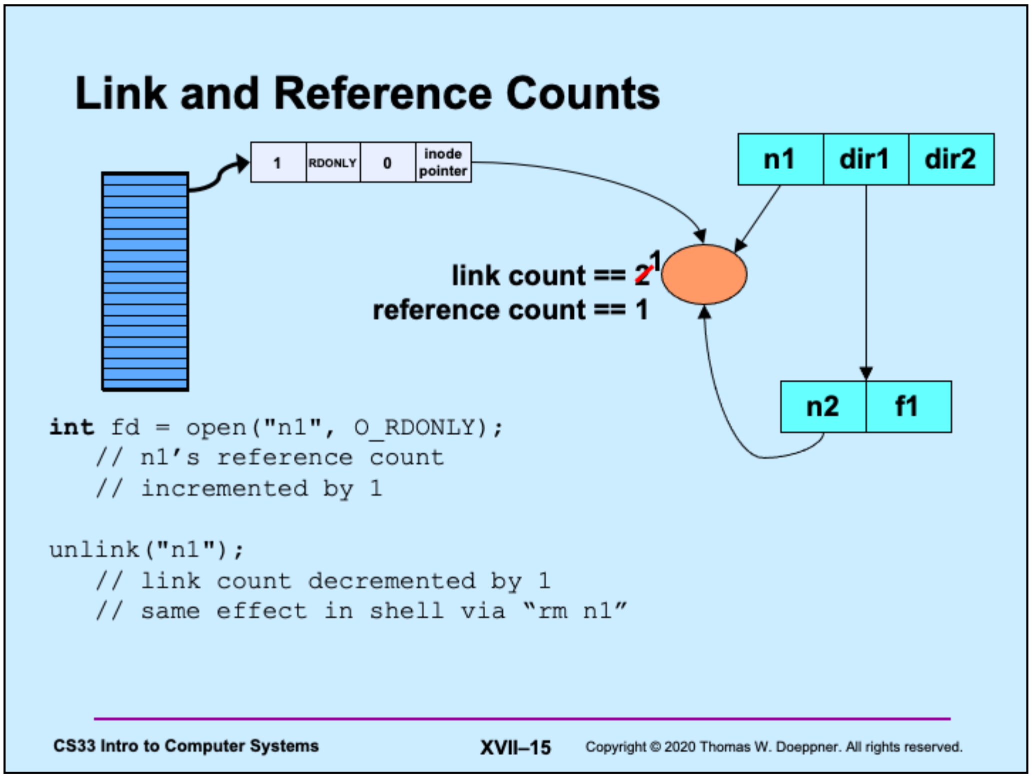
- **Use either *open* or *creat***
  - `open(const char *pathname, int flags, mode_t mode)`
    - » **flags must include O_CREAT**
  - `creat(const char *pathname, mode_t mode)`
    - » **open is preferred**
- **The *mode* parameter helps specify the permissions of the newly created file**
  - **permissions = mode & ~umask**

Originally in Unix one created a file only by using the *creat* system call. A separate O_CREAT flag was later given to *open* so that it, too, can be used to create files. The *creat* system call fails if the file already exists. For *open*, what happens if the file already exists depends upon the use of the flags O_EXCL and O_TRUNC. If O_EXCL is included with the flags (e.g., *open("newfile", O_CREAT|O_EXCL, 0777)),* then, as with *creat*, the call fails if the file exists. Otherwise, the call succeeds and the (existing) file is opened. If O_TRUNC is included in the flags, then, if the file exists, its previous contents are eliminated and the file (whose size is now zero) is opened.

When a file is created by either *open* or *creat*, the file's initial access permissions are the bitwise AND of the mode parameter and the complement of the process's umask (explained in the next slide).

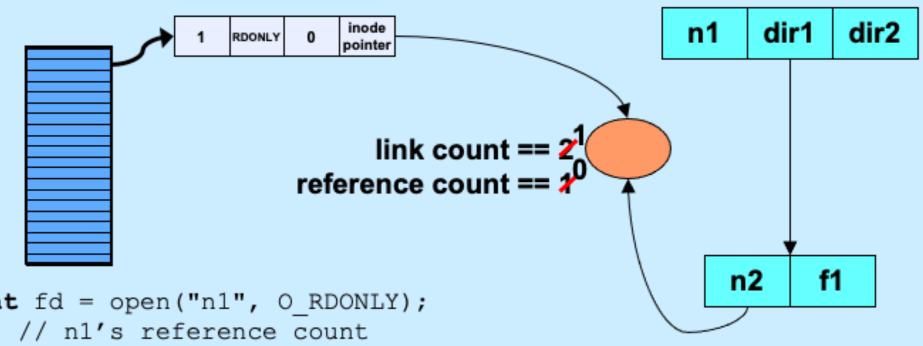


A file's link count is the number of directory entries that refer to it. There's a separate reference count that's the number of file context structures that refer to it (via the inode pointer – see slide XX-17).



Note that the shell's rm command is implemented using unlink; it simply removes the directory entry, reducing the file's link count by 1.

Link and Reference Counts

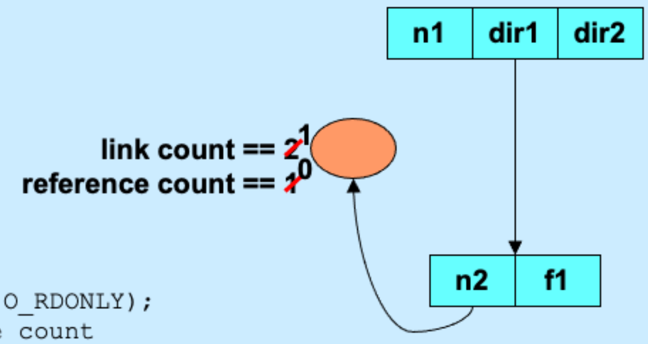



```
int fd = open("n1", O_RDONLY);
   // n1's reference count
   // incremented by 1

unlink("n1");
   // link count decremented by 1

close(fd);
   // reference count decremented by 1
```

Link and Reference Counts



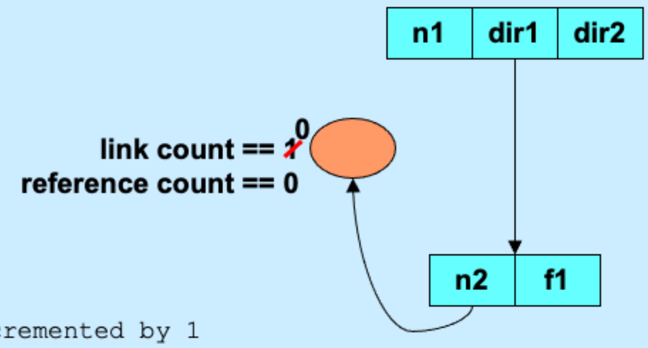

```
int fd = open("n1", O_RDONLY);
   // n1's reference count
   // incremented by 1

unlink("n1");
   // link count decremented by 1

close(fd);
   // reference count decremented by 1
```


A file is deleted if and only if both its link and reference counts are zero.

Link and Reference Counts




```
unlink("dir1/n2");
   // link count decremented by 1
```


A file is deleted if and only if both its link and reference counts are zero.

Quiz 1

```
int main() {
  int fd = open("file", O_RDWR|O_CREAT, 0666);
  unlink("file");
  PutStuffInFile(fd);
  ReadStuffFromFile(fd);
  return 0;
}
```

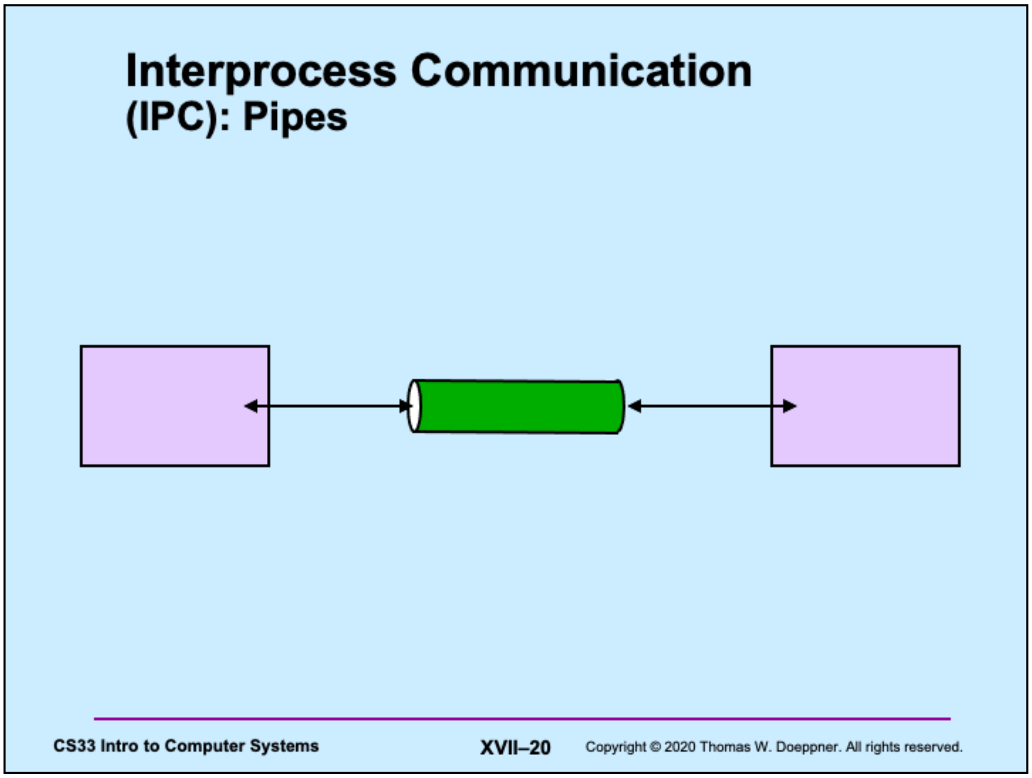
Assume that *PutStuffInFile* writes to the given file, and *ReadStuffFromFile* reads from the file.

a) This program is doomed to failure, since the file is deleted before it's used

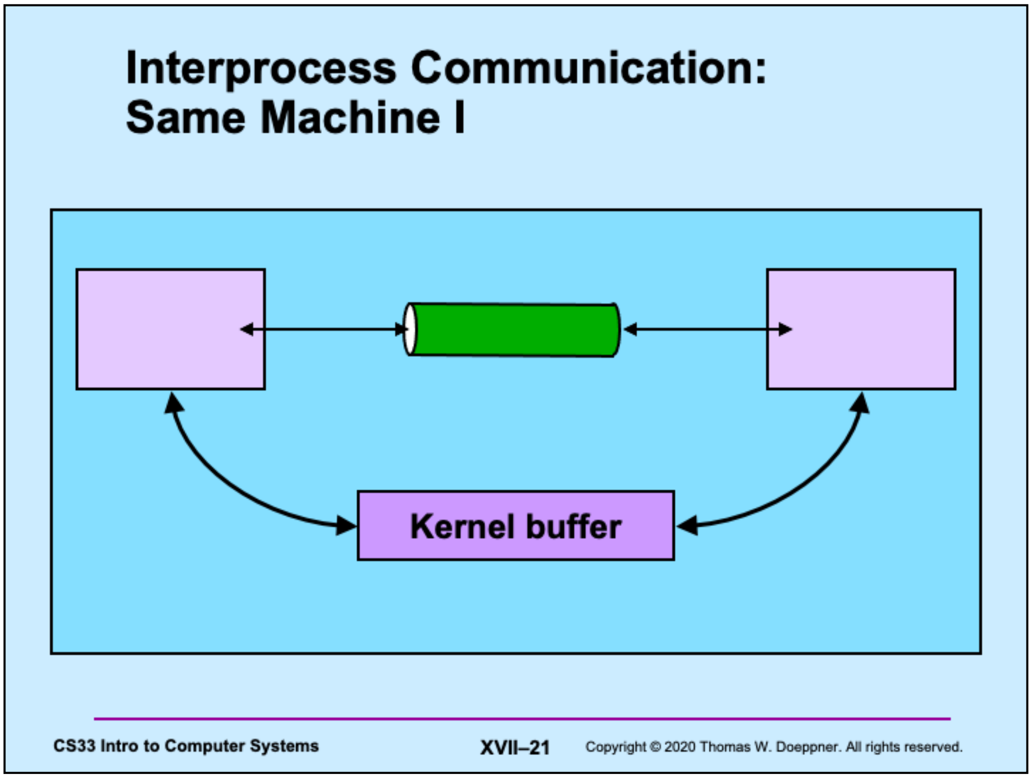
b) Because the file is used after the unlink call, it won't be deleted

c) The file will be deleted when the program terminates

Note that when a process terminates, all its open files are automatically closed.

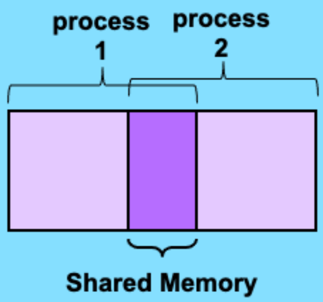


A rather elegant way for different processes to communicate is via a pipe: one process puts data into a pipe, another process reads the data from the pipe.

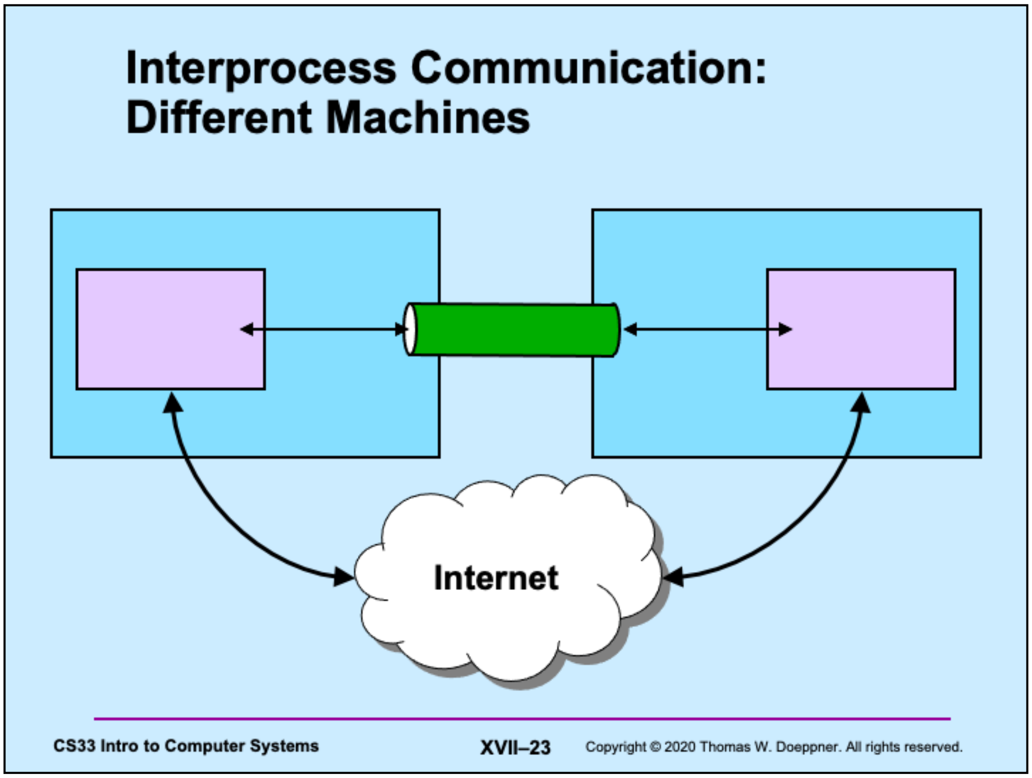


The implementation of a pipe involves the sending process using a write system call to transfer data into a kernel buffer. The receiving process fetches the data from the buffer via a read system call.

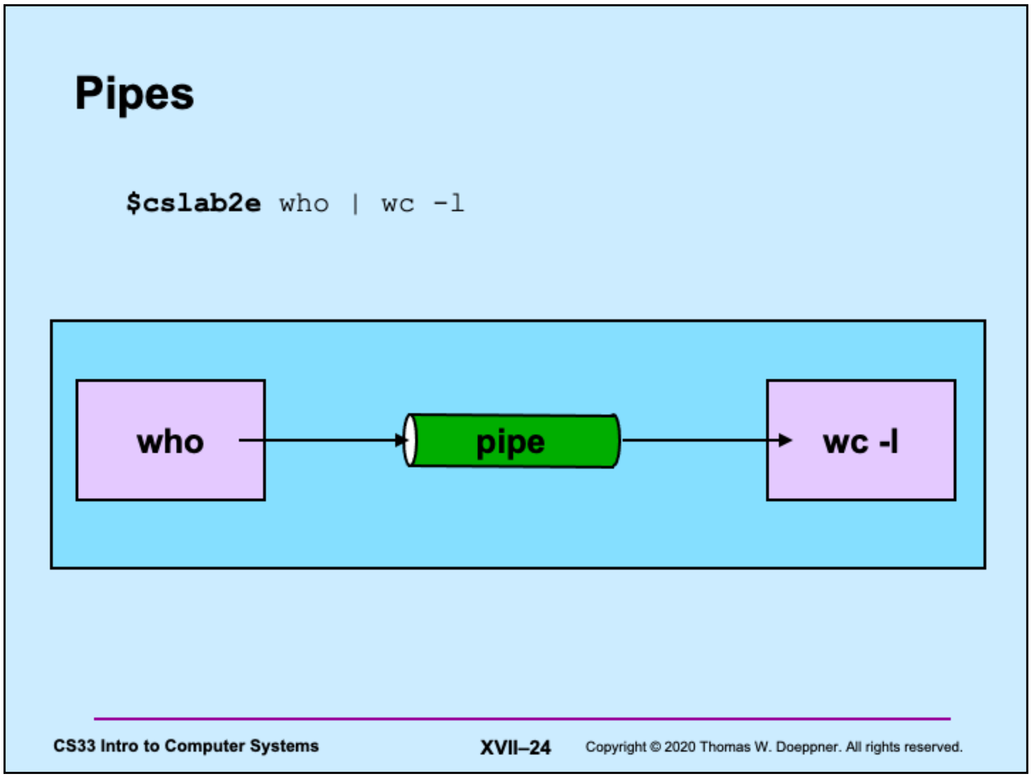
Interprocess Communication: Same Machine II



Another way for processes to communicate is for them to arrange to have some memory in common via which they share information. We discuss this approach later in the semester.



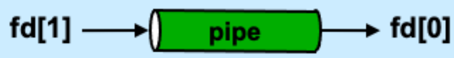
The pipe abstraction can also be made to work between processes on different machines. We discuss this later in the semester.



The vertical bar ("|") is the pipe symbol in the shell. The syntax shown above represents creating two processes, one running who and the other running wc. The standard output of who is setup to be the pipe; the standard input of wc is setup to be the pipe. Thus the output of who becomes the input of wc. The "-l" argument to wc tells it to count and print out the number of lines that are input to it. The who command writes to standard output the login names of all logged in users. The combination of the two produces the number of users who are currently logged in.

Intramachine IPC

```
$cslab2e who | wc -l
```




```
int fd[2];
pipe(fd);
if (fork() == 0) {
  close(fd[0]);
  close(1);
  dup(fd[1]); close(fd[1]);
  execl("/usr/bin/who", "who", 0); // who sends output to pipe
}
if (fork() == 0) {
  close(fd[1]);
  close(0);
  dup(fd[0]); close(fd[0]);
  execl("/usr/bin/wc", "wc", "-l", 0); // wc's input is from pipe
}
close(fd[1]); close(fd[0]);
// …
```


The *pipe* system call creates a “pipe” in the kernel and sets up two file descriptors. One, in fd[1], is for writing to the pipe; the other, in fd[0], is for reading from the pipe. The input end of the pipe is set up to be *stdout* for the process running *who*, and the output end of the pipe is closed, since it’s not needed. Similarly, the input end of the pipe is set up to be *stdin* for the process running *wc*, and the input end is closed. Since the parent process (running the shell) has no further need for the pipe, it closes both ends. When neither end of the pipe is open by any process, the system deletes it. If a process reads from a pipe for which no process has the input end open, the read returns 0, indicating end of file. If a process writes to a pipe for which no process has the output end open, the write returns -1, indicating an error and *errno* is set to EPIPE; the process also receives the SIGPIPE signal, which we explain in the next lecture.

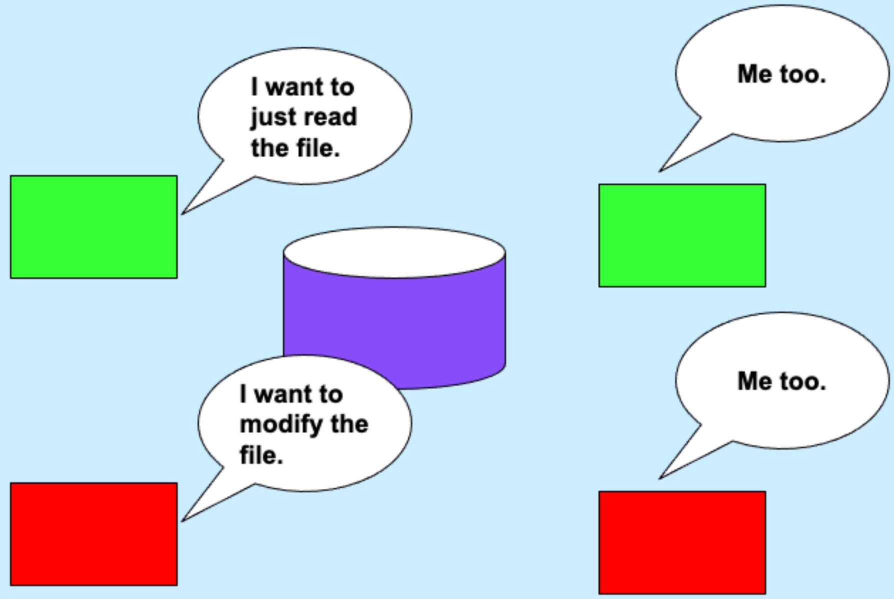
Sharing Files

- You're doing a project with a partner
- You code it as one 15,000-line file
  - the first 7,500 lines are yours
  - the second 7,500 lines are your partner's
- You edit the file, changing 6,000 lines
  - it's now 5am
- Your partner completes her changes at 5:01am
- At 5:02am you look at the file
  - your partner's changes are there
  - yours are not

Lessons

- Never work with a partner
- Use more than one file
- Read up on git
- Use an editor and file system that support file locking

What We Want ...

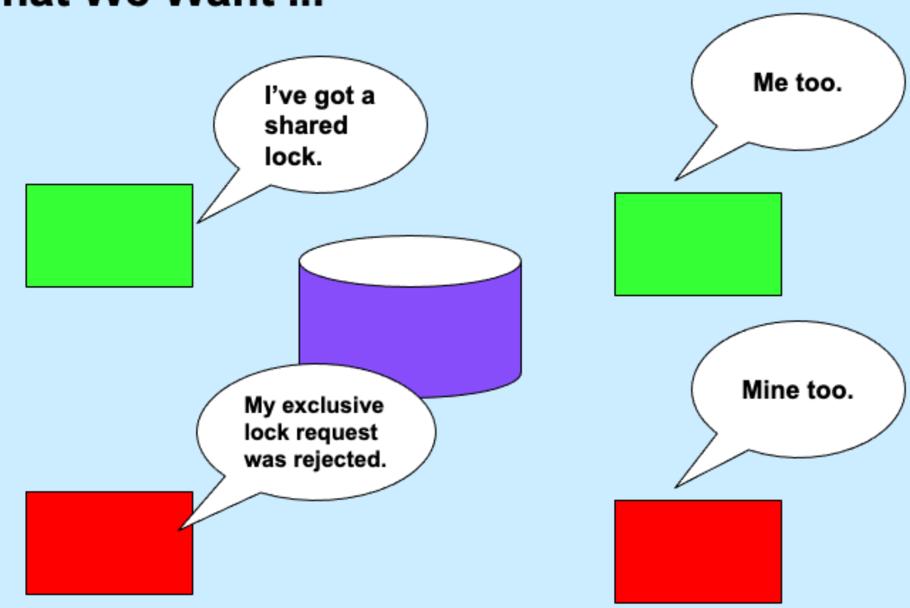


I want to just read the file.
Me too.
I want to modify the file.
Me too.

Types of Locks

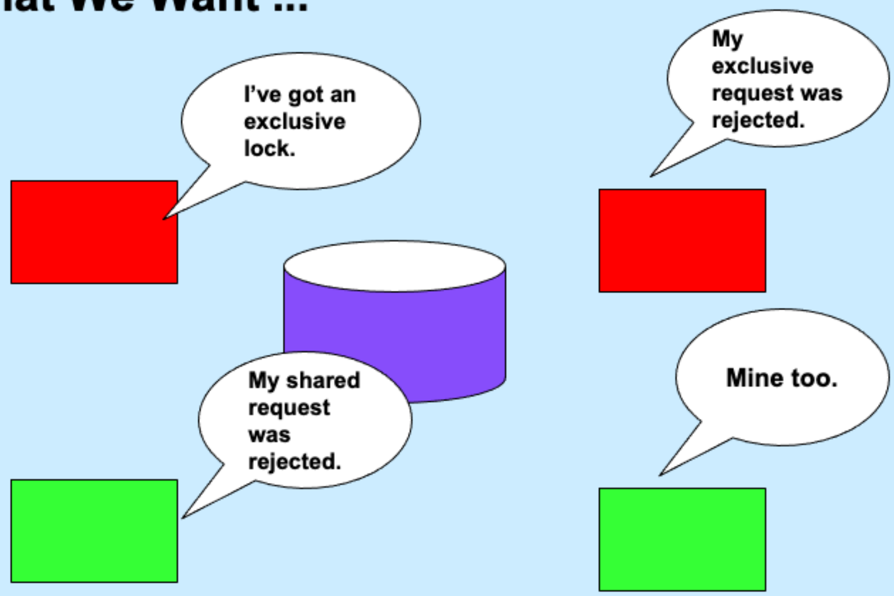
- Shared (readers) locks
  - any number may have them at same time
  - may not be held when an exclusive lock is held
- Exclusive (writers) locks
  - only one at a time
  - may not be held when a shared lock is held

What We Want ...



I've got a shared lock.
Me too.
My exclusive lock request was rejected.
Mine too.

What We Want ...


I've got an exclusive lock.
My exclusive request was rejected.
My shared request was rejected.
Mine too.

Locking Files

- **Early Unix didn't support file locking**
- **How did people survive?**
  - `open("file.lck", O_RDWR|O_CREAT|O_EXCL, 0666);`
    - » **operation fails if *file.lck* exists, succeeds (and creates file.lck) otherwise**
    - » **requires cooperative programs**

Locking Files (continued)

- How it's done in "modern" Unix
  - "advisory locks" may be placed on files
    - » may request shared (readers) or exclusive (writers) lock
      - *fcntl* system call
    - » either succeeds or fails
    - » *open*, *read*, *write* always work, regardless of locks
    - » a lock applies to a specified range of bytes, not necessarily to the whole file
    - » requires cooperative programs
  - "mandatory locks" supported as a per-file option
    - » set along with permission bits
    - » if set, file can't be used unless process possesses appropriate locks

Locking Files (still continued)

- **How to:**

```
struct flock fl;
fl.l_type = F_RDLCK;       // read lock
// fl.l_type = F_WRLCK;    // write lock
// fl.l_type = F_UNLCK;    // unlock
fl.l_whence = SEEK_SET;    // starting where
fl.l_start = 0;            // offset
fl.l_len = 0;              // how much? (0 = whole file)
fd = open("file", O_RDWR);
if (fcntl(fd, F_SETLK, &fl) == -1)
  if ((errno == EACCES) || (errno == EAGAIN))
    // didn't get lock
  else
    // something else is wrong
else
  // got the lock!
```


Alternatively, one may use l_type values of F_RDLCKW and F_WRLCKW to wait until the lock may be obtained, rather than to return an error if it can't be obtained.

Whether the lock is mandatory or advisory depends upon the per-file settings.

Quiz 2

- Your program currently has a shared lock on a portion of a file. It would like to "upgrade" the lock to be an exclusive lock. Would there be any problems with adding an option to *fcntl* that would allow the holder of a shared lock to wait until it's possible to upgrade to an exclusive lock, then do the upgrade?

  a) at least one major problem

  b) either no problems whatsoever or some easy-to-deal-with problems