Input/Output

CS 351: Systems Programming

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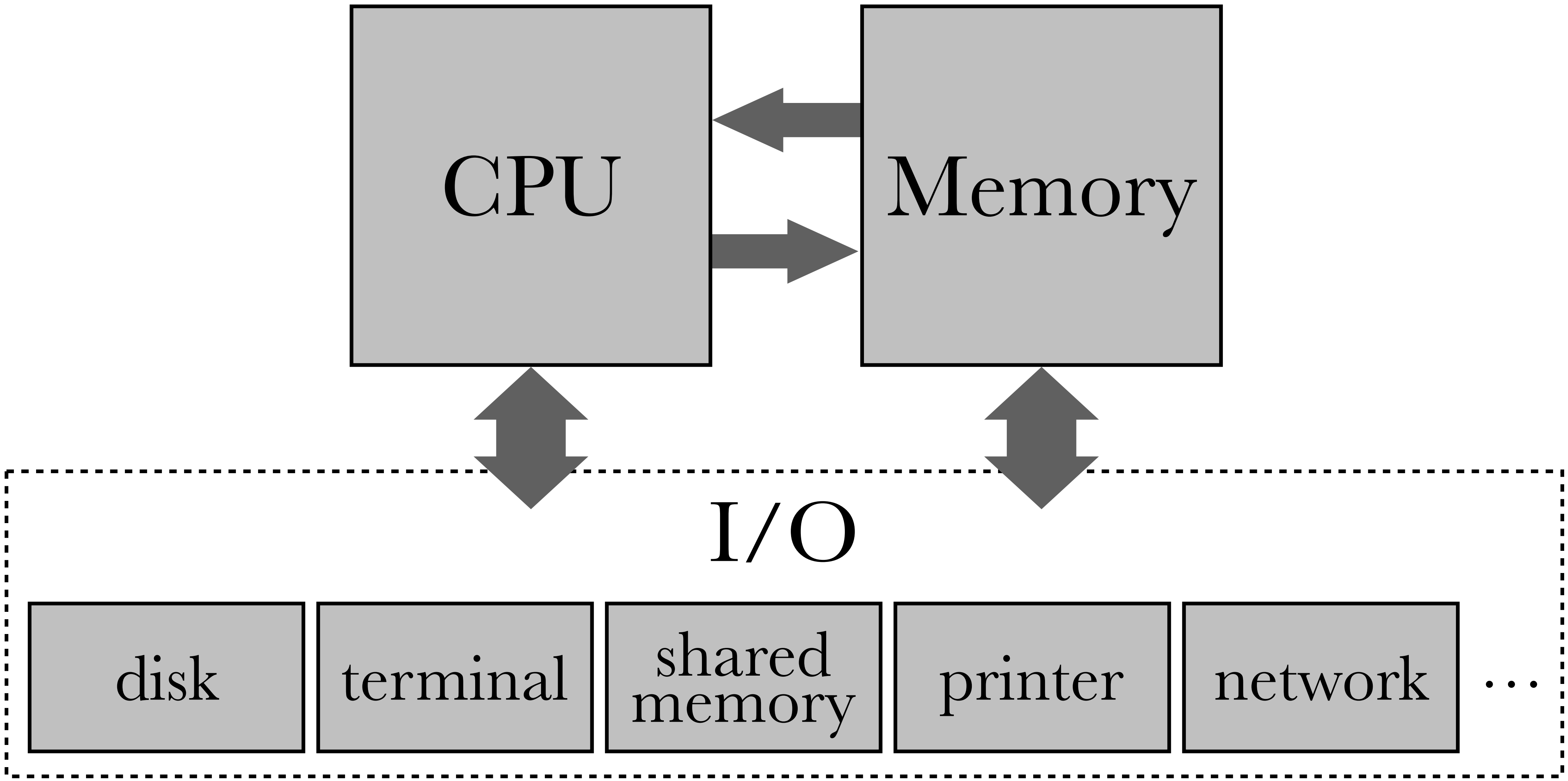
Science

Computer Science

IIT College of Science

ILLINOIS INSTITUTE OF TECHNOLOGY


CPU
Memory
I/O
disk
terminal
shared memory
printer
network
...

disk	terminal	shared memory	printer	network	…

- vast number of different mechanisms
- but overlapping requirements:
    - read/write operations
    - metadata (e.g., name, position)
    - robustness, thread-safety

programming concerns:

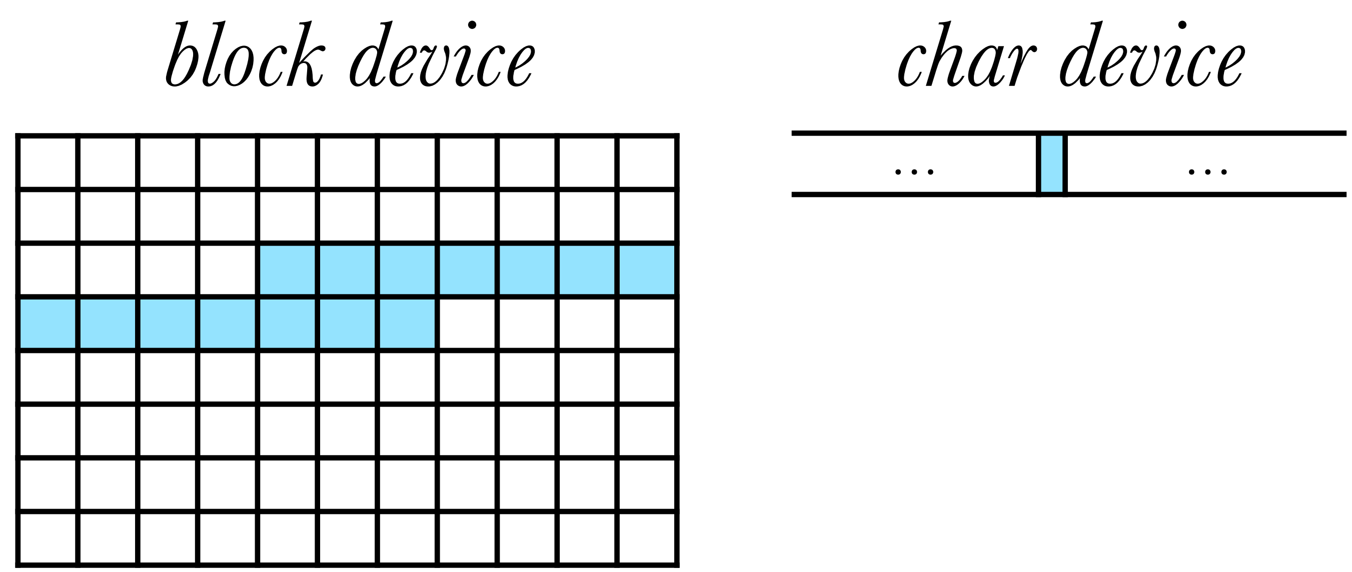
- how are I/O endpoints represented?
- how to perform I/O?
- how to perform I/O *efficiently*?

focus on **Unix system-level I/O**

§Unix I/O & Filesystem Architecture Brief

2 general classes of I/O devices:

- *block*: accessed in fixed-size chunks; support for seeking & random access
- *character*: char-by-char streaming access; no seeking / random access


block device
char device
...
...

2 general classes of I/O devices:

- *block*: e.g., disk, memory
- *character*: e.g., network, mouse

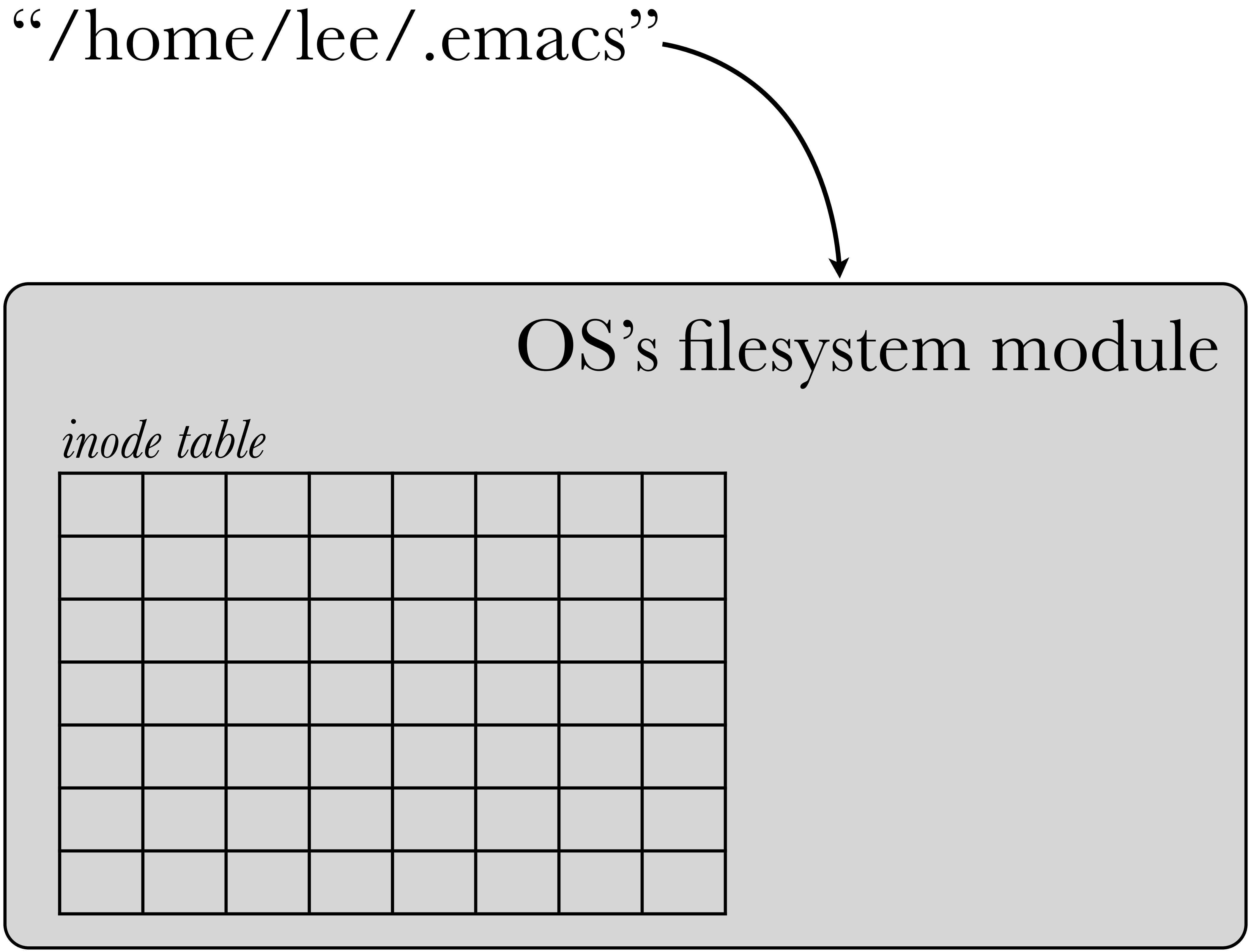
the **filesystem** acts as a *namespace* for data residing on different devices *regular files* consist of ASCII or binary data, stored on a block device *special files* may represent directories, in-memory structures, sockets, or raw devices i.e., “files” are a *general OS abstraction* for arbitrary data objects!

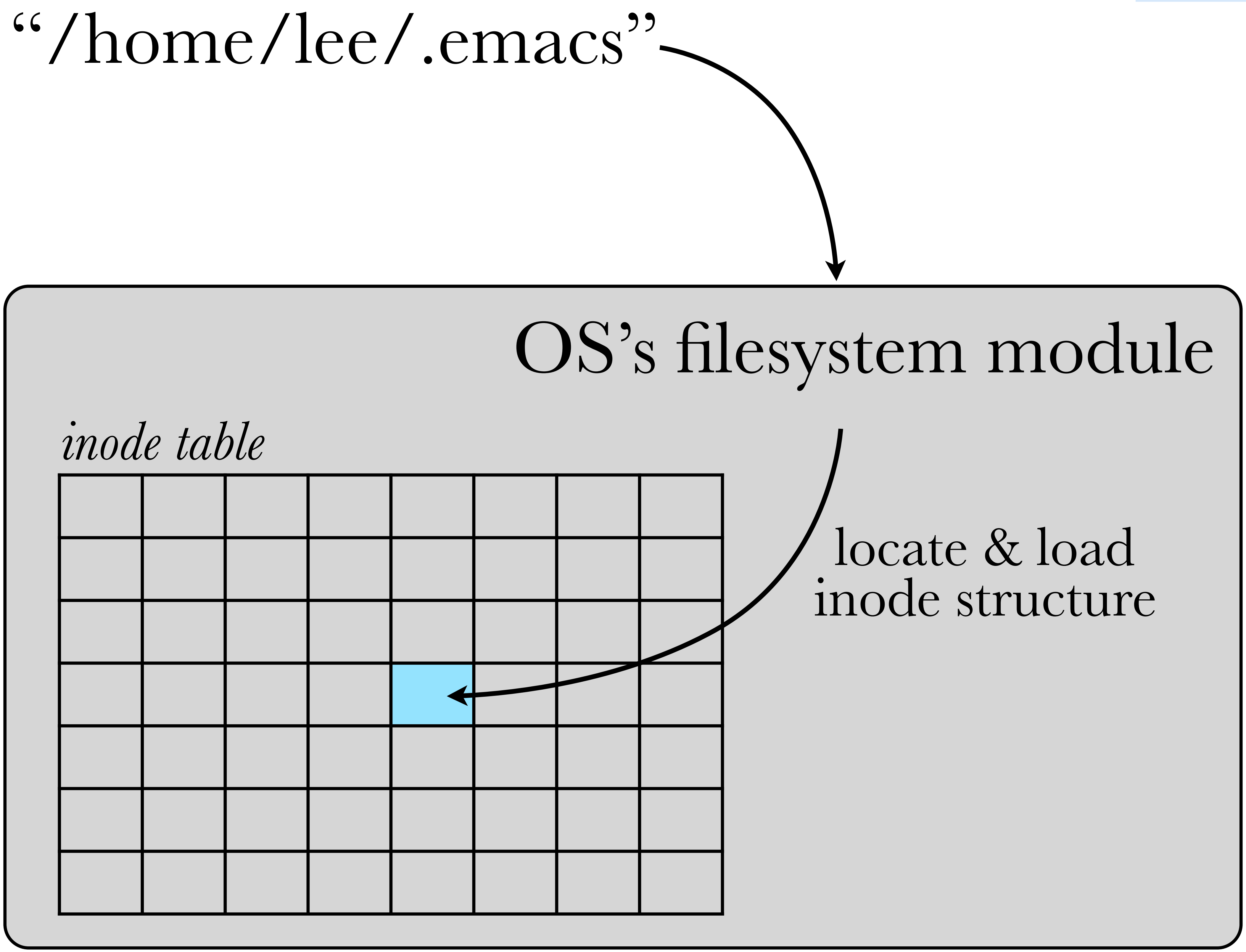
each file has a unique **inode** data structure in the filesystem, tracking:

- ownership & permissions
- size, type, and location
- number of *links*

a given i-node can be referenced using one or more *fully qualified path(s)*, e.g.,

- /home/lee/.emacs
- /proc/sys/kernel/version
- /dev/tty


"/home/lee/.emacs"
OS's filesystem module
inode table



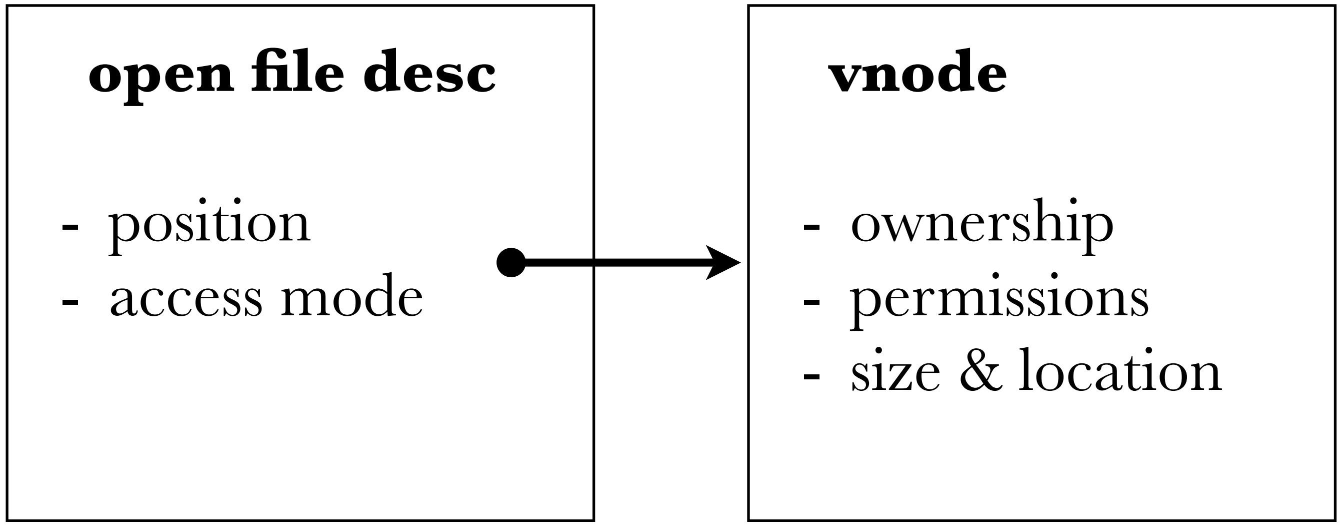
* filename → inode association = *link*

every currently open file has a *single* in-memory inode, aka. "vnode"

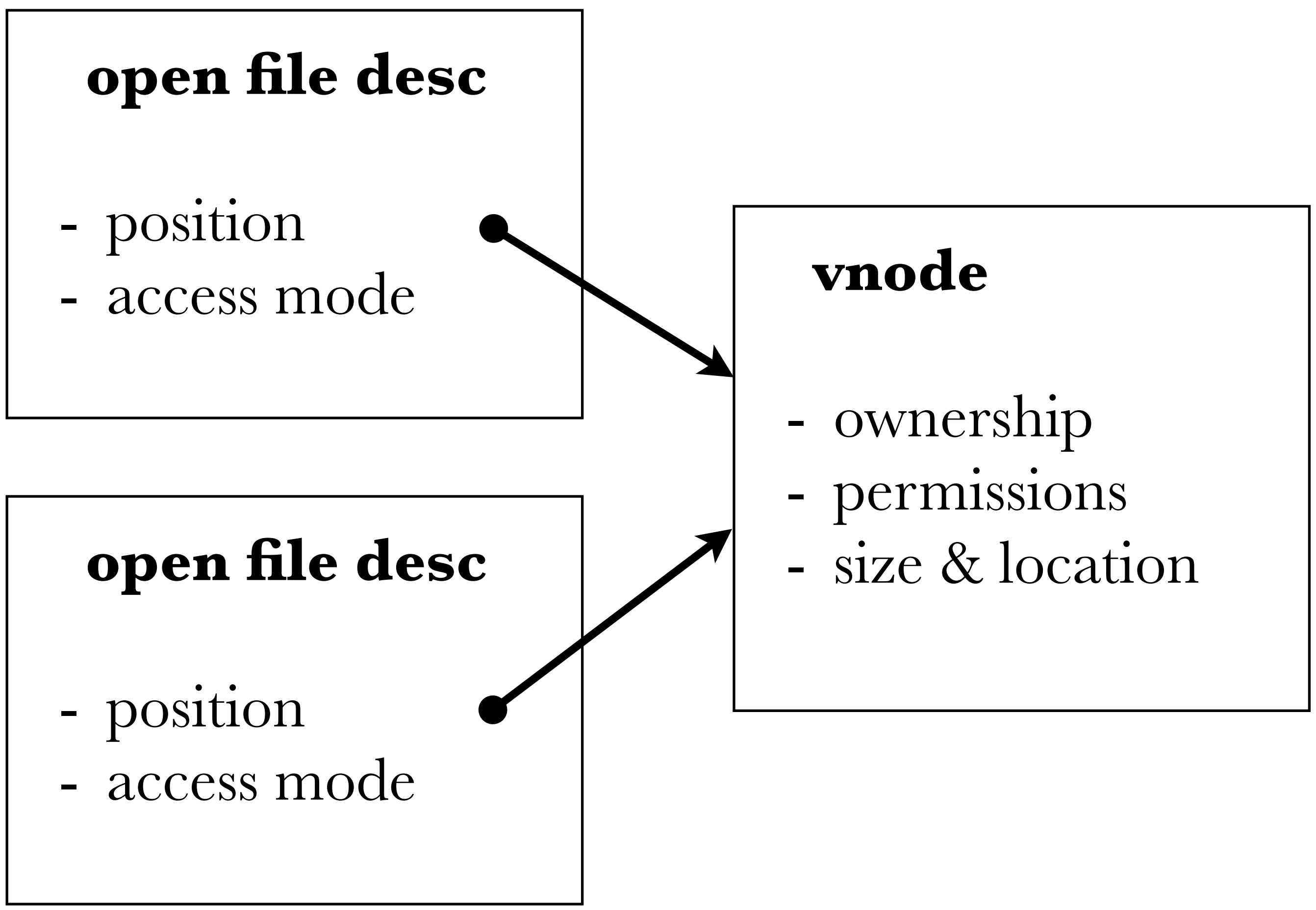
vnode

- ownership
- permissions
- size & location

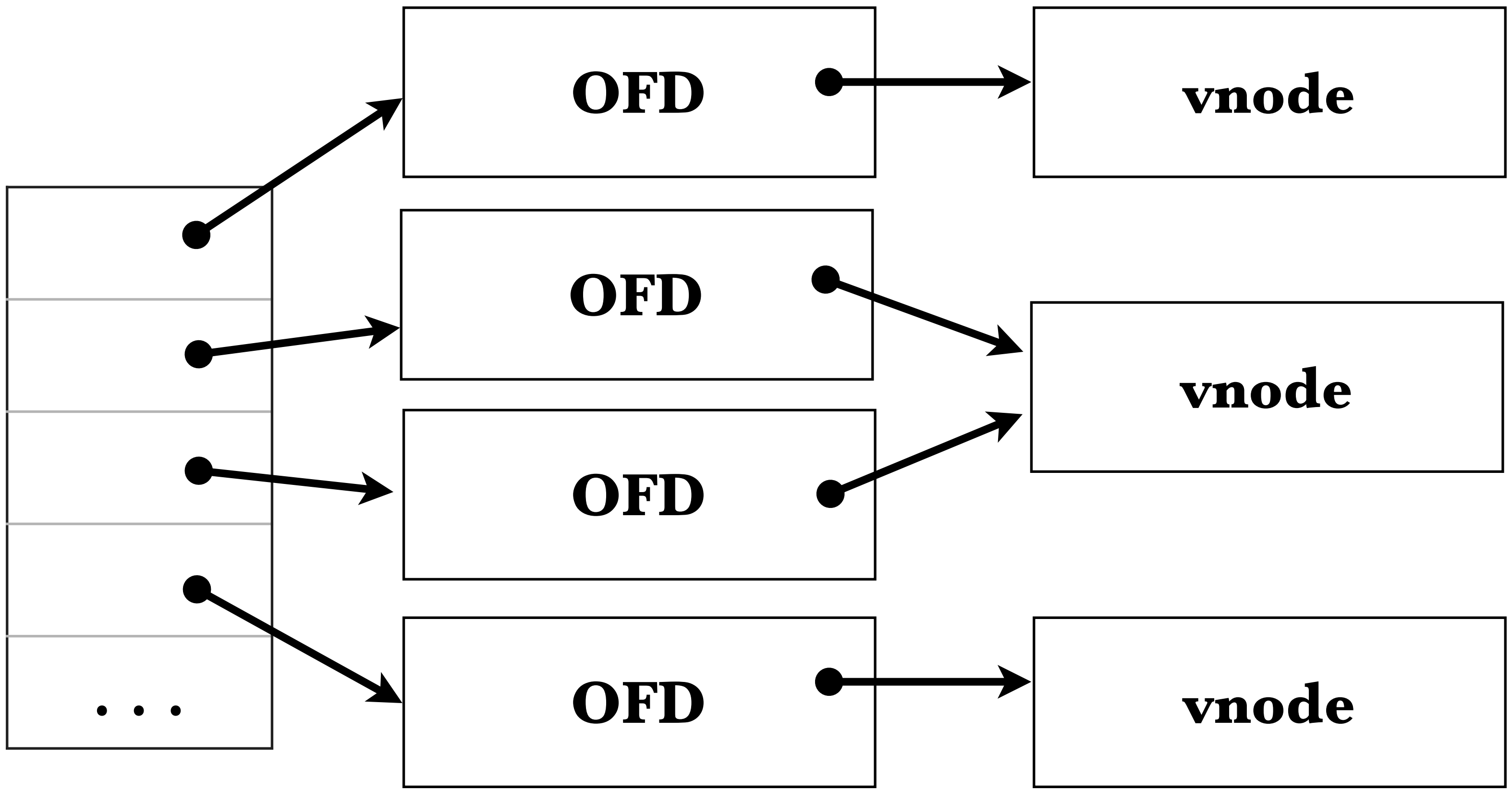
each open file is also tracked by the kernel using an *open file description* structure



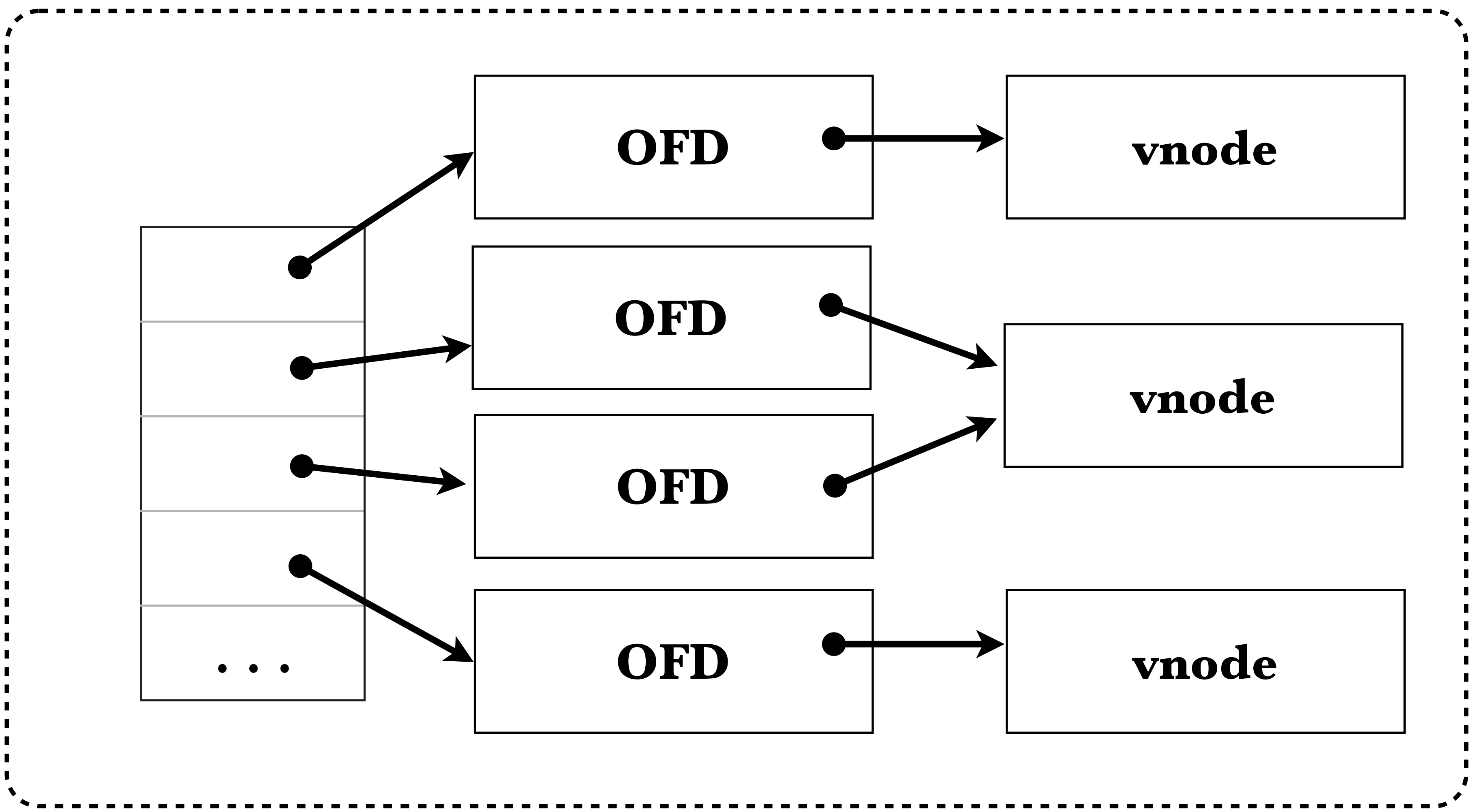
can have *multiple open file descriptions* referencing a *single vnode* (e.g., to track separate read/write positions)



for *each process*, the kernel maintains a table of pointers to its open file structures

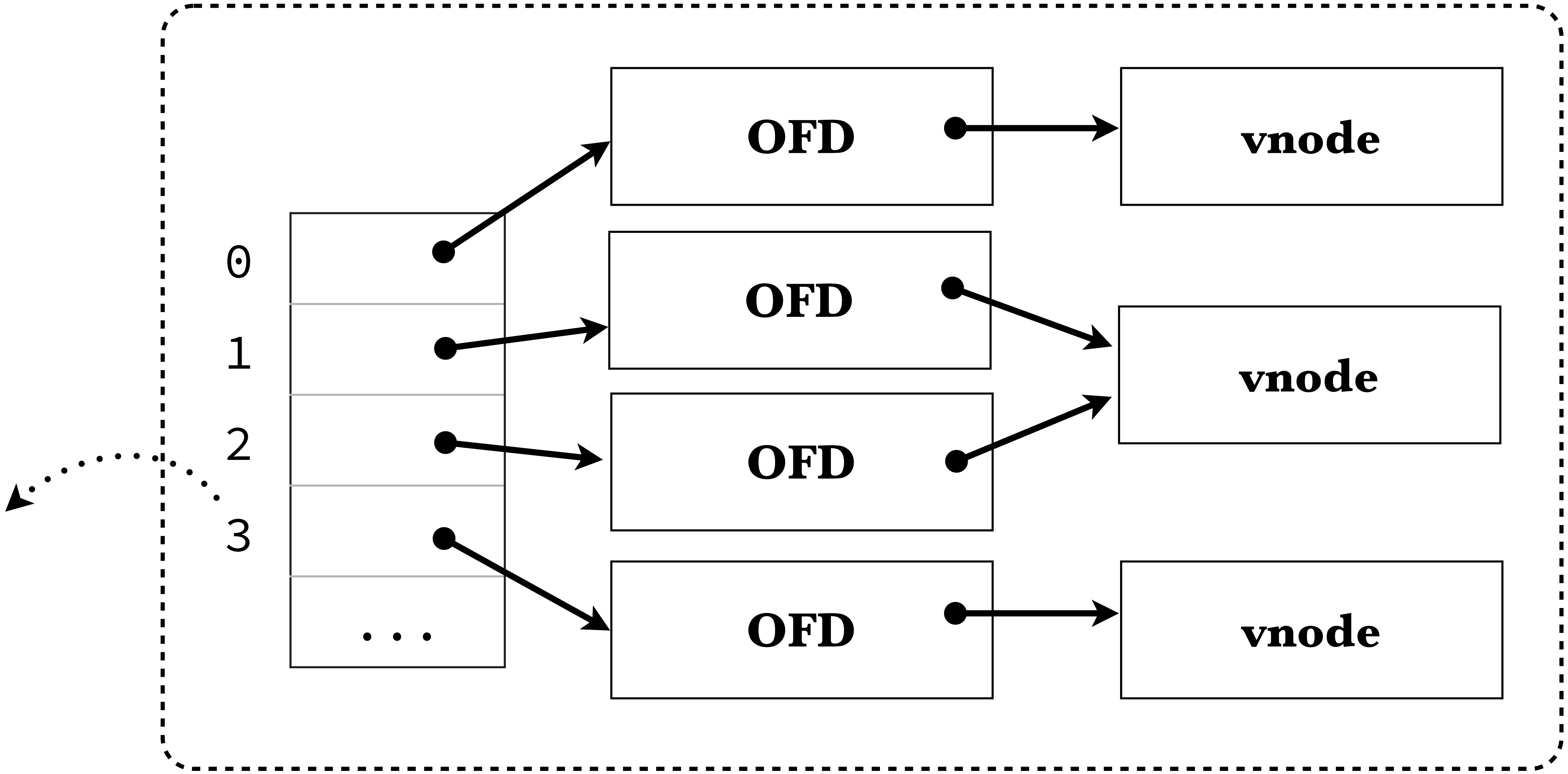


all these structures reside in *kernel memory* (off-limits to user processes)!

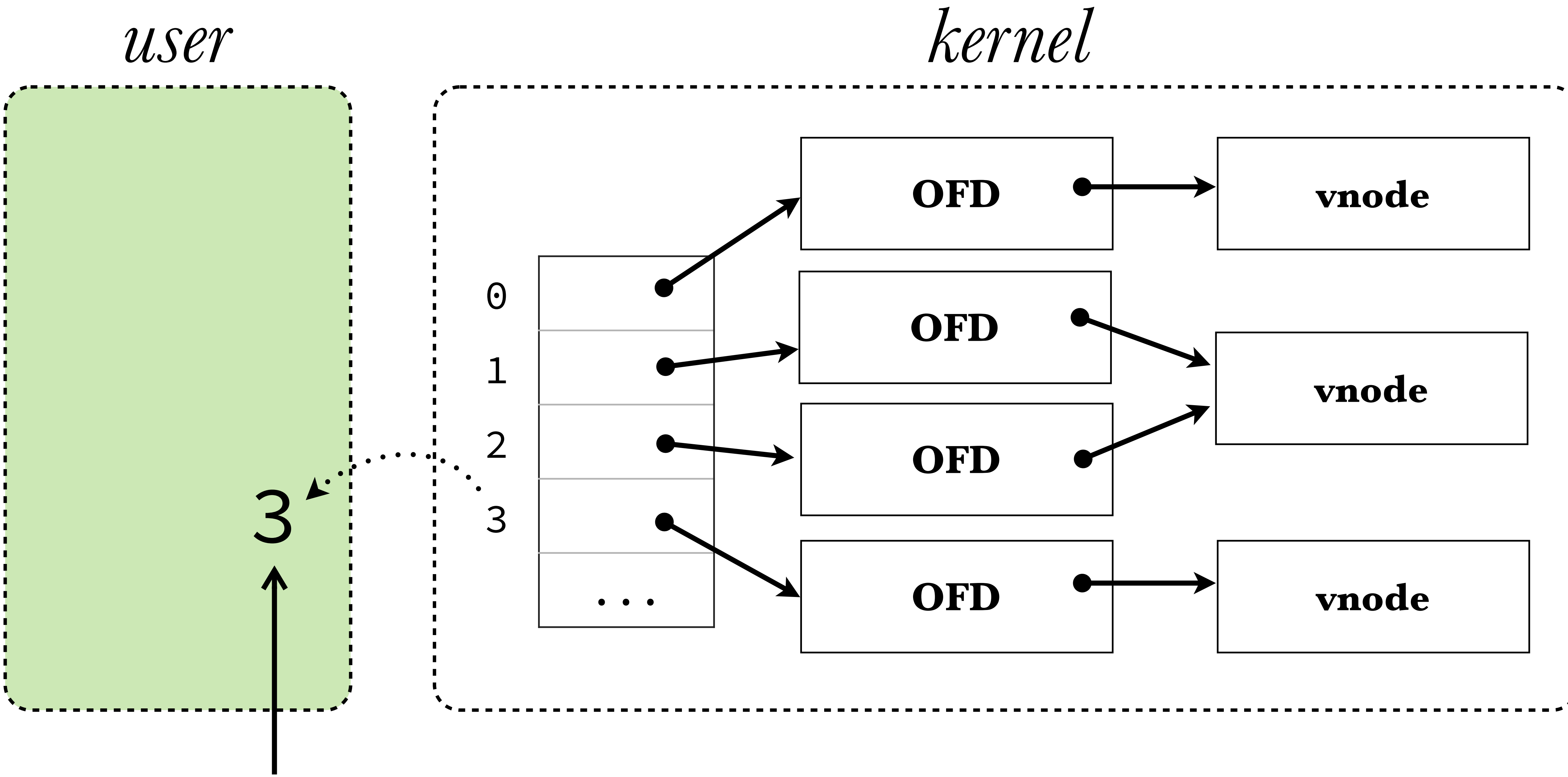


protected memory

to let a process reference an open file, the kernel returns *an index into* the table



protected memory



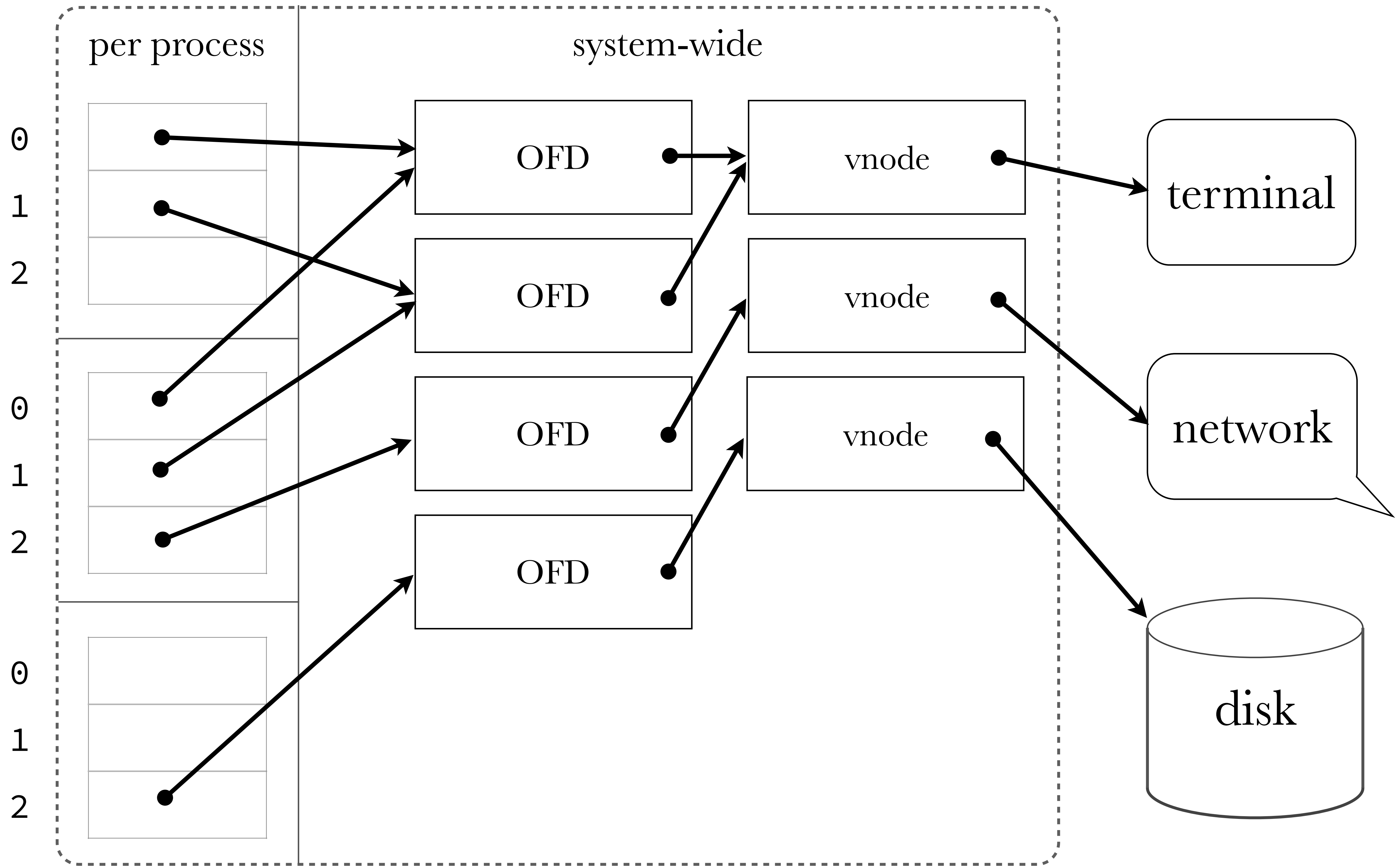
call this a **file descriptor** (FD)

by convention, processes …

- read from FD `0` for *standard input*
- write to FD `1` for *standard output*
- write to FD `2` for *standard error*

after opening a file, ***all*** *file operations* are performed using file descriptors!

kernel space



FDs *obscure* kernel I/O & FS implementation details from the user, and enable an *elegant, abstract* I/O API

§ System-level I/O API

```
    int   open   ( const char *path, int oflag, ... );
    int   fstat  ( int fd, struct stat *buf );
    int   dup    ( int fd );
    int   dup2   ( int fd1, int fd2 );
    int   close  ( int fd );
  off_t   lseek  ( int fd, off_t offset,    int whence );
ssize_t   read   ( int fd, void *buf,       size_t nbytes );
ssize_t   write  ( int fd, const void *buf, size_t nbytes );
```

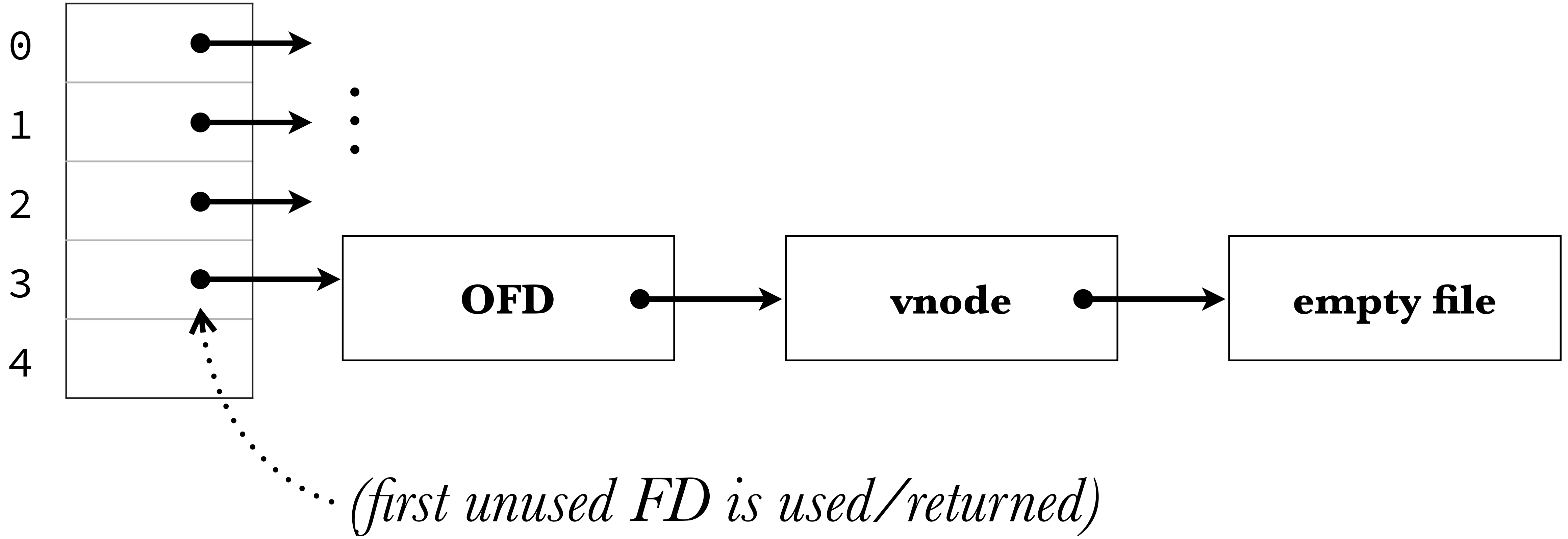
```
int open(const char *path,
         int oflag, ...);
```

- loads *vnode* for file at `path` (if not already loaded)
- creates & inits a new OFD
- returns a **FD** referring to the new OFD

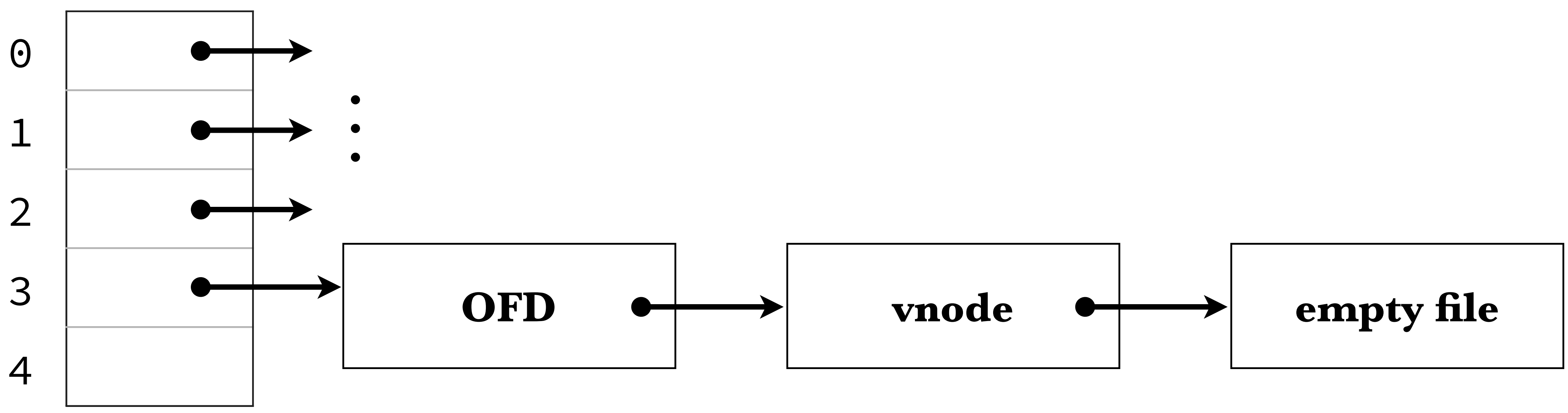
```c
int open(const char *path,
         int oflag, ...);
```

- `oflag` is an *or*-ing of `O_RDONLY`, `O_WRONLY`, `O_RDWR`, `O_CREAT`, `O_TRUNC`, etc.
- if `O_CREAT`, must specify access permissions of new file ("rwx" flags)

```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
```



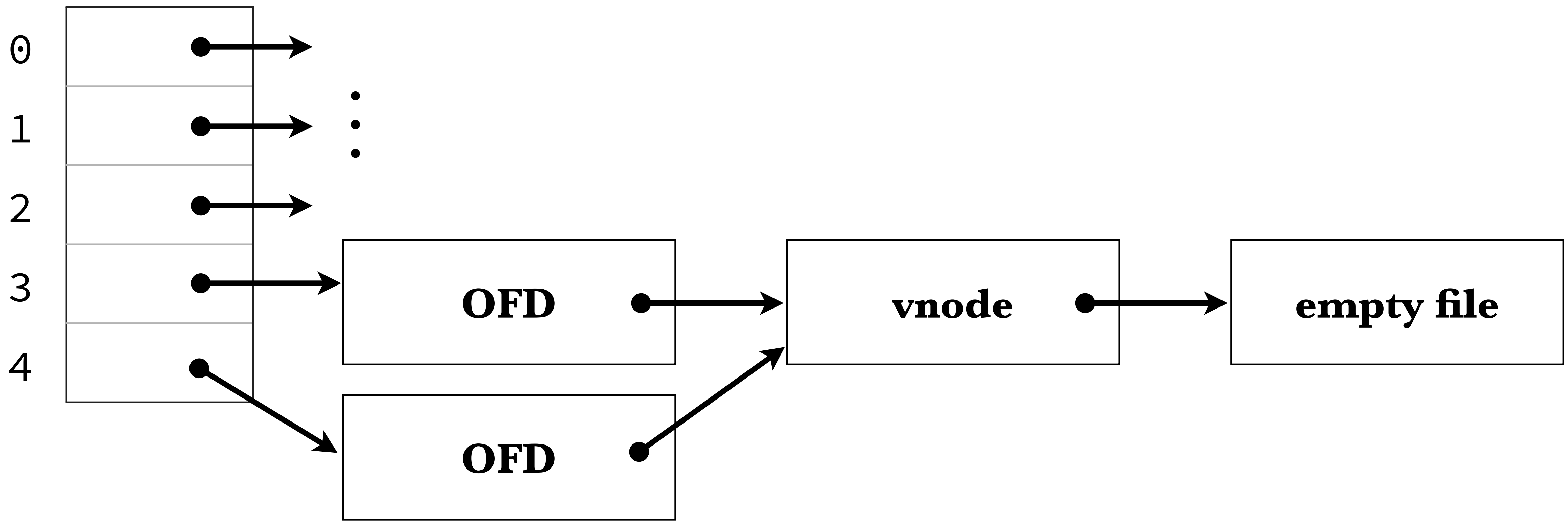
```
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
```




```
$ ls -l foo.txt
-rw-r--r-- 1 lee staff 5 Feb 15 18:23 foo.txt
```

rwx flags from (octal) `0644`

```
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = open("foo.txt", O_RDONLY);
```

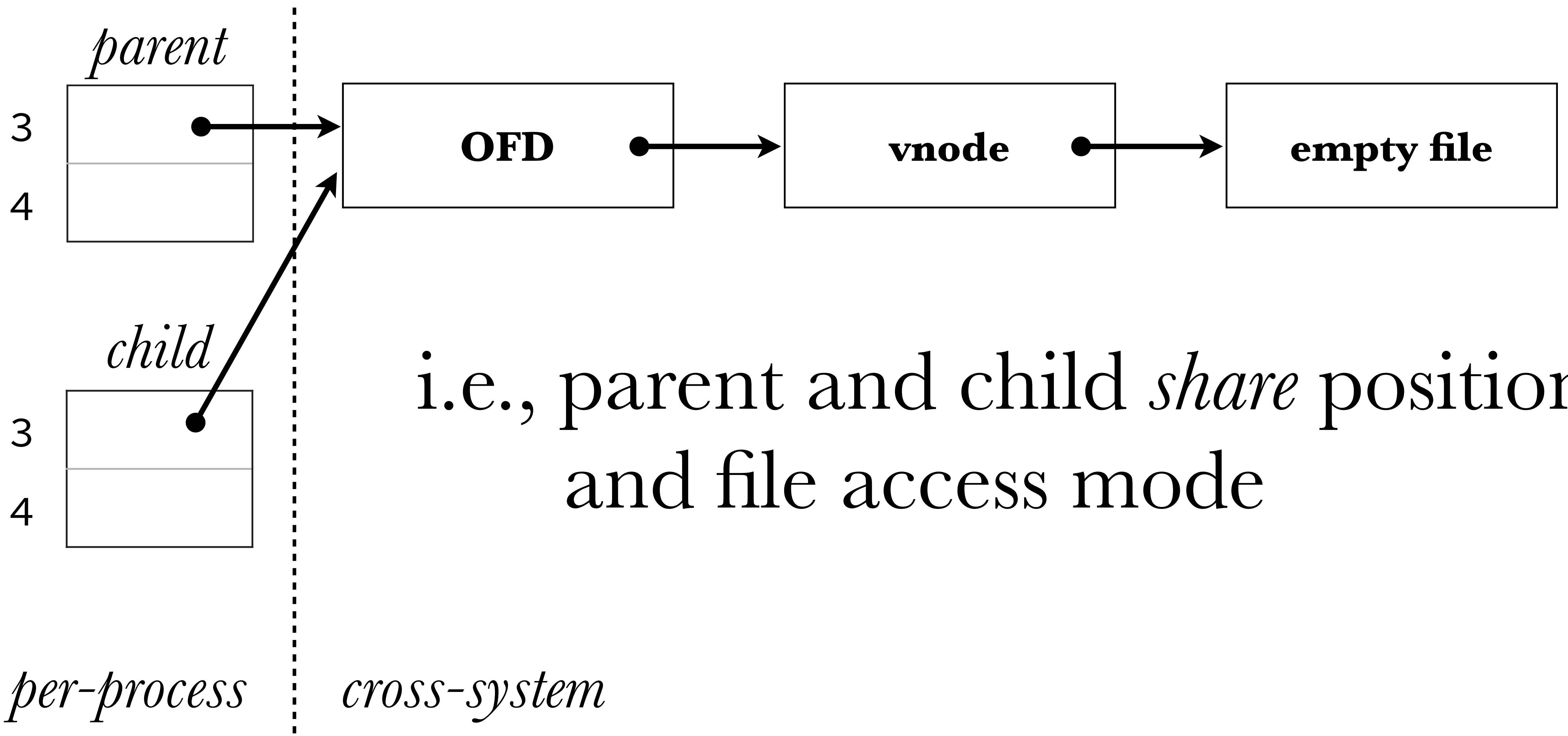


```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);

struct stat stat;

/* query file metadata */
fstat(fd1, &stat);

printf("Inode # : %lu\n", stat.st_ino);
printf("Size    : %lu\n", stat.st_size);
printf("Links   : %lu\n", stat.st_nlink);
```

```
Inode # : 19603149
Size    : 0
Links   : 1
```

† a process inherits its parent's open files across a `fork`, and *retains them post-*`exec`!

```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
fork();
```

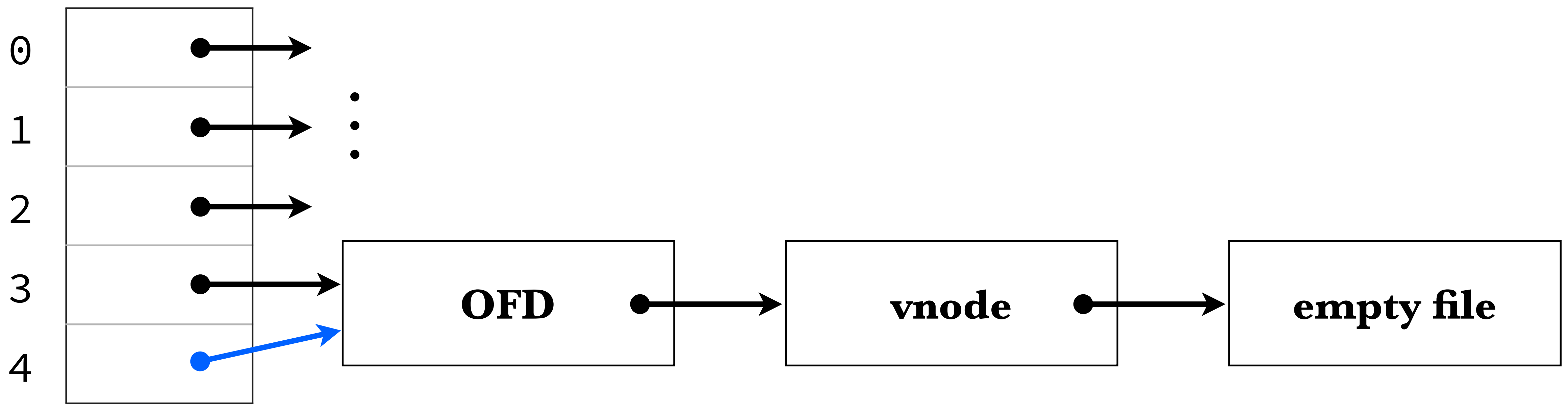


i.e., parent and child *share* position and file access mode

sharing an OFD can be very handy —
e.g., for coordinating output to terminal

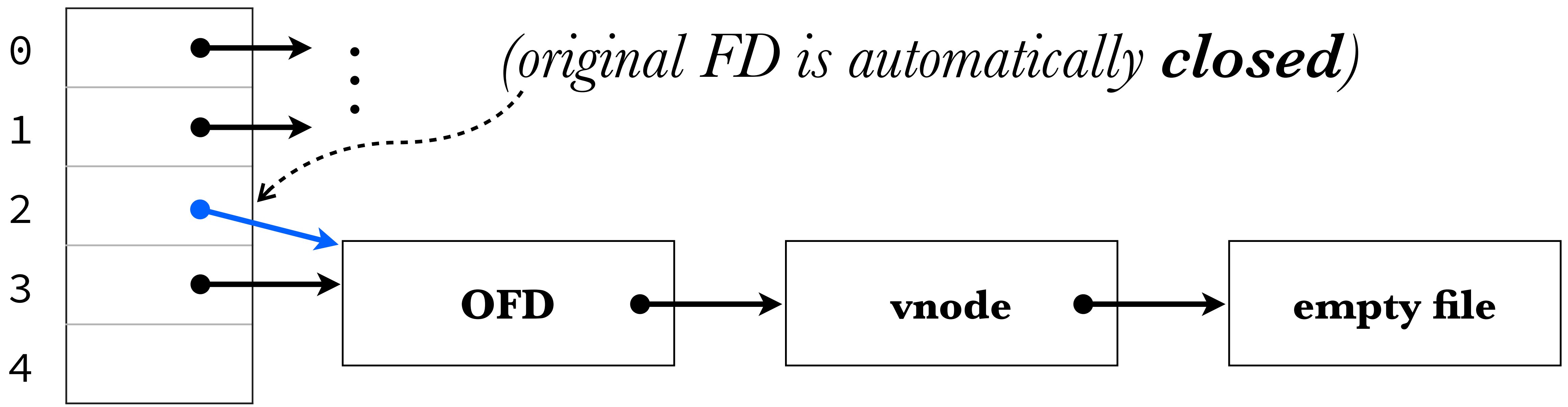
can also explicitly "share" position from separate FDs using `dup` syscalls

```
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = dup(fd1);
```



i.e., reading/writing FD 4 is equivalent to doing so with FD 3

```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
dup2(fd1, 2); /* second arg is "destination" fd */
```

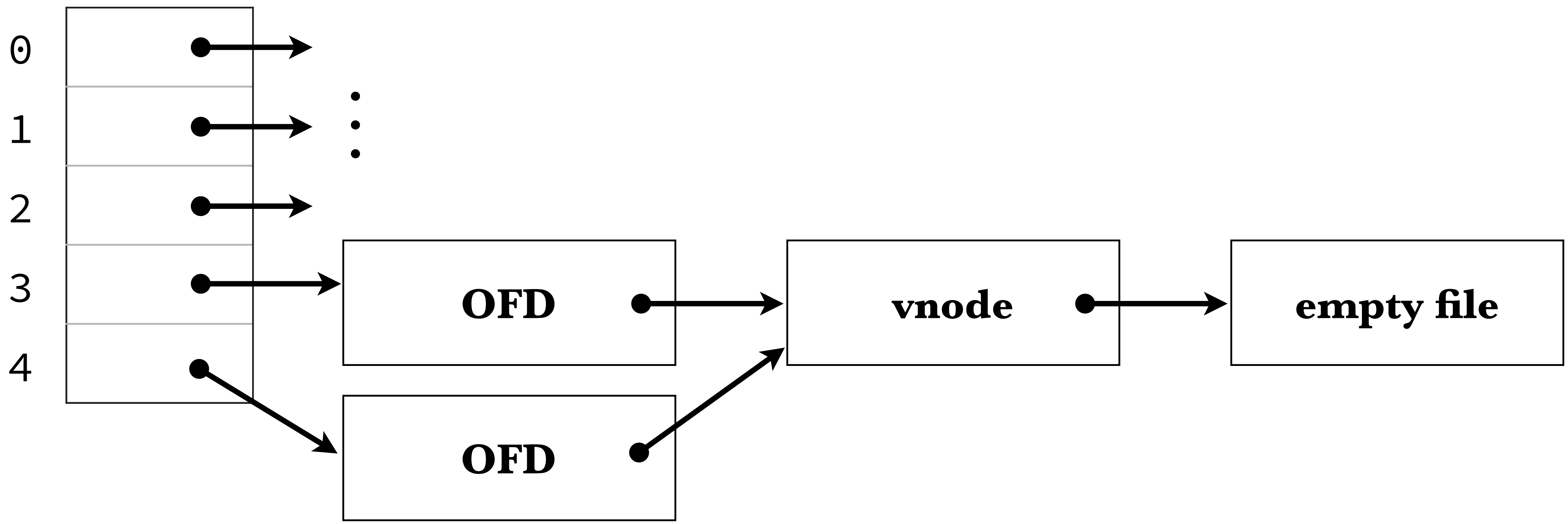


i.e., reading/writing FD 2 (*stderr*) is equivalent to doing so with FD 3

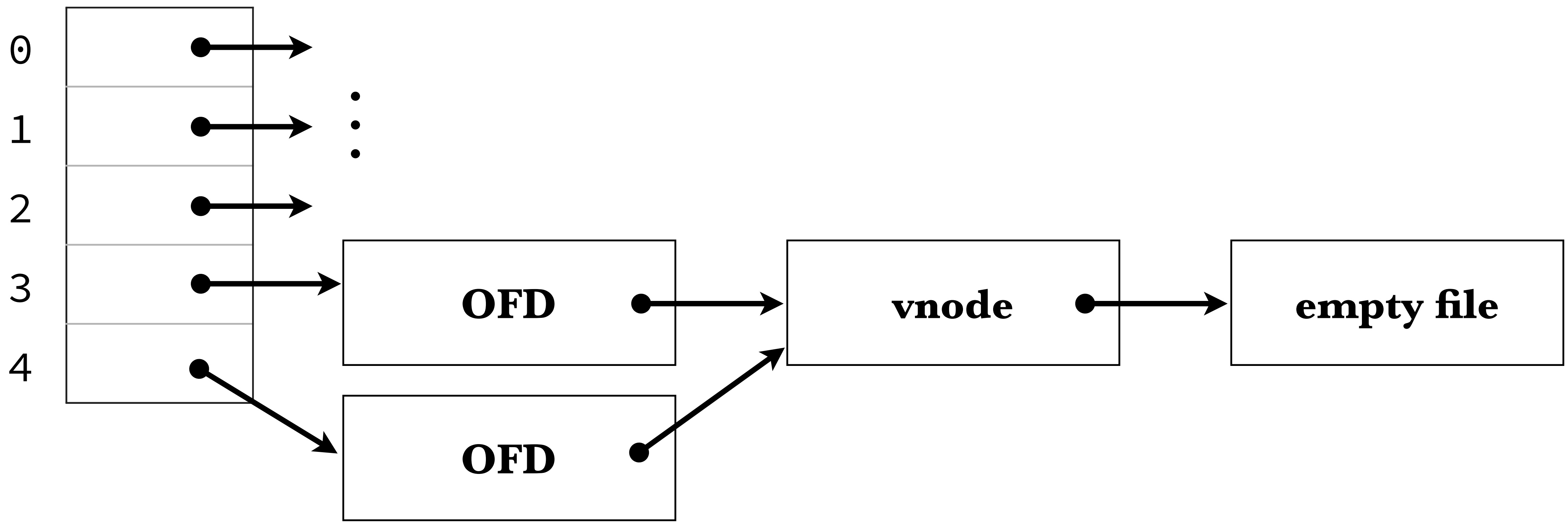
```c
int close(int fd);
```

- delete OFD pointer in file table for `fd`
- if the OFD has no referring FDs (in any process), deallocate it

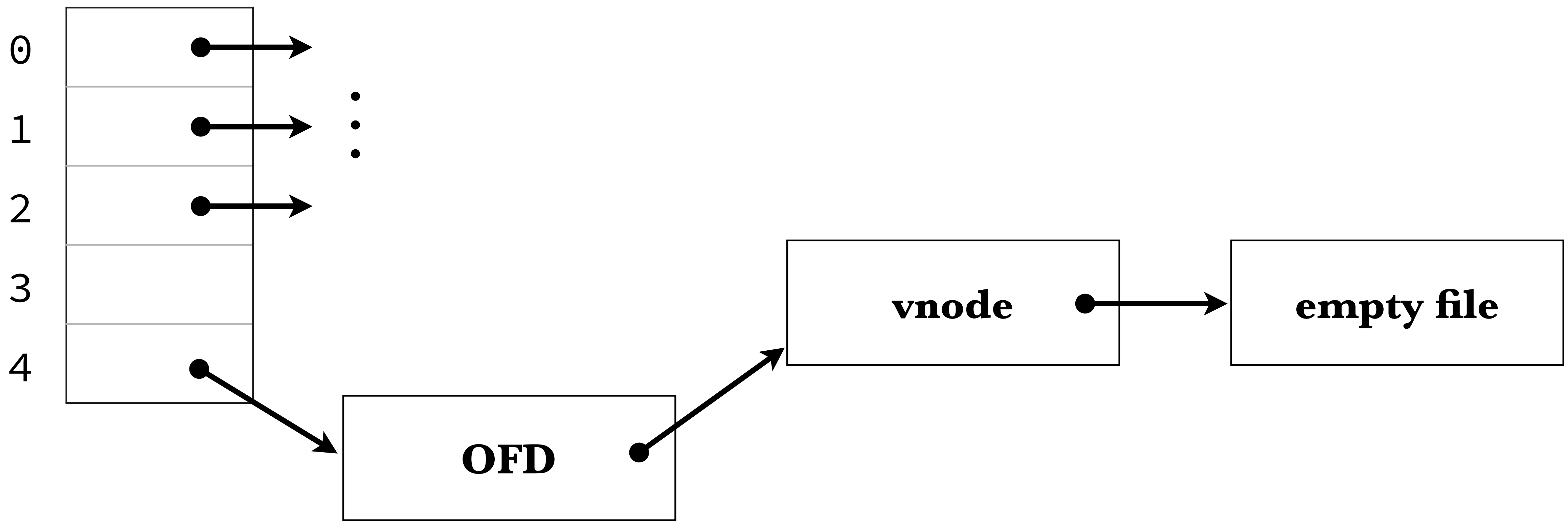
```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = open("foo.txt", O_RDONLY);
```



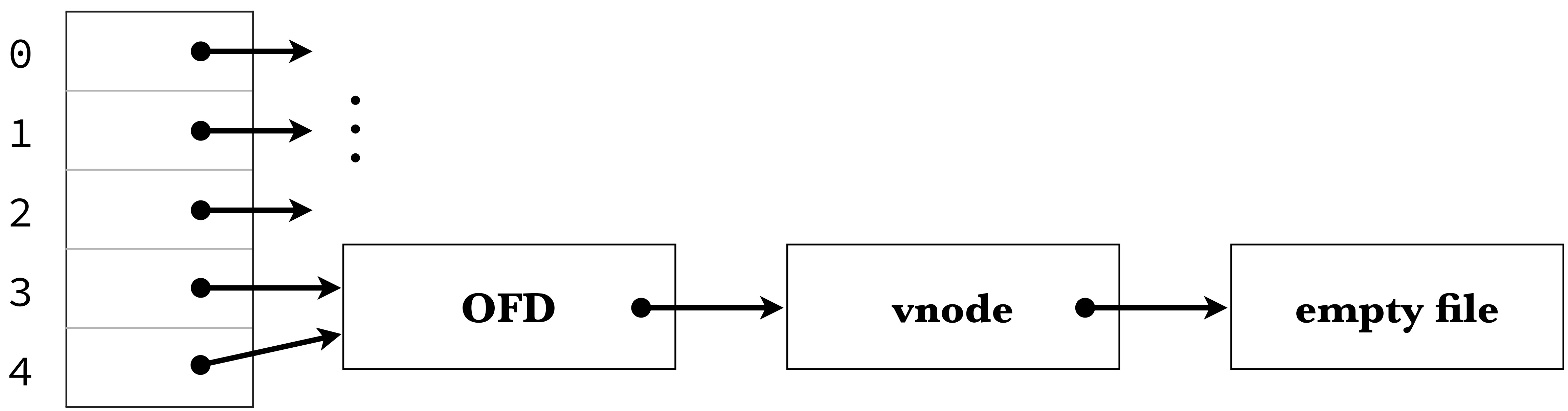
```
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = open("foo.txt", O_RDONLY);
close(fd1);
```



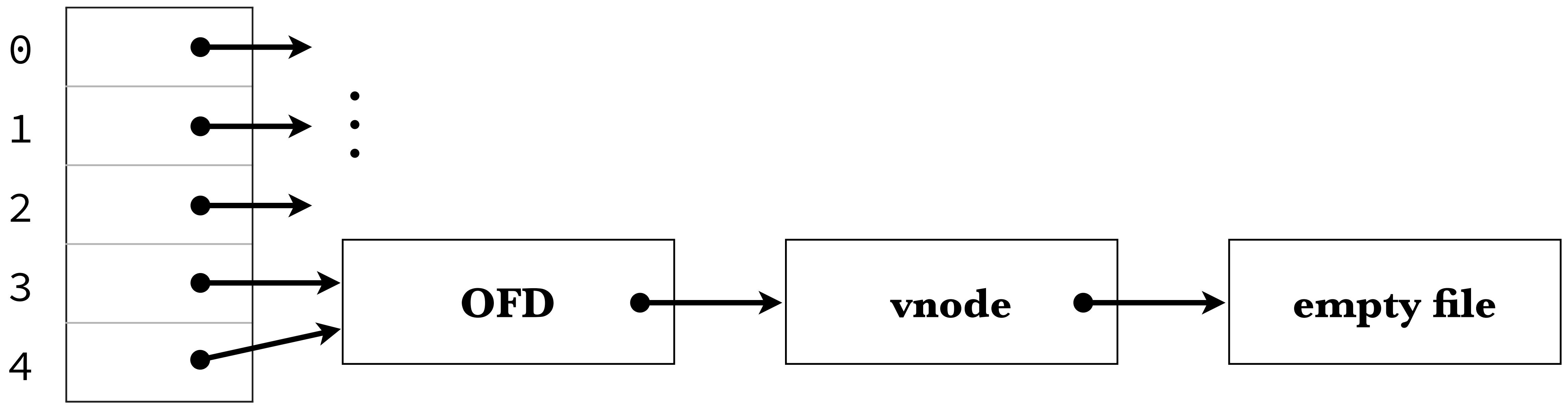
```
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = open("foo.txt", O_RDONLY);
close(fd1);
close(fd2);
```



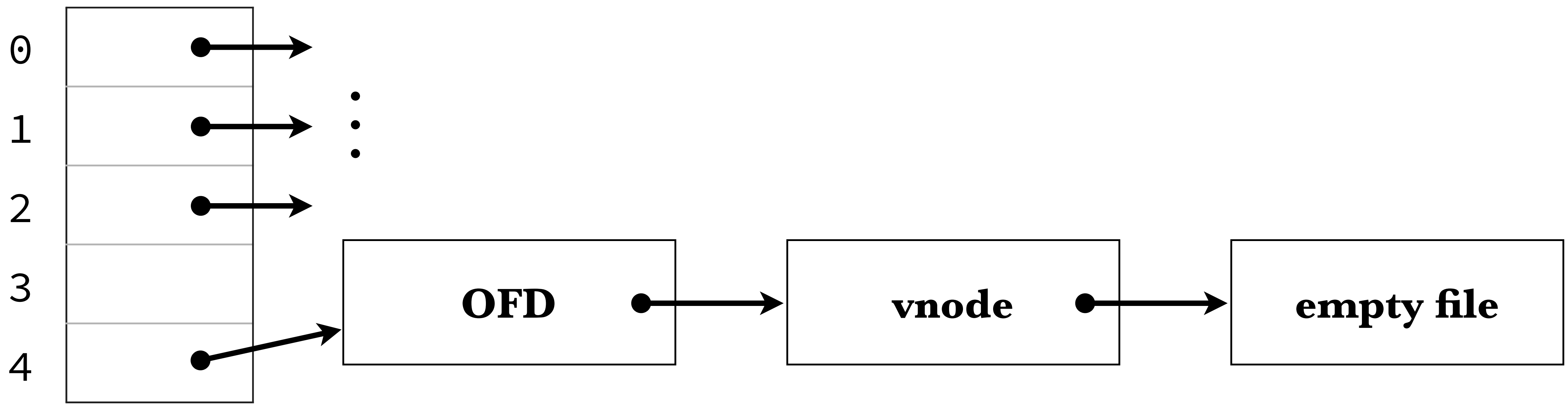
```
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = dup(fd1);
```



```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = dup(fd1);
close(fd1);
```



```c
int fd1 = open("foo.txt", O_CREAT | O_TRUNC | O_RDWR, 0644);
int fd2 = dup(fd1);
close(fd1);
close(fd2);
```



application: *input/output* ***redirection***

- leverage FD usage conventions
- `0` = *stdin*, `1` = *stdout*, `2` = *stderr*
  - recall: FD says nothing about the actual file/device it refers to!

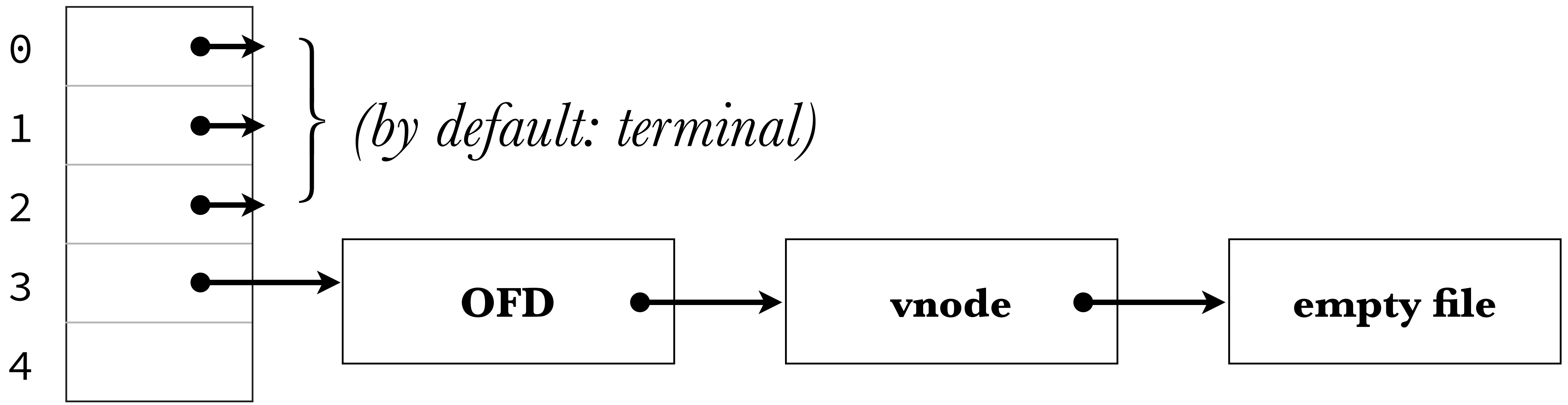
Demo:

Shell I/O redirection

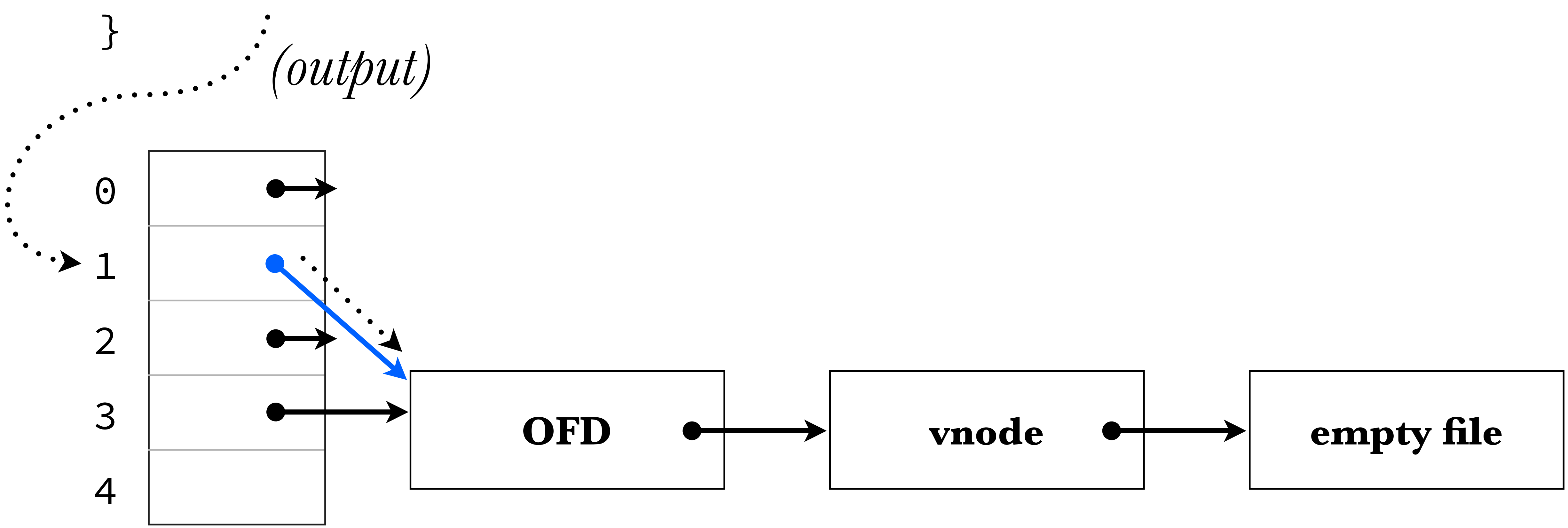
```c
int main(int argc, char *argv[]) {
    int fd = open("foo.txt", O_CREAT|O_TRUNC|O_RDWR, 0644);
    dup2(fd, 1);
    printf("Arg: %s\n", argv[1]);
}
```

```
$ ./a.out hello!
$ ls -l foo.txt
-rw-r--r-- 1 lee staff 12 Feb 19 20:36 foo.txt
$ cat foo.txt
Arg: hello!
```

```c
int main(int argc, char *argv[]) {
    int fd = open("foo.txt", O_CREAT|O_TRUNC|O_RDWR, 0644);
    dup2(fd, 1);
    printf("Arg: %s\n", argv[1]); /* printf prints to stdout */
}
```



```c
int main(int argc, char *argv[]) {
    int fd = open("foo.txt", O_CREAT|O_TRUNC|O_RDWR, 0644);
    dup2(fd, 1);
    printf("Arg: %s\n", argv[1]); /* printf prints to stdout */
}
```



```
int main() {
    int fd = open("foo.txt", O_CREAT|O_TRUNC|O_RDWR, 0644);
    if (fork() == 0) {
        dup2(fd, 1);
        execlp("echo", "echo", "hello!", NULL);
    }
    close(fd);
}
```

```
$ ./a.out
$ cat foo.txt
hello!
```

```
int main() {
    int fd = open("foo.txt", O_CREAT|O_TRUNC|O_RDWR, 0644);
    if (fork() == 0) {
        dup2(fd, 1);
        execlp("echo", "echo", "hello!", NULL);
    }
    close(fd);
}
```

illustrates a powerful technique that requires separating `fork` & `exec`

- original program sets up *new process environment* before `exec`-ing

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

- reads up to `nbytes` bytes *from* open file at `fd` *into* `buf`
  - by default, *block* for at least 1 byte
- returns # bytes read (or `-1` for error)

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

- writes up to `nbytes` bytes *into* open file at `fd` *from* `buf`
  - by default, *block* for at least 1 byte
- returns # bytes written (or `-1` for error)

“up to `nbytes` bytes”

i.e., *short counts* can occur

— process asks OS to write k bytes, but only $l < k$ bytes are actually written why?

reads:

- EOF, unreadable FD, “slow” file, interrupt, etc.

writes:

- out of space, unwritable FD, “slow” file, interrupt, etc.

`read`/`write` are the lowest level I/O calls

— kernel objective is to support *maximum performance* & *minimum latency* e.g., if reading from slow network, return to process asap and allow it to decide to read again or do something else

(but usually, short counts are a royal pain)

```
ssize_t robust_read(int fd, void *buf, size_t n) {
    size_t  nleft = n;
    ssize_t nread;
    char *p = buf;

    while (nleft > 0) {
        if ((nread = read(fd, p, nleft)) < 0)
            return -1; /* error in read */
        else if (nread == 0)
            break;     /* read returns 0 on EOF */
        nleft -= nread;
        p += nread;
    }

    return (n - nleft);
}
```

(yuck)

good news: short counts only occur on EOF for reads on regular files but there’s another concern…

```c
char buf[10];
int fd, x, y, z;

fd = open("data.txt", O_RDONLY);

read(fd, buf, 2);  buf[2] = 0;
x = atoi(buf);

read(fd, buf, 2);  buf[2] = 0;
y = atoi(buf);

read(fd, buf, 2);  buf[2] = 0;
z = atoi(buf);

printf("%d %d %d", x, y, z);
```

data.txt

```
102030
```

```
10 20 30
```

```c
char buf[10];
int fd, x, y, z;

fd = open("data.txt", O_RDONLY);

read(fd, buf, 2);  buf[2] = 0;
x = atoi(buf);

read(fd, buf, 2);  buf[2] = 0;
y = atoi(buf);

read(fd, buf, 2);  buf[2] = 0;
z = atoi(buf);

printf("%d %d %d", x, y, z);
```

data.txt

```
102030
```

one syscall per integer read = **inefficient**!!!

```c
fd = open("data.txt", O_RDONLY);

read(fd, buf, 2);  buf[2] = 0;
x = atoi(buf);

read(fd, buf, 2);  buf[2] = 0;
y = atoi(buf);

read(fd, buf, 2);  buf[2] = 0;
z = atoi(buf);

printf("%d %d %d", x, y, z);
```

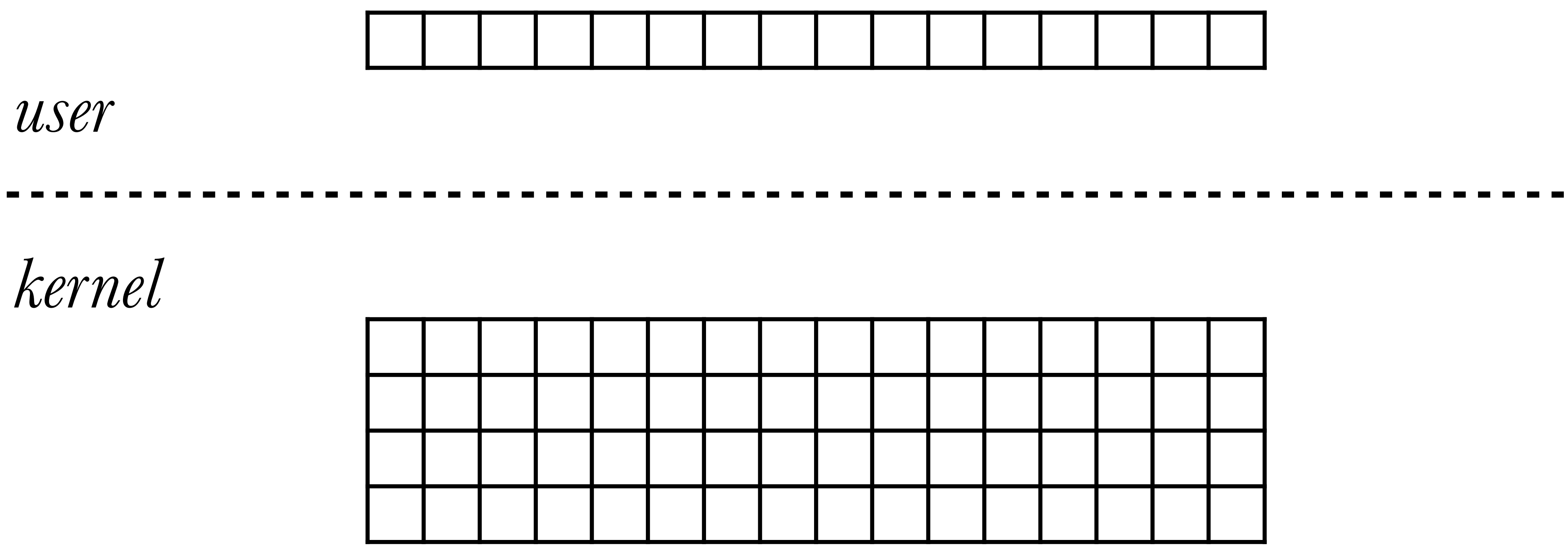
data.txt

```
102030
```

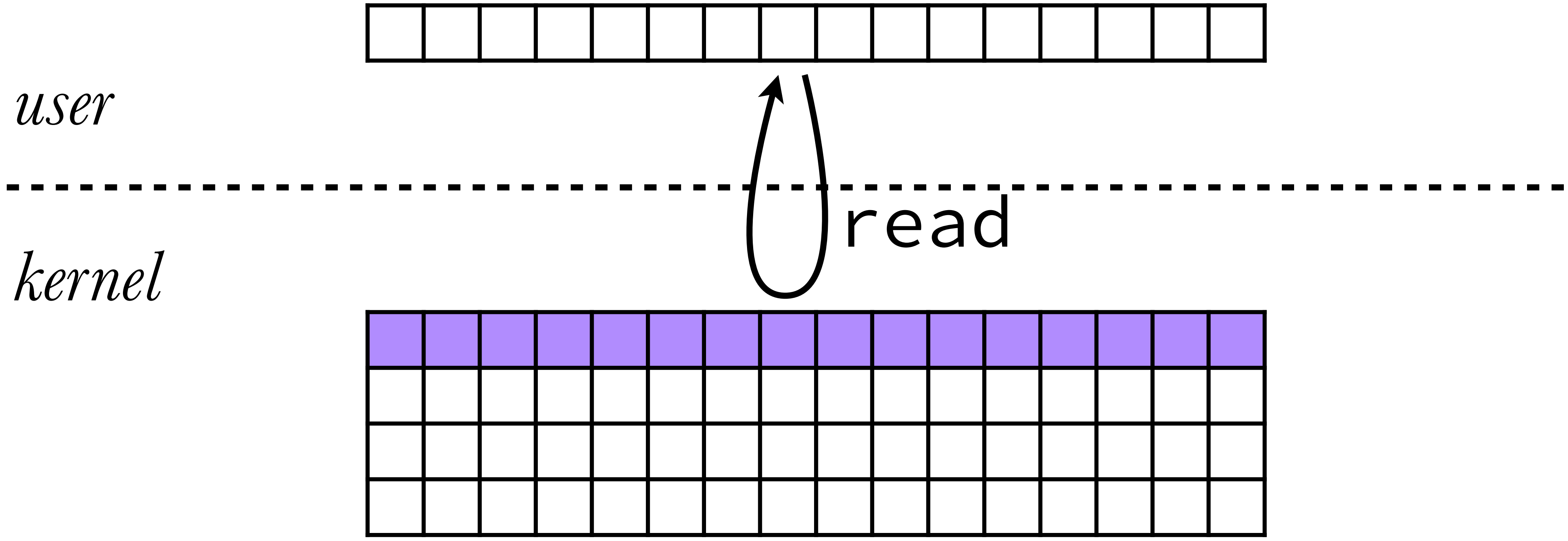
```
$ strace ./a.out
execve("./a.out", ["./a.out"], [/* 67 vars */]) = 0
...
open("data.txt", O_RDONLY)                = 3
read(3, "10", 2)                          = 2
read(3, "20", 2)                          = 2
read(3, "30", 2)                          = 2
write(1, "10 20 30", 8)                   = 8
...
```

solution: *buffering*

step 1: read more bytes than we need into a separate *backing buffer*



step 1: read more bytes than we need into a separate *backing buffer*

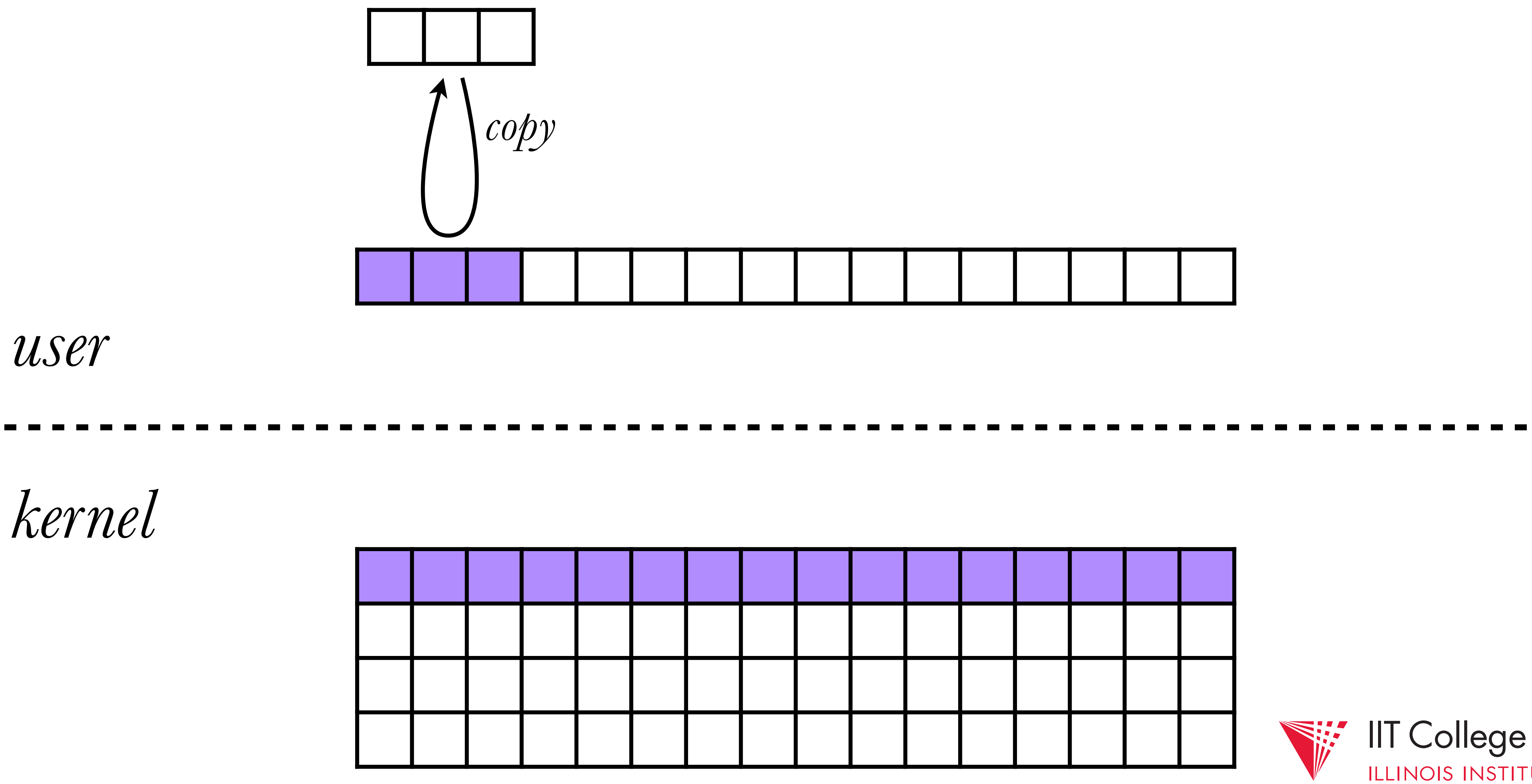


```
char buf[10], bbuf[80];
int fd, x, y, z;

fd = open("data.txt", O_RDONLY);
read(fd, bbuf, sizeof(bbuf));
```

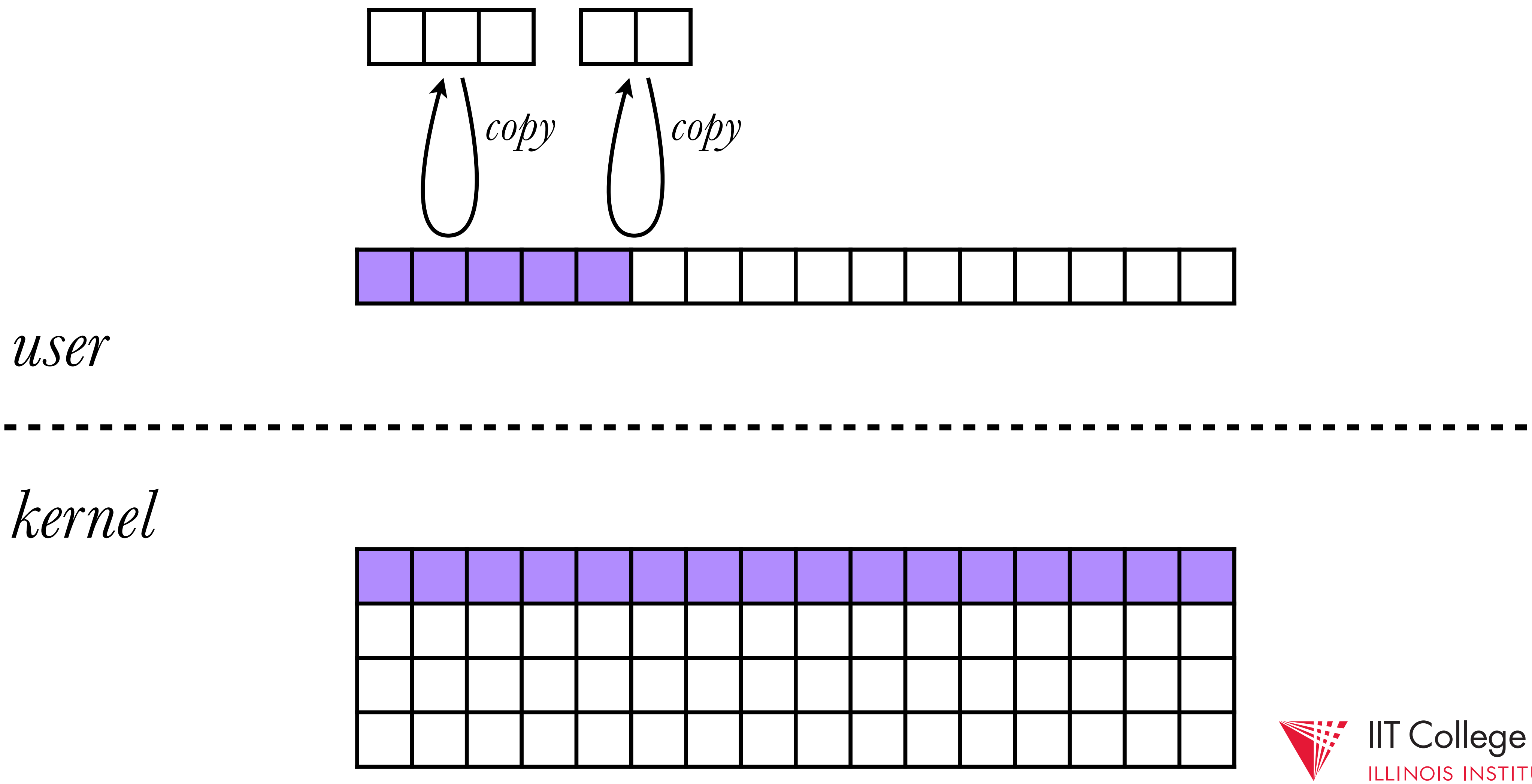
data.txt

```
102030
```

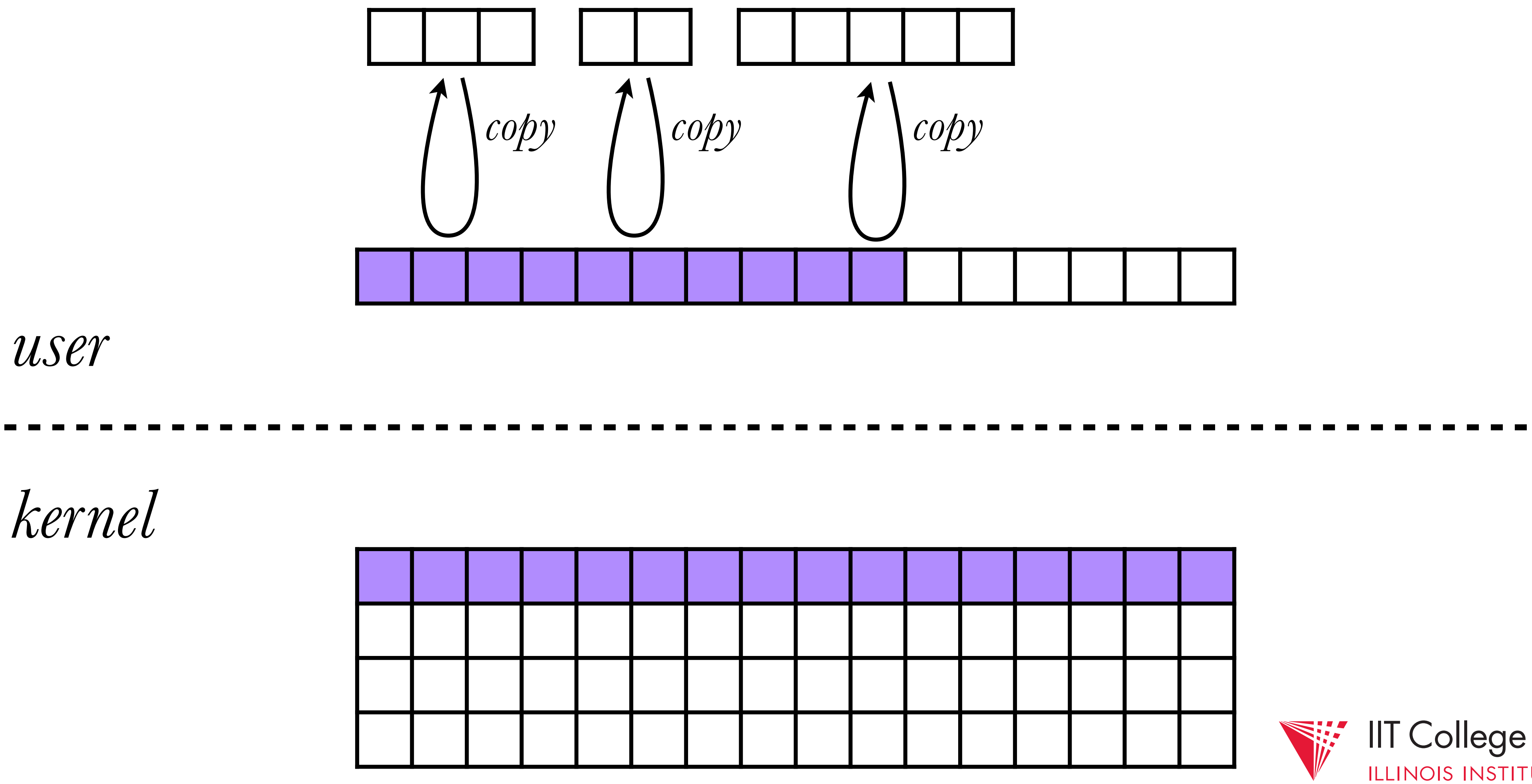
step 2: avoid syscalls and process future "reads" from that buffer



step 2: avoid syscalls and process future "reads" from that buffer



step 2: avoid syscalls and process future "reads" from that buffer



```c
char buf[10], bbuf[80];
int fd, x, y, z;

fd = open("data.txt", O_RDONLY);
read(fd, bbuf, sizeof(bbuf));

buf[2] = 0;
memcpy(buf, bbuf, 2);
x = atoi(buf);
```

data.txt

```
102030
```

```
char buf[10], bbuf[80];
int fd, x, y, z;

fd = open("data.txt", O_RDONLY);
read(fd, bbuf, sizeof(bbuf));

buf[2] = 0;
memcpy(buf, bbuf, 2);
x = atoi(buf);

memcpy(buf, bbuf+2, 2);
y = atoi(buf);
```

data.txt

```
102030
```

```c
char buf[10], bbuf[80];
int fd, x, y, z;

fd = open("data.txt", O_RDONLY);
read(fd, bbuf, sizeof(bbuf));

buf[2] = 0;
memcpy(buf, bbuf, 2);
x = atoi(buf);

memcpy(buf, bbuf+2, 2);
y = atoi(buf);

memcpy(buf, bbuf+4, 2);
z = atoi(buf);
```

data.txt

```
102030
```

```
fd = open("data.txt", O_RDONLY);
read(fd, bbuf, sizeof(bbuf));

buf[2] = 0;
memcpy(buf, bbuf, 2);
x = atoi(buf);

memcpy(buf, bbuf+2, 2);
y = atoi(buf);

memcpy(buf, bbuf+4, 2);
z = atoi(buf);
```

data.txt

```
102030
```

```
$ strace ./a.out
execve("./a.out", ["./a.out"], [/* 67 vars */]) = 0
...
open("data.txt", O_RDONLY)                   = 3
read(3, "102030\n", 80)                      = 7
write(1, "10 20 30", 8)                      = 8
...
```

to generalize, bundle together:

(1) FD

(2) backing buffer

(3) num unused bytes

(4) pointer to next byte

```c
typedef struct {
    int  fd;          /* (1) wrapped FD              */
    char buf[100];    /* (2) backing buffer          */
    int  count;       /* (3) num unused bytes        */
    char *nextp;      /* (4) pointer to next byte */
} bufio_t;


void bufio_init(bufio_t *bp, int fd) {
    bp->fd    = fd;
    bp->count = 0;
    bp->nextp = bp->buf;
}
```

```c
ssize_t bufio_read(bufio_t *bp, char *buf, size_t n) {
    int ncpy;

    /* fill backing buffer if empty */
    if (bp->count <= 0) {
        bp->count = read(bp->fd, bp->buf, sizeof(bp->buf));
        if (bp->count <= 0)
            return bp->count;     /* EOF or read error */
        else
            bp->nextp = bp->buf; /* re-init buf position */
    }

    /* copy from backing buffer to user buffer */
    ncpy = (bp->count < n)? bp->count : n;
    memcpy(buf, bp->nextp, ncpy);
    bp->nextp += ncpy;
    bp->count -= ncpy;

    return ncpy;
}
```

```c
char buf[10];
int fd, x, y, z;
bufio_t bbuf;

fd = open("data.txt", O_RDONLY);
bufio_init(&bbuf, fd);

buf[2] = 0;
bufio_read(&bbuf, buf, 2);
x = atoi(buf);

bufio_read(&bbuf, buf, 2);
y = atoi(buf);

bufio_read(&bbuf, buf, 2);
z = atoi(buf);
```

data.txt

```
102030
```

`open` is now a distraction… we never use the FD directly (except to initialize buffer) next step: hide syscalls from user — wrap `open` together with buffer initialization

```c
bufio_t *buf_open(const char *path) {
    bufio_t *buf = malloc(sizeof(bufio_t));
    int fd = open(path, O_RDWR);
    bufio_init(buf, fd);
    return buf;
}

int main() {
    bufio_t *bbuf = buf_open("data.txt");
    char buf[10];
    int x, y, z;

    bufio_read(bbuf, buf, 2);
    ...
}
```

Stop!

`<stdio.h>` does all this for us!

fclose fdopen feof ferror
fflush fgetc fgetln fgetpos
fgets **fopen** **fprintf** fputc fputs
fread freopen **fscanf** fseek
fsetpos **fwrite** getc mktemp
perror **printf** putc putchar puts
remove **rewind** **scanf** sprintf
sscanf strerror tmpfile ungetc
vfprintf vprintf vscanf ...

… all use buffered I/O

stdio functions operate on *stream* objects

i.e., buffered wrappers on FDs

```
FILE*  fopen   ( const char *filename, const char *mode );
FILE*  fdopen  ( int fd, const char *mode );
  int  fclose  ( FILE *stream );
  int  fseek   ( FILE *stream, long offset, int whence );
size_t fread   ( void *ptr, size_t size, size_t nitems, FILE *stream );
size_t fwrite  ( void *ptr, size_t size, size_t nitems, FILE *stream );

  int  fprintf ( FILE *stream, const char *format, ... );
  int  fscanf  ( FILE *stream, const char *format, ... );
char*  fgets   ( char *str, int size, FILE *stream );
```

```c
int x, y, z;
FILE *infile = fopen("data.txt", "r");

fscanf(infile, "%2d", &x);
fscanf(infile, "%2d", &y);
fscanf(infile, "%2d", &z);

printf("%d %d %d", x, y, z);

fclose(infile); /* or memory leak! */
```

```
$ strace ./a.out
execve("./a.out", ["./a.out"], [/* 67 vars */]) = 0
...
open("data.txt", O_RDONLY)                     = 3
read(3, "102030\n", 4096)                      = 7
write(1, "10 20 30", 8)                        = 8
close(3)                                       = 0
...
```

```c
printf("h");
printf("e");
printf("l");
printf("l");
printf("o");
```

```
$ strace ./a.out
...
write(1, "hello", 5)                         = 5
...
```

(writes are buffered too!)

stream buffer can *absorb* multiple writes before being flushed to underlying file flush happens on:

- buffer being filled
- (normal) process termination
- newline, in a line-buffered stream
- explicitly, with `fflush`

```c
int main() {
    printf("h");
    printf("e");
    printf("l");
    printf("l");
    printf("o");
    fork();
}
```

```
$ ./a.out
hellohello
```

@#$%^&*!!!

```c
int n, fd = open("fox.txt", O_RDONLY);
char buf[10];

n = read(fd, buf, sizeof(buf));
write(1, buf, n);
if (fork() == 0) {
    n = read(fd, buf, sizeof(buf));
    write(1, buf, n);
    exit(0);
}
wait(NULL);
n = read(fd, buf, sizeof(buf));
write(1, buf, n);
```

fox.txt

```
the quick brown
fox jumps over
the lazy dog
```

```
$ ./a.out
The quick brown fox jumps over
```

```c
int n;
FILE *stream = fopen("fox.txt", "r");
char buf[10];

n = fread(buf, 1, sizeof(buf), stream);
write(1, buf, n);
if (fork() == 0) {
    n = fread(buf, 1, sizeof(buf), stream);
    write(1, buf, n);
    exit(0);
}
wait(NULL);
n = fread(buf, 1, sizeof(buf), stream);
write(1, buf, n);
```

fox.txt

```
the quick brown
fox jumps over
the lazy dog
```

```
$ ./a.out
The quick brown fox brown fox
```

@#$%^&*!!!

things gets even more confusing when we perform *both* input & output

```
int fd = open("fox.txt", O_RDWR);
char buf[10];

/* output followed by input */
write(fd, "a playful ", 10);
read(fd, buf, sizeof(buf));

write(1, buf, sizeof(buf));
```

fox.txt

```
a playful brown
fox jumps over
the lazy dog
```

```
$ ./a.out
brown fox
```

```c
int fd = open("fox.txt", O_RDWR);
FILE *stream = fdopen(fd, "r+");
char buf[10];

/* output followed by input */
fwrite("a playful ", 1, 10, stream);
read(fd, buf, sizeof(buf));

write(1, buf, sizeof(buf));
```

fox.txt

```
the quick a
playful jumps
over the lazy
dog
```

```
$ ./a.out
the quick
```

@#$%^&*!!!

```c
int fd = open("fox.txt", O_RDWR);
char buf[10];

/* input followed by output */
read(fd, buf, sizeof(buf));
write(fd, "green cat ", 10);

write(1, buf, sizeof(buf));
```

fox.txt

```
the quick green
cat jumps over
the lazy dog
```

```
$ ./a.out
the quick
```

```
FILE *stream = fopen("fox.txt", "r+");
char buf[10];

/* input followed by output */
fread(buf, 1, sizeof(buf), stream);
fwrite("green cat ", 1, 10, stream);

write(1, buf, sizeof(buf));
```

fox.txt

```
the quick brown
fox jumps over
the lazy dog
green cat
```

```
$ ./a.out
the quick
```

@#$%^&*!!!

When a file is opened with update mode ..., both input and output may be performed on the associated stream. However, output shall not be directly followed by input without an intervening call to the **`fflush`** function or to a file positioning function ..., and input shall not be directly followed by output without an intervening call to a file positioning function, unless the input operation encounters end- of-file.

ISO C99 standard, 7.19.5.3 (par 6)

input shall not be directly followed by output without an intervening call to a file positioning function

but not all files support "file positioning functions"! (e.g., no seeks on *character devices*) lessons:

- buffered stdio functions help minimize system overhead & simplify I/O
- use whenever possible!

lessons:

- but need to beware of glitches
- don't mix buffered & unbuffered I/O
- and not appropriate for some devices (e.g., network)
  - use low-level, robust I/O for these