I/O Management

Goals of this Lecture

Help you to learn about:

- The C/Unix **file** abstraction
- Unix I/O
  - Data structures & functions
- C library I/O
  - Data structures & functions
- The implementation of Standard C I/O using Unix I/O
- Programmatic redirection of stdin, stdout, and stderr
- Pipes

Agenda

The C/Unix file abstraction

Unix I/O system calls

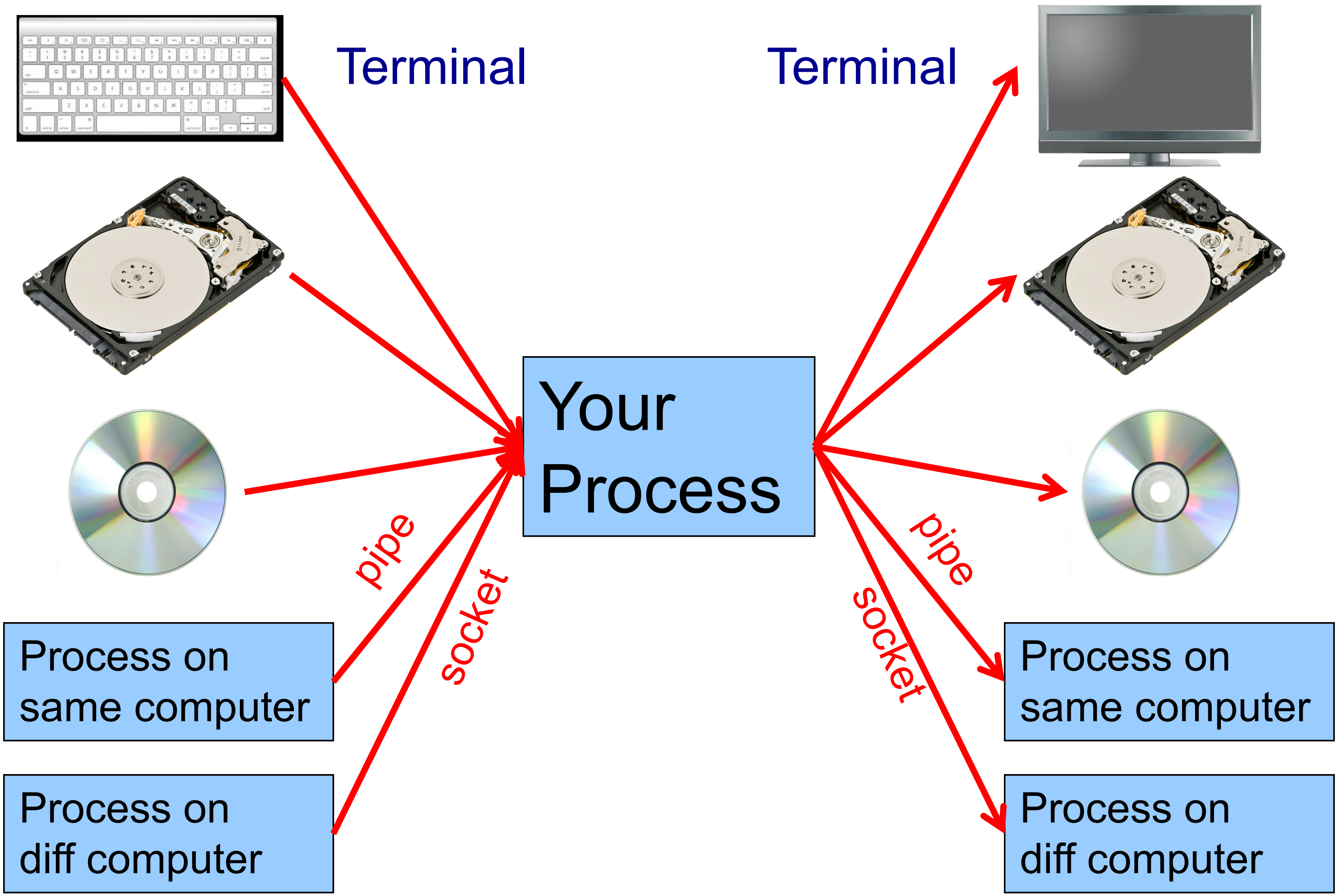
C's Standard IO library (FILE *)

+ Implementing standard C I/O using Unix I/O

Redirecting standard files

Pipes

Data Sources and Destinations



C/Unix File Abstraction

Problem:

- At the physical level…
- Code that **reads** from **keyboard** is very different from code that reads from **disk**, etc.
- Code that **writes** to **video screen** is very different from code that writes to **disk**, etc.
- Would be nice if application programmer didn't need to worry about such details

Solution:

- **File**: a sequence of bytes
- C and Unix allow application program to treat any data source/destination as a **file**

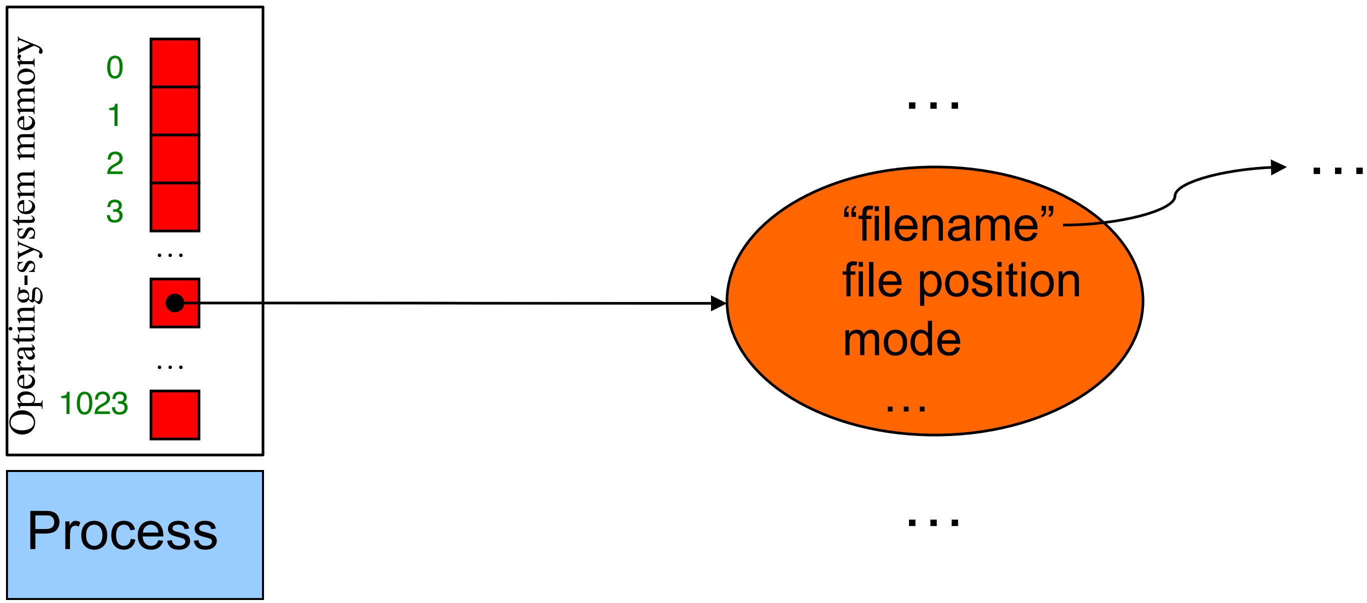
Commentary: **Beautiful** abstraction!

C/Unix File Abstraction

Each file has an associated **file position**

- Starts at beginning of file (if opened to read or write)
- Starts at end of file (if opened to append)

Unix I/O Data Structures



File descriptor: Integer that uniquely identifies an open file

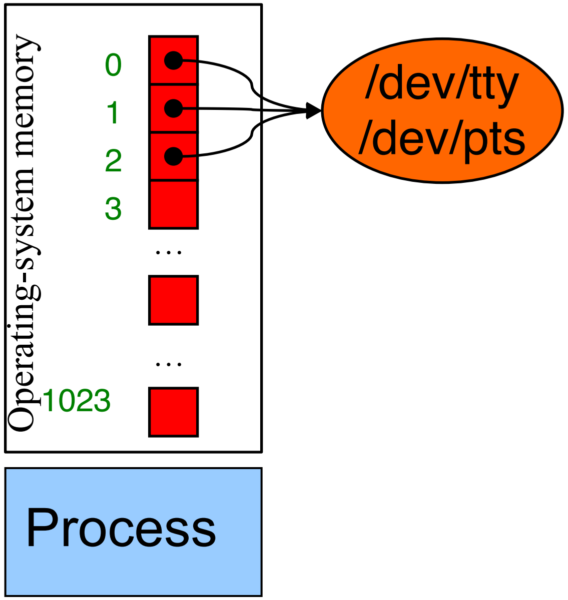
File descriptor table: an array for one process

- Indices are file descriptors; elements are pointers to file tables
- One unique file descriptor table for each process

File table: a list for all processes

- Entries are in-memory surrogate for an open file
- Created when a process opens file; keeps mode, file position
- Shared across all processes

Unix I/O Data Structures




```
armlab02:~$ echo $$
40951
armlab02:~$ ls -l /dev/std*
lrwxrwxrwx. 1 root root 15 Feb  3 12:13 /dev/stderr -> /proc/self/fd/2
lrwxrwxrwx. 1 root root 15 Feb  3 12:13 /dev/stdin -> /proc/self/fd/0
lrwxrwxrwx. 1 root root 15 Feb  3 12:13 /dev/stdout -> /proc/self/fd/1
armlab02:~$ ls -l /proc/40951/fd/
total 0
dr-x------. 2 cos217 37  0 Apr 27 02:05 .
dr-xr-xr-x. 9 cos217 37  0 Apr 27 02:05 ..
lrwx------. 1 cos217 37 64 Apr 27 02:05 0 -> /dev/pts/19
lrwx------. 1 cos217 37 64 Apr 27 02:05 1 -> /dev/pts/19
lrwx------. 1 cos217 37 64 Apr 27 02:05 2 -> /dev/pts/19
lrwx------. 1 cos217 37 64 Apr 27 02:05 255 -> /dev/pts/19
lr-x------. 1 cos217 37 64 Apr 27 02:05 3 -> /var/lib/sss/mc/passwd
armlab02:~$ echo "hi" > /proc/40951/fd/1
hi
armlab02:~$ read i < /proc/40951/fd/0
42
armlab02:~$ echo $i
42
```

At process start-up files with fd 0, 1, 2 are open automatically
- (By default) each references file table for a file named /dev/tty or /dev/pts

/dev/tty or /dev/pts
- In-memory terminal structure ({tty: physical, pts: networked} connection)

Terminal
- Combination keyboard/video screen interface (physical or virtual)

System-Level Functions

As noted in the ***Exceptions and Processes*** lecture…

Linux system-level functions for **I/O management**

Function	Description
read()	Read data from file descriptor Called by getchar(), scanf(), etc.
write()	Write data to file descriptor Called by putchar(), printf(), etc.
open()	Open file or device (mode varies by flags) Called by fopen(…, “r”)
close()	Close file descriptor Called by fclose()
creat()	Open file or device for writing (creates/truncates) Called by fopen(…, “w”)
lseek()	Change file position Called by fseek()

System-Level Functions

As noted in the ***Exceptions and Processes*** lecture..

Linux system-level functions for **I/O redirection** and **inter-process communication**

Function	Description
dup()	Duplicate an open file descriptor
pipe()	Create a channel of communication between processes

Agenda

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Redirecting standard files

Pipes

Unix I/O Functions

```
int creat(char *filename, mode_t mode);
```

- Create a new empty file named `filename`
  - `mode` indicates permissions of new file
- Implementation:
  - Create new empty file on disk
    - or truncate an existing one to 0 bytes
  - Create file table entry
    - Update entry in case of existing file
    - Set access mode to write-only
    - Set file position to 0
  - Set first unused file descriptor to point to file table entry
  - Return file descriptor used, -1 upon failure

Unix I/O Functions

```
int open(char *filename, int flags, …);
```

- Open the file whose name is **`filename`**
  - **`flags`** often is **`O_RDONLY`**
- Implementation (assuming **`O_RDONLY`**):
  - Find existing file on disk
  - Create file table
  - Set first unused file descriptor to point to file table
  - Return file descriptor used, -1 upon failure

Unix I/O Functions

`int close(int fd);`

- Close the file **`fd`**
- Implementation:
  - Destroy file table referenced by element **`fd`** of file descriptor table
    - As long as no other process is pointing to it!
  - Set element **`fd`** of file descriptor table to **`NULL`**
    - allows **`open`** to reuse it

```
armlab02:~/Test$ cat fdtablemax.c
#define _GNU_SOURCE
#include <unistd.h>
#include <stdio.h>
int main() {
   printf("%d\n", getdtablesize());
   return 0;
}
```

```
armlab02:~/Test$ gcc217 fdtablemax.c
-o fdtablemax
armlab02:~/Test$ ./fdtablemax
8192
```

Unix I/O Functions

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

- Read into **buf** up to **count** bytes from file **fd**
- Return the number of bytes read; 0 indicates end-of-file

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

- Writes up to **count** bytes from **buf** to file **fd**
- Return the number of bytes written; -1 indicates error

```
int lseek(int fd, int offset, int whence);
```

- Set the file position of file **fd** to file position **offset**.
- **whence** indicates if the file position is measured from the beginning of the file (**SEEK_SET**), from the current file position (**SEEK_CUR**), or from the end of the file (**SEEK_END**)
- Return the file position from the beginning of the file

Unix I/O Functions

Note

- Only 6 system-level functions support all I/O from all kinds of devices!

Commentary: **Beautiful** interface!

Unix I/O Example 0

Proto-getchar()

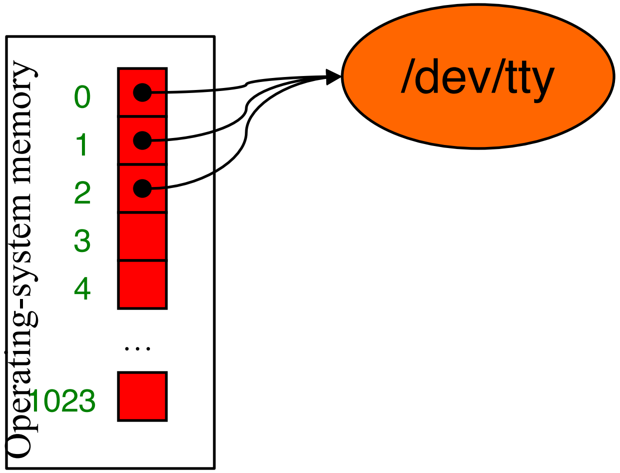
```
#include <string.h>
#include <unistd.h>

int proto_getchar(void)
{   char buf[1];
    int n;

    n = read(0, buf, 1);
    if (n==1)
       return buf[0];
    else return EOF;
}
```

# of bytes to (try to) read

0 is the file descriptor of the standard input



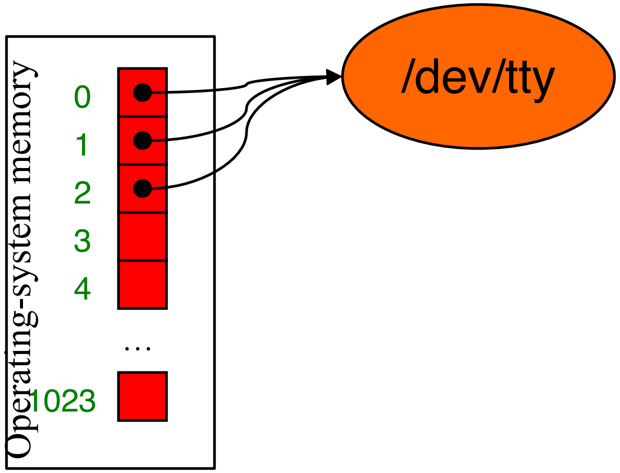
and the problem is . . . too slow.

Does a system call for every character.

Unix I/O Example 1

Write "hello, world\n" to /dev/tty

```
#include <string.h>
#include <unistd.h>
int main(void)
{   char hi[] = "hello, world\n";
    size_t countWritten = 0;
    size_t countToWrite = strlen(hi);
    while (countWritten < countToWrite)
        countWritten +=
            write(1, hi + countWritten,
                  countToWrite - countWritten);
    return 0;
}
```

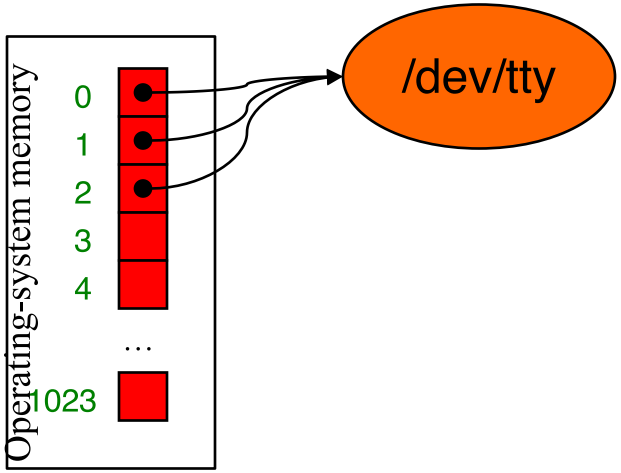


To save space, no error handling code is shown

Unix I/O Example 2

```
#include <fcntl.h>
#include <unistd.h>
int main(void)
{   enum {BUFFERSIZE = 10};
    int fdIn, fdOut;
    int countRead, countWritten;
    char buf[BUFFERSIZE];
    fdIn = open("infile", O_RDONLY);
    fdOut = creat("outfile", 0600);
    for (;;)
    {   countRead =
            read(fdIn, buf, BUFFERSIZE);
        if (countRead == 0) break;
        countWritten = 0;
        while (countWritten < countRead)
            countWritten +=
                write(fdOut,
                    buf + countWritten,
                    countRead - countWritten);
    }
    close(fdOut);
    close(fdIn);
    return 0;
}
```

Copy all bytes from infile to outfile



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    for (;;)
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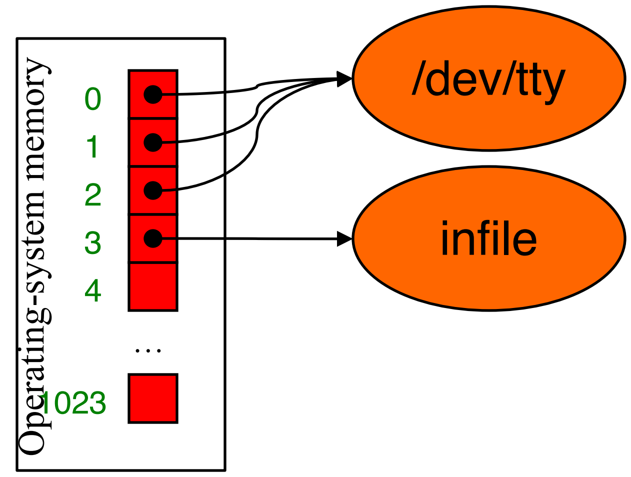
        if (countRead == 0) break;
        countWritten = 0;
        while (countWritten < countRead)
            countWritten +=
                write(fdOut,
                    buf + countWritten,
                    countRead - countWritten);
    }
    close(fdOut);
    close(fdIn);
    return 0;
}
```

3



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            write(fdOut,
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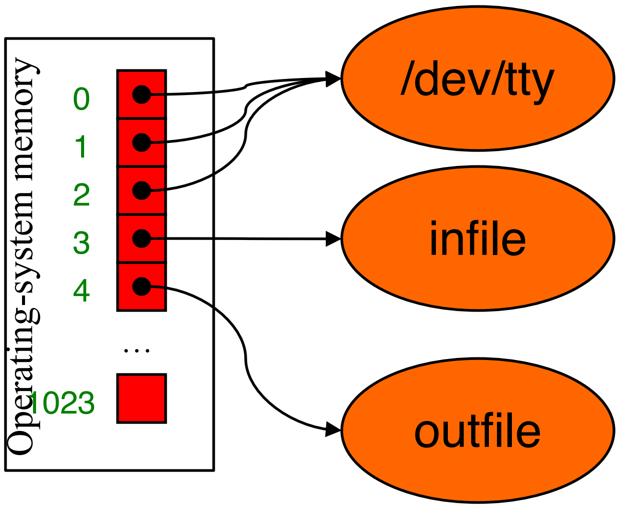
               countRead - countWritten);
   }
   close(fdOut);
   close(fdIn);
   return 0;
}
```

3

4



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        countWritten = 0;
        while (countWritten < countRead)
           countWritten +=
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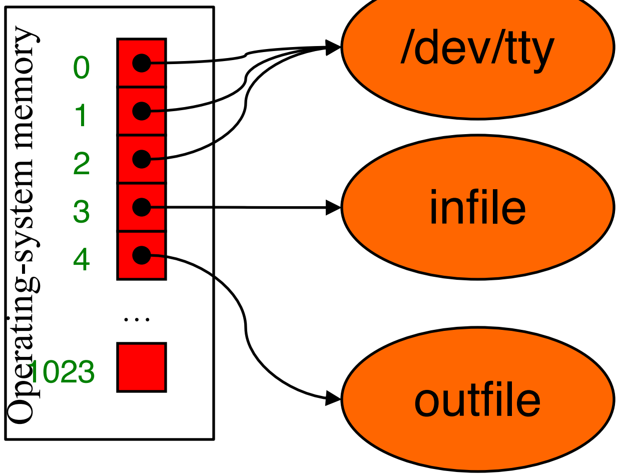
                 countRead - countWritten);
    }
    close(fdOut);
    close(fdIn);
    return 0;
}
```



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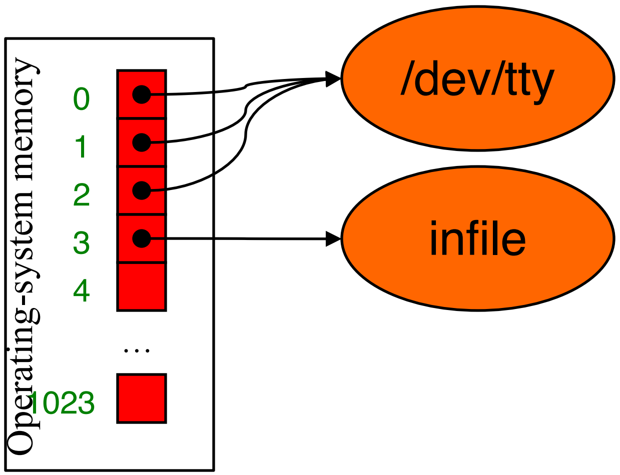
   for (;;)
   {  countRead =
         read(fdIn, buf, BUFFERSIZE);
      if (countRead == 0) break;
      countWritten = 0;
      while (countWritten < countRead)
         countWritten +=
            write(fdOut,
               buf + countWritten,
               countRead - countWritten);
   }
   close(fdOut);
   close(fdIn);
   return 0;
}
```

3

4



Unix I/O Example 2

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int main(void)
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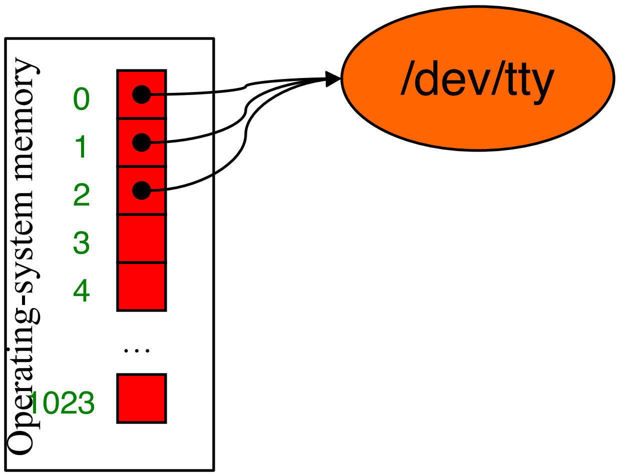
   int fdIn, fdOut;
   int countRead, countWritten;
   char buf[BUFFERSIZE];
   fdIn = open("infile", O_RDONLY);
   fdOut = creat("outfile", 0600);
   for (;;)
   {  countRead =
         read(fdIn, buf, BUFFERSIZE);
      if (countRead == 0) break;
      countWritten = 0;
      while (countWritten < countRead)
         countWritten +=
            write(fdOut,
               buf + countWritten,
               countRead - countWritten);
   }
   close(fdOut);
   close(fdIn);
   return 0;
}
```

3

4



Agenda

The C/Unix file abstraction

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+ Implementing standard C I/O using Unix I/O

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Pipes

Standard C I/O Data Structure

We want 1-character-at-a-time I/O   (getc(), putc())

We want a-few-characters-at-a-time I/O (scanf, printf)

We *could* do this with read() and write() system calls,

BUT IT WOULD BE TOO SLOW to do 1 syscall per byte

Solution: Buffered input/output as an Abstract Data Type

The **FILE** ADT

- A **`FILE`** object is an in-memory surrogate for an opened file
  - Created by **`fopen()`**
  - Destroyed by **`fclose()`**
- Contains metadata about the file, including underlying file descriptor
- Contains *buffers* filled/consumed in bulk, accessed by I/O calls

Implementing Buffering

Problem: poor performance

- **`read()`** and **`write()`** access a physical device (e.g., a disk)
- Reading/writing one char at a time can be time consuming
- Better to read and write in larger blocks
  - Recall ***Storage Management*** lecture

Solution: buffered I/O

- **Read** a large block of chars from source device into a buffer
  - Provide chars from buffer to the client as needed
- **Write** individual chars to a buffer
  - "Flush" buffer contents to destination device when buffer is full, or when file is closed, or upon client request

Standard C I/O Functions

Some of the most popular:

```
FILE *fopen(const char *filename, const char *mode);
```

- Open the file named **`filename`** for reading or writing
- **`mode`** indicates data flow direction
  - "r" means read; "w" means write, "a" means append)
- Creates **`FILE`** structure
- Returns address of **`FILE`** structure

```
int fclose(FILE *file);
```

- Close the file identified by **`file`**
- Destroys **`FILE`** structure whose address is **`file`**
- Returns 0 on success, EOF on failure

Implementing the `FILE` ADT

```
enum {BUFFERSIZE = 4096};

struct File
{   unsigned char  buffer[BUFFERSIZE];  /* buffer */
    int            bufferCount; /* num chars left in buffer */
    unsigned char *bufferPtr;   /* ptr to next char in buffer */
    int            flags;       /* open mode flags, etc. */
    int            fd;          /* file descriptor */
};

typedef struct File FILE;

/* Initialize standard files. */
FILE *stdin  = …
FILE *stdout = …
FILE *stderr = …
```

Derived from K&R Section 8.5

More complex on our system

Implementing `fopen` and `fclose`

`f = fopen(filename, "r")`

- Create new **`FILE`** structure; set **`f`** to point to it
- Initialize all fields
- **`f->fd = open(filename, …)`**
- Return **`f`**

`f = fopen(filename, "w")`

- Create new **`FILE`** structure; set **`f`** to point to it
- Initialize all fields
- **`f->fd = creat(filename, …)`**
- Return **`f`**

`fclose(f)`

- **`close(f->fd)`**
- Destroy **`FILE`** structure

Standard C Input Functions

Some of the most popular:

`int fgetc(FILE *file);`

- Read a char from the file identified by **`file`**
- Return the char on success, **`EOF`** on failure

`int getchar(void);`

- Same as **`fgetc(stdin)`**

`char *fgets(char *s, int n, FILE *file);`

- Read at most **`n-1`** characters from **`file`** into array **`s`**
- Stop at EOF or after **`\n`**. Terminate **`s`** with **`\0`**.
- Return **`s`** on success, **`NULL`** on failure or no chars before EOF

`char *gets(char *s);`

- Essentially same as **`fgets(s, INT_MAX, stdin)`**
- *Buffer overflow waiting to happen!*

Standard C I/O Example 0

Recall proto-getchar() was too slow

```
#include <string.h>
#include <unistd.h>

int proto_getchar(void)
{   char buf[1];
    int n;

    n = read(0, buf, 1);
    if (n==1)
       return buf[0];
    else return EOF;
}
```

# of bytes to (try to) read

0 is the file descriptor of the standard input

Is getchar() any better?

- Not if only called once. Yes if called repeatedly!

Implementing `getchar` and `putchar`

`getchar()` calls **`read()`** to read one byte from fd 0

`putchar()` calls **`write()`** to write one byte to fd 1

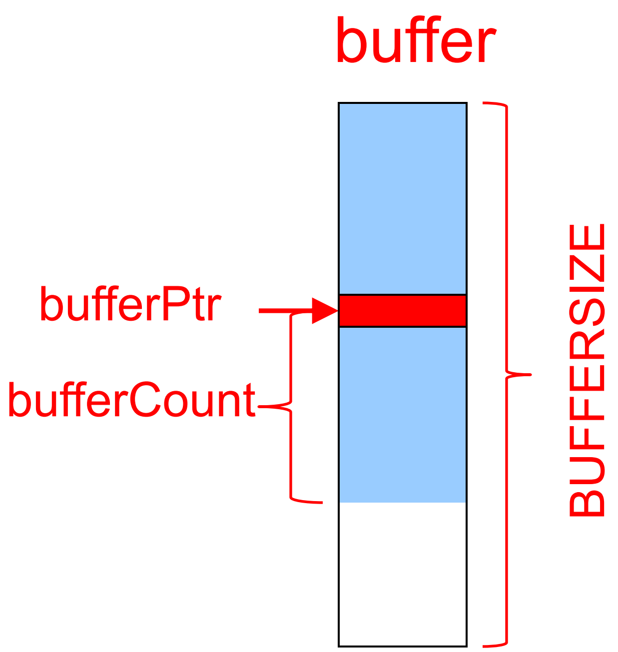
```
int getchar(void)
{   unsigned char c;
    if (read(0, &c, 1) == 1)
        return (int)c;
    else
        return EOF;
}
```

```
int putchar(int c)
{   if (write(1, &c, 1) == 1)
        return c;
    else
        return EOF;
}
```

Implementing `getchar` Version 2

`getchar()` calls **`read()`** to read multiple chars from fd 0 into buffer

```
int getchar(void)
{   enum {BUFFERSIZE = 4096}; /*arbitrary*/
    static unsigned char buffer[BUFFERSIZE];
    static unsigned char *bufferPtr;
    static int bufferCount = 0;
    if (bufferCount == 0) /* must read */
    {   bufferCount =
            read(0, buffer, BUFFERSIZE);
        if (bufferCount <= 0) return EOF;
        bufferPtr = buffer;
    }
    bufferCount--;
    bufferPtr++;
    return (int)(*(bufferPtr-1));
}
```



Implementing `fgetc`

```
int fgetc(FILE *f)
{   if (f->bufferCount == 0) /* must read */
    {   f->bufferCount =
           read(f->fd, f->buffer, BUFFERSIZE);
        if (f->bufferCount <= 0) return EOF;
        f->bufferPtr = f->buffer;
    }
    f->bufferCount--;
    f->bufferPtr++;
    return (int)(*(f->bufferPtr-1));
}
```

- Accepts FILE pointer f as parameter
- Uses fields within f
- Reads from f->fd instead of 0

iClicker Question

Q: Consider this admonition from the **`fgetc man`** page. Why is it not advisable?

```
BUGS

It  is  not  advisable to mix calls to input functions from the stdio library
with low-level calls to read(2) for the file descriptor associated with the
input stream; the results will be undefined and very probably not what you
want.
```

A. `read` after `fgetc` may skip some input

B. `fgetc` after `read` may skip some input

C. Poor performance.

D. The same data may be input twice

Standard C Input Functions

Some of the most popular:

```
int fscanf(FILE *file, const char *format, ...);
```

- Read chars from the file identified by **`file`**
- Convert to values, as directed by **`format`**
- Copy values to memory
- Return count of values successfully scanned

```
int scanf(const char *format, ...);
```

- Same as **`fscanf(stdin, format,`** …)

Standard C Output Functions

Some of the most popular:

```
int fputc(int c, FILE *file);
```

- Write **`c`** (converted to a char) to file
- Return **`c`** on success, **`EOF`** on failure

```
int putchar(int c);
```

- Same as **`fputc(c, stdout)`**

```
int fputs(const char *s, FILE *file);
```

- Write string **`s`** to **`file`**
- Return non-negative on success, **`EOF`** on error

```
int puts(const char *s);
```

- Essentially same as **`fputs(s, stdout)`**

Standard C Output Functions

Some of the most popular:

```
int fprintf(FILE *file, const char *format, ...);
```

- Write chars to the file identified by **`file`**
- Convert values to chars, as directed by **`format`**
- Return count of chars successfully written
- Works by calling **`fputc()`** repeatedly

```
int printf(const char *format, ...);
```

- Same as **`fprintf(stdout, format, ...)`**

Implementing `putchar` Version 2

`putchar()` calls **`write()`** to write multiple chars from buffer to fd 1

```
int putchar(int c)
{   enum {BUFFERSIZE = 4096};
    static char buffer[BUFFERSIZE];
    static int bufferCount = 0;
    if (bufferCount == BUFFERSIZE) /* must write */
    {   int countWritten = 0;
        while (countWritten < bufferCount)
        {   int count =
                write(1, buffer+countWritten, BUFFERSIZE-countWritten);
            if (count <= 0) return EOF;
            countWritten += count;
        }
        bufferCount = 0;
    }
    buffer[bufferCount] = (char)c;
    bufferCount++;
    return c;
}
```

Real implementation also flushes buffer in other conditions.

Implementing `fputc`

```
int fputc(int c, FILE *f)
{   if (f->bufferCount == BUFFERSIZE) /* must write */
    {   int countWritten = 0;
        while (countWritten < f->bufferCount)
        {   int count =
                write(f->fd, f->buffer+countWritten,
                      BUFFERSIZE-countWritten);
            if (count <= 0) return EOF;
            countWritten += count;
        }
        f->bufferCount = 0;
    }
    f->buffer[f->bufferCount] = (char)c;
    f->bufferCount++;
    return c;
}
```

Real implementation likely calls fflush() or similar, to avoid code copying within module, facilitate flushing for other conditions.

- Accepts FILE pointer f as parameter
- Uses fields within f
- Writes to f->fd instead of 1

Standard C I/O Example 1

Write "hello, world\n" to **stdout**

```
#include <stdio.h>
int main(void)
{   char hi[] = "hello world\n";
    size_t i = 0;
    while (hi[i] != '\0')
    {   putchar(hi[i]);
        i++;
    }
    return 0;
}
```

Simple
Portable
Efficient (via buffering)

```
#include <stdio.h>
int main(void)
{   puts("hello, world");
    return 0;
}
```

```
#include <stdio.h>
int main(void)
{   printf("%s", "hello, world\n");
    return 0;
}
```

Standard C I/O Example 2

Copy all bytes from infile to outfile

```
#include <stdio.h>
int main(void)
{   int c;
    FILE *inFile;
    FILE *outFile;
    inFile = fopen("infile", "r");
    outFile = fopen("outfile", "w");
    while ((c = fgetc(inFile)) != EOF)
        fputc(c, outFile);
    fclose(outFile);
    fclose(inFile);
    return 0;
}
```

Simple
Portable
Efficient (via buffering)

Standard C I/O Functions

Some of the most popular:

```
int fflush(FILE *file);
```

- On an output file: write any buffered chars to **`file`**
- On an input file: behavior undefined / nonportable
- **`file == NULL`** ⇒ flush buffers of **all** open files

```
int fseek(FILE *file, long offset, int origin);
```

- Set the file position of **`file`**
- Subsequent read/write accesses data starting at that position
- Origin: **`SEEK_SET`**, **`SEEK_CUR`**, **`SEEK_END`**

```
int ftell(FILE *file);
```

- Return file position of **`file`** on success, -1 on error

Standard C Buffering

Question: When are buffers guaranteed to be flushed?

Answers:

If writing to an ordinary file

(1) when File's buffer becomes full

(2) when Process calls **`fflush()`** on that file

(3) when Process terminates normally

If writing to **`stdout`** (in addition to previous)

(4) if **`stdout`** is bound to terminal:

when **`'\n'`** is appended to buffer

(5) if **`stdin`** and **`stdout`** are both bound to terminal:

when read from **`stdin`** occurs

If writing to **`stderr`**

- Irrelevant; **`stderr`** is unbuffered

Standard C Buffering Example

```
#include <stdio.h>
int main(void)
{  int dividend, divisor, quotient;

   printf("Dividend: ");
   scanf("%d", &dividend);

   printf("Divisor: ");
   scanf("%d", &divisor);

   printf("The quotient is ");
   quotient = dividend / divisor;
   printf("%d\n", quotient);
   return 0;
}
```

Output buffered

Buffer flushed

Output buffered

Buffer flushed

Output buffered

Buffer flushed …
if it gets here.

```
$ pgm
Dividend: 6
Divisor: 2
The quotient is 3
$
```

```
$ pgm
Dividend: 6
Divisor: 0
Floating point exception
$
```

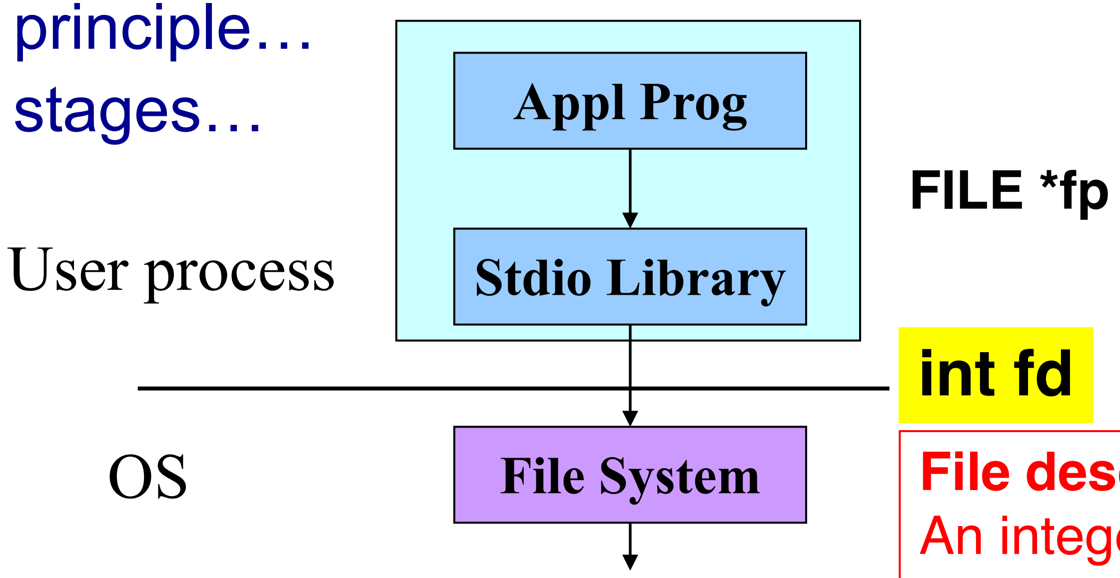
Standard C I/O Summary

Question:

- How to implement standard C I/O data structure and functions using Unix I/O data structures and functions?

Answer:

- In principle…
- In stages…



File descriptor: An integer that uniquely identifies an open file

Implementing Standard C I/O Functions

Standard C Function	In Unix Implemented by Calling
fopen()	**open()** or **creat()**
fclose()	**close()**

Implementing Standard C I/O Functions

Standard C Function	In Unix Implemented by Calling
fgetc()	**read()**
getchar()	fgetc()
fgets()	fgetc()
gets()	fgets()
fscanf()	fgetc()
scanf()	fscanf()

Implementing Standard C I/O Functions

Standard C Function	In Unix Implemented by Calling
fputc()	**write()**
putchar()	fputc()
fputs()	fputc()
puts()	fputs()
fprintf()	fputc()
printf()	fprintf()

Implementing Standard C I/O Functions

Standard C Function	In Unix Implemented by Calling
fflush()	**write()**
fseek()	**lseek()**
ftell()	**lseek()**

Agenda

The C/Unix file abstraction

Unix I/O system calls

C's Standard IO library (FILE *)

+ Implementing standard C I/O using Unix I/O

Redirecting standard files

Pipes

Redirection

Unix allows programmatic redirection of **`stdin`**, **`stdout`**, or **`stderr`**

How?

- Use **`open()`**, **`creat()`**, and **`close()`** system-level functions
- Use **`dup()`** system-level function

`int dup(int oldfd);`

- Create a copy of file descriptor **`oldfd`**
- Old and new file descriptors may be used interchangeably; they refer to the same open file table and thus share file position and file status flags
- Uses the lowest-numbered unused descriptor for the new descriptor
- Returns the new descriptor, or -1 if an error occurred.

Paraphrasing man page

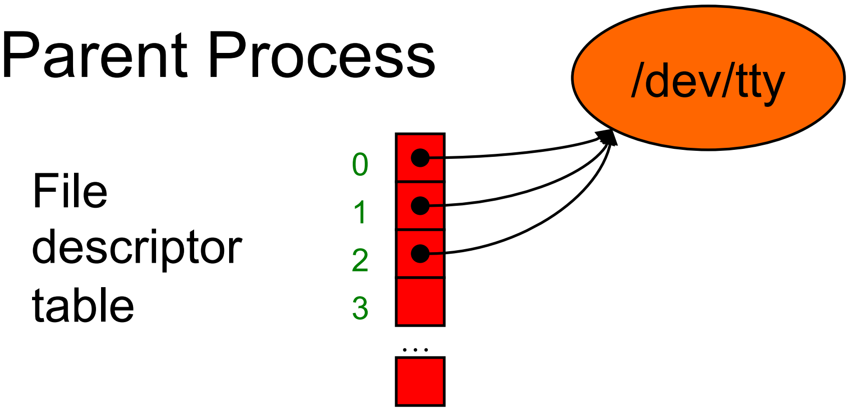
Redirection Example

How does shell implement **somepgm > somefile**?

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Redirection Example Trace (1)

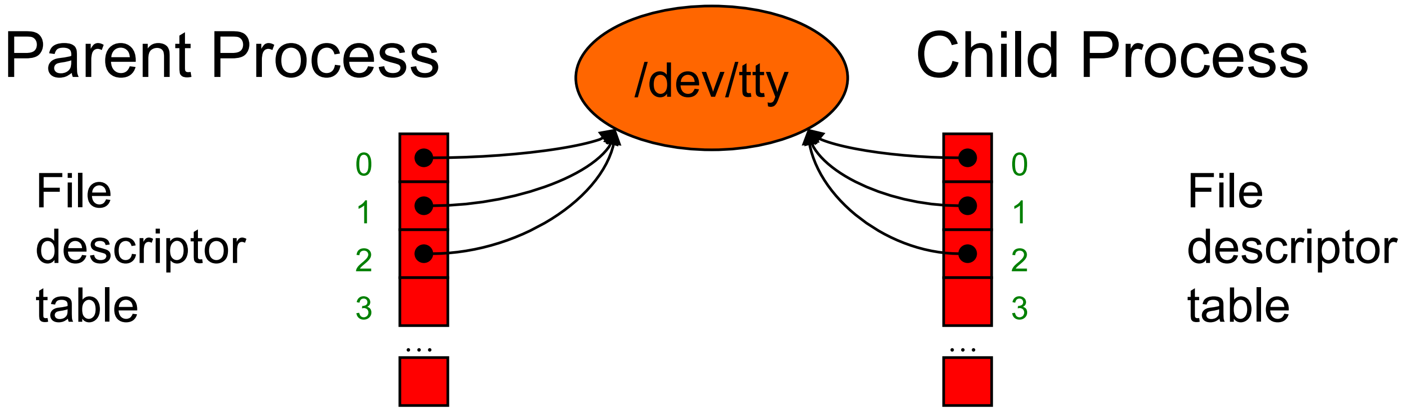
Parent Process




```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Parent has file descriptor table; first three point to “terminal”

Redirection Example Trace (2)

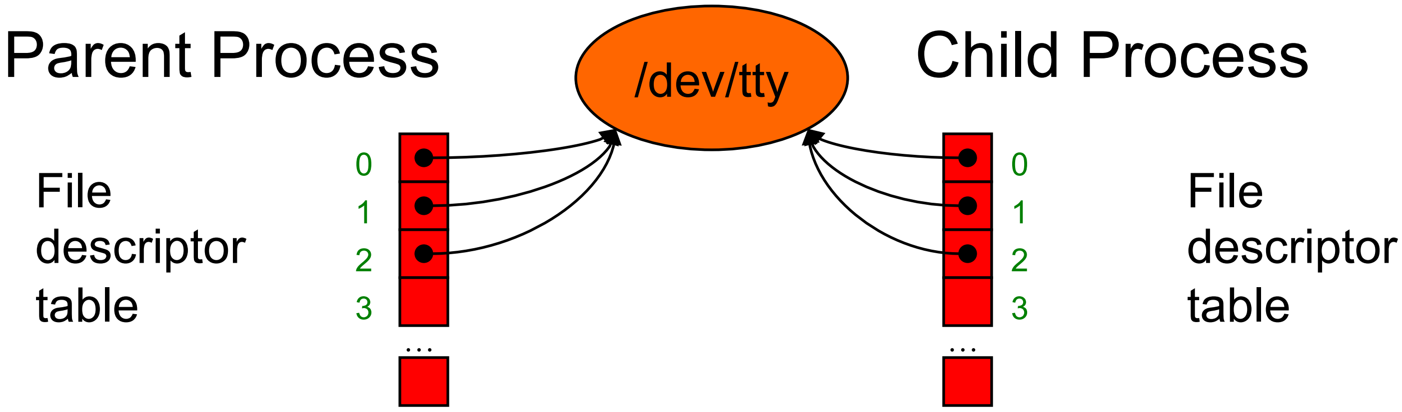



```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Parent forks child; child has identical-but distinct file descriptor table

Redirection Example Trace (3)




```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

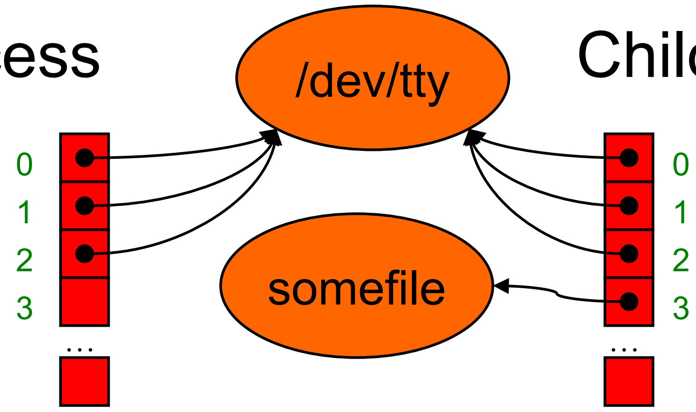
```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 060);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Let's say OS gives CPU to parent; parent waits

Redirection Example Trace (4)

Parent Process

File descriptor table



Child Process

File descriptor table

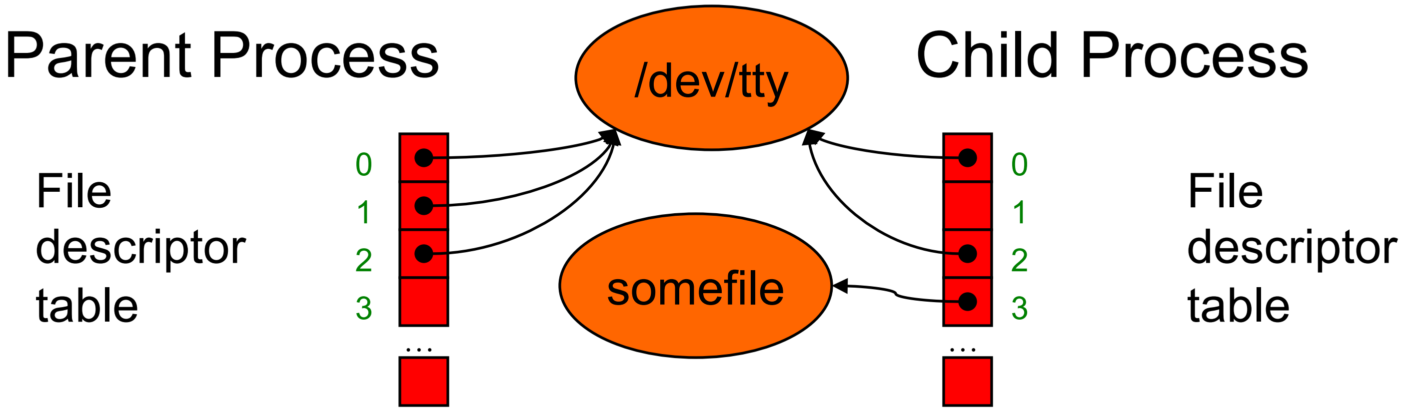
```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

3

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

OS gives CPU to child; child creates somefile

Redirection Example Trace (5)



Parent:

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

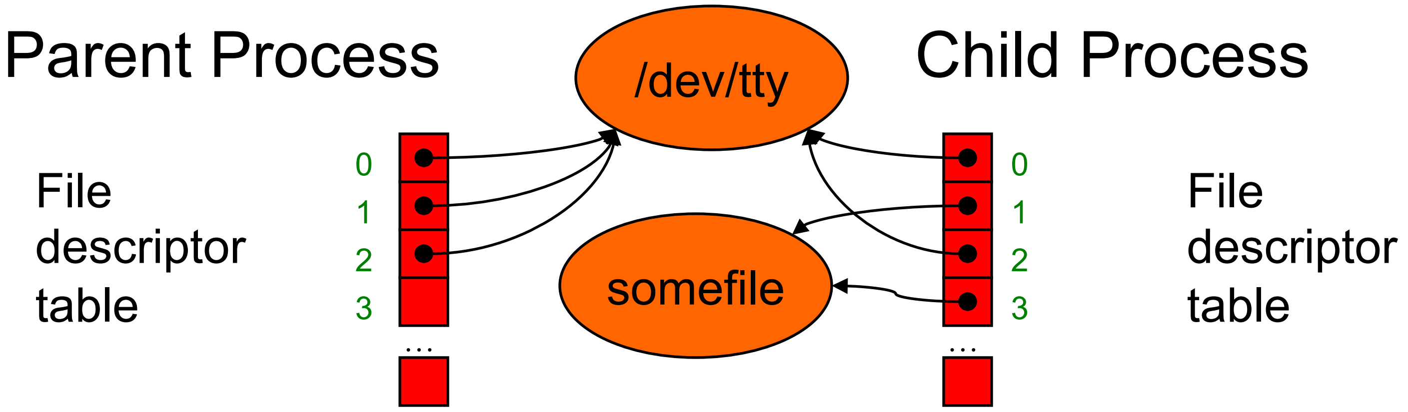
3

Child:

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Child closes file descriptor 1 (stdout)

Redirection Example Trace (6)



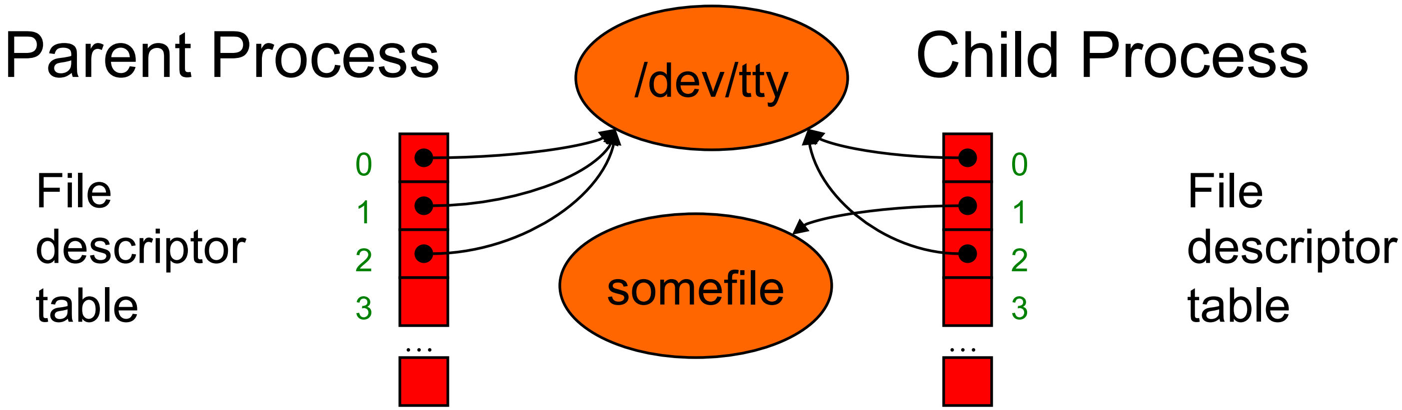

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

3

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Child duplicates file descriptor 3 into first unused spot

Redirection Example Trace (7)



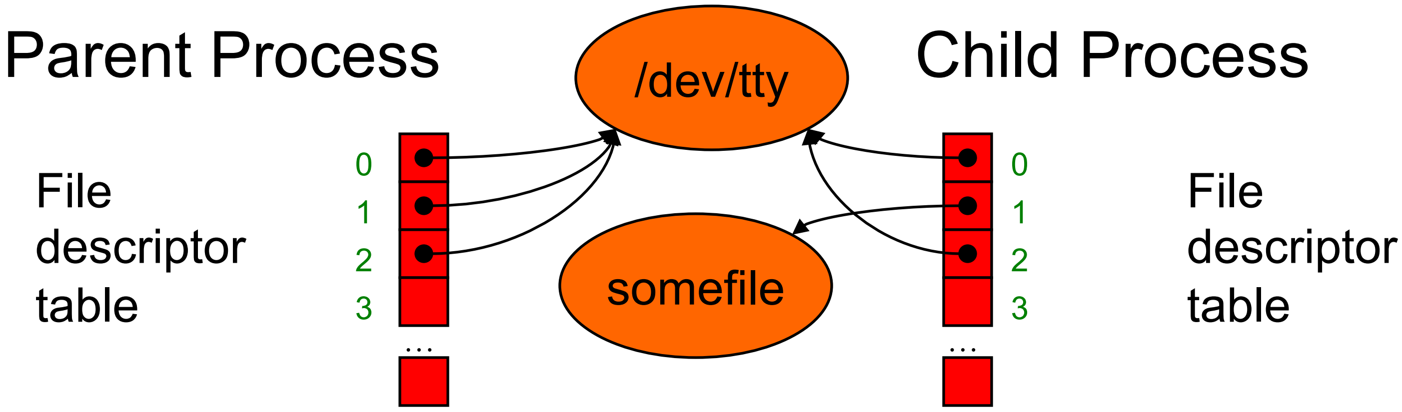

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

3

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Child closes file descriptor 3

Redirection Example Trace (8)



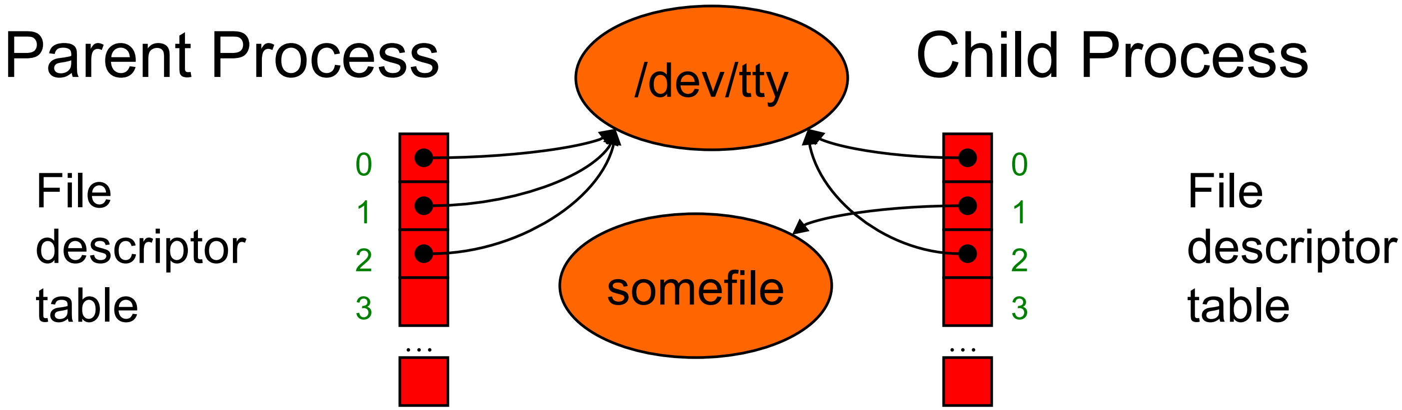

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

3

```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Child calls **`execvp()`**

Redirection Example Trace (9)

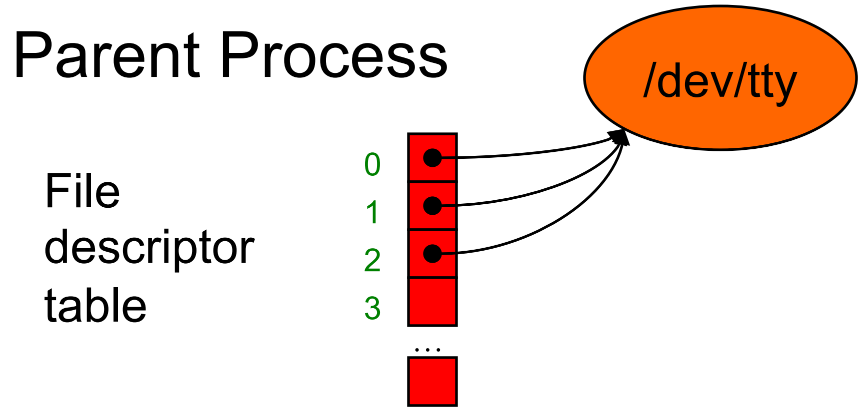



```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepfm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

somepgm

Somepgm executes with stdout redirected to somefile

Redirection Example Trace (10)




```
pid = fork();
if (pid == 0)
{  /* in child */
   fd = creat("somefile", 0600);
   close(1);
   dup(fd);
   close(fd);
   execvp(somefile, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
```

Somepgm exits; parent returns from **`wait()`** and proceeds

Agenda

The C/Unix file abstraction

Unix I/O system calls

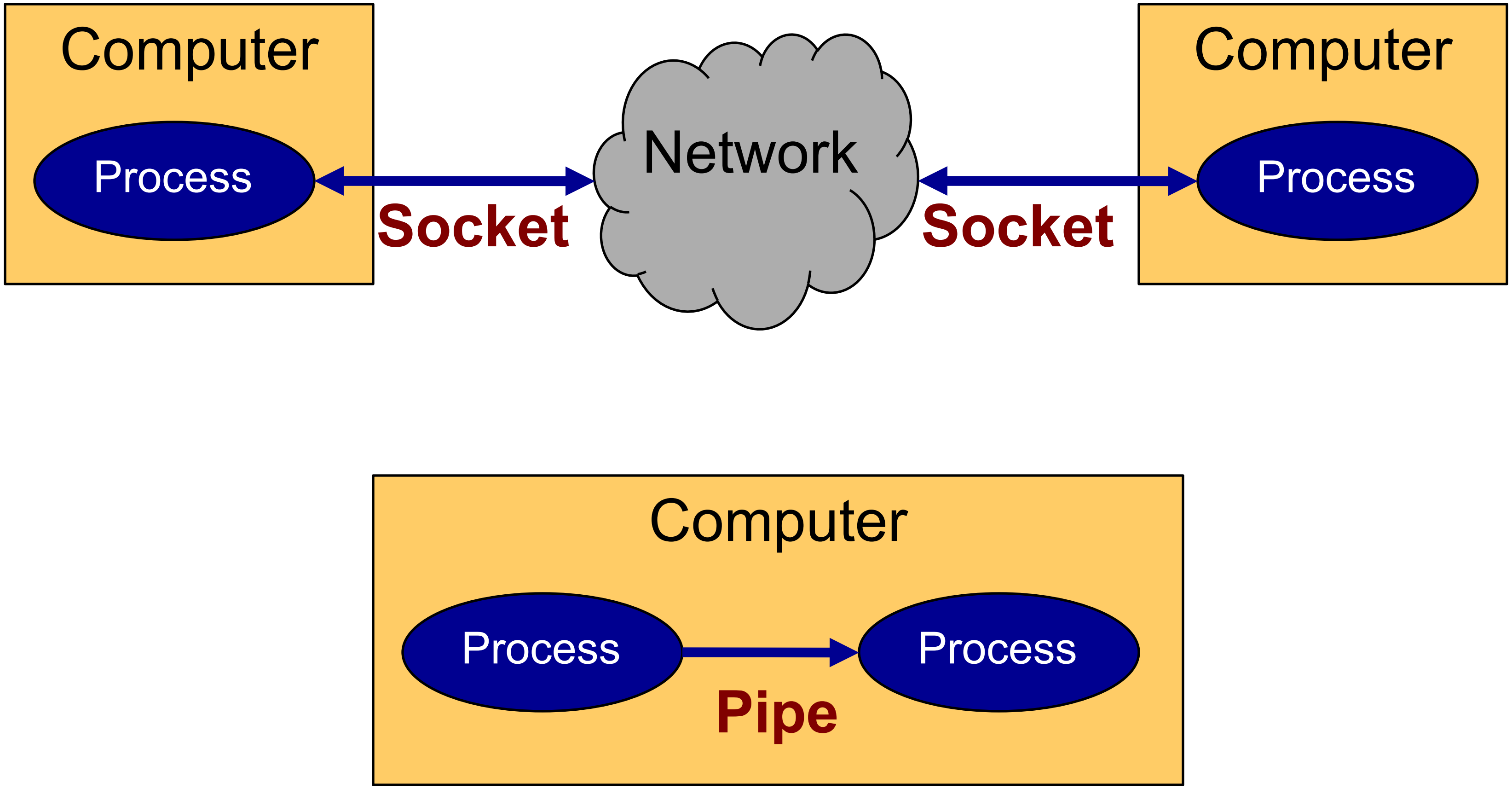
C's Standard IO library (FILE *)

+ Implementing standard C I/O using Unix I/O

Redirecting standard files

Pipes

Inter-Process Communication (IPC)



IPC Mechanisms

Socket

- Mechanism for **two-way** communication between processes on **any computers** on same network
- Processes created independently
- Used for client/server communication (e.g., Web)

Pipe

- Mechanism for **one-way** communication between processes on the **same computer**
- Allows parent process to communicate with child process
- Allows two "sibling" processes to communicate
- Used mostly for a **pipeline** of **filters**

Both support **file** abstraction

Pipeline Examples

When debugging your shell program…

```
grep alloc *.c
```

- In all of the .c files in the working directory, display all lines that contain "alloc"

```
cat *.c | decomment | grep alloc
```

- In all of the .c files in the working directory, display all non-comment lines that contain "alloc"

```
cat *.c | decomment | grep alloc | more
```

- In all of the .c files in the working directory, display all non-comment lines that contain "alloc", one screen at a time

Creating a Pipe

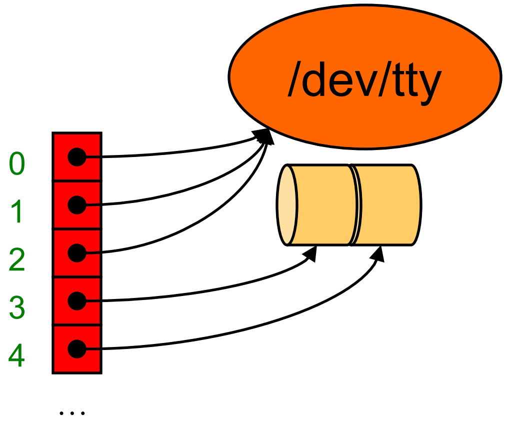
`int pipe(int pipefd[2])`

- **`pipe()`** creates a pipe, a unidirectional data channel that can be used for interprocess communication
- The array **`pipefd`** is used to return two file descriptors referring to the ends of the pipe
- **`pipefd[0]`** refers to the read end of the pipe
- **`pipefd[1]`** refers to the write end of the pipe
- Data written to the write end of the pipe is buffered by the kernel until it is read from the read end of the pipe

  - Quoting **`man -s2 pipe`**

Pipe Example 1 (1)

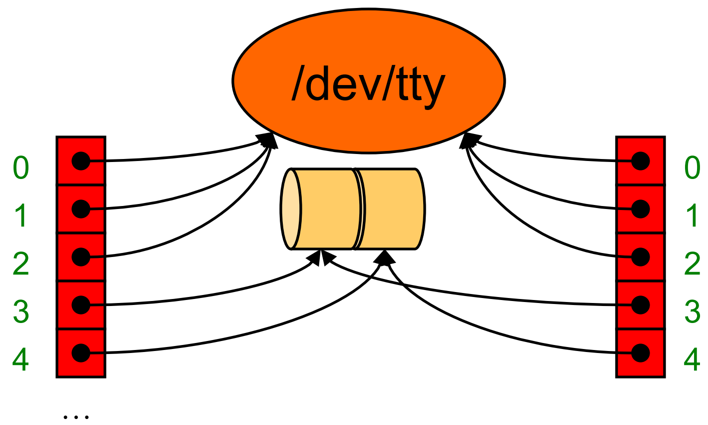
```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```




```
p[0] = 4
p[1] = 3
```

Pipe Example 1 (2)

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```



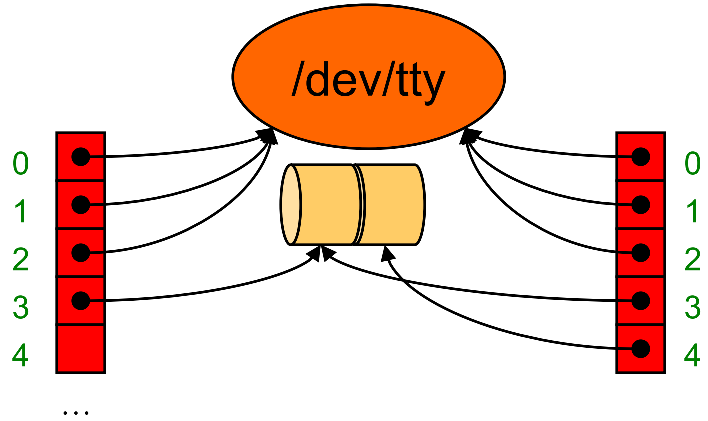

```
p[0] = 4
p[1] = 3
```


```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```

Pipe Example 1 (3)

Parent process sends data to child process

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```



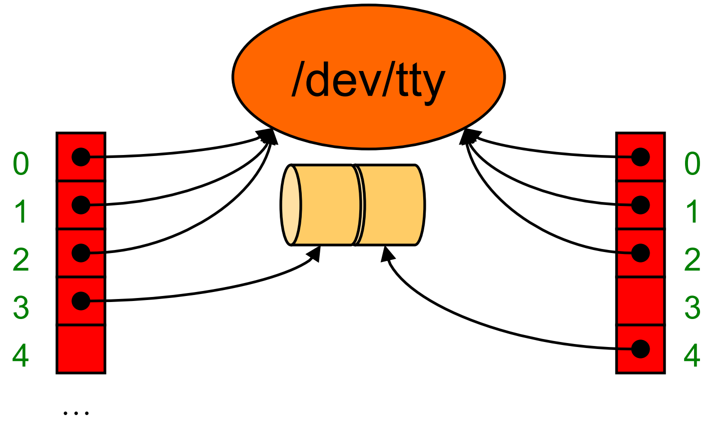

```
p[0] = 4
p[1] = 3
```

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```

Pipe Example 1 (4)

Child process receives data from parent process

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```

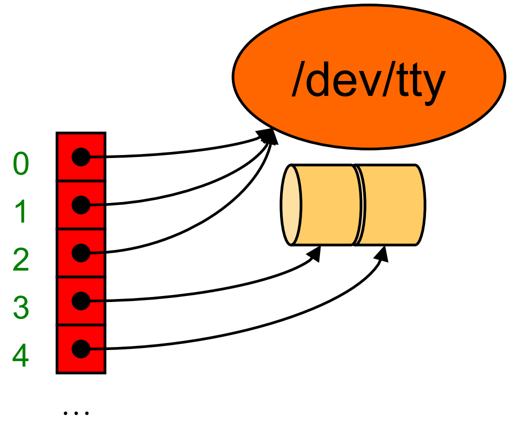



```
p[0] = 4
p[1] = 3
```

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(p[1]);
   /* Read from fd p[0] */
   exit(0);
}
/* in parent */
close(p{0});
/* Write to fd p[1] */
wait(NULL);
```

Pipe Example 2 (1)

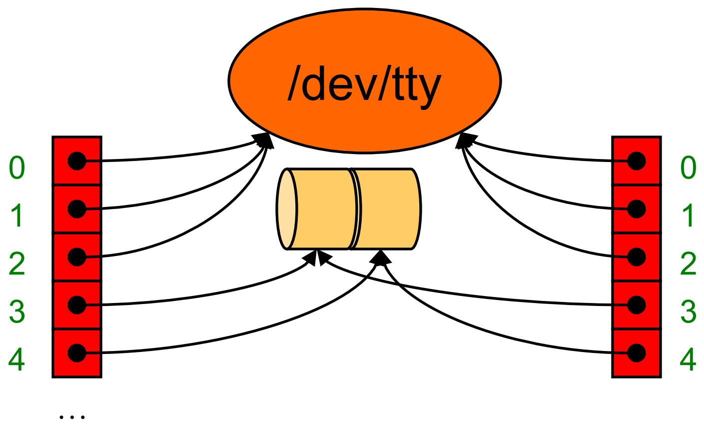
```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{  /* in child */
   close(0);
   dup(p[0]);
   close(p[0]);
   close(p[1]);
   /* Read from stdin */
   exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```



p[0] = 4
p[1] = 3

Pipe Example 2 (2)

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{   /* in child */
    close(0);
    dup(p[0]);
    close(p[0]);
    close(p[1]);
    /* Read from stdin */
    exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```



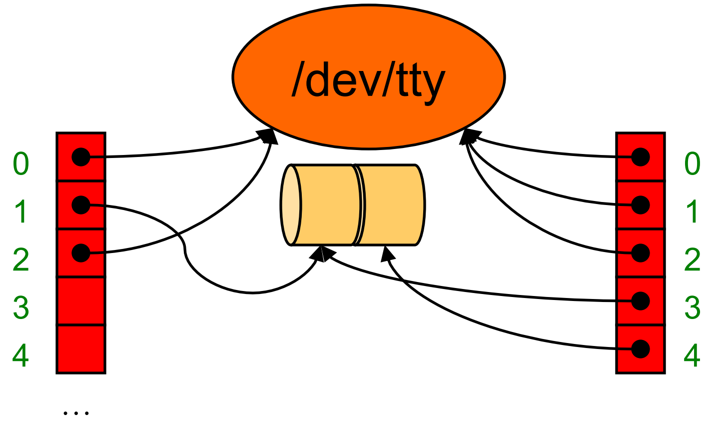

```
p[0] = 4
p[1] = 3
```


```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{   /* in child */
    close(0);
    dup(p[0]);
    close(p[0]);
    close(p[1]);
    /* Read from stdin */
    exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```

Pipe Example 2 (3)

Parent sends data to child through stdout

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{   /* in child */
    close(0);
    dup(p[0]);
    close(p[0]);
    close(p[1]);
    /* Read from stdin */
    exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```



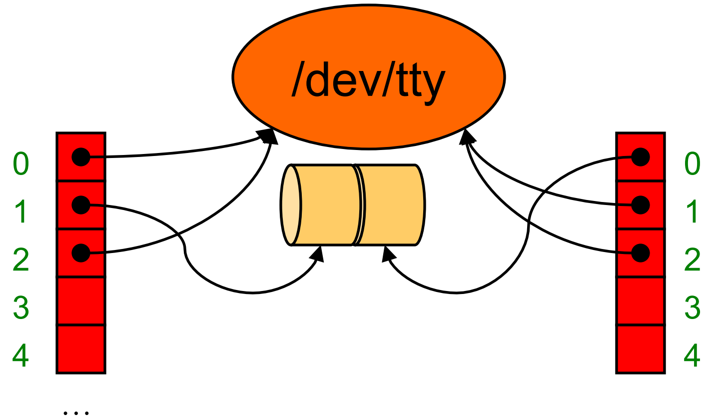

```
p[0] = 4
p[1] = 3
```

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{   /* in child */
    close(0);
    dup(p[0]);
    close(p[0]);
    close(p[1]);
    /* Read from stdin*/
    exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```

Pipe Example 2 (4)

Child receives data from parent through stdin

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{   /* in child */
    close(0);
    dup(p[0]);
    close(p[0]);
    close(p[1]);
    /* Read from stdin */
    exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```




```
p[0] = 4
p[1] = 3
```

Now add in execs, and you get the shell's implementation of pipes!

```
int p[2];
…
pipe(p)
pid = fork();
if (pid == 0)
{   /* in child */
    close(0);
    dup(p[0]);
    close(p[0]);
    close(p[1]);
    /* Read from stdin */
    exit(0);
}
/* in parent */
close(1);
dup(p[1])
close(p[1]);
close(p[0]);
/* write to stdout */
wait(NULL);
```

Summary

The C/Unix file abstraction

Unix I/O

- File descriptors, file descriptor tables, file tables
- **`creat()`**, **`open()`**, **`close()`**, **`read()`**, **`write()`**, **`lseek()`**

C's Standard I/O

- **`FILE`** structure
- **`fopen()`**, **`fclose()`**, **`fgetc()`**, **`fputc()`**, …

Implementing standard C I/O using Unix I/O

- Buffering

Redirecting standard files

- **`dup()`**

Pipes

- **`pipe()`**