CS111, Lecture 7
File Descriptors and System Calls

Optional reading:

Operating Systems: Principles and Practice (2nd Edition): Sections 13.1-13.2

CS198 Section Leading!

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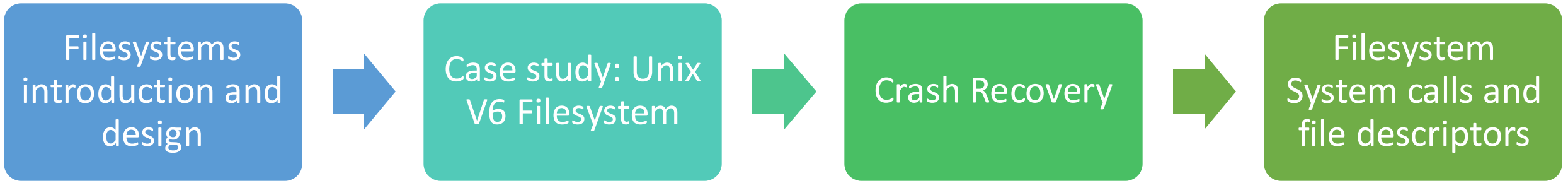
https://docs.google.com/presentation/d/1jzb7xIxI0eTClhT839XT2MYUBeEETF6D80ViJ6ZP1Tw/edit?usp=sharing

cs198.stanford.edu – application due 1/30

CS111 Topic 1: Filesystems

Key Question: *How can we design filesystems to manage files on disk, and what are the tradeoffs inherent in designing them? How can we interact with the filesystem in our programs?*



assign2: implement a program that can repair a filesystem after a crash, and explore some of the security and ethical implications of OSes / filesystems.

Learning Goals

- Learn about the **open**, **close**, **read** and **write** functions that let us interact with files
- Get familiar writing programs that read, write and create files
- Learn what the operating system manages for us so that we can interact with files

Plan For Today

- System calls
- **open()** and **close()**
- **Practice:** creating files
- **read()** and **write()**
- **Practice:** copying files

```
cp -r /afs/ir/class/cs111/lecture-code/lect7 .
```

Plan For Today

- **System calls**
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```
cp -r /afs/ir/class/cs111/lecture-code/lect7 .
```

OS vs. User Mode

- The operating system runs code in a privileged “kernel mode” where it can do things and access data that regular user programs cannot. E.g. only OS can call **readSector**.
- System tracks whether it is in “user mode” or “kernel mode”
- The OS provides public functions that we can call in our user programs – **system calls**. When these functions are called, it switches over to “kernel mode”.

System Calls

Functions to interact with the operating system are part of a group of functions called **system calls**.

- A system call is a public function provided by the operating system.
- The operating system handles these tasks because they require special privileges that we do not have in our programs. When a system call runs, it runs in **kernel mode**, and we switch back to user mode when it's done.
- The operating system *kernel* runs the code for a system call, completely isolating the system-level interaction from the (potentially harmful) user program.
- We are going to examine the system calls for interacting with files. When writing production code, you will often use higher-level methods that build on these (like C++ streams or FILE *), but let's see how they work!

open()

Call **open** to open a file:

```
int open(const char *pathname, int flags);
```

- **pathname**: path to open
- **flags**: bitwise OR of options specifying the behavior for opening the file
- returns a **file descriptor** representing the opened file, or -1 on error

Many possible flags! (see manual page for full list).

- **Must have exactly 1 of**: **O_RDONLY** (read-only), **O_WRONLY** (write-only), **O_RDWR** (read and write). These say how you will use the file in this program.
- Optional: **O_TRUNC** - if the file exists already, truncate (clear) it.

open()

Call **open** to open a file:

```
int open(const char *pathname, int flags, mode_t mode);
```

You can also create a new file if the specified file doesn't exist, by including **O_CREAT** as one of the flags. You must also specify a third **mode** parameter.

- **mode**: the permissions to attempt to set for a created file, e.g. 0644 (octal!)

open()

Call **open** to open a file:

```
int open(const char *pathname, int flags, mode_t mode);
```

You can also create a new file if the specified file doesn't exist, by including **O_CREAT** as one of the flags. You must also specify a third **mode** parameter.

- **mode**: the permissions to attempt to set for a created file, e.g. 0644 (octal!)

Another useful flag: **O_EXCL**, which says the file must be created from scratch, and to fail if the file already exists.

Aside: how are there multiple signatures for **open** in C? See here.

File Descriptors

A **file descriptor** is like a "ticket number" representing your currently-open file.

- It is a unique number assigned by the operating system to refer to that instance of that file in this program.
- Each program has its own file descriptors
- You can have multiple file descriptors for the same file - every time you call open, you get a new file descriptor.
- When you wish to refer to the file (e.g. read from it, write to it) you must provide the file descriptor.
- file descriptors are assigned in ascending order (next FD is lowest unused)
- The OS remembers information associated with each of your file descriptors, like where in the file you currently are (if reading/writing). E.g. separate locations in the file for each file descriptor.

close()

Call **close** to close a file when you're done with it:

```
int close(int fd);
```

- **fd:** the file descriptor you'd like to close.
- Returns: 0 on success, -1 on error (we usually won't error-check **close**)

Important to close files when done with them to preserve system resources.

- You can use **valgrind** to check if you forgot to close any files. (--track-fds=yes)

Plan For Today

- System calls
- **open()** and **close()**
- **Practice: creating files**
- **read()** and **write()**
- **Practice:** copying files

```
cp -r /afs/ir/class/cs111/lecture-code/lect7 .
```

Example: Creating a File (touch)

```
// ./touch newfile.txt
int main(int argc, char *argv[]) {
  int fd = open(argv[1], O_WRONLY | O_CREAT | O_EXCL, 0644);

  // If an error occurs, print out an error message
  if (fd == -1) {
    printf("There was a problem creating \"%s\"!\n", argv[1]);
    return 1;
  }

  // Close the file, we are done with it (no error checking)
  close(fd);
  return 0;
}
```

touch.c

Example: Creating a File (touch)

```
// ./touch newfile.txt
int main(int argc, char *argv[]) {
  int fd = open(argv[1], O_WRONLY | O_CREAT | O_EXCL, 0644);

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    return 1;
  }

  // Close the file, we are done with it (no error checking)
  close(fd);
  return 0;
}
```

touch.c

Open the file to be written to

Example: Creating a File (touch)

```
// ./touch newfile.txt
int main(int argc, char *argv[]) {
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    return 1;
  }

  // Close the file, we are done with it (no error checking)
  close(fd);
  return 0;
}
```

If the file doesn't exist, create it

touch.c

Example: Creating a File (touch)

```
// ./touch newfile.txt
int main(int argc, char *argv[]) {
  int fd = open(argv[1], O_WRONLY | O_CREAT | O_EXCL, 0644);

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    printf("There was a problem creating \"%s\"\n", argv[1]);
    return 1;
  }

  // Close the file, we are done with it (no error checking)
  close(fd);
  return 0;
}
```

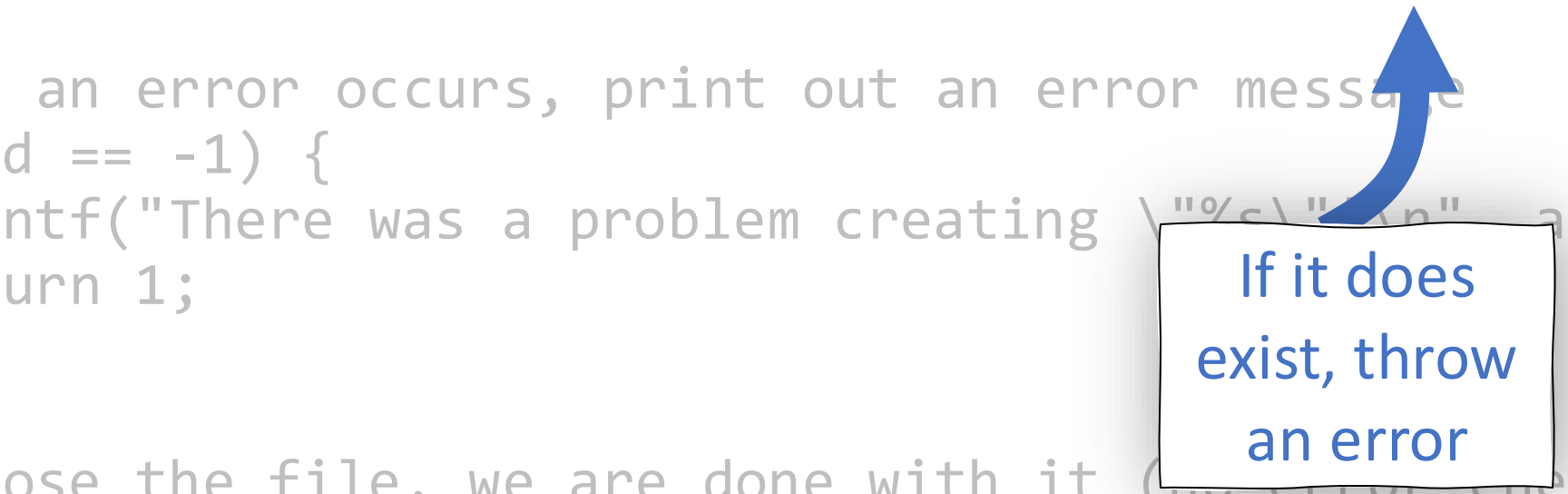

touch.c

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  // Close the file, we are done with it (no error checking)
  close(fd);
  return 0;
}
```

If we create a new file, it should have these permissions (don't worry about specifics for now)

touch.c

Example: Creating a File (touch)

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// ./touch newfile.txt
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  int fd = open(argv[1], O_WRONLY | O_CREAT | O_EXCL, 0644);

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touch.c

Example: Creating a File (touch)

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  close(fd);
  return 0;
}
```

touch.c

Specify how we are going to use this file in *this program*

Example: Creating a File (touch)

```
// ./touch newfile.txt
int main(int argc, char *argv[]) {
  int fd = open(argv[1], O_WRONLY | O_CREAT | O_EXCL, 0644);

  // If an error occurs, print out an error message
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    return 1;
  }

  // Close the file, we are done with it (no erro
  close(fd);
  return 0;
}
```

Specify permissions for everyone on disk if this call creates a new file

touch.c

Plan For Today

- System calls
- **open()** and **close()**
- **Practice:** creating files
- **read() and write()**
- **Practice:** copying files

```
cp -r /afs/ir/class/cs111/lecture-code/lect7 .
```

read()

Call **read** to read bytes from an open file:

```
ssize_t read(int fd, void *buf, size_t count);
```

- **fd**: the file descriptor for the file you'd like to read from
- **buf**: the memory location where the read-in bytes should be put
- **count**: the number of bytes you wish to read
- returns -1 on error, 0 if at end of file, or nonzero if bytes were read (will never return 0 but not be at end of file)

Key idea: read may not read all the bytes you ask it to! This is not necessarily an error – e.g. if there aren't that many bytes, or if interrupted. The return value tells you how many were read. If we must have all bytes, we can call **read** more.

Key idea #2: the operating system keeps track of where in a file a file descriptor is reading from. So the next time you read, it will resume where you left off.

write()

Call **write** to write bytes to an open file:

```
ssize_t write(int fd, const void *buf, size_t count);
```

- **fd**: the file descriptor for the file you'd like to write to
- **buf**: the memory location storing the bytes that should be written
- **count**: the number of bytes you wish to write from buf
- returns -1 on error, or otherwise the number of bytes that were written (nonzero assuming count > 0)

Key idea: write may not write all the bytes you ask it to! This is not necessarily an error – e.g. if not enough space, or if interrupted. The return value tells you how many were written. If we must write all bytes, we can call **write** more.

Key idea #2: the operating system keeps track of where in a file a file descriptor is writing to. So the next time you write, it will write to where you left off.

Example: Copy

Let's write an example program **copy** that emulates the built-in **cp** command. It takes in two command line arguments (file names) and copies the contents of the first file to the second.

E.g. **`./copy source.txt dest.txt`**

1. Open the source file and the destination file and get file descriptors
2. Read each chunk of data from the source file and write it to the destination file

(*note: we won't worry about error-checking open/close/read/write, but full version here includes error checking).*

`copy-soln.c` and **`copy-soln-full.c`** (with error checking)

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
static const int kDefaultPermissions = 0644;


int main(int argc, char *argv[]) {
    int sourceFD = open(argv[1], O_RDONLY);
    int destinationFD = open(argv[2],
        O_WRONLY | O_CREAT | O_EXCL, kDefaultPermissions);

    copyContents(sourceFD, destinationFD);

    close(sourceFD);
    close(destinationFD);
    return 0;
}
```

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
static const int kDefaultPermissions = 0644;


int main(int argc, char *argv[]) {
    int sourceFD = open(argv[1], O_RDONLY);
    int destinationFD = open(argv[2],
        O_WRONLY | O_CREAT | O_EXCL, kDefaultPermissions);

    copyContents(sourceFD, destinationFD);

    close(sourceFD);
    close(destinationFD);
    return 0;
}
```

"create the file to write to, and it must not already exist"

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    // Goal: while there's more data from source, read the next
    // chunk and write it to the destination.
}
```

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        ...
    }
}
```

Loop through the source file one chunk at a time – for each chunk, write it to the destination file.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ...
    }
}
```

Read a chunk of at most **kCopyIncrement** (arbitrary amount) bytes at a time.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ssize_t bytesRead = read(sourceFD, buffer, sizeof(buffer));
        if (bytesRead == 0) break;

        ...
    }
}
```

Read a chunk of bytes. It may not be **kCopyIncrement** bytes! If **read** returns 0, there are no more bytes to read.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ssize_t bytesRead = read(sourceFD, buffer, sizeof(buffer));
        if (bytesRead == 0) break;

        ...
    }
}
```

Cool behavior: the next time through the loop when we call **read**, it will automatically read the next chunk of bytes from the file!

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ssize_t bytesRead = read(sourceFD, buffer, sizeof(buffer));
        if (bytesRead == 0) break;
        writeAllBytes(destinationFD, buffer, bytesRead);
    }
}
```

Now we write this chunk of bytes to the destination file. We cannot just call **write**, as it may not write all the bytes in one go – we will make a helper that calls **write** in a loop until all these bytes are written.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ssize_t bytesRead = read(sourceFD, buffer, sizeof(buffer));
        if (bytesRead == 0) break;
        writeAllBytes(destinationFD, buffer, bytesRead);
    }
}
```

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) { … }

void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
            ...
    }
}
```

Now we write this chunk of bytes to the destination file. We must loop until **write** writes them all.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) { … }

void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
        ssize_t count = write(...);
        bytesWritten += count;
    }
}
```

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) { … }

void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
        ssize_t count = write(destinationFD, buffer + bytesWritten,
                              nbytes - bytesWritten);
        bytesWritten += count;
    }
}
```

Since **write** may write only some of the bytes, we need to just give it the *rest* of the bytes that it hasn't written yet.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) { … }

void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
        ssize_t count = write(destinationFD, buffer + bytesWritten,
                              nbytes - bytesWritten);
        bytesWritten += count;
    }
}
```

Cool behavior: each time through the loop, **write** knows where we left off writing in the file from before. However, it doesn't know *what* to write – we must do pointer arithmetic to specify that.

Example: Copy

The **copy** program emulates **cp**; it copies the contents of a source file to a specified destination.

```
void copyContents(int sourceFD, int destinationFD) { … }

void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
        ssize_t count = write(destinationFD, buffer + bytesWritten,
                              nbytes - bytesWritten);
        bytesWritten += count;
    }
}
```

Example: Copy

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ssize_t bytesRead = read(sourceFD, buffer, sizeof(buffer));
        if (bytesRead == 0) break;
        writeAllBytes(destinationFD, buffer, bytesRead);
    }
}

void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
        ssize_t count = write(destinationFD, buffer + bytesWritten,
                              nbytes - bytesWritten);
        bytesWritten += count;
    }
}
```

Example: Copy

Respond on PollEv:
pollev.com/cs111

Would it also work if we used **sizeof(buffer)** like below?

```
void copyContents(int sourceFD, int destinationFD) {
    while (true) {
        char buffer[kCopyIncrement];
        ssize_t bytesRead = read(sourceFD, buffer, sizeof(buffer));
        if (bytesRead == 0) break;
        writeAllBytes(destinationFD, buffer, sizeof(buffer));
    }
}
void writeAllBytes(int destinationFD, char buf[], int nbytes) {
    size_t bytesWritten = 0;
    while (bytesWritten < nbytes) {
        ssize_t count = write(destinationFD, buffer + bytesWritten,
                              nbytes - bytesWritten);
        bytesWritten += count;
    }
}
```

Would using sizeof(buffer) in this way also work?

Yes - we are reading bytes into the buffer, and we want to write the entire contents of the buffer each time

0%

No - read may not read enough bytes to fill the whole buffer, and therefore we shouldn't write all bytes in the buffer

0%

No - read may read more bytes than fit in the buffer, and therefore sizeof(buffer) is not the right amount

0%

No - we should use (sizeof(buffer) - bytesRead) to ensure the correct number of bytes are written each time

0%

Recap

- System calls
- **open()** and **close()**
- **Practice:** creating files
- **read()** and **write()**
- **Practice:** copying files

Lecture 7 takeaway: System calls are functions provided by the operating system to do tasks we cannot do ourselves. open, close, read and write are 4 system calls that work via file descriptors to work with files.

Next time: introduction to multiprocessing

```
cp -r /afs/ir/class/cs111/lecture-code/lect7 .
```