IPADS INSTITUTE OF PARALLEL AND DISTRIBUTED SYSTEMS

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

inode-based File System

Yubin Xia

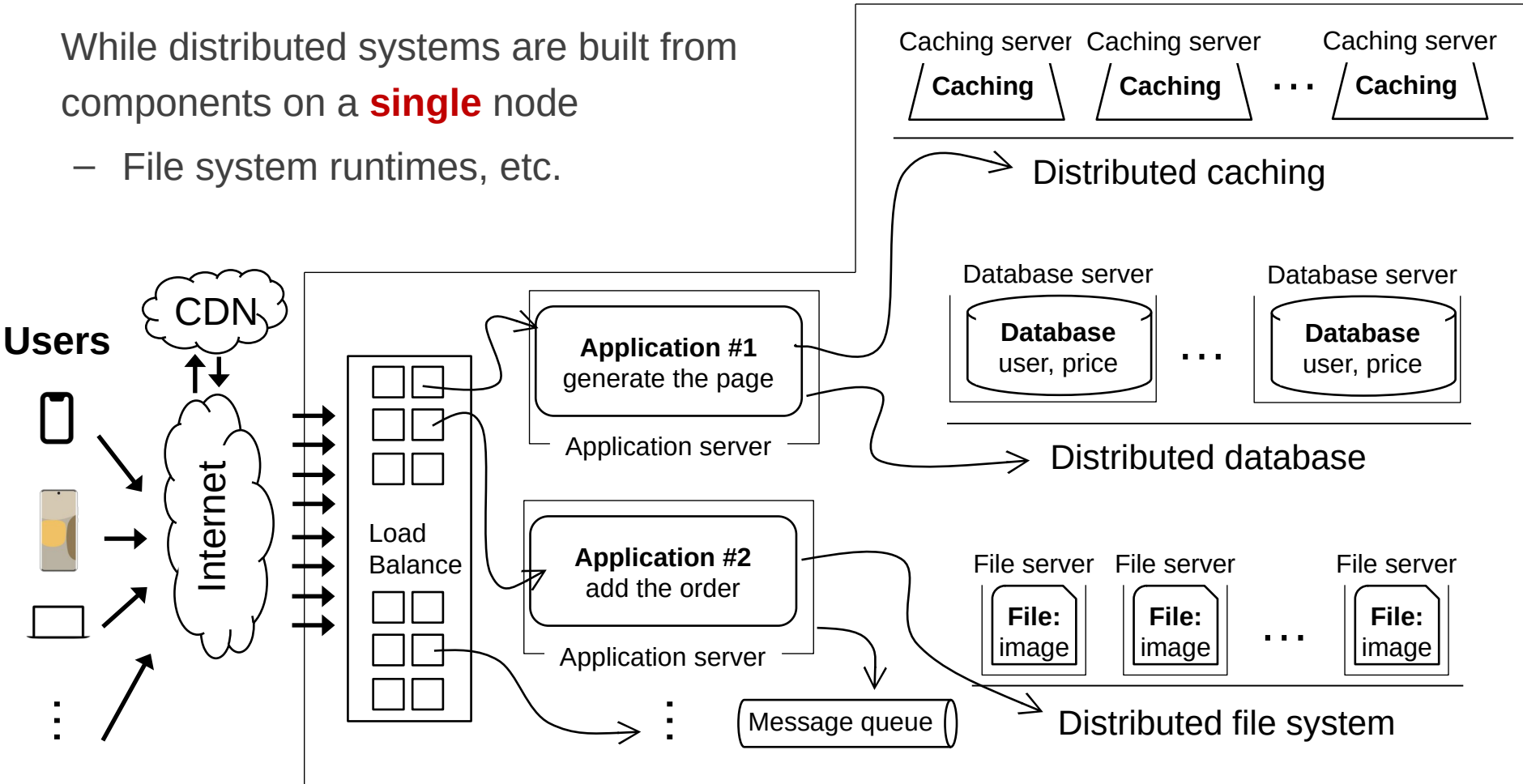
IPADS, Shanghai Jiao Tong University

https://www.sjtu.edu.cn

Large-scale websites are built from distributed systems

While distributed systems are built from components on a **single** node

- File system runtimes, etc.



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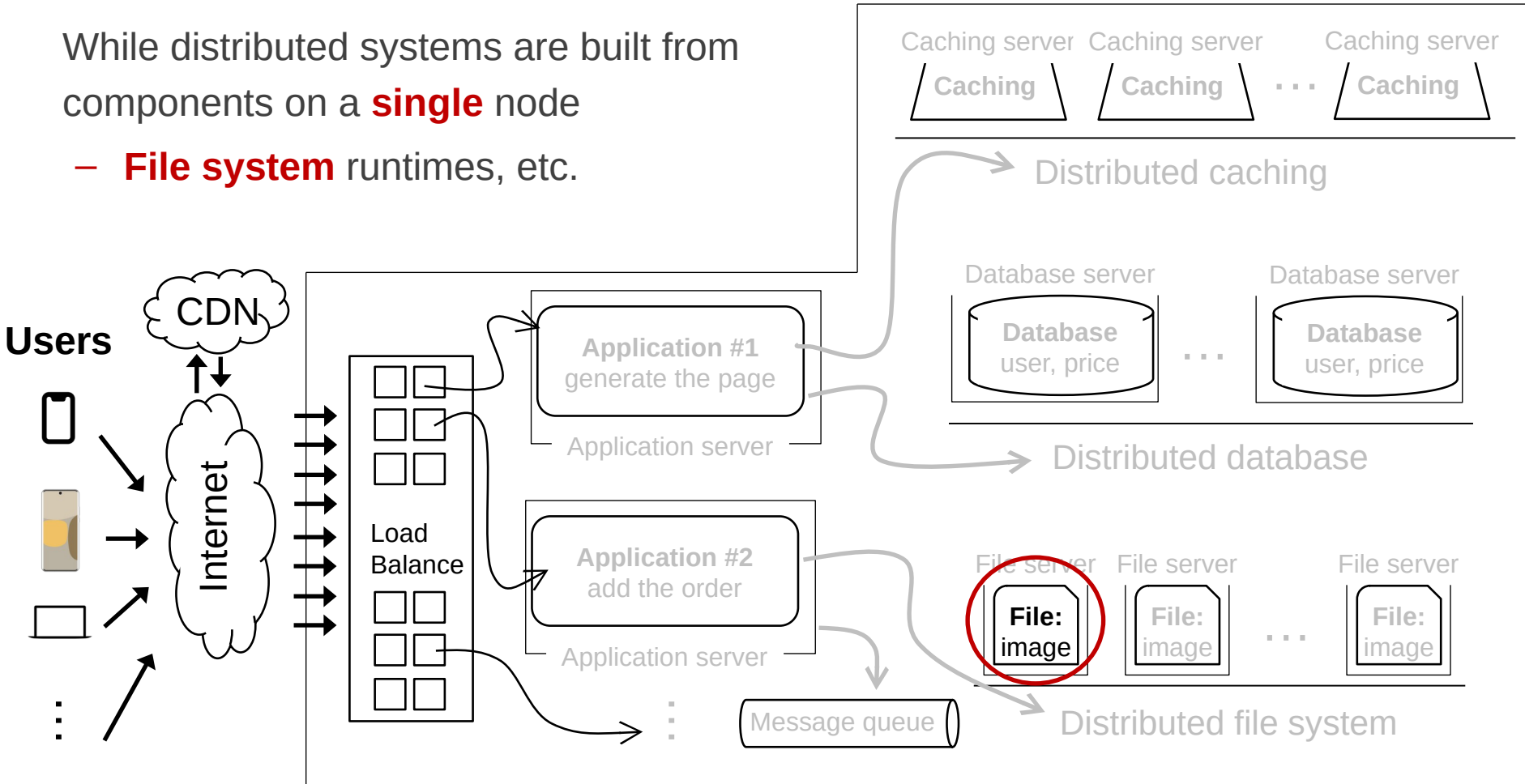
- **File system** runtimes, etc.



iNode-based File System

What is a file?

Storage as files

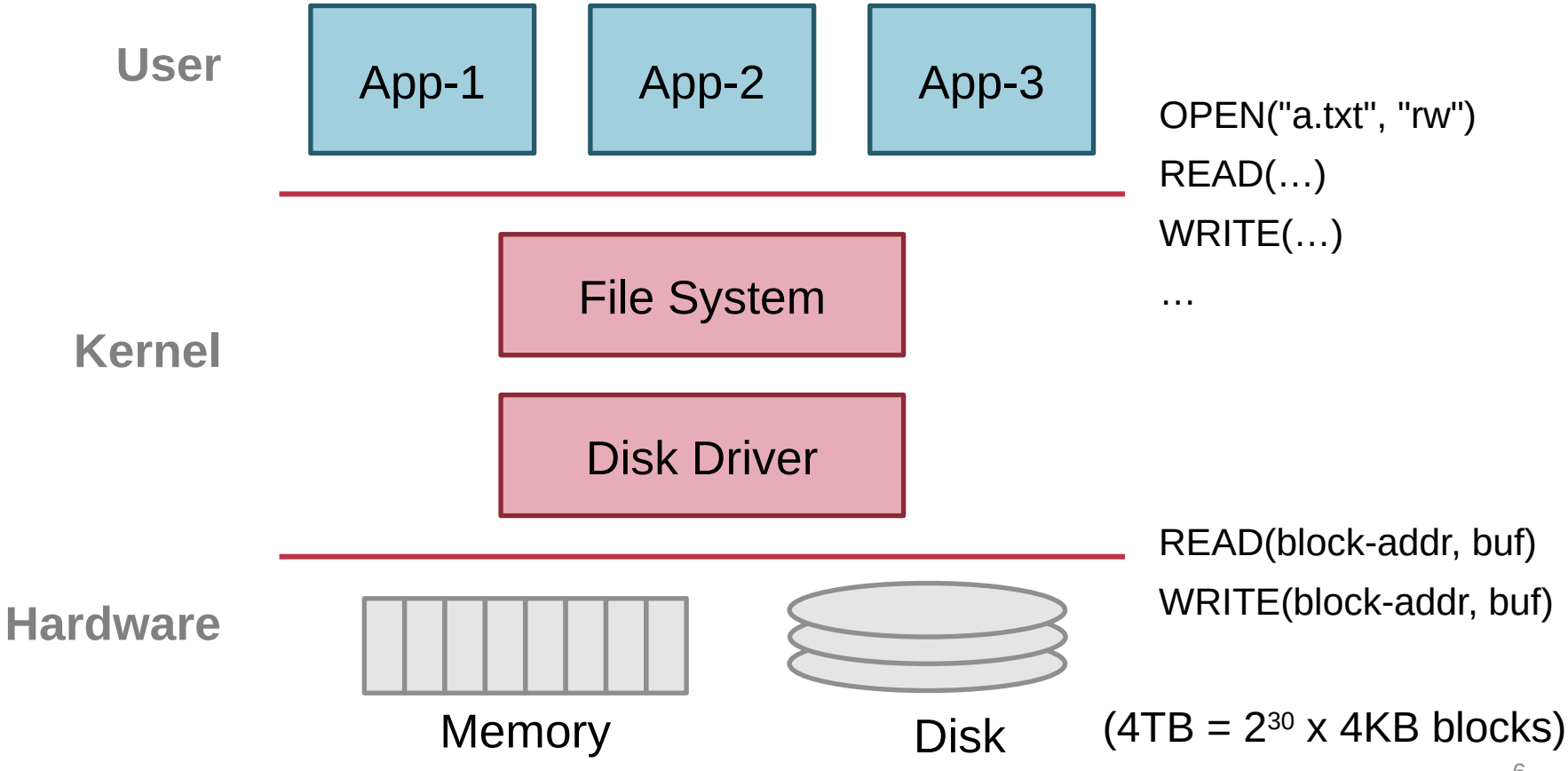
A file has **two key properties:**

- It is **durable** & has a **name**
- It is a high-level version of the memory abstraction

System layer implements files using **modules from hardware layer**

- **Divide-and-conquer** strategy
- Makes use of several hidden layers of machine-oriented names (addresses), one on another, to implement files
- Maps user-friendly names to these files

The Big Picture



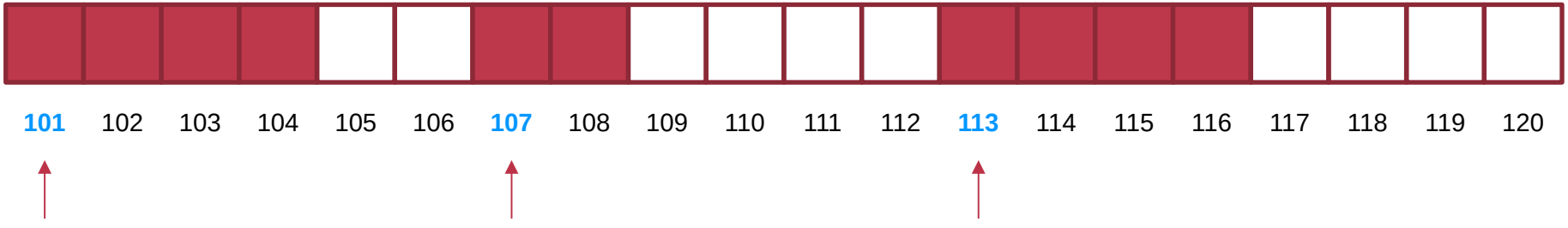
Abstraction: API of UNIX File System

```
OPEN, READ, WRITE, APPEND, SEEK, CLOSE

FSYNC

STAT, CHMOD, CHOWN

RENAME, LINK, UNLINK, SYMLINK

MKDIR, CHDIR, CHROOT

MOUNT, UNMOUNT

….
```

A Naive File System

Each file occupies one continuous range of blocks

- Use **block index** as file name, e.g., 107, 113
- Every file write will either **append** or **reallocate**



What are the **problems**?

inode: 7 software layers

The Naming Layers of the UNIX FS (version 6)

Layer	Purpose	
Symbolic link layer	Integrate multiple file systems with symbolic links.	↑
Absolute path name layer	Provide a root for the naming hierarchies.	user-oriented names
Path name layer	Organize files into naming hierarchies.	↓
File name layer	Provide human-oriented names for files.	machine-user interface
Inode number layer	Provide machine-oriented names for files.	↑
File layer	Organize blocks into files.	machine-oriented names
Block layer	Identify disk blocks.	↓

L1: Block Layer

Block num	Disk Block

Mapping: block number -> block data

```
procedure BLOCK_NUMBER_TO_BLOCK(integer b)-> block
  return devices[b]
```

How to know the **size** of block?

- How to know which block is free?
- These **metadata** will also be stored on the same disk
- Super block! 

Super Block

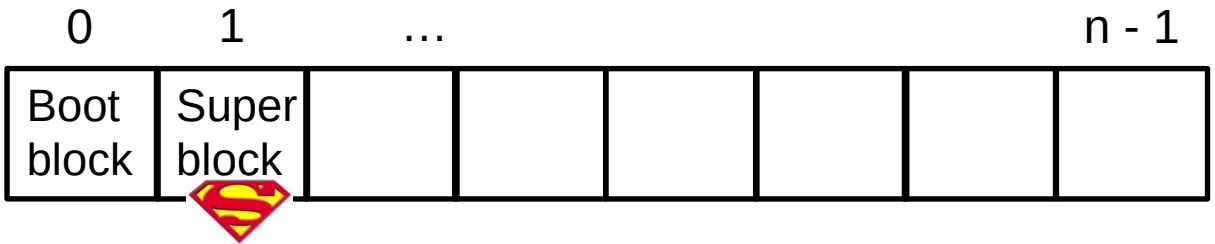
Block num	Disk Block

One superblock per file system

- Kernel reads superblock when mount the FS

Superblock **contains**:

- Size of the blocks
- Number of free blocks
- A list of free blocks
- Other metadata of the file system (including inode info)



L1: Block Layer

Block num	Disk Block

Block size: a trade-off

- Neither too small or too big

Question

- What will happen if the block size is too small? What if too big?
- How to efficiently track free blocks?

L1: Block Layer

Block num	Disk Block

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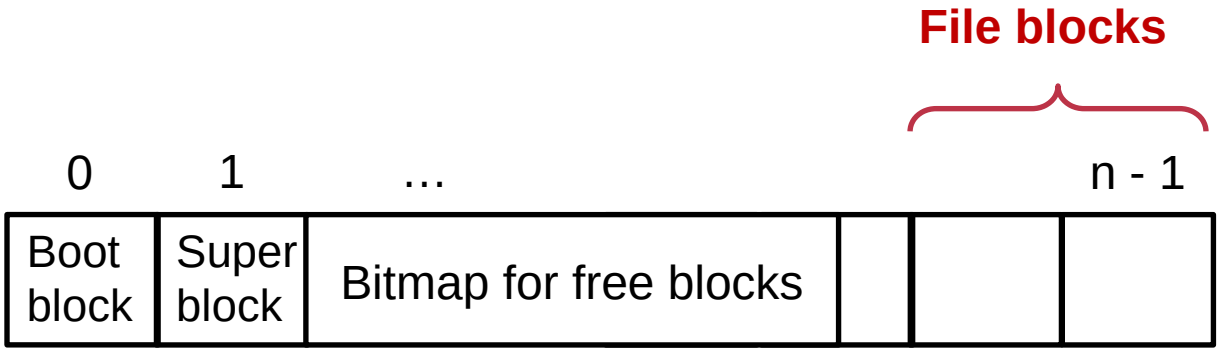
Use a bitmap



L2: File Layer

File (inode)	Block num	Disk Block

File requirements

- Store items that are larger than one block
- May grow or shrink over time
- A file is a linear array of bytes of arbitrary length
- Record which blocks belong to each file

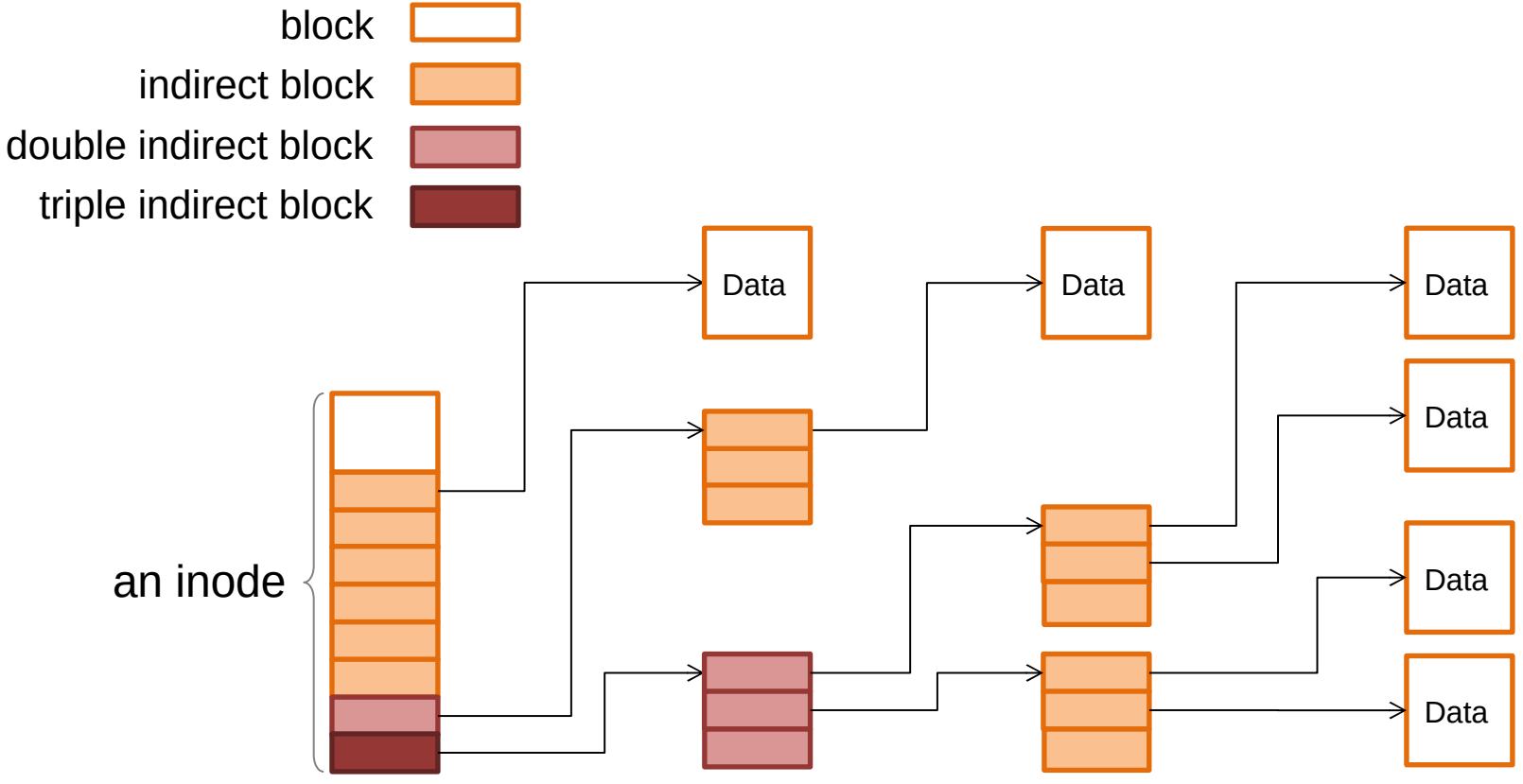
inode (index node)

- A container for **metadata** about the file

```
struct inode
  integer block_nums[N]
  integer size
```

inode for Larger Files

File (inode)	Block num	Disk Block



L2: File Layer

File (inode)	Block num	Disk Block

Given an inode, can map a block index number (of a file) to a block number (of a disk)

- Index number: e.g., the 3rd block of a file is number 78

```
procedure INODE_TO_BLOCK(integer offset, inode i)-> block
    o <- offset / BLOCKSIZE
    b – INDEX_TO_BLOCK_NUMBER(i,o)
    return BLOCK_NUMBER_TO_BLOCK(b)
```

```
    procedure INDEX_TO_BLOCK_NUMBER(inode i, integer
    index)-> integer
        return i.block_nums[index]
```

L3: inode Number Layer

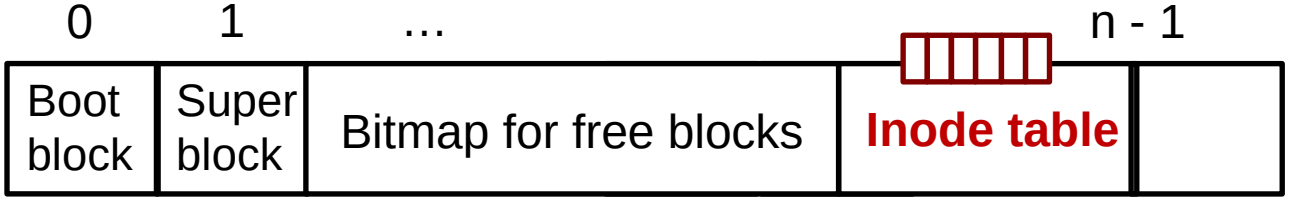
Inode num	File (inode)	Block num	Disk Block

Mapping: **inode number -> inode**

```
procedure INODE_NUMBER_TO_INODE(integer num)-> inode
  return inode_table[num]
```

inode table: at a fixed location on storage

- inode number is the index of inode table
- Track which inode number are in use, e.g. free list, a field in inode



Put Layers so far Together

Inode num	File (inode)	Block num	Disk Block

```
procedure INODE_NUMBER_TO_BLOCK(integer offset,
integer inode_number)-> block
  inode i = INODE_NUMBER_TO_INODE(inode_number)
  o <- offset / BLOCKSIZE
  b <- INDEX_TO_BLOCK_NUMBER(i,o)
  return BLOCK_NUMBER_TO_BLOCK(b)
```

inode number is sufficient to operate a file. However,

- inode numbers are convenient names only for computer
- inode numbers change on different storage device

A file needs a more **user-friendly name**!

L4: File Name Layer

File name	Inode num	File (inode)	Block num	Disk Block

File name

- Hide metadata of file management
- Files and I/O devices

Mapping

- Mapping table is saved in directory
- Default context: **current working directory**
  - Context reference is an inode number
  - The current working directory **is also a file**

```
struct inode
  integer block_nums[N]
  integer size
  integer type
```

Overview of inode content

File name	inode num
helloworld.txt	12
cse2021.md	73

```
procedure name_to_inode(string filename, integer dir)-> integer
    return LOOKUP(dir, filename)
```

- Max length of a file name is **14 bytes** in UNIX version 6 (what does it mean?)

LOOKUP in a Directory

File name	Inode num	File (inode)	Block num	Disk Block

```
procedure LOOKUP(string filename, integer dir)-> integer
  block b
  inode i = INODE_NUMBER_TO_INODE(dir)
  if i.type != DIRECTORY then return FAIURE
  for offset from 0 to i.size – 1 do
      b <- INODE_NUMBER_TO_BLOCK(offset, dir)
      if STRING_MATCH(filename, b) then
        return INODE_NUMBER(filename, b)
     offset <- offset + BLOCKSIZSE
  return FAILURE
```

Name comparing method: `STRING_MATCH`

- LOOKUP(”cse2021", dir) will return 73

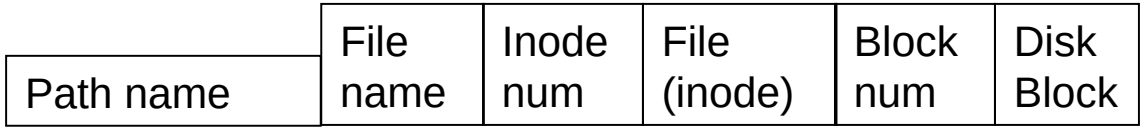
Next problem**:**

- What if there are too many files?

Overview of inode content

File name	inode num
helloworld.txt	12
cse2021.md	73

L5: Path Name Layer



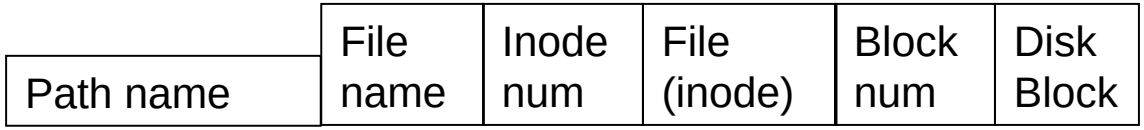
Hierarchy of directories and files

- Structured naming: E.g. "projects/paper"

```
procedure PATH_TO_INODE_NUMBER(string path, integer dir)-> integer
    if PLAIN_NAME(path)return NAME_TO_INODE_NUMBER(path,dir)
    else
        dir <- LOOKUP(FIRST(path), dir)
        path <- REST(path)
        return PATH_TO_INODE_NUMBER(path,dir)
```

Context: the working directory **`dir`**

Links



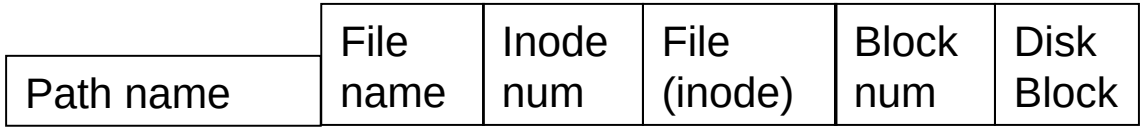
LINK: create shortcut for long names

- LINK("Mail/inbox/new-assignment", "assignment")
- Turns strict hierarchy into a directed graph
    - Users cannot create links to directories -> acyclic graph
- Different filenames, same inode number

UNLINK

- Remove the binding of filename to inode number
- If UNLINK last binding, put inode/blocks to a free-list
    - A reference counter is needed

Links



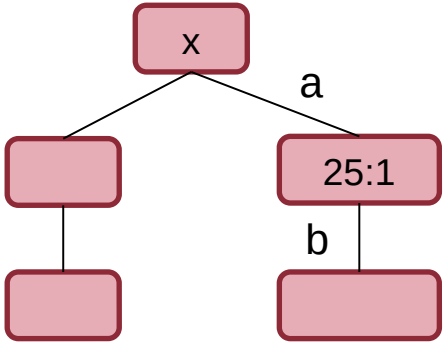
Reference count

- An inode can bind multiple file names
- +1 when **LINK**, -1 when **UNLINK**
- A file will be deleted when reference count is 0
- **No cycle allowed**
  - Except for '.' and '..'
  - Naming current and parent directory with no need to know their names

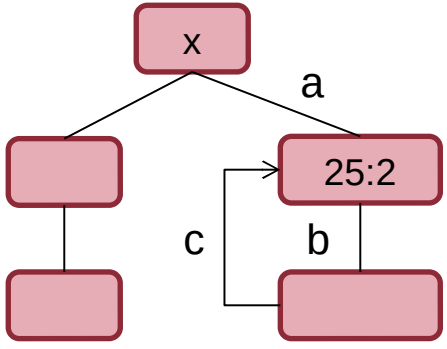
```
struct inode
  integer block_nums[N]
  integer size
  integer type
  integer refcnt
```

No Cycle for LINK

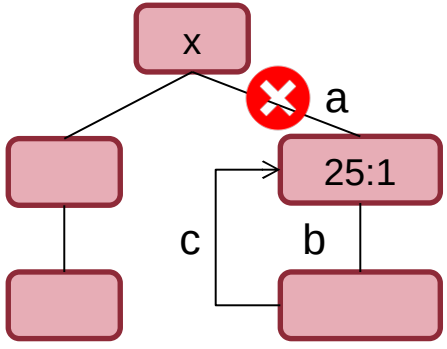
Path name	File name	Inode num	File (inode)	Block num	Disk Block



- /a/b is a directory
- The refcnt of a is 1
- a's inode num is 25



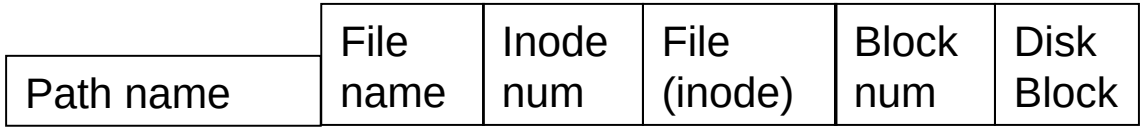
- LINK ("/a/b/c", a")
- Cause a cycle!
- Refcnt of a is 2



- UNLINK ("/a")
- Refcnt of a is 1, so the inode 25 is not deleted
- Now inode 25 is dis-connected from graph
- No one can get it!

Think: Why deleting a directory requires to delete all the files in it first?

Renaming - 1




```
1 UNLINK(to_name)
2 LINK(from_name, to_name)
3 UNLINK(frome_name)
```

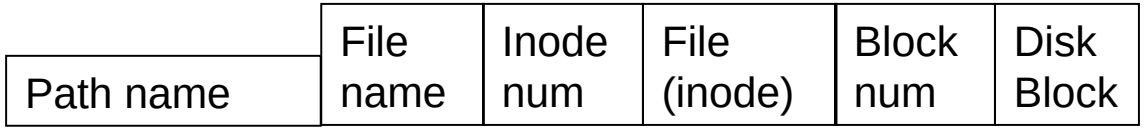
Text edit usually save editing file in a **temp** file

- Edit in `.a.txt.swp`, then rename `.a.txt.swp` to `a.txt`

What if the computer **fails between 1 & 2**?

- The file `to_name` will be lost, which will surprise the user
- Need **atomic** action (in later lectures)

Renaming - 2




```
1 LINK(from_name, to_name)
2 UNLINK(frome_name)
```

Weaker specification without atomic actions

- 1. Changes the inode number in for `to_name` to the inode number of `from_name`
- 2. Removes the directory entry for `from_name`

If fails between 1 & 2

- Must increase reference count of `from_name`'s inode on recovery

If `to_name` already exists

- It will always exist even if the machine fails between 1 & 2

L6: Absolute Path Name Layer

Absolute path / Path name	File name	Inode num	File (inode)	Block num	Disk Block

HOME directory

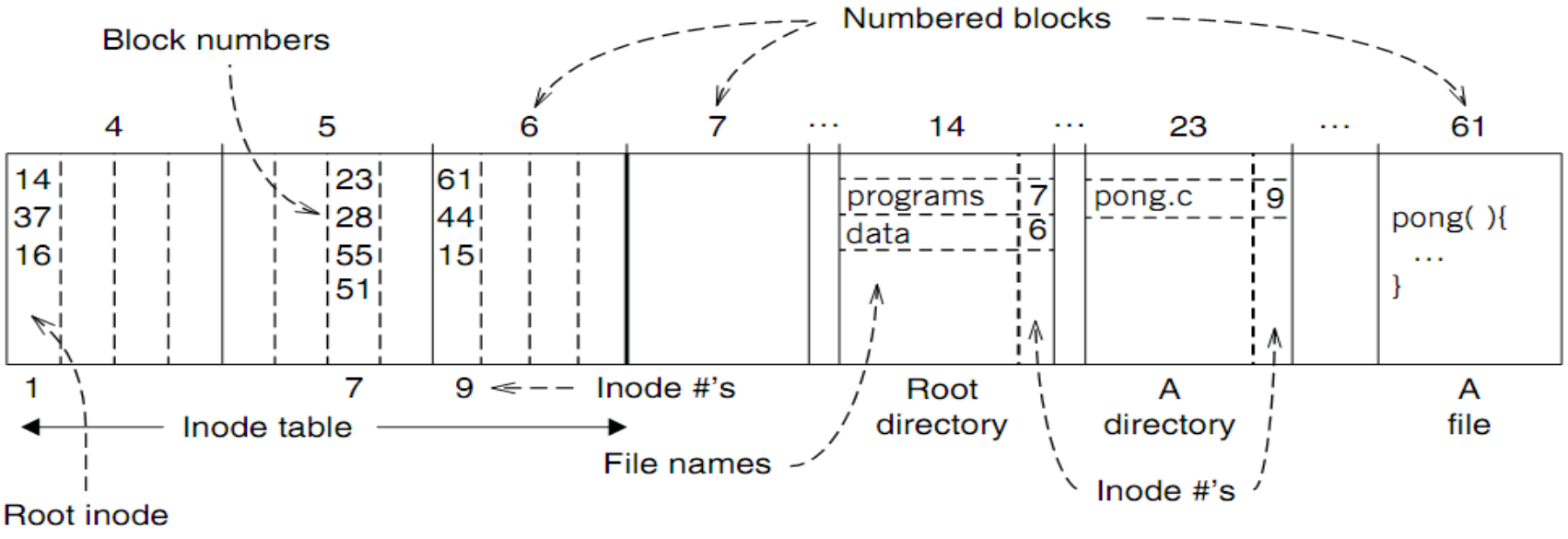
- Every user has a default working directory (HOME) after login
- Problem: no sharing of files between users

Introducing the **root** directory

- A universal context for all users
- A well-known name: '/'
- Both '/.' and '/..' are linked to '/'

```
procedure GENERATEPATH_TO_INODE_NUMBER(string path)-> integer
  if path[0] = "/" return PATH_TO_INODE_NUMBER(path,1)
  else return PATH_TO_INODE_NUMBER(path, wd)
```

An Example: Find Blocks of "/programs/pong.c"



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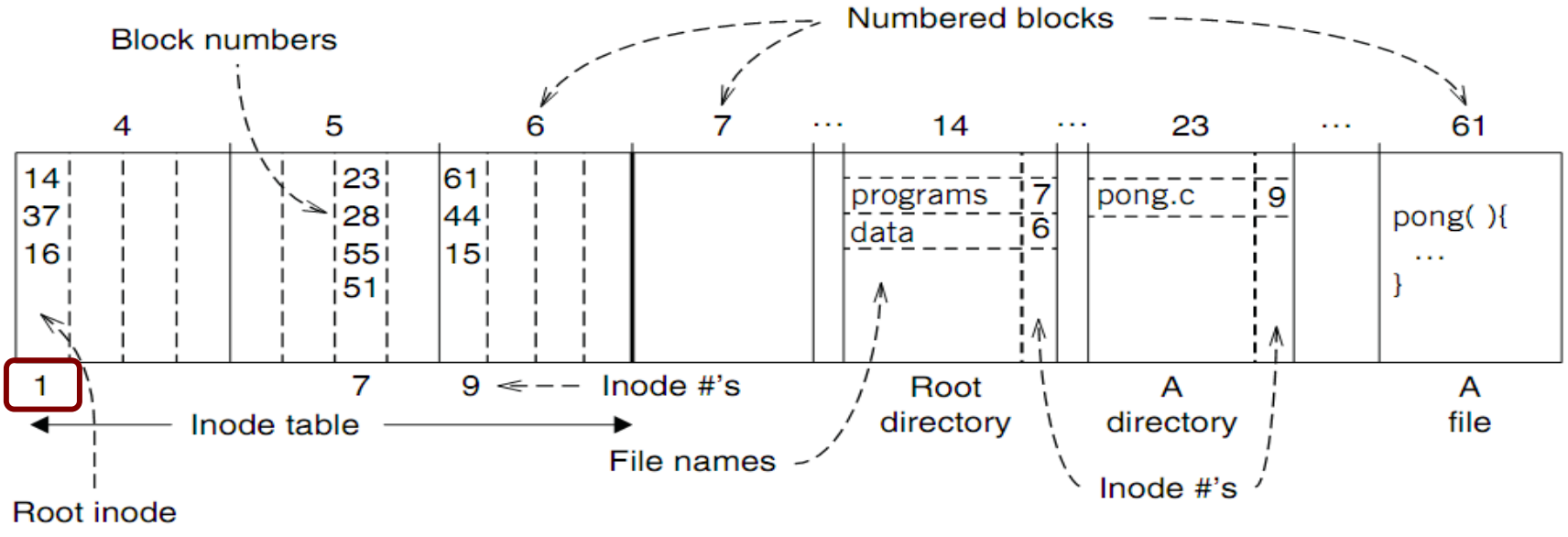
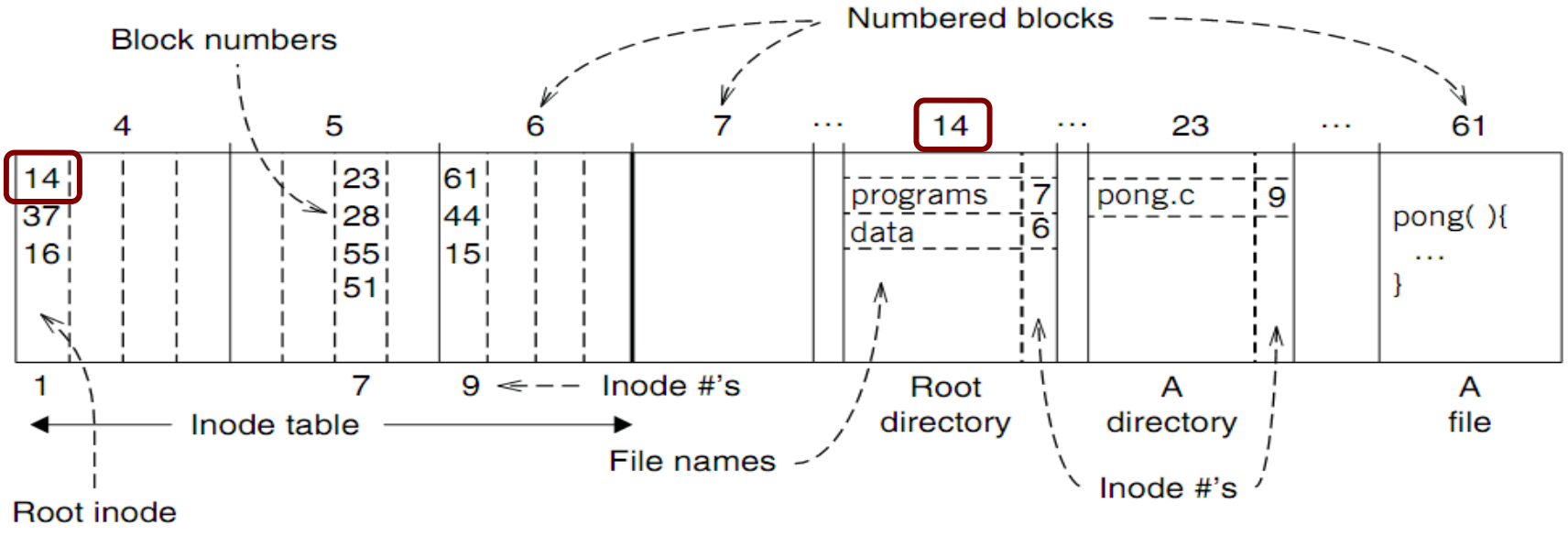


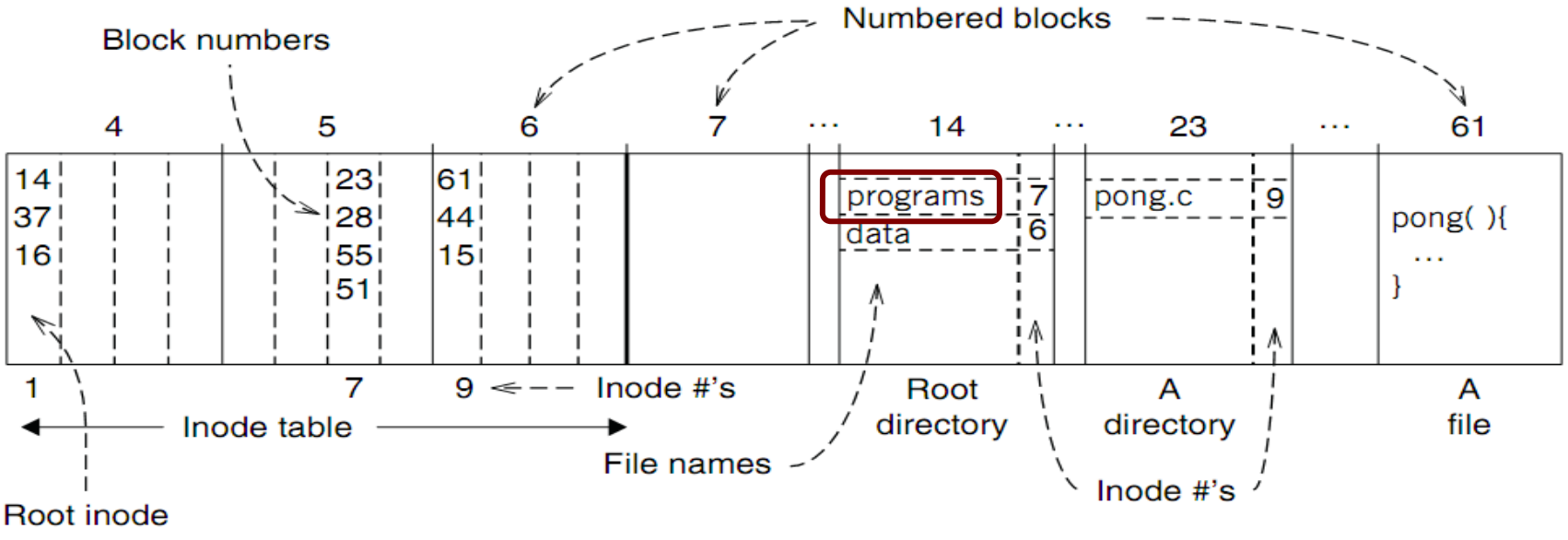
'/' root directory: inode is 1

An Example: Find Blocks of "/programs/pong.c"



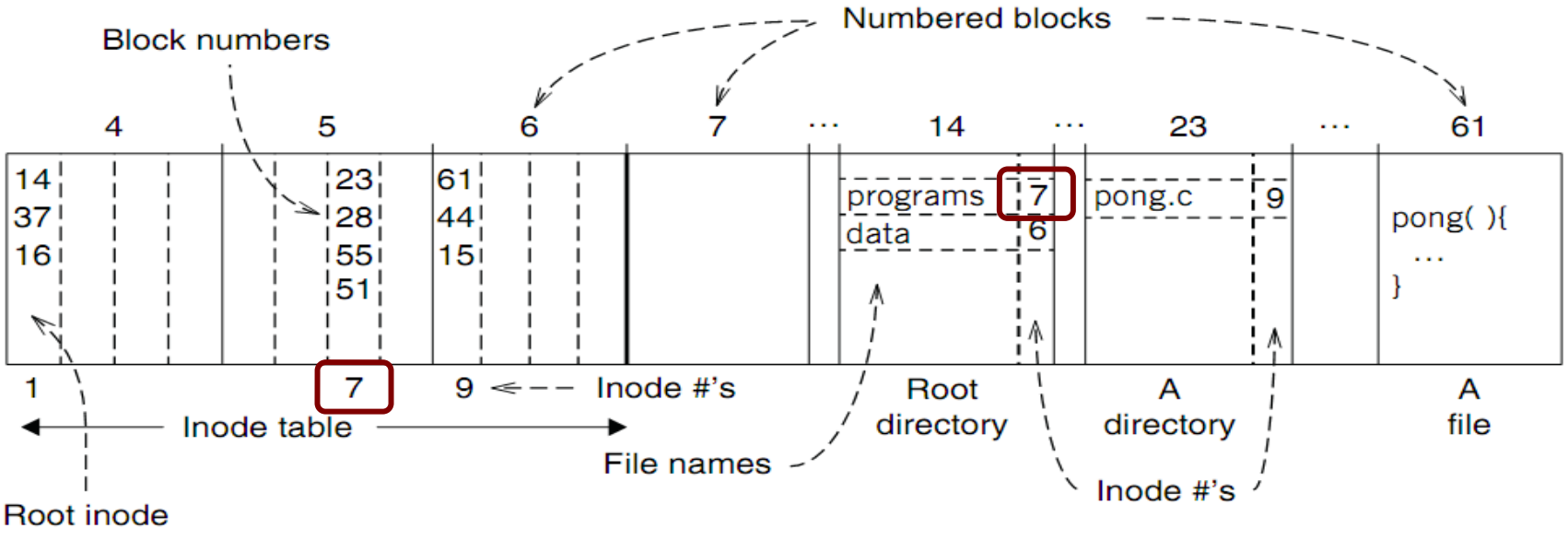
Find the first directory in '/' by block number

An Example: Find Blocks of "/programs/pong.c"



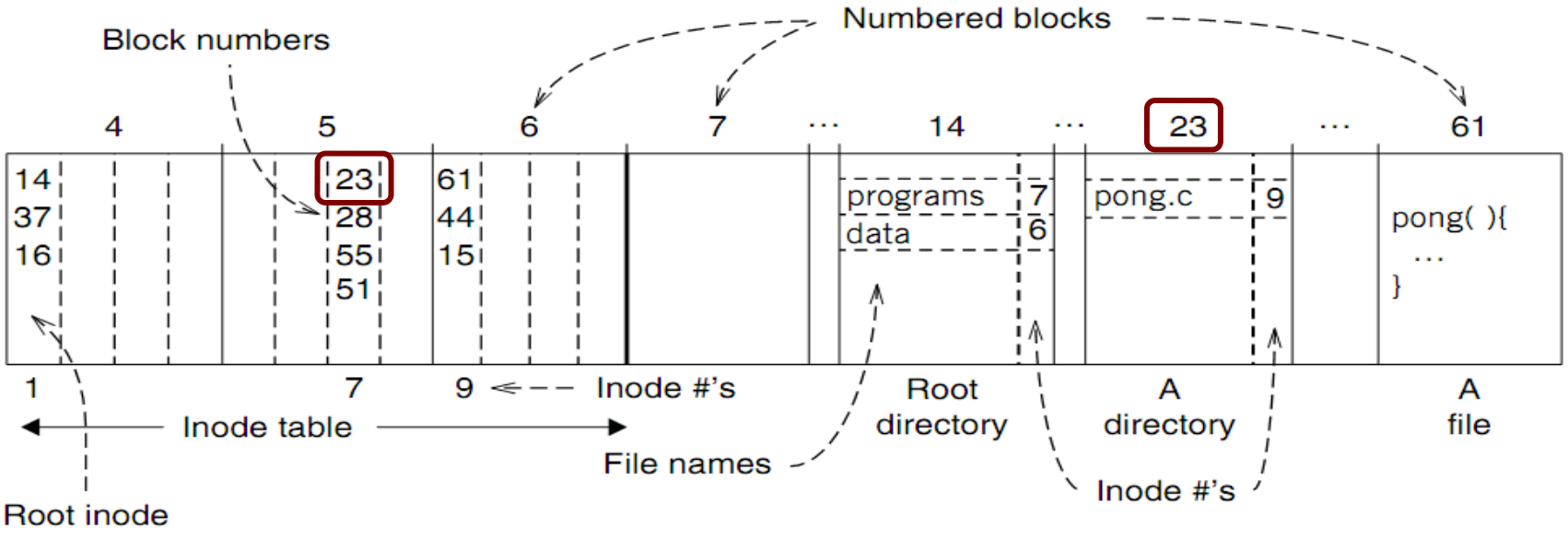
Find '/programs' by comparing name

An Example: Find Blocks of "/programs/pong.c"



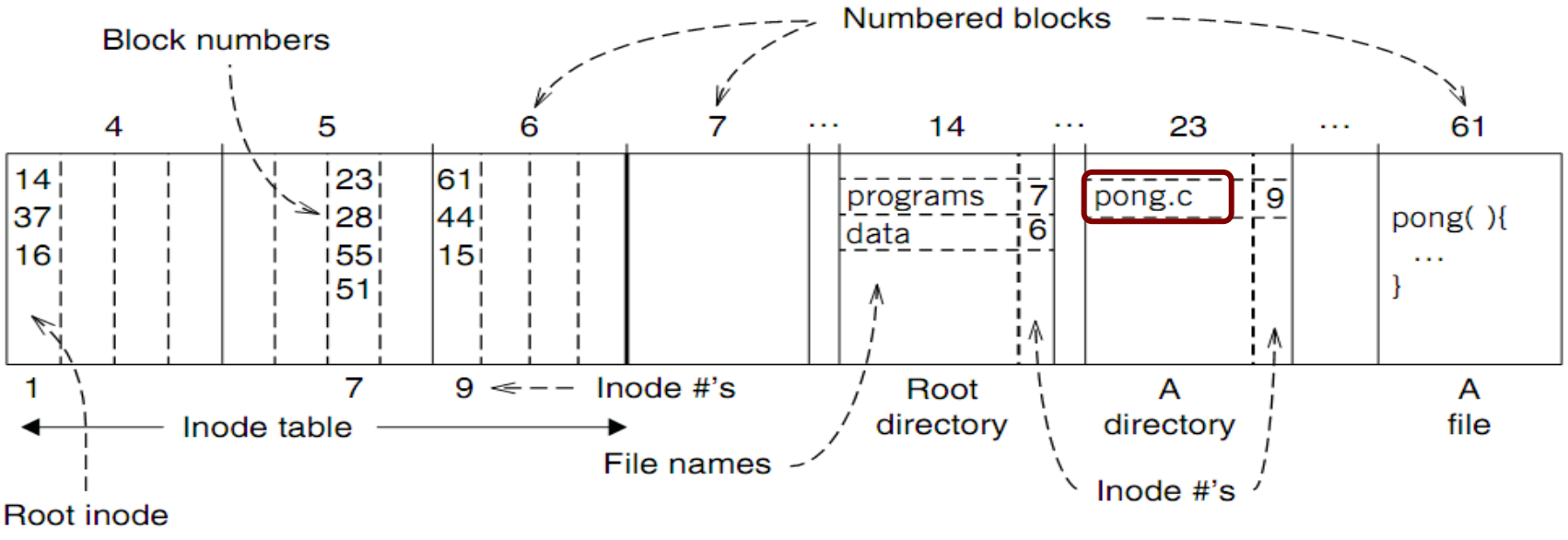
Find '/programs' inode by its inode number 7

An Example: Find Blocks of "/programs/pong.c"



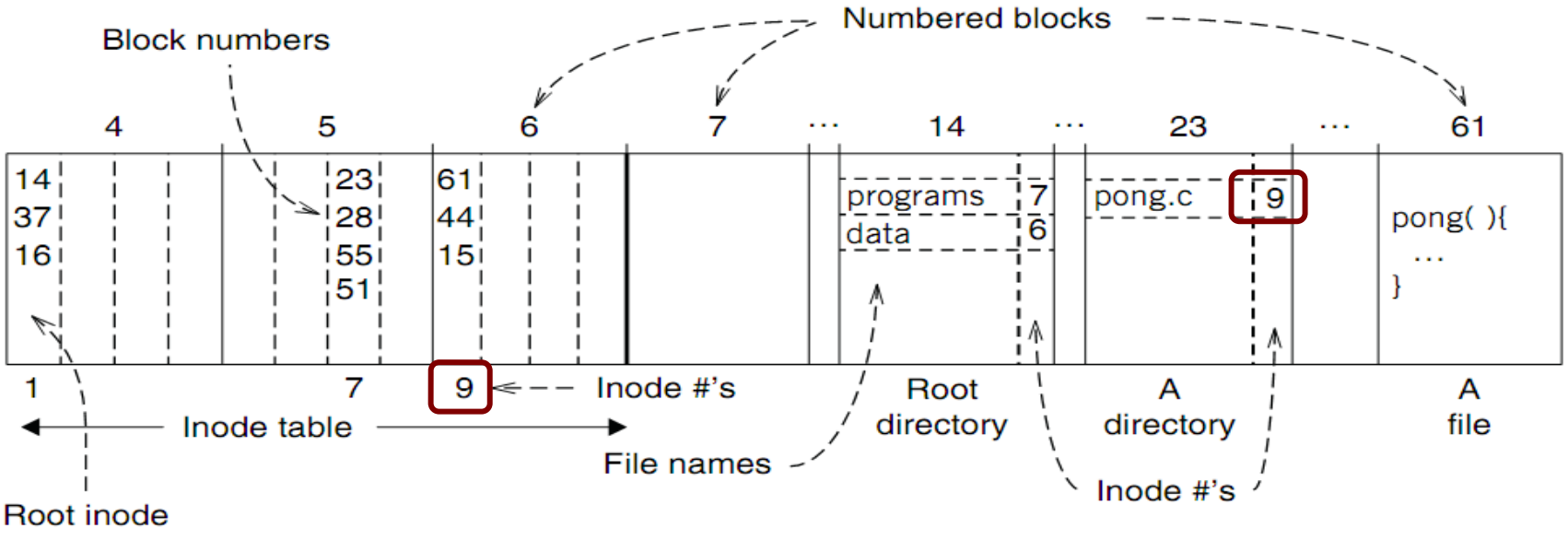
Find the first file in '/programs/'

An Example: Find Blocks of "/programs/pong.c"



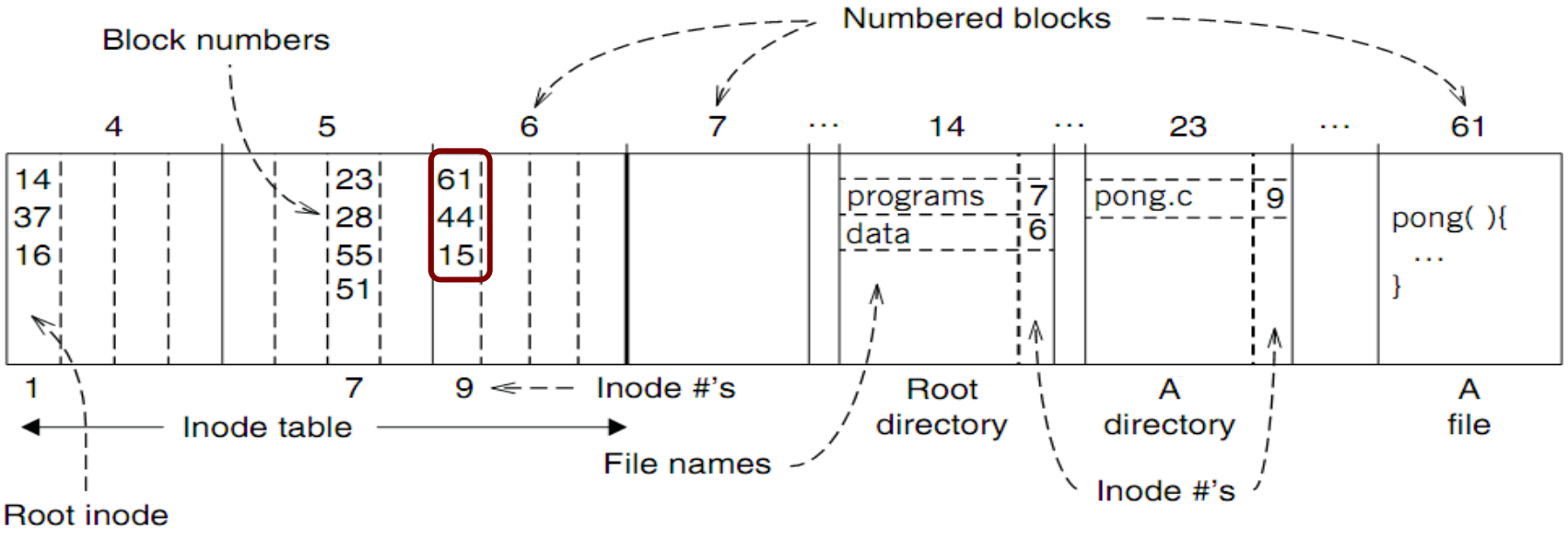
Find '/programs/pong.c' by comparing its name

An Example: Find Blocks of "/programs/pong.c"



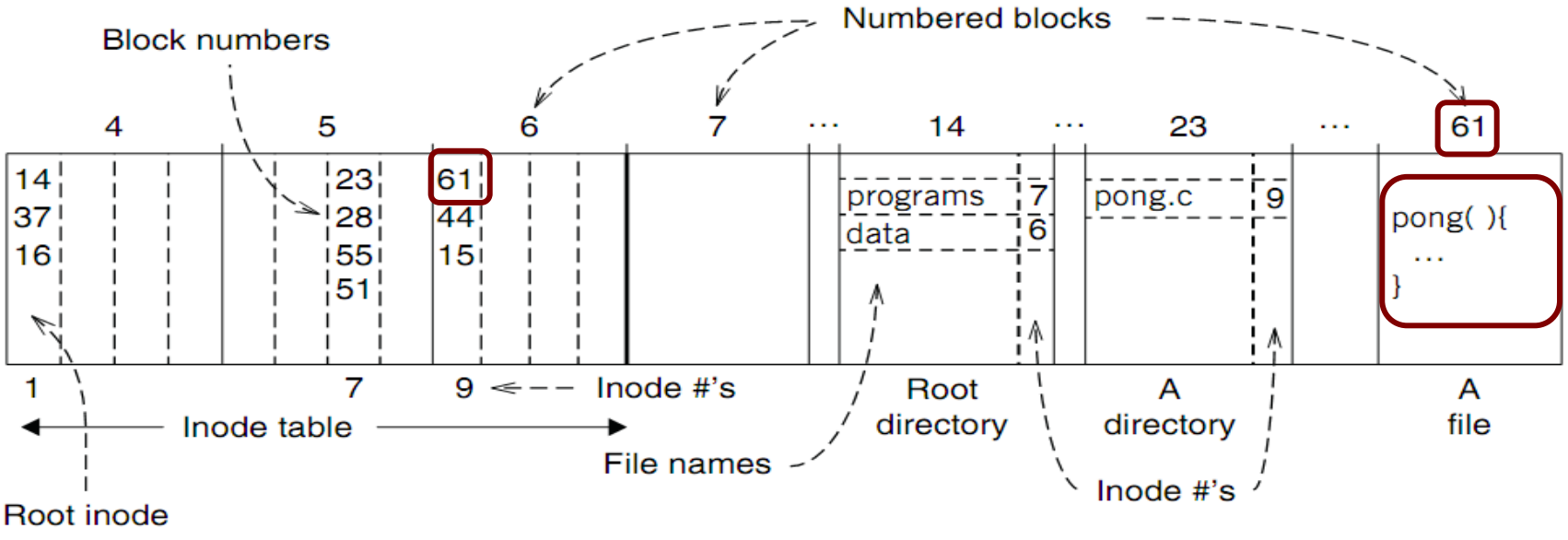
Find inode of '/programs/pong.c' by the inode number 9

An Example: Find Blocks of "/programs/pong.c"



Find block number of '/programs/pong.c'

An Example: Find Blocks of "/programs/pong.c"



Find data of block 61 by its block number

- And data of block 44 & 15

Directly Dump a Directory

```
$ ls -ai temp
7536909 .  7530417 ..  7536939 a  7536940 b  7536941 c  7536942 d

$ echo “obase=16;7536909;7530417;7536939;7536940;7536941;7536942" | bc
73010D  72E7B1  73012B  73012C  73012D  73012E

$ sudo /sbin/debugfs /dev/sda1
debugfs 1.43.4 (31-Jan-2017)
debugfs:  dump temp temp.out
debugfs:  quit

$ xxd temp.out
0000000: 0d01 7300 0c00 0102 2e00 0000 b1e7 7200  ..s...........r.
0000010: 0c00 0202 2e2e 0000 2b01 7300 0c00 0101  ........+.s.....
0000020: 6100 0000 2c01 7300 0c00 0101 6200 0000  a...,.s.....b...
0000030: 2d01 7300 0c00 0101 6300 0000 2e01 7300  -.s.....c.....s.
0000040: c40f 0101 6400 0000 0000 0000 0000 0000  ....d...........
0000050: ...
```

Directly Dump a Directory

```
struct ext4_dir_entry {
  uint32_t inode_number;
  uint16_t dir_entry_length;
  uint8_t  file_name_length;
  uint8_t  file_type;
  char     name[EXT4_NAME_LEN];
}
```

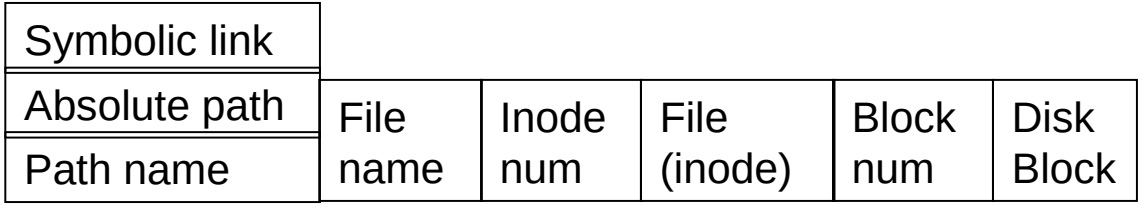
```
0d01 7300 0c00 0102 2e00 0000
b1e7 7200 0c00 0202 2e2e 0000
2b01 7300 0c00 0101 6100 0000
2c01 7300 0c00 0101 6200 0000
2d01 7300 0c00 0101 6300 0000
2e01 7300 c40f 0101 6400 0000
```

File Type
- 0x0: Unknown
- 0x1: Regular file
- 0x2: Directory
- 0x3: Character device file
- 0x4: Block device file
- 0x5: FIFO
- 0x6: Socket
- 0x7: Symbolic link

```
0d01 7300 0c00 0102 2e00 0000
```

```
0d01 7300: inode number
     0c00: entry length is 12 bytes
       01: file name length is 1 byte
       01: file type is regular file
2e00 0000: file name (2e -> ".")
```

L7: Symbolic Link Layer



Name files **on other disks**

- Inode is different on other disks
- Supports to attach new disks to the name space

Two options

- Make inodes unique across all disks (not good)
- Create synonyms for the files on the other disks

Introducing layer 7: soft link (symbolic link)

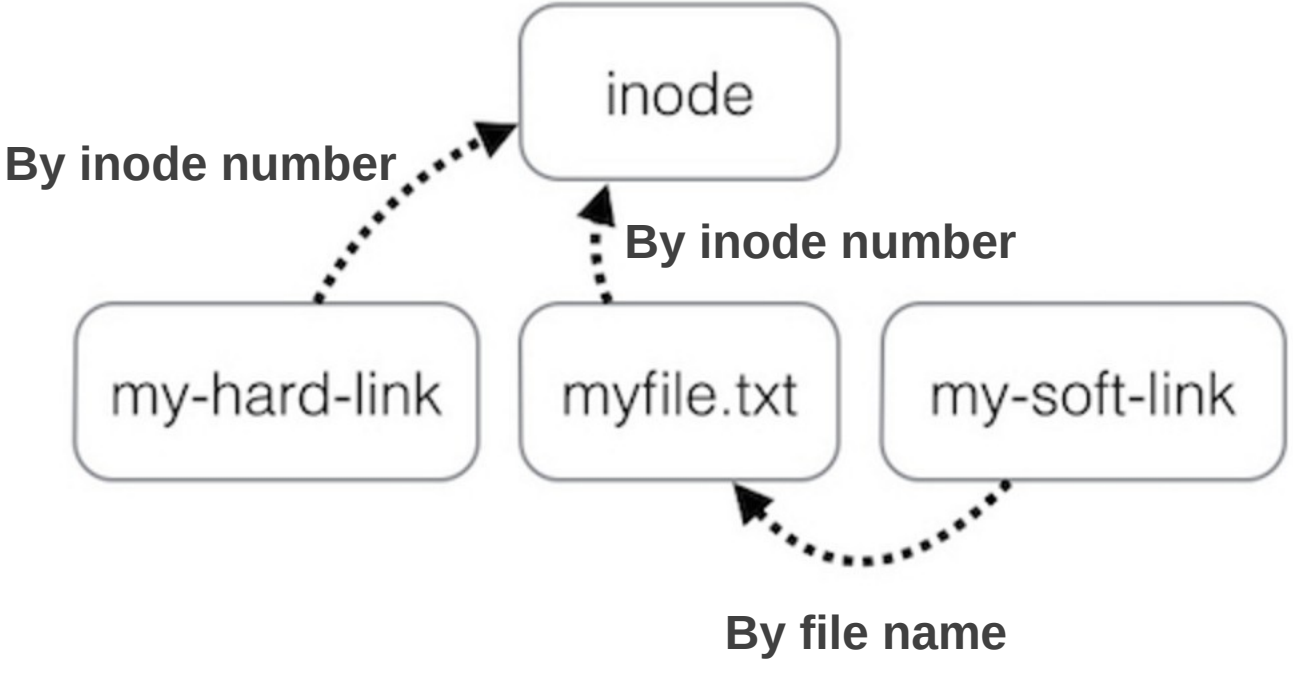
- SYMLINK
- Add another type of inode

Directly Dump a Symbolic Link

```
$ ln -s "/tmp/abc" s-link

$ ls –l s-link
7536945 lrwxrwxrwx 1 xiayubin 8 Sep 20 08:01 s-link -> /tmp/abc

$ readlink s-link
/tmp/abc

$ cat s-link
cat: slink: No such file or directory

$ echo "hello, world" > /tmp/abc

$ cat s-link
hello, world
```

What does "8" means? **File size**

Two Types of Links (Synonyms)



Sidebar: Notice the Context Change

Another **interesting behavior** of soft link

- There is a directory: "/Scholarly/programs/www"
- The root directory contains a soft link
    - "/CSE-web" -> "/Scholarly/programs/www"
- Run following commands
    - `cd CSE-web`
    - `cd ..`
- What is the current directory? Why?
    - ".." is resolved in a new default context: by bash, not file system

Sidebar: Notice the Context Change

The bash tries to be **"human-friendly"**

- When you `cd /into/a/symlink/`, the shell remembers the old location (in **$OLDPWD**) and will use that directory when you `cd ..` under the assumption that you want to return to the directory you were just in

If you want to use the real .., then you must also use **"cd -P .."**

> *The -P option says to use the physical directory structure instead of following symbolic links (see also the -P option to the set built-in command); the -L option forces symbolic links to be followed.*

```
$ cd
$ cd a/b/symlink
$ cd -P ..
$ pwd -P
/home/sarnold
$
```

Summary of File System's 7 Layers

File name is not part of a file

- Name is **not** a part of an inode
- Name is data of a directory, and metadata of a file system
- One inode can have several names (hard links)

Hard links are equal

- If a file has two names, both are links (instead of "a link and a name")

Directory size is small

- Only mapping from name to inode number
- The term "folder" is somewhat misleading