Persistence: File System API

Questions answered in this lecture:

How to **name** files?

- What are **inode numbers**?
- How to **lookup** a file based on pathname?
- What is a **file descriptor**?

What is the difference between **hard and soft links**?

How can **special requirements** be communicated to file system (fsync)?

What is a File?

- **Array of persistent bytes that can be read/written**

- **File system consists of many files**
  - Refers to collection of files
  - Also refers to part of OS that manages those files

- **Files need names to access correct one**
  - What is the name of a file?

File Names

- **Three types of names**
  - Unique id: inode numbers
  - Path
  - File descriptor

Inode Number

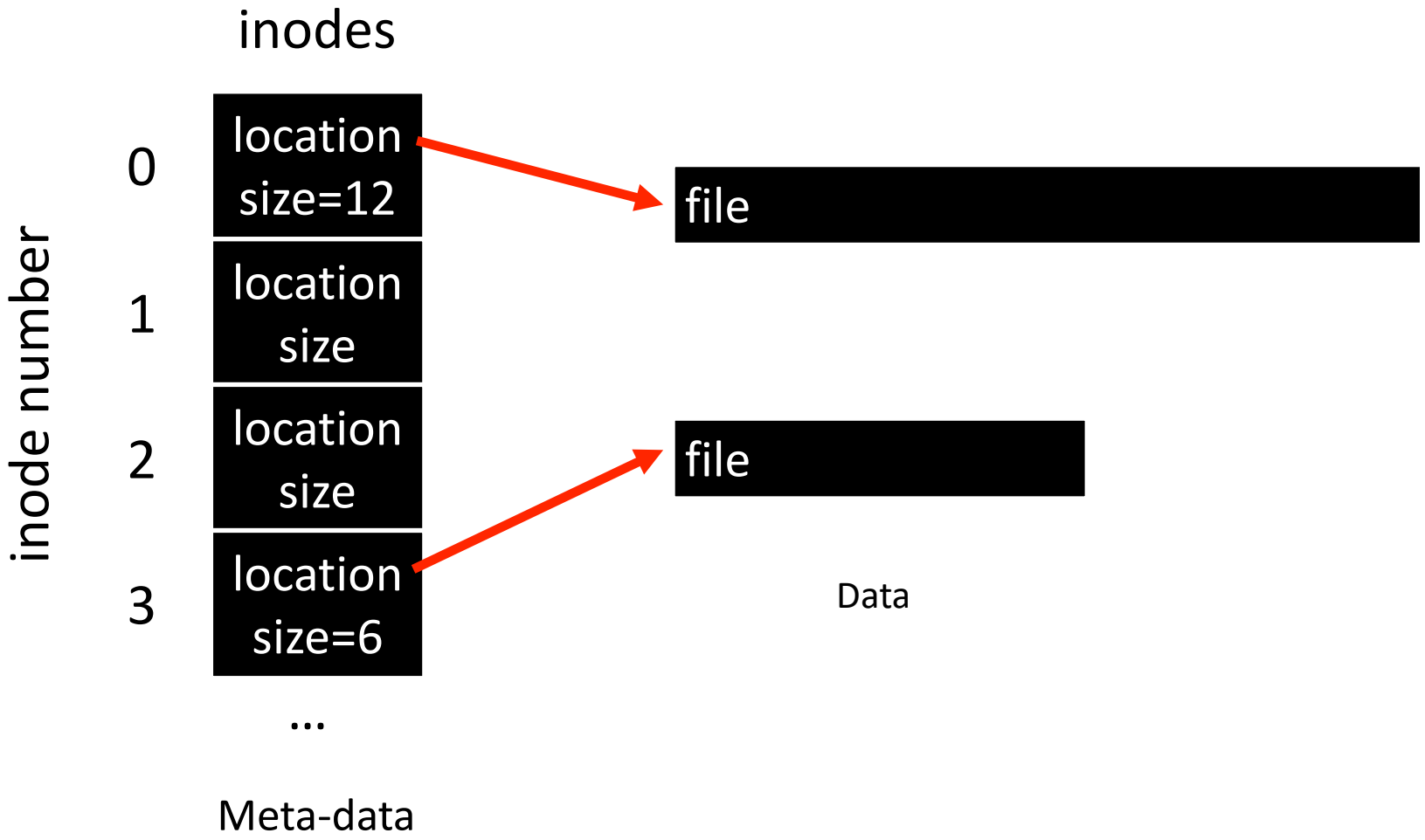
- Each file has exactly one inode number
- Inodes are unique (at a given time) within file system
- Different file system may use the same number, numbers may be recycled after deletes
- See inodes via “ls –i”; see them increment…

What does “i” stand for?

“In truth, I don't know either. It was just a term that we started to use. ‘Index’ is my best guess, because of the slightly unusual file system structure that stored the access information of files as a flat array on the disk…”

~ Dennis Ritchie

The farther of C, Key developer of Unix


inodes
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
Meta-data
file
file
Data

File API (attempt 1)

read(int inode, void *buf, size_t nbyte)

write(int inode, void *buf, size_t nbyte)

seek(int inode, off_t offset)

seek does not cause disk seek until read/write

- Disadvantages?
  - names hard to remember
  - no organization or meaning to inode numbers
  - semantics of offset with multiple processes

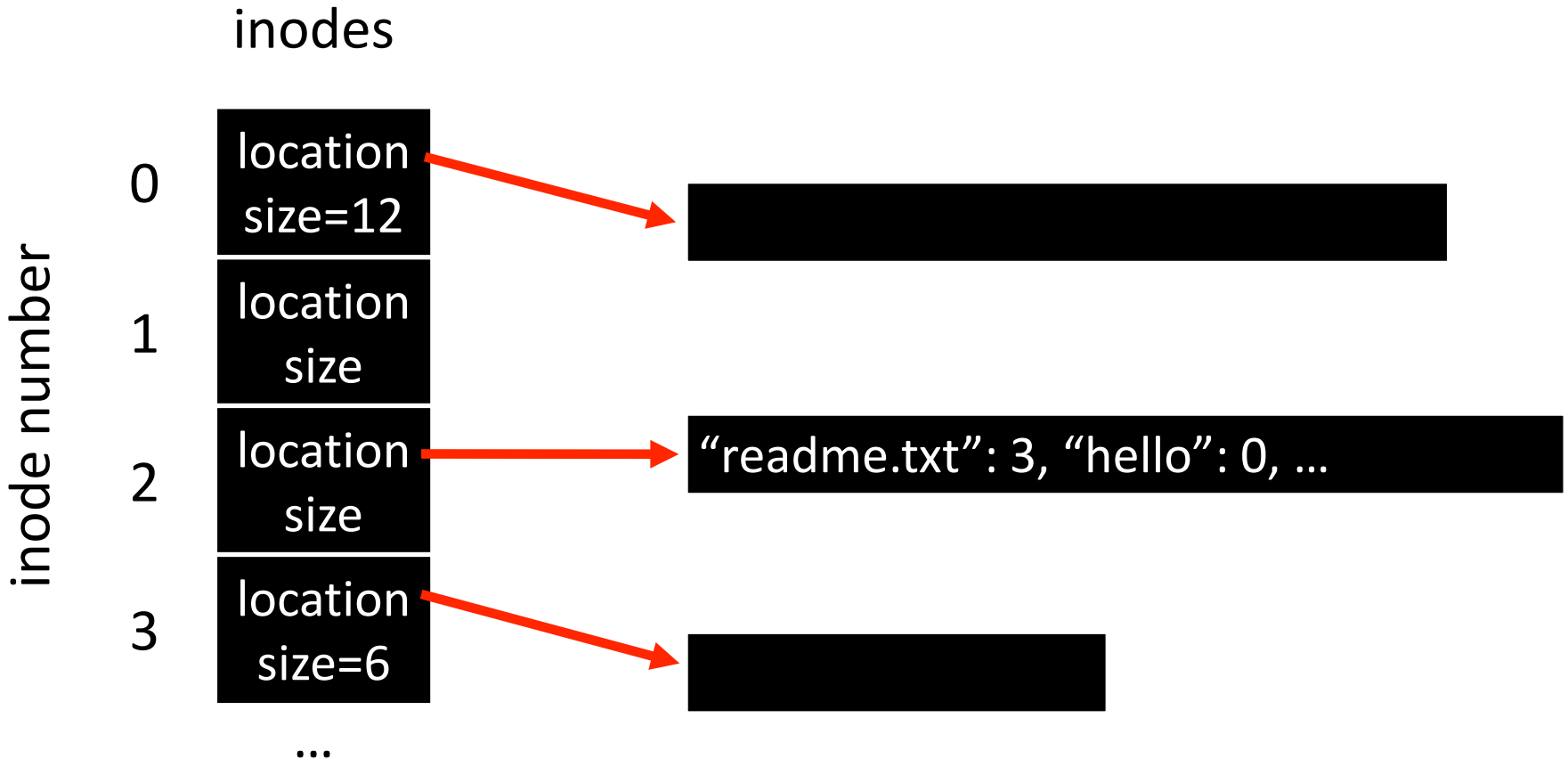
File Names

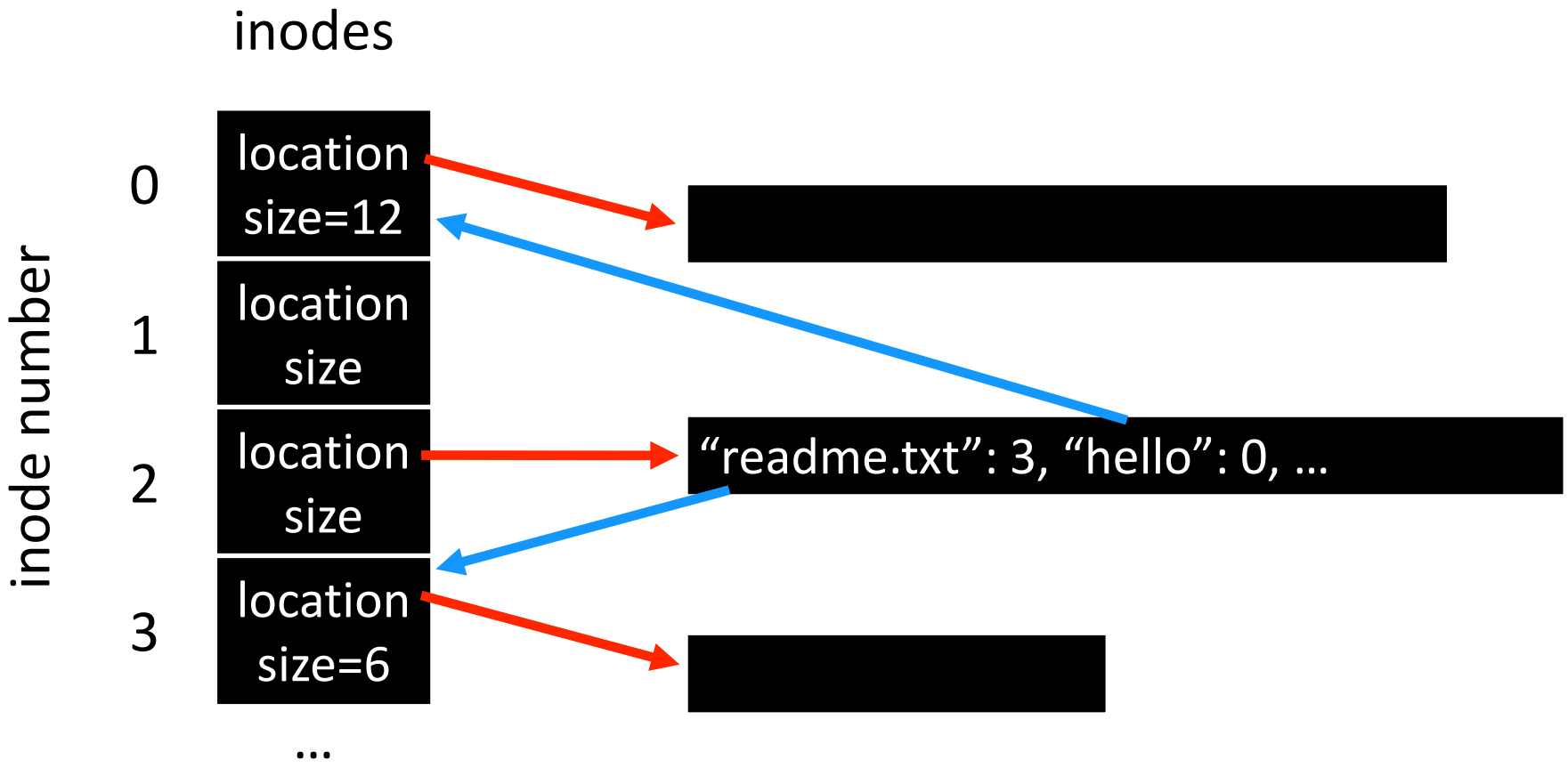
- **Three types of names**
  - Unique id: inode numbers
  - Path
  - File descriptor

Paths

- String names are friendlier than number names
- File system still interacts with inode numbers
- Store *path-to-inode* mappings in predetermined "root" file (typically inode 2)
  - Directory!


inodes
inode number
0
location
size=12
1
location
size
2
location
size
3
location
size=6
...

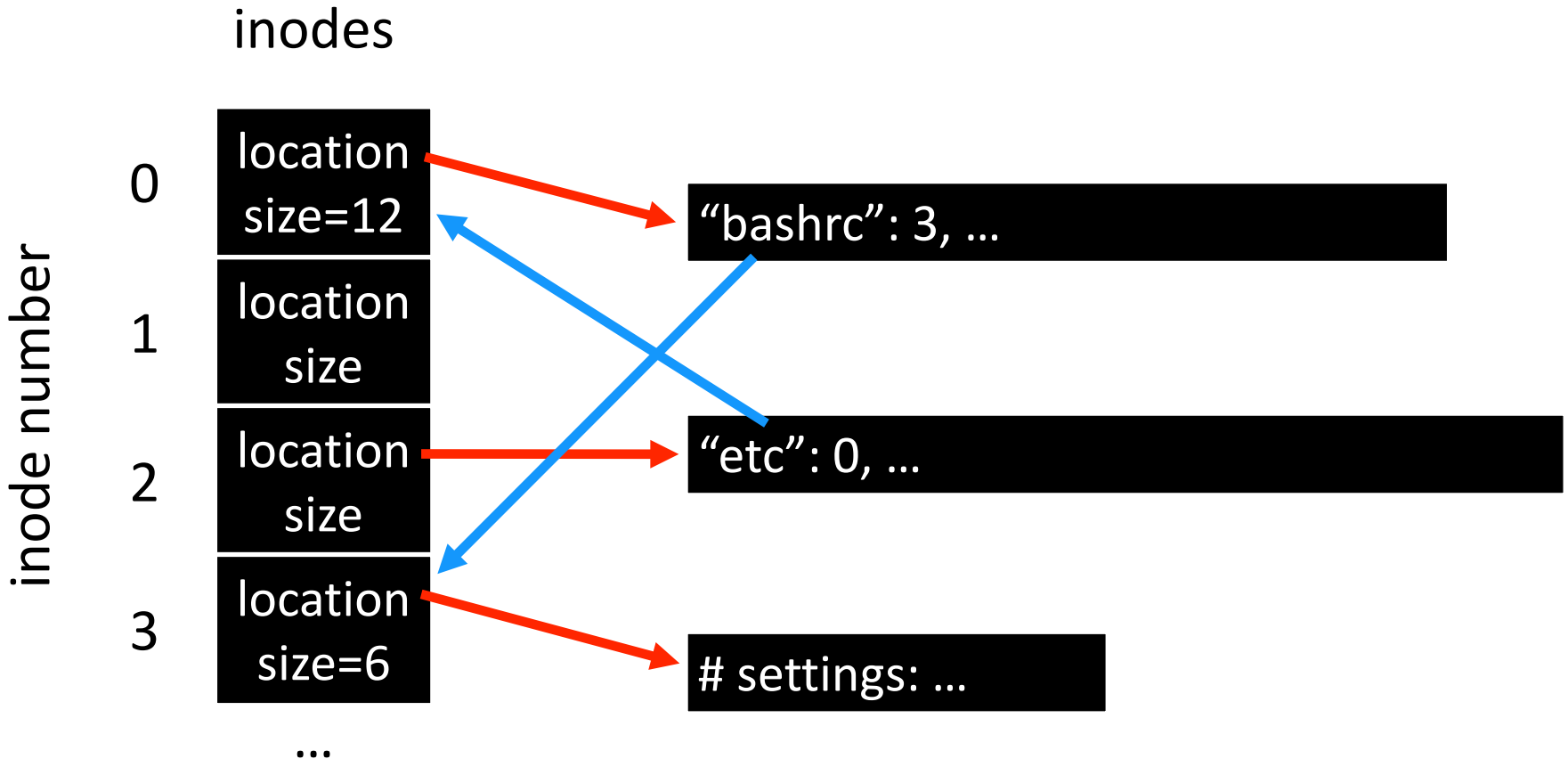

inodes
inode number
0
location
size=12
1
location
size
2
location
size
3
location
size=6
...
“readme.txt”: 3, “hello”: 0, …

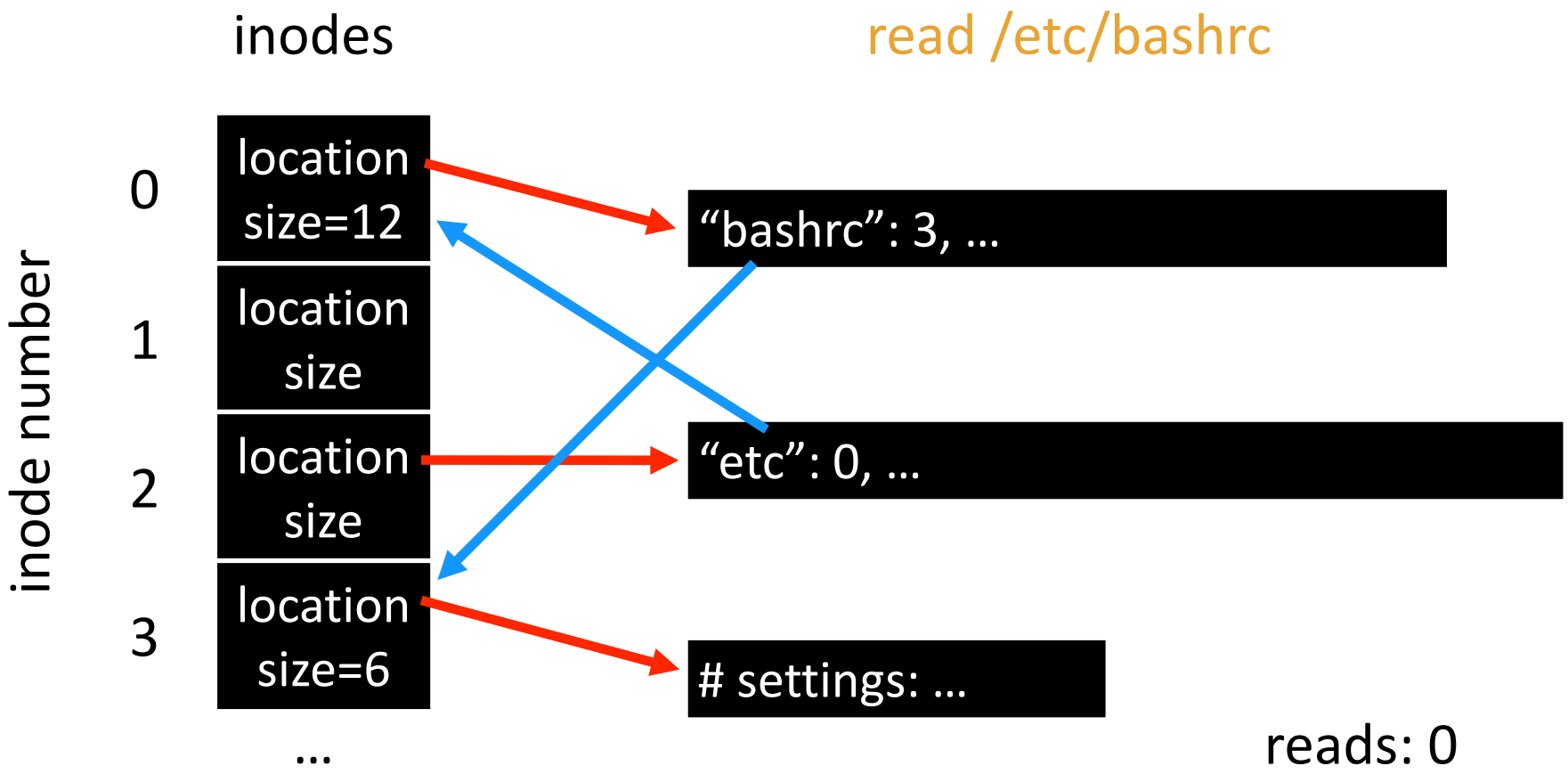


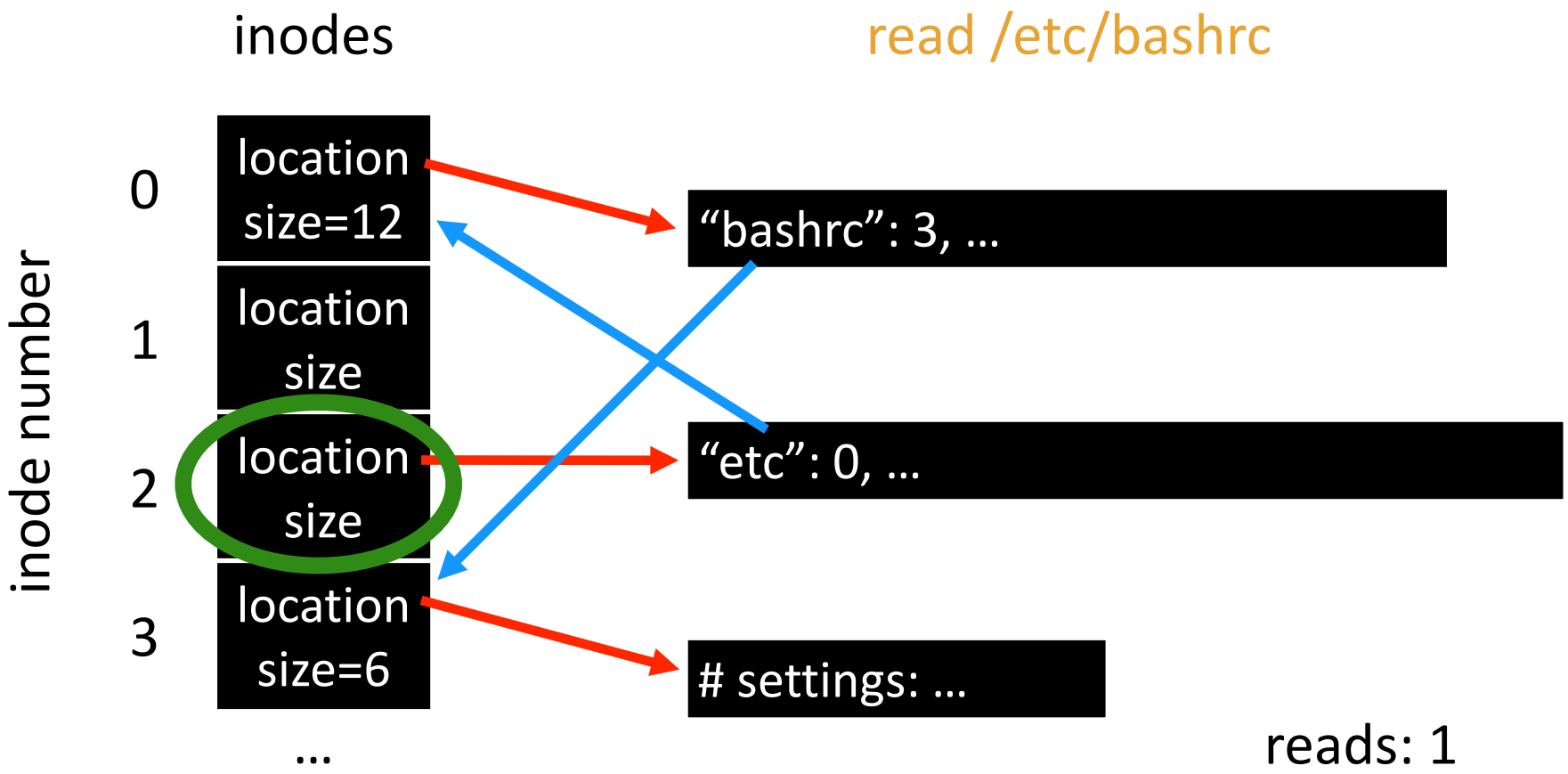
Can not have two files with the same name

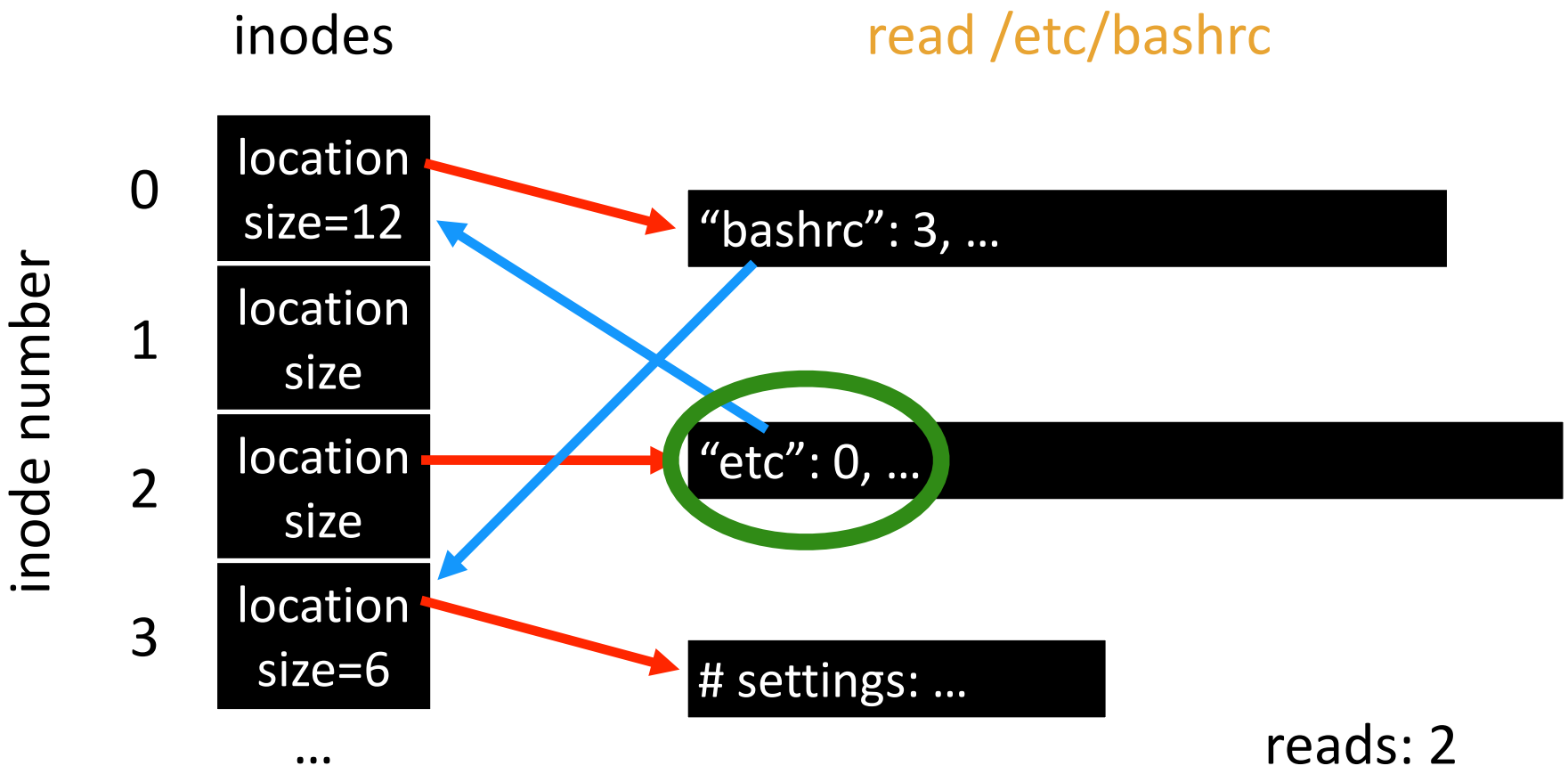
Paths

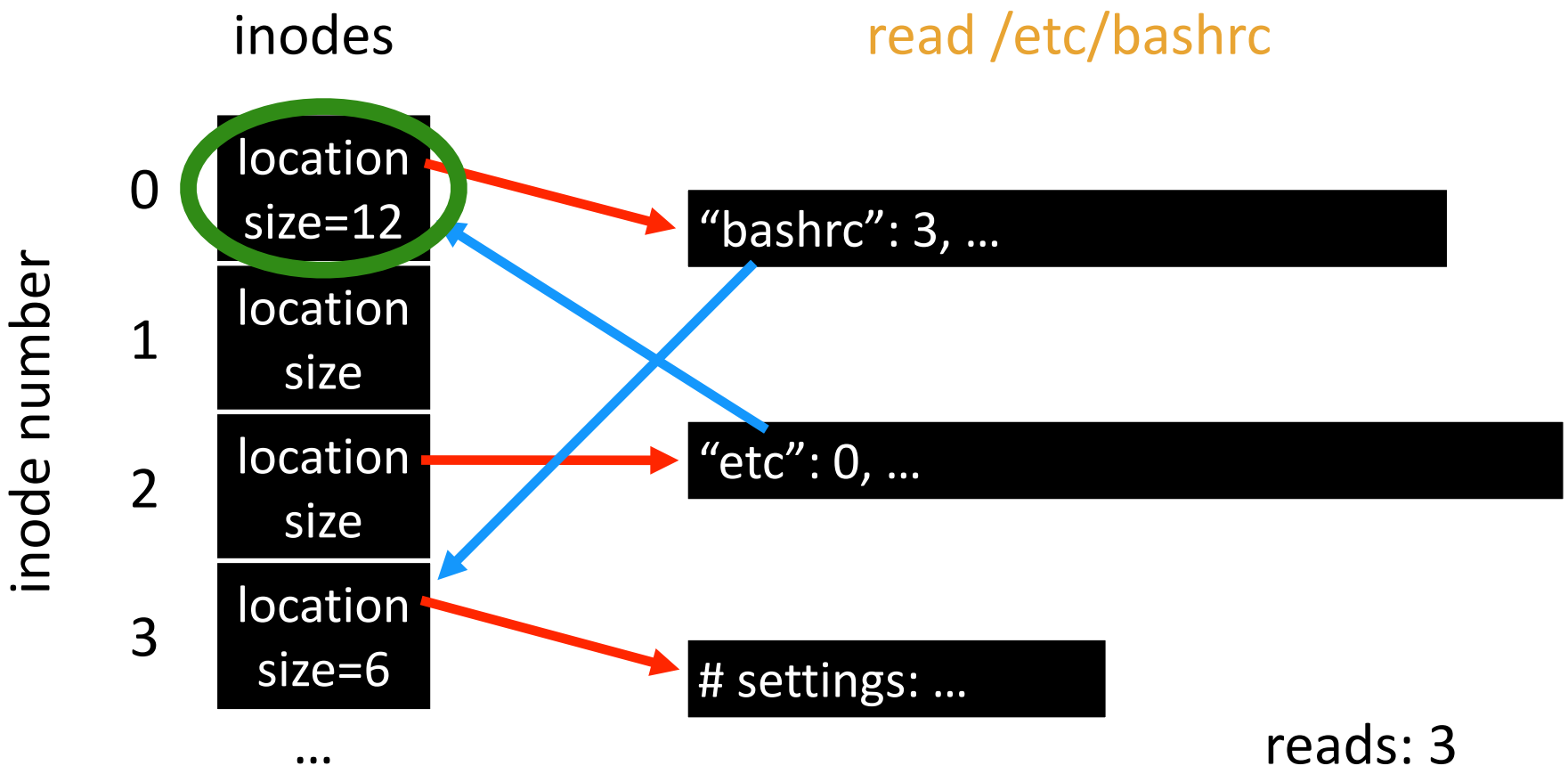
- **Generalize!**
- **Directory Tree instead of single root directory**
- **Only path+file name needs to be unique**
  - /usr/dusseau/file.txt
  - /tmp/file.txt
- **Store file-to-inode mapping for each directory**

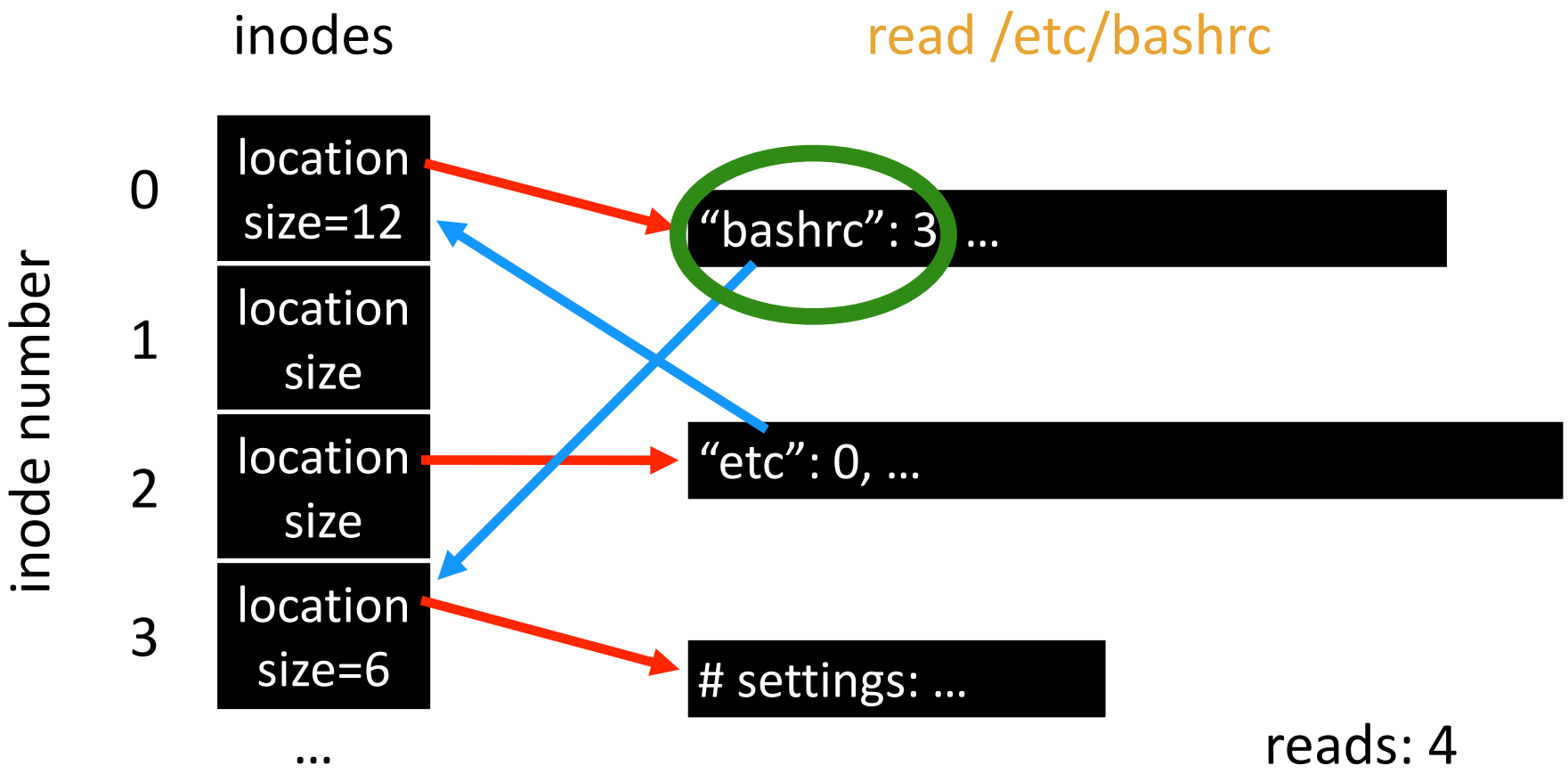

inodes
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
“bashrc”: 3, …
“etc”: 0, …
settings: …

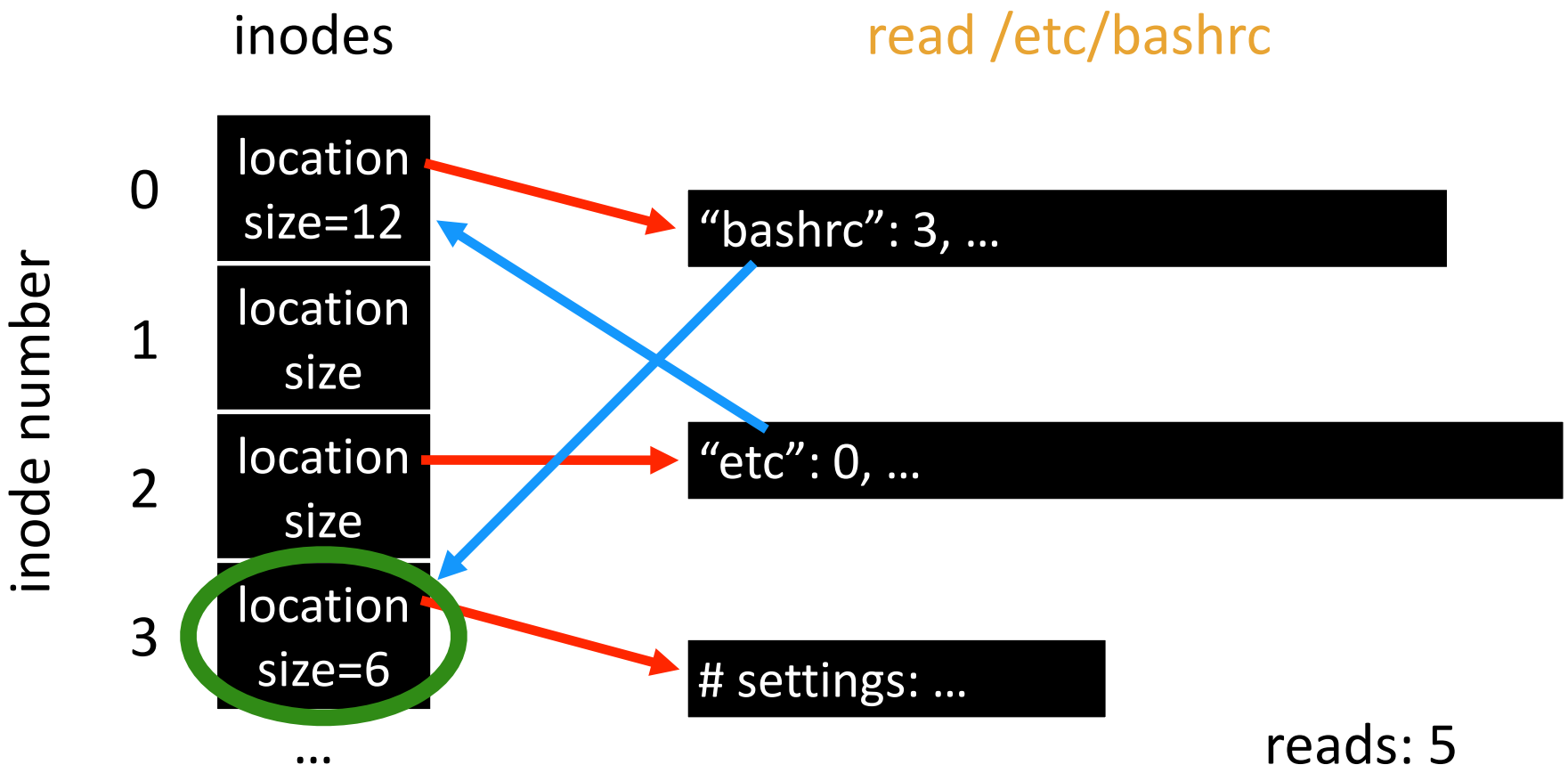

inodes
read /etc/bashrc
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
“bashrc”: 3, …
“etc”: 0, …
settings: …
reads: 0

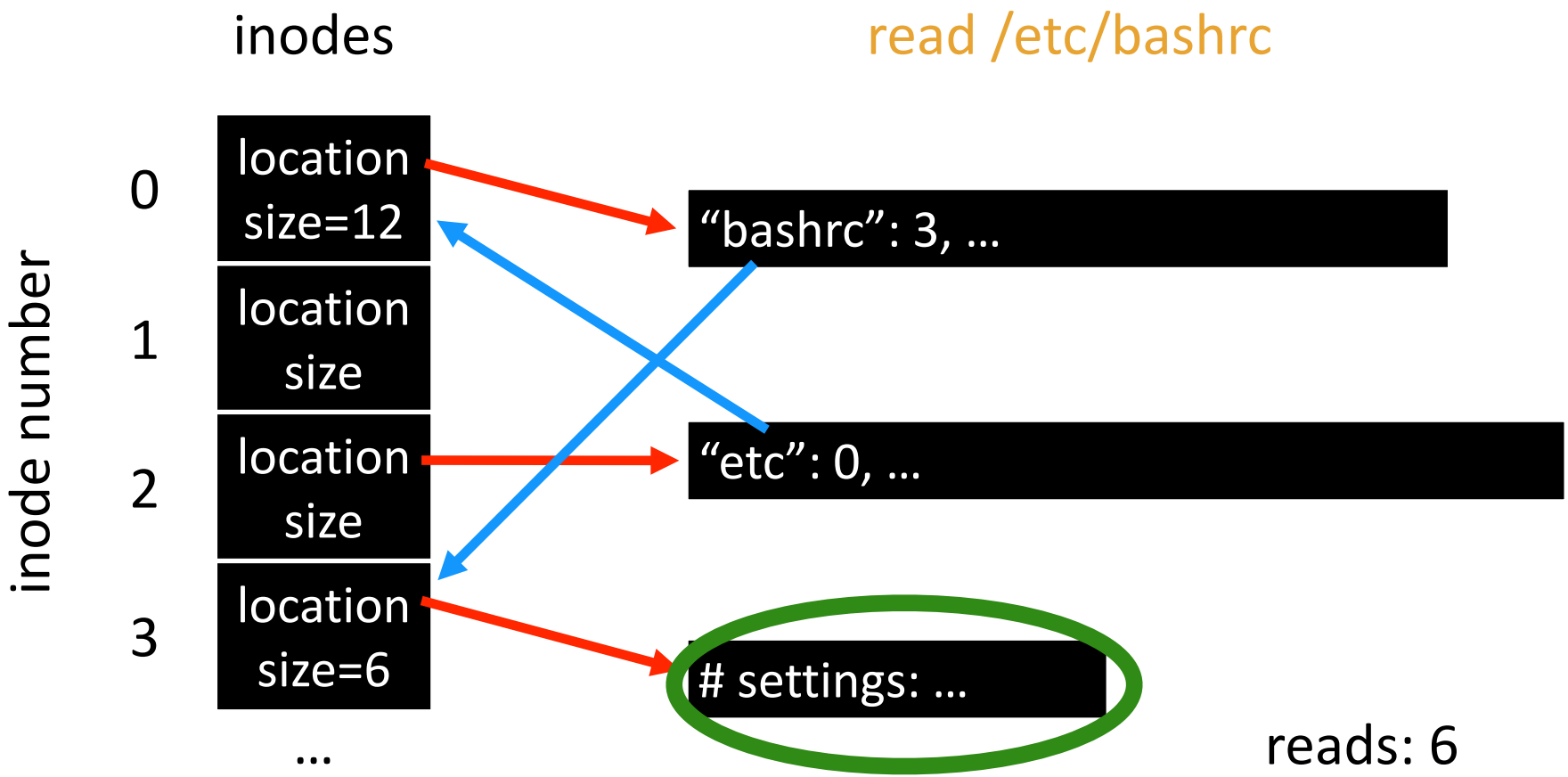

inodes
read /etc/bashrc
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
…
“bashrc”: 3, …
“etc”: 0, …
settings: …
reads: 1


inodes
read /etc/bashrc
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
“bashrc”: 3, …
“etc”: 0, …
settings: …
reads: 2


inodes
read /etc/bashrc
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
“bashrc”: 3, ...
“etc”: 0, ...
settings: ...
reads: 3


inodes
read /etc/bashrc
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
“bashrc”: 3 ...
“etc”: 0, ...
settings: ...
reads: 4


inodes
read /etc/bashrc
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
“bashrc”: 3, …
“etc”: 0, …
settings: …
reads: 5



Reads for getting final inode called “traversal”

Read root dir (inode and data);
read etc dir (inode and data);
read bashrc file (indode and data)

Directory Calls

- **mkdir: create new directory**
- **readdir: read/parse directory entries**
- **Why no writedir?**

Special Directory Entries

```
$ ls -la
total 728
drwxr-xr-x  34 trh  staff    1156 Oct 19 11:41 .
drwxr-xr-x+ 59 trh  staff    2006 Oct  8 15:49 ..
-rw-r--r--@  1 trh  staff    6148 Oct 19 11:42 .DS_Store
-rw-r--r--   1 trh  staff     553 Oct  2 14:29 asdf.txt
-rw-r--r--   1 trh  staff     553 Oct  2 14:05 asdf.txt~
drwxr-xr-x   4 trh  staff     136 Jun 18 15:37 backup
…
```

cd /; ls -lia

File API (attempt 2)

pread(char *path, void *buf,
off_t offset, size_t nbyte)

pwrite(char *path, void *buf,
off_t offset, size_t nbyte)

- Disadvantages?

  Expensive traversal!
  Goal: traverse once

File Names

- **Three types of names:**
  - inode
  - path
  - file descriptor

File Descriptor (fd)

- **Idea:**
  - Do expensive traversal once (open file)
    store inode in descriptor object (kept in memory).
  - Do reads/writes via descriptor, which tracks offset

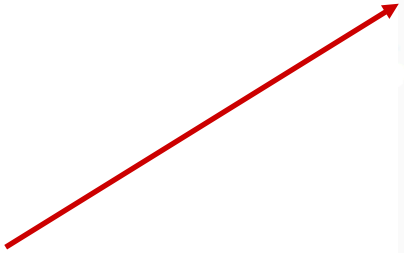
- **Each process:**
  - File-descriptor table contains pointers to open file descriptors

- **Integers used for file I/O are indexes into this table**
  - stdin: 0, stdout: 1, stderr: 2

FD Table (xv6)

```
struct file {
  ...
  struct inode *ip;
  uint off;
};

// Per-process state
struct proc {
  ...
  struct file *ofile[NOFILE];  // Open files
  ...
}
```

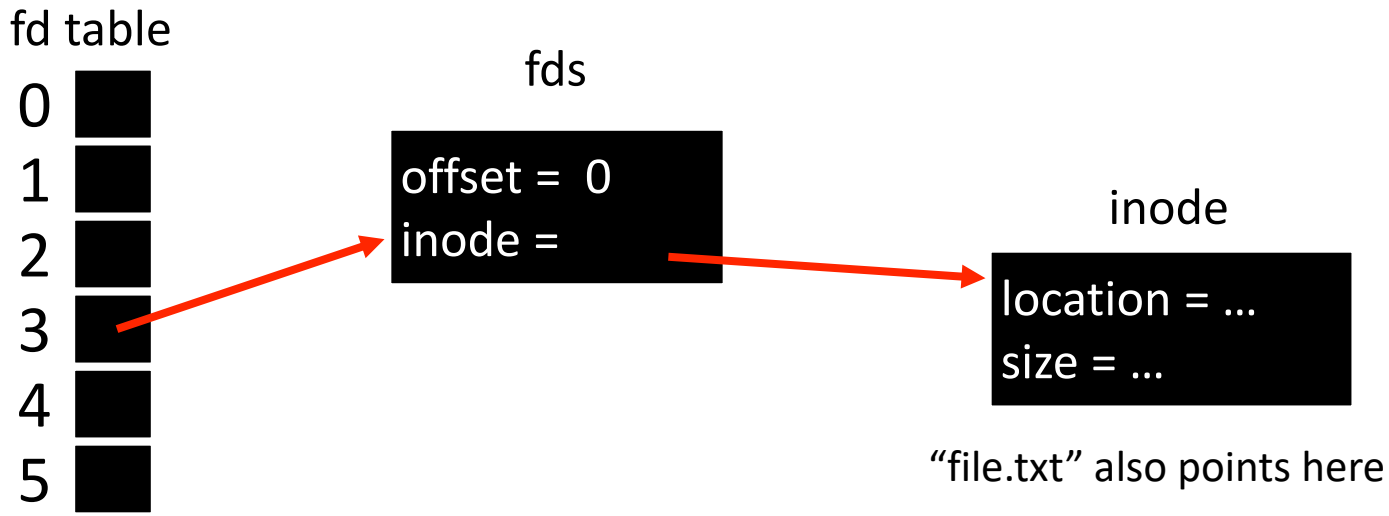


Data Fields	
uint	dev
uint	inum
int	ref
int	flags
short	type
short	major
short	minor
short	nlink
uint	size
uint	addrs [NDIRECT+1]

Code Snippet

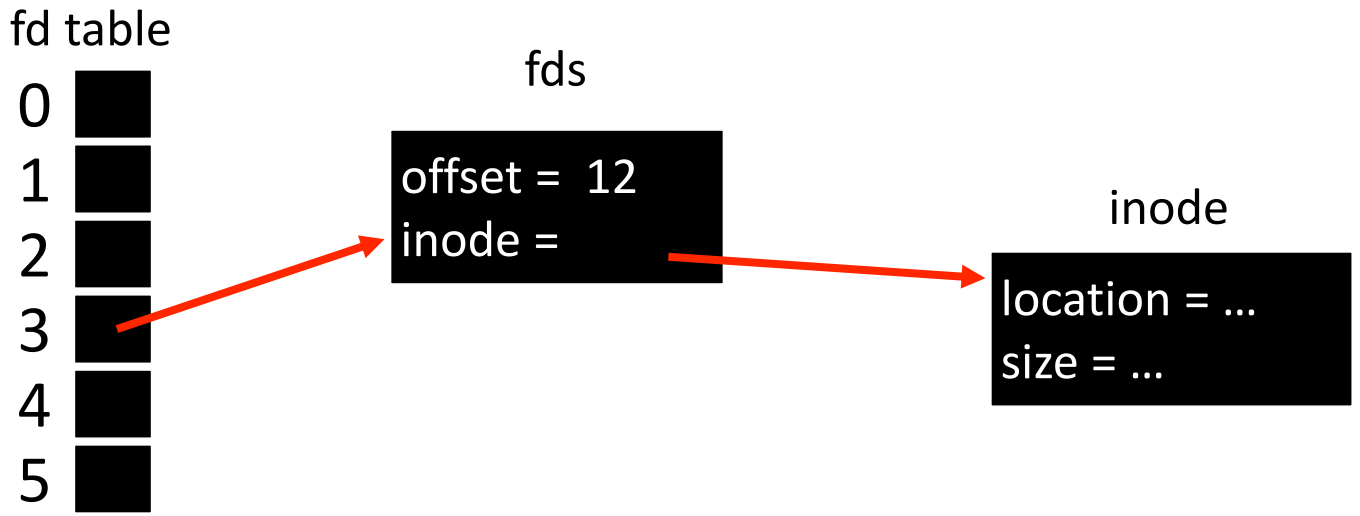
```
int fd1 = open("file.txt"); // returns 3
read(fd1, buf, 12);
int fd2 = open("file.txt"); // returns 4
int fd3 = dup(fd2);         // returns 5
```

Code Snippet



int fd1 = open(“file.txt”); // returns 3

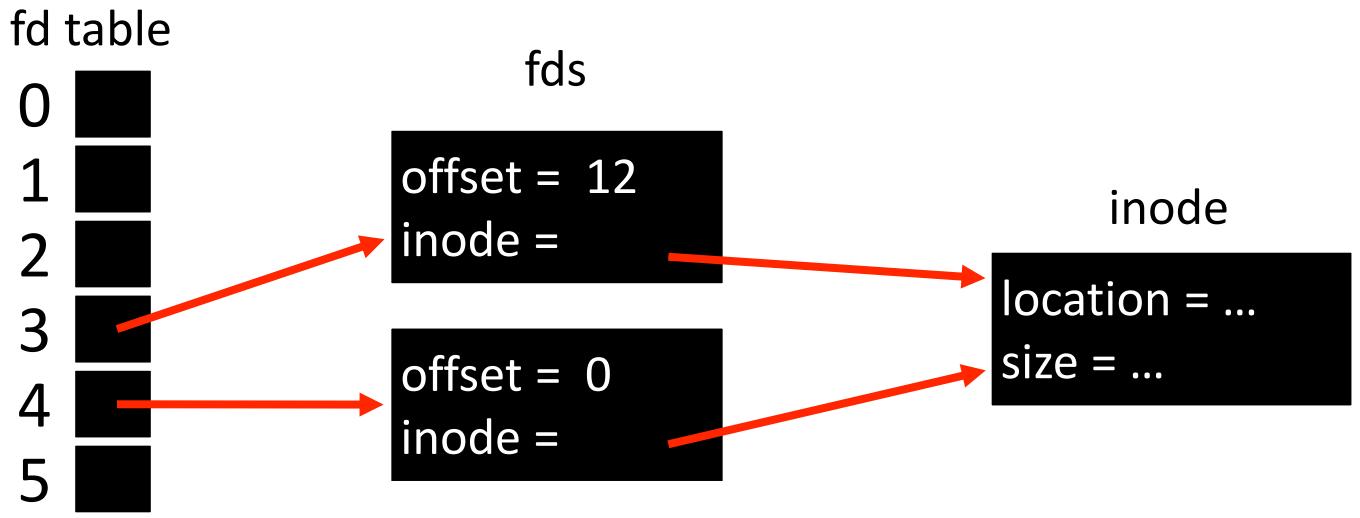
Code Snippet



int fd1 = open(“file.txt”); // returns 3

read(fd1, buf, 12);

Code Snippet

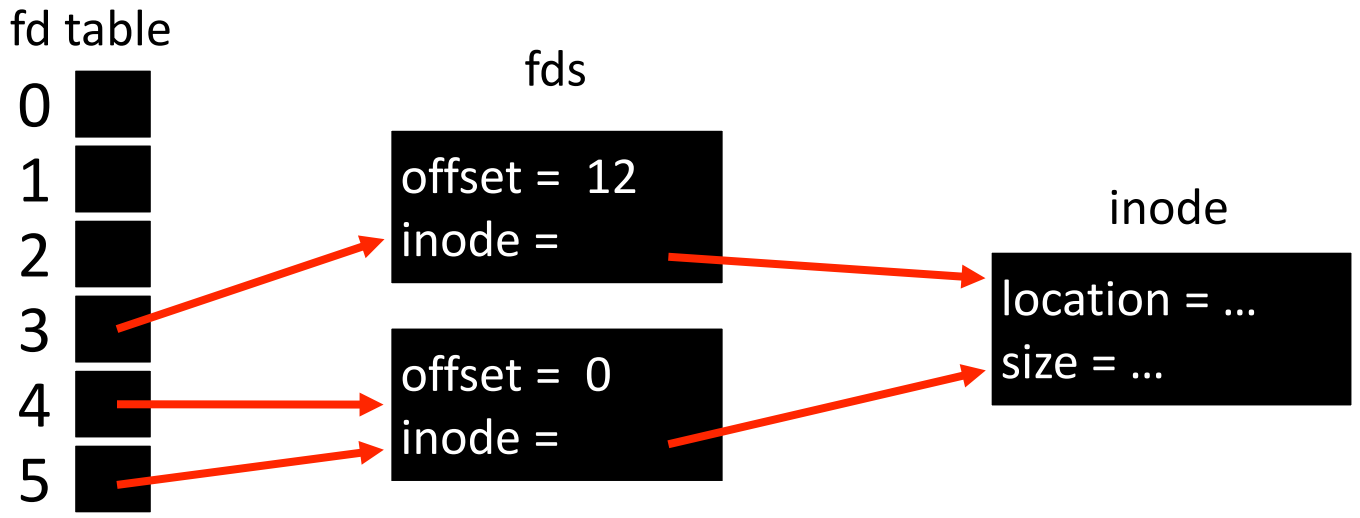


int fd1 = open(“file.txt”); // returns 3

read(fd1, buf, 12);

int fd2 = open(“file.txt”); // returns 4

Code Snippet




```
int fd1 = open("file.txt"); // returns 3
read(fd1, buf, 12);
int fd2 = open("file.txt"); // returns 4
int fd3 = dup(fd2);         // returns 5
```

File API (attempt 3)

int fd = open(char *path, int flag, mode_t mode)

read(int fd, void *buf, size_t nbyte)

write(int fd, void *buf, size_t nbyte)

close(int fd)

- Advantages:
  - string names
  - hierarchical
  - traverse once
  - different offsets precisely defined

Deleting Files

- There is no system call for deleting files!
- Inode (and associated file) is garbage collected when there are no references (from paths or fds)
- Paths are deleted when: unlink() is called
- FDs are deleted when: close() or process quits

Network File System Designers

A process can open a file, then remove the directory entry for the file so that it has no name anywhere in the file system, and still read and write the file. This is a disgusting bit of UNIX trivia and at first we were just not going to support it, but it turns out that all of the programs we didn't want to have to fix (csh, sendmail, etc.) use this for temporary files.

~ Sandberg *et al.*

Links: Demonstrate

- **Show hard links: Both path names use same inode number**

  File does not disappear until all removed; cannot link directories

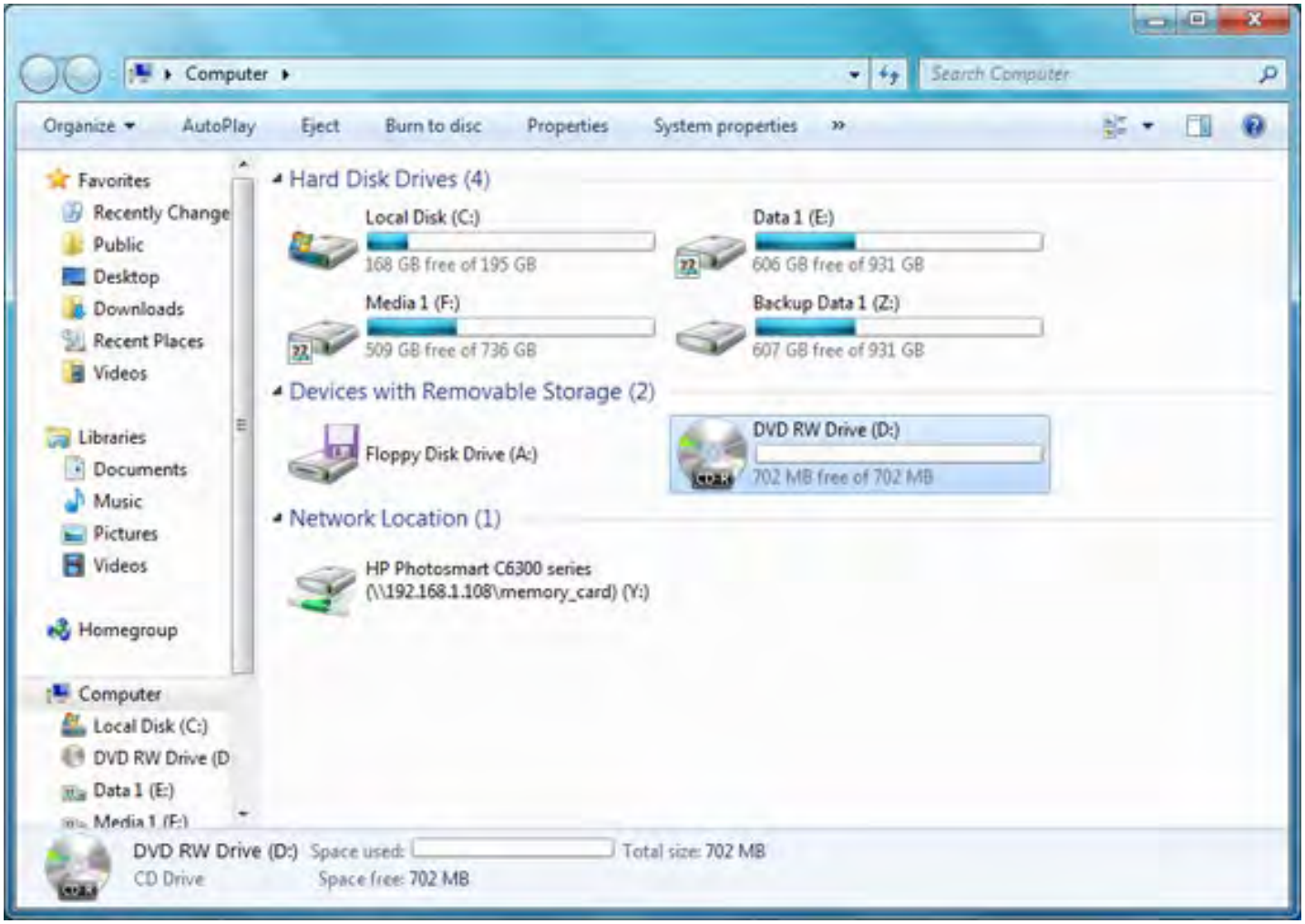
  ```
  Echo "Beginning…" > file1
  "ln file1 link"
  "cat link"
  "ls –li" to see reference count
  Echo "More info…" >> file1
  "mv file1 file2" // rename
  "rm file2" // decreases reference count
  ```

- **Soft or symbolic links: Point to second path name; can softlink to dirs**
  - `"ln –s oldfile softlink"`
  - Another file type (besides regular file and directory), 快捷方式
  - **Records the path of the file** as its file data
  - Confusing behavior: "**file does not exist**"!
  - Confusing behavior: "cd linked_dir; **cd ..**; in different parent!

Many File Systems

- **Users often want to use many file systems**
- **For example:**
  - main disk
  - backup disk
  - Andrew File System (AFS)
  - thumb drives
- **What is the most elegant way to support this?**

Many File Systems: Approach 1



- http://www.ofzenandcomputing.com/burn-files-cd-dvd-windows7/

Many File Systems: Approach 2

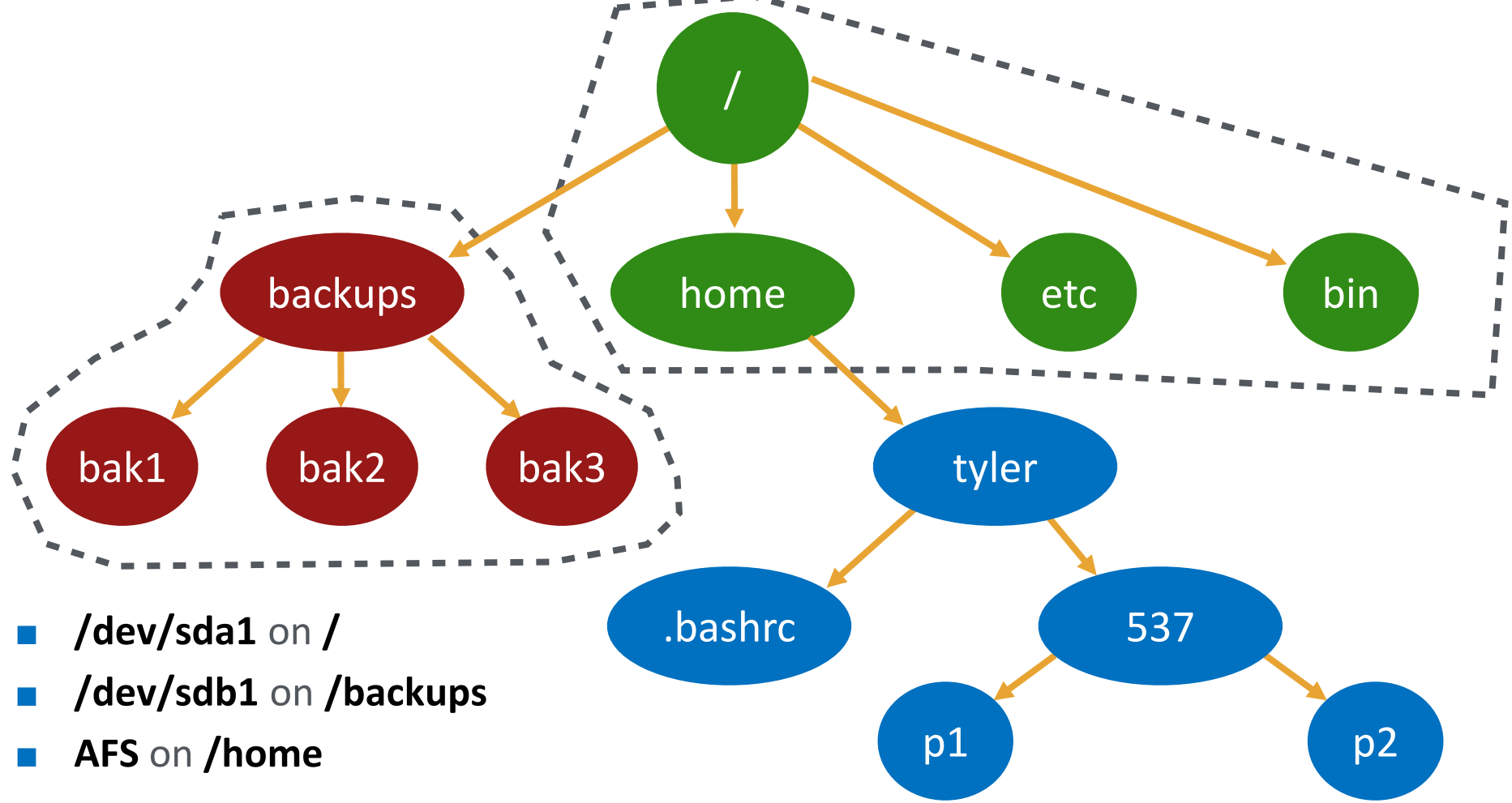
Idea: stitch all the file systems together into a super file system!

sh> mount

/dev/sda1 on / type ext4 (rw)

/dev/sdb1 on /backups type ext4 (rw)

AFS on /home type afs (rw)



- **/dev/sda1** on **/**
- **/dev/sdb1** on **/backups**
- **AFS** on **/home**

Communicating Requirements: fsync

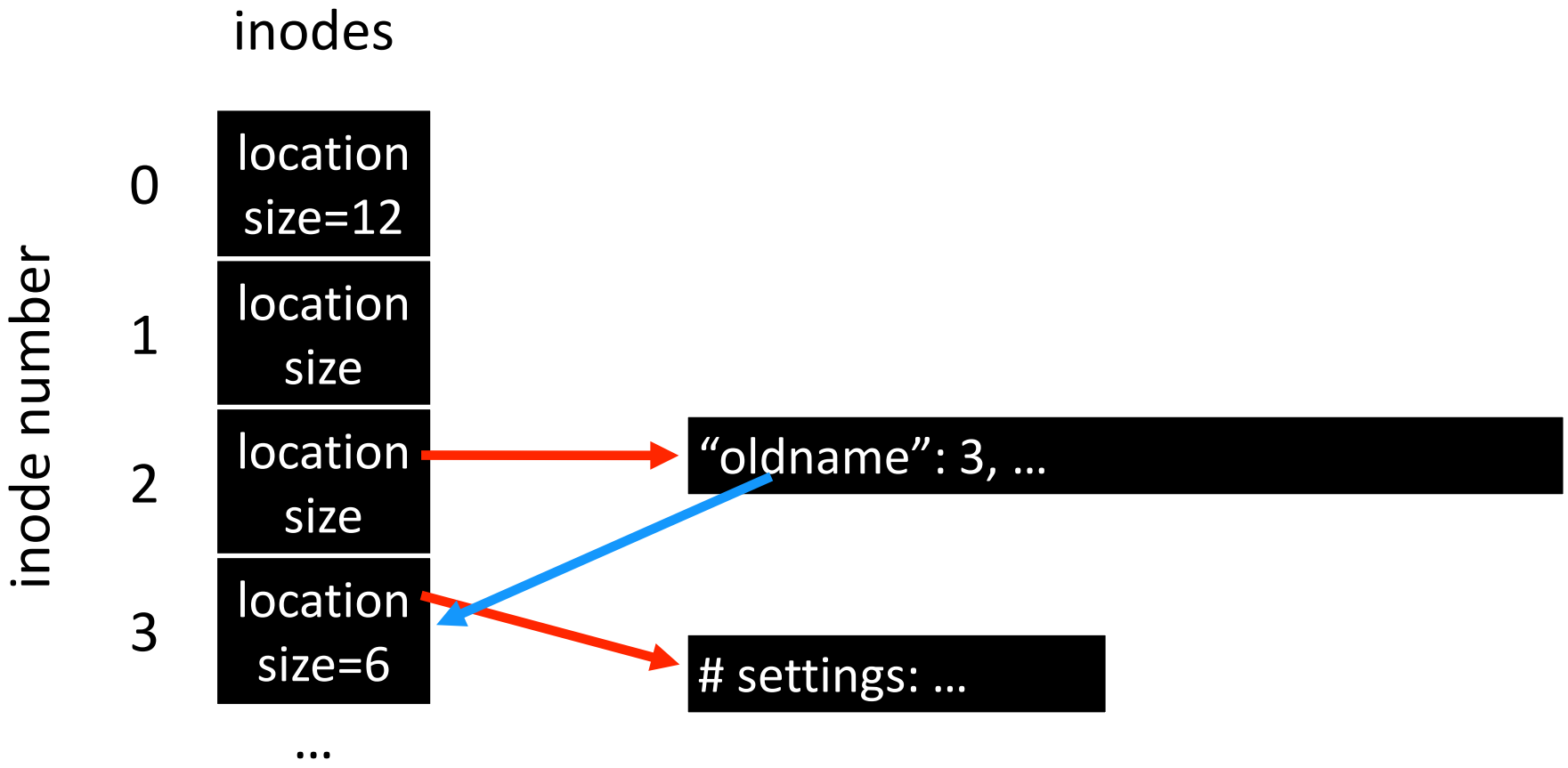
- **File system keeps newly written data in memory for a while**
  - Write buffering improves performance (why?)

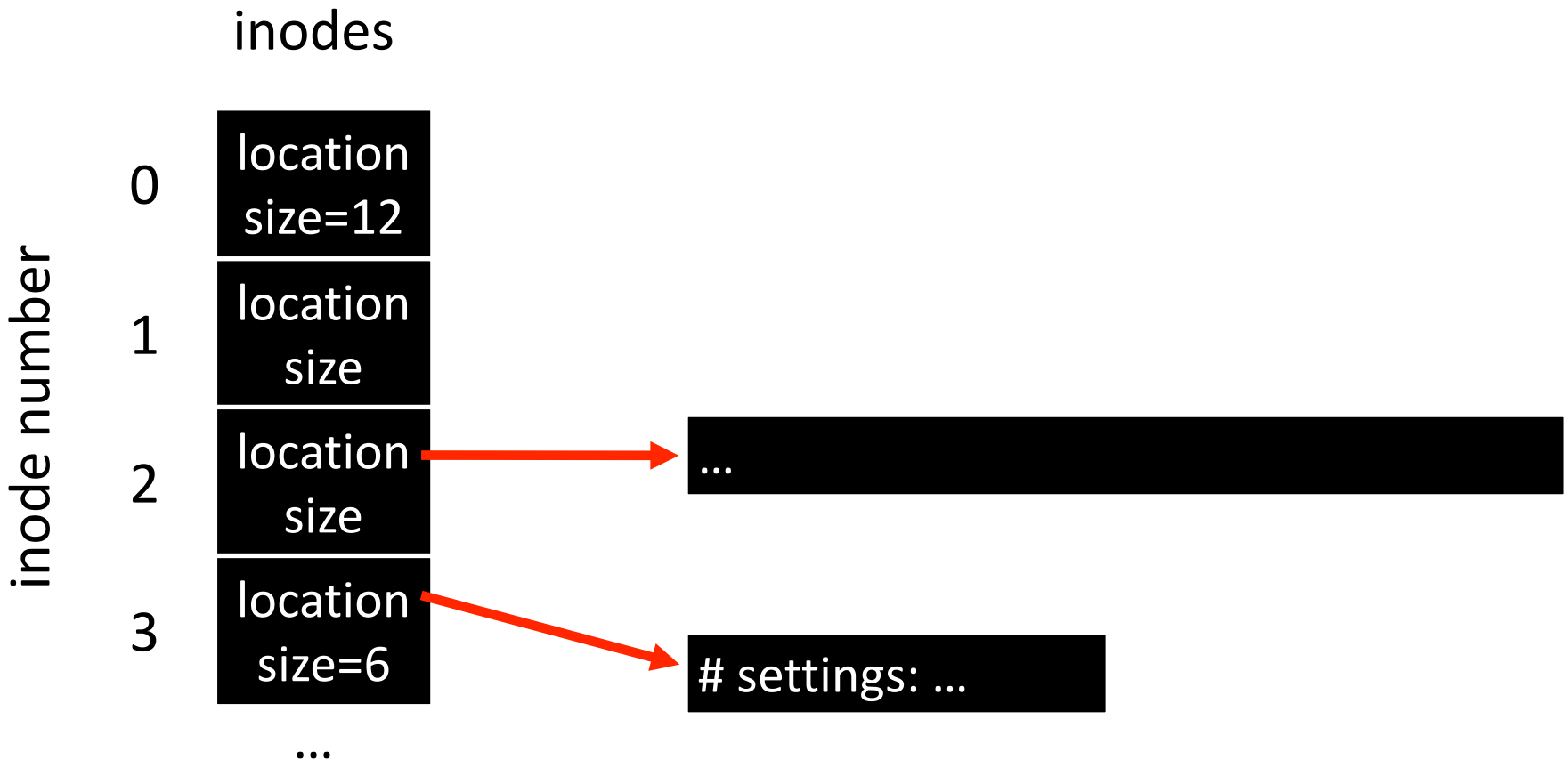
- **But what if system crashes before buffers are flushed?**
- **If application cares:**
  - `fsync(int fd)` forces buffers to flush to disk, and (usually) tells disk to flush its write cache too
- **Makes data durable**

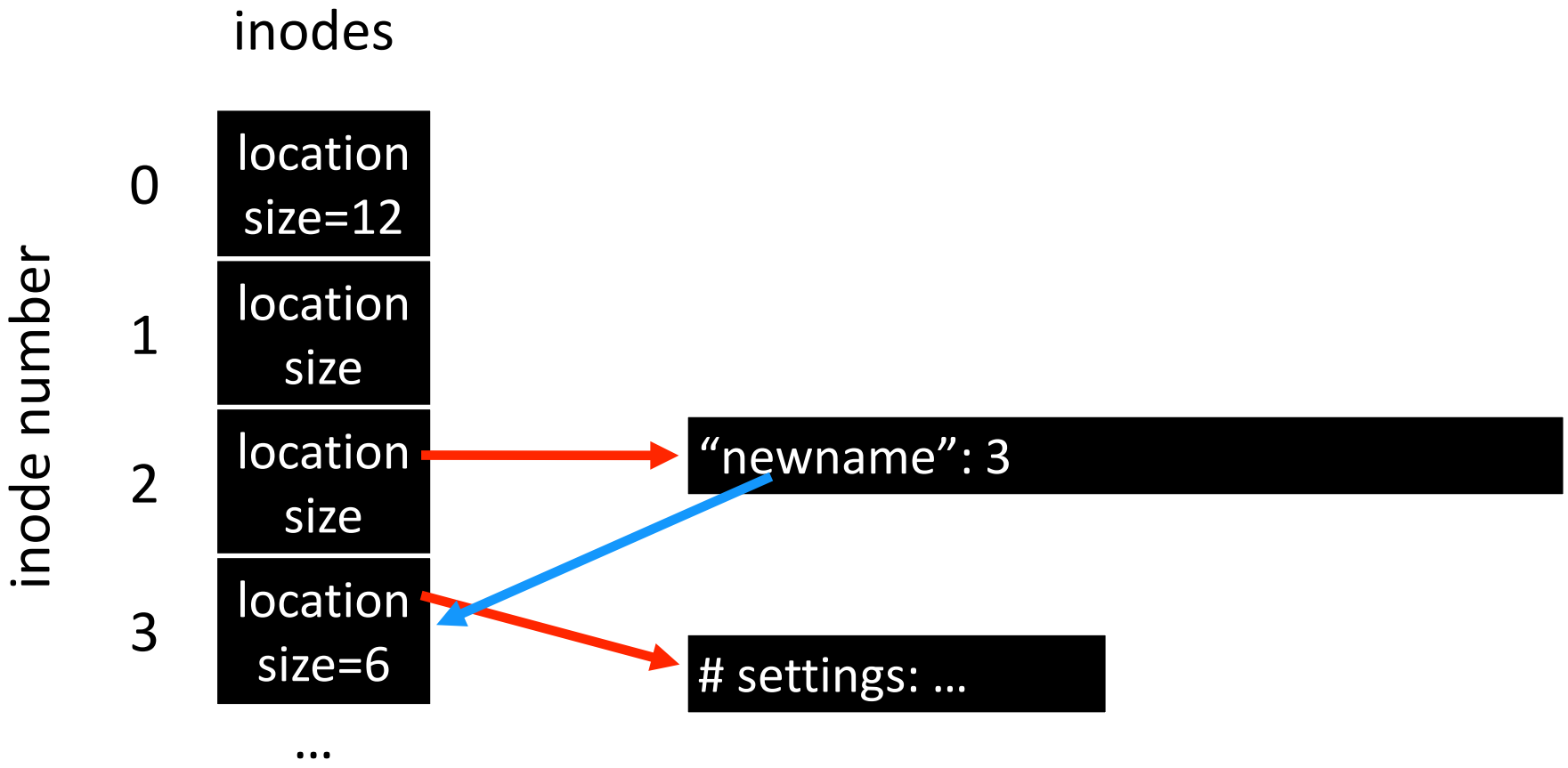
rename

- rename**(char *old, char *new):**
  - deletes an old link to a file
  - creates a new link to a file
  - use “mv” command

- **Just changes name of file, does not move data**
  - Even when renaming to new directory


inodes
inode number
0
location
size=12
1
location
size
2
location
size
3
location
size=6
...
“oldname”: 3, …
settings: …


inodes
inode number
0
1
2
3
location
size=12
location
size
location
size
location
size=6
...
...
settings: ...


inodes
inode number
0
location
size=12
1
location
size
2
location
size
3
location
size=6
...
“newname”: 3
settings: …

rename

- rename**(char *old, char *new):**
  - deletes an old link to a file
  - creates a new link to a file

- **What if we crash?**
  - FS does extra work to guarantee atomicity
  - the file will either has the old name and the new name if crashes
  - return to this issue later…

Atomic File Update

- **Say application wants to update `file.txt` atomically**
  - If crash, should see only old contents or only new contents

- **1. write new data to `file.txt.tmp` file**
- **2. `fsync file.txt.tmp`**
- **3. `rename file.txt.tmp` over `file.txt`, replacing it**

Summary

- **Using multiple types of name provides**
  - convenience
  - efficiency
- **Mount and link features provide flexibility.**

- **Special calls (fsync, rename) let developers communicate special requirements to file system**