Low-Level I/O – the POSIX Layer

CSE 333

Instructor: Alex Sanchez-Stern

Teaching Assistants:

Justin Tysdal

Sayuj Shahi

Nicholas Batchelder

Leanna Mi Nguyen

Administrivia

- Exercise 6 was due this morning
  - Reminder: there is no exercise 5 this quarter
- Exercise 7 is ready, due on Friday
- No sections tomorrow

- Today, we cover the materials for Exercise 7:
  - POSIX I/O for directories and reading data from files
  - Read a directory and open/copy text files found there
    - Copy *exactly* and ***only*** the bytes in the file(s). No extra output, no "formatting", no "titles", no other transformations.

Administrivia

- Homework 1 due on **Friday at 11pm**

Poll Everywhere

pollev.com/uwcse333wntbs

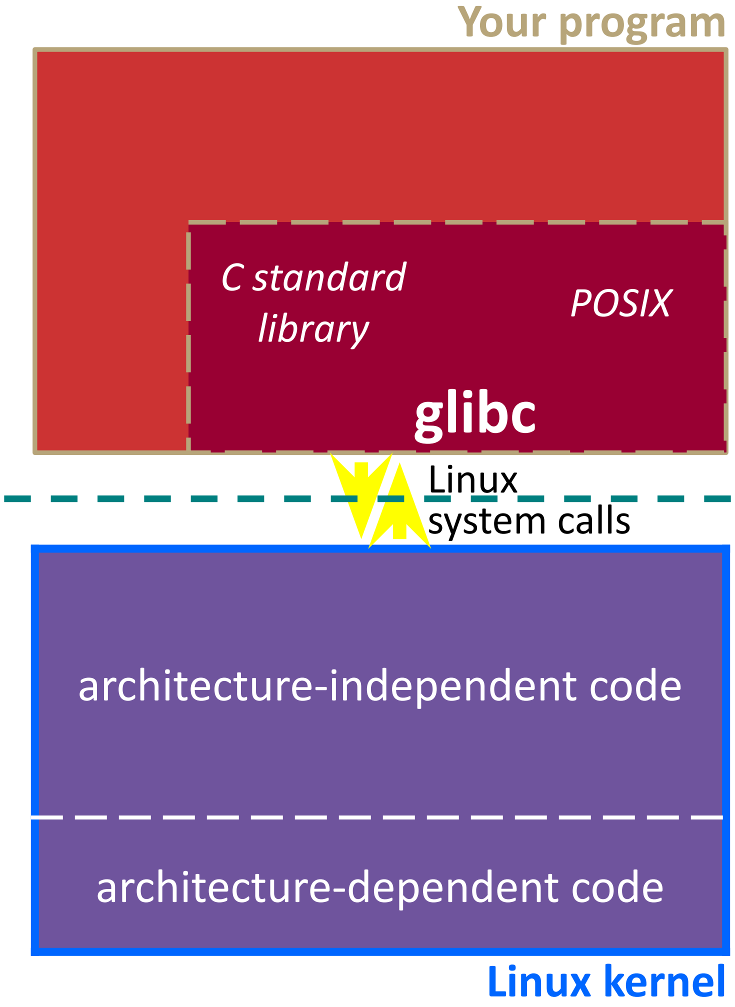
- What are two pieces of functionality that the OS provides to processes that run on it?

POSIX (Portable Operating System Interface)

- Standards for Unix-like operating system interfaces
- Maintained by the IEEE
- Allows more code to be portable across OS's
- Mostly handling:
  - I/O (including from files, terminals, and the network)
  - Threading

Remember This Picture?

- Your program can access many layers of APIs:
  - C standard library
    - Some are just ordinary functions (<string.h>, for example)
    - Some also call OS-level (POSIX) functions (<stdio.h>, for example)
  - POSIX compatibility API
    - C-language interface to OS system calls (fork(), read(), etc.)
  - Underlying OS system calls
    - Assembly language ☺



What’s Tricky about (POSIX) File I/O?

- Communication with input and output devices doesn’t always work as expected
  - May not process all data or fail, necessitating read/write *loops*

- Different system calls have a variety of different failure modes and error codes
  - Look up in the documentation and use pre-defined constants!
  - Lots of error-checking code needed
    - Need to handle resource cleanup on *every* termination pathway

Lecture Outline

- **Reading and Writing Files**
- Reading and Writing Directories

C Standard Library File I/O

- So far you've used the C standard library to access files
  - Use a provided `FILE*` *stream* abstraction
  - `fopen()`, `fread()`, `fwrite()`, `fclose()`, `fseek()`
- These are convenient and portable
  - They are buffered
  - They are implemented using lower-level OS calls

Lower-Level File Access

- Most UNIX-en support a common set of lower-level file access APIs: POSIX – Portable Operating System Interface
  - `open()`, `read()`, `write()`, `close()`, `lseek()`
    - Similar in spirit to their `f*()` counterparts from C std lib
    - Lower-level and unbuffered compared to their counterparts
    - Also less convenient
  - We will have to use these to read file system directories and for network I/O, so we might as well learn them now

open()/close()

- To open a file:
  - Pass in the filename and access mode
    - Similar to **fopen**()
  - Get back a "file descriptor"
    - Similar to `FILE*` from **fopen**(), but is just an `int`
    - Defaults: **0** is `stdin`, **1** is `stdout`, **2** is `stderr`

```
#include <fcntl.h>    // for open()
#include <unistd.h>   // for close()
  ...
  int fd = open("foo.txt", O_RDONLY);
  if (fd == -1) {
    perror("open failed");
    exit(EXIT_FAILURE);
  }
  ...
  close(fd);
```

Optional third argument

Reading from a File

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

  - Returns the number of bytes read
    - Might be fewer bytes than you requested (!!!)
    - Returns `0` if you're already at the end-of-file
    - Returns `-1` on error

  - **`read`** has some surprising error modes…

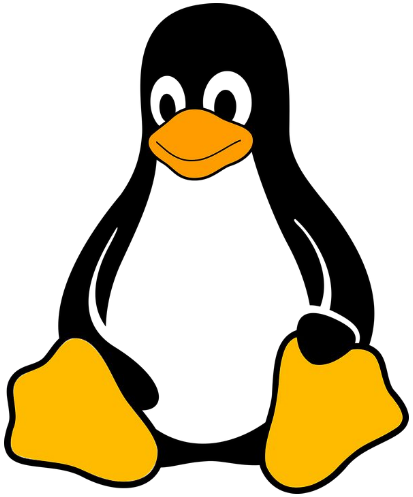
Read error modes

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

  - On error, `read` returns -1 and sets the global **`errno`** variable

  - You need to check **`errno`** to see what kind of error happened
    - `EBADF:` bad file descriptor
    - `EFAULT:` output buffer is not a valid address
    - `EINTR:` read was interrupted, please try again (ARGH!!!! 😤😠)
    - And many others…

I/O Analogy – Messy Roommate



- The Linux kernel (Tux) now lives with you in room #333
- There are N pieces of trash in the room
- There is a single trash can, `char bin[N]`
  - (For some reason, the trash goes in a particular order)
- You can tell your roommate to pick it up, but they are unreliable

I/O Analogy – Messy Roommate

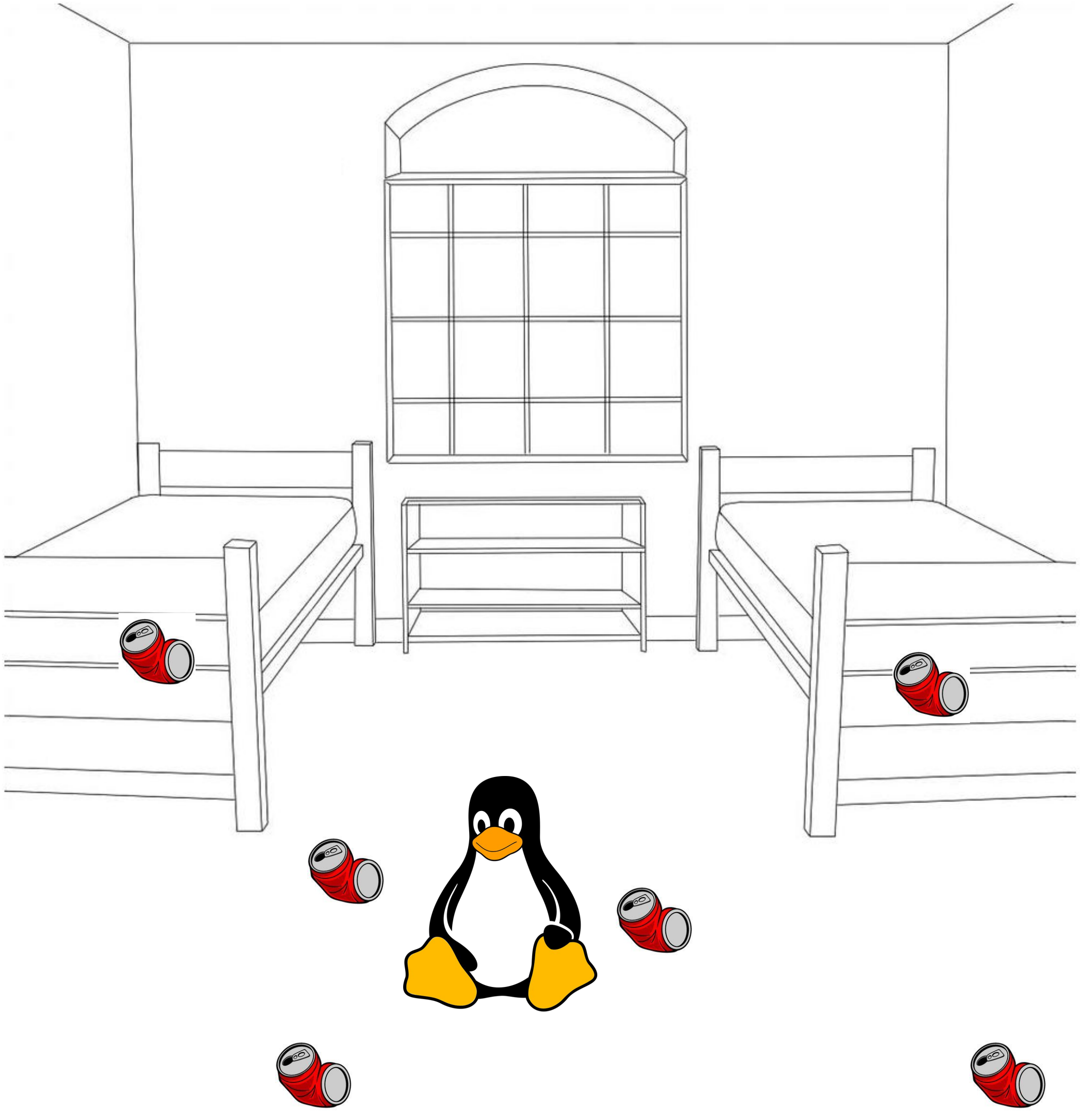
```
num_trash = Pickup(room_num, trash_bin, amount)
```

"*I tried to start cleaning, but something came up*"
(got hungry, had a midterm, room was locked, etc.)
	`num_trash == -1`
	`errno == excuse`

"*You told me to pick up trash, but the room was already clean*"	`num_trash == 0`
"*I picked up some of it, but then I got distracted by my favorite show on Netflix*"	`num_trash < amount`
"*I did it! I picked up all the trash!*"	`num_trash == amount`

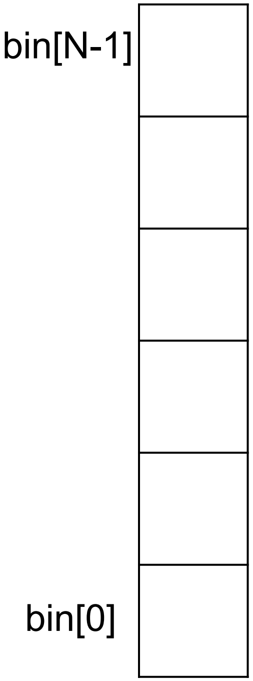
```
num_trash = Pickup(room_num, trash_bin, amount)
```

How do we get the room clean?



`num_trash == -1,`
`errno == excuse`

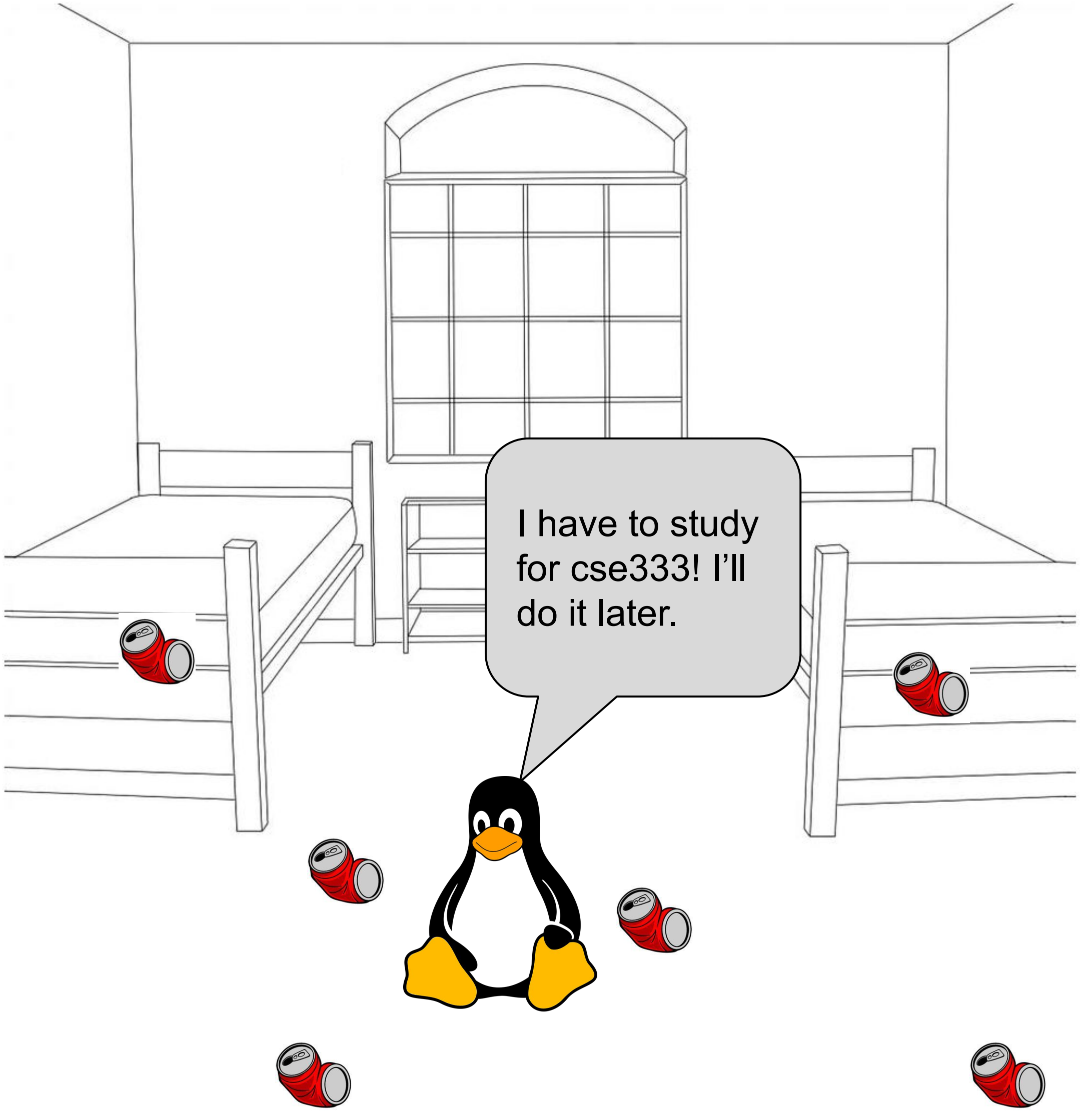
`num_trash == 0`
`num_trash < Amount`
`num_trash == Amount`



What do we do in the following scenarios?

```
num_trash = Pickup(room_num, trash_bin, amount)
```

How do we get the room clean?

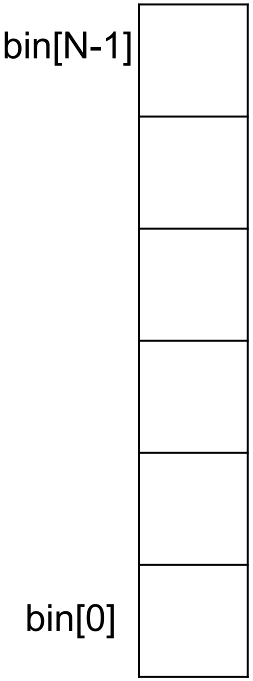


```
num_trash == -1,
errno == excuse
```

```
num_trash == 0
```

```
num_trash < Amount
```

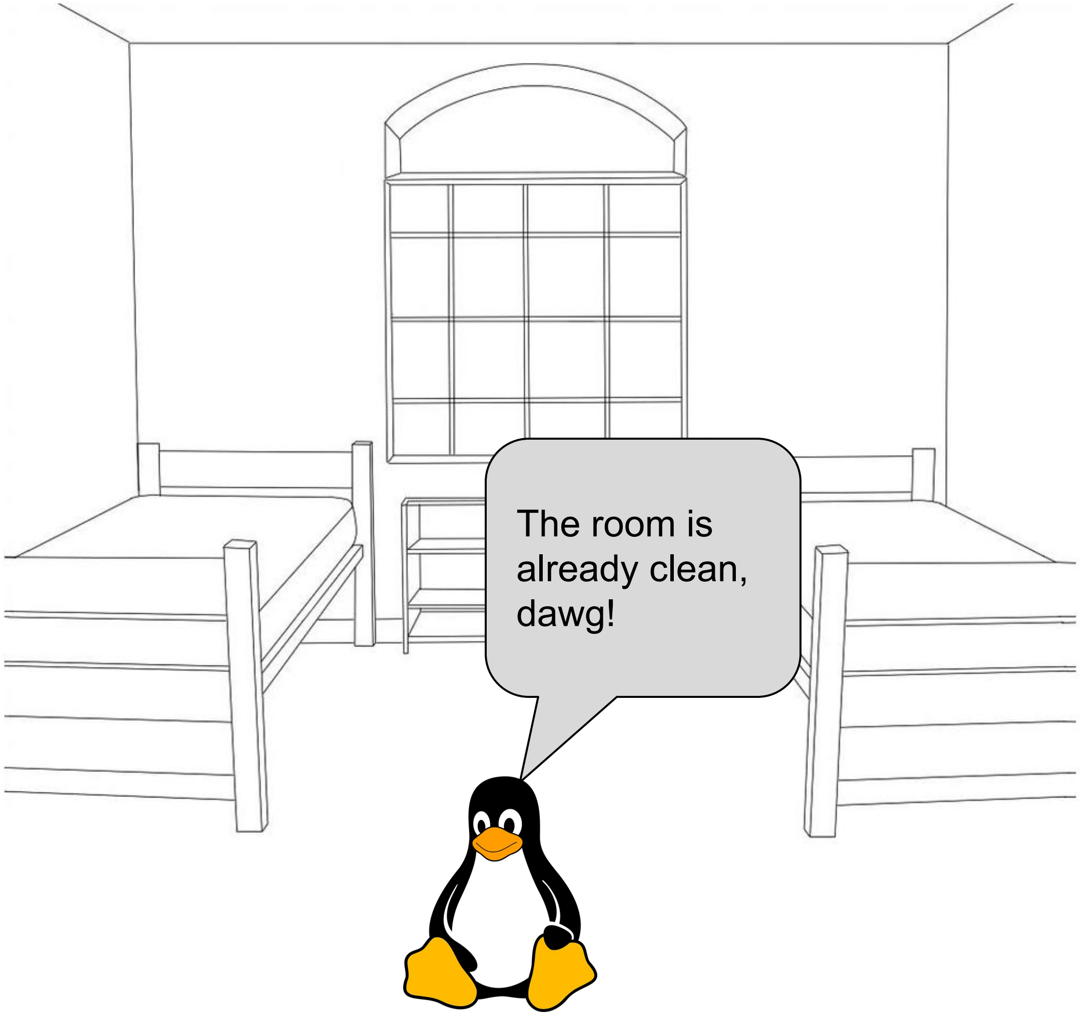
```
num_trash == Amount
```



Decide if the excuse is reasonable, and either let it be or ask again.

```
num_trash = Pickup(room_num, trash_bin, amount)
```

How do we get the room clean?

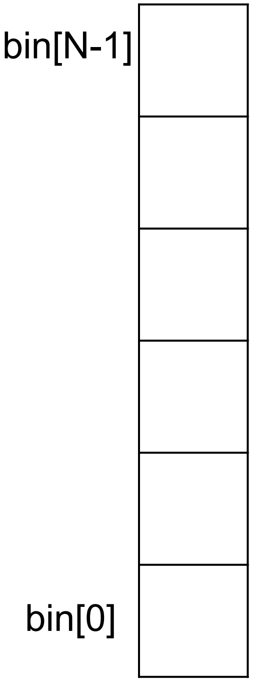


```
num_trash == -1,
errno == excuse
```

```
num_trash == 0
```

```
num_trash < Amount
```

```
num_trash == Amount
```



Stop asking them to clean the room! There’s nothing to do.

```
num_trash = Pickup(room_num, trash_bin, amount)
```

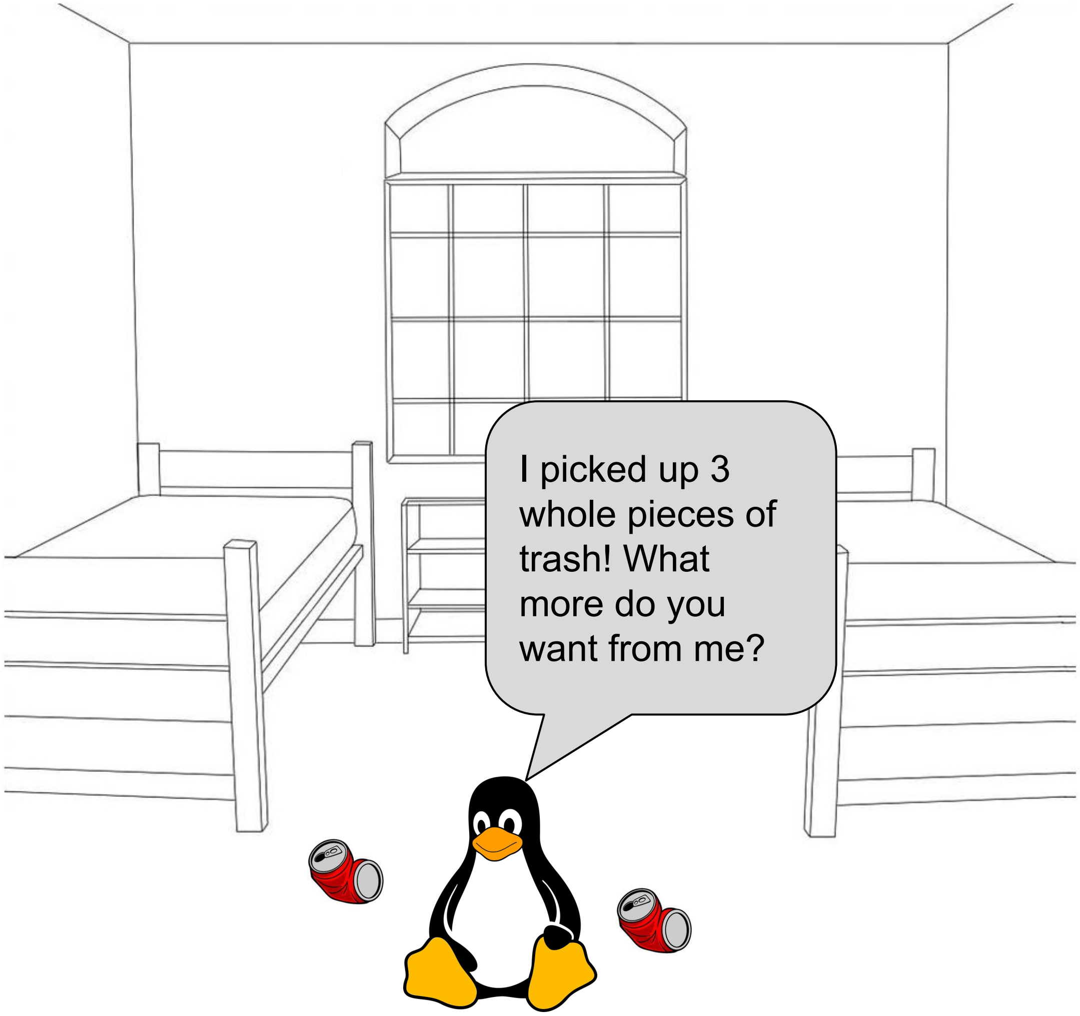
How do we get the room clean?

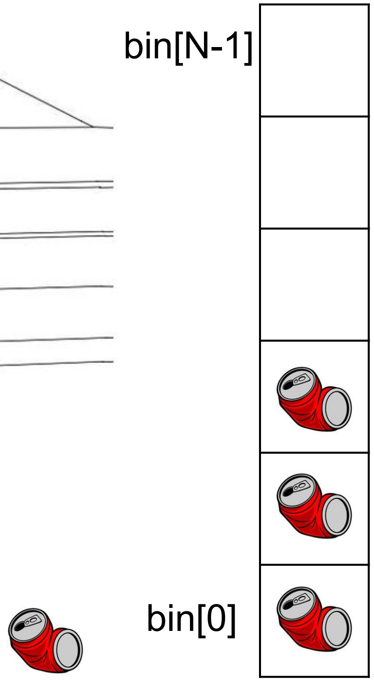
```
num_trash == -1,
errno == excuse
```

```
num_trash == 0
```

```
num_trash < Amount
```

```
num_trash == Amount
```

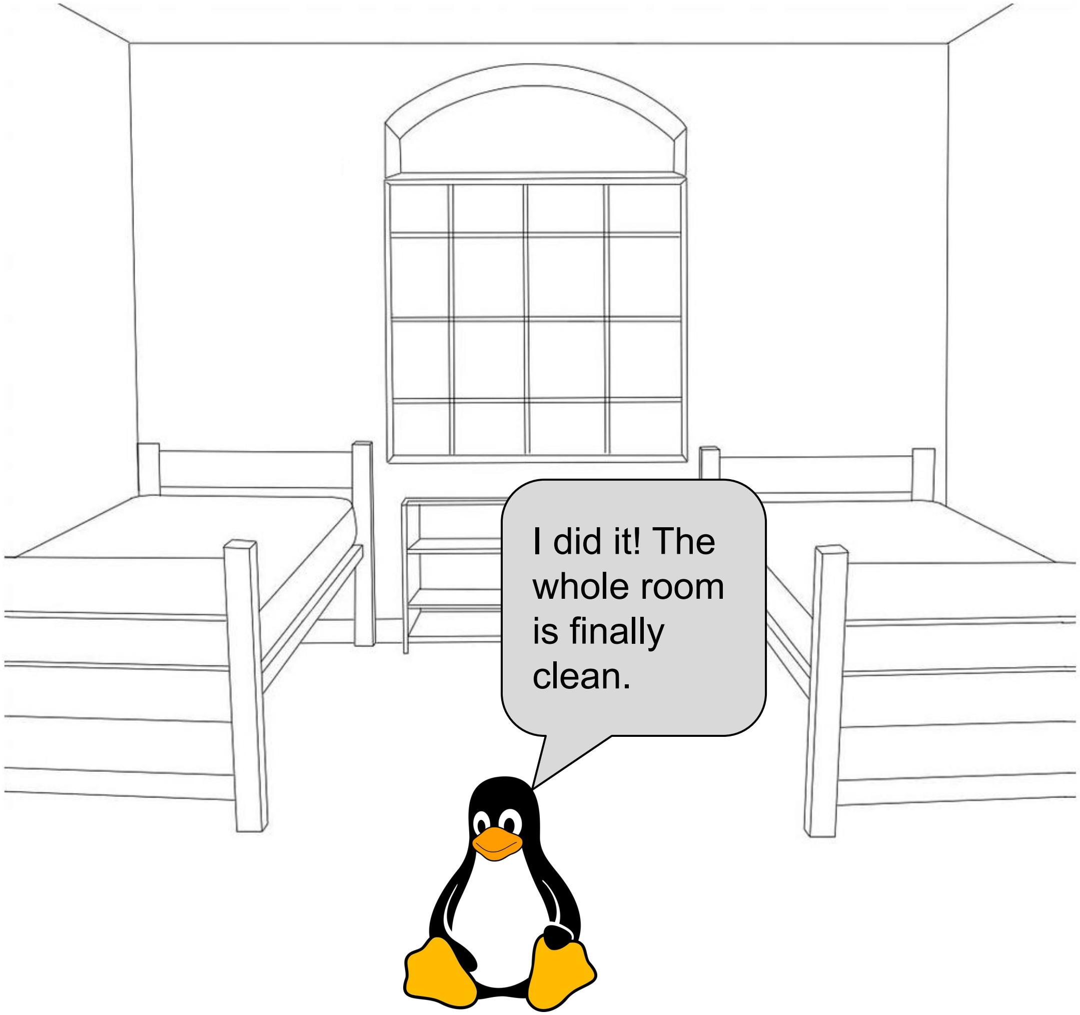

I picked up 3 whole pieces of trash! What more do you want from me?



Ask them again to pick up the rest of it.

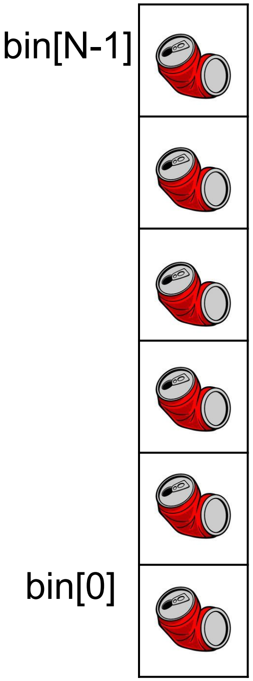
```
num_trash = Pickup(room_num, trash_bin, amount)
```

How do we get the room clean?



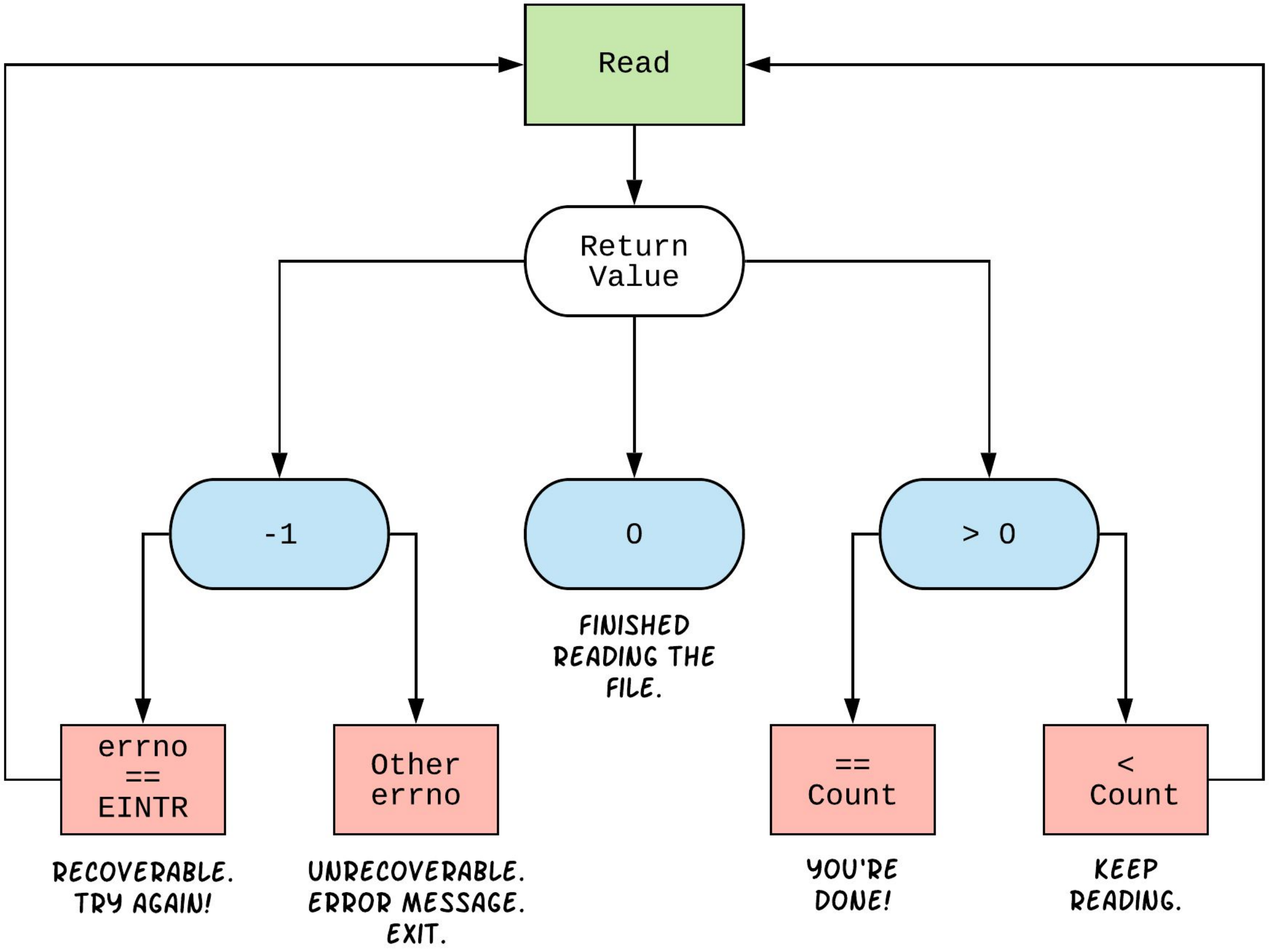
`num_trash == -1,`
`errno == excuse`

`num_trash == 0`
`num_trash < Amount`
`num_trash == Amount`



They did what you asked, so stop asking them to pick up trash.

Not fully comprehensive, please refer to the man pages



Poll Everywhere

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- Assume you want to read *n* bytes from a file. Which is the correct completion of the blank below?

```
char* buf = ...;  // at least size n
int bytes_left = n;
int result;       // result of read()

while (bytes_left > 0) {
  result = read(fd, ______, bytes_left);
  if (result == -1) {
    if (errno != EINTR) {
      // a real error happened,
      // so return an error result
    }
    // EINTR happened,
    // so do nothing and try again
    continue;
  }
  bytes_left -= result;
}
```

A. buf

B. buf + bytes_left

C. buf + bytes_left - n

D. buf + n - bytes_left

E. I'm lost…

One way to `read()` n bytes

```c
int fd = open(filename, O_RDONLY);
char* buf = ...;  // buffer of at least size n
int bytes_left = n;
int result;

while (bytes_left > 0) {
  result = read(fd, buf + (n - bytes_left), bytes_left);
  if (result == -1) {
    if (errno != EINTR) {
      // a real error happened, so return an error result
    }
    // EINTR happened, so do nothing and try again
    continue;
  } else if (result == 0) {
    // EOF reached, so stop reading
    break;
  }
  bytes_left -= result;
}

close(fd);
```

readN.c

Other Low-Level Functions

- Read man pages to learn more about POSIX I/O:
  - **`write`**`()` – write data
  - **`fsync`**`()` – flush data to the underlying device
    - Make sure you read the section 3 version (*e.g.* `man 3 fsync`)

- A useful shortcut sheet (from CMU): http://www.cs.cmu.edu/~guna/15-123S11/Lectures/Lecture24.pdf

Exercises 1-4

```
int open(char *name, int flags);
```

- `name` *is a string representing the name of the file. Can be relative or absolute.*
- `flags` *is an integer code describing the access. Some common flags are listed below:*
  - `O_RDONLY` – *Open the file in read-only mode.*
  - `O_WRONLY` – *Open the file in write-only mode.*
  - `O_RDWR` – *Open the file in read-write mode.*
  - `O_APPEND` – *Append new information to the end of the file.*
- Returns an integer which is the file descriptor. Returns `-1` if there is a failure.

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

- `fd` *is the file descriptor (as returned by open()).*
- `buf` *is the address of a memory area into which the data is read or written.*
- `count` *is the* maximum *amount of data to read from or write to the stream.*
- Returns the *actual* amount of data read from or written to the file.

```
int close(int fd);
int fd = open("333.txt", O_WRONLY);   // open 333.txt
int n = ...;
char *buf = ...;  // Assume buf initialized with size n
int result;
char *ptr = buf;    // initialize variable for loop

...  // code that populates buf happens here

while (ptr < buf + n) {
    result = write(fd, ptr, buf + n - ptr);
    if (result == -1) {
        if (errno != EINTR && errno != EAGAIN) {
            // a real error happened, return an error result
            close(fd);   // cleanup
            perror("Write failed");
            return -1;
        }
        continue;  // EINTR or EAGAIN happened, so loop around
    }
    ptr += result;    // update loop variable
}
close(fd);   // cleanup
```

(ℹ️) This is just ONE possible way to solve this exercise!

Lecture Outline

- Reading and Writing Files
- **Reading and Writing Directories**

Directories

- A directory is a special file that stores the names and locations of the related files/directories
    - This includes itself (`.`), its parent directory (`..`), and all of its children (*i.e.*, the directory's contents)
    - Take CSE 451 to learn more about the directory structure

- Accessible via POSIX (`dirent.h` in C/C++)
    - Basic operation is listing files/directories in a directory

POSIX Directory Basics

- Basic operations a lot like reading files
  - `opendir()` - Open a directory for reading
  - `readdir()` - Read the contents of a directory
  - `closedir()` - Close a directory when you're done
- Like C standard file I/O, but instead of `FILE *`, these use `DIR *`
  - `opendir()` returns a `DIR *`
  - `readdir()` and `closedir()` take a `DIR *`
- Instead of file bytes, reading a directory returns a `struct dirent`
  - describes a directory entry

Full Prototypes

- `DIR *opendir(const char *name);`
- `struct dirent *readdir(DIR *dirp);`
- `int closedir(DIR *dirp);`

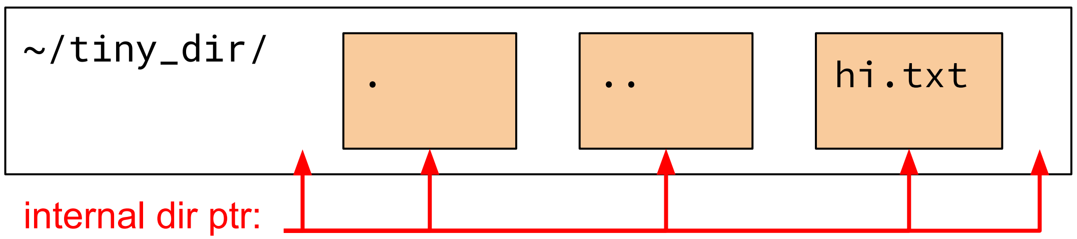
Return `-1` when it fails, and sets `errno`

Return `NULL` pointers when they fail, and set `errno`

Using `readdir()`

- The DIR * has **state**; it changes each time you read it.
- Each read returns one file or subdirectory, moves the DIR * to the next one
- After all directory contents have been read, returns NULL
  - Doesn’t change errno if it’s just the end of the directory

readdir() Example



```
➡DIR *dirp = opendir("~/tiny_dir");    // opens directory
➡struct dirent *file = readdir(dirp); // gets ptr to "."
➡file = readdir(dirp);  // gets ptr to ".."
➡file = readdir(dirp);  // gets ptr to "hi.txt"
➡file = readdir(dirp);  // gets NULL
➡closedir(dirp);   // clean up
```

struct dirent

- Returned value from `readdir`
- Fields are “unspecified” (depends on your operating system)
  - glibc specifies:

```
struct dirent {
  ino_t          d_ino;
  off_t          d_off;
  unsigned short d_reclen;
  unsigned char  d_type;
  char           d_name[256];
};
```

directory entry metadata stored in integer types

Null-terminated directory entry name (what we care about in 333)

- Does *not* need to be “freed” or “closed”

Exercise 5

Given the name of a directory, write a C program that is analogous to ls, *i.e.* prints the names of the entries of the directory to stdout. Be sure to handle any errors!

```
int main(int argc, char** argv) {
  /* 1. Check to make sure we have a valid command line arguments */
  if (argc != 2) {
    fprintf(stderr, "Usage: ./dirdump <path>\n");
    return EXIT_FAILURE;
  }
  /* 2. Open the directory, look at opendir() */

  DIR *dirp = opendir(argv[1]);
  if (dirp == NULL) {
    fprintf(stderr, "Could not open directory\n");
    return EXIT_FAILURE;
  }
…
```

Given the name of a directory, write a C program that is analogous to ls, *i.e.* prints the names of the entries of the directory to stdout. Be sure to handle any errors!

```
  ...
  /* 3. Read through/parse the directory and print out file names
        Look at readdir() and struct dirent */
  struct dirent *entry;
  entry = readdir(dirp);
  errno = 0;
  while (entry != NULL) {
    printf("%s\n", entry->d_name);
    entry = readdir(dirp);
  }
  if (errno != 0) {
    fprintf(stderr, “Error reading directory”);
    return EXIT_FAILURE;
  }
  /* 4. Clean up */
  closedir(dirp);
  return EXIT_SUCCESS;
}
```

Extra Exercise #1

- Write a program that:
  - Loops forever; in each loop:
    - Prompt the user to input a filename
    - Reads a filename from `stdin`
    - Opens and reads the file
    - Prints its contents to `stdout` in the format shown:

```
00000000 50 4b 03 04 14 00 00 00 00 00 9c 45 26 3c f1 d5
00000010 68 95 25 1b 00 00 25 1b 00 00 0d 00 00 00 43 53
00000020 45 6c 6f 67 6f 2d 31 2e 70 6e 67 89 50 4e 47 0d
00000030 0a 1a 0a 00 00 00 0d 49 48 44 52 00 00 00 91 00
00000040 00 00 91 08 06 00 00 00 c3 d8 5a 23 00 00 00 09
00000050 70 48 59 73 00 00 0b 13 00 00 0b 13 01 00 9a 9c
00000060 18 00 00 0a 4f 69 43 43 50 50 68 6f 74 6f 73 68
00000070 6f 70 20 49 43 43 20 70 72 6f 66 69 6c 65 00 00
00000080 78 da 9d 53 67 54 53 e9 16 3d f7 de f4 42 4b 88
00000090 80 94 4b 6f 52 15 08 20 52 42 8b 80 14 91 26 2a
000000a0 21 09 10 4a 88 21 a1 d9 15 51 c1 11 45 45 04 1b
... etc ...
```

- Hints:
  - Use `man` to read about `fgets`
  - Or, if you're more courageous, try `man 3 readline` to learn about `libreadline.a` and Google to learn how to link to it