System Programming: File Management

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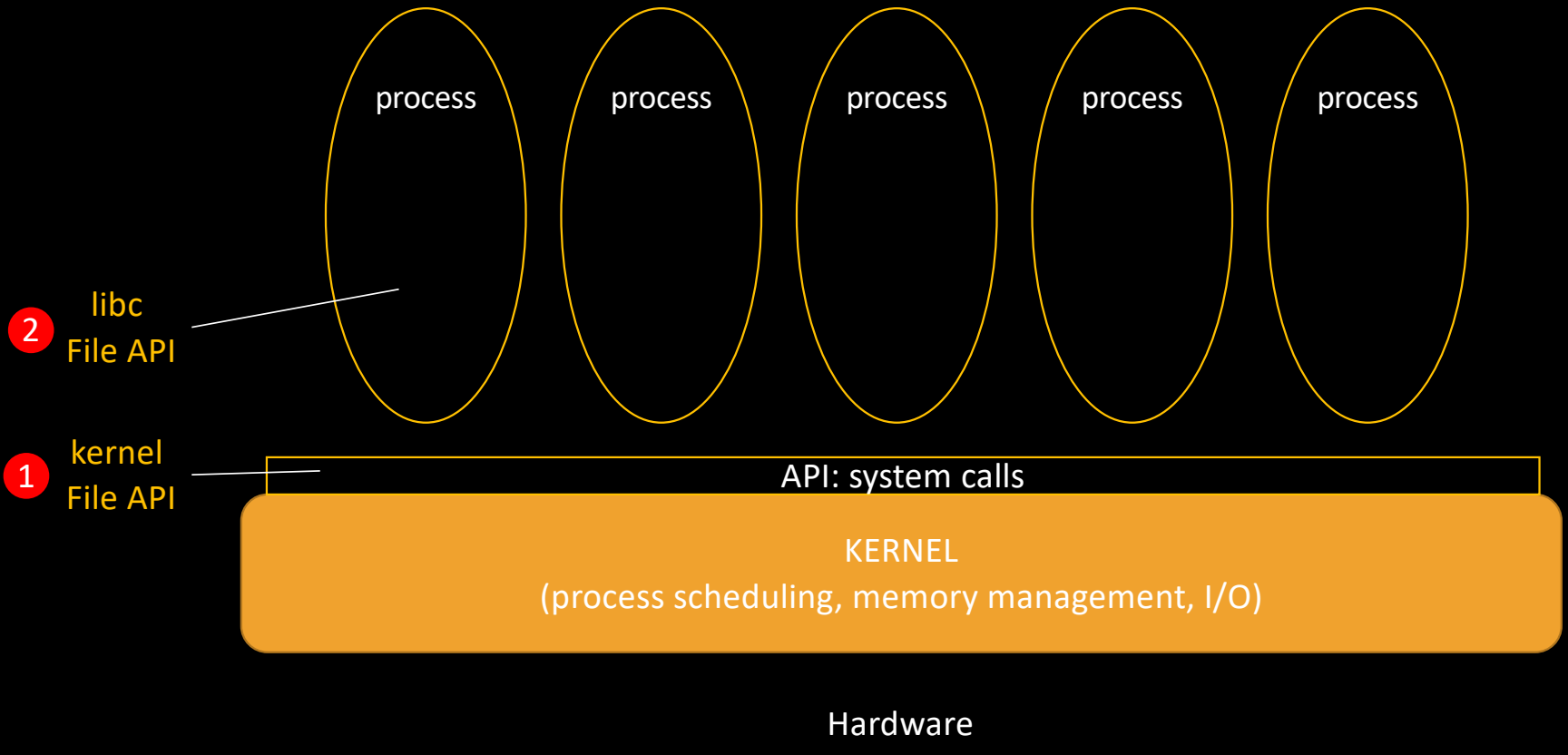
https://gforgeron.gitlab.io/progsys/

The concept of File

- A central concept in Unix
  - "*All is File*" philosophy
    - Regular disk files, but also
      - Terminal
      - Devices (mouse, keyboard)
      - Network sockets
      - Etc.

- User view of a Disk File
  - Contiguous series of bytes
  - Known length, but may expand/shrink dynamically
  - Access rights (`rwx`)
  - Can be referenced by multiple links (paths)

Two File Management APIs



The concept of File

- Before we can read from/write into a file, we must *open* it
  - Why can't we just read directly ?
    - read ("/net/cremi/dupont/myfile.txt", buffer1, …)
    - read ("/net/cremi/dupont/myfile.txt", buffer2, …)
    - …

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    - …
  - Partly for efficiency reasons
    - To access file "/net/cremi/dupont/myfile.txt", the OS must check
      - That there is a "net" entry in the "/" directory
      - That "/net" is a directory and that the user can traverse it (x)
      - That there is a "cremi" entry in the "/net" directory
      - That "/net/cremi" is a directory and that the user can traverse it (x)
      - …
      - That "/net/cremi/dupont/myfile.txt" is a file and that the user can read it (r)

Opening Files

- Before we can read from/write into a file, we must *open* it

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

  - Open performs the appropriate checks, and returns a *file descriptor*
    - This file descriptor is a *key* which will
      - Accelerate upcoming read/write operations
      - Maintain the “current position” in the file

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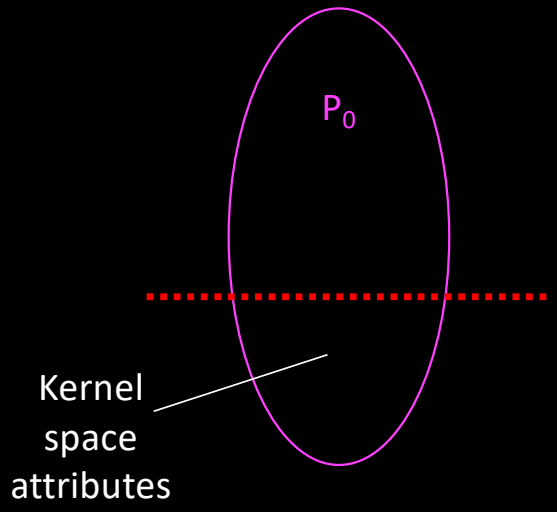
      - Maintain the "current position" in the file
  - `oflag`:
    - `O_RDONLY, O_WRONLY or O_RDWR`
    - Optionally combined with: `O_CREAT, O_TRUNC, O_SYNC`, etc.
  - When a file is created, the third parameter sets access rights (octal notation)
    - 0750 = 111 101 000 = `rwxr-x---`
    - 0666 = 110 110 110 = `rw-rw-rw-`

Opening Files

- See ouverture.c…

Side note about process representation

Processes can be represented this way:



Side note about process representation

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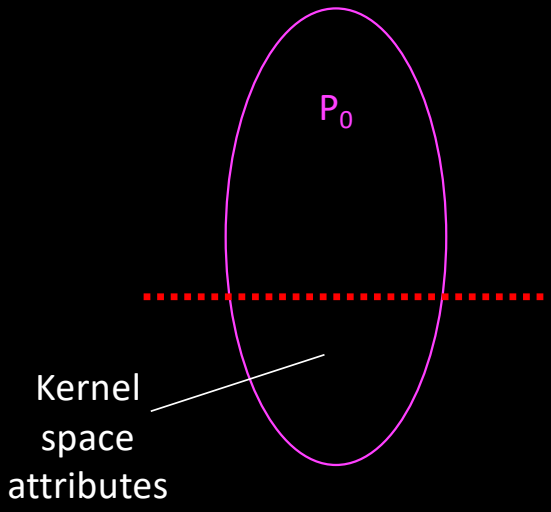
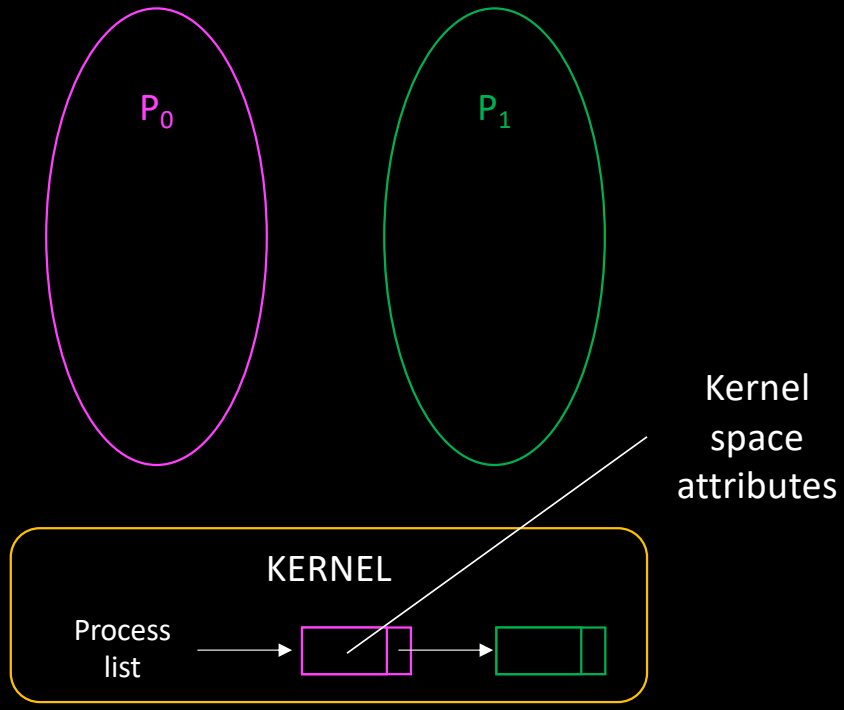
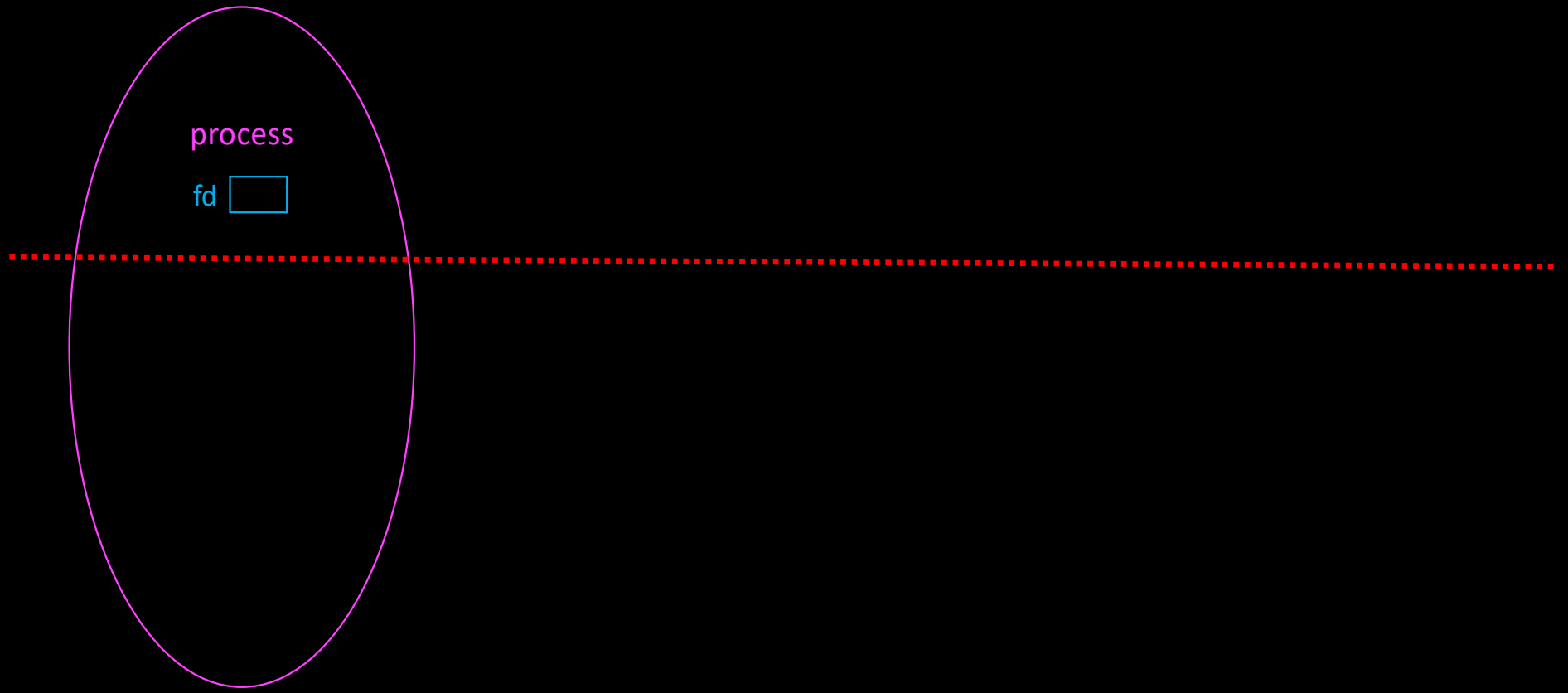


But reality is (obviously) more like:



fd = open (“file.txt”, O_RDONLY);



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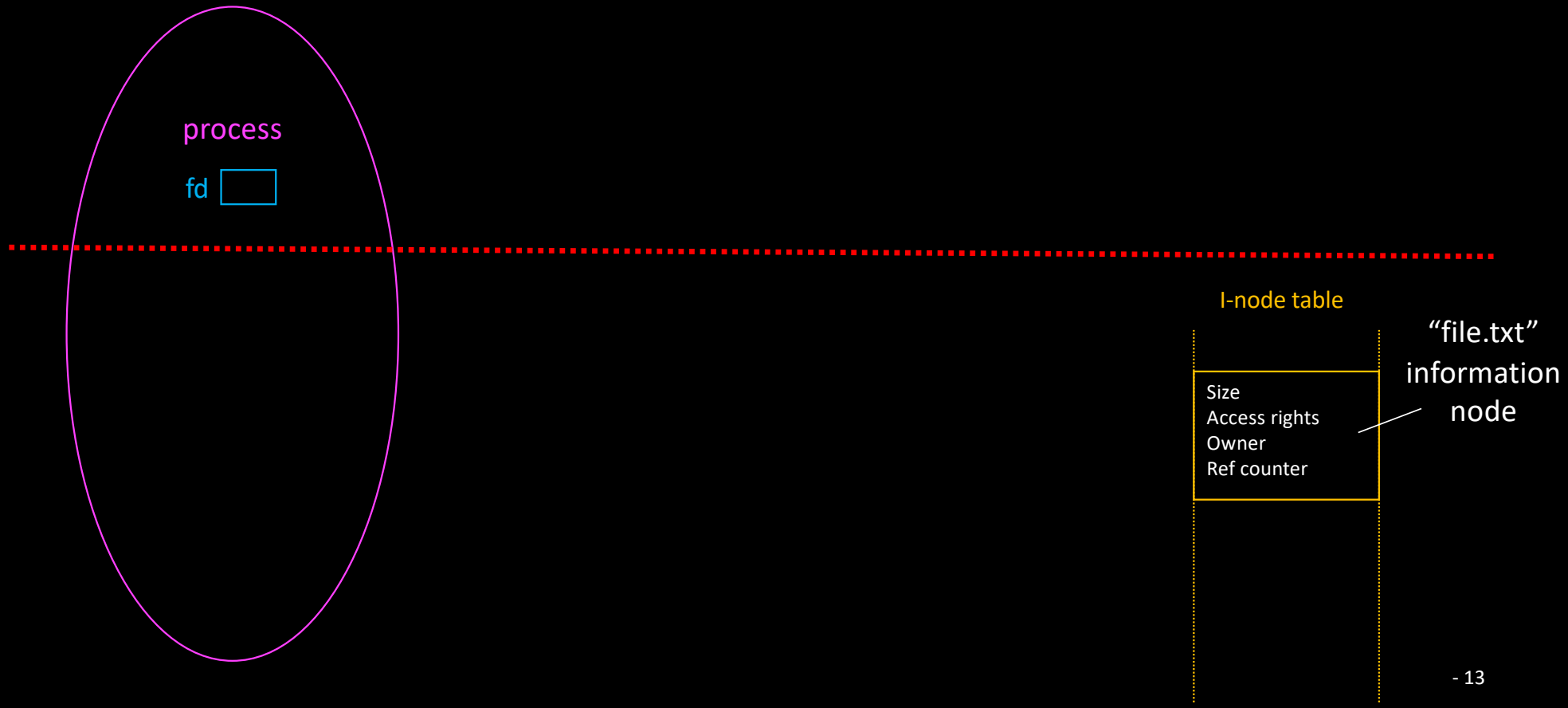

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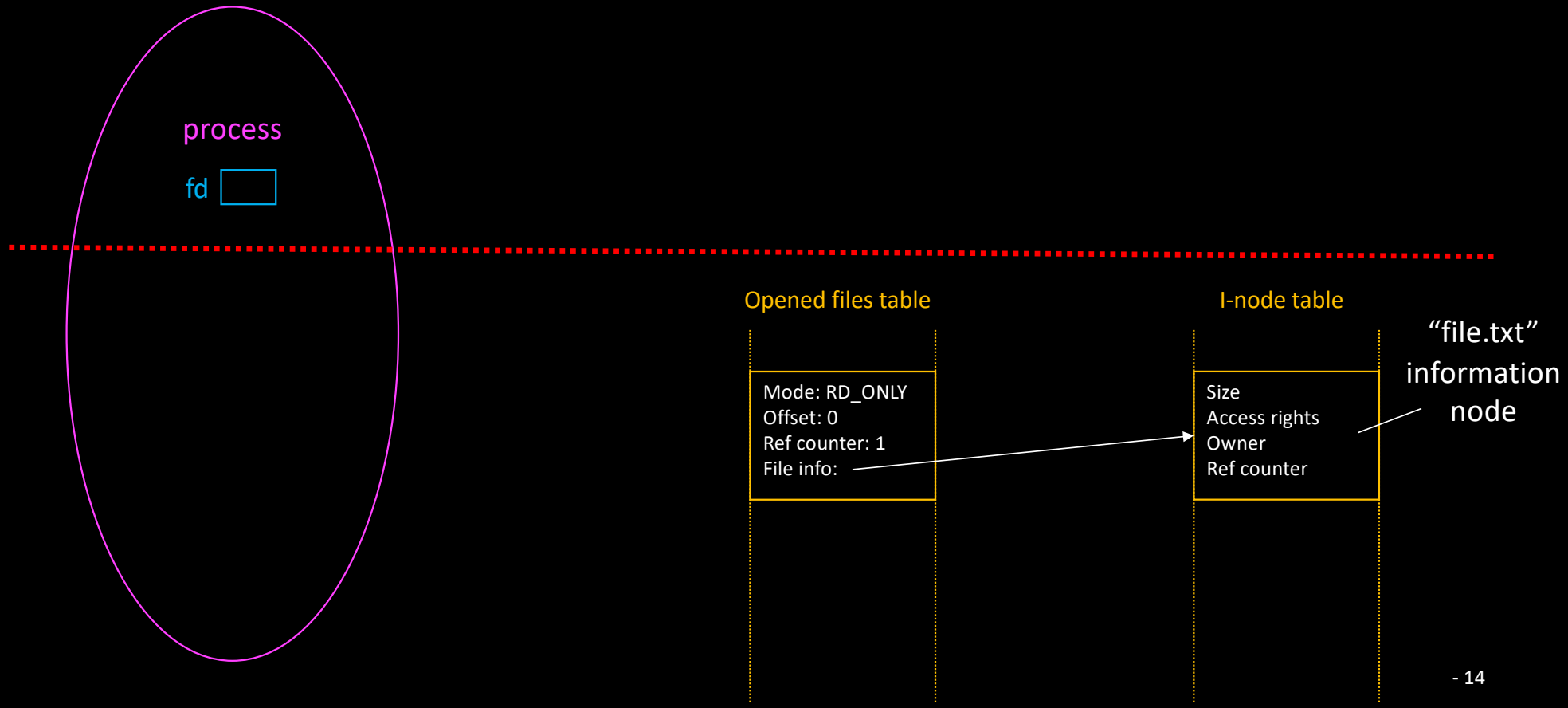

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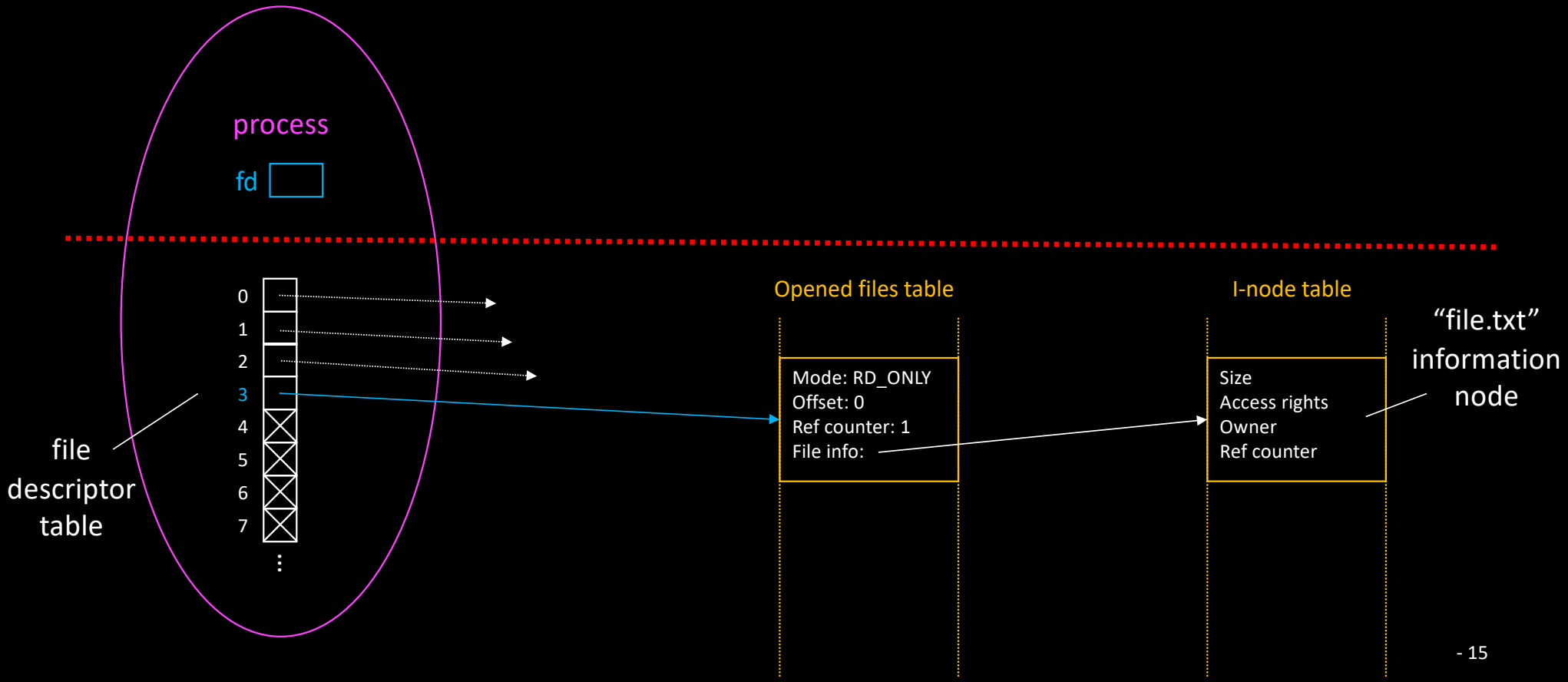
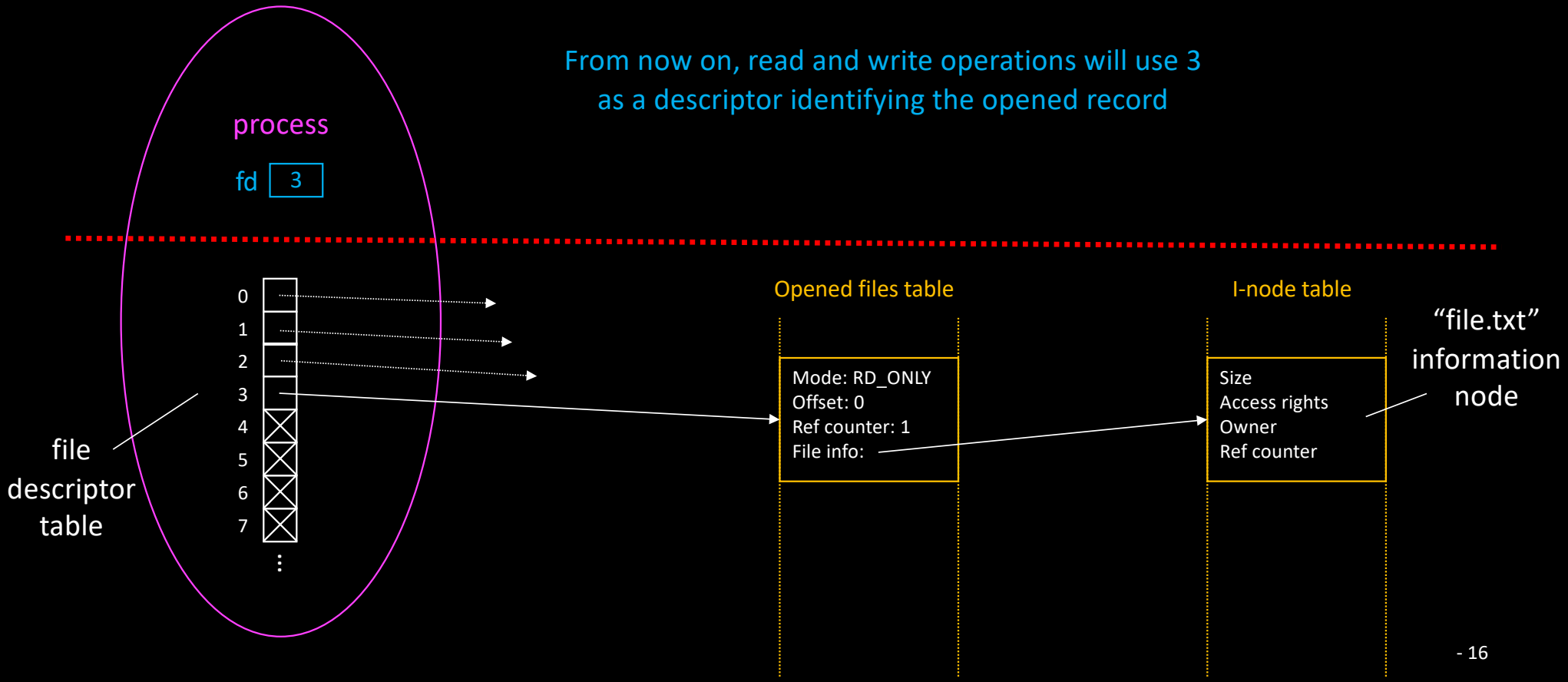


fd = open ("file.txt", O_RDONLY);

From now on, read and write operations will use 3 as a descriptor identifying the opened record



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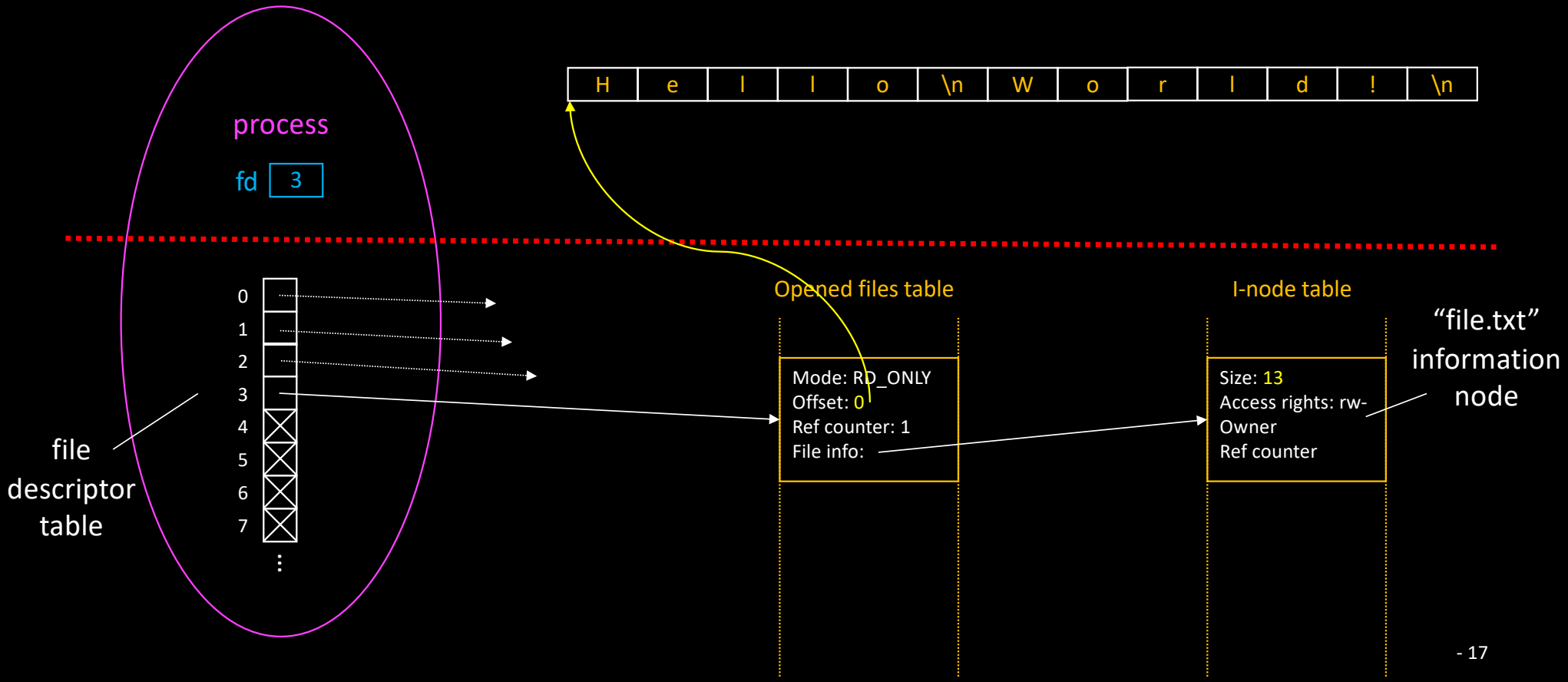
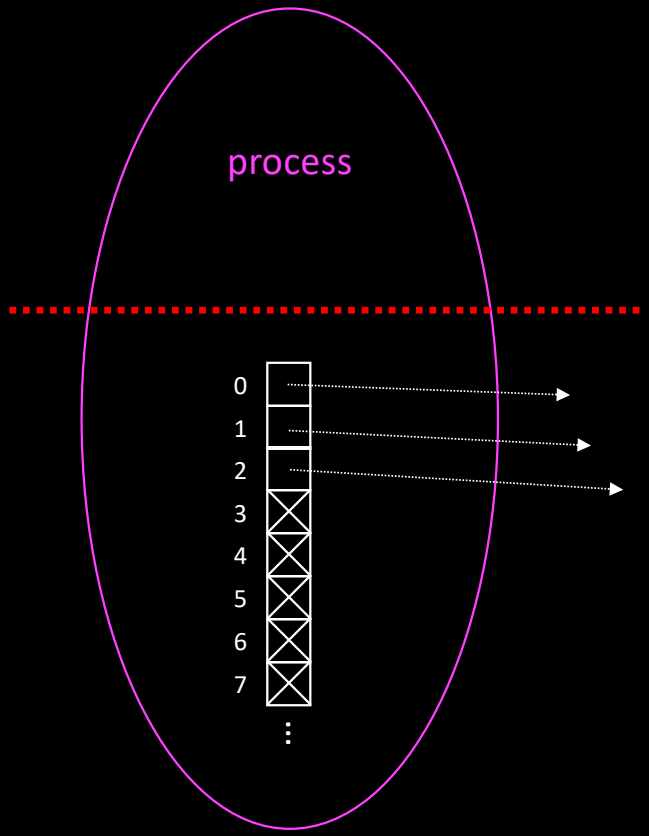
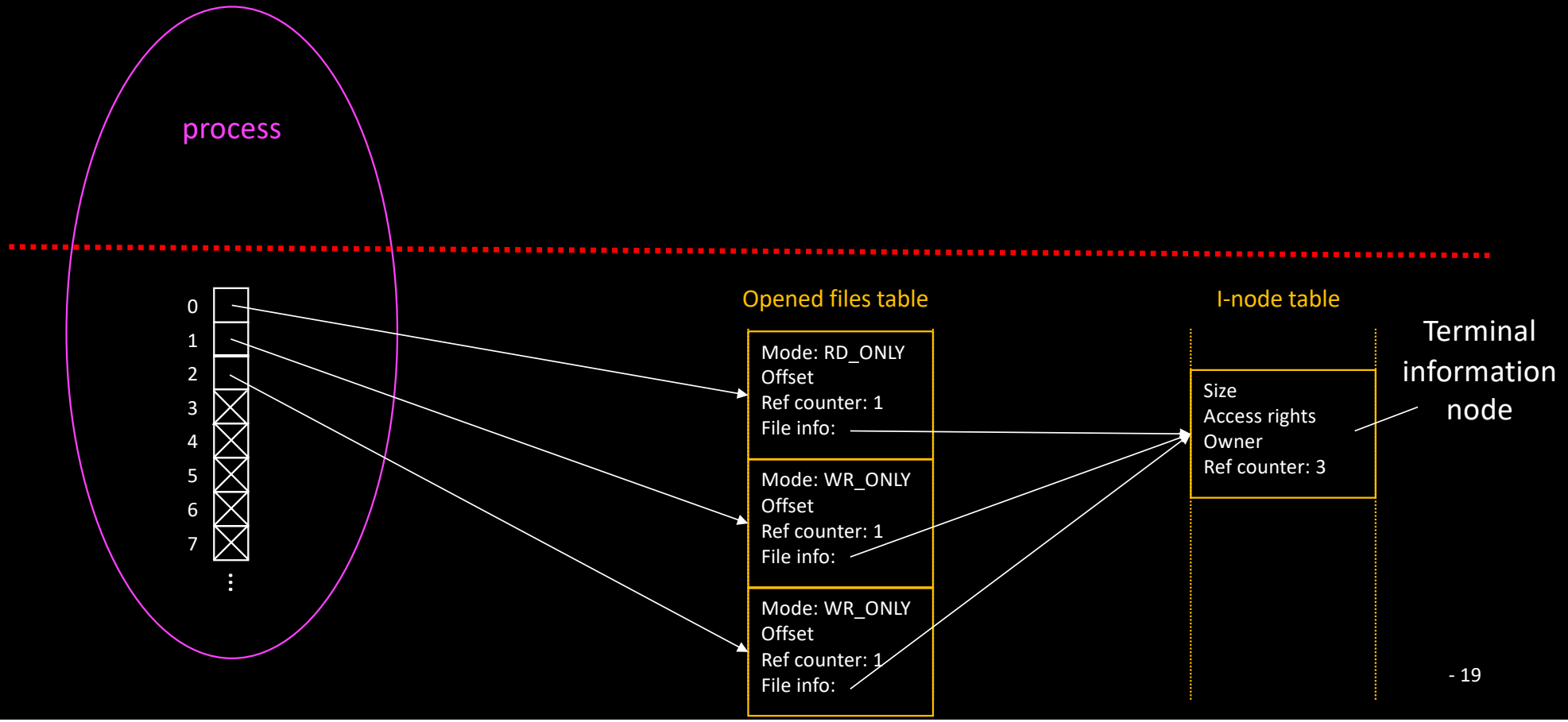


Pre-opened descriptors



- Standard input/output
  - E.g. Terminal
    - `0: STDIN_FILENO`
    - `1: STDOUT_FILENO`
    - `2: STDERR_FILENO`

Pre-opened descriptors



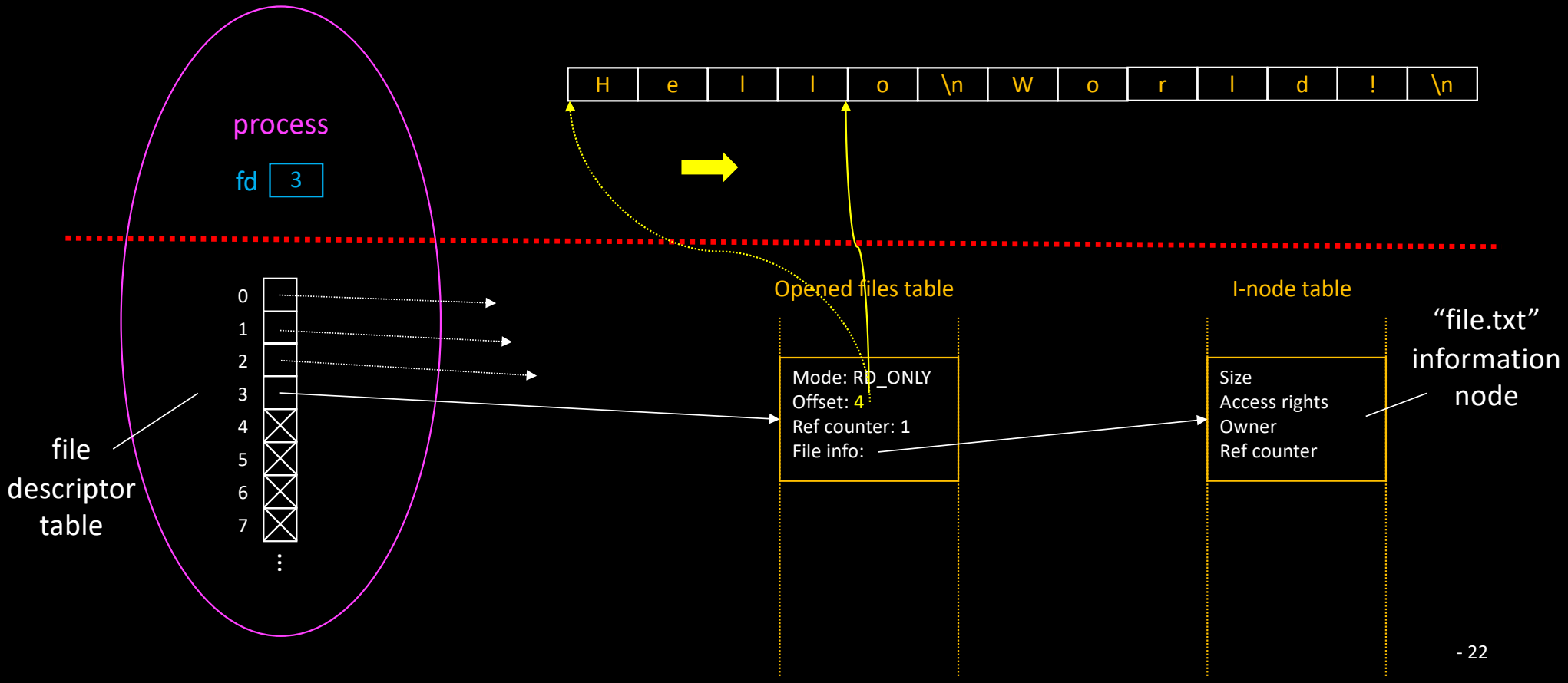
Reading from a File

- Reading from the file and writing to process memory

```
ssize_t read(int fildes, void *buf, size_t nbyte);
```

  - Return value:
    - -1 if error
    - Number of bytes read (and copied to buf)
      - If zero, then we have reached the End Of File

read (fd, buffer, 4)



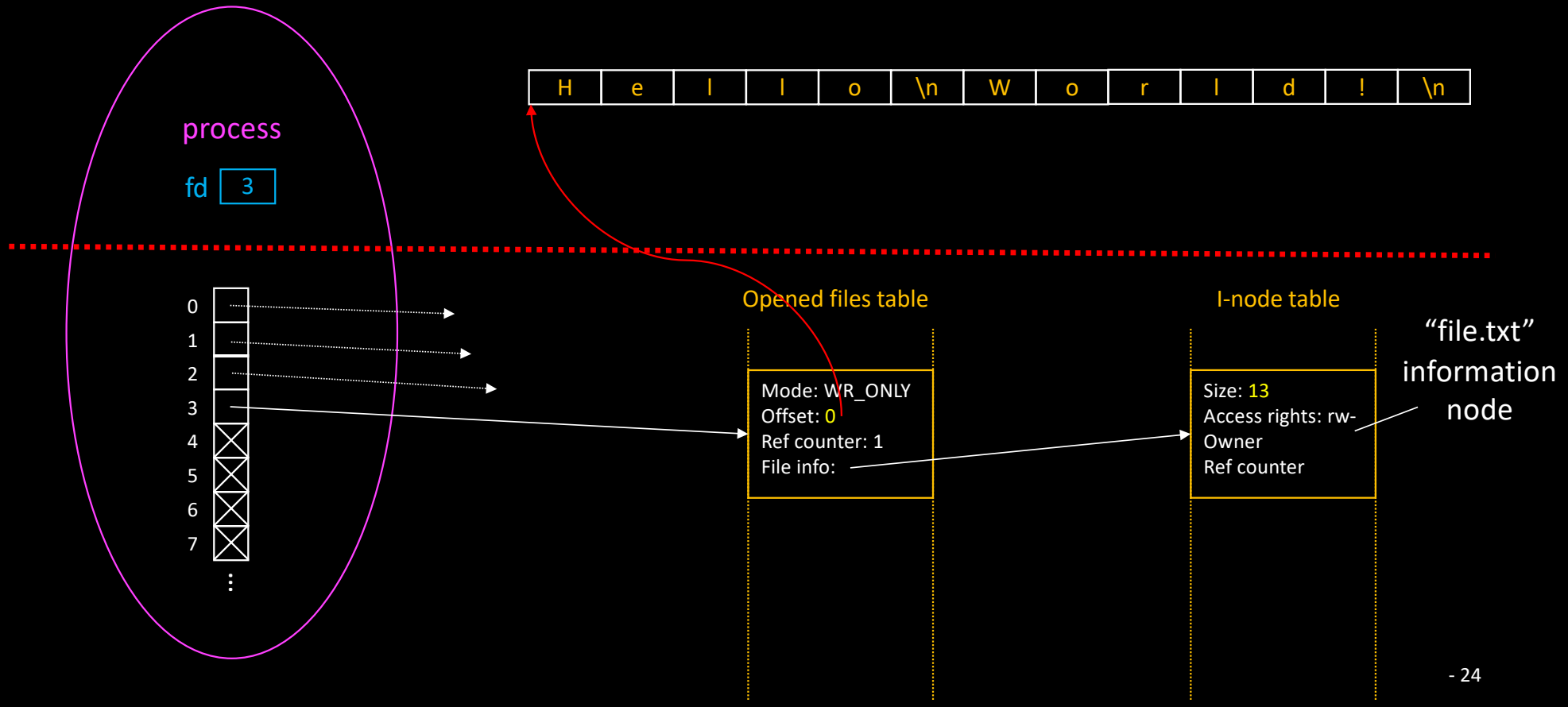
Writing into a File

- Reading from memory and writing to the file

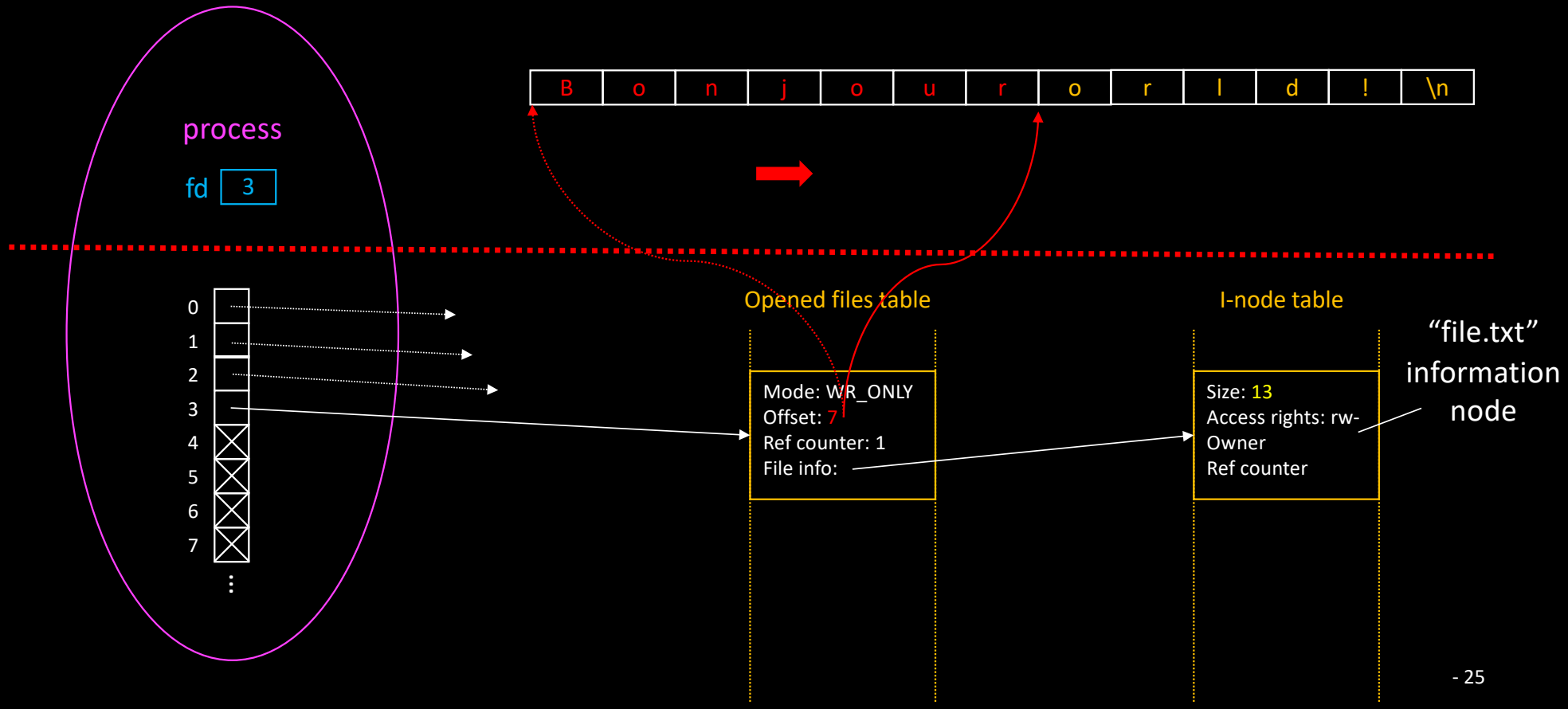
```
ssize_t write(int fildes, void *buf, size_t nbyte);
```

  - Return value:
    - -1 if error
    - Number of bytes written
      - Can be less than `nbyte`…
  - Writing beyond end-of-file automatically extends the file

fd = open ("file.txt", O_WRONLY | O_CREAT, 0666);



write (fd, "Bonjour", 7);



Writing into a File

- See cat.c

Coping with structured data

- How to store integers into a file?
  - Say we have a function that generates a series of integers
- There are several ways
    - Ascii representation
    - Raw integers

Coping with structured data

- Writing the ascii representation into a File
  - Convert integer into string
    - E.g. using `sprintf`
  - Write string to file
    - Think about a separator…
- Pros
  - Readable like a text file
  - Portable
- Cons

Coping with structured data

- Writing the ascii representation into a File
  - Convert integer into string
    - E.g. using `sprintf`
  - Write string to file
    - Think about a separator…
- Pros
  - Readable like a text file
  - Portable
- Cons
  - Reading back the file
    - Finding separators
    - Convert string back to integer
  - No efficient (direct) access to the N^{th} integer

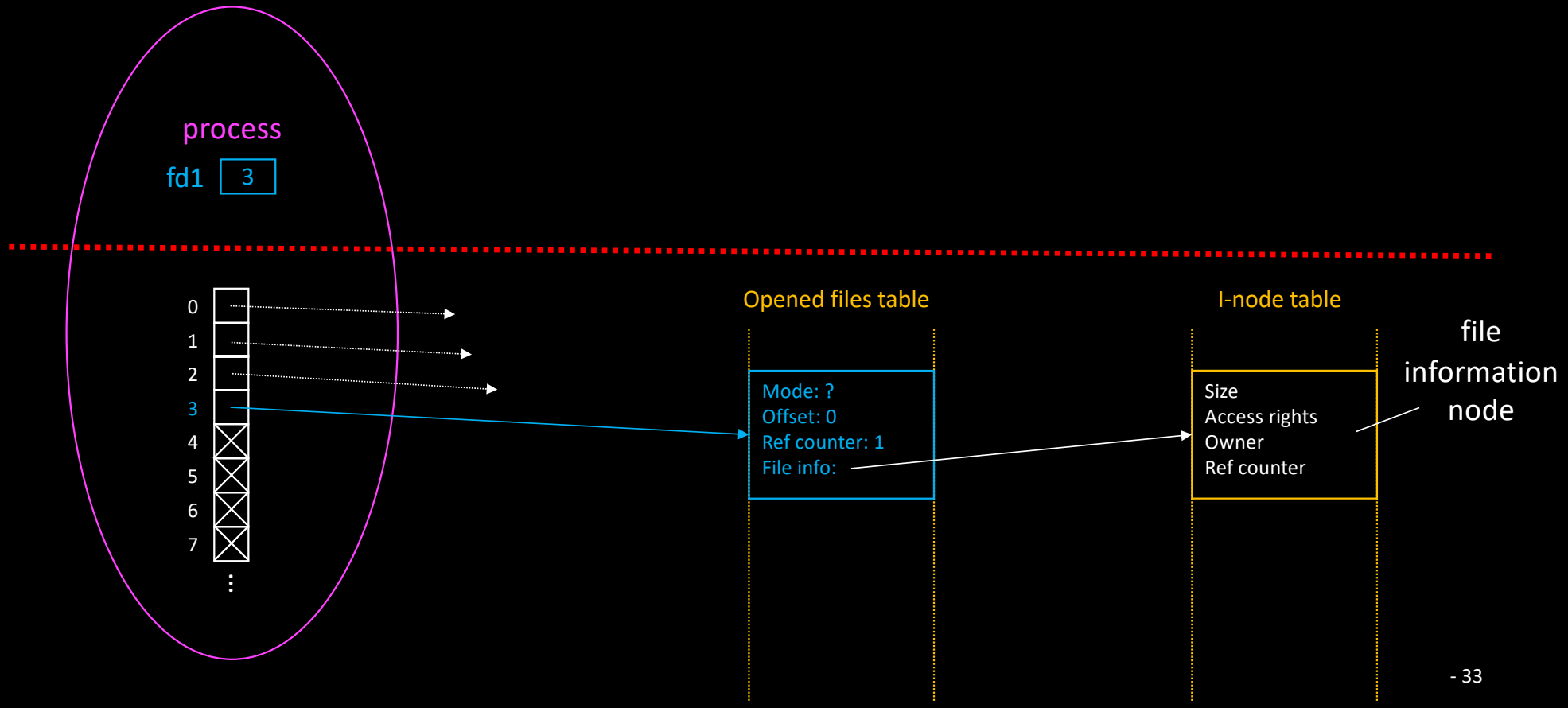
Coping with structured data

- Writing the binary representation into a File
  - `int i = …; write (fd, &i, sizeof(int));`
- Pros
  - Performance of both read/write operations
  - Efficient (direct) access to the N^{th} integer
    - Index files
- Cons

Coping with structured data

- Writing the binary representation into a File
  - `int i = …; write (fd, &i, sizeof(int));`
- Pros
  - Performance of both read/write operations
  - Efficient (direct) access to the N^{th} integer
    - Index files
- Cons
  - File readability
    - Hexdump ☺
  - Portability
    - Only works if file is generated AND accessed on the same processor architecture

What happens when opening the same file multiple times?



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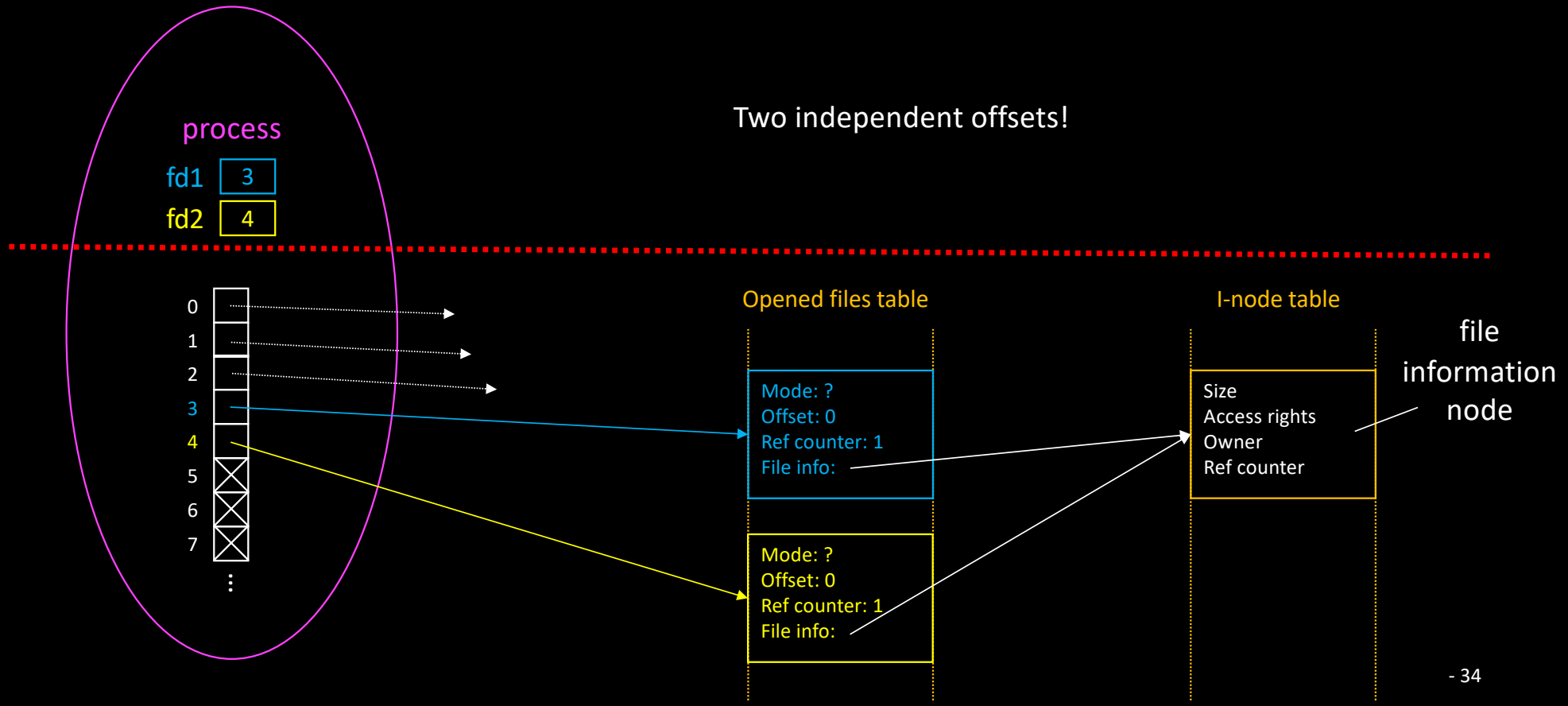

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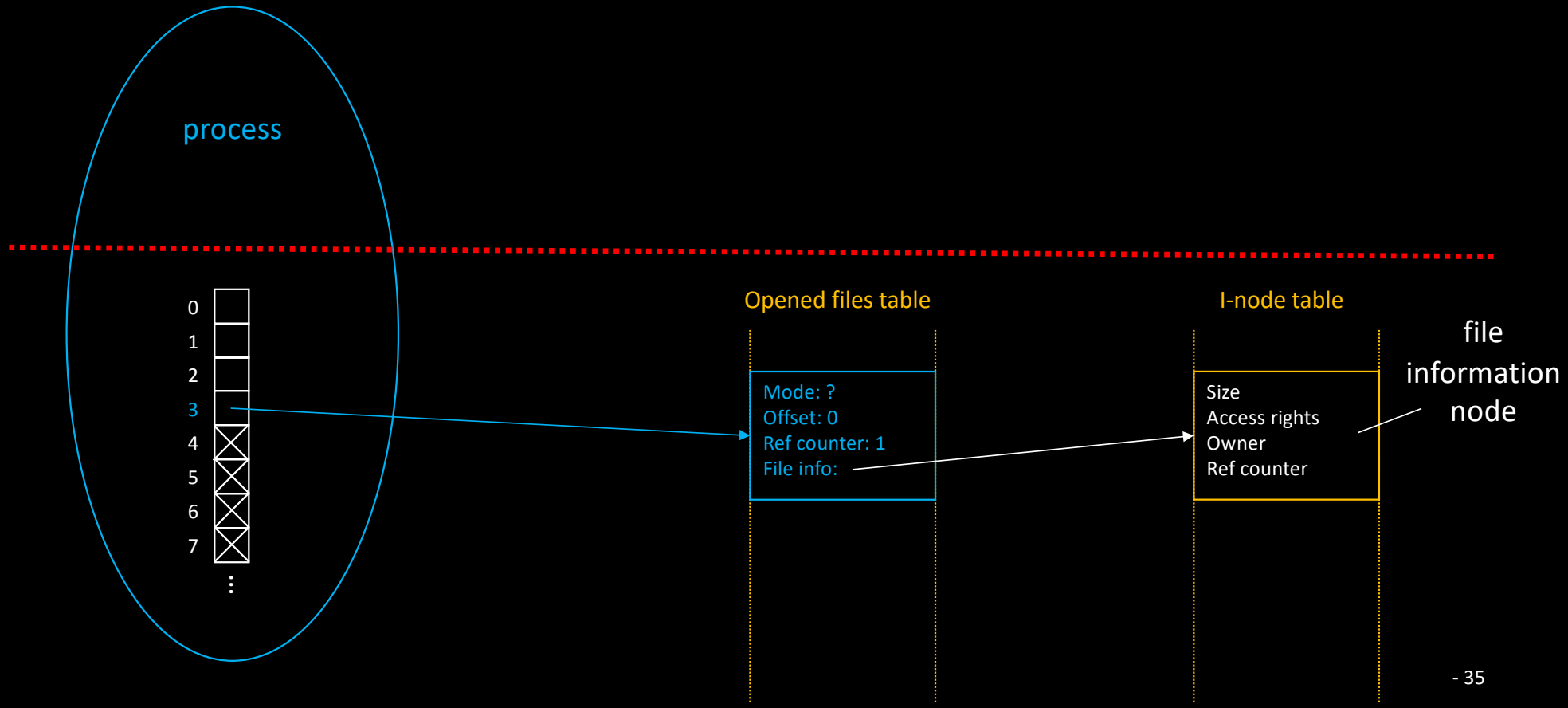

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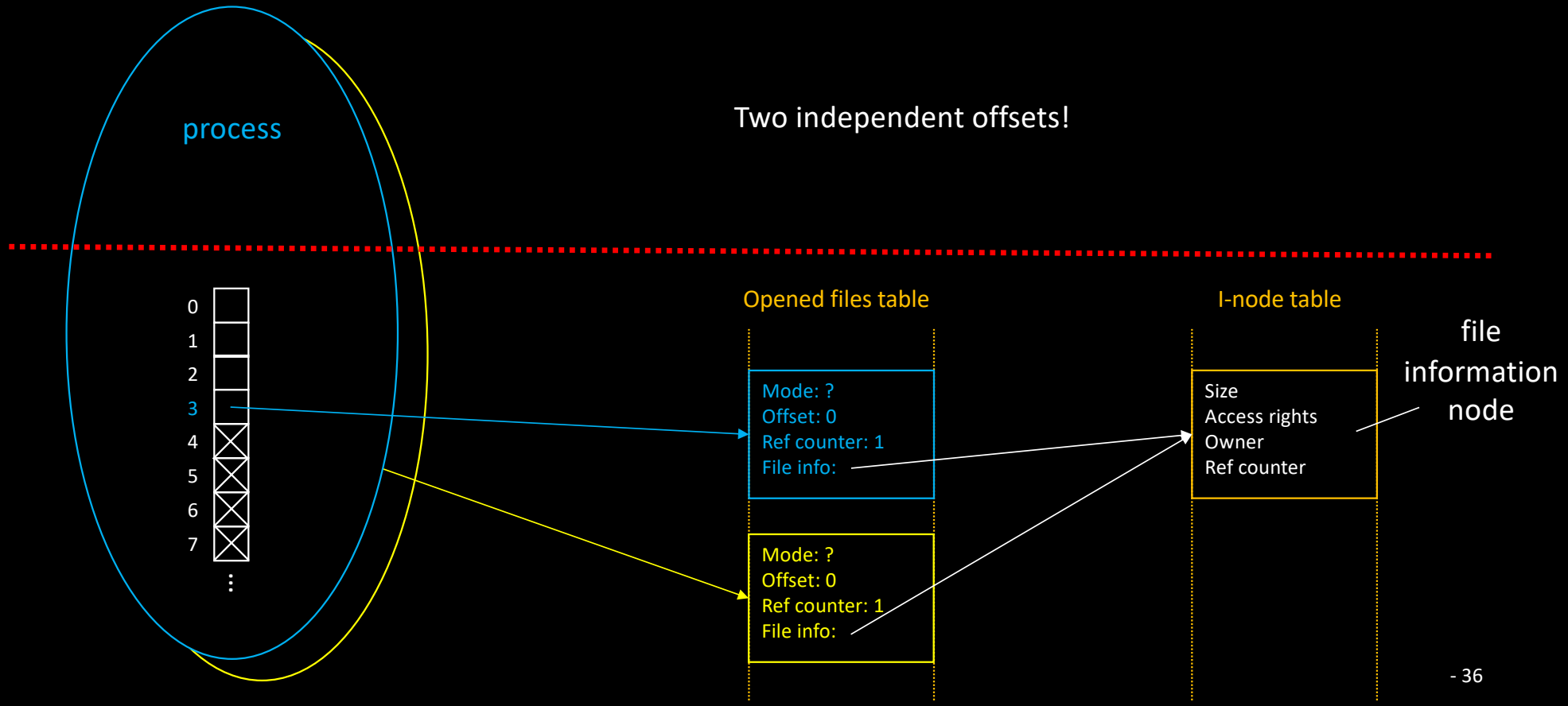
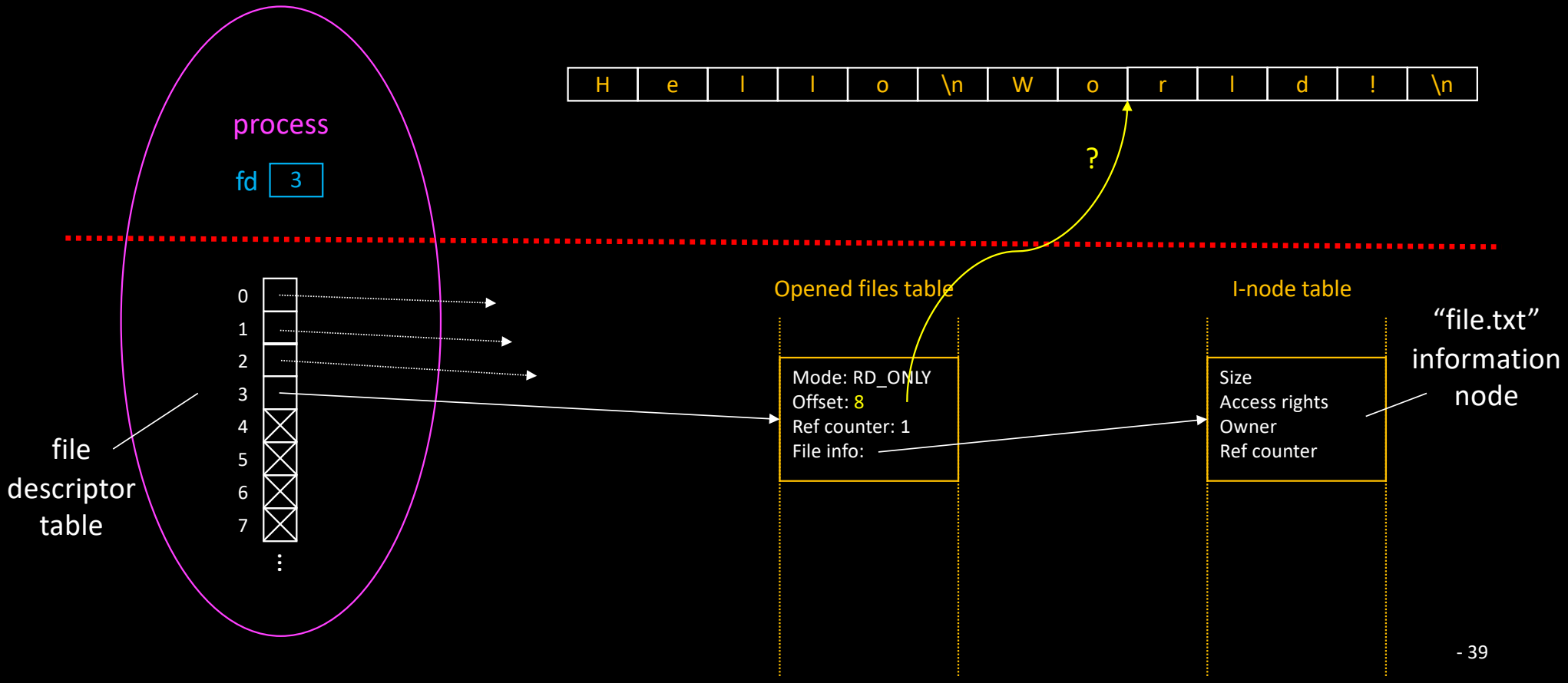


Random access to files

What if we quickly need to jump to an arbitrary position?



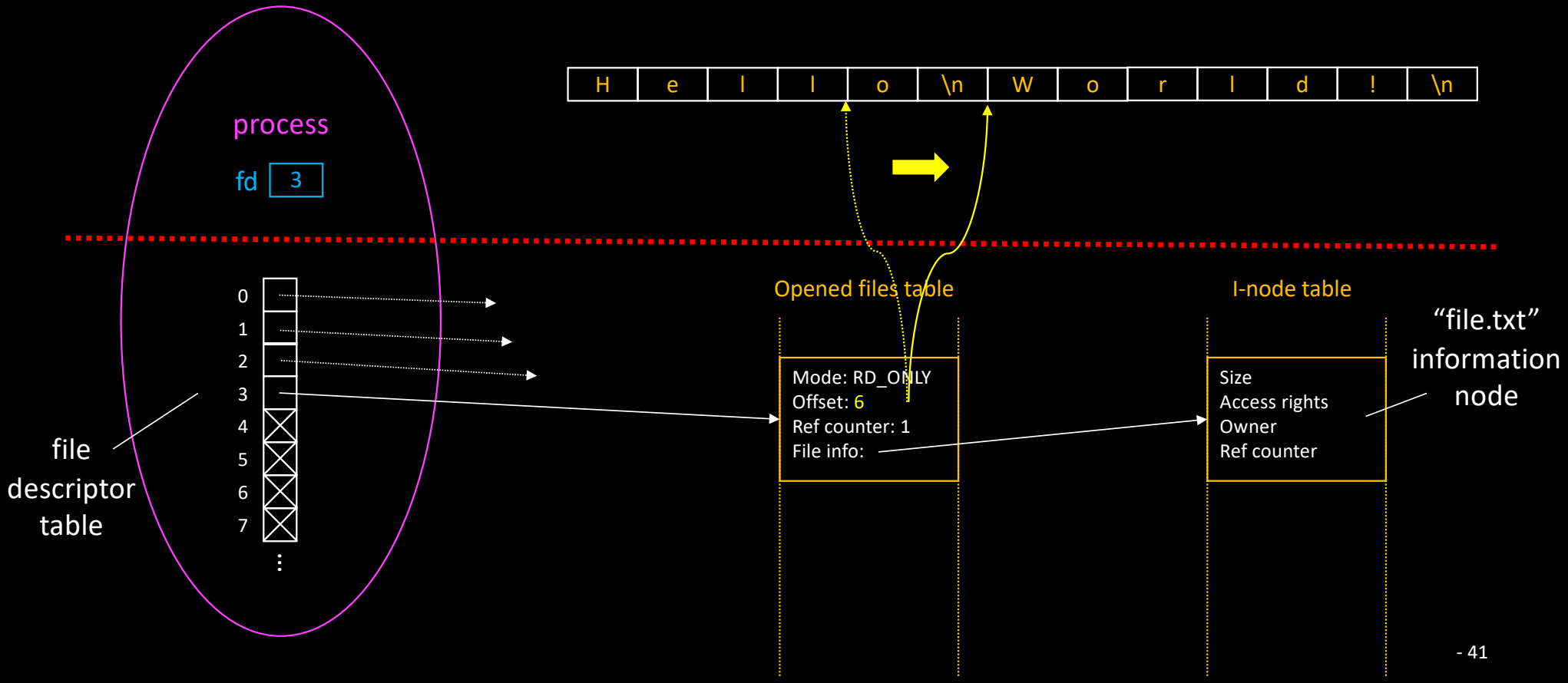
Changing current position

- Reading from the file and writing to the process memory

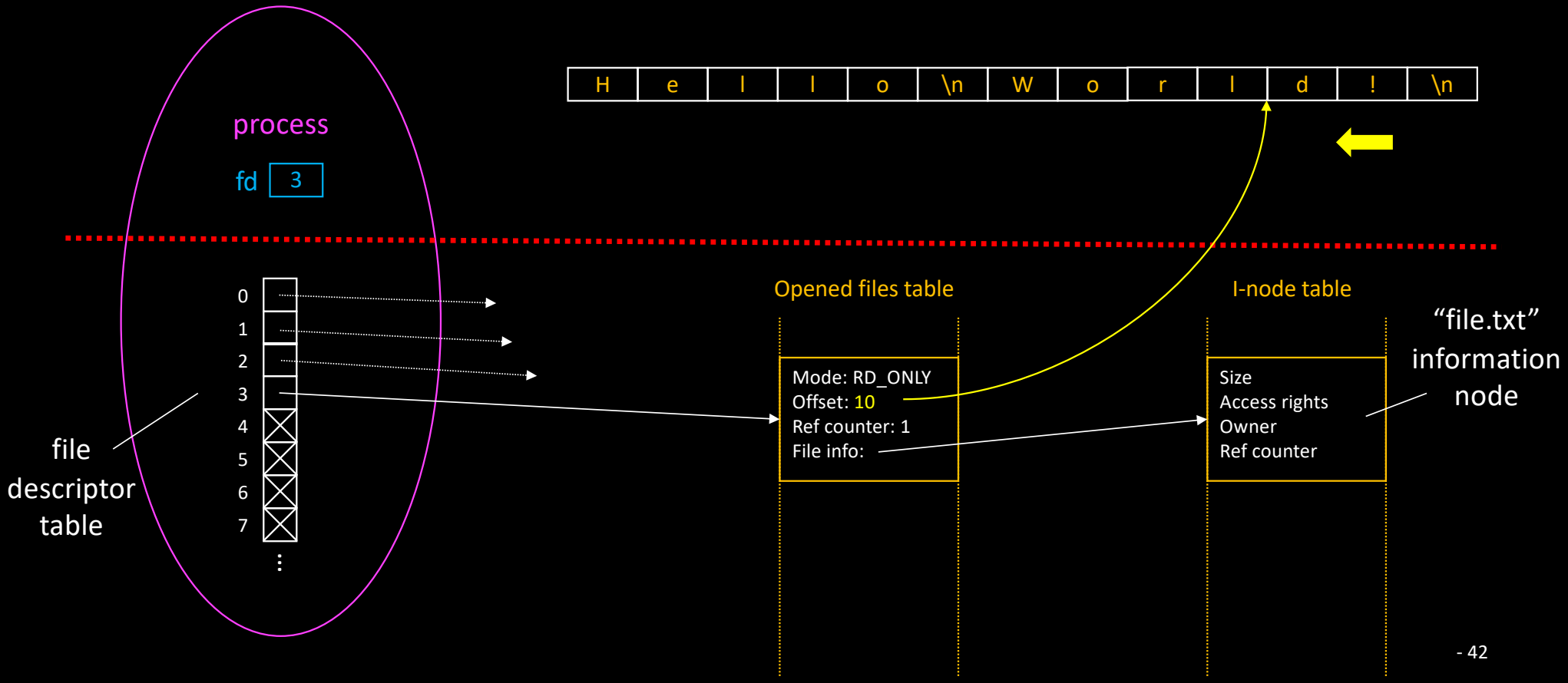
```
off_t lseek(int fildes, off_t offset, int whence);
```

  - `whence` can be:
    - SEEK_SET
    - SEEK_CUR
    - SEEK_END
  - Return value:
    - Absolute offset
      - Cannot be negative

lseek (fd, 2, SEEK_CUR)



lseek (fd, -3, SEEK_END)

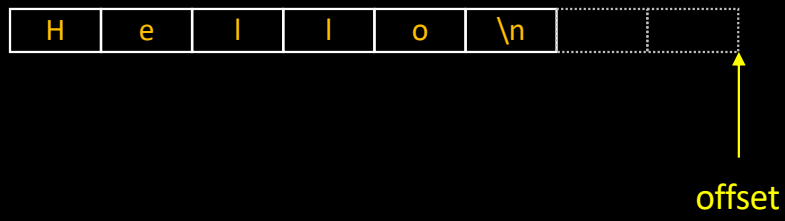


lseek

- seek.c, reverse.c

Changing current position

- Setting offset beyond end-of-file is possible
  - Remember: lseek performs no file access
- What happens upon read?
- What happens upon write?



lseek

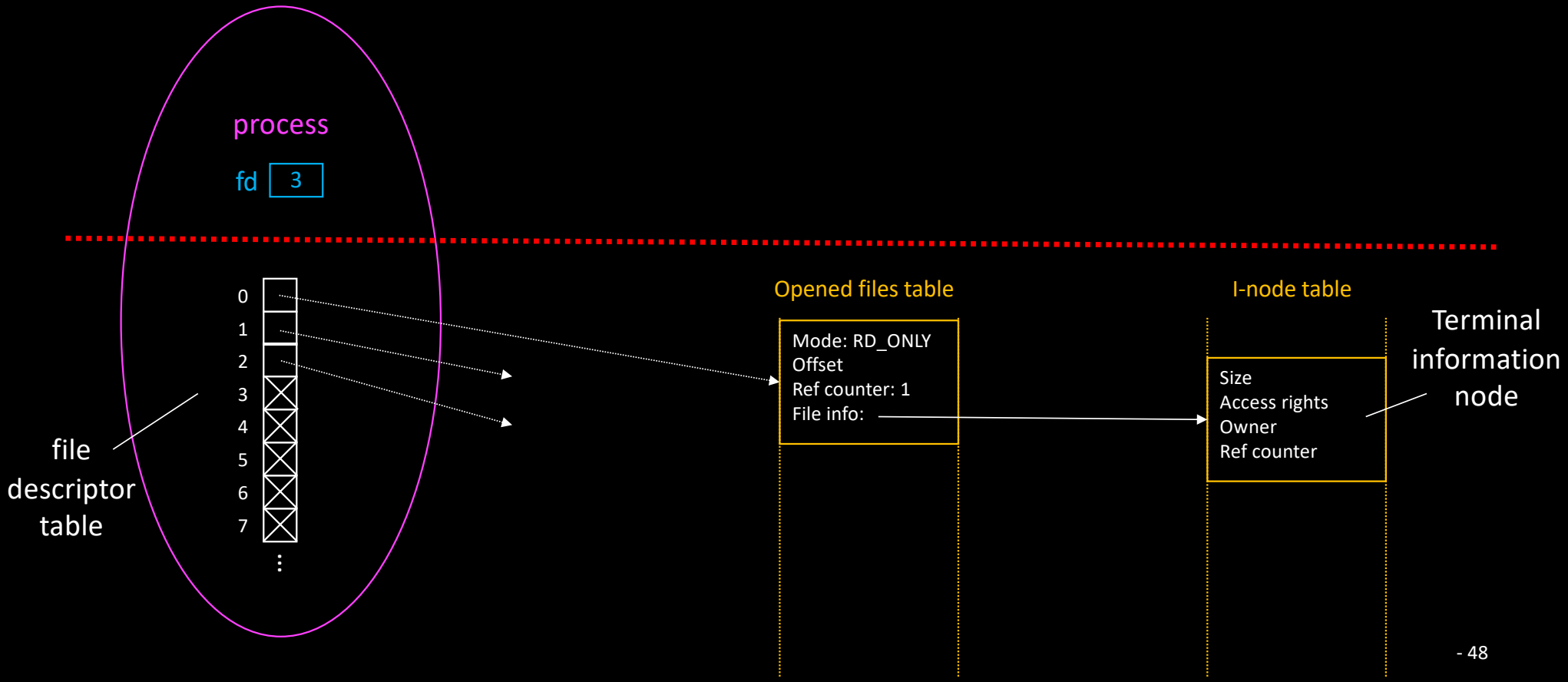
- create_big_file.c

I/O redirections

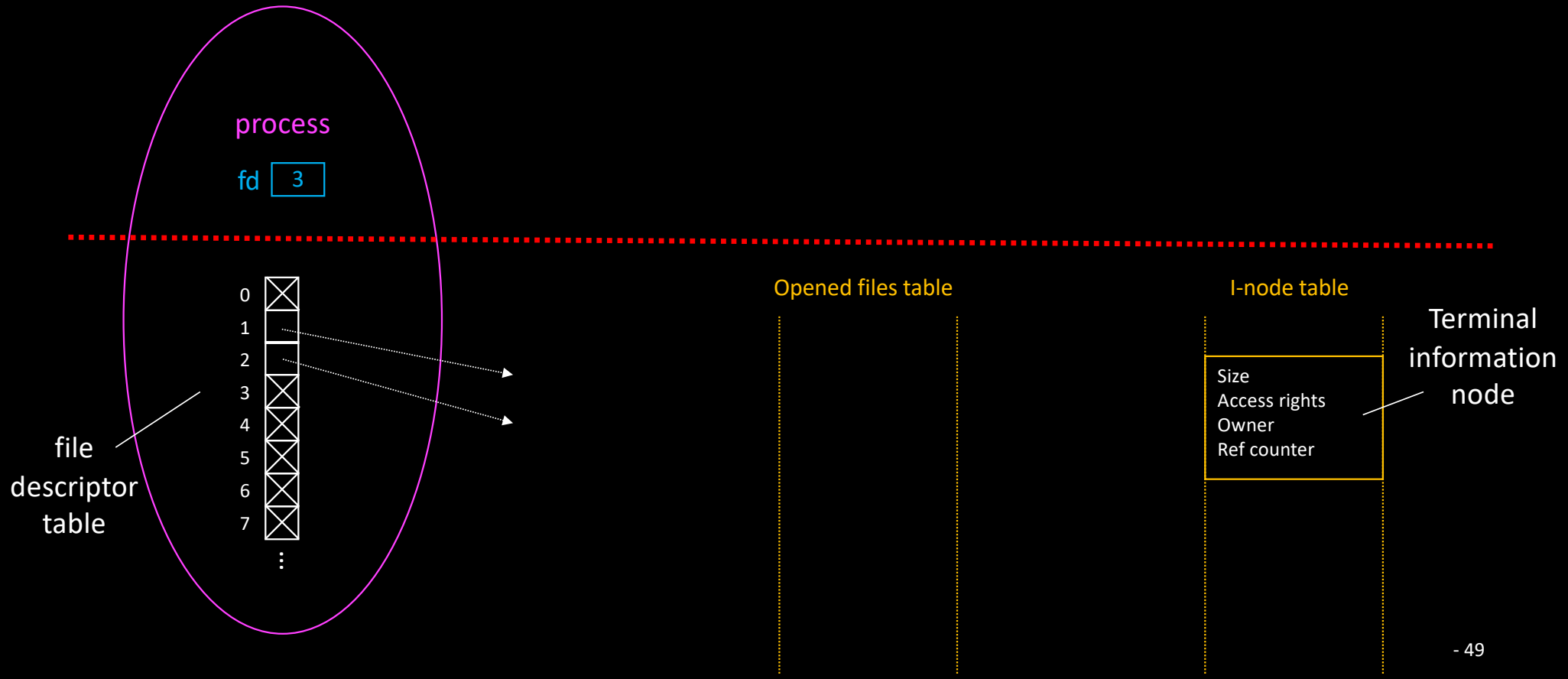
Back to pre-opened descriptors…

```
int main (int argc, char *argv[])
{
  close (STDIN_FILENO);
  int fd = open (“file.txt”, O_RDONLY);
  …
  read (STDIN_FILENO, …);  // What happens?
  …
}
```

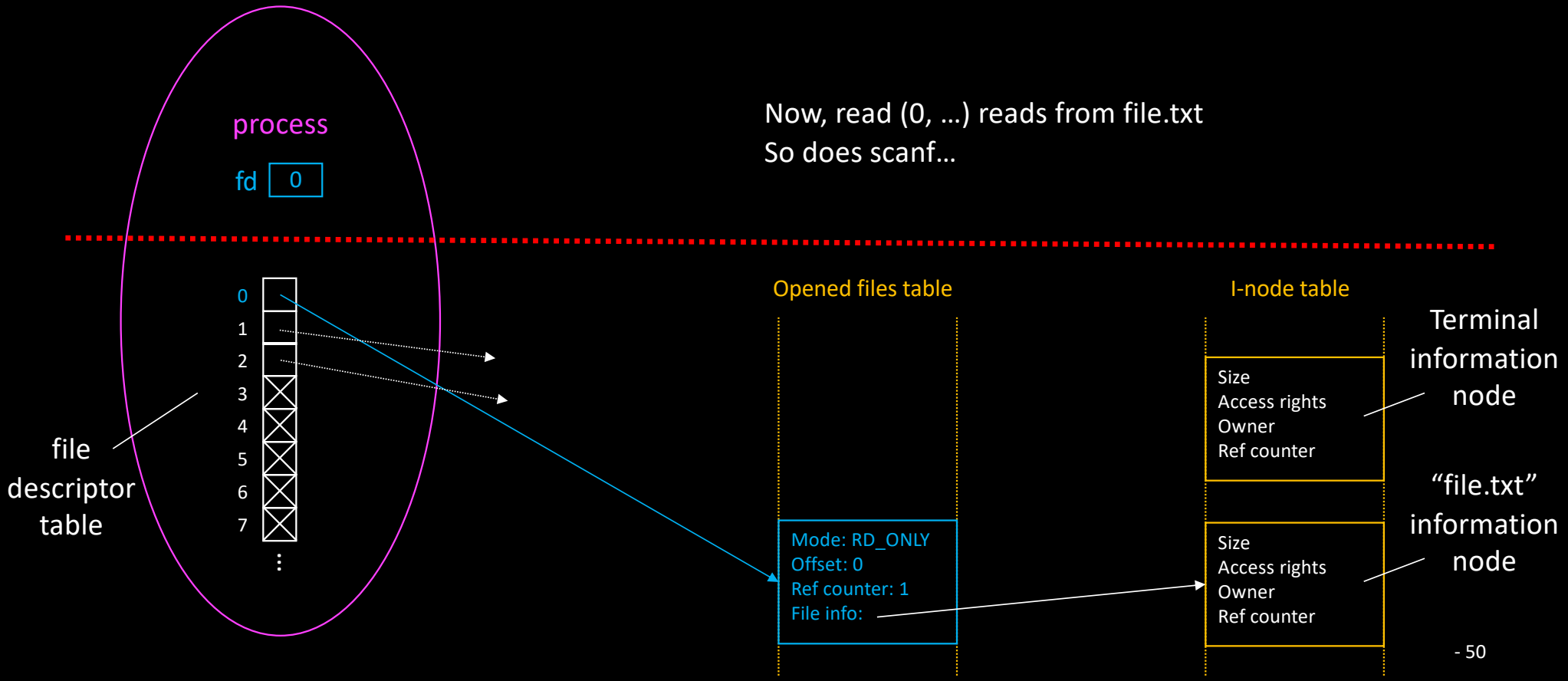
At launch time



close (0);


process
fd
3
0
1
2
3
4
5
6
7
file descriptor table
Opened files table
I-node table
Size
Access rights
Owner
Ref counter
Terminal information node

close (0); fd = open ("file.txt", O_RDONLY);



Back to pre-opened descriptors…

```
int main (int argc, char *argv[])
{
  close (STDIN_FILENO);
  int fd = open (“file.txt”, O_RDONLY);
  …
  // From now on, standard input is redirected to file.txt
  // ./prog < file.txt
  …
}
```

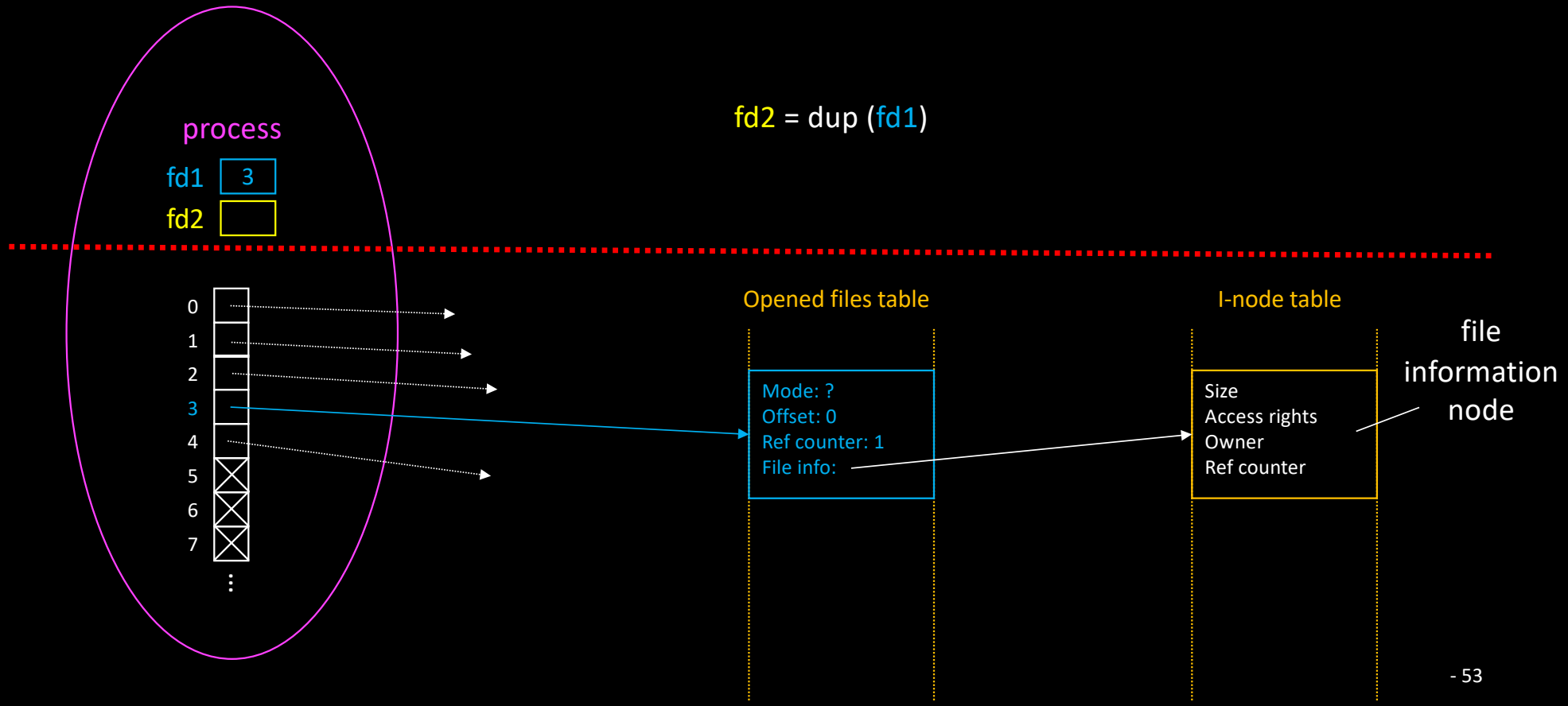
File descriptor manipulation

- Duplicating file descriptors
  - i.e. duplicating pointers in the file descriptor table

```
int dup (int fildes);

int dup2 (int src_fd, int dst_fd);
```

File descriptor manipulation



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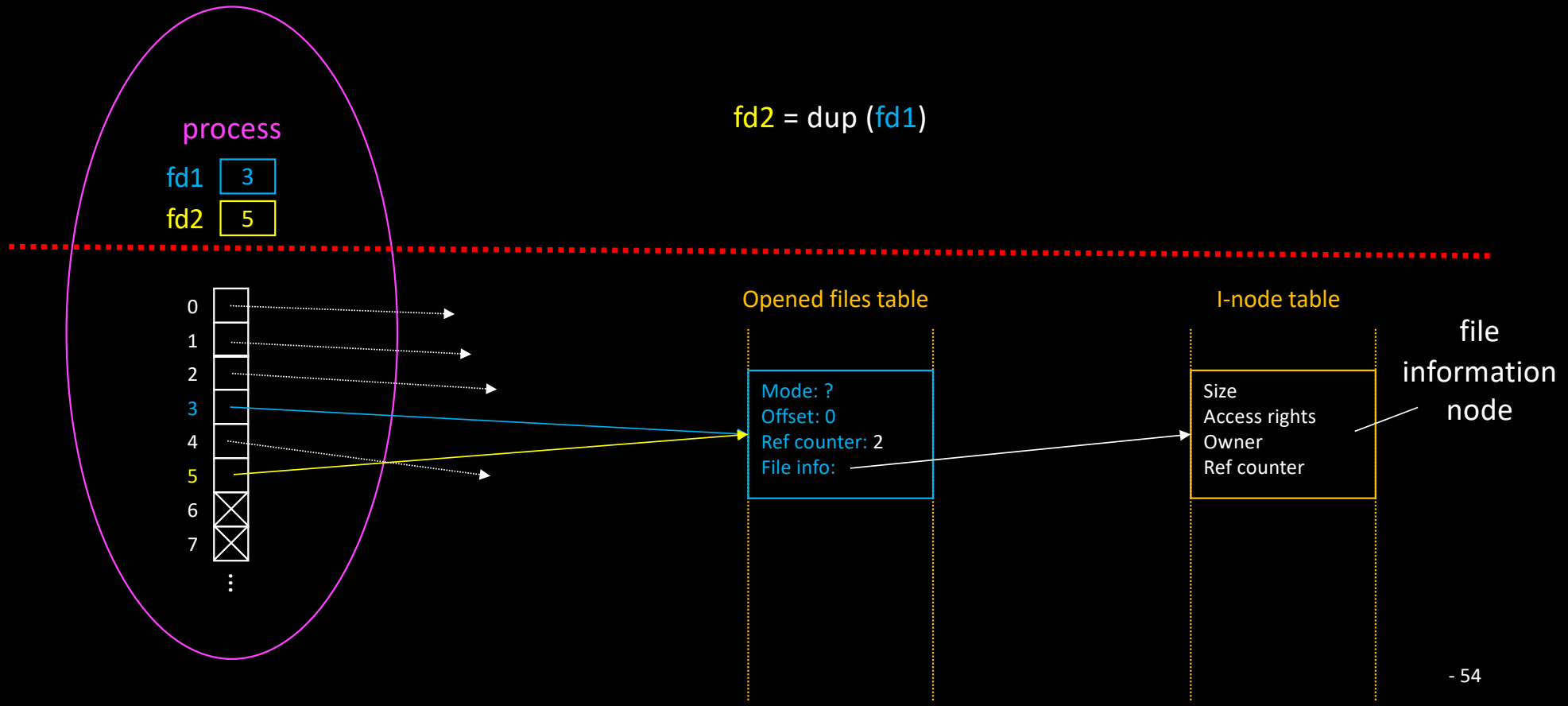


Using dup redirect I/O is a bad idea

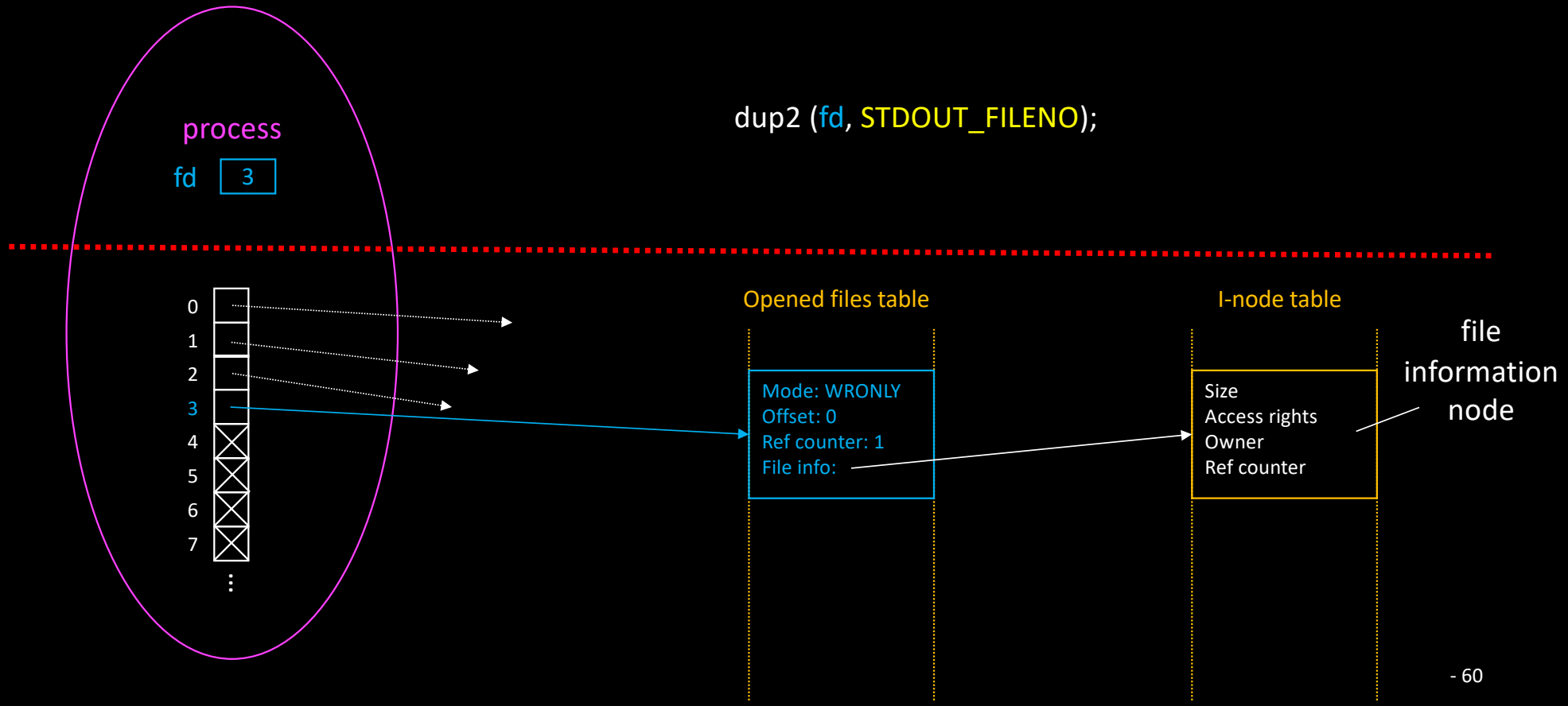
- As dangerous as the “close + open” solution

```
int fd = open (…);

… // what if STDIN_FILENO is closed here?

close (STDOUT_FILENO);
dup (fd);
close (fd);
```

STDOUT redirection (with dup2)



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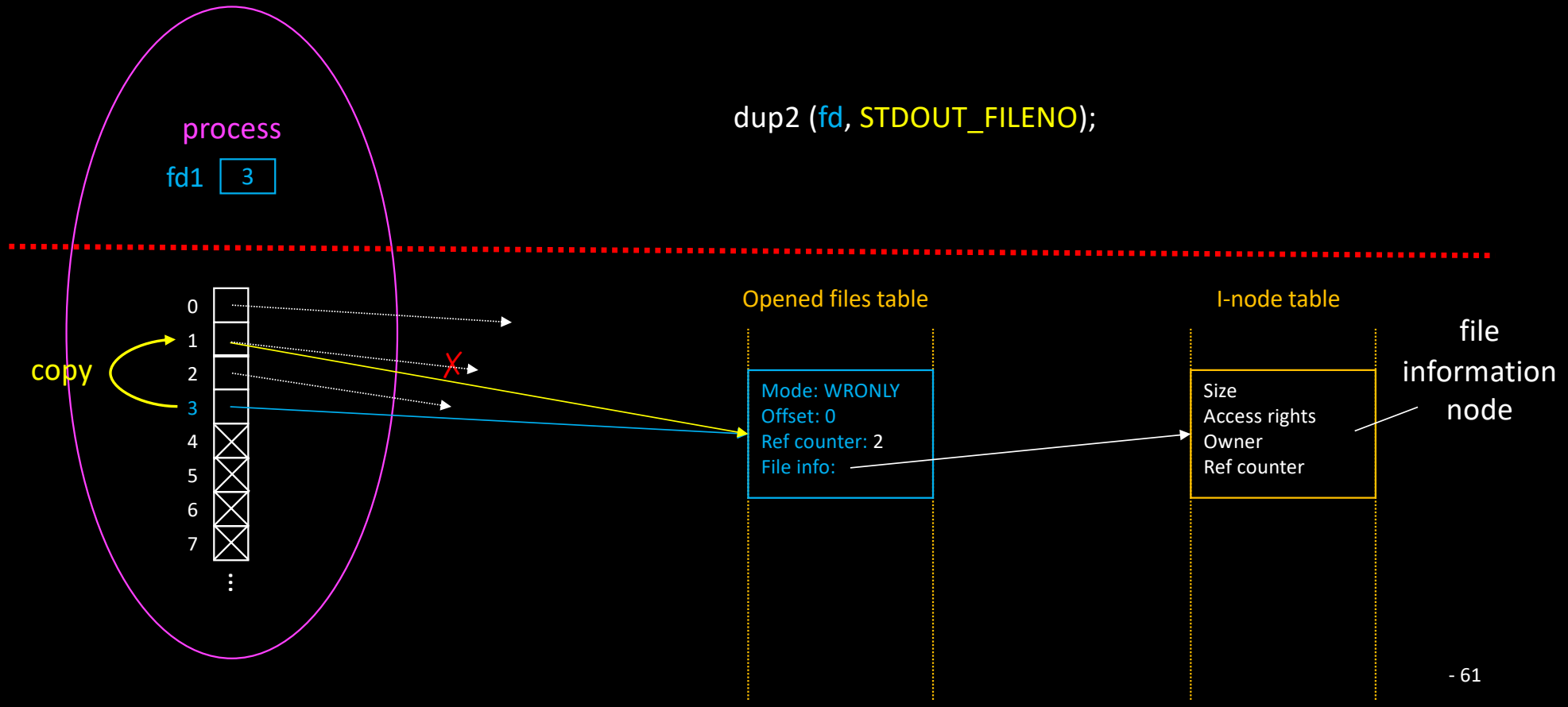
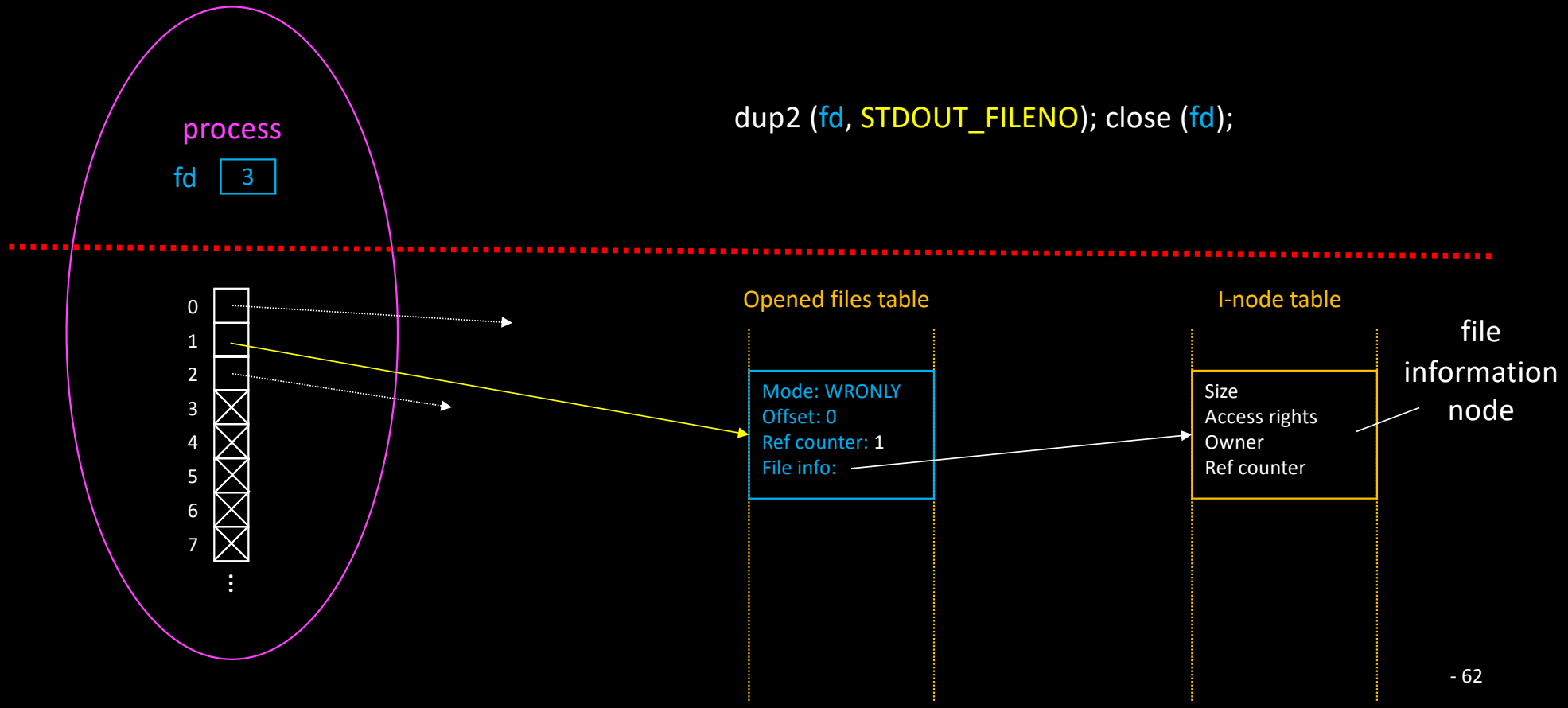


STDOUT redirection (with dup2)



STDOUT redirection (with dup2)

- `dup2` is a safe way to replace the target descriptor

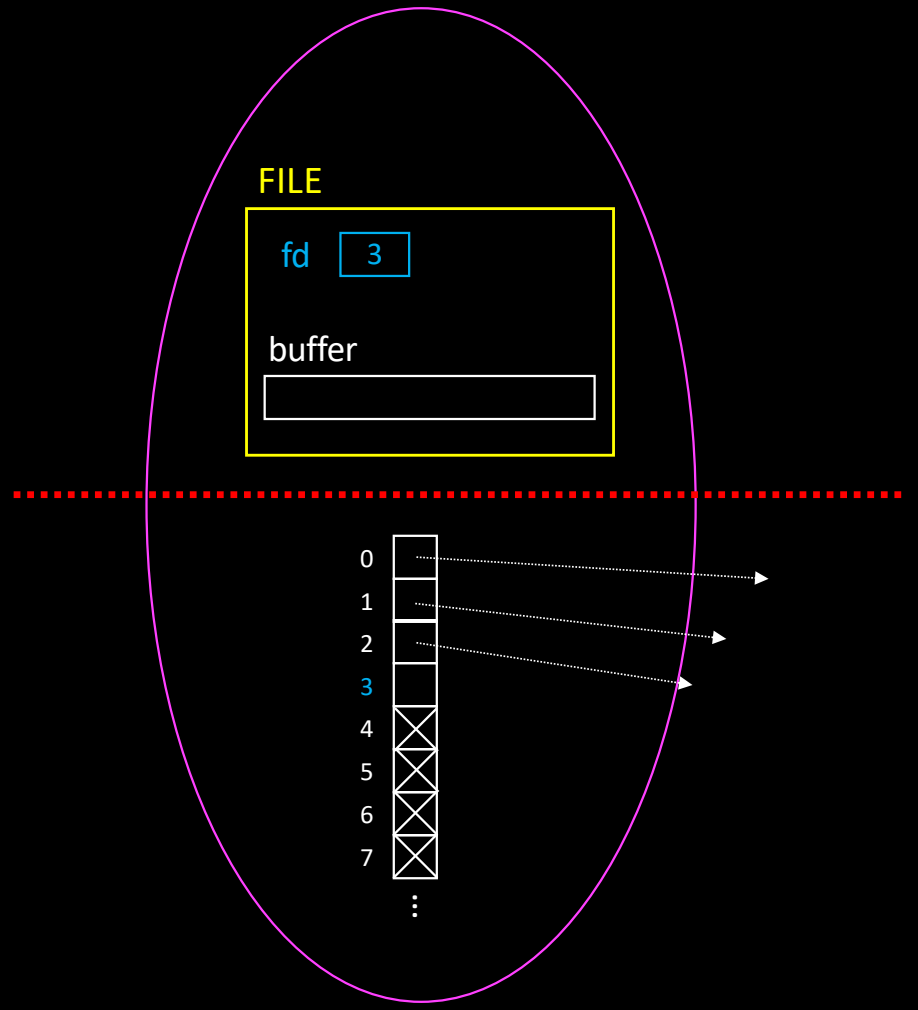
```
int fd = open (…);
…
dup2 (fd, STDOUT_FILENO);
// STDOUT is automatically closed
// before fd is copied
close (fd);
```

C standard file API

- Files are manipulated through FILE* handlers (≠ file descriptor)
  - FILE* fopen (…)
  - fread (…, FILE *f), fwrite (…, FILE *f), fprintf (FILE *f, …), fscanf (FILE *f, …), …
  - extern FILE *stdin, *stdout, *stderr;
- Implemented in user mode (libc)
  - fopen relies on open
  - fread relies on read
  - Etc.

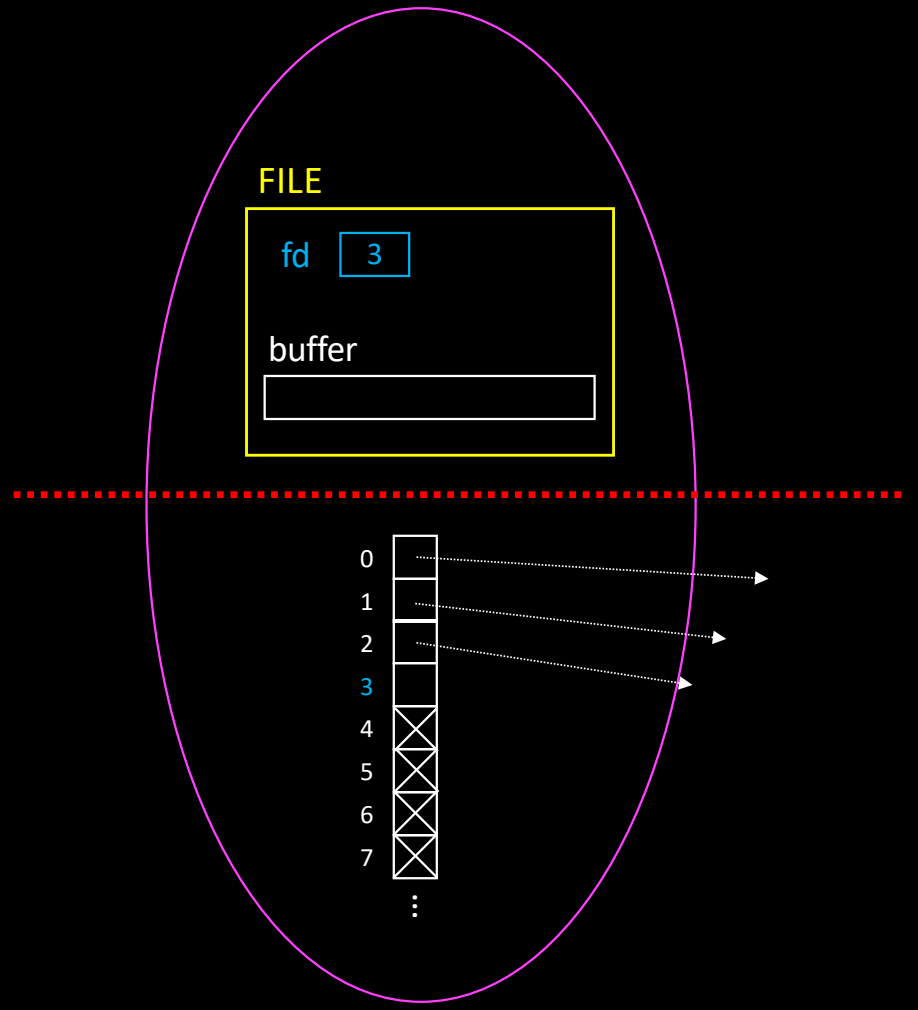
C standard file API

- One could think that these routines introduce overhead
  - But libc routines are usually (much) faster!
  - Reason?
    - The FILE struct contains a buffer
      - 1KB ~ 8KB
    - Read operations use prefetching
    - Write operation use buffering



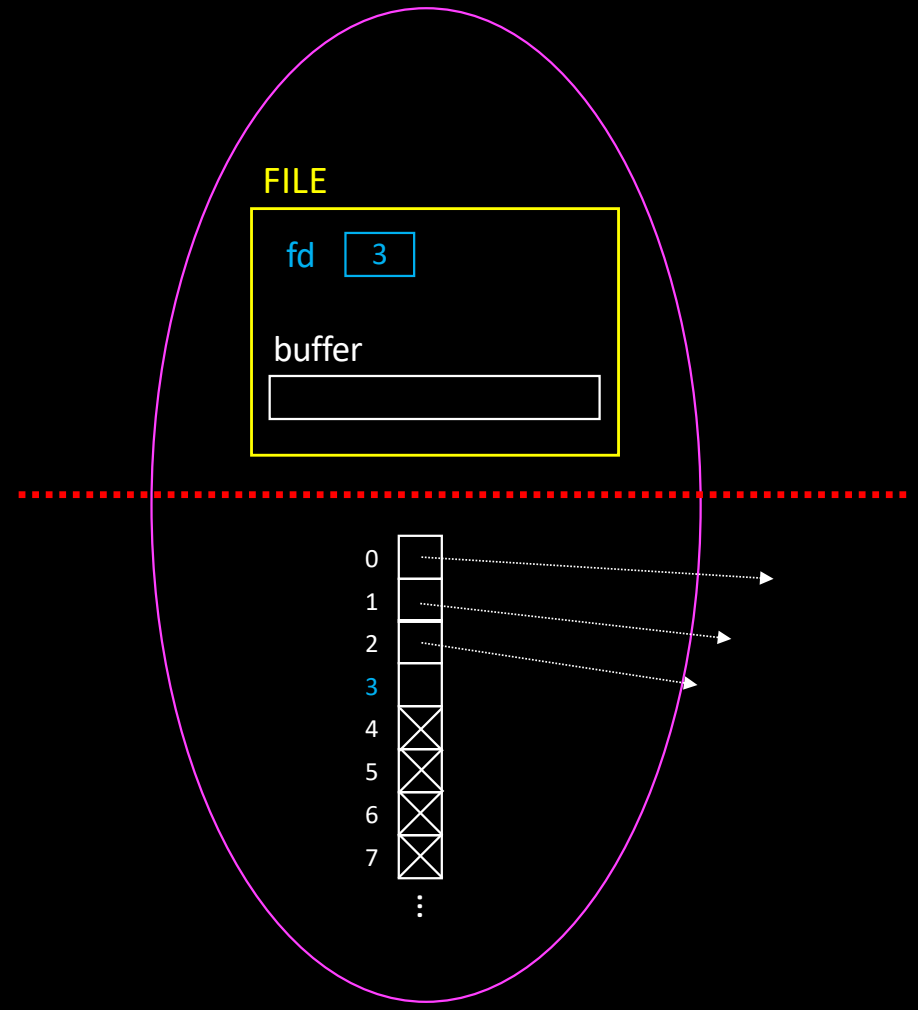
C standard file API

- Read prefetching
  - The first fread prefetches BUFSIZE bytes (if possible) using read
  - Next fread operations simply copy from buffer to destination
- As a result
  - fcopy performs a lot less *system calls* than copy



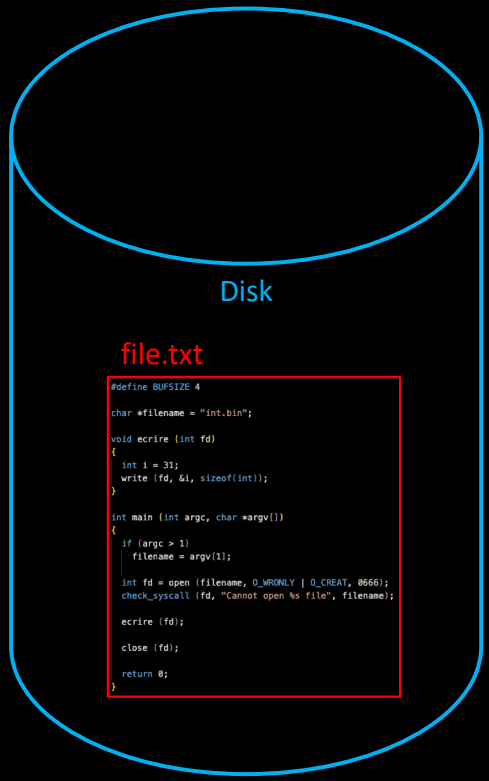
C standard file API

- Write buffering
  - fwrite copies data into buffer
  - When the buffer is full, it gets flushed to the kernel (write)
- Special buffering policies
  - stderr is unbuffered
  - stdout is line buffered
    - printf (“hello”) vs printf (“hello\n”)
    - fflush (FILE *f)



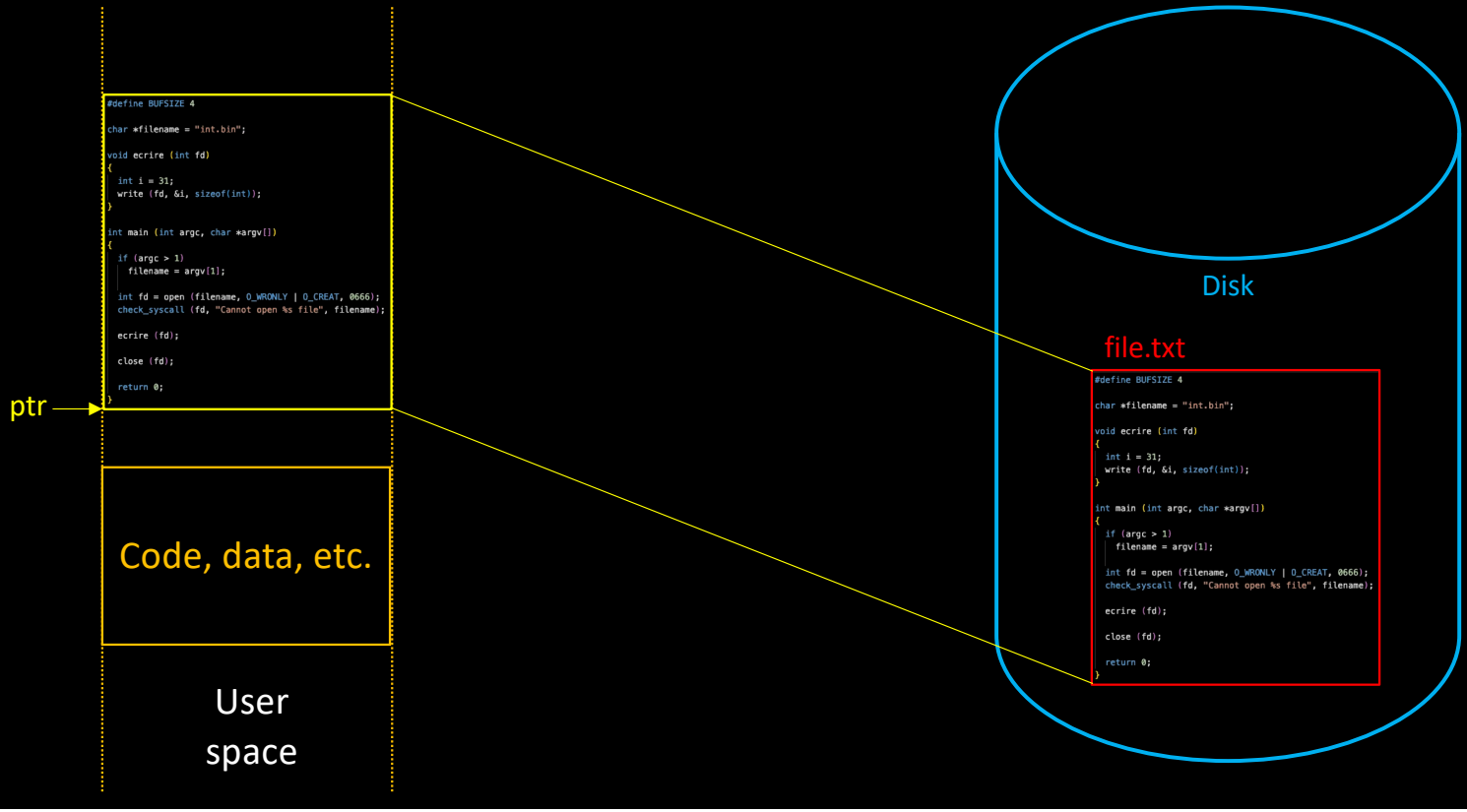
Memory-mapped files

- Accessing files as if they were in memory ?



Memory-mapped files

- Accessing files as if they were in memory ? It is called: *file mapping*



Memory-mapped files

- Accessing files as if they were in memory ? It's called *file mapping*
  - Processes can map a (portion of a) file in their address space

```
void *mmap(void *addr, size_t len, int prot, int flags, int fd, off_t offset);
```

Suggested address (or NULL)

access mode

file

  - Example:

```
char *addr = mmap (NULL, len, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);
```

Memory-mapped files

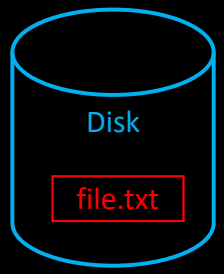
- Accessing files as if they were in memory ? It's called *file mapping*
  - Processes can map a (portion of a) file in their address space

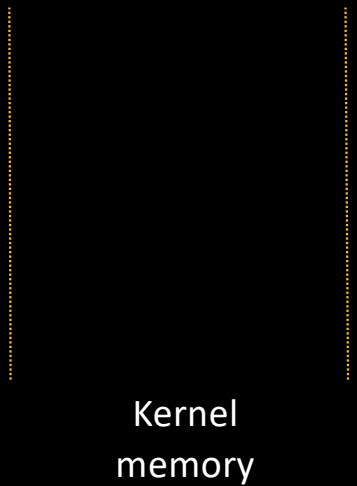
```
int fd = open ("file.txt", O_RDWR);

off_t len = lseek (fd, 0, SEEK_END);

char *region = mmap (NULL, len, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);
```

  - Then, file contents can be accessed as an array

```
strcpy (region, "Hello World!");
```

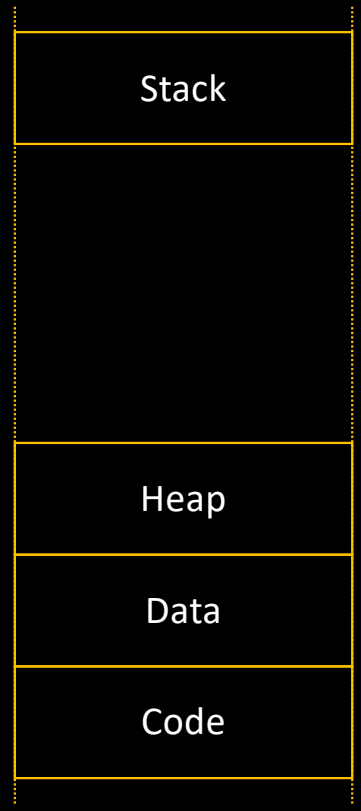
mmap

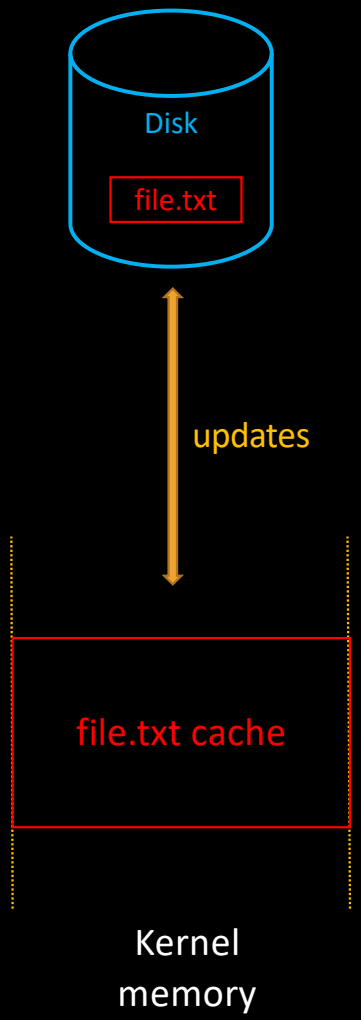




- mmap takes a file descriptor as a parameter

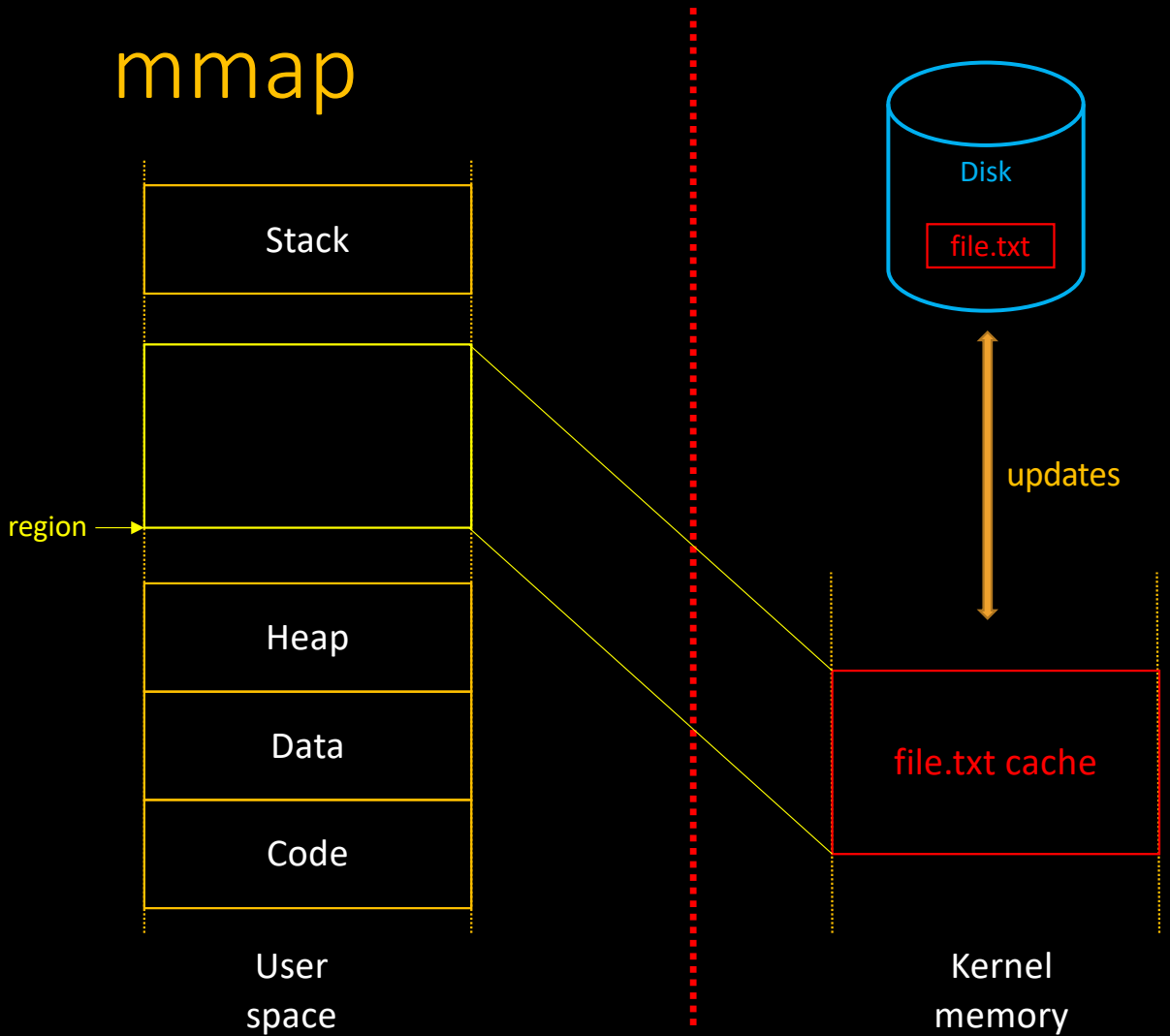
mmap





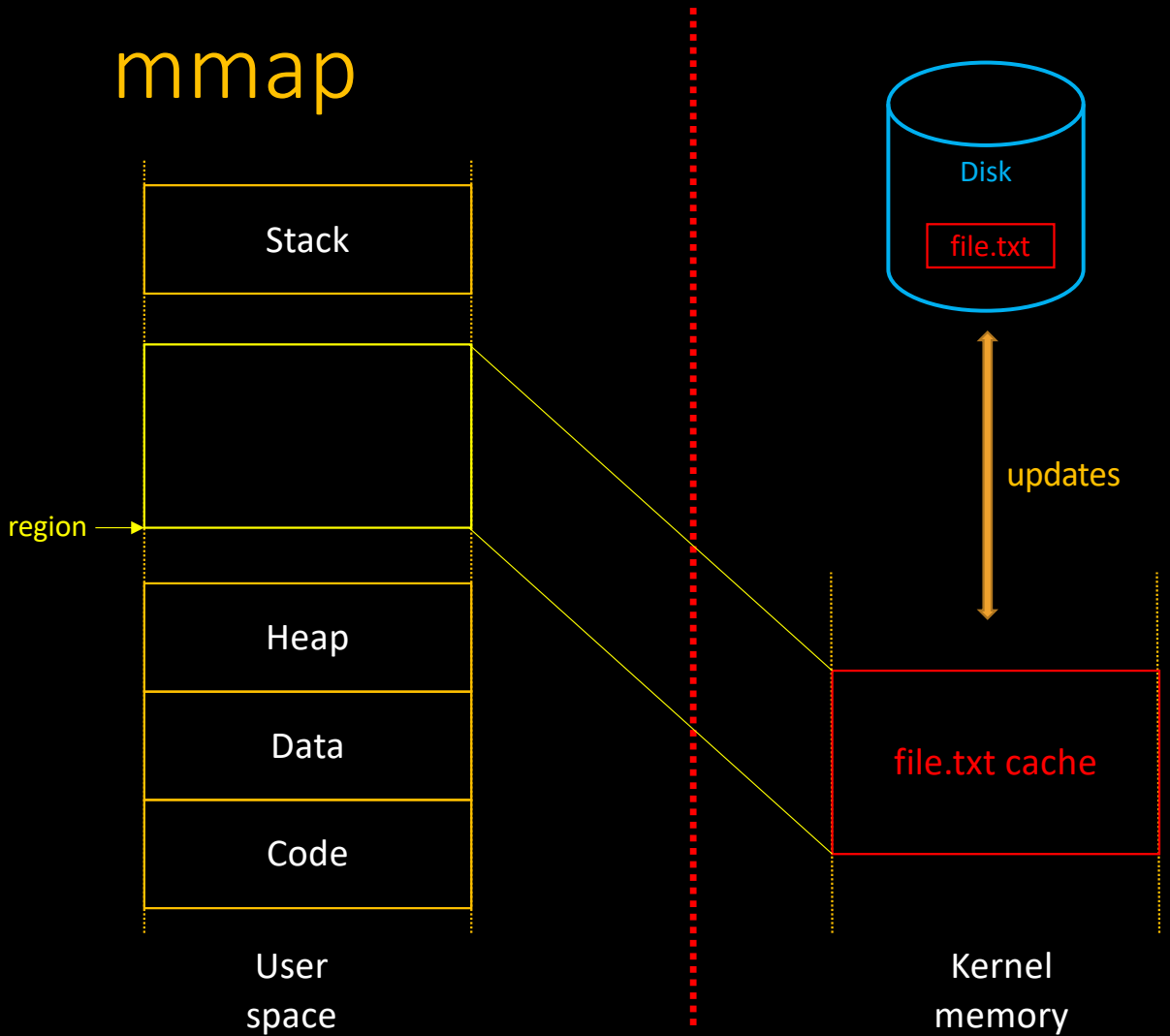
- (Part of) file.txt is loaded into kernel memory
  - Acts as a cache:
    - Actually, all read/write operations go through the cache
  - Disk file will be automatically updated…

mmap

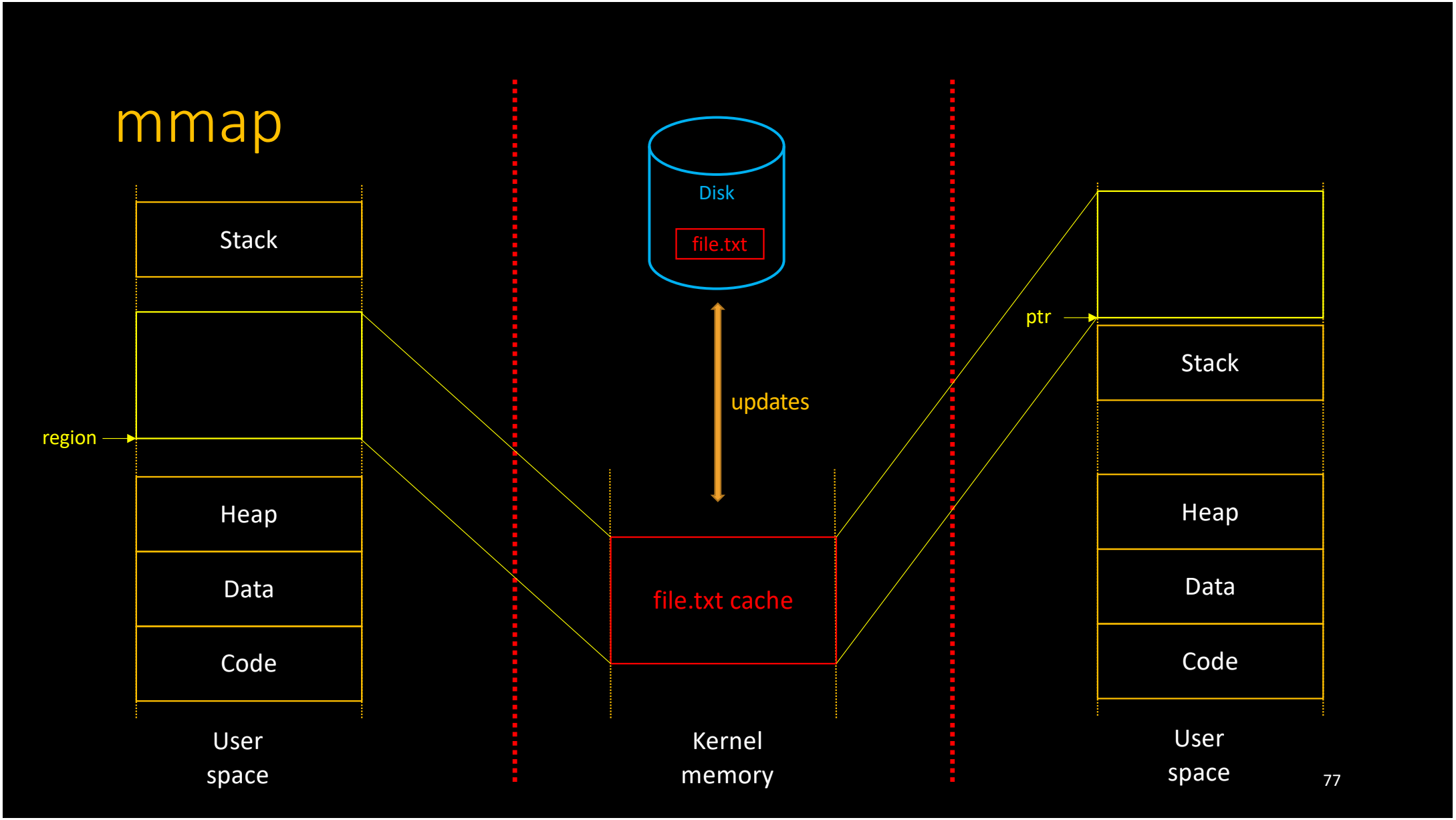


- Kernel cache is mapped directly in process' address space
  - No memory allocation
    - Purely virtual
  - CPU load/store operations directly operate on the kernel cache

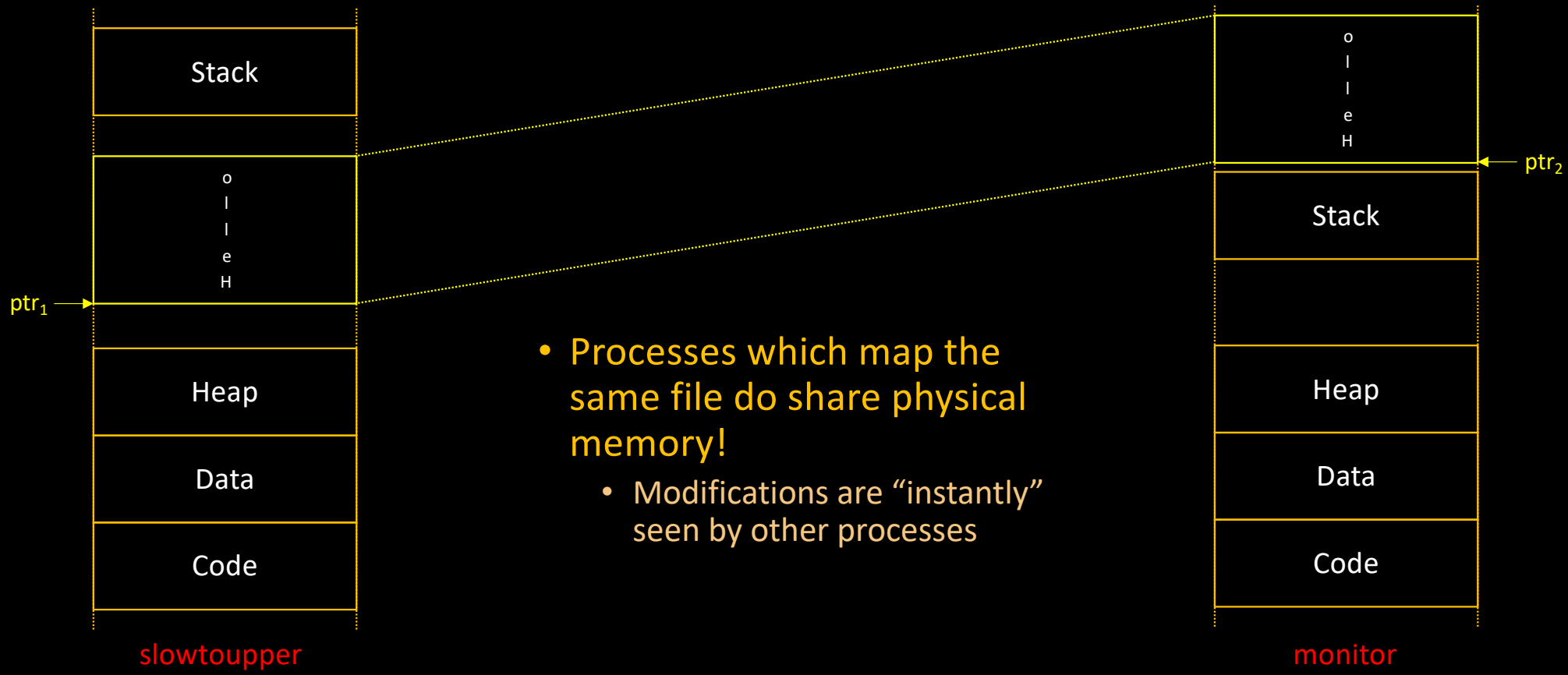
mmap



- In fact, *file mapping* is the most efficient way to cope with non-growing files
  - Direct memory access
  - No system calls!
  - See reverse.c, toupper.c

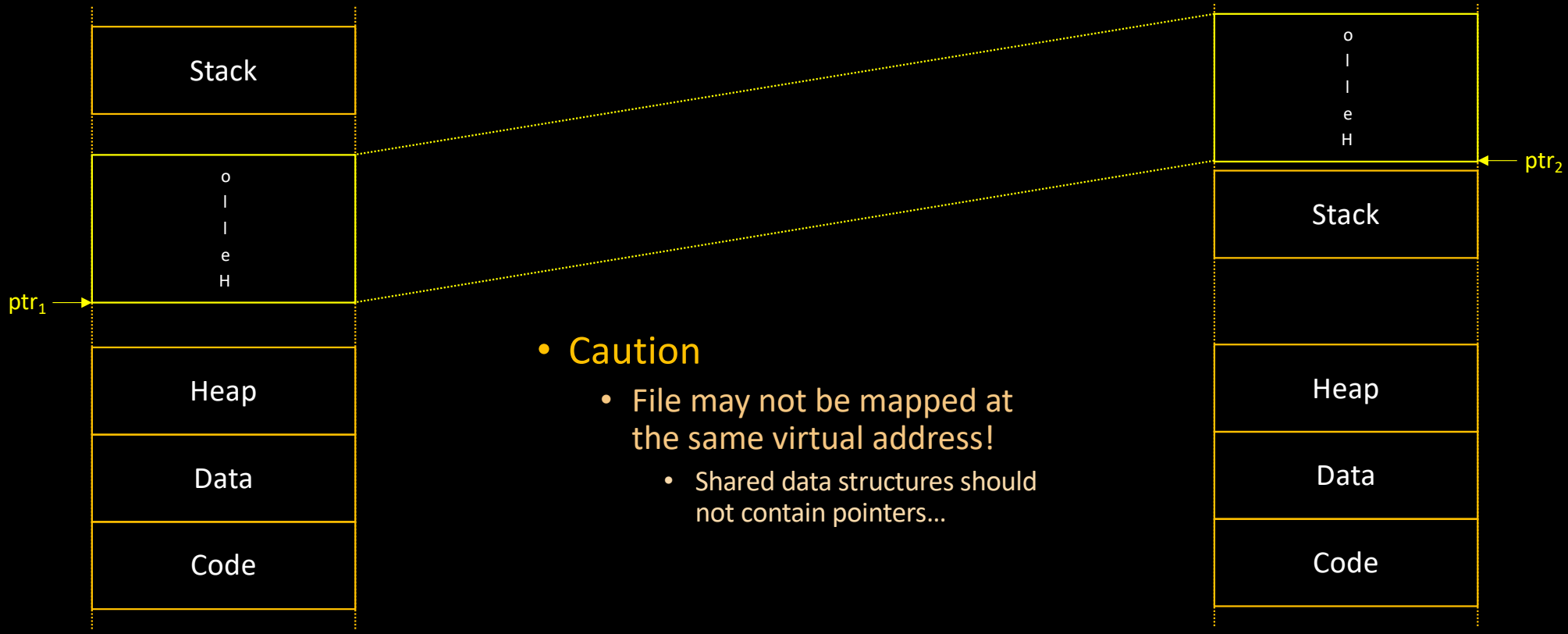

mmap
Disk
file.txt
Stack
region
Heap
Data
Code
updates
file.txt cache
ptr
Stack
Heap
Data
Code
User space
Kernel memory
User space

Communication between processes



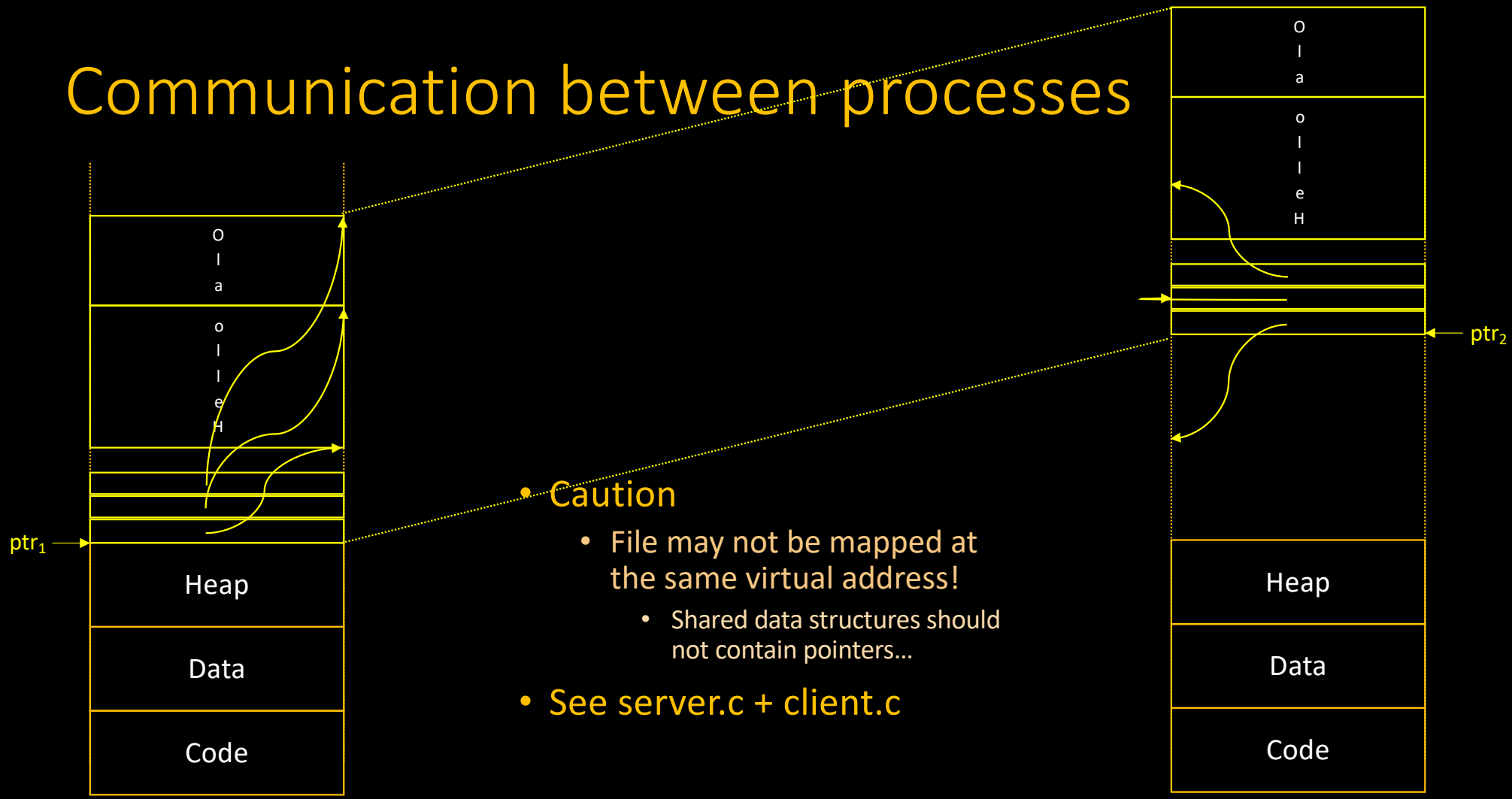
- Processes which map the same file do share physical memory!
  - Modifications are “instantly” seen by other processes

Communication between processes



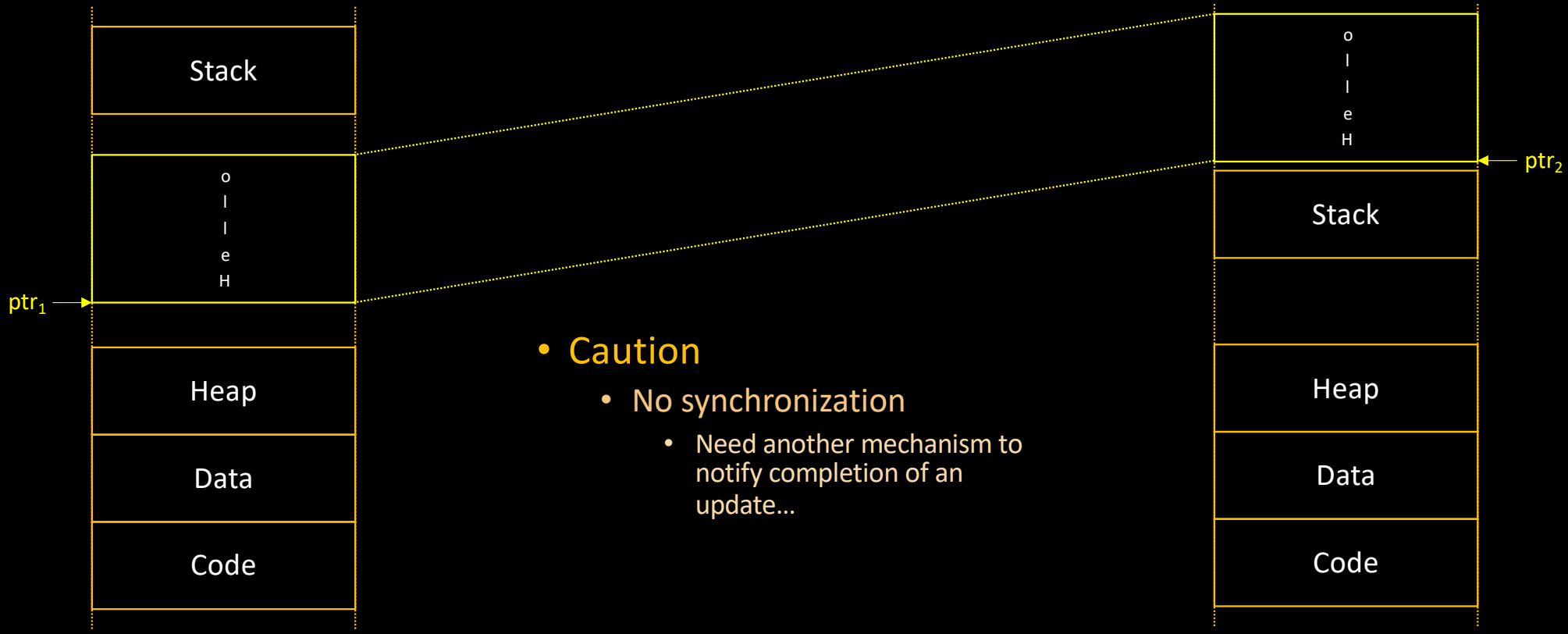
- Caution
  - File may not be mapped at the same virtual address!
    - Shared data structures should not contain pointers…

Communication between processes



- Caution
  - File may not be mapped at the same virtual address!
    - Shared data structures should not contain pointers…
- See server.c + client.c

Communication between processes



- Caution
  - No synchronization
    - Need another mechanism to notify completion of an update…

Additional resources
available on
http://gforgeron.gitlab.io/progsys/